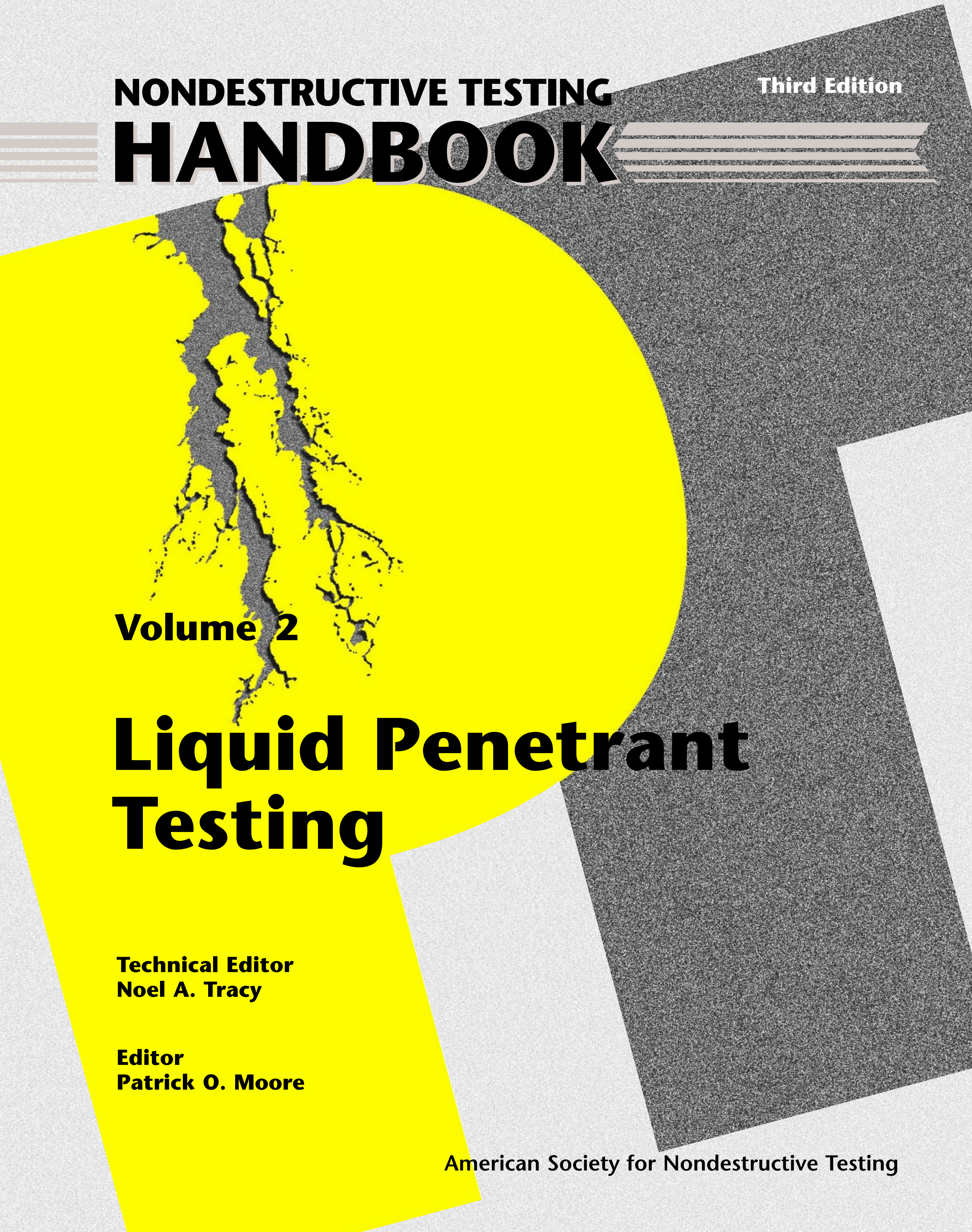
NONDESTRUCTIVE TESTING HANDBOOK

Third Edition



Volume 2

Liquid Penetrant Testing

Technical Editor
Noel A. Tracy

Editor
Patrick O. Moore

American Society for Nondestructive Testing

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President's Foreword

Liquid Penetrant Testing is the second volume of the third edition of the *Nondestructive Testing Handbook*. This volume continues to advance the series' mission of disseminating information about the technology.

Nondestructive testing contributes to public safety and to our quality of life in countless ways. The technology has made possible those advances in technology that are the hallmark of this turn of the century.

Technology typically relies on things that can be counted, on numbers — on measurements and data that can be quantified, processed and stored by computer. In such an age, liquid penetrant testing occupies a special place because it is a qualitative method that has defied quantification. At the same time, the method remains extremely sensitive, reliable, cost effective and useful to industry. Because liquid penetrant testing relies so much on the training and experience of the human inspector, an authoritative handbook is especially important.

ASNT has been fortunate that the Technical Council's Penetrant Committee is superbly qualified to provide the expertise needed to rewrite and review a book of such importance and scope. The collaboration between the volunteers and staff in the writing and review of this volume has made productive use of ASNT's volunteer resources. Scores of authors and reviewers have donated thousands of hours to this volume.

Liquid Penetrant Testing was produced under the guidance of ASNT's Handbook Development Committee. A special note of thanks is extended to Handbook Development Director Gary Workman; to recent Penetrant Committee Chairs William E. Mooz, Vilma G. Holmgren, Brian MacCracken and Michael L. White; to Technical Editor Noel A. Tracy; and to Handbook Editor Patrick Moore for their dedicated efforts.

The existence of *Liquid Penetrant Testing* is testimony to the commitment of the American Society for Nondestructive Testing (ASNT) to its missions of providing technical information and instructional materials and of promoting nondestructive testing technology as a profession.

Robert E. Green, Jr.
ASNT National President (1998-99)

Foreword

The Aims of a Handbook

The volume you are holding in your hand is the second in the third edition of the *Nondestructive Testing Handbook.* Now is a good time to reflect on the purposes and nature of a handbook.

Handbooks exist in many disciplines of science and technology, and certain features set them apart from other reference works. A handbook should ideally give the basic knowledge necessary for an understanding of the technology, including both scientific principles and means of application.

The typical reader may be assumed to have completed three years of college toward a degree in mechanical engineering or materials science and hence has the background of an elementary physics or mechanics course. Occasionally an engineer may be frustrated by the difficulty of the discussion in a handbook. That happens because the assumptions about the reader vary according to the subject in any given chapter. Computer science requires a sort of background different from nuclear physics, for example, and it is not possible for the handbook to give all the background knowledge ancillary to nondestructive testing.

A handbook offers a view of its subject at a certain period in time. Even before it is published, it starts to get obsolete. The authors and editors do their best to be current but the technology will continue to change even as the book goes to press.

Standards, specifications, recommended practices and inspection procedures may be discussed in a handbook for instructional purposes, but at a level of generalization that is illustrative rather than comprehensive. Standards writing bodies take great pains to ensure that their documents are definitive in wording and technical accuracy. People writing contracts or procedures should consult real standards when appropriate.

Those who design qualifying examinations or study for them draw on handbooks as a quick and convenient way of approximating the body of knowledge. Committees and individuals who write or anticipate questions are selective in what they draw from any source. The parts of a handbook that give scientific background, for instance, may have little bearing on a practical examination. Other parts of a handbook are specific to a certain industry. Although a handbook does not pretend to offer a complete treatment of its subject, its value and convenience are not to be denied.

The present volume is a worthy addition to the third edition. The editors, technical editors and many contributors and reviewers worked together to bring the project to completion. For their scholarship and dedication I thank them all.

Gary L. Workman
Handbook Development Director

Preface

What could be simpler than directly viewing a part with a suitable light to see an indication of a discontinuity produced by dipping the part in a colored liquid, washing excess liquid off with a water hose and drying the part? As one gains experience with liquid penetrant testing, a more appropriate question may come to mind: how can a *simple* technique be so complex?

Because the liquid penetrant test is fundamentally simple and the equipment (if any) is easy to operate, untrained observers usually think they can save time and money by borrowing some liquid penetrant materials and performing the test themselves. However, as training and experience show, the best materials are worthless without strict adherence to processing guidelines that direct and control the test from the preparation of the inspection surface (including the crack surface), to the visual examination of the part to locate an indication. Furthermore, the materials themselves require some basic care so that they don't spoil. Even experienced inspectors must avoid the trap of apparent simplicity, which breeds complacency. Inattention to processing details and materials maintenance will result in a test that will fail because it is out of control. The editing of this volume has attempted to emphasize these issues.

Perhaps *complex* is the wrong word to describe the test; *methodical* is probably a better descriptor. Apparent disadvantages of the test can usually be overcome by modifying a step or applying a different set of steps. For example, inspectors could work in tandem when testing large areas, for which process control is more difficult, or use liquid penetrant that requires more than just water to remove it if removal of the liquid penetrant from shallow cracks is a concern. In another situation the requirement for strict process control may be turned into an advantage in that methodical adjustments in the process can adjust the sensitivity of the test so that only the relevant discontinuities are detected.

Despite its subtlety liquid penetrant testing does work. Large areas, small areas, plane surfaces, multifaceted surfaces, all can be inspected quickly and economically. Because of this advantage it is tempting to use liquid penetrant testing in place of other, more expensive point sensitive techniques such as eddy current testing. However, in some applications, especially where residual compressive stresses exist, the surface opening of a discontinuity may be too small for reliable liquid penetrant testing. A good example is a small fatigue crack.

Liquid penetrant materials are constantly being improved to meet general or specific application requirements, to make the test process more forgiving or to satisfy new environmental concerns. In some applications water washable liquid penetrants are as sensitive as postemulsifiable types. Equipment is also improving. Properly designed and monitored automated processing systems have the potential to more carefully control the liquid penetrant testing process while alleviating the monotony experienced by an inspector who applies the test steps repetitively.

The technology of liquid penetrant testing lacks a reliable and objective scientific test for evaluating the sensitivity of a liquid penetrant test. Photometers have been used in the laboratory to assign arbitrary sensitivity levels to liquid penetrant systems by measuring the luminance of fluorescent indications. However, even with precisely controlled processing parameters, the luminance measurements on a set of low cycle fatigue cracks have been reproducible only within 20 percent.

Part of the problem has been the difficulty of correlating the physical and chemical phenomena and properties of liquid penetrants to practical liquid penetrant test sensitivity. This difficulty influenced the decision to limit the theoretical discussions in this volume to the practical characteristics of liquid penetrant materials. Because an inspector is ultimately concerned about the presence or absence of a relevant indication, the more that is understood about how the test process affects those characteristics, the more likely a visible indication will be produced.

The future of liquid penetrant testing is sure to include continued efforts to bring machine vision and decision making up to the level of competency achieved with the human eye and brain. Initially, questions of economic feasibility will have to be answered in light of the current economic advantages of liquid penetrant testing, but cheaper technology that works will be used.

The Technical Editor is indebted to the committee members, contributors, reviewers who volunteered to help assemble this book. The aim was to build on the work of those who contributed to previous editions, updating the technical content while preserving the technological story line of lessons learned. The guidance and assistance of the ASNT staff is also gratefully acknowledged.

Noel A. Tracy
Technical Editor

Editor's Preface

The third edition of the *Nondestructive Testing Handbook* continues as the second edition did, with a volume on liquid penetrant testing. This third edition volume is indebted to the preceding edition's volume in many ways. Much of the text is the same, despite significant additions and alterations.

The technical content of this third edition volume differs in several ways from that of the second. (1) Pages have been added to cover new applications, such as filtered particle testing of aerospace composites and quality control of down hole oil field tubular assemblies. (2) A new section on probability of detection may help some facilities to evaluate their inspection procedures. (3) The introduction includes new information on method history and measurement units. (4) The text reflects the fact that materials degrading to the environment have been regulated. (5) A comprehensive glossary is provided. (6) An extensive bibliography lists liquid penetrant testing publications, more than some practitioners of the method might have expected. (7) This third edition volume pays more attention to standards documents than did the second edition; references to current standards have been added throughout.

The contributors and reviewers all brought their gifts individually to this project — collectively they made it better than a product of one person could be. Among these volunteers, the editors would like to thank William E. Mooz for the time he invested in careful reading of the entire book.

ASNT is indebted to Technical Editor Noel A. Tracy and to all the technical experts listed at the end of this foreword. (Please note that people listed as contributors were also reviewers but are listed only once, as contributors.)

It is difficult to overstate the contributions of staff members Hollis Humphries and Joy Grimm to the art, layout and text of the book. I would also like to thank Publications Manager Paul McIntire for his support throughout production.

Patrick O. Moore
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CHAPTER

Introduction to Liquid Penetrant Testing

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PART 1. Nondestructive Testing[1]

Nondestructive testing (NDT) has been defined as comprising those test methods used to examine or inspect a part or material or system without impairing its future usefulness.[1] The term is generally applied to nonmedical investigations of material integrity.

Strictly speaking, this definition of nondestructive testing includes noninvasive medical diagnostics. X-rays, ultrasound and endoscopes are used by both medical and industrial nondestructive testing. Medical nondestructive testing, however, has come to be treated by a body of learning so separate from industrial nondestructive testing that today most physicians never use the word *nondestructive*.

Nondestructive testing is used to investigate specifically the material integrity of the test object. A number of other technologies — for instance, radio astronomy, voltage and amperage measurement and rheometry (flow measurement) — are nondestructive but are not used specifically to evaluate material properties. Radar and sonar are classified as nondestructive testing when used to inspect dams, for instance, but not when they are used to chart a river bottom.

Nondestructive testing asks "Is there something wrong with this material?" Various performance and proof tests, in contrast, ask "Does this component work?" This is the reason that it is not considered nondestructive testing when an inspector checks a circuit by running electric current through it. Hydrostatic pressure testing is another form of proof testing, one that may destroy the test object.

Another gray area that invites various interpretations in defining nondestructive testing is *future usefulness*. Some material investigations involve taking a sample of the inspected part for testing that is inherently destructive. A noncritical part of a pressure vessel may be scraped or shaved to get a sample for electron microscopy, for example. Although future usefulness of the vessel is not impaired by the loss of material, the procedure is inherently destructive and the shaving itself — in one sense the true *test object* — has been removed from service permanently.

The idea of future usefulness is relevant to the quality control practice of sampling. Sampling (that is, less than 100 percent testing to draw inferences about the unsampled lots) *is* nondestructive testing if the tested sample is returned to service. If the steel is tested to verify the alloy in some bolts that can then be returned to service, then the test is nondestructive. In contrast, even if spectroscopy used in the chemical testing of many fluids is inherently nondestructive, the testing is destructive if the samples are poured down the drain after testing.

Nondestructive testing is not confined to crack detection. Other discontinuities include porosity, wall thinning from corrosion and many sorts of disbonds. Nondestructive material characterization is a growing field concerned with material properties including material identification and microstructural characteristics — such as resin curing, case hardening and stress — that have a direct influence on the service life of the test object.

Nondestructive testing has also been defined by listing or classifying the various techniques.[1-3] This approach conveys a sense of nondestructive testing that is a practical sense in that it typically highlights methods in use by industry.

Purposes of Nondestructive Testing

Since the 1920s, the art of testing without destroying the test object has developed from a laboratory curiosity to an indispensable tool of production. No longer is visual testing of materials, parts and complete products the principal means of determining adequate quality. Nondestructive tests in great variety are in worldwide use to detect variations in structure, minute changes in surface finish, the presence of cracks or other physical discontinuities, to measure the thickness of materials and coatings and to determine other characteristics of industrial products. Scientists and engineers of many countries have contributed greatly to nondestructive test development and applications.

The various nondestructive testing methods are covered in detail in the literature, but it is always wise to consider objectives before details. How is nondestructive testing useful? Why do thousands of industrial concerns buy the testing equipment, pay the subsequent operating costs of the testing and even reshape manufacturing processes to fit the needs and findings of nondestructive testing?

Modern nondestructive tests are used by manufacturers (1) to ensure product integrity and, in turn, reliability; (2) to avoid failures, prevent accidents and save human life; (3) to make a profit for the user; (4) to ensure customer satisfaction and maintain the manufacturer's reputation; (5) to aid in better product design; (6) to control manufacturing processes; (7) to lower manufacturing costs; (8) to maintain uniform quality level; and (9) to ensure operational readiness.

These reasons for widespread profitable use of nondestructive testing are sufficient in themselves, but parallel developments have contributed to its growth and acceptance.

Increased Demand on Machines

In the interest of greater speed and rising costs of materials, the design engineer is often under pressure to reduce weight. This can sometimes be done by substituting aluminum alloys, magnesium alloys or composite materials for steel or iron, but such light parts may not be the same size or design as those they replace. The tendency is also to reduce the size. These pressures on the designer have subjected parts of all sorts to increased stress levels. Even such commonplace objects as sewing machines, sauce pans and luggage are also lighter and more heavily loaded than ever before. The stress to be supported is seldom static. It often fluctuates and reverses at low or high frequencies. Frequency of stress reversals increases with the speeds of modern machines and thus parts tend to fatigue and fail more rapidly.

Another cause of increased stress on modern products is a reduction in the safety factor. An engineer designs with certain known loads in mind. On the supposition that materials and workmanship are never perfect, a safety factor of 2, 3, 5 or 10 is applied. However, because of other considerations, a lower factor is often used that depends on the importance of lighter weight or reduced cost or risk to consumer.

New demands on machinery have also stimulated the development and use of new materials whose operating characteristics and performance are not completely known. These new materials create greater and potentially dangerous problems. As an example, an aircraft part was built from an alloy whose work hardening, notch resistance and fatigue life were not well known. After relatively short periods of service some of these aircraft suffered disastrous failures. Sufficient and proper nondestructive tests could have saved many lives.

As technology improves and as service requirements increase, machines are subjected to greater variations and to wider extremes of all kinds of stress, creating an increasing demand for stronger or more damage tolerant materials.

Engineering Demands for Sounder Materials

Another justification for nondestructive tests is the designer's demand for sounder materials. As size and weight decrease and the factor of safety is lowered, more and more emphasis is placed on better raw material control and higher quality of materials, manufacturing processes and workmanship.

An interesting fact is that a producer of raw material or of a finished product sometimes does not improve quality or performance until that improvement is demanded by the customer. The pressure of the customer is transferred to implementation of improved design or manufacturing. Nondestructive testing is frequently called on to deliver this new quality level.

Public Demands for Greater Safety

The demands and expectations of the public for greater safety are apparent everywhere. Review the record of the courts in granting higher and higher awards to injured persons. Consider the outcry for greater automobile safety, as evidenced by the required auto safety belts and the demand for air bags, blowout-proof tires and antilock braking systems. The publicly supported activities of the National Safety Council, Underwriters Laboratories, the Occupational Safety and Health Administration and the Federal Aviation Administration in the United States, as well as the work of similar agencies abroad, are only a few of the ways in which this demand for safety is expressed. It has been expressed directly by passengers who cancel reservations following a serious aircraft accident. This demand for personal safety has been another strong force in the development of nondestructive tests.

Rising Costs of Failure

Aside from awards to the injured or to estates of the deceased and aside from costs to the public (e.g. evacuation due to chemical leaks), consider briefly other factors in the rising costs of mechanical failure. These costs are increasing for many reasons. Some important ones are (1) greater costs of materials and labor; (2) greater costs of complex parts; (3) greater costs due to the complexity of assemblies; (4) greater probability that failure of one part will cause failure of others because of overloads; (5) trend to lower factors of safety; (6) probability that the failure of one part will damage other parts of high value; and (7) part failure in an automatic production machine, shutting down an entire high speed, integrated, production line. When production was carried out on many separate machines, the broken one could be bypassed until repaired. Today, one machine is tied into the production of several others. Loss of such production is one of the greatest losses resulting from part failure.

Applications of Nondestructive Testing

Nondestructive testing is a branch of the materials sciences that is concerned with all aspects of the uniformity, quality and serviceability of materials and structures. The science of nondestructive testing incorporates all the technology for detection and measurement of significant properties, including discontinuities, in items ranging from research specimens to finished hardware and products in service. By definition, nondestructive testing methods are means for inspecting materials and structures without disruption or impairment of serviceability. Nondestructive testing makes it possible for internal properties or hidden discontinuities to be revealed or inferred by appropriate methods.

Nondestructive testing is becoming increasingly vital in the effective conduct of research, development, design and manufacturing programs. Only with appropriate nondestructive testing methods can the benefits of advanced materials science be fully realized. The information required for appreciating the broad scope of nondestructive testing is available in many publications and reports.

Classification of Methods

In a report, the National Materials Advisory Board (NMAB) Ad Hoc Committee on Nondestructive Evaluation adopted a system that classified techniques into six major method categories: visual, penetrating radiation, magnetic-electrical, mechanical vibration, thermal and chemical-electrochemical.[3] A modified version is presented in Table 1.[1]

Each method can be completely characterized in terms of five principal factors: (1) energy source or medium used to probe object (such as X-rays, ultrasonic waves or thermal radiation); (2) nature of the signals, image and/or signature resulting from interaction with the object

Table 1. Nondestructive testing method categories.

Categories	Objectives
Basic Categories	
Mechanical-optical	color; cracks; dimensions; film thickness; gaging; reflectivity; strain distribution and magnitude; surface finish; surface flaws; through-cracks
Penetrating radiation	cracks; density and chemistry variations; elemental distribution; foreign objects; inclusions; microporosity; misalignment; missing parts; segregation; service degradation; shrinkage; thickness; voids
Electromagnetic-electronic	alloy content; anisotropy; cavities; cold work; local strain, hardness; composition; contamination; corrosion; cracks; crack depth; crystal structure; electrical and thermal conductivities; flakes; heat treatment; hot tears; inclusions; ion concentrations; laps; lattice strain; layer thickness; moisture content; polarization; seams; segregation; shrinkage; state of cure; tensile strength; thickness; disbonds
Sonic-ultrasonic	crack initiaion and propagation; cracks, voids; damping factor; degree of cure; degree of impregnation; degree of sintering; delaminations; density; dimensions; elastic moduli; grain size; inclusions; mechanical degradation; misalignment; porosity; radiation degradation; structure of composites; surface stress; tensile, shear and compressive strength; disbonds; wear
Thermal and infrared	bonding; composition; emissivity; heat contours; plating thickness; porosity; reflectivity; stress; thermal conductivity; thickness; voids
Chemical-analytical	alloy identification; composition; cracks; elemental analysis and distribution; grain size; inclusions; macrostructure; porosity; segregation; surface anomalies
Auxiliary Categories	
Image generation	dimensional variations; dynamic performance; anomaly characterization and definition; anomaly distribution; anomaly propagation; magnetic field configurations
Signal image analysis	data selection, processing and display; anomaly mapping, correlation and identification; image enhancement; separation of multiple variables; signature analysis

(attenuation of X-rays or reflection of ultrasound, for example); (3) means of detecting or sensing resultant signals (photoemulsion, piezoelectric crystal or inductance coil); (4) method of indicating and/or recording signals (meter deflection, oscilloscope trace or radiograph); and (5) basis for interpreting the results (direct or indirect indication, qualitative or quantitative and pertinent dependencies).

The objective of each method is to provide information about the following material parameters:

1. discontinuities and separations (cracks, voids, inclusions, delaminations etc.);
2. structure or malstructure (crystalline structure, grain size, segregation, misalignment etc.);
3. dimensions and metrology (thickness, diameter, gap size, discontinuity size etc.);
4. physical and mechanical properties (reflectivity, conductivity, elastic modulus, sonic velocity etc.);
5. composition and chemical analysis (alloy identification, impurities, elemental distributions etc.);
6. stress and dynamic response (residual stress, crack growth, wear, vibration etc.); and
7. signature analysis (image content, frequency spectrum, field configuration etc.).

Terms used in this block are further defined in Table 2 with respect to specific objectives and specific attributes to be measured, detected and defined.

The limitations of a method include conditions required by that method: conditions to be met for method application (access, physical contact, preparation etc.) and requirements to adapt the probe or probe medium to the object examined. Other factors limit the detection and/or characterization of discontinuities, properties and other attributes and limit interpretation of signals and/or images generated.

Classification Relative to Test Object

Nondestructive testing methods may be classified according to how they detect indications relative to the surface of a test object. Surface methods include liquid penetrant testing, visual testing, grid and moiré testing, holography and shearography. Surface/near-surface methods include tap, potential drop, magnetic particle and electromagnetic testing. When surface or surface/near-surface methods are applied during intermediate manufacturing processes, they provide preliminary assurance that volumetric methods performed on the completed object or component will reveal few rejectable discontinuities. Volumetric methods include radiography, ultrasonic testing, acoustic emission testing, certain infrared thermographic techniques and less familiar methods such as acoustoultrasonic testing and magnetic resonance imaging. Through-boundary methods described include leak testing, some infrared thermographic techniques, airborne ultrasonic testing and certain techniques of acoustic emission testing. Other less easily classified methods are material identification, vibration analysis and strain gaging.

No one nondestructive testing method is all-revealing. That is not to say that one method or technique of a method is rarely adequate for a specific object or component. However, in most cases it takes a series of test methods to do a complete nondestructive test of an object or component. For example, if surface cracks must be detected and eliminated and the object or component is made of ferromagnetic material, then magnetic particle testing would be the obvious choice. If that same material is aluminum or titanium, then the choice would be liquid penetrant or electromagnetic testing. However, for either of these situations, if internal discontinuities were to be detected, then ultrasonics or radiography would be the selection. The exact technique in either case would depend on the thickness and nature of the material and the type or types of discontinuities that must be detected.

Value of Nondestructive Testing

The contribution of nondestructive testing to profits has been acknowledged in the medical field and computer and aerospace industries. However, in industries such as heavy metals, though nondestructive testing may be grudgingly promoted, its contribution to profits may not be obvious to management. Nondestructive testing is sometimes thought of only as a cost item. One possible reason is industry downsizing. When a company cuts costs, two vulnerable areas are quality and safety. When bidding contract work, companies add profit margin to all cost items, including nondestructive testing, so a profit should be made on the nondestructive testing. However, when production is going poorly and it is anticipated that a job might lose money, it seems like the first corner that production personnel will try to cut is nondestructive testing. This is accomplished by subtle pressure on nondestructive testing technicians to accept a product that does not quite meet a code or standard requirement. The attitude toward nondestructive testing is gradually improving as management comes to appreciate its value.

Nondestructive testing should be used as a control mechanism to ensure that manufacturing processes are within design performance requirements. It should never be used in an attempt to obtain quality in a product by using nondestructive testing at the end of a manufacturing process. This approach will ultimately increase production costs. When used properly, nondestructive testing saves money for the manufacturer. Rather than costing the manufacturer money, nondestructive testing should add profits to the manufacturing process.

TABLE 2. Objectives of nondestructive testing methods.

Objectives	Attributes Measured or Detected
Discontinuites and separations	
Surface anomalies	roughness; scratches; gouges; crazing; pitting; inclusions and imbedded foreign material
Surface connected anomalies	cracks; porosity; pinholes; laps; seams; folds; inclusions
Internal anomalies	cracks; separations; hot tears; cold shuts; shrinkage; voids; lack of fusion; pores; cavities; delaminations; disbonds; poor bonds; inclusions; segregations
Structure	
Microstructure	molecular structure; crystalline structure and/or strain; lattice structure; strain; dislocation; vacancy; deformation
Matrix structure	grain structure, size, orientation and phase; sinter and porosity; impregnation; filler and/or reinforcement distribution; anisotropy; heterogeneity; segregation
Small structural anomalies	leaks (lack of seal or through-holes); poor fit; poor contact; loose parts; loose particles; foreign objects
Gross structural anomalies	assembly errors; misalignment; poor spacing or ordering; deformation; malformation; missing parts
Dimensions and metrology	
Displacement; position	linear measurement; separation; gap size; discontinuity size, depth, location and orientation
Dimensional variations	unevenness; nonuniformity; eccentricity; shape and contour; size and mass variations
Thickness; density	film, coating, layer, plating, wall and sheet thickness; density or thickness variations
Physical and mechanical properties	
Electrical properties	resistivity; conductivity; dielectric constant and dissipation factor
Magnetic properties	polarization; permeability; ferromagnetism; cohesive force
Thermal properties	conductivity; thermal time constant and thermoelectric potential
Mechanical properties	compressive, shear and tensile strength (and moduli); Poisson’s ratio; sonic velocity; hardness; temper and embrittlement
Surface properties	color; reflectivity; refraction index; emissivity
Chemical composition and analysis	
Elemental analysis	detection; identification, distribution and/or profile
Impurity concentrations	contamination; depletion; doping and diffusants
Metallurgical content	variation; alloy identification, verification and sorting
Physiochemical state	moisture content; degree of cure; ion concentrations and corrosion; reaction products
Stress and dynamic response	
Stress; strain; fatigue	heat treatment, annealing and cold work effects; residual stress and strain; fatigue damage and life (residual)
Mechanical damage	wear; spalling; erosion; friction effects
Chemical damage	corrosion; stress corrosion; phase transformation
Other damage	radiation damage and high frequency voltage breakdown
Dynamic performance	crack initiation and propagation; plastic deformation; creep; excessive motion; vibration; damping; timing of events; any anomalous behavior
Signature analysis	
Electromagnetic field	potential; strength; field distribution and pattern
Thermal field	isotherms; heat contours; temperatures; heat flow; temperature distribution; heat leaks; hot spots
Acoustic signature	noise; vibration characteristics; frequency amplitude; harmonic spectrum and/or analysis; sonic and/or ultrasonic emissions
Radioactive signature	distribution and diffusion of isotopes and tracers
Signal or image analysis	image enhancement and quantization; pattern recognition; densitometry; signal classification, separation and correlation; discontinuity identification, definition (size and shape) and distribution analysis; discontinuity mapping and display

PART 2. Management of Liquid Penetrant Testing[4]

Synopsis of Liquid Penetrant Testing

Liquid penetrant testing can be defined as a physical and chemical nondestructive testing procedure designed to detect and expose surface connected discontinuities in nonporous engineering materials. The method relies on the physical interaction between an appropriately formulated chemical liquid and the surface of a part. This interaction causes the liquid to enter surface cavities and later to emerge, visually indicating the location and approximate size and shape of the surface opening. The objective of liquid penetrant testing is to provide visual evidence of cracks, porosity, laps, seams and other surface discontinuities rapidly and economically with a high degree of reliability. This objective is facilitated by formulating the liquid to include dyes that are highly visible with either white or near ultraviolet radiation. With proper technique, liquid penetrant testing will detect a wide variety of discontinuities ranging in size from readily visible to microscopic.

The liquid penetrant process consists of six basic steps.

1. Preclean and dry the test surfaces of the object to be tested. Cleaning is a critical part of the liquid penetrant process and is emphasized because of its effect on the test results. Contaminants, soils or moisture, either inside a discontinuity or on the part surface at the discontinuity opening, can reduce or completely destroy the effectiveness of the test. Etching and pickling are used at this stage to remove smeared surface metal.
2. Apply liquid penetrant to the test surfaces and permit it to dwell on the part surface for a period of time to allow it to enter and fill any discontinuities open to the surface.
3. Remove excess liquid penetrant from the test surfaces. Care must be exercised to prevent removal of liquid penetrant contained in discontinuities.
4. Apply a developer, which aids in drawing any trapped liquid penetrant from discontinuities and spreading it on the test surface for improved discontinuity detection. Developer enhances the brightness of fluorescent indications and provides a contrasting white background for visible (red) dye liquid penetrant indications.
5. Visually examine surfaces for liquid penetrant indications; interpret and evaluate the indications.
6. Postclean the part to remove process residues if they will be detrimental to subsequent operations or the part's intended function. (In some cases, a treatment to prevent corrosion may be required.)

Liquid penetrant testing is popular because it is relatively easy to use and has a wide range of applications. Because it uses physical and chemical properties rather than electrical or thermal phenomena, it can be used in the field, far from power sources. Test equipment can be as simple as a small, inexpensive kit of aerosol cans or as extensive as a large mechanized and automated installation. However, in all cases, the success of liquid penetrant testing depends on cleanliness of test surfaces, on absence of contamination or surface conditions that can interfere with liquid penetrant entry into and subsequent emergence from surface openings of discontinuities, and on care by inspectors/operators to ensure proper processing techniques and observation of test indications. Previous manufacturing processes also may inhibit detection of some types of discontinuities by liquid penetrants. For example, many seams and laps are forged shut by the hot rolling or piercing processes that create these elongated discontinuities; in addition, local welding of the metal or trapping of heat treat byproducts within the opening can inhibit or prevent entry of the liquid penetrant, making testing ineffective.

Liquid penetrant testing is also used for leak testing. The same basic fundamentals apply but the liquid penetrant removal step may be omitted. The container is either filled with liquid penetrant or the liquid penetrant is applied to one side of the container wall. The developer is applied to the opposite side, which is visually examined after allowing time for the liquid penetrant to seep through any leak points. This method may be used on thin parts where there is access to both surfaces and where the discontinuity is expected to extend through the material.

It may be further enhanced by the application of a pressure differential.

Reasons for Selecting Liquid Penetrant Testing

Some of the reasons for choosing liquid penetrant testing are as follows.

1. Liquid penetrant testing can quickly examine all the accessible surfaces of objects. Complex shapes can be immersed or sprayed with liquid penetrant to provide complete surface coverage.
2. Liquid penetrant testing can detect very small surface discontinuities. It is one of the most sensitive nondestructive testing methods for detecting surface discontinuities.
3. Liquid penetrant testing can be used on a wide variety of materials: ferrous and nonferrous metals and alloys; fired ceramics and cermets; powdered metal products; glass; and some types of organic materials. Restrictions on materials imposed by the nature of the liquid penetrant process are covered in the discussion of limitations, below.
4. Liquid penetrant testing can be accomplished with relatively inexpensive, nonsophisticated equipment. If the area to be tested is small, the test can be accomplished with portable equipment.
5. Liquid penetrant testing magnifies the apparent size of discontinuities, making the indications more visible. In addition, the discontinuity location, orientation and approximate size and shape are indicated on the part, making interpretation and evaluation possible.
6. Liquid penetrant testing is readily adapted to volume processing, permitting 100 percent surface testing. Small parts may be placed in baskets for batch processing. Specialized systems may be partially or fully automated to process many parts per hour.
7. The sensitivity of a liquid penetrant testing process may be adjusted through appropriate selection of liquid penetrant, removal technique and type of developer. This allows the liquid penetrant process to be adapted to characteristics (e.g., composition, surface condition) of the part requiring testing and to be tailored to detect specified minimum allowable discontinuities. Thus, inconsequential discontinuities can be suppressed whereas larger discontinuities of more concern are indicated.
8. Liquid penetrant testing is a direct nondestructive testing method in that the inspector can visually see the discontinuity. Other methods such as ultrasonic testing and eddy current testing have a signal output that has to be compared to that of a reference standard.

Disadvantages and Limitations of Liquid Penetrant Testing

1. Liquid penetrant testing depends on the ability of liquid penetrant to enter and fill discontinuities. Liquid penetrant testing will only reveal discontinuities open to the surface.
2. Surfaces of objects to be tested must be clean and free of organic or inorganic contaminants that will prevent interaction of the penetrating media with a surface. Organic surface coatings, such as paint, oil, grease or resin, are in this category. Any coating that covers or blocks the discontinuity opening will prevent liquid penetrant entry. Even when the coating does not cover the opening, material at the edge of the opening may affect entry or exit of liquid penetrant and greatly reduce reliability of the test. Coatings in the vicinity of a discontinuity will also retain liquid penetrant, causing background indications. Cleaning test surfaces is discussed in more detail below.
3. It is also essential that the inside surface of discontinuities be free of materials such as corrosion, combustion products or other contaminants that would restrict entry of liquid penetrant. Because it is impossible to check inside discontinuities, one must trust that processes selected to clean test surfaces will clean inside surfaces of discontinuities also.
4. Mechanical operations, such as shot peening, some types of plastic media blasting (PMB), machining, honing, abrasive blasting, buffing, brushing, grinding or sanding will smear or peen the surface of metals. This mechanical working closes or reduces the surface opening of existing discontinuities. Mechanical working (smearing or peening) also occurs during service when parts are in contact or rub together. Liquid penetrant testing will not reliably detect discontinuities when it is performed after a mechanical operation or service use that smears or peens the surface. Depending on the severity of the mechanical operation, chemical removal (etching) of smeared metal may restore test reliability.

5. Unless special procedures are used, liquid penetrant testing is impractical on certain materials, such as some types of anodized aluminum surfaces, other protective coatings and certain nonmetallic parts. Liquid penetrant rapidly enters pores of the material and becomes trapped. This can result in an overall background fluorescence or color that could mask any potential discontinuity indications. In addition, removal of the liquid penetrant may not be possible after the test.
6. Penetrants, emulsifiers and some types of developers have very good wetting and detergent properties. They can act as solvents for fats and oils. They also can clean ferrous materials so thoroughly that rust will begin almost immediately if corrosion inhibitor is not applied. If allowed to remain in contact with human skin for extended periods, they may cause irritation.

Reasons for Using Liquid Penetrant Testing

Liquid penetrant testing is often the first nondestructive testing method management considers for testing of industrial products (1) because it often requires minimal capital expenditure for implementation and (2) because it can accommodate a variety of test object materials, shapes and sizes, test locations and environmental conditions. However, the outcome of a liquid penetrant test is largely dependent on the human operator. Liquid penetrant testing is a labor intensive method. Therefore, labor constitutes a high recurring test cost. In short, the quality of the test and the cost of testing warrant considerable management attention to the selection, training, management and audit of liquid penetrant testing personnel.

Liquid penetrant testing detects only those discontinuities that are present on or are open to the surface of the part. Therefore, if only surface discontinuities are of interest, liquid penetrant processes may be appropriate in the following situations.

1. When the test material is a nonmagnetic metal (such as annealed austenitic stainless steel, titanium, aluminum, magnesium and copper alloys) or a nonmetallic material (such as plastics or ceramics). Although magnetic particle testing is usually thought of for magnetic materials, liquid penetrant testing could also be used.
2. When the geometry of the part is such that the shape itself may hide or obscure indications (of surface discontinuities) produced by other nondestructive test techniques. For instance, a forged steel bracket might have such a sharp change of section that test processes such as magnetic particle tests would show nonrelevant indications in that area. Or a weld might be so located that a change in thickness could mask the X-ray indication of a crack.
3. When the size or shape of the surface discontinuity is such that it can escape detection by other techniques. An aluminum forging may have a forging lap, almost sealed shut, which is so small that only liquid penetrant testing can show it. A tiny crack in the radius of a turbine bucket is very difficult to find by any means other than liquid penetrant testing.
4. When parts are to be tested in locations where electric power is not available or is too expensive or too inconvenient to use or where electricity creates a safety hazard. When the surface of parts must be checked in the field, perhaps in remote areas, liquid penetrant systems are especially advantageous.

However, if the test material is ferromagnetic, magnetic tests may offer advantages over liquid penetrant tests in detection of near-surface discontinuities and surface discontinuities that do not permit entry of a liquid penetrant. If tests for internal and surface soundness are required, then liquid penetrant testing can be used in addition to other nondestructive test methods such as penetrating radiation, ultrasonic or eddy current tests.

Choosing Which Liquid Penetrant Process

When the decision to use liquid penetrant testing has been made, which system should be selected? There are varieties of penetrants, liquid penetrant removal systems and developers; there are also many ways to combine these different liquid penetrant system elements. The manager must consider the specific application. For the great majority of parts, the conventional water washable or postemulsifiable penetrants are suitable and adequate. However, many factors must be considered when selecting the optimum liquid penetrant system. For example, the preferred system should (1) indicate significant discontinuities open to part surfaces; (2) not adversely affect the material or the part in later service, (3) be affordable and (4) not take so much time that it unreasonably disrupts production schedules.

What Material Is in Test Parts?

Most materials, both metallic and nonmetallic, can be satisfactorily tested by conventional fluorescent or visible dye penetrants. But austenitic stainless steels, nickel base alloys and titanium (at elevated temperatures) are subject to stress corrosion; for these metals, the liquid penetrant materials should be low in sulfur and in halogens, especially chlorine. For materials harmed by water, a nonaqueous system is indicated. Some nonmetallic materials are affected by oil base liquid penetrants or emulsifiers; for these test objects, a water base liquid penetrant system should be selected.

What Type of Service Is Expected for Test Parts?

Ordinary liquid penetrant systems are suitable for nearly all parts. But if the service involves exposure to liquid oxygen or gaseous oxygen or in nuclear applications, special penetrants should be selected.

What Size of Discontinuity Is Significant in Test Parts?

The optimum liquid penetrant process indicates surface discontinuities that could adversely affect the serviceability of test parts while minimizing nonrelevant indications from such causes as surface roughness. To select this optimum system, engineering must decide which discontinuities are important: what type, size and location will really affect service. Prior history from similar parts is very helpful in making such decisions. If the operation is new or lacking good service records, management can draw on the experience of liquid penetrant system suppliers or reported information on the capabilities of liquid penetrant testing.

For instance, if small shallow discontinuities on the surface do not affect the part, one might select a water washable fluorescent liquid penetrant process. But if shallow discontinuities are of major concern, this is not the best choice, because trapped liquid penetrant can be washed out of shallow discontinuities so the discontinuity indications cannot be formed. Sometimes, one part will present a special problem because both large and small discontinuities are of consequence; a special liquid penetrant may be the solution in this case.

What Facility Should Test Occasional Critical Test Parts?

In typical cases, the great majority of parts to be checked may be much alike, with only one critical item demanding utmost test sensitivity. Depending on the quantity involved, it may be more economical to install a conventional liquid penetrant system for the majority of parts and send the one item with stricter requirements to a commercial nondestructive testing laboratory for processing. (In like manner, many companies have their own X-ray machine for normal applications but have a commercial nondestructive test laboratory handle parts requiring very large X-ray equipment.)

How Many Parts Are to Be Tested and How Often?

After having established the size and type of discontinuity that must be found, managers may find that there are several liquid penetrant systems that would probably be equally suitable. Therefore, the choice in this case, will usually be based on cost factors such as the capital investment required, the materials used, the volume of parts to be processed, the necessity for treating waste water or the plant space needed for test operations.

Where Is Test to Be Performed?

Management must ask, especially if there are only a small number of parts to be tested, whether it would be cheaper to use a commercial nondestructive testing laboratory. Are commercial facilities easily accessible or would it cause an unacceptable delay to ship parts into and out of the plant? How much space is available in the plant for liquid penetrant processing and where is it located? When is the part to be checked: in receiving inspection, in process, just before final assembly, as the finished product or at several of these areas? Are there some items that must be checked on test stands or high in the air, or in the field away from other installations? For these, portable liquid penetrant kits may be the best selection.

What Handling of Parts Is Involved?

What is the range of size, shape and weight of part to be checked by liquid penetrant? Are the parts large, heavy and unwieldy or are they small lightweight items or a mixture of both? Are additional handling facilities required?

What Is Surface Condition of Test Parts?

If most parts are checked in the as-cast condition, this will be a big factor in selecting the best liquid penetrant system. If some are rough as-cast or as-forged parts and others are highly machined, the liquid penetrant test procedure may have to be modified to get equally good results on both types of surfaces.

Checklist of Factors for Choosing Liquid Penetrant Testing Technique

Managers are urged to consider the following important factors and to discuss them with suppliers of liquid penetrant test equipment and processing materials before reaching a decision on the type of liquid penetrant testing system to install or use:

1. test object material (aluminum, magnesium, copper alloys, austenitic stainless steel, nickel alloys, titanium, iron, steel or others);
2. number of test parts or test areas to be tested (per hour, per shift, per day or per week);
3. size of test object to be handled (largest dimension under 20 mm, 100 mm, 500 mm, 1 m, 2 m, 5 m, 10 m etc.);
4. weight of test objects to be handled (1 to 300 g, 300 g to 1 kg, 1 to 3 kg, 3 to 10 kg, 10 to 30 kg, 30 to 100 kg etc.).
5. location at which testing is required (receiving department, in process along production line, during assembly, as final inspection, in field during erection, in service or at maintenance bases);
6. types of discontinuities to be detected: small, deep, large, shallow, clustered or scattered; porosity, cracks, seams, laps, roughness;
7. surface condition of parts to be tested (as-cast, as-forged, machined, ground, lapped, polished, plated, painted, corroded, oily, engine varnish, eroded, scratched, scaled);
8. conditions to which parts will be subjected after testing (medical, nuclear, liquid or gaseous oxygen systems; welding, plating or finishing operation; high temperature, aerospace, industrial or transportation uses; inaccessible locations; consumer products; etc.).

PART 3. Personnel Selection and Qualification for Liquid Penetrant Testing[4]

Qualification of Liquid Penetrant Testing Capabilities

Reliable liquid penetrant testing in industry requires (1) qualification of the test method for revealing critical conditions in test parts to be evaluated; (2) qualification of the test personnel for the method and performance level required; and (3) management of test operations to ensure consistent performance.

Productivity in liquid penetrant testing requires consistent and reliable test performance at minimum cost.

Skill and Integrity of Liquid Penetrant Testing Personnel

The success of a liquid penetrant test depends primarily on the personnel performing the varying processing steps and on their interpretation of the cause and criticality of indications produced by the test process. Qualification, skill and excellence in performance are important to reliable liquid penetrant testing.

Liquid penetrant testing involves skillful and judicious processing to produce visible evidence of the soundness of a part. Vigilant observation and decision making based on this visual evidence is used to ascertain acceptance of test parts for service. Thus, liquid penetrant testing is people dependent. In most cases, the skill and integrity of the liquid penetrant inspector must be equal to or greater than that of the operator who produced the part. Unlike the production of the part, there is usually no tangible evidence (no permanent record) of the quality of testing completed. The reliability of and confidence in the test (and ultimately in the part) depend on the test operator. The test operator is a professional and must be selected and treated as one. Management inattention to human factors in liquid penetrant testing will waste production resources and may compromise the reliability of the hardware submitted for testing.

Liquid Penetrant Testing Dependence on Management Interest

Inspectors with the proper temperament, discipline, vigilance and integrity must be selected and sustained by management to ensure consistent and reliable performance in the testing environment. The effectiveness of liquid penetrant testing depends on management policy, personnel selection and motivation and direct interest and involvement.

However, liquid penetrant testing is also process dependent. Proper selection and control of liquid penetrant process variables are mandatory to qualify a liquid penetrant testing process to reveal critical conditions in the part to be tested and to establish inspector confidence that the task objectives of detection of critical discontinuities are attainable. (Variables in the liquid penetrant process are described in detail elsewhere in this volume.)

Requirements for Liquid Penetrant Testing Personnel

Liquid penetrant testing requires that test personnel be (1) physically and mentally qualified to perform the required processing steps; (2) skilled and experienced in performing the actual processing steps; (3) alert to consistent processing and resultant indications; (4) motivated to perform with vigilance at the required detection and reliability level; and (5) capable of consistent, independent and unbiased decisions based on interpretation of resultant liquid penetrant indications.

Qualification of Personnel for Liquid Penetrant Testing

Personnel qualification depends on requirements of the test to be performed, the individual capabilities of the inspector and the management philosophy and skill applied. Qualification for one liquid penetrant testing operation may not be reasonable or valid for a second operation. Personnel qualification cannot be separated from the operating facility. Thus, the nondestructive test method and management factors must be considered for each application.

The apparent simplicity of liquid penetrant testing is deceptive. Very slight process variations during the performance of a test can invalidate the test by counteracting the formation of indications. It is essential that personnel performing liquid penetrant testing be trained and experienced in the liquid penetrant process. All individuals who apply liquid penetrant materials or examine components for penetrant indications should be qualified.

Qualification requires classroom and practical training, passing marks on examinations and experience. Typical qualification requirements are contained in ANSI/ASNT CP-189, *Standard for Qualification and Certification of Nondestructive Testing Personnel;*[5] in EN 473, *Qualification and Certification of NDT Personnel — General Principles;*[6] in ISO 9712, *Nondestructive Testing — Qualification and Certification of Personnel;*[7] and in AIA/NAS 410, *NAS Certification & Qualification of Nondestructive Test Personnel.*[8] Another widely used document intended as a guideline for employers to establish their own written practice for the qualification and certification of their nondestructive testing personnel is *ASNT Recommended Practice No. SNT-TC-1A.*[9] In the 1990s, the American Society for Nondestructive Testing introduced the ASNT Central Certification Program.[10]

Physical Qualifications of the Liquid Penetrant Inspector

A liquid penetrant inspector must be physically qualified to perform liquid penetrant testing reliably. The inspector's capability depends on the inspector's health, physical strength and dexterity, good vision and consistency in performance.

Motor Ability and Dexterity of the Liquid Penetrant Inspector

The liquid penetrant inspector's coordination must be sufficient to enable performance of precise, time dependent execution of all processing steps. Liquid penetrant inspectors must have the physical capabilities necessary for timely application of fluids to test objects or for timely movement of test parts through various processing fluid exposures. Inspectors must also be able to visually test all critical areas of the test objects for evidence of anomalies. Physical strength, motor ability and dexterity requirements vary with the hardware to be tested and with the nature of the production operation. In general, the inspector should able to perform the test with little physical discomfort and minimal fatigue during the test.

Ensuring Good Vision of Liquid Penetrant Inspectors

Liquid penetrant testing requires visual examination of part surfaces under conditions unique to the test process. The conditions under which the human eye is used play a large role in determining the behavior of the eye and must always be taken into account. No single test or set of tests has been devised to screen operators for all conditions and characteristics important to liquid penetrant testing. Factors that have been identified as influencing the visual capabilities of liquid penetrant inspectors include vision acuity, vernier acuity, color vision, motion detection, distance perception and dark adaptation. The characteristic of the eye that is probably of greatest interest to the optical engineer is its ability to recognize small, fine details. Vision acuity is defined and measured in terms of the angular size of the smallest character that can be recognized.

Filtered mercury arc ultraviolet sources emit a substantial amount of 405 nm (violet) radiation only dimly seen by the human eye. The plastic lens implants that result from cataract surgery are transparent at 405 nm. An inspector with such plastic lens implants is thus inspecting against a bright violet light background and can easily overlook tiny fluorescent indications. Goggles that filter ultraviolet radiation would be appropriate.

Vision Acuity Examinations

Various eye test methods have been devised and are used routinely in industry to measure vision acuity. The vision acuity of the liquid penetrant operator must be sufficient to detect and evaluate the indications produced by the test process. To confirm natural or corrected vision, eyes should be examined initially and periodically to ensure continuing performance. Specifications and industrial standards set requirements for vision acuity and the frequency of its reverification for liquid penetrant testing personnel.

Ensuring Adequate Color Vision

The inspector must perceive color brightness and contrast to perform liquid penetrant testing with visible dye (color contrast) penetrants. One of the challenging unsolved problems of vision is determination of the response of the human eye to colors that differ in hue and saturation as well as brightness.

Tests of inspectors for color blindness are required by some liquid penetrant specifications, with varying criteria for acceptance. Although such tests provide an indication of operator capability for performing liquid penetrant testing, they do not definitively measure operator capability. If color vision tests indicate a color deficiency, the operator should be tested on his ability to distinguish actual liquid penetrant indications. Color blindness is usually inherited. Most forms of inherited color blindness can occur without being associated with other kinds of visual anomalies. Color blindness is usually found in both eyes but is occasionally confined to one eye. There are also acquired types of color blindness that may affect performance. The type and severity of color blindness will determine the capability of an inspector for liquid penetrant testing. In some cases, the type and severity of color blindness will permit the inspector to perform fluorescent liquid penetrant testing (color contrast discrimination not required) even though the inspector is incapable of performing testing with color contrast visible dye penetrants.

Ensuring Adequate Brightness Discrimination

Brightness discrimination is necessary for fluorescent liquid penetrant inspectors. The sensitivity of fluorescent liquid penetrant is usually measured in terms of the brightness of the indications it produces. Although color blindness is the usual cause for variation in discrimination of brightness or contrast in white light, other factors may contribute. Inherited anomalies, eye disease and external factors such as photosensitive eyeglasses may affect brightness discrimination. This factor is evaluated by observance of actual liquid penetrant indications.

Ensuring Adequate Dark Adaptation

The lowest level of brightness that can be seen or detected is determined by the light level to which the eye has become accustomed. When the illumination level is reduced, the pupil of the eye expands, admitting more light. The retina of the eye becomes more sensitive by switching from cone vision to rod vision and also by an electrochemical mechanism involving rhodopsin, the visual purple pigment. This process is called dark adaptation.

Everyone has had the experience of not being able to see a thing on passing from a brightly lighted room into a dark one. After a short time, the eyes adjust or adapt to the low light level and objects in the dark room become visible. The time required for dark adaptation before visual examination for indications can be performed varies with the individual and depends on the overall health and age of the individual operator. A dark adaptation time of 1 min is usually sufficient for fluorescent liquid penetrant testing. (Complete dark adaptation may take as long as 20 min.)

Suitable red lens eyeglasses may reduce the required time for dark adaption but should not be worn during inspection.

Disuse of Photosensitive Eye Glasses

Photosensitive eyeglasses darken in the presence of ultraviolet radiation. Lens darkening is proportional to the amount of incident radiation. Although this type of lens has advantages in sunlight conditions, such glasses can decrease the ability of an operator to perform fluorescent liquid penetrant testing. Use of photosensitive eyeglass lenses by liquid penetrant operators is not permitted. On the other hand, suitable red eyeglasses may aid dark adaptation. Eyeglass frames that fluoresce and cause an unnecessary background during fluorescent liquid penetrant testing should not be used.

Magnification in Evaluation of Small Liquid Penetrant Indications

Testing using optical magnification can assist vision acuity of liquid penetrant inspectors, particularly when small indications are involved. A 10× magnifying glass or 10× magnifier on a supporting stand should be included in the standard equipment available to liquid penetrant inspectors. In this connection, the value of a broad field microscope for critical viewing cannot be overemphasized. The microscope is an indispensable tool for the analysis of microindications (with 20× to 100× enlargements) as well as for determining the extent and nature of macroindications (with 5× to 20× enlargements).

Mental and Skill Qualifications Required of the Liquid Penetrant Inspector

Liquid penetrant testing requires skillful, repetitive performance of multiple processing steps and the interpretation of the resultant visual indications. To qualify as a liquid penetrant inspector, the operator must not only understand and be familiar with test principles and execution steps but also with factors that may influence the success and/or results of the liquid penetrant testing process. Liquid penetrant testing principles and practices are discussed in detail throughout this volume. The inspector should be able to answer written and verbal questions concerning processing principles and to demonstrate a thorough knowledge of the subject. Demonstrated knowledge should include interpretation of causes for failure of the liquid penetrant process to reveal material anomalies. This knowledge should cover test procedures used and the production history of the articles to be tested.

Ensuring Inspector Knowledge of Types and Locations of Indications Sought

Liquid penetrant testing reveals a variety of material surface conditions. Knowledge of the source and kinds of material anomalies to be revealed by the liquid penetrant process is required to use liquid penetrant process principles effectively. In short, the inspector must know where to look for indications, how to interpret the indications and how to judge acceptability of test objects for use in service. The liquid penetrant inspector must be able to recognize relevant indications and to distinguish relevant indications from nonrelevant (noise) indications. The inspector must then evaluate relevant indications with respect to the requirements of the product being tested. This skill is gained by observation and experience in liquid penetrant testing.

The liquid penetrant inspector must be able not only to perform the required liquid penetrant process and locate and evaluate liquid penetrant indications but the inspector must also determine the frequency and severity of discontinuities and analyze these with respect to specification requirements. At first glance this task appears to be straightforward. For inspectors who work for a producer who checks similar parts each day to company specifications, this may be true. However, the situation is quite different for inspectors working for commercial laboratories. Interpretation and grading of liquid penetrant test indications must be done in accordance with requirements of the particular part involved and may involve understanding and interpretation of both written and verbal instructions.

Acquiring written and verbally demonstrated knowledge of liquid penetrant testing principles, part production techniques, indications of a relevant nature and specification interpretation comprise the elements of the training process for liquid penetrant inspectors. Skill in execution of liquid penetrant testing must then be developed by practice. Ideally, practice would include experimental cross sectioning of tested parts to determine the nature of discontinuities whose indications were observed and whose indications were missed. This process of metallurgical evaluation is too costly in most industrial operations, and practical skill must be gained by working with an experienced, knowledgeable and skilled inspector. Practice should develop skill in executing the liquid penetrant testing process, skill in performing the process and confidence in the outcome of the process.

After knowledge of the liquid penetrant process has been demonstrated by verbal and written examination and after skill in the methods has been developed by practice, the inspector should be able to demonstrate ability in liquid penetrant tests of typical production hardware containing known and documented discontinuities. Demonstrations should be repeated periodically to ascertain a measure of performance and confidence in the test. Skill and technique must be developed for each liquid penetrant system for each part type. Skill in testing of one part type, e.g., forgings, cannot be assumed in testing of a second part type, e.g., weldments. Skill and technique for varying situations are developed by experience and no substitute for experience is known.

Attaining Productivity by Judicious Application of Tools Available

Liquid penetrant testing must detect discontinuities reliably and economically to be of value in the production process. The liquid penetrant inspector must in turn perform the test reliably in the shortest practical time to be productive. Productivity is measured both by the number of tests completed and by the reliability of detection of rejectable discontinuities, without rejection of acceptable test objects.

Test process output may be increased by the addition of tools, jigs, materials and parts sequencing in the same manner as any other production process step. Learning curves and shop efficiency factors familiar to those dealing with other shop operations are applicable to liquid penetrant testing. However, check and balance measurements with respect to operator performance are not as simple and available as are those for other processes. No increase in productivity is gained unless the reliability and

FIGURE 1. Aluminum alloy flat plate by crack length: (a) as machined; (b) after etch; (c) after proof.

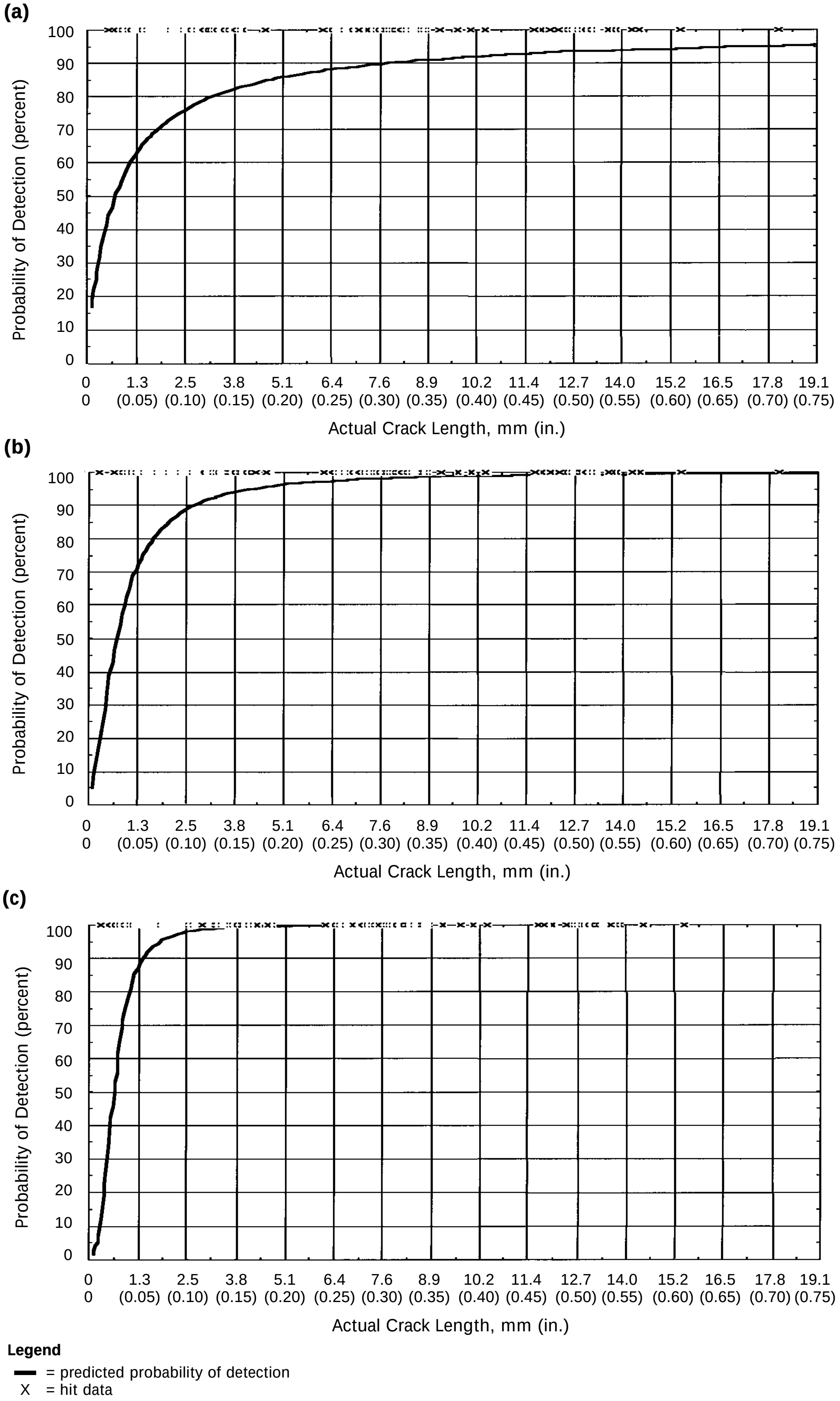
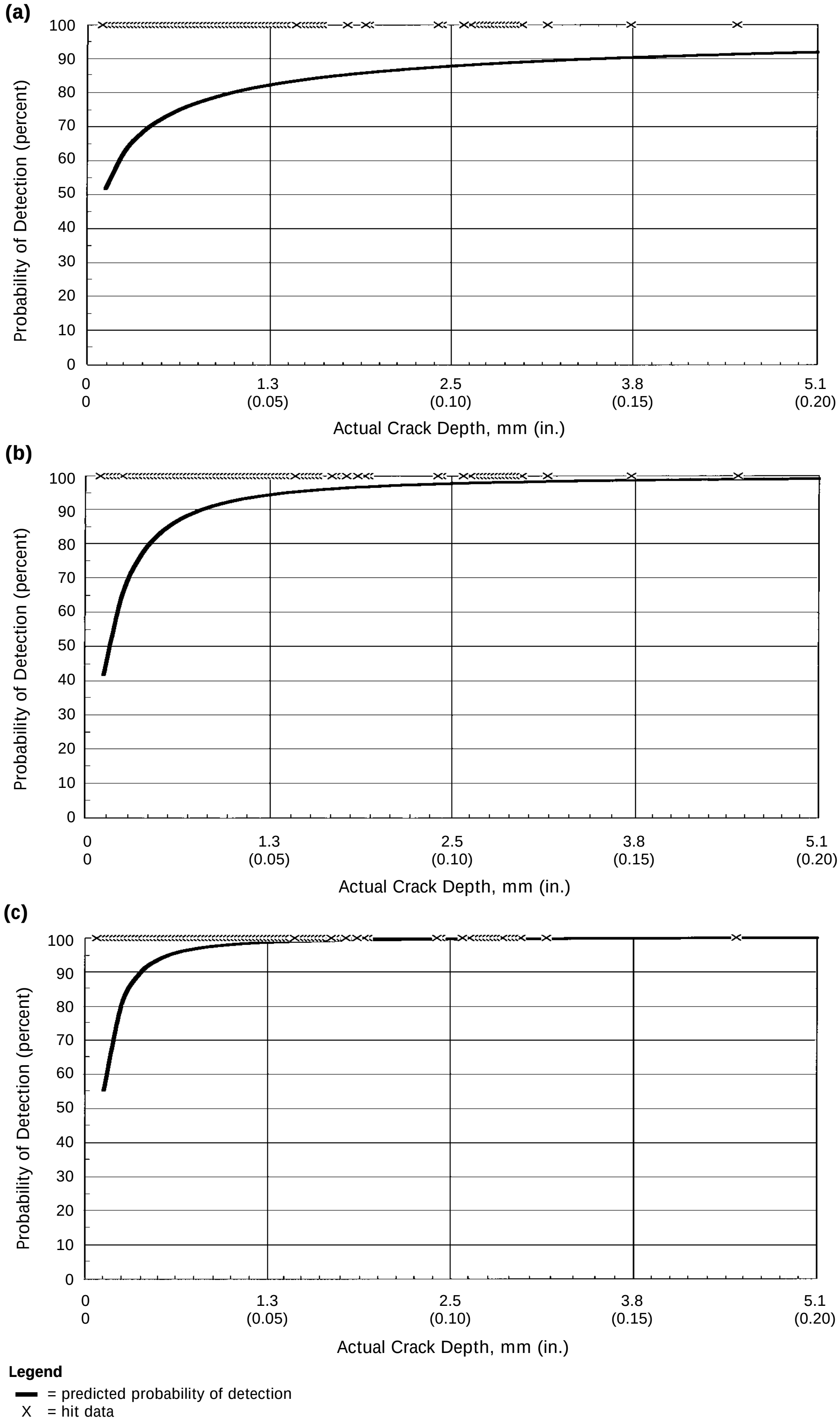


FIGURE 2. Aluminum alloy flat plate by crack depth: (a) as machined; (b) after etch; (c) after proof.



consistency of the testing process are maintained.

Ensuring Reliability of Test Results

When a test is performed, there are four possible outcomes: (1) a discontinuity can be found when a discontinuity is present; (2) a discontinuity can be missed even when a discontinuity is present; (3) a discontinuity can be found when none is present; and (4) no discontinuity is found when none is present. A reliable testing process and a reliable inspector should find all discontinuities of concern with no discontinuities missed (no errors as in case 2, above) and no false callouts (case 3, above).

To achieve this goal, the probability of finding a discontinuity must be high and the inspector must be both proficient in the testing process and motivated to perform a maximum efficiency. A reckless inspector may accept parts that contain discontinuities, with the resultant consequences of possible inservice part failure. A conservative inspector may reject parts that contain actual discontinuities but the inspector also may reject parts that do not contain discontinuities, with the resultant consequences of unnecessary scrap and repair. Neither inspector is doing a good job.

Measuring Inspector Performance in Terms of Throughput and Reliability

Before measuring an inspector's performance, it is necessary to ensure that rejectable discontinuities can be found by the testing process. This task is a part of the design qualification for a new production part. Reliable detection of rejectable discontinuities should have been demonstrated by actual test or by similarity to parts for which testing has been demonstrated.

Because all discontinuities are not equally detectable, the type of discontinuity to be detected must be the basis for testing qualification. For example, machining tears may be easily detected by a given liquid penetrant process whereas grinding cracks may be completely missed by that specific process. The liquid penetrant testing process must be qualified to the part produced.

Because discontinuity size affects detection, the size of discontinuity to be detected must be the basis for test qualification. Figures 1 and 2 and Table 3 show actual demonstrated liquid penetrant detection reliability as a function of fatigue crack size in aluminum alloy flat plate. A discontinuity size is shown at the inflection point of the curve. This process would be expected to reliably detect discontinuities greater than the threshold size. Acceptance criteria should be based on discontinuities of this size or larger.

Table 3. Probability of detection for fluorescent liquid penetrant testing of aluminum flat plates (see Figs. 1 and 2). False calls were not documented.

Data Set	Condition	Quantity of Cracks Detected/Present	Threshold for 90 Percent Probability of Detection mm (in.)
Crack Length			
C1001C (Fig. 1a)	as machined	233/311	7.95 mm (0.313 in.)
C1002C (Fig. 1b)	after etch	260/311	2.69 mm (0.106 in.)
C1003C (Fig. 1c)	after proof testing	280/306	1.50 mm (0.059 in.)
Crack Depth			
C1001C (Fig. 2a)	as machined	233/311	3.56 mm (0.140 in.)
C1002C (Fig. 2b)	after etch	260/311	0.79 mm (0.031 in.)
C1003C (Fig. 2c)	after proof testing	280/306	0.38 mm (0.015 in.)

PART 4. History of Liquid Penetrant Testing[11]

Through their efforts, a number of creative people made significant contributions to the technology of liquid penetrant testing, a major method of nondestructive testing. The story should be especially interesting to readers familiar with the *green stuff,* with its features and problems, with its tremendous capabilities and its frustrating limitations. It is the story of problems and how ingenious people solved them.

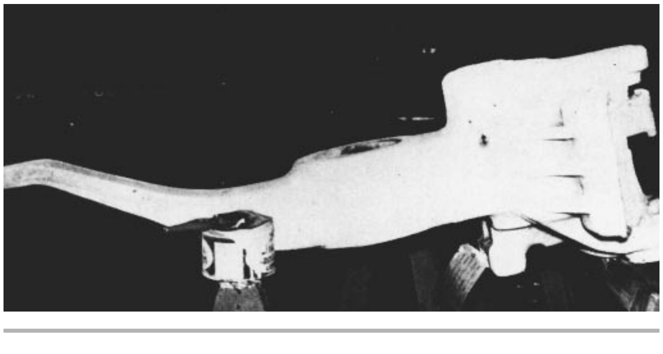
Oil and Whiting

It is generally agreed that the origins of the liquid penetrant testing method lie in the railroad industry in a technique known as the *oil-and-whiting method.*[12] This approach was in use early in this century and possibly even before. It was a craft that was used to test critical steel components for discontinuities.

Basically, the oil-and-whiting technique worked as follows. The part to be tested was cleaned and immersed in dirty crankcase oil diluted in kerosene.[12] (The oil used in the large railroad engines was very heavy, on the order of 600 weight, and experience showed that dirty oil worked best.) The part was then allowed to drain and was cleaned with a solvent. After this, it was covered with whiting (powdered chalk).[13] The entrapped oil would then bleed into the whiting (Fig. 3). It also has been reported that alcohol based or water based chalk suspension was used as the *developer.*[4]

The technique was widely used but never refined. Results were not consistent, and only gross discontinuities could be found. There were no standards, no penetration time, nothing about the quality of the materials or even what kinds of materials to use. People who used it could find gross discontinuities, but the results were not consistent. The interesting thing was that, although the approach found and located discontinuities, it had little to do with the innovations that led to the useful and practical techniques routinely used in the fluorescent technique of liquid penetrant testing. With the introduction of the magnetic particle method in the 1930s, the oil-and-whiting technique became obsolete.[4]

FIGURE 3. In the early 1930s, the oil-and-whiting method is used in a railroad shop on a locomotive coupler. Bleeding of oil indicates crack.



Need for Nonferrous Surface Testing

In the mid-1930s, the use of aluminum and other nonmagnetic metals was increasing significantly. The need for a simple and effective nondestructive testing method for locating surface discontinuities in these materials was obvious. Carl E. Betz, F.B. Doane and Taber DeForest were a few of the people who were experimenting with everything and anything that might solve this industrial need. Techniques using brittle lacquer, electrolysis, anodizing, etching and color contrast penetrants were all evaluated and generally discarded with the exception of the anodizing process.[14] This was used by the military for detailing cracks in critical aluminum airframe members. A specification was generated to define and control this process.[15]

In the fall of 1941, Carl E. Betz (Fig. 4) received a telephone call from a person who identified himself as Robert C. Switzer (Fig. 5). Switzer said that he had developed a new method for the detection of surface cracks, and the claims had just been allowed on the patent application. He knew of Magnaflux and thought it might be interested in some sort of license.

At that time, Betz was in charge of Magnaflux's sales office in New York, NY. Switzer had assumed that Magnaflux was centered out of New York whereas it was actually located in Chicago. This turned out to be a fortunate mistake. Because of Betz's previous work on the development of nondestructive testing methods for

FIGURE 4. Carl E. Betz.

FIGURE 5. Robert C. Switzer.

FIGURE 6. James R. Alburger.

nonmagnetic materials, he was quick to realize the potential value of Switzer's claims. The phone call lasted several hours and was soon followed by a visit to Switzer by A.V. DeForest and his son Taber.[10]

Early Applications of Fluorescence

Fluorescent liquid penetrant is partially rooted in the theater. John "Pop" Shannon supplied liquid penetrant material to Flo Ziegfield who staged shows using fluorescent costumes and lighting. James Alburger (Fig. 6), Shannon's son-in-law, eventually branched out from theatrical and esoteric fluorescent applications into liquid penetrant.[16]

In another part of the country teenager Joseph Switzer had a magic act that consisted of an invisible presentation in which the performers were all dressed in black. When a particular event was to be shown, it was painted white. The stage was darkened, and white lights were used so that only the objects that were painted white were visible. Switzer had the idea of using ultraviolet radiation and fluorescent paint instead of white paint and white lights.[17] Ultimately Joseph Switzer and his brother Robert set up a business called Switzer Brothers Ultra-Violet Laboratories and started to manufacture and sell fluorescent equipment and chemicals in August 1934.

The Switzer brothers abilities were brought to the attention of Continental Lithograph Corporation, Cleveland, Ohio. Continental was a subsidiary of Warner Brothers motion pictures and did all of the printing for Warner's advertising. In 1936 the brothers moved to Cleveland, licensed Continental in all fields of fluorescence and continued their development work.

A very interesting use for fluorescence that had significant later implications for nondestructive testing was in law enforcement. The Federal Bureau of Investigation and the postal authorities used some of Switzer's materials and equipment to track suspects. A superfine pigment that had brilliant fluorescent properties was often dusted on evidence such as currency and was used as an invisible branding mark. If the suspect stole the evidence, the fine invisible pigment was usually smeared all over the suspect, the suspect's household and in many cases members of the suspect's family. Because the pigment was invisible under normal lighting, the suspect was not aware that he was being tracked.

When the law enforcement people closed in and used ultraviolet radiation in a darkened area, the results were devastating and confessions usually occurred on the spot.

Invention of Fluorescent Liquid Penetrant

One of the important observations made was that it was difficult to remove the fluorescent material. It was difficult enough to remove the material even when you were aware of it, so the chances of accidental removal were practically zero. It was noted that you could scrub and scrub, and the stuff would stay in the cracks and pores of your hands. This observation was the key to the later use of fluorescent materials for nondestructive testing.

It turned out that Robert Switzer, Joseph's brother, had more interest finding uses for fluorescent materials. In late 1937, Switzer became aware of a serious problem that one of the local casting companies was having with Ford Motor Company. It seemed that a very large batch of aluminum castings was found to contain a significant number of discontinuities, specifically surface cracks. The cracks did not become visible until the parts were machined.

Ford Motor was in the process of attempting to collect damages for all machining expenses as well as the cost of the parts. Switzer remembered the experience with the superfine fluorescent pigment remaining in the cracks and pores of his hands. He thought he might be able to use that property of the fine material to detail the surface cracks. He had a friend who worked with the company and was able to obtain samples of the castings for his experiments.

Like most good ideas, it did not work at first. His initial approach was to use the pigment that was used in the crime detection effort. But surface cracks in castings were not the same as the cracks in one's hands. Switzer persisted and developed the idea of using liquids to carry the fluorescent material into the cracks.

He was not satisfied with his results and continued his developmental efforts. The work was done mostly in his home because both Continental and his brother Joseph Switzer were not interested in this activity. On August 17, 1938, Robert Switzer applied for a patent on the process.[18] Robert asked Joseph for his share of the patent filing fee, which amounted to fifteen dollars. Joseph refused to spend the money.

Switzer did his own patent work and, while performing the search, ran across a number of Magnaflux Corporation patents on discontinuity detection. He was impressed with the scope of coverage and decided to investigate the company further. He read everything he could about Magnaflux while prosecuting his patent application.

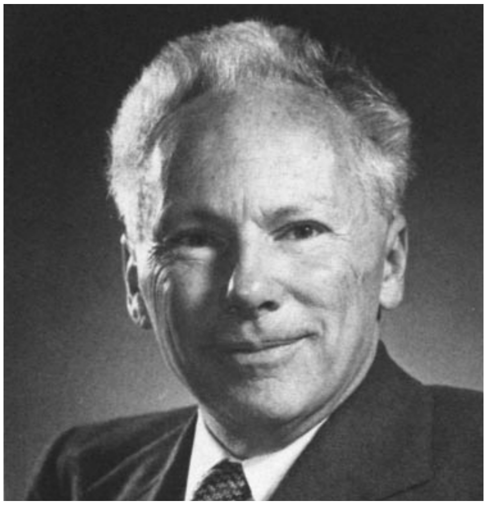
The patent office finally notified Switzer in the summer of 1941 that his claims were allowed and that the patent would be issued. Switzer immediately called Carl Betz at Magnaflux's New York office.

Successful Demonstration of Liquid Penetrant Testing

The two people that came to Switzer's development were also very remarkable individuals (Fig. 7). A.V. DeForest had already made his name as the chief inventor of the magnetic particle process.[19] Taber DeForest's many

FIGURE 7. The DeForest brothers: (a) A.V. DeForest; (b) Taber DeForest.

(a)



(b)

significant contributions to the nondestructive testing field were yet to come. However, he had been working on a visible dye liquid penetrant for several years with no measurable success.[12]

Switzer met with his guests at the Continental Lithograph laboratories and spent most of the day trying to demonstrate his process. Things did not go well. His samples were castings that he hoped contained surface discontinuities. In his earlier work, after liquid penetrant testing revealed a discontinuity, Switzer had to section and thereby destroy the test sample. So he would start the test without knowing whether the sample contained discontinuities. As mentioned above, he was never completely satisfied with his results.

At the end of many frustrating hours, A.V. DeForest quietly suggested that Robert Switzer try a sample that DeForest pulled from an old leather satchel. This was a sample that DeForest relied on for comparison between various experimental magnetic particle materials. He knew where each discontinuity was located. Switzer processed the part. As the indications became visible, all three were astounded by the results. Discontinuities were displayed that DeForest had not seen before (Fig. 8). They looked back at the castings and quickly noted that the surfaces of these parts had been peened, so any discontinuities present were probably closed, making the samples very unsuitable for liquid penetrant testing. The effort that Switzer had spent improving the process from 1937 to 1941 had paid off: the method was very sensitive to fine discontinuities.

FIGURE 8. Photograph of first penetrant test sample.

Liquid Penetrant Testing Process

The process used that day was very similar in many ways to the process used today. The part was cleaned in a strong chlorinated solvent, probably carbon tetrachloride. The part was then immersed in the liquid penetrant solution for more than 10 min. Sometimes the part was heated. After penetration, it was rinsed with a strong solvent and was wiped dry until clean while being observed under ultraviolet radiation. It was then subjected to repeated hammer blows. The purpose of the last operation was to drive the entrapped material out of the surface cracks into the openings on the surface. Then the part was examined for discontinuities under ultraviolet radiation.

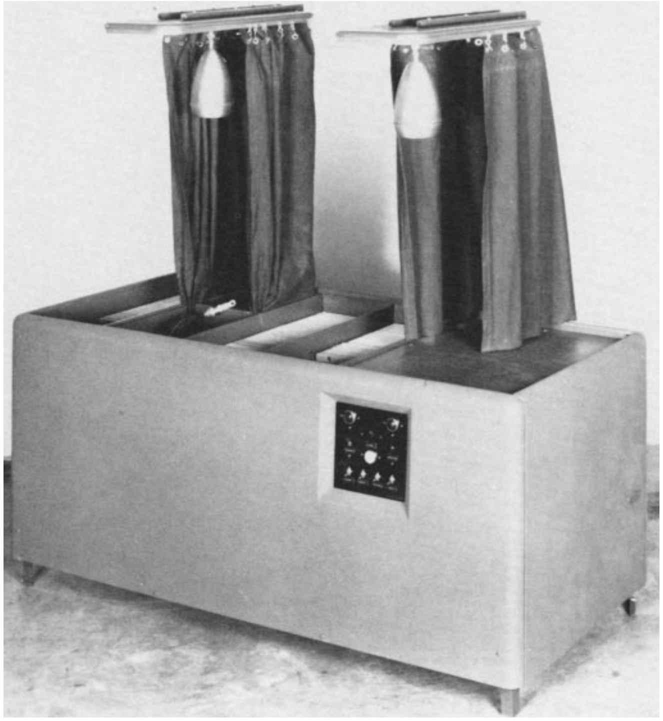
The number of variables was significant and results were not very repeatable. Magnaflux's experience with magnetic particle testing had shown that repeatability was a key to acceptance. It was decided to continue the development effort to make the processing techniques more suitable to the production environment.

Magnaflux Corporation and the Switzer Brothers then entered into a license agreement through Continental Lithograph.[12] A joint development effort was initiated. Many formulations were tried and many different techniques were evaluated. The astounding results formed the basis for developments years later. The Magnaflux effort was led by Greer Ellis (Fig. 9) and Taber DeForest. The development work at Switzer Brothers was done by Joseph Switzer (Fig. 10), who was now very interested, and by R.A. Ward.[12]

FIGURE 9. Greer Ellis.

FIGURE 10. Joseph Switzer (left) and Robert Switzer.

FIGURE 11. The first liquid penetrant testing unit, model ZA1, delivered on October 23, 1942.



Water Washable Liquid Penetrant

The most significant development to come from this joint effort was the water washable liquid penetrant. A line of equipment for handling and processing parts was also developed. In June 1942, water washable materials and equipment were offered for sale (Fig. 11). A flood of inquiries resulted and a number of companies started using the process. The first equipment sale occurred in October 1942 to Aluminum Industries, Cincinnati, Ohio, for the testing of aluminum castings.[12]

Some of the early applications were for the testing of aluminum propeller blades and engine oil cases. Pistons, valves, spark plug housings and critical airframe structures also were tested. The most significant early use of the process was in the maintenance and overhaul of aircraft engines. The method worked very well and in a short time gained wide acceptance.[11,12]

A patent on the water washable process was applied for in June 1942 and was issued in July 1945 to R.A. Ward.[20] It is interesting to note that in column five of the patent's text, Ward states that the emulsifier agent could be used in the wash water and need not be included in the testing agent. Thus postemulsification was mentioned long before it became a commercial reality. Also, in describing the inclusion in the wash water, Ward had essentially described the hydrophilic remover process. This was not introduced commercially until 1963.

Developers

The introduction of developers shortly followed.[21] This was the result of efforts of Harry Kuhrt and Taber DeForest and was heavily influenced by whiting in the oil-and-whiting process. The first commercial products were dry, yellowish materials consisting mainly of talc. The wet developer process did not appear until late in 1944.[11]

By 1942, a fluorescent water washable liquid penetrant and a dry developer were commercially available. Processing equipment was available and many trials in industrial plants had been completed. The first sale had taken place.

Development of Dye Liquid Penetrant

During this period, a need arose for a less complex technique of surface crack testing for nonferrous components. The fluorescent liquid penetrant testing process as it existed required holding tanks, a water supply, electricity and a darkened area for viewing the indications.

A great deal of development work was going on in fluorescent liquid penetrant testing technology: sensitivity and reliability were significantly improved, but the techniques were becoming more complex in the process. The water washable technique was relatively simple and reasonably fast, but something even simpler was needed.

A Northrop metallurgist named Rebecca Smith (later Rebecca Smith Sparling) in the mid-1940s had developed a process that satisfied these needs.[4,12] This was the dye liquid penetrant testing technique, which has become one of the most commonly used techniques for surface discontinuity detection.

Smith Sparling (Fig. 12) graduated from Vanderbilt University Nashville, Tennessee, in 1932 with a master's degree in physical chemistry. During the next ten years, she worked at a number of forging companies and in 1941 was in southern Wisconsin, working for Lakeside Malleable Casting. At this location, she had her first detailed introduction to the oil-and-whiting technique. Lakeside was involved in the manufacture of castings for both the railroad and the automotive industries. She became familiar with the process.[11]

FIGURE 12. Rebecca Smith Sparling (1949).

In the mid-1940s, Smith Sparling was working in the Turbodyne Engine Division of Northrop Corporation. She was involved in the final testing of jet engines and was concerned with certain crack formation occurring on turbine blades during the test cycle. The engines were located at the top of a gantry some 3 m (10 ft) off the floor, close to the ceiling where overhead windows were located. The area was very bright in the California daylight. Smith Sparling tried various ways to use the fluorescent techniques, but to no avail. She remembered her experience with the oil-and-whiting technique in her early railroad days. She decided to try to improve the process.

She stated in one conversation, "All housewives know this about cleaning porcelain sinks. Dirt will remain in the cracks in the sink and will be highlighted against the white background of the porcelain." Smith Sparling enlisted the help of a Northrop chemist by the name of Loy Sockman (Fig. 13),[22] as well as a young man by the name of Elliot Brady, and pursued the development of this idea.

FIGURE 13. Rebecca Smith Sparling and Loy Sockman (1950).

Smith Sparling would suggest an approach and the chemists would work on it. She would then evaluate and comment on their progress and they would modify and innovate. This process continued for a number of years and resulted in the first practical dye liquid penetrant.[19] A patent was applied for by Sockman in March 1949.[23] Smith Sparling was also involved in setting up a number of standards that were eventually to become industry references for the dye liquid penetrant testing technique.

This new technique filled an important market need that Northrop recognized. The technology and patents were sold to Turco Products. Sockman left Northrop and founded the company Met-L-Chek in the early 1950s; there he developed and sold a dye liquid penetrant. Magnaflux offered their version of dye liquid penetrant in 1952.[19]

A few years later, an interesting point developed with respect to the Sockman patent: a patent interference occurred between it and claims filed by Robert Switzer. To understand this fully, the original claims filed by Switzer in August 1938 must be remembered. In this patent application, Switzer included claims for visible as well as fluorescent penetrants. The patent office required division of the fluorescent from the visible claims as one of the early office actions. The fluorescent patent was issued in 1941 to Switzer, as stated earlier.

Robert Switzer filed the visible claims in 1945 as a continuation of the earlier filing. The interference occurred after Sockman's patent was issued in 1954. To complicate the issue further, a number of other similar patents for dye penetrants were issued in this period.[24,25] After a number of years, the patent office ruled in favor of the Switzer claims, allowing the early filing date and assigning a number of the issued visible dye liquid penetrant patents to Switzer.[11,18,26]

Postemulsification in Fluorescent Liquid Penetrant Testing

The next significant improvement occurred in 1952 with the development of the postemulsification process.[27] This development was precipitated by the fact that Rebecca Smith Sparling used visible dye liquid penetrant to find cracks in turbine buckets that fluorescent liquid penetrant had missed.[16] Tabor DeForest and Donald Parker (Fig. 14), both of Magnaflux, set out to improve the performance of fluorescent liquid penetrant. Parker was concerned with the overwash problem of the water washable process. A great deal of effort had been expended in an attempt to solve this problem, but with little success.

FIGURE 14. Donald Parker (1955).

Parker realized that the overwash was caused by the emulsifier's being mixed in the liquid penetrant. For certain types of gross discontinuities, the wash water could penetrate the discontinuity and emulsify the retained liquid penetrant, and the wash cycle would remove the fluorescence. Parker removed the emulsifier from the liquid penetrant and applied it later as a separate, independent operating step, so shallow, open cracks could be detected easily with no overwash problem.

In addition to this, a significant new capability for increased sensitivity was added to liquid penetrant testing: the emulsification time and wash time were now mutually exclusive variables. Each variable could now be adjusted for the optimum time independently of the other.

The first postemulsification products were introduced in 1953. A patent was applied for by Taber DeForest and Parker in July 1954 on the process.[28] In 1955, Parker developed two new emulsifiers and applied for a patent in 1956.[29]

Parker and DeForest also experimented with other ideas concerning the removal of the fluorescent background. Instead of washing it off, they thought of quenching its fluorescence.[30] This was eventually done by large quantities of ultraviolet radiation acting on the dye's instability to high doses of energy. This approach, called the fugitive dye technique, was patented by DeForest and Parker. Although much time was spent trying to make it practical, it was never used commercially.[31]

Cascading Dyes

The next significant development was of cascading dyes, first accomplished by James Alburger. This became another Parker effort.[27] This approach permitted another quantum leap in sensitivity. Parker discovered that sensitivity could be improved dramatically by combining several different dyes in the liquid penetrant. What occurred in this mixture was a cascading effect or a linking between the dyes. One dye had its absorption peak in the ultraviolet range whereas its main emission peak was in the blue range. The other dye had its main absorption in the blue and its main emission in the yellow or yellow-green range. The cascading effect had a net efficiency greater than that of a single dye. A patent was applied for by Parker and Joseph Switzer, and the process was incorporated into commercial products in 1954.[32]

Value and Price

In the mid-1950s, an interesting event pointed out the relationship and communication between users and product developers. After the breakthrough in cascading dyes, Parker decided to develop the *ultimate liquid penetrant*. This would not be a commercial product; rather, it would represent what a liquid penetrant could do. It would be a laboratory material — a standard that all new products would be referenced against. It contained such a high level of dye that the selling price would be prohibitive.[20] Parker developed the liquid penetrant, and it was good. One day, he demonstrated it to personnel of a large aircraft manufacturer and showed them how it could find very minute cracks on their turbine blades. The user's comment on Parker's material was that they couldn't afford not to use it. So it became a product. In fact, with some small refinements, it still is in use today.

Military Standards

The first military specification for liquid penetrant testing was AN-1-30a, issued on September 18, 1946.[33] It covered both the process and the material. It was a very general specification and allowed a great deal of latitude. A detailed process specification, MIL-I-6866, was issued in 1950.[34]

A key milestone occurred when the military material specification MIL-I-25135 was issued on August 6, 1956.[35] This last specification resulted from a meeting attended by industry and military experts in 1955.[9] As a result of this meeting, the first specific military standards for liquid penetrant testing materials were established. Some important long term policies were specified, such as the concept of families of penetrants. This standard lasted for thirty years with only minor changes.

Quantitative Approaches Used

In the late 1950s and early 1960s, a great deal of work was done quantitatively to analyze the performance of penetrants. Many data were generated. Details such as effect of liquid penetrant film thickness, ultraviolet radiation absorption and theoretical effects of developers were studied and applied to new liquid penetrant development. The industry moved toward a more scientific phase of development.[36]

So, in 1961, twenty years after Switzer had the first successful demonstration of fluorescent penetrants, both fluorescent and visible dye penetrants were being used by a number of industries. Materials of great sensitivity were available. Industry and government standards were being established. Water washable and postemulsification processes were in use, and developers were in common use.

Other Contributors

A number of other people have contributed to the development of liquid penetrant testing technology during this period. Frank Catlin of Magnaflux worked on both fluorescent and dye penetrants in the early years.[13] Ferdi Stern of Magnaflux worked with Greer Ellis on the field trials of the early penetrants. Orlando Molino of Rockwell developed and patented the high resolution liquid penetrant testing process in the late 1950s. About the same time major improvements in the sensitivity of water washable liquid penetrants were introduced by James Alburger, who was also the first to commercially introduce hydrophilic emulsifier a little later. J. Thomas Schmidt of Magnaflux developed and refined the quality control and test procedures for product uniformity in the 1960s. People like Al Robinson at General Electric, Victor McBride at Pratt & Whitney, O.E. Stutsman of Wright Field and William Hitt of Douglas critiqued materials and refined the processes. Other people, unnamed here, made contributions to liquid penetrant testing in this period.

As a result of the efforts of all of these pioneering people, there has been a dramatic increase in the reliability of our aircraft engines and airframes. The contributions of these people have made possible also some of the very significant advances in aircraft performance that have occurred in this period. Application of liquid penetrant testing has followed the increased use of a variety of nonferrous metals in critical applications in the nuclear, automotive, space, ordnance and electronic fields.

The next twenty-five years were to see the following developments: (1) development of hydrophilic remover, (2) development of the high sensitivity water washable products, (3) refinements of military standards, (4) introduction of automatic test techniques and (5) investigations of heat fade and statistical techniques of measurement. Because of its sensitivity and economy, liquid penetrant testing will remain one of the most important nondestructive testing methods in the twenty-first century.

PART 5. Units of Measure for Nondestructive Testing

Origin and Use of the SI System

In 1960 the General Conference on Weights and Measures devised the International System of Units. *Le Systeme Internationale d'Unites* (SI) was designed so that a single set of interrelated measurement units could be used by all branches of science, engineering and the general public. Without SI, this *Nondestructive Testing Handbook* volume could have contained a confusing mix of Imperial units, obsolete centimeter-gram-second (cgs) metric system version units and the units preferred by certain localities or scientific specialties.

SI is the modern version of the metric system and ends the division between metric units used by scientists and metric units used by engineers and the public. Scientists have given up their units based on centimeter and gram and engineers made a fundamental change in abandoning the kilogram-force in favor of the newton. Electrical engineers have retained their ampere, volt and ohm but changed all units related to magnetism. The main effect of SI has been the reduction of conversion factors between units to *one* (1) — in other words, to eliminate them entirely.

Table 4 lists seven base units. Table 5 lists derived units with special names. Table 6 gives examples of conversions to SI units. In SI, the unit of time is the second (s) but hour (h) is recognized for use with SI.

For more information, the reader is referred to the information available through national standards organizations and specialized information compiled by technical organizations.[36,37]

TABLE 4. Base SI units.

Quantity	Unit	Symbol
Length	meter	m
Mass	kilogram	kg
Time	second	s
Electric current	ampere	A
Temperature[a]	kelvin	K
Amount of substance	mole	mol
Luminous intensity	candela	cd

a. Kelvin can be expressed in degrees celsius (°C = K – 273.15).

Multipliers

Very large or very small numbers with units are expressed by using the SI multipliers, prefixes of 10^3 intervals (Table 7) in science and engineering. The multiplier becomes a property of the SI unit. For example, a millimeter (mm) is 0.001 meter (m). The volume unit cubic centimeter (cm^3) is $(0.01)^3$ or 10^{-6} m^3. Unit submultiples such as the centimeter, decimeter, dekameter (or decameter) and hectometer are avoided in scientific and technical uses of SI because of their variance from the 10^3 interval. However, dm^3 and cm^3 are in use specifically because they represent a 10^3 variance.

TABLE 5. Derived SI units with special names.

Quantity	Units	Symbol	Relation to Other SI Units[a]
Frequency (periodic)	hertz	Hz	$1 \cdot s^{-1}$
Force	newton	N	$kg \cdot m \cdot s^{-2}$
Pressure (stress)	pascal	Pa	$N \cdot m^{-2}$
Energy	joule	J	$N \cdot m$
Power	watt	W	$J \cdot s^{-1}$
Electric charge	coulomb	C	$A \cdot s$
Electric potential[b]	volt	V	$W \cdot A^{-1}$
Capacitance	farad	F	$C \cdot V^{-1}$
Electric resistance	ohm	Ω	$V \cdot A^{-1}$
Conductance	siemens	S	$A \cdot V^{-1}$
Magnetic flux	weber	Wb	$V \cdot s$
Magnetic flux density	tesla	T	$Wb \cdot m^{-2}$
Inductance	henry	H	$Wb \cdot A^{-1}$
Luminous flux	lumen	lm	$cd \cdot sr$
Illuminance	lux	lx	$lm \cdot m^{-2}$
Plane angle	radian	rad	1
Radioactivity	becquerel	Bq	$1 \cdot s^{-1}$
Radiation absorbed dose	gray	Gy	$J \cdot kg^{-1}$
Radiation dose equivalent	sievert	Sv	$J \cdot kg^{-1}$
Solid angle	steradian	sr	1
Time	hour	h	3600 s
Volume[c]	liter	L	dm^3

a. Number one expresses dimensionless relationship.
b. Electromotive force.
c. The only prefixes that may be used with liter are milli (m) and micro (μ).

Table 6. Examples of conversions to SI units.

Quantity	Measurement in Non-SI Unit	Multiply by	To Get Measurement in SI Unit
Area	square inch (in.^{2})	645	square millimeter (mm^2)
Distance	angstrom (Å)	0.1	nanometer (nm)
	inch (in.)	25.4	millimeter (mm)
Energy	British thermal unit (BTU)	1.055	kilojoule (kJ)
	calorie (cal)	4.19	joule (J)
	British thermal unit per hour (BTU·h^{-1})	0.293	watt (W)
Specific heat	British thermal unit per pound per degree Fahrenheit (BTU·lb$_m^{-1}$·°F^{-1})	4.19	kilojoule per kilogram per kelvin (kJ·kg^{-1}·K^{-1})
Force (torque, couple)	foot-pound (ft-lb$_f$)	1.36	joule (J)
Force or pressure	pound force per square inch (lb$_f$·in.$^{-2}$)	6.89	kilopascal (kPa)
Frequency (cycle)	cycle per minute	1/60	hertz (Hz)
Illuminance	footcandle (ftc)	10.76	lux (lx)
	phot (ph)	10 000	lux (lx)
Luminance	candela per square foot (cd·ft^{-2})	10.76	candela per square meter (cd·m^{-2})
	candela per square inch (cd·in.$^{-2}$)	1 550	candela per square meter (cd·m^{-2})
	footlambert	3.426	candela per square meter (cd·m^{-2})
	lambert	3 183 (= 10 000/π)	candela per square meter (cd·m^{-2})
	nit (nt)	1	candela per square meter (cd·m^{-2})
	stilb (sb)	10 000	candela per square meter (cd·m^{-2})
Radioactivity	curie (Ci)	37	gigabecquerel (GBq)
Ionizing radiation exposure	roentgen (R)	0.258	millicoulomb per kilogram (mC·kg^{-1})
Mass	pound (lb$_m$)	0.454	kilogram (kg)
Temperature (difference)	degree fahrenheit (°F)	0.556	degree celsius (°C)
Temperature (scale)	degree fahrenheit (°F)	(°F – 32)/1.8	degree celsius (°C)
			(°F – 32)/1.8) + 273.15 kelvin (K)

Table 7. SI multipliers.

Prefix	Symbol	Multiplier
yotta	Y	10^{24}
zetta	Z	10^{21}
exa	E	10^{18}
peta	P	10^{15}
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
hecto[a]	h	10^{2}
deka (or deca)[a]	da	10
deci[a]	d	10^{-1}
centi[a]	c	10^{-2}
milli	m	10^{-3}
micro	µ	10^{-6}
nano	n	10^{-9}
pico	p	10^{-12}
femto	f	10^{-15}
atto	a	10^{-18}
zepto	z	10^{-21}
yocto	y	10^{-24}

a. Avoid these prefixes (except in dm^3 and cm^3) for science and engineering.

Note that 1 cm^3 is not equal to 0.01 m^3. Also, in equations, submultiples such as centimeter (cm) or decimeter (dm) should be avoided because they disturb the convenient 10^3 or 10^{-3} intervals that make equations easy to manipulate.

In SI, the distinction between upper and lower case letters is meaningful and should be observed. For example, the meanings of the prefix *m* (milli) and the prefix *M* (mega) differ by nine orders of magnitude.

SI Units to Express Particular Quantities in Nondestructive Testing

Pressure

The pascal (Pa), equal to one newton per square meter (1 N·m^{-2}), is used to express pressure, stress etc. It is used in place of units of pound force per square inch (lb$_f$·in.$^{-2}$), atmosphere, millimeter of mercury (mm Hg), torr, bar, inch of mercury (in. Hg), inch of water (H_2O) and other units. The text must indicate whether *gage, absolute* or *differential* pressure is meant.

Volume

The cubic meter (m^3) is the only volume measurement unit in SI. It takes the place of cubic foot, cubic inch, gallon, pint, barrel and more. In SI, the liter (L) is also approved for use. The liter is a special name for cubic decimeter (1 L = 1 dm^3 = 10^{-3} m^3). Only the *milli* (m) and *micro* (µ) prefixes may be used with liter.

The fundamental units of time, temperature, pressure and volume are expressed every time movement of a fluid (liquid or gas) is measured.

Light

Light is electromagnetic radiation in the visible range of wavelength or frequency.

Vision requires a source of illumination. The light source is measured in candela (cd), defined as the *luminous intensity* in a given direction of a source that emits monochromatic radiation of 540 × 10^{12} hertz (540 THz) at a radiant intensity of 1/683 watt per steradian (about 0.0015 $W \cdot sr^{-1}$).

The *luminous flux* in a steradian (sr) is measured in lumen (lm). The measurement in lumen is the product of candela and steradian (1 lm = 1 cd·sr).

A light flux of one lumen (1 lm) striking one square meter (1 m^2) on the surface of the sphere around the source illuminates it with one lux (1 lx), the unit of *luminance*, or brightness. If the source itself is scaled to one square meter and emits one candela (1 cd), the luminance of the source is 1 $cd \cdot m^{-2}$.

Some terms have been replaced in SI. *Illumination* is now *illuminance*. *Transmission factor* is now *transmittance*. *Meter-candle* is now *lux*. *Nit* is *candela per square meter* ($cd \cdot m^{-2}$).

Old units are to be converted (Table 6). Footcandle (ftc) and phot (ph) now convert to lux (lx). Stilb (sb), footlambert and lambert convert to candela per square meter ($cd \cdot m^{-2}$). For measurement of wavelength, nanometer (nm) obviates angstrom (Å): 10 Å = 1 nm.

Viscosity

Dynamic viscosity is expressed in SI by the pascal second. An older unit is the poise (P), or centipoise (cP): 100 cP = 1 P = 0.1 Pa·s.

Kinematic viscosity is expressed in SI as square meter per second, equivalent to the dynamic viscosity divided by mass density. An older unit is the stokes (St): 1 cSt = 0.01 St = 1 $mm^2 \cdot s^{-1}$; 1 St = 0.0001 $m^2 \cdot s^{-1}$.

Porosity

Porosity is reported as a ratio of volume to volume and can be expressed as a percentage. For example, if hydrogen content in aluminum is measured as 2.5 $mm^3 \cdot g^{-1}$, this value reduces to 2.50 $mm^3 \cdot (0.37\ cm^3)^{-1} \times 1000\ mm^3 \cdot cm^{-3}$ = 0.675 or about 0.7 percent. Therefore the hydrogen content should be reported as 6.75 $mm^3 \cdot cm^{-3}$ in volume for a porosity of 0.7 percent.

Abrasives and Finish Treatment

Surface abrading is a matter of concern in liquid penetrant testing because grinding, shot peening and sand blasting can close surface breaking cracks and so keep them from being indicated in tests. Finish also affects adherence of materials to a surface. In preparation of test panels for evaluation, the type and size of abrasive blasting is often specified.

Abrasive particle size (coarse versus fine) in the United States has traditionally been specified using industry accepted gage numbers that correspond to the number of lines (or wires) per inch in sieves used to sift the abrasive grit. A number of standards govern grit specifications in the abrasive industries — for example, ANSI B 74.16 for industrial diamonds. Table 8 shows several of the many levels of grit designations based on particle size.[39]

Organizations that issue standards in this area include the American National Standards Institute (ANSI), the American Society for Testing and Materials (ASTM), the Federation of the European Producers of Abrasives (FEPA) and the International Standardization Organization (ISO).

TABLE 8. Abrasive particle size and sieve apertures.

Mesh Designation		Nominal ISO	Sieve Lines	
USA Grit	FEPA Grit	Sieve Aperture (µm)	per 10 mm	(per 1.0 in.)
70 to 80	213	212 to 180	30.3	(76.9)
80 to 100	181	180 to 150	39.4	(100.0)
100 to 120	151	150 to 125	43.7	(111.1)
120 to 150	126	125 to 106	49.2	(125.1)
140 to 170	107	106 to 90	59.1	(150.1)

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2

CHAPTER

Principles of Liquid Penetrant Testing

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PART 1. Elements of Liquid Penetrant Testing

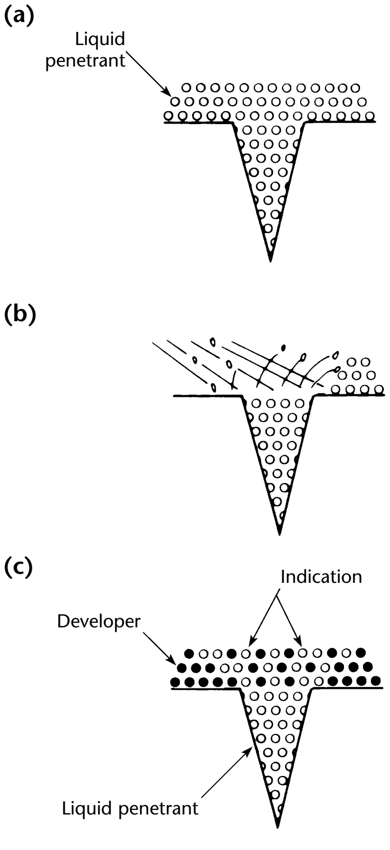
Basic Liquid Penetrant Testing Process

The basic principles of the liquid penetrant testing process have not changed from the oil-and-whiting days. These principles are shown in Fig. 1. As the liquid penetrant testing process evolved, additional steps were specified. Presently, the process consists of six basic steps.

1. *Preclean and dry the test surfaces of the object to be inspected.* Cleaning is a critical part of the liquid penetrant process and is emphasized because of its effect on the test results. Contaminants, soils or moisture, either inside the discontinuity or on the part surface at the discontinuity opening, can reduce or completely destroy the effectiveness of the test.
2. *Apply liquid penetrant to the test surfaces* and permit it to dwell on the part surface for a period of time to allow it to enter and fill any discontinuities open to the surface.
3. *Remove the excess liquid penetrant from the test surfaces.* Care must be exercised to prevent removal of liquid penetrant contained in discontinuities.
4. *Apply a developer*, which aids in drawing any trapped liquid penetrant from discontinuities and spreading that liquid penetrant on the test surface to improve the visibility of indications. The developer also provides a contrasting background on a part surface, especially for nonfluorescent indications.
5. *Visually examine surfaces for liquid penetrant indications; interpret and evaluate the indications.*
6. *Postclean the part* to remove process residues if they will be detrimental to subsequent operations or the part's intended function. (In some cases, a treatment to prevent corrosion may be required.)

These six basic steps are followed regardless of the type of fluorescent or visible color dye used to form the liquid penetrant indications. The fourth step, application of a developer, is sometimes omitted when testing newly manufactured parts with fluorescent liquid penetrants but at the cost of lower test sensitivity due to reduced visibility of indications.

FIGURE 1. Basic liquid penetrant process: (a) apply liquid penetrant; (b) remove excess; (c) apply developer.



Materials That Can Be Inspected by Liquid Penetrant Tests

Liquid penetrant testing is one of the best test methods for all types of discontinuities open to accessible surfaces in solid nonpermeable materials. Laminations and lack of bond between layers of laminated materials can be detected with liquid penetrants only if these laminar discontinuities extend to exposed edges or holes where the liquid penetrant can enter and indications can be observed. Liquid penetrant testing has been used with excellent success on ferrous and nonferrous metals and alloys, fired ceramics and cermets, powdered metal products, glass and some types of plastics and synthetic organic materials. Liquid penetrants are also used for detection of leaks in tubing, tanks, welds and components.

Reasons for Selecting Liquid Penetrant Testing

Some of the reasons for choosing liquid penetrant testing are as follows.

1. Liquid penetrant testing can quickly examine all the accessible surfaces of objects. Complex shapes can be immersed or sprayed with liquid penetrant to provide complete surface coverage.
2. Liquid penetrant testing can detect very small surface discontinuities. It is one of the most sensitive nondestructive test methods for detecting surface discontinuities.
3. Liquid penetrant testing can be used on a wide variety of materials: ferrous and nonferrous metals and alloys; fired ceramics and cermets; powdered metal products; glass; and some types of organic materials. Restrictions on materials imposed by the nature of the liquid penetrant process are covered in the discussion of limitations, below.
4. Liquid penetrant testing can be accomplished with relatively inexpensive, nonsophisticated equipment. If the area to be inspected is small, the test can be accomplished with portable equipment.
5. Liquid penetrant testing magnifies the apparent size of discontinuities making the indications more visible. In addition, the discontinuity location, orientation and approximate size and shape are indicated on the part, making interpretation and evaluation possible.
6. Liquid penetrant testing is readily adapted to volume processing, permitting 100 percent surface inspection. Small parts may be placed in baskets for batch processing. Specialized systems may be partially or fully automated to process many parts per hour.
7. The sensitivity of a liquid penetrant testing process may be adjusted through appropriate selection of liquid penetrant, removal technique and type of developer. This allows the liquid penetrant process to be adapted to characteristics (e.g., composition, surface condition) of the part requiring testing and to be tailored to detect specified minimum rejectable discontinuities. Thus, detection of inconsequential discontinuities can be minimized whereas larger discontinuities of more concern are indicated.

Movie. Bleeding suggests discontinuity severity.

Disadvantages and Limitations of Liquid Penetrant Testing

1. Liquid penetrant testing depends on the ability of liquid penetrant to enter and fill discontinuities. Penetrant testing will only reveal discontinuities open to the surface.
2. Surfaces of objects to be inspected must be clean and free of organic or inorganic contaminants that will prevent interaction of the penetrating media with a surface. Organic surface coatings, such as paint, oil, grease or resin, are in this category. Any coating that covers or blocks the discontinuity opening will prevent liquid penetrant entry. Even when the coating does not cover the opening, material at the edge of the opening may affect entry or exit of liquid penetrant and greatly reduce reliability of the test. Coatings in the vicinity of a discontinuity will also retain liquid penetrant, causing background fluorescence. Cleaning test surfaces is discussed in more detail below.
3. It is also essential that the inside surface of discontinuities be free of materials such as corrosion, fluids, combustion products or other contaminants that would restrict entry of liquid penetrant. Because it is impossible to check inside discontinuities, one must trust that processes selected to clean test surfaces will clean inside surfaces of discontinuities also.
4. Mechanical operations, such as shot peening, plastic media blasting (PMB), machining, honing, abrasive blasting, buffing, brushing, grinding or sanding will smear or peen the surface of metals. This mechanical working closes or reduces the surface opening of existing discontinuities. Mechanical working (smearing or peening) also occurs during service when parts are in contact or rub together. Penetrant testing will not reliably detect discontinuities when it is performed after a mechanical operation or service use that smears or peens the surface. In some cases chemical removal (etching) of smeared metal may restore test reliability.
5. Unless special procedures are used, liquid penetrant testing is impractical

on porous materials, such as some types of anodized aluminum surfaces, other protective coatings and porous nonmetallic parts. Penetrant rapidly enters pores of the material and becomes trapped. This can result in an overall background fluorescence or color that could mask any potential discontinuity indications. In addition, removal of the liquid penetrant may not be possible after the test.

6. Penetrants, emulsifiers and some types of developers have very good wetting and detergent properties. They can act as solvents for fats and oils. They also can clean ferrous materials so thoroughly that rust will begin almost immediately if corrosion inhibitor is not applied. If allowed to remain in contact with human skin for extended periods, they may cause irritation.

Classification of Liquid Penetrants by Dye Type

Liquid penetrants are generally classified by type according to the dye contained in the liquid penetrant. The liquid penetrant testing process relies on liquid penetrant entering a discontinuity and subsequently being drawn back out and made easily visible on the surface of a part. The amount of liquid penetrant material entrapped in discontinuities is usually very small. If the discontinuity is to be detected, the very small amount of liquid penetrant must be highly visible. In the oil-and-whiting days, it was found that used or dirty oil was much more visible than clean machine oil. Today chemists make liquid penetrants visible by dissolving highly colored dyes in a penetrating oil or other vehicle. Based on the dye, liquid penetrants are classified as one of the three types described below.

Movie. Fluorescent liquid penetrant.

Movie. Liquid penetrant seeps into discontinuity.

Fluorescent Liquid Penetrant

Fluorescent liquid penetrants contain fluorescent dye that emits yellowish green light when exposed to near ultraviolet radiation (with a wavelength of 320 to 400 nm). This property is termed fluorescence. Very small quantities of fluorescent liquid penetrant will emit highly visible indications when exposed to ultraviolet radiation.

Visible Liquid Penetrant

Visible dye or color contrast liquid penetrants contain a dye that is visible under natural or white light. The visibility is further enhanced during the liquid penetrant process by the application of a white developer. The white developer provides a high contrast background for the colored liquid penetrant when viewed under the appropriate light. Red dye is most common, although some blue dye is also used.

Dual Mode (Both Visible and Fluorescent) Liquid Penetrant

Dual mode liquid penetrants contain dyes that are both colored under white light and fluorescent under ultraviolet radiation. However, the intensities of the visible color (usually red) and the fluorescent color (usually orange) are less than the colors produced by the single mode visible and fluorescent liquid penetrants respectively.

Classification of Liquid Penetrants by Removal Method

A liquid penetrant is further classified by the technique used to remove it from the surface of a part after it has been on the part a specified amount of dwell time during the test process. The liquid penetrants are formulated and manufactured for specific removal techniques designed to minimize removal of the liquid penetrant that has seeped into a discontinuity. Each removal technique has advantages and disadvantages, discussed below.

Water Washable Liquid Penetrant

Most liquid penetrants contain an oil base insoluble in and immiscible with water. This means that the excess liquid penetrant on a part cannot be removed with water. However, some liquid penetrants are carefully compounded mixtures of an oil base and an emulsifier, and others have water or a surfactant as a base rather than oil. Manufacturers provide these alternative formulations in ready-to-use liquid penetrants, which may be removed with water immediately after the liquid penetrant dwell. Depending on requirements imposed on the liquid penetrant testing procedure by applicable process specifications, the removal may be accomplished by wiping the part surface with a wet lintfree cloth (after wiping with a dry lintfree cloth first), by directing a controlled spray onto the part or by dipping and agitating the part in water.

Postemulsifiable Liquid Penetrant

When used in the postemulsification process, liquid penetrants can be formulated to optimize their penetrating and visibility characteristics for higher sensitivity. Because postemulsifiable liquid penetrants do not contain any emulsifying agent, they are less likely to be removed from the discontinuity when the surface liquid penetrant is being removed with water. Removal from a surface is accomplished by applying an emulsifier in a separate process step, normally by dipping the part into a tank of the emulsifier or spraying the emulsifier onto the part. Depending on the type of emulsifier used, the emulsifier either converts the excess surface liquid penetrant into a mixture that forms an emulsion with the addition of water (lipophilic) or acts directly with the liquid penetrant to form an emulsion subsequently removed with water (hydrophilic).

A postemulsifiable liquid penetrant usually can be used with any emulsifier. However, qualifying/approving agencies may choose to qualify a liquid penetrant–emulsifier combination from the same manufacturer. The manufacturer may offer the same liquid penetrant for use with different emulsifiers. A user could use any liquid penetrant–emulsifier combination that met the approval of a customer.

Solvent Removable Liquid Penetrant

The term *solvent removable* is often used as if it applied to a discrete class of liquid penetrants. In fact, all liquid penetrants can be removed with solvents. In most applications the liquid penetrants used in the solvent removable process are postemulsifiable; however, water washable liquid penetrants can also be used. For some applications a manufacturer may choose to offer a liquid penetrant qualified for the solvent removable process only.

With this technique excess liquid penetrant is removed from a test surface by first wiping the surface with a clean, dry, lintfree cloth or paper towel. After most of the surface liquid penetrant has been removed, the remainder is removed with another clean cloth slightly moistened with the solvent. Because the solvent removable technique is very labor intensive, it is normally used only when it is necessary to inspect a localized area of a part or a part at its inservice site rather than in a production environment. When properly applied, the solvent removable technique can be one of the most sensitive liquid penetrant testing techniques available.

Movie.
Solvent removes excess liquid penetrant from part surface.

Types of Emulsifiers

Lipophilic emulsifiers are composed of liquid blends that combine with oil based liquid penetrants to form a mixture that can be removed with a water spray. They are supplied in a ready-to-use form. Their mode of action is based primarily on diffusion and solubility into an oil base liquid penetrant. Parts are generally dipped into tanks of lipophilic emulsifier, withdrawn and placed at a drain station for a specified time. The diffusion rate (emulsification time) will vary depending on the viscosity of the emulsifier and the physical action of drainoff. Therefore, it is important to control the emulsification time to prevent emulsification of the liquid penetrant in the discontinuity.

Hydrophilic emulsifiers, often referred to as removers, are composed of emulsifying agents dissolved in water and are supplied in a concentrate form. They are diluted with water at concentrations of 5 to 30 percent and used as an immersion dip with mild air or mechanical agitation or as a forced water spray rinse at dilution ratios up to a maximum of 5 percent. A prerinse with a water spray normally precedes the application of hydrophilic emulsifiers, so liquid penetrant contamination of the emulsifier is reduced. The term hydrophilic can be defined as having an affinity for water, whereas lipophilic means having an affinity for oil.

Hydrophilic emulsifiers function through their detergent and scraping or scrubbing (kinetic) action. Diffusion does not take place in this mechanism of action. The surface active agent in the remover helps displace liquid penetrant from the surface and prevents redeposition. Removal of excess surface liquid penetrant with hydrophilic emulsifiers in an immersion or dip mode begins as the remover detaches the liquid penetrant from the surface. Mild agitation removes the displaced liquid penetrant from the part so that it cannot redeposit. When a spray is used, the impinging droplets of water have the same effect as agitation in a tank. The hydrophilic emulsifier contact time is directly related to its concentration. This applies to both immersion and spray applications. The hydrophilic emulsification process affords better control and, in addition, allows for an effective and practical treatment and recycling of the liquid penetrant prerinse solution, thereby minimizing waste water pollution.

Solvent Removers

Solvent removers have traditionally been petroleum base or chlorinated solvents. However, because the former is flammable and production of the latter ceased in December 1995, use of detergent cleaners or water base solvents is increasing. Water itself can be used as a *solvent* for water washable liquid penetrants. Often an emulsifier contains enough solvency to function as a hand wipe remover also.

Types of Developers

The developer increases the intensity (brightness) of fluorescent liquid penetrant indications and the contrast of visible dye liquid penetrant indications. The developer also provides a blotting action, which serves to draw liquid penetrant from within the discontinuity to the part surface until the thickness of the surface film of liquid penetrant exuded from the discontinuity is increased to levels above the threshold of visibility. Another developer function is to spread the liquid penetrant on the surface, enlarging the appearance of the indication.

Dry powder developers are applied to dry part surfaces by air suspension, electrostatic spraying or part immersion. The powder is light and fluffy and clings to the part surfaces in a fine film. Dry powder developers should not be used with visible liquid penetrant because they do not produce a satisfactory contrast coating on the surface of the part. Electrostatic spraying is common in automated systems. For reasons of human safety, dry powder developers should be handled with care. Like any other dust particle, it can dry the skin and irritate the lining of the breathing passages.

Water soluble developers consist of a powder dissolved in water and applied by dipping a part in the solution, by flowing the solution over a part or by spraying the solution onto the part. As the part is dried, a thin layer of the powder remains on the part. Stationary test equipment usually includes a tank module for aqueous developer. Complete coverage is easily obtained by dipping parts. However, puddling of the developer in recesses of complex parts must be avoided so that all water evaporates during drying and the developer coating has a uniform thickness.

Water suspendible developers are similar to the water soluble type except that the powder, insoluble in water, remains in suspension until it precipitates onto the part as it is dried. Aqueous suspendible developers are used in the same manner as the aqueous soluble developers. However, suspendible developers must be constantly agitated to keep the developer suspended. Removal of dried suspendible developers may be more difficult because they are not soluble in water. All aqueous developers necessarily contain biocides, corrosion inhibitors and wetting agents.

Nonaqueous (solvent suspendible) developers are supplied in the ready-to-use condition, frequently in aerosol cans. This type of developer is the most sensitive form because the solvent action contributes to the absorption and adsorption mechanisms of the developer by entering the discontinuity and dissolving into the liquid penetrant. This action increases the volume and reduces the viscosity of the liquid penetrant and leaches it to the surface. Nonaqueous developers are suitable for testing of installed parts or in nonproduction situations involving few parts or small areas. With the discontinued use of chlorinated solvents, because of environmental concerns, flammable solvents may be the only choice.

MOVIE. Nonaqueous wet developer enhances visible dye contrast.

Qualified/Approved Liquid Penetrant Materials

Although a qualifying/approving agency may be an independent organization designated and approved by a governing body or end user, a qualifying/approving agency is ultimately a customer that requires liquid penetrant materials to pass designated tests in order to be used for inspecting the products it buys. A customer may designate specific liquid penetrant materials to be used to inspect its products or may allow organizations performing tests to make appropriate selections from a list of qualified/approved liquid penetrant materials to which the customer subscribes. All materials in a given classification category on such a list are considered equivalent in meeting generic specification requirements. Consequently, any manufacturer's product listed on a qualified/approved list may be substituted for any other product listed under the same classification. In its listings of materials, a qualified/approved list may formalize the classification of types of liquid penetrants, techniques of removal, classes of solvents and forms of developers with number and/or letter designations for easy reference.

A typical example of a qualified and approved list is QPL-AMS-2644,[1] a qualified products list that has been generated by the United States Air Force for the Department of Defense and replaces QPL-25135.[2] This qualified products list itemizes materials that meet or exceed the requirements of the SAE AMS 2644 specification for liquid penetrant testing materials.[3] The current trend is to have consensus industry specifications instead of military specifications, so the Department of Defense (the customer) has chosen the SAE document for its liquid penetrant product requirements.

Listing of liquid penetrant materials on a qualified products list does not guarantee that subsequent batches of the same formulation will be acceptable. Listing on a qualified products list merely indicates that the original raw materials, formulation and compounding practice can result in an acceptable liquid penetrant test product. Many factors and conditions involved in compounding and manufacturing liquid penetrants can affect their performance. Specifications for liquid penetrant testing materials may include an option for a procuring activity to contractually require a manufacturer to provide quality conformance test results for the lot/batch to be supplied and/or a sample of the material for independent testing.

Sensitivity

When applied to liquid penetrant testing processes, the term *sensitivity* refers to the ability to detect discontinuities. In this context, sensitivity is a relative factor. Higher sensitivity indicates that a test process can detect smaller discontinuities than less sensitive processes. Several factors influence the sensitivity of a given liquid penetrant testing process. The cleaning techniques, the selected liquid penetrant materials and the procedure by which the materials are processed affect the sensitivity of the liquid penetrant testing process.

The *sensitivity* of a liquid penetrant testing *process* is not to be confused with *sensitivity level of a liquid penetrant system*, a term used to classify the relative sensitivity of liquid penetrant systems that are processed according to a standardized procedure. A liquid penetrant *system* is normally designated by type of dye in the liquid penetrant and technique of removal. A postemulsifiable liquid penetrant system includes a liquid penetrant and an emulsifier, normally from the same manufacturer. The sensitivity level facilitates the selection of a system to obtain the desired test process sensitivity.

Therefore, if all processing variables are equal, a penetrant system with a higher level of sensitivity will produce a detectable indication of a very small discontinuity, whereas a system with lower sensitivity may not.

Brightness and Sensitivity of Fluorescent Liquid Penetrants

There is considerable difference of opinion over the synonymous use of the terms *brightness* and *sensitivity* to describe performance of liquid penetrant materials and techniques. The difficulty arises from the absence of a reliable and objective scientific test for evaluating liquid penetrant sensitivity. Sensitivity tests rely mostly on comparative visual observation of indications of known crack patterns on reference blocks. Such comparisons leave considerable uncertainty in individual interpretation of sensitivity. In addition to individual differences in interpretation, individual differences in processing of reference blocks or test parts may have a decided influence on evaluation performed in this manner.

The human perception of brightness is a qualitative experience influenced by the dark adaptation of the inspector's eyes and the contrast of the indication intensity against the surrounding background intensity. Instruments can measure the luminous intensity per unit projected area (of the light source). For example, intensity data gathered with a photometer has been used to assign the sensitivity levels to liquid penetrant systems during qualification testing for inclusion in QPL-AMS-2644.[3]

Luminescence measurements are made of fluorescent liquid penetrant indications produced by known crack patterns in specimens processed with standardized procedures. The assignment of sensitivity levels is based on the premise that more sensitive liquid penetrant systems produce brighter crack indications. Because of variables such as surface cleanliness, process control and interpretation, this premise is valid only in a carefully controlled scenario such as this qualification application. There is no doubt that brighter indications are easier to detect, but the sensitivity of a liquid penetrant process must be determined empirically for each application. To reiterate, the sensitivity level of a liquid penetrant system is only a reference point from which to start the empirical process.

Major Requirements of Liquid Penetrants

A satisfactory liquid penetrant must meet several rather exacting requirements, some of which are more or less in conflict with the others. High on the list of desirable characteristics is penetrating action or the ability to enter extremely fine surface openings in test objects. Fortunately most oily liquids penetrate well, so this is not a restrictive requirement.

In other cases, the ability of a liquid penetrant to become entrapped and held can become a problem. This need conflicts with the equally important requirement for suitable removability of excess liquid penetrant from the surface of the part after discontinuities have been penetrated.

Another characteristic, of at least equal importance to penetrating action, is visibility or the contrast between the liquid penetrant indication and the background against which it is viewed by the inspector.

The degree to which each of the above features is present in a particular liquid penetrant will depend on the application for which it is intended but each property will be found in any materials suitable for testing purposes. The means by which each property is obtained will also vary widely among the various available liquid penetrants.

Liquid Vehicle Properties and Penetrating Ability of Liquid Penetrants

Unfortunately, there is neither a simple rule for formulating a highly penetrating liquid penetrant nor is there a fixed set of characteristics which, if provided, will ensure a final material that is completely satisfactory. Some properties that would seem absolutely necessary have little or no effect on the ability of the liquid penetrant to enter surface discontinuities, although there may be other reasons for their control. Viscosity of liquid penetrants serves as a good illustration. It would seem logical to assume that a low viscosity material would enter small discontinuities more rapidly than one with a higher viscosity; however, many highly viscous liquids are excellent liquid penetrants because normal liquid penetrant dwell times are long enough to let tiny cracks be filled, regardless of viscosity. The chemical composition of the liquid penetrant material also influences the liquid penetrant's ability to seep into cracks.

The penetrating ability of a complete liquid penetrant material is mainly a function of the properties of the liquid carrier or vehicle of the liquid penetrant material. The functions of the liquid carrier or vehicle are (1) to hold the dye in solution or suspension; (2) to distribute the liquid penetrant evenly and completely over the surface to be inspected; and (3) to carry the liquid penetrant into any discontinuities present on the test surface.

Body and Volatility of Liquid Penetrants

In addition to inherent penetrating ability of the carrier liquid, numerous secondary qualities are necessary to permit use of its penetrating power. The material should have sufficient body to hold the dye throughout the time necessary for penetration to take place. Some liquid penetrants exhibit a certain amount of volatility. It is reasoned that a small amount of evaporation at the discontinuity could help to intensify dye brilliance and also prevent excessive spreading of indications. At the same time, a liquid that is too highly volatile is undesirable. The highly volatile liquid penetrants will evaporate rapidly from processing tanks. This evaporation can change the performance characteristics of the liquid penetrant material and release vapors that may be a nuisance or even a hazard.

Wetting Ability of Liquid Penetrants

Wetting ability is another property that does not seem to correlate directly with ability to penetrate but it does have an important effect on overall performance. A material that has good wetting properties will spread completely over the surface of the treated part in a smooth, even film despite the presence of a reasonable amount of surface contamination. On the other hand, a liquid of poor wetting characteristics will pull back on itself, leaving areas of the test surface completely devoid of liquid penetrant. When this occurs, discontinuities that may be present in the uncovered areas will not be visible, for there is no indicating material to enter them. This is very important when the test surface is smooth (as with stainless steel forgings).

Liquid Penetrant Requirements for Special Applications

The aerospace and nuclear industries have imposed some special requirements on liquid penetrants for specific applications that may or may not require specially formulated products. Examples of special types of liquid penetrants include the following.

1. Liquid penetrants used in inspection of liquid oxygen or high pressure gaseous oxygen systems. These must leave no contaminants or residues that react with the oxygen.

2. Liquid penetrants with low content of sulfur and/or halogen (e.g., chloride). Sulfur or chlorine may be detrimental to stainless steel or titanium metals or alloy surfaces under subsequent high temperature processing or service.
3. Liquid penetrants low in alkali metals such as sodium and potassium and low in low melting temperature metals such as lead, tin and mercury.
4. Liquid penetrants for use at very low or very high temperatures.

Whether or not these particular requirements are imposed, the basic procedures of liquid penetrant testing and the mechanisms of operation of liquid penetrant materials remain unchanged. The difference lies only in the special liquid penetrant products being used.

Liquid Penetrants for Liquid or Gaseous Oxygen System Components

Aerospace systems sometimes use liquid oxygen or gaseous oxygen in their propellant and life support systems. Formulation of a liquid oxygen or gaseous oxygen insensitive liquid penetrant presents a formidable problem because all organic chemicals are reactive with liquid oxygen or gaseous oxygen to some degree. Many of the common ingredients of liquid penetrants are organic and are therefore subject to liquid oxygen reactivity. Even if organic ingredients are present in very low concentrations, there is always the possibility that they can become concentrated through evaporation or accumulation. ASTM D 2512 covers the commonly accepted test techniques for liquid oxygen compatibility.[4] Liquid penetrants that meet these test requirements are available.

PART 2. Liquid Penetrant Testing Processes

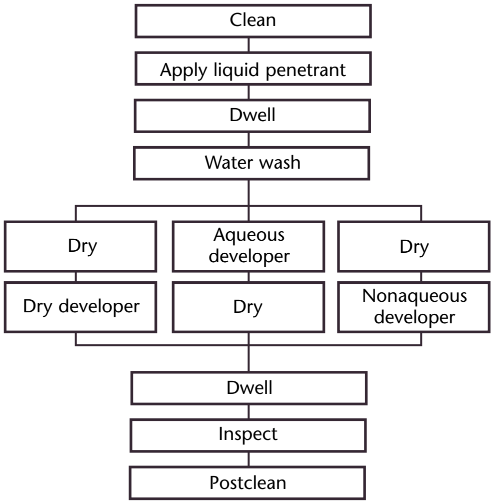
Because the processes for fluorescent liquid penetrant and visible dye liquid penetrant are similar, the process flow charts (Figs. 2, 3 and 5) are applicable to both. Processing variables — including liquid penetrant dwell time, emulsification time, rinse water temperature and pressure, drying temperature and time, and intensity of ultraviolet or visible radiation (visible light) — are established by customer designated processing specifications. It is very important to adhere to the established parameters to control the quality of the test.

Water Washable Liquid Penetrant Process

To ensure that testing is reliable and reproducible and remains sufficiently sensitive for the purpose intended, the water washable liquid penetrant test procedure includes the following operational steps.

1. Preclean and dry the surfaces (including crack surfaces) to be inspected. A contaminated surface will not provide reliable liquid penetrant indications. In some cases, etching may be necessary to open up entrapment areas under smeared metal surfaces.
2. Apply liquid penetrant to the dry part surfaces and allow sufficient time (termed dwell time) for the surface liquid penetrant to enter the discontinuities to form liquid penetrant entrapments (Fig. 1a). Liquid penetrant should wet the entire test surface area with a uniform liquid film. If the liquid penetrant pulls away leaving bare areas, the part surface is not clean enough.
3. Following a suitable dwell time, remove the excess surface liquid penetrant by room temperature water rinsing with a coarse spray applied at an angle as sketched in Fig. 1b. Rinsing should continue until no traces of residual liquid penetrant are visible on test surfaces when viewed under suitable illumination. If wet aqueous developer is to be used, it should be applied to the wet part surfaces following water rinsing.
4. If dry or nonaqueous developers will be used later, dry the test parts thoroughly following removal of excess surface liquid penetrant. If wet aqueous developer was used, dry the test parts as soon as the excess developer coating has drained off the test parts. Oven drying may be desirable to reduce drying time. In the drying step, it is necessary to guard against excessive exposure to high temperature. Excessive oven temperature can degrade the fluorescent dyes in the liquid penetrant. This can decrease test sensitivity by decreasing or eliminating the brightness of a fluorescent indication.
5. If aqueous developer has not previously been applied to the wet parts, apply dry or nonaqueous developer to the dry test parts. Liquid penetrant is drawn out of discontinuity entrapments to the part surface during the so called *development time* or *developer dwell time.* This liquid penetrant may spread into the developer coating to form enhanced indications, as sketched in Fig. 1c.
6. Observe and interpret the liquid penetrant indications of surface discontinuities under suitable

FIGURE 2. Water washable liquid penetrant process.



illumination. Evaluate each indication to determine if the indications constitute cause for rejection, rework, disposal or other action. This is an essential step in any test process.

7. Perform postcleaning and treatment of test parts to remove residue of liquid penetrant processing materials and provide protection against corrosion.

Lipophilic Postemulsification Liquid Penetrant Process

Figure 3a shows the procedure steps used with the lipophilic postemulsification liquid penetrant technique. The initial steps of precleaning, drying, applying liquid penetrant and allowing liquid penetrant to drain for an adequate dwell time are identical to those used with water washable liquid penetrants. Because the liquid penetrant does not contain an emulsifier, an additional step of applying emulsifier (Fig. 4b) and carefully controlling emulsifier dwell time (Fig. 4c) must be provided to make the excess surface liquid penetrant removable by water spray washing (Fig. 4d). Following washing to remove surface liquid penetrant, test parts are dried, developer is applied, aqueous developers are applied before drying and parts are inspected for liquid penetrant indications in the same way as in other liquid penetrant processes.

Hydrophilic Postemulsification Liquid Penetrant Process

Figure 3b is a flow chart for the hydrophilic postemulsification liquid penetrant process. The initial steps of precleaning, applying liquid penetrant and allowing for a liquid penetrant dwell and drain period are identical for all the liquid penetrant testing processes. As with the lipophilic process, an emulsification/removal step is required. However, an additional prerinse is added immediately following the liquid penetrant dwell time. After this first wash, usually only a thin film of liquid penetrant held by molecular attraction remains on part surfaces. Through the mechanical action of a water spray, much of the excess surface liquid penetrant is removed. Application of the emulsifier/remover is accomplished by dipping a part in a hydrophilic emulsifier solution or spraying a much more diluted solution onto the part for a controlled amount of time. Subsequent processing steps are identical to the water washable and lipophilic postemulsification process.

Because the prior water rinse removes the bulk of the surface liquid penetrant,

Movie. Hydrophilic prerinse.

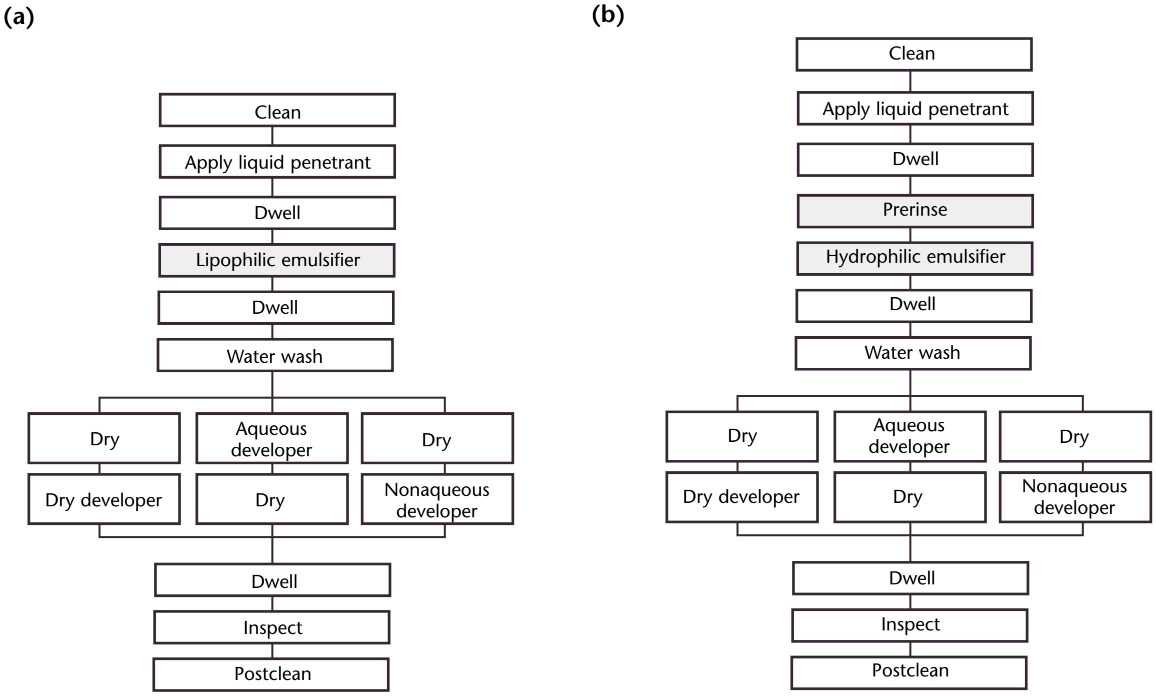
Movie. Dip in hydrophilic emulsifier; dwell.

Movie. Water wash.

Movie. Developer application.

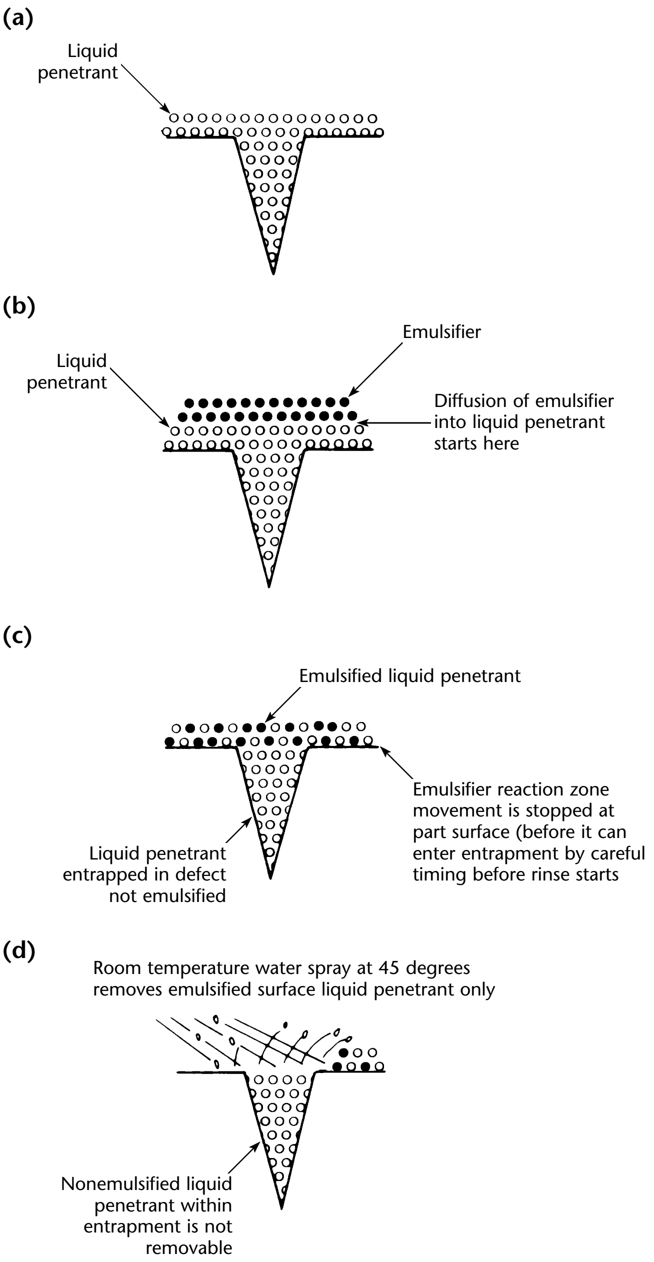
Movie. Viewing of developed indications.

Figure 3. Postemulsifiable liquid penetrant processes: (a) lipophilic; (b) hydrophilic. Shaded areas indicate steps that differ between lipophilic and hydrophilic techniques.



emulsifier contamination is minimized. Emulsifier diluted with three parts of water leaves only a thin surface film so emulsifier dragout is reduced. The prewash hydrophilic emulsifier technique decreases emulsifier consumption and lowers emulsifier cost. The biggest advantage of this technique may be its improved control of pollution caused by liquid penetrant process waste materials. The residual liquid penetrant removed in the first water rinse is not water soluble. It separates from the rinse water because its density is less than water's. The liquid penetrant waste floats and can be skimmed off the surface of the water, which prevents discharge of oily waste into sewers and streams. In some cases, the liquid penetrant materials collected in this manner can be recycled and reused.

FIGURE 4. Lipophilic postemulsifiable liquid penetrant process: (a) before emulsifier application; (b) after liquid penetrant dwell time; (c) surface liquid penetrant being emulsified; (d) water spray removing emulsified liquid penetrant.

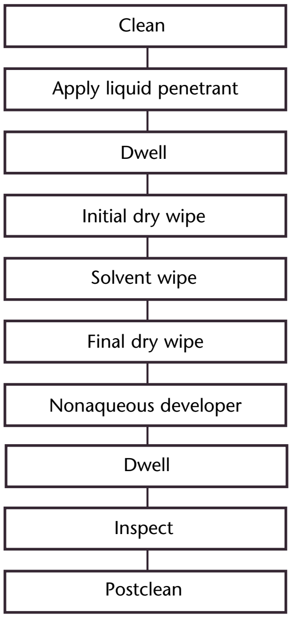


Solvent Technique for Hand Wipe Liquid Penetrant Removal

The procedures for the third technique of removing liquid penetrant by hand wiping or solvent removal are shown in Fig. 5. Materials used to remove excess surface liquid penetrant are referred to as *removers* or as *cleaners*. The term cleaning refers to preparation of the surface before testing and not to the removal of liquid penetrant process residues following completion of the test process. The term remover is more appropriate to describe the solvents used for removal of excess surface liquid penetrant during processing of test parts in liquid penetrant testing. With the solvent removal process, the available removers are often used also for precleaning and for postcleaning of test objects to remove liquid penetrant processing residues. However, the primary purpose of solvent removers is removal of excess liquid penetrant before application of developer.

Removers are normally petroleum base solvents but may be any solvent

FIGURE 5. Solvent removable liquid penetrant process.



MOVIE. Developer is applied.

combination. Often an emulsifier contains enough solvency to function as a remover. Alternatively, a product may be formulated for the express purpose of functioning as either a remover or an emulsifier. Removers are subject to the same precautions in use as those described for use of liquid penetrants and emulsifiers.

Movie. Wipe part.

Procedures for Hand Wipe Solvent Removal of Surface Liquid Penetrant

Liquid penetrant removers are used to remove excess surface liquid penetrant following liquid penetrant application. Because the removers function by solvent action, overremoval may be a problem if remover is used to excess. The recommended hand wipe removal procedure includes the following steps.

1. Wipe the test object surfaces with a dry wiping instrument such as a dry rag or soft absorbent paper.
2. Remove the remaining liquid penetrant residues by wiping with a wiping instrument dampened with solvent.
3. Wipe again with a dry rag or absorbent paper to remove any film of solvent remaining on the surfaces.

When fine, shallow discontinuities are under examination on smooth surfaces such as test panels with cracked chrome plating, dry wiping is sufficient. Use of any remover will result in overremoval of liquid penetrant residues and resultant loss in sensitivity.

Caution. The hand wipe technique is difficult to use on test parts with rough surfaces or on recesses such as threads because of the difficulty of wiping to the bottom of small, sharp recesses or cleaning deep grooves. In addition, the cleaning cloth or paper should only be moistened lightly with solvent for final removal of surface liquid penetrant residues. Never immerse the cloth in solvent nor saturate it with sprayed on solvent when removing excess surface liquid penetrant from test parts. The excess solvent would then diffuse into liquid penetrant entrapments within discontinuities and tend to remove part or all of the liquid penetrant needed to form discontinuity indications.

Operating Mechanisms of Liquid Penetrant Systems

The mechanisms of operation of liquid penetrants and processing materials would appear to be related to their surface energies or activities and to their capillary actions, diffusion characteristics and solubilities. The speed with which test liquids enter into surface discontinuities has a direct relation to their viscosities. However, viscosity does not appear to have any significant effect on the ultimate sensitivity or capability of a liquid penetrant to enter fine discontinuities, form a stable entrapment and later migrate from this entrapment to form a visible liquid penetrant indication on the part surface or developer coating. Many fine cracks are so shallow that even viscous liquids penetrate them easily. The characteristics of liquid penetrants and processing materials are discussed in detail elsewhere in this volume.

Movie. Visible red dye liquid penetrant bleeds out.

The difficulty of correlating the physical and chemical phenomena and properties of liquid penetrant liquids to practical liquid penetrant test sensitivity has thus far prevented the development of accurate analytical models and predictions of liquid penetrant system performance sensitivity. Efforts to use synthetic voids formed by mating two finely machined surfaces did not show the differences in inspection liquid penetration that were anticipated from chemical and physical considerations. However, useful comparisons of performance between various liquid penetrant and processing materials can be readily made with various types of liquid penetrant comparators or reference panels.

Measurements of surface energies, contact angles and other physical properties of liquid penetrants have suggested an elementary theory for predicting ability of liquid penetrants to enter fine surface cracks and discontinuities. Additional work has been done by many research laboratories and by liquid penetrant manufacturers. Liquid penetrant testing has found wide and useful application despite the lack of generally accepted theories for the phenomena involved.

Examination of Liquid Penetrant Indications

Visible dye liquid penetrant indications can be viewed in daylight or by artificial white light from tungsten filament or fluorescent tubular lamps. Fluorescent liquid penetrant shows discontinuity indications as luminous yellow-green lines or spots that provide a brightness contrast with the darkened background. Fluorescent dye liquid penetrants require excitation by near ultraviolet (ultraviolet-A) radiation to produce visible indications. These fluorescent indications must be observed under subdued ambient (white or scattered) light or in darkened booths. Minimum ultraviolet radiation intensities are normally required by applicable specifications.

Dual response liquid penetrants produce indications visible under both ultraviolet radiation and natural or artificial white light. These liquid penetrants also have dual sensitivity as well. The larger discontinuities are visible under both ultraviolet radiation and natural white light. However, extremely tight discontinuities (fine cracks) may be seen as fluorescent indications visible only under near ultraviolet radiation. Typically, with dual sensitivity liquid penetrants, the visible dye indication is red whereas the indication under ultraviolet radiation fluorescences as bronze-orange or blue-green.

In each case, the test operator must be trained to look for relevant indications. (Indications that have no relation to material discontinuities are *nonrelevant indications* and not cause for rejection of materials.)

Caution. Fluorescent liquid penetrants should not be applied to test objects that retain traces of visible dye liquid penetrants or processing materials from prior testing and vice versa. Water washable and postemulsification types of liquid penetrant should not be used on the same object. Residues from prior liquid penetrant processing often diminish the contrast and visibility of indications produced in subsequent processing with a different liquid penetrant system.

Advantages of Fluorescent Liquid Penetrants

The inspector or operator can usually see fluorescent indications in a dark test booth more readily than the inspector can see relatively light red marks on a white background produced by visible dye liquid penetrants under normal light conditions. This is especially true in the case of liquid penetrant indications of minute cracks or pinholes. Therefore, because the fluorescent liquid penetrant indications are more visible, it is generally conceded that fluorescent liquid penetrant testing is more sensitive to small discontinuities than visible dye liquid penetrant testing is. Also, because the operator can locate luminous discontinuity marks readily, the fluorescent dye liquid penetrant lends itself to faster readout. Aerospace industry specifications often call for fluorescent liquid penetrant testing of critical parts under very well controlled conditions because very small discontinuity indications must be sought and detected reliably.

Advantages of Visible Dye Penetrants

Through its overall performance is considered lower and production testing of small parts is slower, the visible dye liquid penetrant process has some advantages of its own. It does not require a darkened area or a source of electric power for illumination. For these reasons, it is more often used as a portable testing tool in the shop or field. Large test parts, difficult to move to a dark booth, can be inspected where they are located with visible dye liquid penetrants. The visible dye liquid penetrant is widely used for inspection of weldments both in the shop and in the field. A weld discontinuity can be clearly visible when shown to the welder who can grind out the discontinuity, reweld and reinspect, all under natural light in the normal work area.

MOVIE. Indication in root pass of weld.

Selection of Liquid Penetrant Material and Process

Fluorescent Liquid Penetrant

The techniques capable of the greatest sensitivity are often the most costly. Many tests require the ultimate sensitivity. However, high sensitivity is frequently not required and may even produce misleading results.

Users are urged to consider the following important factors and to discuss them with suppliers of liquid penetrant test equipment and liquid penetrant materials before deciding on the type of liquid penetrant testing system to install and/or use:

1. composition of parts to be inspected;
2. number of parts or test areas to be inspected per unit of time;
3. size and weight of parts to be handled;
4. location at which testing is required (that is, receiving department, in process along a production line, during assembly, as final inspection, in the field during erection, at maintenance facilities or in service);
5. types of discontinuities to be expected, for example, porosity, cracks, seams or laps;
6. size of discontinuities to be detected (for example, small, deep, large, shallow, clustered or scattered);
7. surface condition of parts to be inspected (such as as-cast, as-forged, machined, ground, lapped, polished, plated, painted, corroded, oily, covered with combustion, scratched or scaled parts); and

Table 1. Selection of fluorescent liquid penetrant test method as function of test object surface condition and type of discontinuity. The type of developer affects liquid penetrant system sensitivity. Nonaqueous wet developers are the most sensitive, followed by aqueous developer, dry developer and no developer, in that order.

Type Fluorescent	Polished or smooth surface with very fine shallow discontinuities	Normal fine, tight discontinuities on smooth or roughened surfaces	Broad, shallow discontinuities on smooth or roughened surfaces	Very rough or porous cast surfaces	High temperature titanium or other alloys sensitive to extraneous elements
Water Washable Liquid Penetrant					
Regular or high performance	A	A	A	C, E	A, F
High or very high performance	A	A	A	C, E	A, F
Postemulsifiable Liquid Penetrant					
Regular performance	A	A	A	C, E	A, F
High or very high performance	A	A	A	C, E	A, F
Solvent Removable Liquid Penetrant					
Regular performance	B	B	B	D, E	B, F
High performance	B	B	B	D, E	B, F

A = Caution is required in rinsing to avoid overrinsing.
B = If solvent remover is used, use as little as possible. The wiping material should be barely damped to avoid overremoval of liquid penetrant.
C = Liquid penetrants may leave excessive background on rough surfaces. The less sensitive types are preferred to the more sensitive types. visible penetrant is commonly used in this situation.
D = Solvent remover is not recommended. Use only dry, clean, lint-free wiping material.
E = Also available are special low sensitivity penetrants for tests of rough castings and other objects where only gross indications are of concern.
F = Use low sulfur chloride liquid penetrant and/or emulsifier or remover.

8. condition to which parts will be subjected after testing (for example, medical, nuclear or oxygen systems; welding, plating or finishing operations; high temperature, aerospace, industrial or transportation uses; inaccessible locations; or consumer products).

The selection may be influenced by such additional factors as specification requirements, education and experience of personnel and the quality level of test required. The quality of the test parts to be inspected should never be allowed to influence the quality level of testing. The test quality is determined by the nature of test parts and the service conditions for which they are intended. The regular performance water washable, fluorescent liquid penetrant is generally more practical for rough surface parts such as sand castings. The higher performance liquid penetrants are favored for inspecting forgings, machined surfaces and more critical load carrying parts. Table 1 may be used as a guide in selecting the grade of liquid penetrant to be used on parts with different surface conditions.

Visible Dye Liquid Penetrant

The selection of a visible dye liquid penetrant is relatively uncomplicated when compared to selection among classes of fluorescent liquid penetrants. If the test is to take place in the field, a portable system using a solvent remover wipe-off technique is usually the first choice. Selection of a visible dye liquid penetrant is largely dependent on economic factors and the facilities available. The visible dye liquid penetrant class is not divided into performance grades as is the fluorescent liquid penetrant class.

The visibility or degree of contrast of the red indications with respect to the white developer background is a key factor in successfully revealing tight discontinuities by the visible dye liquid penetrant technique. Color contrast fulfills the same role as brightness in the fluorescent technique. The visibility of colored contrast liquid penetrants depends on the color dye concentration. Threshold (minimum perceptible) indications can be seen only by using ultrahigh dye concentrations not normally encountered in the usual visible dye liquid penetrants. Because visible dye liquid penetrants have not been categorized with respect to visibility or performance, the user should determine the differences in sensitivity and select the desired liquid penetrant in accordance with the user's needs.

PART 3. Principles of Emulsification and Removal of Excess Surface Liquid Penetrant

Purpose and Control of Removal of Excess Surface Liquid Penetrant

Liquid penetrants are designed to wet and cling to all exposed surfaces of parts so as to provide a nearly uniform film of the liquid penetrant. This surface liquid penetrant provides the source of liquid penetrant to seep into surface discontinuities during liquid penetrant application and the subsequent liquid penetrant dwell time. While this surface film of liquid penetrant persists, it is not necessary to have parts immersed in liquid penetrant baths to provide the liquid penetrant needed to fill entrapments within discontinuities.

Following a dwell time sufficient to permit the entrapment of liquid penetrant, the excess surface film of liquid penetrant must be removed from part surfaces. Emulsifiers act like detergent to loosen and to suspend or dissolve liquid penetrant. The two major classes of emulsifiers are oil based, or lipophilic (Fig. 6), and water based, or hydrophilic (Fig. 7).

Ideally, during removal of surface liquid penetrant, all excess surface liquid penetrant should be removed from all surface areas (including fillets, corners and recesses) without removing the liquid penetrant entrapments. It is these small quantities of liquid penetrant trapped within subsurface volumes of the discontinuities that form the visible or fluorescent indications of surface connected discontinuities.

Unfortunately, with rough or porous surfaces on test parts or with some types of cracked or porous surface coatings, these intentional surface irregularities behave like discontinuities in the underlying base metal, in that they can trap and hold minute amounts of liquid penetrant. If such nonsignificant minute surface entrapments of the liquid penetrant cannot be removed, they form visible or fluorescent surface background effects that reduce the contrast and may even hide indications of significant discontinuities.

An important purpose of surface liquid penetrant removal is to improve the signal-to-noise ratio of liquid penetrant testing. (Here, *signal* refers to the indications of significant discontinuities. *Noise* refers to confusing background layers of liquid penetrant materials that reduce the contrast and visibility of significant indications.)

With good removal of excess surface liquid penetrant, the discontinuity indications (after development) stand forth clearly with high color or brightness contrast and can be seen readily. With inadequate removal of excess surface liquid penetrant, the background color or fluorescence reduces color or brightness contrast. In this case, the observer will have considerable difficulty in discriminating significant discontinuity indications from nonrelevant surface background. In critical applications of liquid penetrant testing, this loss of test reliability and sensitivity to small discontinuities could be intolerable. Thus, care and control in removal of excess surface liquid penetrant are vital to reliability assurance with liquid penetrant testing.

Advantages of Drain-Dwell Technique during Penetration

Test parts can be immersed in the tank of liquid penetrant and then removed to drain excess liquid penetrant off the part surface while penetration into surface discontinuities continues. The penetration time with this drain-dwell technique is important in two ways. Longer penetration times mean that less liquid penetrant is still on the surface when the liquid penetrant is washed off or when the emulsifier is applied. A thinner layer of liquid penetrant calls for a shorter wash or emulsifier dwell time because less emulsifier diffusion is needed. Further, with a thinner surface layer of liquid penetrant, the wash water contains less liquid penetrant and the emulsifier that drains back carries less liquid penetrant contamination into the emulsifier reservoir.

Water Washing of Self-Emulsifiable Liquid Penetrants

Water rinsing is the most common technique of liquid penetrant removal.

Figure 6. Mechanism of action of lipophilic emulsifiers: (a) liquid penetration; (b) add emulsifier; (c) solution and diffusion begins; (d) diffusion proceeds; (e) rinsing; (f) clean surface.

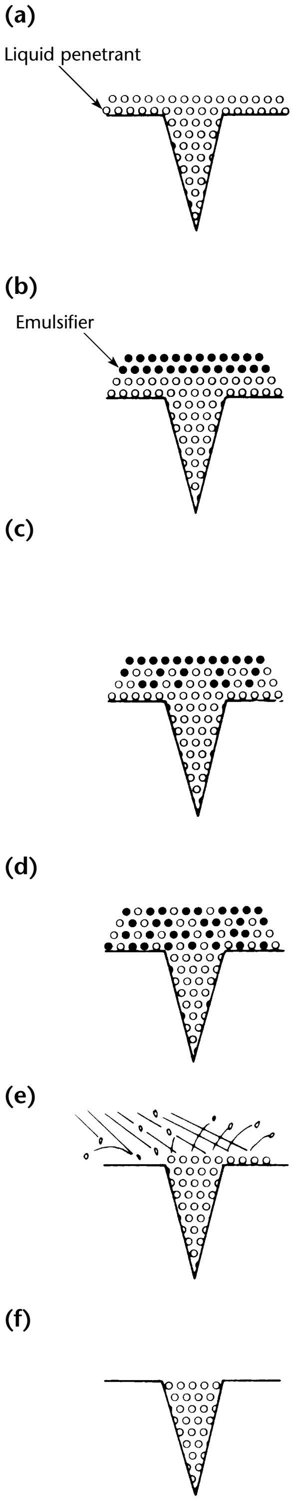
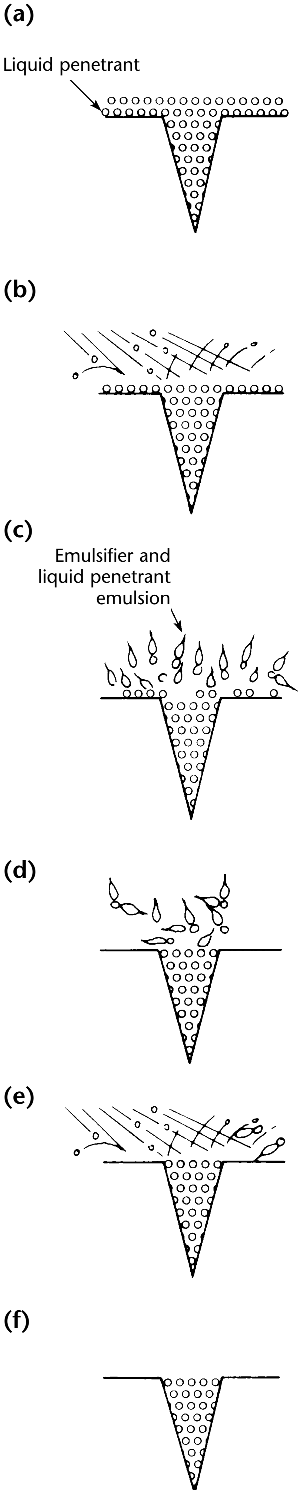


Figure 7. Mechanism of action of hydrophilic emulsifiers: (a) liquid penetration; (b) add prerinsing; (c) detergent scrubbing begins; (d) agitation and emulsification; (e) rinsing; (f) clean surface.



Water washable or self-emulsifiable liquid penetrants contain the emulsifier as an integral part of their formulation. Following penetration, it is merely necessary to rinse the excess liquid penetrant from the surfaces of the test objects. The obvious advantage of water wash removal lies in economies when the separate step of applying an emulsifier is not required. The water wash time, pressure and temperature must be precisely controlled because the liquid penetrant trapped within the discontinuities, as well as the excess surface liquid penetrant, is emulsifiable. Water washable liquid penetrants have different degrees of water solubility. Some wash readily from rough test object surfaces whereas others with a lower degree of solubility are almost impossible to remove from such rough surfaces. The water washable liquid penetrant that is highly water soluble will be more susceptible to over removal (removal of trapped liquid penetrant as well as surface liquid penetrant). Thus, extreme care must be exercised in selecting a water washable liquid penetrant that is least susceptible to overremoval but that does not leave an interfering background of surface liquid penetrant on the types of part surfaces being processed. Because emulsifier is already contained in self-emulsifiable water washable liquid penetrants, the test operator does not have control of emulsifier dwell time. (By contrast, with the postemulsifier and liquid penetrant, control of contact time between emulsifier and liquid penetrant is essential to prevent overremoval and, at the same time, to attain a low degree of color or fluorescent background on part surfaces.)

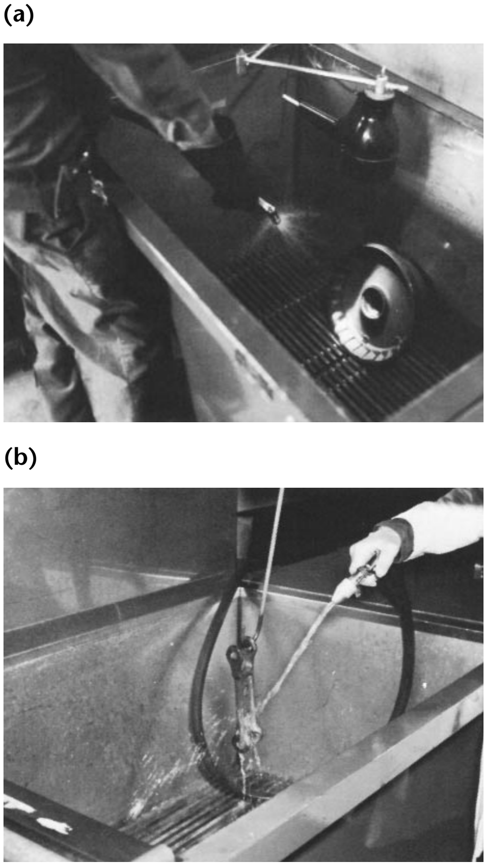
Water Rinse Removal of Excess Surface Self-Emulsifiable Liquid Penetrant

After the necessary liquid penetrant dwell time, the surface film of liquid penetrant remaining on the test parts is removed by water washing (Figs. 8 and 9). Washing is best done with a coarse pressure spray, (rather than by a solid stream) of room temperature water. A trial rinse is recommended to avoid rinsing complications. Special attention is given to holes and threads to ensure that they are washed clean. The use of a spray nozzle is very desirable because the liquid penetrant is more easily removed with the physical agitating action of the water droplets. With fluorescent liquid penetrant, this washing operation should be carried out under ultraviolet radiation to permit monitoring for complete cleaning of all surfaces and cavities of the test objects.

MOVIE.
Water wash.

Small test parts may be washed individually or by the basketful in a tank suitable for containing the water spray from either fixed or portable nozzles. Small runs of parts are more easily washed with a hose and nozzle. However, in automatic production line washing units, the design and placement of fixed spray nozzles can readily accomplish an excellent washing job. Excessively high water pressures greater than 275 kPa (40 $\text{lb}_f\cdot\text{in.}^{-2}$) or extended rinse times greater than 120 s (2 min) should be avoided to guard against overrinsing, particularly where surface discontinuities may be wide and shallow. A good indicator of overwashing is the total lack of liquid penetrant residue on the part surfaces.

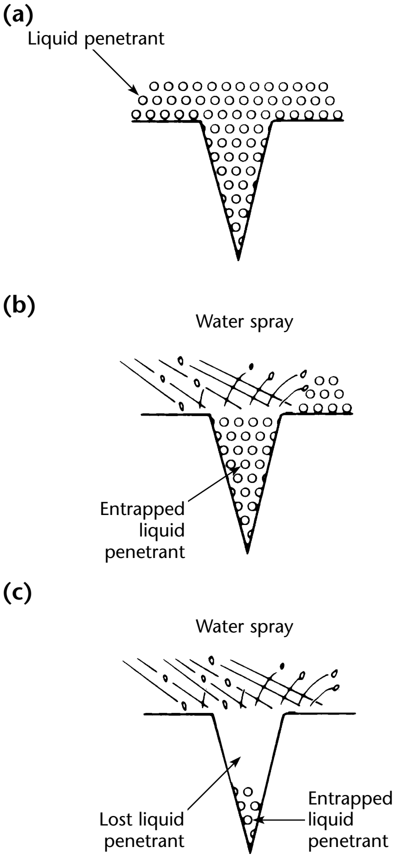
FIGURE 8. Techniques for water rinse removal of excess liquid penetrant: (a) proper use of coarse water spray at 45 degree angle to wash parts to remove water washable liquid penetrant; (b) improper adjustment of water hose nozzle for parts washing.



Selection of Rinse Water Temperature

Rinse water temperature around 20 °C (70 °F) is adequate when rinsing for removal of water washable surface liquid penetrant. Low temperature rinse water (below 10 °C or 50 °F) may reduce the ease with which liquid penetrants can be rinsed off the test parts. Some manufacturers of liquid penetrants recommend elevated rinse temperatures of 30 to 45 °C (or 90 to 110 °F). Preferably, rinse water temperatures should be kept reasonably constant to avoid variations in rinse effectiveness which can result from wide extremes of rinse water temperature.

FIGURE 9. Optimum technique for water washing to remove excess liquid penetrant avoids both underwashing that leaves liquid penetrant background on test parts and overwashing that can remove liquid penetrant from flaw entrapments, thus weakening or preventing formation of flaw indications: (a) penetrated flaw; (b) removal of excess liquid penetrant; (c) overwashing.



Controlling of Removal of Surface Liquid Penetrant by Water Washing

The adequacy of the water rinse is normally judged through visual observation of test object surfaces during the rinse operation. With fluorescent liquid penetrant, rinsing is performed under near ultraviolet (ultraviolet-A) radiation illumination in a semidarkened area. The purpose is to rinse test objects completely enough to remove background fluorescence but not so thoroughly that relevant indications are removed. Where smooth surfaces are involved, background is relatively absent. However, in the case of rough or porous surfaces, the problem assumes a different dimension. It can readily be seen that the test operator may be working against himself, so to speak, because rinsing thoroughly enough to remove background may also remove relevant indications. The test operator should monitor the rate of background removal. When the rate decreases to a barely noticeable amount further washing would probably be detrimental to retaining relevant indications. Often it is possible to differentiate between background and relevant indications but this is not always the case.

Liquid Penetrant Removal by Postemulsification and Water Washing

The second common technique of liquid penetrant removal is by the procedure known as postemulsification. Following penetration (liquid penetrant dwell time), a material known as an emulsifier is applied to the excess liquid penetrant on the test object surface. The action of the emulsifier on the liquid penetrant results in a mixture of emulsifier and liquid penetrant, and the mixture is removable with water. Rinsing with water removes the excess liquid penetrant and emulsifier mixture from the surface of the parts. Care must be taken that removal of liquid penetrant from discontinuity entrapments does not occur with postemulsification processing.

When background fluorescence has been removed, rinsing is discontinued. With visible liquid penetrants, absence of visible color indicates that rinsing is complete. Both high rinse water pressures and overly long water rinse times should be avoided to minimize the possibility of removing entrapped liquid penetrant from discontinuities.

Overrinsing alone may remove liquid penetrant entrapments from discontinuities. This depends somewhat on the configuration of the discontinuity, because mechanical action (scrubbing action) of water sprays can remove even nonemulsified liquid penetrant from both part surfaces and discontinuities. (This technique finds application in the case of hydrophilic removers using agitation, described elsewhere in this chapter.) Because broad, shallow discontinuities do not retain enough entrapped water washable self-emulsifiable liquid penetrant to ensure visible indications, postemulsifiable and other types of liquid penetrants are preferred for detection of wide, shallow surface cracks.

Avoidance of Overremoval of Surface Liquid Penetrant

The activity of an emulsifier determines its speed of interaction with liquid penetrants. Emulsifier efficiency is a principal contributor to activity. For lipophilic emulsifiers viscosity is also a major player; for hydrophilic emulsifiers concentration plays an important role. Overremoval of surface liquid penetrant by an emulsifier leads to removal of liquid penetrant from within discontinuity entrapments and causes loss of liquid penetrant test indications. Causes of overremoval by emulsifiers include (1) poor design such that lipophilic emulsifier is overactive and diffuses into the liquid penetrant too rapidly, (2) improper mixing of hydrophilic emulsifier that results in excessive concentration and (3) excessive emulsifier dwell time which results from leaving the emulsifier in contact with the liquid penetrant for too long a period. (With very active emulsifiers, control of emulsifier dwell time becomes difficult because parts must be handled or rinsed after short, precisely timed intervals.) In either case, emulsification of entrapped liquid penetrant occurs and subsequent water rinsing may also remove emulsified liquid penetrant from discontinuities. This can lead to failure to produce visible discontinuity indications.

Significance of Emulsifier Dwell Time with Postemulsifiable Liquid Penetrants

Careful control of emulsifier dwell time is probably the most critical timing function in liquid penetrant test processing. It is likely that liquid penetrant retained within entrapments resists mixing with the emulsifier only because it is inaccessible in fine, tight surface discontinuities. Time of exposure to the emulsifier must normally be controlled for this reason. Abnormally long duration emulsification times have an overemulsification effect. Abnormally short emulsification times are insufficient to permit the emulsifier to react adequately with excess surface liquid penetrant so as to ensure its removal.

Action of Lipophilic Emulsifiers

Lipophilic emulsifiers are composed of emulsifying agents dispersed or dissolved in an oil base and are used as supplied. Therefore, they are readily soluble and diffuse into oily liquid penetrants. Their mode of action is based primarily on diffusion and solubility into the oily liquid penetrant. This renders excess liquid penetrant water emulsifiable. Figure 6 illustrates the basic mechanism of action.

The emulsifiers are applied to the outer surface of the liquid penetrant and blending of diffusion begins there. Application by dipping is recommended for uniform diffusion over the surface of the liquid penetrant. Diffusions occurs in both directions; as the emulsifier diffuses into the liquid penetrant layer, liquid penetrant is diffusing outwardly into the emulsifier. A gradient is set up with pure emulsifier on the outside, pure liquid penetrant on the inside (or within cracks) and a continuously varying mixture in between. Diffusion is a dynamic phenomenon and concentrations keep changing until the total combined film of emulsified liquid penetrant has the same composition everywhere and is everywhere water washable, even within cracks.

The diffusion rate (emulsification time) will vary depending on the viscosity of the lipophilic emulsifier. High viscosity emulsifiers on the order of 60 to 100 $mm^2 \cdot s^{-1}$ (60 to 100 cSt) are relatively slow acting (2 to 4 min emulsification). Low viscosity emulsifiers, on the order of 30 to 50 $mm^2 \cdot s^{-1}$ (30 to 50 cSt), are relatively fast acting (under 2 min emulsification). Another factor affecting the diffusion rate or emulsification rate is the drain-off or flow-off of emulsifier from the surface of the part. In other words, if a part were only immersed in an emulsifier bath and not withdrawn and drained, the diffusion (emulsification) rate into the liquid penetrant would be significantly slower in comparison to the dip and drain procedure usually used in most liquid penetrant lines. As emulsifier drains off the part, it provides turbulence that mixes it into the liquid penetrant layer faster than diffusion alone and speeds up a process that otherwise would take hours.

For emulsifiers to function selectively, the diffusion must be stopped when enough emulsifier has diffused to the test piece surface to make all the excess surface liquid penetrant emulsifiable. The diffusion is stopped, of course, by washing the emulsified liquid penetrant off the test surface with water. At that moment, some emulsifier has begun to diffuse into the liquid penetrant entrapments as well. If diffusion is stopped at this point, there will not be enough emulsifier present to make more than the outer edge of the entrapment emulsifiable. If diffusion is not stopped quickly enough, some of the entrapment will become emulsified and the liquid penetrant emulsifier system will be no more selective than an ordinary water washable liquid penetrant system.

Control of Emulsifier Dwell Time

Timing of emulsifier dwell is crucial. Too short a dwell time results in a heavy background of residual liquid penetrant on the test part surface. Too long a dwell means diminished contrast and visibility of test indications. Control of the dwell time is improved if the diffusion is slowed down (by making liquid penetrant and/or emulsifier more viscous) or by making the emulsifier less efficient in any of several ways. Then more emulsifier must diffuse into the liquid penetrant layer to make it emulsifiable.

Advantages of Drain-Dwell Technique during Emulsification

Diffusion is not the only mechanism by which emulsifier combines with surface liquid penetrant when a drain-dwell technique is used during emulsification. If it were, emulsifier dwell times would be many times longer than they are because diffusion is quite slow. The other mechanism is turbulence. When emulsifier is applied to a test piece or surface, it drains downward and while doing so mixes into the liquid penetrant. What drains off is clearly a blend of emulsifier and liquid penetrant that has been generated by disruptive flowing of the emulsifier. Because such turbulence does not readily extend into fine cracks, this mechanism assists the selectivity of the technique besides speeding it up enough to make it practical.

Mechanism of Action of Hydrophilic Emulsifiers

The term *hydrophilic* means having an affinity for water, whereas *lipophilic* means having an affinity for oil. Hydrophilic emulsifiers (sometimes referred to as liquid penetrant removers or detergent scrubbers), on the other hand, are composed of emulsifying agents (usually nonionic surfactant concentrates) dissolved in water and used as an immersion dip (concentration range of 5 to 30 percent with mild air or mechanical agitation) or as a forced water spray rinse at dilution ratios of five percent maximum. Hydrophilic emulsifiers function through their detergent and scraping or scrubbing (kinetic) action, as shown in Fig. 7.

As a spray liquid penetrant remover, the hydrophilic emulsifier concentrate is metered into the forceful water spray rinse in high dilution ratios. The spray remover serves to scrub layer after layer of excess surface liquid penetrant from the part, always using a fresh detergent water solution. Diffusion does not take place in this mechanism of action. The active agent in the remover helps displace liquid penetrant from the surface and prevents redeposition. Removal of excess surface liquid penetrant with hydrophilic emulsifiers in an immersion or dip mode is basically a detergent action wherein the remover detaches the liquid penetrant from the surface. Mild agitation removes the displaced liquid penetrant from the part so that it cannot redeposit. The hydrophilic emulsifier contact time is directly related to its concentration. This applies to both immersion and spray application. This process affords better control and, in addition, allows for an effective and practical treatment and recycling of the liquid penetrant prerinse solution, thereby minimizing waste water pollution.

Test Conditions Influencing Selection of Emulsification Time

It is advisable to select the emulsification time with consideration of the following influential factors: (1) liquid penetrant and emulsifier being used, (2) type of surface under test, (3) performance desired and (4) type of rinse used. It can be seen that compatibility of liquid penetrant and emulsifier can be an important consideration. It is also obvious that the rinse time, pressure and temperature may influence the process. Some suppliers advocate elevated rinse water temperatures but the optimum temperature depends on the chemical makeup of the emulsifier and its emulsifying characteristics.

Reprocessing Test Parts after Inadequate Removal of Surface Liquid Penetrant

An error in past practice in some facilities using postemulsification liquid penetrants has been to return a part that does not rinse clean easily to the emulsifier tank for reemulsification. Reemulsification of parts that have been in contact with rinse water is not an acceptable practice because it has two deleterious effects: (1) reemulsification would cause loss of control of both the emulsification time and the emulsification process and (2) reemulsification introduces water contamination into the emulsifier tank.

Presently accepted good practice with test parts that do not rinse freely is to reprocess these test parts through the entire liquid penetrant testing process. It is important to begin this reprocessing with thorough cleaning of each test object to remove all residues of prior liquid penetrant, emulsifier, emulsified liquid penetrant and water. Thorough drying of parts is essential before reprocessing. If these products were carried back into the liquid penetrant immersion tank (if used), liquid penetrant contamination and prior blockage of passageways into surface discontinuities could occur. To improve the rinsability of test parts being entirely reprocessed, it may be desirable to increase the emulsification time or strengthen the emulsifier bath by the addition of new emulsifier.

Causes and Effects of Contamination of Emulsifier Tanks

It is apparent from the nature of the postemulsification process that liquid penetrant carried into the emulsifier tank on the test objects may gradually contaminate the emulsifier bath. When liquid penetrant content exceeds the liquid penetrant tolerance of the emulsifier, the activity of the emulsifier is lowered. With reduced emulsifier activity, it is necessary to use longer emulsifier dwell times to attain results equivalent to those obtained in uncontaminated emulsifier with normal emulsification dwell time. When emulsifier contamination reaches excess levels, both emulsification and test object rinsing to remove excess surface liquid penetrant are impaired. Hydrophilic emulsifiers are more susceptible to liquid penetrant contamination because of their high water content.

Another common contaminant found in lipophilic emulsifier tanks is water. Although rinsing should be conducted under conditions that result in the least amount of splashing or direct water access to the emulsifier tank, this practice is not always followed. Another source of water contamination results from reemulsification of test parts or the indirect emulsification process. Excessive water contamination can usually be seen by test operators because it is likely to cause thickening, a creamy appearance or separation of the lipophilic emulsifier. (The care and maintenance of liquid penetrant processing materials are discussed elsewhere in this volume.)

PART 4. Principles of Application and Operation of Developers

Functions of Developers in Liquid Penetrant Testing

The most important basic function of a developer in liquid penetrant testing is to extract liquid penetrant from an entrapment within a discontinuity or surface discontinuity below the test part surface and to transfer at least some of this liquid penetrant to the surface to form a liquid penetrant indication that can be seen by the inspector. The developer may also provide a mechanism whereby the effective thickness of the surface film of liquid penetrant exuded from the liquid penetrant entrapment is increased to levels above the threshold of visibility.

Another developer function is to spread or disperse the liquid penetrant over the part surface, thus increasing the apparent size (mainly width) of the indication exposed to the eye. The developer also provides a contrast increase that enhances detection of an indication. Under near ultraviolet (ultraviolet-A) radiation, the developer appears blue-black whereas the entrapped liquid penetrant fluoresces yellowish green. Visible dye developers provide a white background for the red or orange liquid penetrant indication. They also reduce light reflection from shiny surfaces of test parts so that eye fatigue is reduced.

Types of Developers

There are several types of developers in common use in liquid penetrant testing: (1) dry powder, (2) water soluble, (3) water suspendible and (4) nonaqueous (solvent suspendible).

The basic component of all developers is manufactured as a powder and performs its basic function as a powder on the surface of a part being inspected. The developers are distinguished by the listed types according to the condition of the developer at the time of application to a part during the liquid penetrant testing process. The second and third listed types are often referred to as *aqueous wet* or simply *aqueous* and the fourth as *nonaqueous wet* because they are wet when applied.

Actions of Developers

Actions of Developers in Forming Liquid Penetrant Indications

Developer action appears to be a combination of solvency effect, adsorption and absorption. (Adsorption implies collection by adhesion to a surface. Absorption refers to assimilation of liquid into the bulk of an absorbent material.) The developer powder exerts a combination of adsorptive and absorptive effects on liquid penetrant residues, drawing entrapped liquid penetrant to the test part surface. As the liquid penetrant disperses in the developer powder, it forms test indications that can be readily observed by the inspector. In the case of the nonaqueous wet and special film type developers, solvent action has been shown to play a part in promoting the withdrawal action and enhancing the liquid penetrant test indications.

Undesirable Actions of Improperly Applied Developers

Care is required to ensure that excess surface liquid penetrant has been removed from test object surfaces and that thin, uniform developer coatings provide complete coverage of the entire test surface. Application of developer coatings of excessive thickness can cover, obscure or extinguish the fluorescent or visible color discontinuity indications by the thick overlying layer of porous powder developer. A normal effect of developer layers of appropriate thickness is the lateral diffusion or bleeding of liquid penetrant from discontinuity entrapments. This lateral migration of liquid penetrant through the developer coating may cause small adjacent discontinuity indications to eventually become lost within the spreading indications from large discontinuity entrapments. For this reason, it is often desirable for test operators to examine the test parts soon after developer application and periodically thereafter throughout the recommended development time, to observe the initial appearance and growth of discontinuity indications.

Dry Developer

Techniques for Applying Dry Developer

Movie. Developer application.

The dry developer is readily distinguishable from the powder used in water for wet type developers by the very fluffy nature and low bulk density of dry developer. In normal use, the dry developer is blown onto the surfaces of test parts from which excess liquid penetrant has been removed and surfaces have been completely dried. A flock type spray gun or an electrostatic spray gun can be used to apply this dry powder. Alternatively, fluidized bed systems create clouds of dry powder, effective in coating dry test parts with a thin film of developer. The powder cloud can be created when a small amount of dry developer power is agitated by means of an air blast from the bottom of the dry developer tank.

In other cases, test operators dip dry test parts into a tank of fluffy dry developer powder. With each application system and especially when dipping parts into dry powder, excess developer is removed either by blowing it off with light puffs of air or by shaking the test objects. The fine adhering dry developer particles tend to absorb residual entrapped liquid penetrant and draw it from discontinuities. Liquid penetrant indications usually appear within a few minutes after developer application as entrapped liquid penetrant bleeds back into the thin developer coating. A typical developing period is about half of liquid penetrant dwell time. Often it is advantageous to examine parts for developing indications during development period to resolve fine indications before they are lost in adjacent bleedouts.

Caution. Dry powder developer beds can become contaminated with excess liquid penetrant left on test parts. Visual examination of the developer powder under near ultraviolet (ultraviolet-A) radiation will show fluorescent indications of this contamination. This simple check should be made periodically and contaminated developer replaced with fresh clean developer when needed.

Advantages of Dry Developers

The major advantage of using dry developer is the simplicity of handling it. It is easy to apply (even though monitoring coverage is difficult). Dry powder developer is in no way corrosive and gives off no hazardous vapors. It leaves no film behind to hinder subsequent processing or operations.

Disadvantages of Using Dry Developers

An obvious disadvantage of dry developers is their extreme dustiness, which requires air cleaning equipment and/or the use of respirators. Because dry developers leave a nearly invisible film, it is often difficult to determine if a test surface has been adequately covered.

A subtle but extremely important disadvantage of dry powder developers stems from the fact that the test surface must be dried before developer application. Excessive drying at test piece temperatures over 60 °C (140 °F) for more than 10 min can decrease the intensity of the fluorescent dye in liquid penetrants, especially the top layer. When the developer is subsequently applied, the top layer of liquid penetrant that comes in contact with the developer will form an indication of diminished fluorescent intensity. Solvent developers avoid this failure to form indications because the solvent reaches the deeper levels of entrapped liquid penetrant and leaches it to the surface. Aqueous developers do not encounter this problem to the same degree because the heating does not take place until the developer is already in position and aqueous developers seem to insulate fluorescent indications against rapid thermal degradation.

Aqueous Developers

Types of Aqueous Developers

Two types of aqueous developer are in common use in liquid penetrant testing. The first consists of insoluble developer particles suspendible in water, whereas the second contains a powder that is actually dissolved in water. The suspended aqueous developer is mixed into water in a concentration recommended by its manufacturer. Frequent stirring or agitation is needed to prevent the developer powder from settling out of its water suspension.

The soluble or aqueous developers are prepared merely by diluting them with water in the proportions recommended by their manufacturers. These developers are applied to test parts in the same manner as the wet aqueous suspension developers just described. With soluble developers, agitation is not required to maintain uniform consistency after the developer has been initially mixed with water.

Aqueous wet developers usually contain wetting agents and corrosion inhibitors to minimize attack on test objects and liquid penetrant processing equipment. When applied by dipping or flowing, the thickness of the dried developer coating on test objects after evaporation of the water vehicle is determined by the concentration of developer in the water. With spray application of aqueous developer, coating thickness must be carefully controlled. If a heavy film is applied, an excess of developer powder remains after drying. Excess developer coating thickness tends to obscure or hide liquid penetrant test indications and so reduces the reliability of liquid penetrant testing.

Techniques for Applying Aqueous Wet Developer

Wet aqueous powder developer can be applied to test part surfaces that have previously been processed by liquid penetrant application followed by dwell time and removal of excess surface liquid penetrant by water washing. The preferred techniques of application of wet developer are gentle spraying, dipping or flowing onto test parts. Caution must be used when spraying, dipping or flowing aqueous developers because they contain wetting agents and function much as do very dilute hydrophilic removers. Not only does an additional and unwanted removal occur but the developer can become contaminated with liquid penetrant.

Because the developer is in water suspension or solution, it is possible to apply it to test objects whose surface liquid penetrant has been removed by water spraying without requiring intermediate drying of the test parts. Following the application of aqueous developer, test parts are normally dried in ovens operating at temperatures adequate to evaporate the water from the surface, to leave a uniform coating of dried developer. Care is required to ensure that an excessive amount of wet developer is not applied because a high buildup of developer coating will obscure or hide discontinuity indications.

Techniques for Drying of Wet Aqueous Developer Coatings

To promote drying into uniform coatings, it is preferable to heat the test part surface after the application of wet aqueous developers. Many users prefer to apply the wet developer suspension by spraying it onto the wet test part surface resulting from the postemulsification or water washable removal process. Following developer application, the surface is oven dried to promote evaporation of water from the developer coating. As with drying operations before using other developers, test piece temperature should not exceed 60 °C (140 °F). Indication dimming by heat is minimal and the test pieces can be handled less cautiously.

Advantages of Using Aqueous Developers

Aqueous developers give off no noxious and/or flammable vapors and no annoying or hazardous dusts and thus require no use of elaborate safety equipment. Compared to solvent developers, harmless and inexpensive water is being driven off, not costly and hazardous solvents. Whereas dry developers do not produce visible coatings, aqueous developers have the advantage of making the extent of developer coverage visible. If there is a void in coverage, it is obvious.

Disadvantages of Using Wet Aqueous Developers

The wetting agent functions as a liquid penetrant remover when aqueous developer is applied by dipping or flowing onto test parts. As a result, wet developers must be applied with some care to prevent developer loss and liquid penetrant loss from discontinuities.

For most applications, aqueous developers are not recommended for use with water washable liquid penetrants. Such usage may cause blurring or loss of discontinuity indications because liquid penetrant entrapments are subject to detergent action and removal by wetting agents in the developer system. If specifications allow, developer choice should be based on application specific evaluations

Spraying can lead to a nonuniform coating of developer, leaving some areas devoid and others with excessive coating, which can hide indications. Being liquid, aqueous developers flow (like solvent developers) before being fixed by drying and may fill up recesses with gross excesses of developer. Avoidance of this requires care in application and in positioning test pieces.

Compared with solvent based developers, aqueous developers suffer a disadvantage (shared with dry developers) in that there is no solvent action to assist in forming indications, only capillary action. This makes aqueous (and dry) developers noticeably less sensitive than some solvent developers. Also, because they contain wetting agents, aqueous developers tend to cause foaming if handled too forcefully

Aqueous developer powders are prone to deterioration in storage, a result of the corrosion inhibitor reacting with other essential ingredients of the developer. Also, while in the developer tank, soluble developers are susceptible to attack by bacteria and fungi. To guard against this problem, the developer contains biocides. If a developer tank does become infected, it is necessary to dispose of the developer, to sanitize the developer tank if it becomes infected and then to change the solution. The problem can be identified immediately because clumps or colonies of the attacking microorganisms will be visible in the solution and may stink. These colonies can interfere with the test process by absorbing liquid penetrant and then appearing as a false indication.

Advantages of Water Soluble Wet Developer

Developer solubility eliminates the necessity of agitating the developer to keep undissolved solids in suspension while retaining the other advantages of the wet developer. Drying results in a uniform film that performs the developer function. In addition, because the dried developer coating is water soluble, it is much easier to remove the developer coating during postcleaning than it is to remove the insoluble water suspended developer coatings.

Disadvantages of Water Soluble Wet Developer

The water soluble wet developer also retains some of the disadvantage of the suspension type powder developer. It does not have much solvent action. Dip application may result in local accumulations or a nonuniform developer film, thus impairing liquid penetrant test sensitivity.

Another disadvantage of soluble developers is that they are difficult to monitor for the correct solution concentration and are difficult to correct if necessary. The proper concentration is important because the sensitivity of the developer is a function of concentration and because deviations from it will affect the sensitivity of the test. Monitoring the concentration requires that both the temperature and the specific gravity be measured simultaneously because one varies with the other. Correcting the solution concentration requires involved calculations that ought to be performed by laboratory personnel.

Movie. Nonaqueous wet developer enhances visible dye contrast.

Nonaqueous Wet Developer

Another common developer type is the so called nonaqueous wet developer whose developer solids come premixed and suspended in a volatile solvent. The volatile solvent tends to pull liquid penetrant from indications by solvent action. It also accelerates drying so that a supplementary drying operation is not required. However, the test part surface must be completely dry before applying the nonaqueous developer.

A thin film of the nonaqueous wet developer is desirable to give the ultimate in sensitivity. Electrostatic spray guns or a fine atomizing spray from a paint spray gun or aerosol spray can will provide this fine developer coverage. As with the suspension type aqueous developer, it is necessary to agitate the nonaqueous wet developer before use to ensure that developer particles are fully suspended. Agitation before application is also essential with nonaqueous wet developers packaged in spray cans. The use of nonaqueous developer results in indications with high visibility and enables reliable detection of smaller discontinuities.

Movie. Shake the spray can.

Film Type Developer

The film type developer, as the name implies, forms a plastic film over the liquid penetrant area as it dries. This developer is used infrequently, in special applications. It is normally spray applied, as with the nonaqueous wet type, and the solvent carrier acts to draw liquid penetrant into the developer film. As the film dries, the exposed liquid penetrant indications set in a pattern indicative of the discontinuities in the surface being inspected. This film provides a permanent record of the discontinuity pattern and can be peeled from the surface and retained for reference. Resolution of the film type developer is of a high order but its use is somewhat restricted to special applications because of the labor involved in stripping the film from test parts. This is more difficult than the ordinary tank type removal techniques used for other types of developer.

Nonstrippable film developer may be the most efficacious developer. However, its use would be limited to special applications where the film remaining on a surface would not be detrimental.

Part 5. Inspection and Interpretation of Liquid Penetrant Indications

Visibility of Liquid Penetrant Test Indications

Probably the one factor most responsible for the effectiveness of a liquid penetrant is its visibility, often referred to as brightness, contrast or brilliance. Carefully conducted experiments with glass plates clamped together and viewed (through the mating surfaces) under monochromatic light have shown that liquid penetrant materials of only medium or low performance can enter openings that are smaller in width than a half wavelength of sodium light. Liquid penetrant was determined to have entered to a plate gap of only 130 nm (about 5×10^{-6} in.). Taking into consideration the extremely small amount of liquid penetrant contained in a discontinuity of this size and the fact that only a small portion of this liquid penetrant can be bled back to the surface to become visible, it is obvious that everything that will enhance visibility should be used if maximum liquid penetrant test performance is to be obtained.

Visual Examination of Fluorescent Liquid Penetrant Test Indications

The inspector views the processed test surfaces under ultraviolet radiation in a darkened test area when fluorescent liquid penetrant systems are used. Indications of discontinuities fluoresce with an intensity that provides contrast in proportion to the ambient darkness, literally drawing the eye of the inspector to them. The darker the inspection area and the more nearly dark adapted the eyes of the inspector, the more reliable the inspection will be. If outdoor fluorescent liquid penetrant testing is necessary, it is often done at night or the area of interest is shielded as much as possible from visible radiation (white light).

Formation and Bleeding of Liquid Penetrant Indications

Liquid penetrant indications tend to bleed across the developer coating as time progresses after their formation. Thus, as the developer action progresses from the time of its application, discontinuity indications appear gradually and then reach their optimum visibility and clarity. Thereafter, as bleeding of liquid penetrant indications continues, the liquid penetrant spreads laterally into the developer coating. This gradually reduces the definition and intensity of the indications. The optimum indications are typically reached with developing times in the range from 2 to 10 min (Fig. 10). Excessive bleedout of entrapped liquid penetrant may take 30 min or longer (Fig. 11).

Contrast of Visible Dye Liquid Penetrant Test Indications

In the case of visible liquid penetrants, increasing indication visibility means incorporating the largest possible quantities of dye in the liquid penetrant vehicle and choosing the most intense dye colors with the highest contrast with respect to the background against which they will be viewed. In nearly all cases, this contrast is heightened by using the developer in such a manner that developer (1) serves to bring liquid penetrant out of the discontinuity and (2) also covers the surface with a smooth, white coating against which the indication stands out sharply.

Movie. Nonaqueous wet developer enhances visible dye contrast.

All of the visible dye liquid penetrants presently in use make themselves perceptible to the eye in one of two ways — either by reflecting a considerably smaller amount of light than the background or by reflecting light of a different color (usually red) than the background (color contrast). The incident light is not all absorbed by the liquid penetrant, nor does the background reflect all the light that strikes it. The actual contrast ratios are extremely difficult to measure but have been

FIGURE 10. Fluorescent liquid penetrant indications of optimum resolution and clarity, obtained without bleedout or excessive spreading of liquid penetrant across developer film: (a) gears; (b) sprocket; (c) spindle; (d) links.

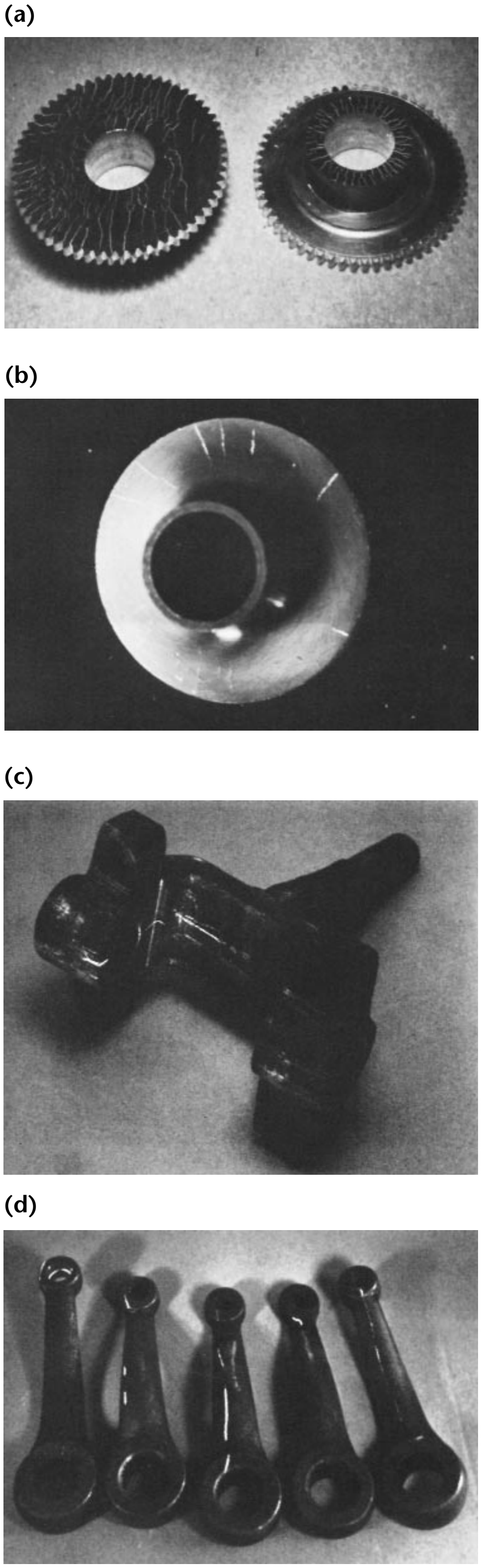
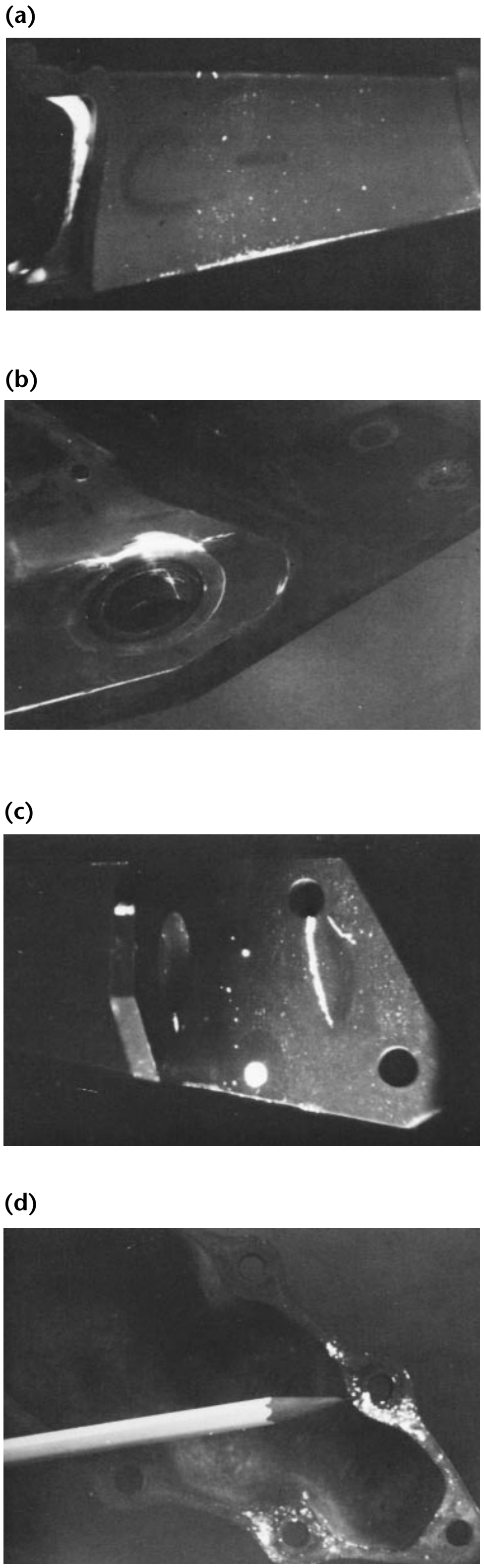


FIGURE 11. Examples of fluorescent liquid penetrant indications with excessive bleedout or spreading of liquid penetrant across developer film: (a) turbine blade; (b and c) structural parts; (d) casting.



estimated at from 10:1 to 20:1, the maximum contrast theoretically obtainable.

Contrast of Fluorescent Liquid Penetrant Test Indications

In the case of fluorescent liquid penetrant discontinuity indications, visual perceptibility is enhanced by light emission mechanisms within the liquid penetrant indications and conditions of viewing are quite different. Using brightness contrast, the bright yellow-green indication is seen against a nearly black or at least a very dark background. The indication itself is actually a source of light which, even though small, is quite intense. Contrast can be exceptionally high. Some estimates give it a value as high as 100 to 1 or even much greater, because it is the presence of light compared to absence of light.

With fluorescent liquid penetrants, the most effective way to increase visibility (and improve resolution of fine discontinuities) is to increase the fluorescent brilliance of the liquid penetrant material. The fluorescent indications are generally viewed in the substantial absence of visible light, so that the background remains unseen.

Visibility of Fluorescent Liquid Penetrant Indications

From the point of view of color contrast, most fluorescent liquid penetrants provide yellow or yellow-green indications against a black background. This has been proven by research into visibility of such objects as highway signs to be one of the most seeable combinations possible. The normal human eye has its highest sensitivity in the yellow or yellow green wavelength range. In fluorescent testing, the eye looks at a fine source of light of high brightness. Under this condition, probably because of halation, the source size appears to be greatly exaggerated whereas the dark background tends to be minimized.

Background Fluorescence Caused by Rough or Porous Surfaces

In some practical applications where the test object surface is porous or rough, fluorescent liquid penetrant tends to be retained on the surface as well as in discontinuities. This condition reduces contrast between the background and indications and may impair discrimination. For this reason, a compromise between the removability of surface liquid penetrant and intensity of fluorescence is necessary to reduce the background fluorescence to a practical limit.

Placement of Light Sources in Liquid Penetrant Testing Booth

Consideration should be given to the disposition of lights within an inspection booth and to the effect on an operator of placement of light sources. Although ultraviolet-A radiation will not damage the eye permanently, some of the layers of the eyeball exhibit strong tendencies to fluoresce. If the inspection light is placed so that its rays fall directly or are reflected into the eyes of operators, this eyeball fluorescence can become extremely annoying and will impair inspector effectiveness to a very marked degree.

Use of special filtering eyeglasses will increase operator perception and reduce fatigue. Yellow tinted eyeglasses filter out the ultraviolet radiation before it reaches the eye, yet they do not reduce the visibility of fluorescent indications.

Interpretation of Liquid Penetrant Indications

The interpretation of liquid penetrant indications is normally a matter of considerable judgment. It might be said that it involves three phases:
(1) observation of indications,
(2) verification of indication cause and significance and (3) disposition of test objects in accordance with applicable criteria for acceptance and rejection.

The first step is that of visually observing the indication and verifying that it is relevant, i.e., that it is indicating a discontinuity rather than a material characteristic that is a normal condition of the surface under investigation. Figures 12 and 13 show some typical liquid penetrant indications.

The American Society for Testing and Materials (ASTM) has issued ASTM E 433, *Standard Reference Photographs for Liquid Penetrant Inspection.*[5] This publication contains reference photographs to be used as a means of establishing and classifying type and characteristics of surface discontinuities detectable by liquid penetrant test techniques. They may be used as a reference for acceptance standards, specifications and drawings. However, no attempt has been made to establish limits of acceptability or the extent of the metallurgical discontinuity.

FIGURE 12. Fluorescent liquid penetrant test indications under ultraviolet radiation: (a) aluminum spar cap; (b) fatigue crack in bearing shell.

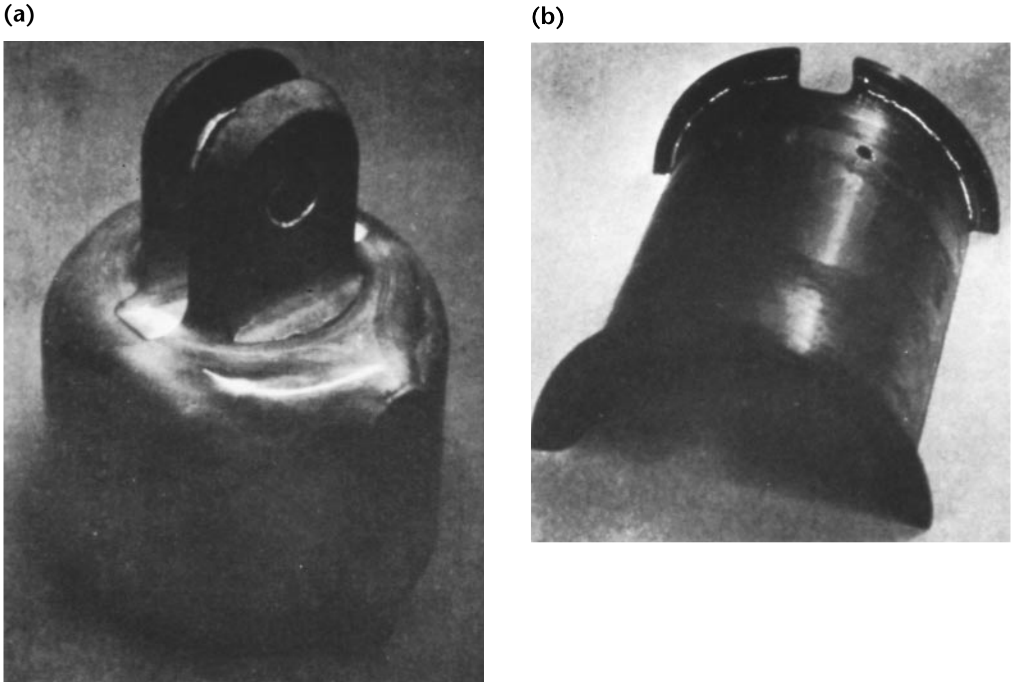
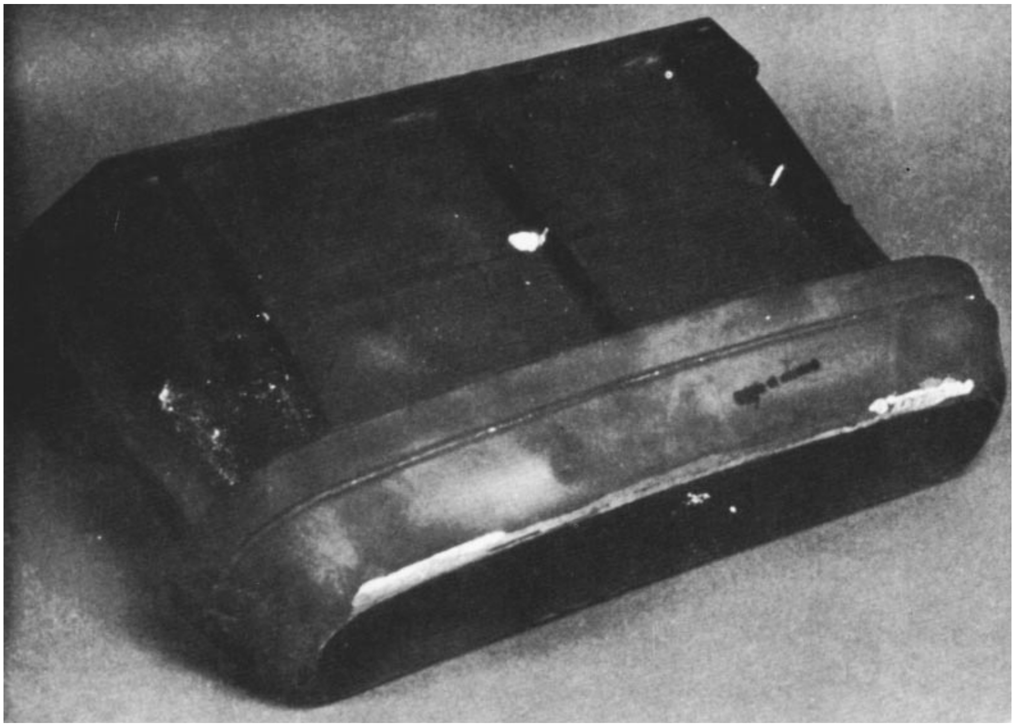


FIGURE 13. Blow holes in casting shown by fluorescent liquid penetrant testing.



In the event of questions of interpretation, supplemental means of observation may be necessary such as viewing liquid penetrant indications under magnification or preparing metallographs of cross sections of discontinuities encountered in production testing.

When it has been determined that an indication is relevant, a further judgment must be made as to the disposition of the test objects to answer questions such as the following.

1. Should supplemental nondestructive tests such as ultrasonic or radiographic testing be used to attempt more complete definition of the discontinuity causing the liquid penetrant indication?
2. Can the surface be accepted as is or be reworked to eliminate the indicating discontinuity?
3. Should the surface or part be discarded as unserviceable?

Interpretation of indications is discussed in detail elsewhere in this volume.

Establishing Criteria for Acceptance or Rejection

Specifications or drawings for the parts or surface under examination should specify the nondestructive test method or methods required for part acceptance. Moreover, drawings should specify the acceptance or rejection criteria or refer the inspector to supplemental documents such as applicable acceptance/rejection specifications. If liquid penetrant tests are being made on critical parts such as nuclear hardware or a jet engine component, an expert in evaluation of indications in the specific industry may have to be called on for a judgment.

To establish acceptance/rejection criteria, it may be necessary to conduct an extensive correlation study between nondestructive test indications and destructive test results. This is the ultimate procedure but even it may leave some doubt because discontinuities or indications do not always occur in exactly the same place, with the same frequency or to the same extent.

Factors Influencing Judgment of Test Object Serviceability

It should be obvious that a number of factors enter into the final judgment. Some of these are as follows.

1. What metal or alloy is involved in test objects?
2. If the test objects have a nonmetallic surface, what is its composition?
3. Where are the indications? Are they in critical radii, on edges that will be ground off, in parts designed for high strength applications or in thick sections that may allow for removal of surface discontinuities without sacrifice of function?
4. Are the surface or surfaces repairable by welding or other means?
5. What is the cost of the part? It may be that the cost of a new part is so low that the expense of repair or rework of an anomalous part is not warranted. Conversely, of course, one would not want to discard an expensive piece of hardware that could be reworked at a considerable savings over the cost of a new part.

Specifications Covering Evaluation of Liquid Penetrant Indications

Some industries have prepared standards for evaluation and acceptance/rejection of hardware on the basis of liquid penetrant indications. These standards vary from quite general to very detailed. Liquid penetrant users may find some of these helpful or may prefer to prepare their own. If they are working under a contract, it is mandatory that they determine the specifications to which the contracting agency intends to hold them and conform thereto. Commonly, a general statement covering inspection policy may be encountered, such as, the inspection department shall pass only those parts that have no relevant liquid penetrant indications. Parts showing liquid penetrant indications should be referred to the metallurgy or design departments for disposition. The metallurgy or design department shall decide which parts shall be accepted, reworked or rejected.

There are many specifications covering the liquid penetrant products, liquid penetrant processing procedures and certification of liquid penetrant test personnel. Some specifications have been prepared by government agencies and others by technical societies such as the American Society of Mechanical Engineers (ASME), the American Society for Testing and Materials (ASTM) and SAE International (formerly the Society of Automotive Engineers, or SAE). Numerous specifications have been developed by companies using liquid penetrant testing. Because of frequent changes in requirements, test personnel and facilities should always check to verify that they are using the revision or amendment of the applicable test specifications called out under contract.

Acceptance/Rejection Criteria for Critical Parts

Test acceptance/rejection criteria for parts or surfaces would normally be referenced by an applicable specification, standard for a particular part or some other governing document that would outline what type of discontinuity would be cause for rejection. An extreme example of this would be the approach taken by companies that are working with fracture mechanics, whereby a particular structure or part is analyzed for specific types of discontinuities that may or may not constitute a rejectable discontinuity. Standards are then drawn up for the items for nondestructive test criteria, which may include liquid penetrant testing. These would include minimum acceptable indication size and strict uniform liquid penetrant processing.

The importance of carefully controlled liquid penetrant testing and the necessity to record the exact techniques used to process the parts on the technique card or other applicable document cannot be over emphasized. In a number of specifications, porosity bleedout diameters are specified as accept/reject criteria. The maximum acceptable size limits for liquid penetrant indications apply to the bleedout indication immediately after wiping the indication one time with a swab or brush dipped in solvent. Bleedback refers to the recurrence of the liquid penetrant indication after once wiping away the original indication.

PART 6. Field Techniques for Liquid Penetrant Testing

Field Techniques for Liquid Penetrant Testing

It is often necessary to carry out liquid penetrant testing in the field where little or no equipment is available. Precleaning before liquid penetrant testing can be accomplished using a solvent cleaner. The liquid penetrant is applied to the part or the area being inspected by means of a clean brush or swab, with a liquid penetrant spray can or with a spray gun. Liquid penetrant should remain on the part for the length of time suggested with water washable and postemulsifiable liquid penetrants.

As in all liquid penetrant techniques, the length of time that the liquid penetrant must be on the part to enter rejectable discontinuities depends to some extent on the type of materials, on temperature and on weather conditions. A nominal visible dye liquid penetrant dwell time of 5 to 10 min is adequate but longer penetration times are in no way detrimental, providing the surface is occasionally rewetted with liquid penetrant, especially in a hot environment.

Field Precautions for Liquid Penetrant Testing

The following precautions should be observed throughout the liquid penetrant testing process.

1. Particular care should be taken in handling liquid penetrant so as not to get it on clothing, bench tops, chairs, floors or parts not being tested. It may be extremely difficult to remove.
2. If liquid penetrant materials are used from pressurized spray cans in a cold environment, the temperature of the cans should be no lower than 16 °C (60 °F). To maintain this temperature, cans may be kept in insulated enclosures until just before use. Pressurized spray cans do not function properly below this temperature. If the materials are applied by brushing, it is possible to inspect at temperatures near the freezing point of the liquid penetrant.
3. Note that pressurized cans and sprays atomize solvent materials, making them more prone to combustion.

Field Preparation of Parts for Liquid Penetrant Testing

The same general preparations used for field inspection with fluorescent liquid penetrants apply to visible liquid penetrants. The parts must be cleaned and the rejectable discontinuities should not be contaminated with any materials that may interfere with the ability of the liquid penetrant to enter the rejectable discontinuity. For field application, a prepared solvent cleaner may be used to remove oils, grease and other materials that may confuse inspection or contaminate rejectable discontinuities and prevent the liquid penetrant from entering. Loose scale, paint, carbon, *engine varnish,* and other materials should be removed. After cleaning, the test surface should be wiped dry with clean lint-free paper toweling or rags. If the towels or rags pick up dirt, the cleaning process should be repeated. The solvent remover used for liquid penetrant removal is a convenient solvent precleaner.

Field Application of Liquid Penetrant

The liquid penetrant is applied to the cleaned area with a brush (Fig. 14), spray gun or from a pressure spray can. Visible or fluorescent liquid penetrant can be used as appropriate. Either water washable or postemulsifiable liquid penetrant is suitable. The entire surface to be inspected should be wet with the liquid penetrant.

If the liquid penetrant is allowed to remain on the part too long, it may be difficult to remove liquid penetrant from the test surface. Should this happen, the inspector should apply more liquid penetrant on the area and then proceed with the cleaning. The reapplication of liquid penetrant will make the surface easy to clean. Reapplication should not be necessary unless unusually long liquid penetrant dwell times are used.

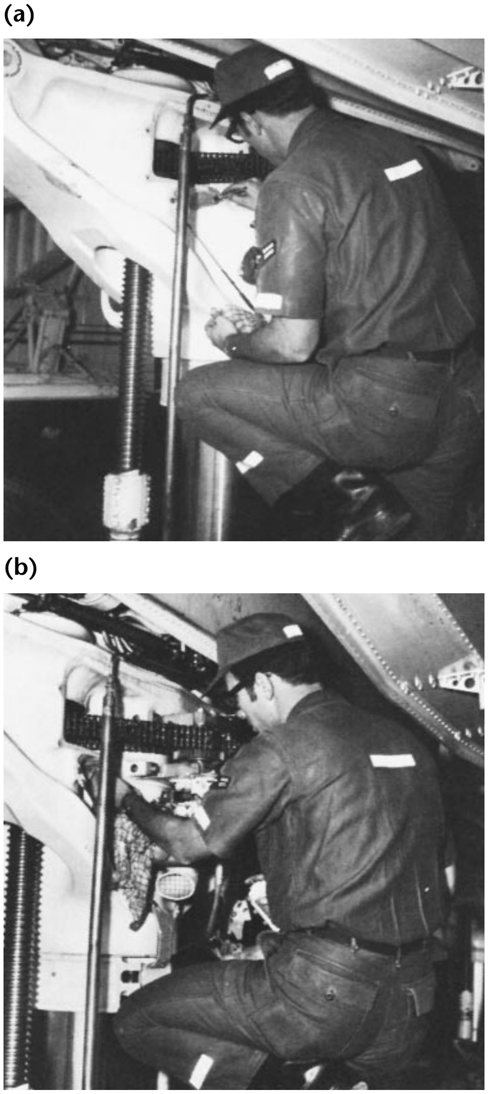


FIGURE 14. Fluorescent liquid penetrant test of landing gear forging on aircraft during maintenance operation: (a) application of liquid penetrant by brush to precleaned test area; (b) wipe removal of excess surface liquid penetrant from test area.

Solvent Wipe Removal of Excess Liquid Penetrant in Field

After sufficient penetration time has elapsed, the excess liquid penetrant is removed from the surface of the test part. Most of the liquid penetrant can usually be removed by wiping with rags or paper toweling (Fig. 14b). Solvent should never be applied directly to test parts during removal of excess surface liquid penetrant. If excessive amounts of solvent are used, some liquid penetrant may be removed from discontinuities. It is preferable to use only enough solvent to obtain a reasonably clean surface free from excessive background. It is best to dampen a cloth slightly with solvent and use it to wipe the part. If water washable liquid penetrant is used, dampen the cloth with water.

Field Application of Nonaqueous Developers

A convenient developer for use under field conditions is nonaqueous developer applied from an aerosol container.

Before applying the developer, the container should be shaken vigorously to make certain the materials are well mixed and all solids are brought into suspension. The developer should be used sparingly. Just enough developer is applied with a spray can to cover the part thinly and evenly. The proper developer thickness will dry to a thin, translucent layer. Too much developer may mask indications. Care should be taken to use a short distance of up to 0.3 m (12 in.) between spray nozzles and test parts to ensure application of a wet developer coat. Excessive spraying distances result in solvent flashoff so that the benefits of a nonaqueous developer that aids liquid penetrant from entrapments to reach the test surface will be lost. The user should exercise caution because some developers sprayed from aerosol cans are flammable.

Viewing of Fluorescent Liquid Penetrant Indications

For field inspection under ultraviolet radiation, curtains or other means of shutting out the natural light are recommended. The darker the inspection area, the more reliable the inspection will be. Outdoor testing is often done at night. Inspectors should accommodate their eyes to darkness before inspection.

Advantages of Solvent Removable Liquid Penetrant Process in Field

In the field, it is common practice to use the solvent removable visible dye liquid penetrant process for liquid penetrant testing in the following circumstances: (1) if there is not a convenient water supply, (2) if it is not permissible or practical to perform a rinsing operation or (3) if the area to be inspected is only a small part of a large assembly or part. The chief advantage of the solvent removable liquid penetrant testing technique is its portability. It is easy to carry the materials needed for testing limited areas. The solvent removal technique is also used for inspecting local areas of large surfaces. Precleaning of test objects is also generally done with solvent, so that water is not required for this operation.

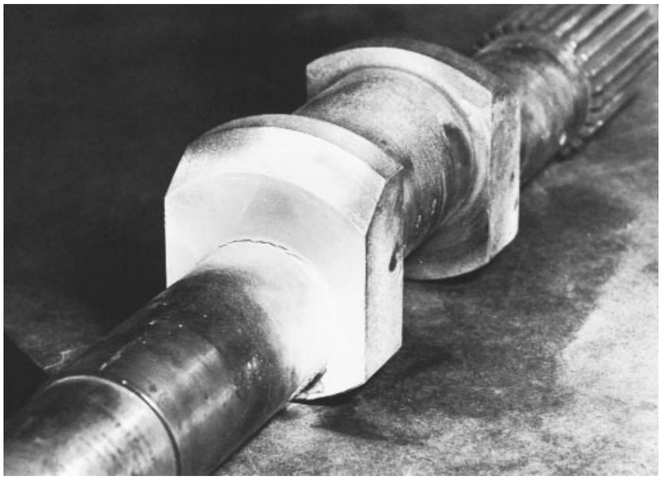
Field Techniques for Visible Dye Liquid Penetrant

Most of the techniques and precautions necessary to the proper use of fluorescent liquid penetrants apply equally well when use is made of visible dye materials. Some basic differences, however, should be taken into consideration. There are some test problems and situations in which the fluorescent liquid penetrant techniques may be very inconvenient or impossible to use. This is particularly true when there is no electric current available for an ultraviolet lamp or when electricity may present a hazard, such as around aircraft fuel tanks. If a darkened inspection area is not available or is not convenient to simulate, fluorescent liquid penetrant testing would be impractical.

Viewing of Visible Dye Liquid Penetrant Indications

Under proper conditions, large cracks will show up immediately as red lines on the part. Finer rejectable discontinuities require a lighter, thinner film of developer and it may take several seconds or minutes before the red dye of the liquid penetrant appears through the thin developer film. Figure 15 shows visible dye liquid penetrant indications of fatigue cracking in service. Discontinuities will be marked by brightly colored indications. If the discontinuity is wide and deep, the indication will grow and spread. Porosity, shrinkage, lack of bond and leaks appear as local dots or areas of color. These too may grow and spread if the rejectable discontinuity is large, covers an extensive area or is quite deep.

Figure 15. Visible dye liquid penetrant indications of fatigue cracking in fillet area of crankshaft.



Leak Testing with Liquid Penetrants

Testing of materials for discontinuities that extend completely through the section is termed *leak testing*. The technique of using liquid penetrants for leak testing is not usually limited to any great degree by the geometry of parts to be inspected. An application especially well suited to this technique is the inspection of items designed to contain liquid or gas. This is particularly true in cases where such containers (pipes, tubes, ducts, vessels etc.) have limited access to their internal surface, thereby precluding visual examination or the execution of other test techniques. It also has the advantage that it can be used on subassemblies before the completion of the finished container. Leak testing by liquid penetrant is equally well suited to ferrous, nonferrous or nonmetallic materials, with the precaution that the latter are not adversely affected by the liquid penetrant. Although there exist numerous variations of the liquid penetrant leak test, the procedure described here shall be considered as basic for this technique.

Leak testing indicates only discontinuities that extend completely through the material. Therefore, the absence of discontinuity indications does not preclude the presence of extensive discontinuities that are not, however, completely through the material. Leak testing by the liquid penetrant technique cannot be substituted for pressure tests directly where the applied stress and the associated proof test factors are significant in the test procedure.

Liquid Penetrant Application for Leak Testing

Any liquid penetrant may be used although the highest sensitivity fluorescent liquid penetrant will reveal the smallest leaks and do so more quickly. For test purposes, no distinction need be made regarding self-emulsification or postemulsification or water soluble or solvent soluble liquid penetrants, except that consideration to final cleaning convenience should be given. Apply the liquid penetrant by a means that will ensure complete coverage of one surface being tested without allowing the liquid penetrant to reach the opposite surface. Exercise care to prevent the liquid penetrant from passing around edges or ends or through designed holes or passages to the opposite surface. Apply sufficient liquid penetrant during the period of test to prevent drying of liquid penetrant on the surface during leak testing.

Developing of Leak Testing Indications

Immediately following liquid penetrant application, a developer is applied to the surface opposite that on which the liquid penetrant was placed. Nonaqueous developer is usually most suitable. Exercise care to prevent the developer from contacting the liquid penetrant at edges, ends or through designed holes or passages and thereby destroying, through absorption of liquid penetrant, the test results over portions of the material being inspected.

Penetration Time for Leak Testing with Liquid Penetrants

Penetration time shall be considered as the period of time allowed for passage of the liquid penetrant through any discontinuities to the surface on which the developer was placed. This time period shall begin immediately on liquid penetrant application. The extent of the time period shall be determined by trial. However, the initial trial period in all cases shall be no less than three times greater than the time normally used for surface inspection of cracks. Generally, the penetration time varies with the thickness of the section being tested.

Viewing Leak Testing Results

Test results shall be considered conclusive only after the lapse of the established development time. The requirements for illumination shall be either visible radiation (white light) or near ultraviolet radiation, whichever is applicable.

Interpretation of Leak Testing Results

When using the liquid penetrant testing technique for leak testing, the interpretation shall be restricted to citing the presence or absence of leak discontinuities and, when present, their general nature (hole, crack etc.), their magnitude and their location.

PART 7. Maintenance of Liquid Penetrant Test Systems

Reasons for Maintenance of Liquid Penetrant Testing Equipment

As in any manufacturing installation, a liquid penetrant nondestructive testing system requires a certain amount of maintenance to ensure continuous reliable test service and to make certain that the results of the tests are consistent. Compared with other shop installations, service requirements are not extensive or difficult. However, a small amount of time spent in making certain that equipment and materials are in proper condition will pay dividends in reliable inspection and absence of downtime. It can also result in large monetary savings by either (1) preventing the scrapping of good parts or (2) preventing use of anomalous parts in service.

Types of Maintenance Required for Liquid Penetrant Testing Systems

Maintenance is ordinarily of two different types. The first applies to the maintenance of mechanical and electrical equipment and of any associated types of accessories. The second has to do with the maintenance of proper characteristics of expendable materials such as the liquid penetrants, emulsifiers, developers and cleaners used to accomplish the tests. The second type is covered elsewhere in this volume.

Mechanical Maintenance of Liquid Penetrant Test Equipment

It is not feasible here to give specific instructions applicable to all test equipment that might be encountered. There are some basic service precautions that should be observed, however. One of the most important items is, of course, lubrication of moving parts of liquid penetrant test equipment. Even in the smaller units there may be fans, pumps and the like that should be inspected for lubrication regularly. In large production type liquid penetrant test equipment, there will undoubtedly be conveyor mechanisms of fairly complicated nature. Manufacturers generally supply information with such equipment, outlining complete lubrication procedures and specifying the various types of oils or grease that should be used for best results.

Electrical Maintenance of Liquid Penetrant Processing Equipment

Electrical equipment, particularly in the more complicated machines, should be inspected regularly. Because many of the liquids used in liquid penetrant processing are electrically conductive, they can contribute to electrolytic corrosion between dissimilar metals. Such corrosion may occur even on a single metal when the liquid gets onto it, particularly where the metal carries current and the liquid happens to be where current can flow through it to the metal. Conductive liquids can at times cause trouble in program control circuits by causing partial short circuits. These may damage electrical equipment or cause faulty operation of sensitive control relays. It is a good policy to look over all electrical circuitry at each maintenance inspection and to remove all evidence of liquids that may have splashed or otherwise gotten onto wiring or electrical devices.

The most important point for electrical maintenance of liquid penetrant test equipment is the dryer. Failure of a dryer fan or thermostat could cause loss of control of drying operations. Overheating of aluminum alloy parts in the dryer could cause overaging of these production parts. Automatic rinse stations should also be watched for conditions of excessive pressure or overly long rinse cycles. The rinse water temperature must also be controlled properly when working with some types of liquid penetrants.

Maintenance of Plant Safety Equipment in Liquid Penetrant Test Areas

Fire extinguishers, fire alarms and other equipment used to prevent fire or explosion must be maintained in accordance with fire prevention codes and insurance requirements. Conformance with all local, state or federal codes, including Occupational Safety and Health Administration regulations, is essential. Large dividends in personnel safety and continuity of operations can be realized through proper observance of fire and safety regulations. Training of personnel in proper procedures to report and to control or extinguish fires is a normal precaution to aid in limiting injury or damage to facilities.

Control of Atmospheric Pollution from Liquid Penetrant Testing Systems

Air sampling to ensure that the area surrounding the liquid penetrant processing is being maintained at safe health levels is an advisable precaution, particularly if toxic solvents are known to be involved. The Environmental Protection Agency (EPA) has placed restrictions on the concentrations of certain volatile solvents in the atmosphere,[6] and the Occupational Safety and Health Administration administers regulations that limit the accumulated exposures of personnel to toxic gases or vapors.[7] Continued monitoring of the atmosphere in work areas and of emissions from exhaust systems into the environmental atmosphere may be necessary to ensure compliance with these requirements. Some liquid penetrant processing materials have been specifically formulated to abide by air pollution restrictions such as those in Los Angeles and San Francisco. Because of the rapid changes in environmental and health regulations, users of liquid penetrants and solvent materials should check their compliance with federal, state and municipal or other applicable codes and regulations on a continual basis.

Ultraviolet Lamp Maintenance

An integral part of the fluorescent liquid penetrant system is the ultraviolet radiation source (ultraviolet lamp), the intensity of which is vital to a reliable result. It is recommended that this intensity be checked weekly or more often if the light is being operated at an intensity level close to the minimum. Ultraviolet radiation intensity should be measured with a meter calibrated to requirements of the National Institute of Standards and Technology. On a commercially available ultraviolet radiation meter, measurements are taken at distances of 380 mm (15 in.) from the face of the filter on the ultraviolet lamp, in the center of the ultraviolet light beam. Various specifications call for minimum ultraviolet radiation intensities of 8.6 to 10.2 $W \cdot m^{-2}$ (865 to 1020 $\mu W \cdot cm^{-2}$). Higher minimum intensities need to be established for each case, to permit detection of discontinuities with sizes approaching the visibility threshold.

Maintaining Cleanliness in Liquid Penetrant Processing and Test Areas

Good housekeeping in and around liquid penetrant test units should be observed at all times. A clean piece of equipment not only looks better but also provides a much better inspection. Accumulations of expendable test materials on equipment should be avoided. Liquid penetrant, either visible or fluorescent, can be especially bad if allowed to collect on work surfaces. It can be picked up by parts and may lead to false indications or, at least, confusion to the inspector. Collection of quantities of fluorescent liquid penetrant on interior surfaces of the ultraviolet radiation inspection booth can be particularly bad. Under the influence of the ultraviolet radiation always present in the inspection booth, masses of fluorescent material can easily emit enough visible light to affect the inspector’s darkness adaptation, thereby lowering the overall sensitivity of the entire liquid penetrant testing process.

Precautions must also be taken to ensure that developer powder is free from liquid penetrant contamination. Fluorescent or color dyes in the developer may be carried onto part surfaces with the developer to produce false indications. Bright fluorescent spots in tank developers may also emit light that may interfere with the inspector’s dark adaptation. Another common source of trouble is the accumulation of dust behind the filter of the ultraviolet lamp. The filter should be removed and the back of the filter and the face of the ultraviolet lamp bulb should both be wiped clean whenever dust accumulates.

PART 8. Health and Safety Precautions

A number of governmental organizations around the world are involved with promoting and enforcing safety and health in the work place. Others aim at protecting the environment from contamination by industrial materials. In the United States two such organizations are the Occupational Health and Safety Administration (OSHA)[7] and the Environmental Protection Agency (EPA).[6] These and similar agencies are continually examining industrial practices and materials to eliminate hazards to personnel and the environment. For example, certain ingredients used formerly in liquid penetrants and emulsifiers have been required to be replaced. One of the most notable has been the elimination of halogenated solvents. This chapter will cover personnel safety and health. Because most filtered particle test fluids consist of particles suspended in light petroleum distillates, the discussion below regarding liquid penetrant fluid materials applies to the filtered particle fluids as well. Environmental concerns with respect to liquid penetrant test effluents are discussed elsewhere in this volume.

Maintaining Good Health of Penetrant Inspectors

The physical health of liquid penetrant testing personnel should not be altered by performance of liquid penetrant testing operations. To ensure health and freedom from accidents or injury, test personnel should be aware of job related hazards and safety precautions. Particular care is required when handling unhealthy or flammable liquids and vapors. Good ventilation must be provided and care should be taken to avoid exposure to hard (short wavelength) ultraviolet radiation. Safety requires good lighting and good housekeeping in work areas. Maintaining good vision and appropriate ambient lighting is essential for reliable visual observation of penetrant test indications.

Prolonged breathing of penetrant vapors, emulsifier vapors or solvent remover vapors may cause headaches, nausea or tightness or pain in the chest. To avoid this problem, forced air ventilation exhausting to the outside of the building may be required in addition to constant alertness to breakdown of the system and/or increased sensitivity of personnel.

Many objects and materials fluoresce under ultraviolet radiation. The teeth and fingernails fluoresce with a bluish white light. Dyes in clothing may fluoresce brightly and not always the same color as that observed under white light. Laundering agents, starches and softeners may fluoresce brightly. These conditions add to eye fatigue and may reduce the reliability of the test. Eye fatigue because of extraneous light sources may be reduced by proper design of the work station and by clothing selected to provide minimum background fluorescence.

General personnel restrictions regarding cleanliness of the work area, wearing of safety shoes or limiting of loads to be lifted manually are applicable to liquid penetrant testing personnel and affect the ability of the operator to perform.

Potential Material Hazards

In the course of a test process liquid penetrant materials can have direct, unsafe effects on human operators, for example, topical exposure to chemical solvents. The expendable materials used in liquid penetrant tests include organic pigments, petroleum distillates, wetting agents, corrosion inhibitors, powders and a variety of cleaning compounds and solvents. As a group, they are not highly dangerous chemicals but they must be used with care.

Topical Exposure to Liquid Penetrant Materials

Liquid penetrant test materials are carefully screened for potential health hazards and are qualified as safe for use by humans in an industrial operation. When used in accordance with the manufacturer's instructions, no general health hazard should be encountered. Humans vary from person to person and may react differently to liquid penetrant materials, usually in the form of allergic reactions. Allergies usually manifest themselves as a form of dermatitis on the hands or arms. Other forms of allergic reaction are more subtle and need to be evaluated by competent medical personnel. If allergies persist, the operator may be unable to perform liquid penetrant testing routinely.

Practically all liquid materials used in liquid penetrant testing, including penetrant, cleaner and developers, have very good wetting and detergent properties. Most of them exhibit excellent solvent power for fats and oils. If these materials are allowed to remain in contact with body surfaces for extended periods, the natural oils will be dissolved from the skin, causing it to become rough and red and eventually to crack. In this condition, secondary infection can take place, causing severe irritation or dermatitis.

Protection of Skin from Dermatosis Caused by Contact with Liquid Penetrant Process Materials

Preventive measures to lessen the likelihood of skin infection should be used to protect personnel who handle liquid penetrant processing materials and test parts that carry these materials on their surfaces. In many instances, synthetic rubber or other impervious gloves are essential for handling baskets and test parts during liquid penetrant processing. In recent years the Federal Occupational Safety and Health Act has imposed restrictions on manufacturers and users of liquid penetrant processing materials.[7] These and state and local government restrictions must be observed in all manufacturing processes, including testing of parts or products. (See *Registry of Toxic Effects of Chemical Substances,*[8] *TLVs and Other Occupational Exposure Values*[9] and *Occupational Diseases — A Guide to Their Recognition.*[10]

The operators' hands or any skin surfaces contacted by liquid penetrants or processing materials should be washed thoroughly with soap and water at least twice during each 8 h shift or working period and before eating. This washing (together with impervious gloves where required) is usually sufficient protection if contact with liquid penetrant processing materials is only occasional.

Where continued or prolonged contact with processing materials is necessary, a protective cream resistant to the test materials being used should be applied to the skin and renewed, after thorough washing of hands, arms or portions of the body exposed to processing materials, as often as this cream wears off. If the skin reddens, the inflammation can often be relieved by the use of cream or lotion such as lanolin that contains animal fat. Lanolin cannot restore the oil lost from the skin but it can serve as a substitute for the lost skin oil. If loss of oil causes dry skin to crack, these cracks may permit infections to develop from any sources in the environment. Skin damage or dermatosis, could result from neglect of the precautions listed.

Flammability of Liquid Penetrant Process Materials

Flash point is the temperature to which a material must be raised to create vapors of a type and quantity that produce a combustible or explosive mixture with the air immediately above the surface of the liquid. Several systems of measurement of flash points are in use. In general, the technique of measurement involves raising the temperature of the liquid in accordance with a predetermined schedule and periodically introducing a flame or other ignition means in the atmosphere immediately above the liquid surface. The temperature at which the vapor-air mixture first ignites is the flash point.[11]

Just what constitutes a safe flash point depends on the conditions under which a material is used and how it is to be shipped. In the United States, rapidly changing regulations of the Occupational Safety and Health Administration (OSHA)[7] and other federal or state and local regulations may dictate minimum allowable flash points that can be used. Requirements of the most recent regulations should be determined and followed in choice of liquid penetrant processing materials and work locations. If materials are used in very small quantities where ventilation is good, extremely high flash points may not be necessary. This is generally true in the case of portable kit-type liquid penetrant test materials, where application is made by brushing or spraying. In this case, materials are kept in small containers that are partially or completely closed. These materials are brought into the open in such small quantities that normal air circulation should dilute their vapors to less dangerous concentrations.

Caution. Smoking while spraying or using highly flammable materials must be prohibited.

Some of the materials intended for use in small portable kits may have considerably lower flash points, possibly as low as 5 °C (40 °F). When used with the precautions and in the manner prescribed by their manufacturers and in work areas with ensured good ventilation, these materials can be used safely. However, it should always be borne in mind that spray application of flammable liquids reduces the product to the form of a fine mist composed of minute droplets. In this form, atmospheric contamination becomes more acute and the flammability hazard is increased.

Where materials are used in large open tanks with extensive exposed surface area, the problem is entirely different. The large surface area fosters rapid liberation of vapors. The dipping of test parts or baskets into the liquid increases this tendency toward evaporation. In addition, the sides of the tank extending above the liquid level act as a barrier that retains the vapors and permits a high vapor concentration to accumulate. In this case, materials that have flash points as high as practical should be used to keep the hazard to a minimum.

In the United States, Occupational Safety and Health Administration (OSHA) regulations established the minimum flash point at 93 °C (200 °F) for flammable liquids in large open tanks, used without special precautions. The Pensky-Martens closed cup technique[11] is the only technique for determining flash point permitted by the Occupational Safety and Health Administration for these applications. It has also been required that specified automatic fire protection apparatus must be installed and maintained in operating condition when liquids with flash points below 93 °C are used in open tanks with liquid surface areas larger than 1 m^2 (10 ft^2).

Many plants have their own regulations as to permissible flash points for solvents and similar materials used in open tanks. In cases where such rulings do not exist, the choice is the responsibility of the facility management, under applicable state and federal regulations. As a rough guide, a flash point of 93 °C (200 °F) should be considered as the minimum allowable for liquid penetrant processing materials used in open tanks, unless required special safety precautions can be enforced and suitable safety equipment is made apart of the installation. In the United States, compliance with all applicable Occupational Safety and Health Administration or other federal, state and local regulations is essential.

Field Precautions for Solvent Removers

Test operators and their management should be aware that most solvent removers present fire and health hazards in use. Do not use flammable solvents near ignition sources. Use volatile solvents only with ventilation adequate to carry solvent vapors away from closed areas. Before repair by welding after solvent applications, use care to make certain that all volatile material has evaporated from test parts.

Sometimes it is not possible to use solvent cleaners and developers only in open, ventilated areas. When testing must take place inside tanks or other closed areas, inspectors should work with a companion. Within closed tanks, all personnel should be provided with adequate ventilation or with equipment to supply breathing air.

Safety Considerations for Developers

All of the developers procured as dry powders offer, to some extent, the possibility of personnel inhalation of developer dust. The extremely fine particle size of the dry developer makes it the most likely to be airborne in reasonably high concentrations. Preferably, this product should be applied in a well ventilated area or within a hood equipped with an exhaust system to reduce inhalation hazard. Nonaqueous wet developer also involves some hazard because of inhalation of the solvent carriers in which the developer particles are suspended. The solvent carriers are normally either relatively flammable, relatively toxic or both. Precautions for use of flammable or toxic solvents should be observed when using nonaqueous developers.

Material Safety Data Sheets

In the past, it was often difficult to know the hazards involved in the use of a chemical product. If the product was highly flammable or toxic, a label was required to carry certain warnings. However, as product liability cases began to award large settlements to users injured by products carrying insufficient warnings, some suppliers began to provide relatively detailed hazard information about their products.

It is standard industrial practice to assess the hazards of chemical products such as liquid penetrant testing materials and to determine their safest use. A ruling by the Occupational Safety and Health Administration, *OSHA Hazard Communication Rule* (29 CFR 1910.1200),[12] has mandated the use of a material safety data sheet (MSDS)[13] (Fig. 16) for any chemical that is hazardous or contains hazardous ingredients. The material safety data sheet must be supplied to a customer with the initial shipment of any applicable chemical and must be updated whenever significant new information is discovered. Material safety data sheets must be available to the user of the product in the work area.

The format for the material safety data sheet may be taken from the United States Department of Labor's nonmandatory form or it may be a supplier's individualized form (alternate versions must meet Occupational Safety and Health Administration requirements and must present all the required information). The nonmandatory form shown in Fig. 16 is described in the text below.

Product and Form Identification

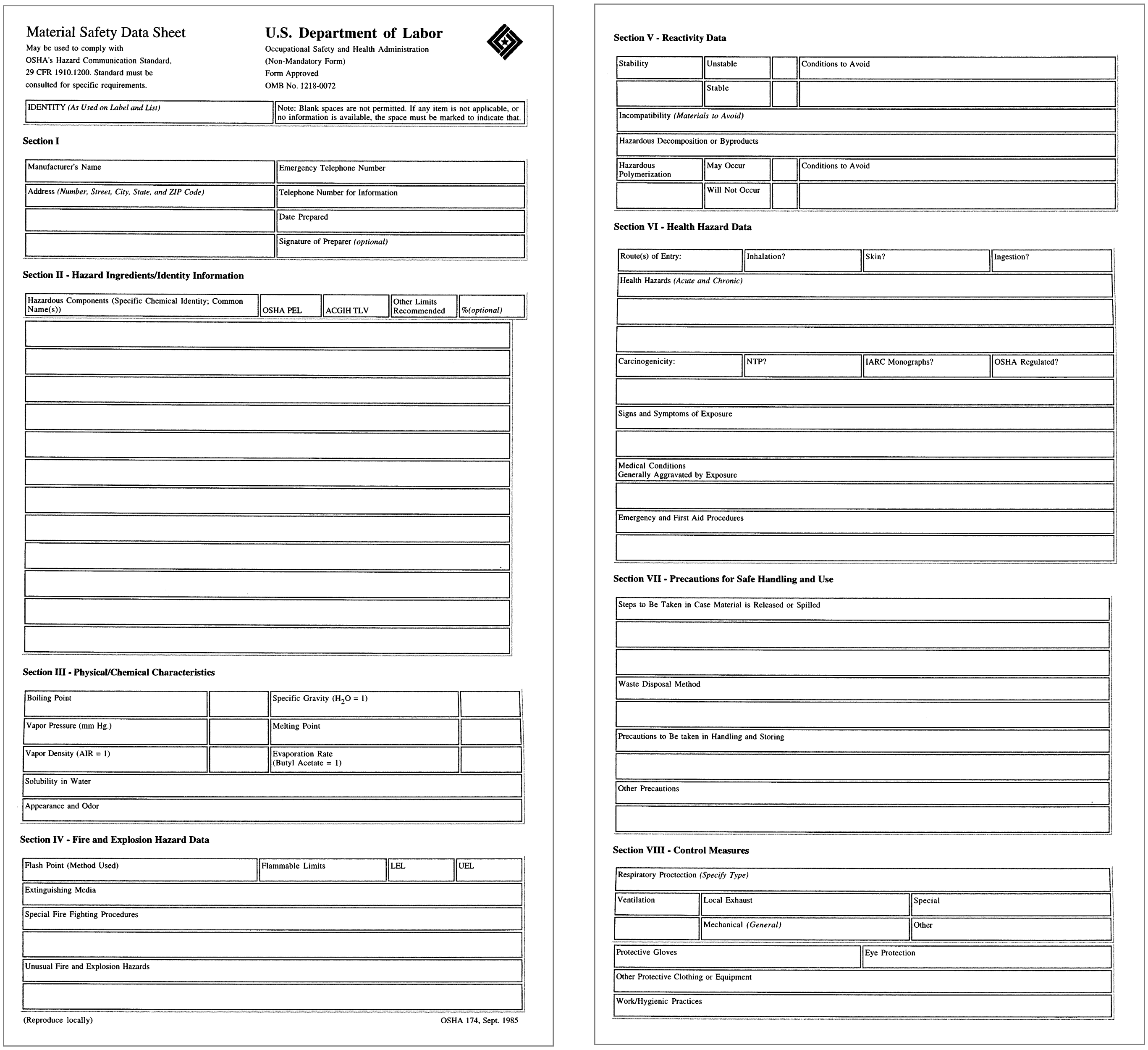
Section I of the form identifies the party responsible for the product. This section includes the product name as found on the container label and the name, address and telephone number of the manufacturer, importer or distributor (a responsible party able to provide additional information about the product).

Section I shows the date of the form's preparation or its latest revision, to indicate the timeliness of its information. Section I optionally identifies the individual who completed the material safety data sheet and could serve as a source for further information.

Materials Listings

Section II lists all the hazardous materials in the product as well as an indication of their breathing hazards. The permissible

FIGURE 16. Material safety data sheet.[13]



Material Safety Data Sheet
May be used to comply with
OSHA's Hazard Communication Standard,
29 CFR 1910.1200. Standard must be
consulted for specific requirements.

U.S. Department of Labor
Occupational Safety and Health Administration
(Non-Mandatory Form)
Form Approved
OMB No. 1218-0072

IDENTITY *(As Used on Label and List)*	Note: Blank spaces are not permitted. If any item is not applicable, or no information is available, the space must be marked to indicate that.

Section I

Manufacturer's Name	Emergency Telephone Number
Address *(Number, Street, City, State, and ZIP Code)*	Telephone Number for Information
	Date Prepared
	Signature of Preparer *(optional)*

Section II - Hazard Ingredients/Identity Information

Hazardous Components (Specific Chemical Identity; Common Name(s))	OSHA PEL	ACGIH TLV	Other Limits Recommended	%*(optional)*

Section III - Physical/Chemical Characteristics

Boiling Point		Specific Gravity (H_2O = 1)	
Vapor Pressure (mm Hg.)		Melting Point	
Vapor Density (AIR = 1)		Evaporation Rate (Butyl Acetate = 1)	

Solubility in Water

Appearance and Odor

Section IV - Fire and Explosion Hazard Data

Flash Point (Method Used)	Flammable Limits	LEL	UEL

Extinguishing Media

Special Fire Fighting Procedures

Unusual Fire and Explosion Hazards

(Reproduce locally) OSHA 174, Sept. 1985

Section V - Reactivity Data

Stability	Unstable		Conditions to Avoid
	Stable		

Incompatibility *(Materials to Avoid)*

Hazardous Decomposition or Byproducts

Hazardous Polymerization	May Occur		Conditions to Avoid
	Will Not Occur		

Section VI - Health Hazard Data

Route(s) of Entry:	Inhalation?	Skin?	Ingestion?

Health Hazards *(Acute and Chronic)*

Carcinogenicity:	NTP?	IARC Monographs?	OSHA Regulated?

Signs and Symptoms of Exposure

Medical Conditions
Generally Aggravated by Exposure

Emergency and First Aid Procedures

Section VII - Precautions for Safe Handling and Use

Steps to Be Taken in Case Material is Released or Spilled

Waste Disposal Method

Precautions to Be taken in Handling and Storing

Other Precautions

Section VIII - Control Measures

Respiratory Protection *(Specify Type)*

Ventilation	Local Exhaust	Special
	Mechanical *(General)*	Other

Protective Gloves	Eye Protection

Other Protective Clothing or Equipment

Work/Hygienic Practices

exposure limit (PEL) mandated by the Occupational Safety and Health Administration is the maximum concentration that an inspector is permitted to breathe during 8 h in 24 h.

The American Conference of Governmental Industrial Hygienists (ACGIH) is an advisory group that recommends the threshold limit value (TLV).[9] This is the concentration of a material that an individual can be exposed to without harm, 8 h per day, indefinitely. These concentrations are usually expressed as parts per million ($\mu L \cdot L^{-1}$) in the air, by weight or as milligrams per cubic meter of air. Exposure limits for dusts are reported in millions of particles per cubic meter. By way of comparison, ethyl alcohol, a typical health hazard, has a threshold limit value of 1000 $\mu L \cdot L^{-1}$ (about 1140 mg per 1 m^3 of breathing air).

In many cases, neither the Occupational Safety and Health Administration nor the American Conference of Governmental and Industrial Hygienists has assigned an exposure limit to certain materials. Industrial chemical substances are so numerous that many have not yet been evaluated. Under these circumstances, the manufacturer may recommend an exposure limit, based on special tests or a close similarity to substances that have already been rated. A material or product may be included in the Section II list because it is a fire hazard, not a health hazard, or because it is hazardous to skin or eyes. For these substances, breathing exposure limits may not have been established. When no actual or recommended limit exists, that fact must be noted on the material safety data sheet.

The Section II list need not be a complete listing of all the product's ingredients. It is a mandatory listing of hazardous ingredients of types and concentrations specified elsewhere.

Physical Properties

Section III lists relevant physical properties of the product. These are important because they can aggravate or sometimes diminish the effects of the hazards listed in Section II.

For instance, a volatile solvent (one having a low boiling point, high vapor pressure or high evaporation rate) is doubly hazardous because much of it will enter the breathing air during use. This may then require special ventilation or respiratory protection for inspectors. Any solvent with a boiling point lower than water at 100 °C (212 °F) can be considered a low boiling point solvent.

By comparison, a moderately toxic air pollutant may have such a high boiling point and low evaporation rate that very little of it can evaporate and enter the atmosphere. Such materials often have a boiling point over 200 °C (400 °F) or vapor pressure under 70 Pa (0.5 mm Hg).

The vapor density of a liquid is another important characteristic noted in Section III. Vapors with high density tend to sink, accumulate and spread. Inspectors standing in the testing area may be unaware that a hazardous concentration of vapor exists at floor level. Most solvent vapors are denser than air and tend to settle. Chlorinated solvent vapors are much denser than air and their tendency to settle is pronounced.

Flammability is a physical property that should be considered along with density and solubility characteristics. Liquids that are insoluble in water and less dense than water will float. If such liquids are also flammable, water cannot extinguish their fire. If ignited, such liquids can float on a water surface, spread or travel with the water host. More detailed fire and explosion hazards can be listed in Section IV of the material safety data sheet.

Fire and Explosion Hazards

Flash point is the accepted means for measuring the fire hazard of liquid test materials. Flash point is a characteristic only of liquids and is defined as the lowest temperature at which the liquid gives off gases sufficient to form an ignitible vapor at the liquid's surface.

As long as the bulk liquid is kept below this temperature, not enough of it will vaporize to make the surrounding atmosphere explosive. The safest oil vehicles have flash points over 90 °C (200 °F). The lower explosive limit (LEL) and upper explosive limit (UEL) indicate the concentrations of vapor in air that are ignitible and potentially explosive. Concentrations below the lower explosive limit are too lean to be fire hazards. Above the upper explosive limit, the concentrations are too rich to burn. A typical lower explosive limit of one percent is equivalent to 10 $mL \cdot L^{-1}$ (10 000 parts per million). A concentration this high is a serious health hazard as well as a fire hazard.

Section IV of the material safety data sheet must list recommended extinguishing media and special fire fighting procedures for hazardous or explosive materials.

Reactive Materials

Section V lists materials that may be dangerously reactive. The intent of this listing is to provide warnings about material compatibilities, as a guide for storage or use of the substances in mutual contact.

Health Hazards

Section VI specifies the types of exposure to guard against (route of entry) and the acute and chronic health conditions that can accompany overexposure to hazardous materials.

A number of organizations are involved in testing chemical substances for carcinogenicity and chief among these organizations are the National Toxicology Program (NTP)[14] and the International Agency for Research on Cancer (IARC), an affiliate of the World Health Organization. The Occupational Safety and Health Administration also publishes a list of carcinogens.[9,12] If any of these groups consider a product or its ingredients carcinogenic, that fact must be noted on the material safety data sheet.

A few chemical substances may aggravate existing medical conditions. Where this relationship is known, it must be mentioned on the material safety data sheet. Regional poison control centers may be contacted for advice in cases of exposures.

The signs or symptoms of overexposure are provided on the form as an aid to early treatment in the event of overexposure.

Spillage of a chemical substance may cause a hazardous condition for personnel in the vicinity. It may also merely be a nuisance, depending on the substance. In either case, techniques of dealing with a spill must be detailed in the material safety data sheet. Waste disposal is an important consideration for protection of the environment.

Handling and Storage Considerations

Earlier sections of the material safety data sheet point out safety hazards and discuss how to deal with them when they arise. Sections VII and VIII discuss preventive measures — the means of avoiding hazards in the first place.

Handling and storage precautions are generally based on simple good housekeeping. Flammable, combustible or pressurized products should not be stored near heat sources.

Chemical substances that are usually hard to ignite can burn vigorously if exposed to high temperatures such as those in a hot fire. Careless exposures should be avoided — breathing dusts, vapors or spray mists, leaving them on the skin or using the products around open flames are all basic but vitally important considerations.

Section VIII on control measures provides detailed instructions on avoiding hazards during the normal use of the specific chemical substance. This is the most difficult section of the material safety data sheet to prepare because the supplier usually is not familiar with the testing environment or the level of exposure at each testing site. The organization that buys the material and receives the material safety data sheet must add its own knowledge of in-house procedures to provide successful safety control measures.

Consider for example a slightly dusty product or a liquid that gives off some vapors. Such a material may be nearly hazard free in an open and well ventilated area, requiring minimum protection and no special ventilation. The same product used in a more confined and poorly ventilated space (a small testing booth, for example) may require approved respiratory protection or specially designed exhaust systems. Used inside a liquid storage tank or any enclosed compartment, the product's safe handling could mandate a full mask with an independent air supply. Entry safety programs must be used when entering confined spaces such as tanks.

The amount of the material being used is a critical safety parameter. Ventilation and personal protection requirements are vastly different when a product is used occasionally or sparingly rather than continually or in large volumes.

Liquid penetrant materials must by law be well described in a material safety data sheet form. However, the ultimate responsibility for a safe workplace rests with the organization that purchases the product and exposes its employees to it.

Purchasers may expect material safety data sheet compliance from their suppliers but it is the purchaser's responsibility to use the information properly, to fully understand and alleviate the hazards involved. This is mandated under the Hazard Awareness Communications Program administered by the United States Department of Labor.

Precautions with Ultraviolet Radiation Sources[15]

Ultraviolet Radiation Source

The ultraviolet radiation used in fluorescent liquid penetrant testing is obtained by filtering hard ultraviolet radiation out of radiation produced by a high intensity discharge (HID) lamp.

Ultraviolet radiation sources are small electrical components that heat up during use and emit ultraviolet radiation. Accordingly, these devices present a number of potential health and safety hazards. They can produce a severe electrical shock. Many models become extremely hot and can cause serious heat and radiation burns. In the presence of flammable vapors, heat from such an ultraviolet source can be sufficient for ignition of the gas. High intensity discharge (HID) lamps operate at pressures above atmospheric pressure and with impact can produce high velocity heated glass shards.

Despite these electrical and mechanical factors, the most serious safety concern is the more subtle and less understood hazard of ultraviolet radiation. Ultraviolet radiation has long been known to produce physical, chemical and physiological effects, so some discussion of these effects is in order. Ultraviolet radiation can produce a variety of physiological effects, depending strongly on wavelength.

Of interest to hygiene directors and safety engineers are the effects of ultraviolet radiation on the operator. It has been rather conclusively demonstrated that ultraviolet radiation in the wavelength range normally used for test purposes can cause no permanent damage to persons exposed, as long as recommended filters are used on the ultraviolet lamps. The 365 nm near ultraviolet (ultraviolet-A) wavelength is well out of the range where physiological effects take place. Such effects as damage to the eye, sunburn and destruction of tissue do not come into evidence until wavelengths are reduced to the neighborhood of 320 nm. Here they become definitely injurious.

Proper operation of the ultraviolet lamp used in fluorescent liquid penetrant testing is essential to good testing and to operator comfort and efficiency. If an ultraviolet lamp becomes damaged, radiation with ultraviolet wavelengths shorter than 310 nm may escape its protective enclosures or filters. Operator exposure to this short wavelength radiation may cause a condition known as photokeratitis followed by conjunctivitis, similar to snowblindness. Symptoms may progress from a feeling of sand in the eyes, allergy to light, tear formation and temporary blindness. These symptoms usually begin 6 to 12 h after exposure and last for 6 to 24 h, with all symptoms disappearing in 48 h. There is no known cumulative effect. It is essential that the ultraviolet lamp not be used unless the proper filter is in place and is undamaged.

Characteristics of Ultraviolet Energy

Ultraviolet radiation is an invisible radiant energy produced by natural and artificial sources and is often accompanied by visible light and infrared radiation. The sun is the primary source of ultraviolet energy and its effects are well known. In industry, artificial sources produce ultraviolet radiation for germicidal applications, carbon arcs, photolithography, food irradiation, vitamin D synthesis, curing certain plastics or paints, welding and cutting torches, as well as fluorescent magnetic particle testing and liquid penetrant testing.

Ultraviolet radiation occupies the portion of the electromagnetic spectrum between X-rays and visible light. The International Committee on Illumination divides ultraviolet radiation into the three following ranges.

Wavelengths from 320 to 400 nm (the edge of the visible spectrum) are referred to as near ultraviolet (ultraviolet-A) or long wave ultraviolet. (The paradoxical term *black light* has become disfavored as a term for ultraviolet radiation because the word *light* denotes radiation that is visible.) The ultraviolet-A wavelengths are those used for fluorescent liquid penetrant tests, display illumination and for curing polymers sensitive to ultraviolet radiation.

The wavelengths from 280 to 320 nm are known as ultraviolet-B, midwave or erythemal ultraviolet, so named for its reddening effect on the skin. The ultraviolet-B wavelengths can cause sunburn and snow blindness. Such sources are not to be used for liquid penetrant applications.

Wavelengths from 100 to 280 nm are known as ultraviolet-C, actinic, germicidal or short wave ultraviolet. The ultraviolet-C wavelengths are used for germicidal purposes, sterilization, in bacteriology, vitamin D production and for erasing information in ultraviolet-erasable, programmable memory and programmable logic semiconductor chips. The ultraviolet-C radiation can cause severe burns and eye damage and, in the presence of oxygen, such short wavelengths can also generate ozone, toxic if inhaled.

Do not use shorter wavelength ultraviolet radiation sources for nondestructive testing applications. The ultraviolet-B and ultraviolet-C ultraviolet radiation they emit is very hazardous and causes severe skin and eye damage after very short exposure.

Measuring Ultraviolet Energy

The segmentation of ultraviolet wavelengths into ultraviolet-A, ultraviolet-B and ultraviolet-C is analogous to the segmentation of visible light into the wavelengths that produce the colors. Blue light, for example, generally has wavelengths between 455 to

492 nm. Yellow light is between 577 and 597 nm.

This analogy might also be helpful to those first learning to measure ultraviolet radiation. A certain intensity of yellow light will produce a certain illuminance on a surface and this illuminance is commonly measured in lux or footcandle. In the same way, a certain amount of ultraviolet radiation will produce an irradiance on a test object surface. Irradiance is a time dependent measure of the amount of energy falling on a prescribed surface area. Because ultraviolet radiation is invisible (not the same wavelengths as visible light), photometric measurement units such as the footcandle, lumen and lux do not apply.

Ultraviolet radiation is commonly measured in microwatt per square centimeter ($\mu W \cdot cm^{-2}$), the power (microwatt) falling on one square centimeter (0.155 in.^{2}) of surface area. At higher irradiance levels, the watt per square meter ($W \cdot m^{-2}$) is used ($100\ \mu W \cdot cm^{-2} = 1\ W \cdot m^{-2}$). Visible light is sometimes expressed in these units but ultraviolet radiation should never be expressed in footcandle, lux or any other photometric unit.

Erythemal Ultraviolet Radiation Hazards

Erythemal ultraviolet or ultraviolet-B radiation typically ranges in wavelength from 280 to 320 nm. It has been shown that ultraviolet-B radiation can damage human tissue. The ultraviolet sources used for liquid penetrant tests are filtered to minimize the output of this midrange ultraviolet but not all such radiation is kept out of the testing environment.

There has been research into the amount of 315 nm radiation transmitted by a 125 W bulb. One manufacturer's source produces 2.9 percent as much radiation in the 315 range as it does in the 365 nm range. Another manufacturer's 100 W lamp, used with a standard filter, produces about 1.5 percent as much 315 nm radiation as it does 365 nm radiation. The same lamp with a different filter produces five percent hazardous ultraviolet-B wavelengths.

Research contracted by the United States Food and Drug Administration included studies of three BLB tubes.[16] The data indicate that the ultraviolet-B content of the sample bulbs ranged from 0.73 percent to 6.2 percent of the radiation (320 to 400 nm) content. The ultraviolet-A content of BLB tubes is much lower than that of 100 W bulbs.

Near Ultraviolet Radiation Exposure Limits

Ultraviolet radiation with wavelengths of 320 to 400 nm is commonly called *near ultraviolet,* or *ultraviolet-A*. One study[17] indicates that, at these wavelengths, the indirect exposure of an inspector's face and eyes at a viewing distance of 750 mm (30 in.) is no greater than $6.5\ \mu W \cdot cm^{-2}$. This is for a standard lamp fixture, a 100 W bulb and an ultraviolet filter at 280 mm (11 in.) from a pitted steel sample plate.

The exposure value represents about 1/150 of the maximum continuous exposure level recommended by the American Conference of Governmental and Industrial Hygienists (ACGIH) and the National Institute for Occupational Safety and Health (NIOSH). Both NIOSH (in Criterion for a Recommended Standard Occupational Exposure to Ultraviolet Radiation)[18] and the American Conference of Governmental and Industrial Hygienists have recommended the following limits for incoherent radiation (not including lasers).

1. For the ultraviolet spectral region of 315 to 400 nm, total irradiance incident on unprotected skin or eyes shall not exceed $1.0\ mW \cdot cm^{-2}$ for periods greater than 1000 s.
2. For exposure times of 1000 s (about 17 min) or less, the total radiant energy density shall not exceed $1000\ mWs \cdot cm^{-2}$ or $1 \times 10^6\ \mu Ws \cdot cm^{-2}$ ($1.0\ J \cdot cm^{-2}$). For the purposes of continuous tests, the total irradiance energy should not exceed $1000\ mW \cdot cm^{-2}$.

It has been noted that, over decades of application, there is no evidence of skin discoloration resulting from fluorescent nondestructive testing procedures.[19] In addition, the International Labour Office in Geneva, Switzerland has reported that no cases of industrially induced skin cancer have been attributable to ultraviolet radiation from a lamp. It is believed that indirect exposure to ultraviolet-A radiation, either dermally or ocularly, does not present a threat to the health and safety of liquid penetrant testing personnel.

The major safety precautions for ultraviolet radiation sources then are as follows.

1. Eliminate the direct irradiation of the unprotected hand when manipulating small test objects. If an inspector's hands are subject to $5000\ \mu W \cdot cm^{-2}$, then the recommended daily ultraviolet-A exposure can be exceeded in 200 s.
2. Eliminate accidental direct viewing of, and dermal exposure to, lamps used in

other testing stations, lamps permanently mounted in the same booth and those being used by other inspectors in the same area.

Lamps using a 100 W bulb have an increased potential for unintentional hand irradiation because of the larger spot area.

Unintentional viewing can occur easily as inspectors move around within the testing area. Varying or multiple source heights increase the possibility of direct exposure to ultraviolet radiation. The use of suitable gloves, protective ultraviolet absorbing eyewear and opaque or closely woven clothing to cover potentially exposed dermal areas are and should be recommended to personnel operating in such situations.

There is now good evidence indicating that near ultraviolet radiation can be hazardous if allowed to fall on the eyes or skin without limit. These effects vary in severity, depending on the extent of the exposure over time. In the past, ultraviolet radiation damage was popularly associated with irradiation of the body at wavelengths shorter than 320 nm. Although the erythemological efficiency may be 200 to 2000 times higher at the shorter wavelengths, animal studies show that damaging effects also can occur from long exposures at ultraviolet-A wavelengths.

The following text details a study of the irradiances experienced in a typical work environment by the unprotected face and hands. Measurements were made with a simple radiometer and radiometers equipped with photodetectors (**a** vacuum photodiode or a broadband silicon detector). At a distance of 1 m (3 ft), the photodiode detected 1500 $\mu W \cdot cm^{-2}$ from one ultraviolet source and 380 $\mu W \cdot cm^{-2}$ from a smaller model. The silicon detector registered 1200 and 270 $\mu W \cdot cm^{-2}$ from the same two sources.

For quantitative indirect exposure of inspectors, several tests were performed using the low irradiance source tested above. The ultraviolet lamp was placed at varying distances from and varying angles to a pitted steel plate. As shown in Table 2, decreasing distance between the object and the source increases exposure to the worker. Table 3 shows the irradiance for three different test objects exposed at 45 degree angles and 280 mm (11 in.) distances.

The study also shows that the angle between the object and the ultraviolet source affects the exposure to the inspector. The closer the source is to perpendicular, the greater the personnel exposure (see Table 4).

Table 2. Reflected radiation from ultraviolet source at 45 degrees from pitted steel plate.[17]

Reflected Ultraviolet Radiation ($\mu W \cdot cm^{-2}$)	Distance between Source and Plate mm (in.)
4.3	180 (7)
3.8	280 (11)
3.2	460 (18)

Table 3. Reflected radiation from ultraviolet source at 45 degrees and 280 mm (11 in.) from plates of various materials.[17]

Plate Materials	Reflected Ultraviolet Radiation ($\mu W \cdot cm^{-2}$)
Pitted steel	3.6 to 3.8
Galvanized steel	3.8 to 4.0
Aluminum	3.0

Table 4. Reflected radiation from ultraviolet source 280 mm (11 in.) from a steel plate at varying angles.[17]

Source-to-Object Angle (angular degrees)	Reflected Ultraviolet Radiation ($\mu W \cdot cm^{-2}$)
5	1.2
25	1.7
30	2.1
45	2.6
60	3.2
80	3.6

Ocular Fluorescence from Long Wavelength Ultraviolet Radiation

As indicated above, long wavelength ultraviolet radiation is a natural component of the environment — Earth's atmosphere does not completely filter out the ultraviolet radiation emitted by the sun. Regardless of the source, natural or artificial, ultraviolet radiation can cause human eye media to fluoresce. This in turn produces uncomfortable sensations, irritation or pressure, especially in low visible light levels. Ocular fluorescence is temporary but can be eliminated entirely by using ultraviolet absorbing eyewear. In some cases, such eyewear can actually increase the contrast (reduce ambient background levels) and thereby improve the sensitivity of fluorescent liquid penetrant tests because the ocular fluorescence will reduce the vision acuity of the inspector.

Long wavelength ultraviolet radiation is considered relatively harmless when compared to other parts of the ultraviolet spectrum. However, in a few cases, permanent histological changes have been reported. Note also that abnormally high sensitivities can be produced by certain drugs and chemicals. People exposed to these sensitizing agents or individuals who are particularly photosensitive should expect adverse reactions to long wavelength ultraviolet radiation. However, it is unusual for the symptoms of photosensitization to be elicited solely by the limited emission spectrum of the lamps used in fluorescent liquid penetrant tests.

Summary of Ultraviolet Radiation Safety

With appropriate precautions, fluorescent penetrant testing can be performed in a safe and effective manner.

The general rules of ultraviolet safety are designed to protect the people who may be exposed to such radiation, directly or accidentally.

The first level of protection includes posting areas where ultraviolet radiation exists in excess of safe limits. Legal signage must display standard caution — ultraviolet radiation warnings and may contain additional health protection information. The color and size of such signs should meet Federal and state requirements (see 29 CFR 1910.115).[7]

Control of the environment is another critical safety measure.

Equipment that produces ultraviolet radiation should be enclosed by partitions, screens or walls painted with nonreflective paint. Paint containing metallic particles should not be used. In addition, this equipment must be labeled to inform individuals of its potential health and safety hazards.

Contact the Occupational Safety and Health Administration (OSHA), the American National Standards Institute (ANSI), the American Conference of Governmental Industrial Hygienists (ACGIH) and the National Institute for Occupational Safety and Health (NIOSH) before performing any fluorescent liquid penetrant test procedure.

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3

CHAPTER

Characteristics of Liquid Penetrant and Processing Materials

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PART 1. Liquid Properties of Liquid Penetrant

Penetrants and their ancillaries must have physical properties that fall within fairly narrow ranges. None are difficult to attain but properties cannot stray very far from optimum. The coverage of these topics is essentially practical. Some physical chemistry is included, particularly relating to capillarity, light absorption and scattering but not enough to require that the reader be a professional physical chemist. Discussions are limited to descriptions of usable processes and how they work. No effort is made to discuss unproved processes or theories.

For readers who have interests in other theories behind the mechanisms of penetration, surface wetting, adsorption and development and other fundamental physical chemistries of liquid penetrant testing, additional readings[1-7] are suggested.

Penetration

The very name *penetrant* suggests that the ability to penetrate into voids is the major feature of a penetrant. This is no doubt true but it is not a critical feature. Very nearly any liquid will wet a solid surface and penetrate into voids. In fact, it is not easy to find a liquid that will not penetrate. If it wets, it will penetrate; if not, it will not.

Wetting of smooth, chemically clean surfaces has been studied extensively with relationships worked out between surface tension, interfacial tension, wetting contact angle, energy of adhesion. None are very appropriate because many of these quantities are not measurable on the kinds of surfaces that are tested with liquid penetrant. Even a cleaned surface can pick up a molecular monolayer of oil or oxide in a very short time. The slightest taint of oil on a surface can change a surface and cause a penetrant film to become less wet and to pull up into droplets. As a practical matter, this is not too serious. Reapplication of penetrant will usually dissolve this film and allow testing to proceed.

Surface tension can be defined as the force needed to expand (or pull apart) the surface of a liquid. It results from the attraction of all the molecules within the liquid for each other. At the surface, with no more liquid outside, the net force is toward the liquid's interior, and the surface acts like a skin. It acts to minimize the surface area of the liquid and it requires effort (the surface tension) to stretch this skin.

Contact angle is the measured angle that a drop of liquid makes with a solid surface. If contact angle θ is zero, $\cos \theta = 1$ and the liquid will wet and spread. If the contact angle is 90 degrees or more, $\cos \theta = 0$ and the liquid will not wet but will remain as a rounded drop. Intermediate contact angles indicate intermediate degrees of wetting. Contact angles can be measured on special sample surfaces with special equipment.

Energy of adhesion is a measure of the strength of attraction of a liquid to a solid surface and is of more theoretical than practical value.

Penetration of a discontinuity is primarily a capillary effect. The forces involved are those associated with capillary action and are called *capillary pressure* or excess surface pressure. This pressure is given by Eq. 1:

$$P = \frac{2\gamma}{R} \tag{1}$$

where γ is the surface tension of the liquid and R is the radius of curvature of the liquid surface. The effect of this capillary pressure can best be shown by examining the two systems depicted in Figs. 1a and 1b.

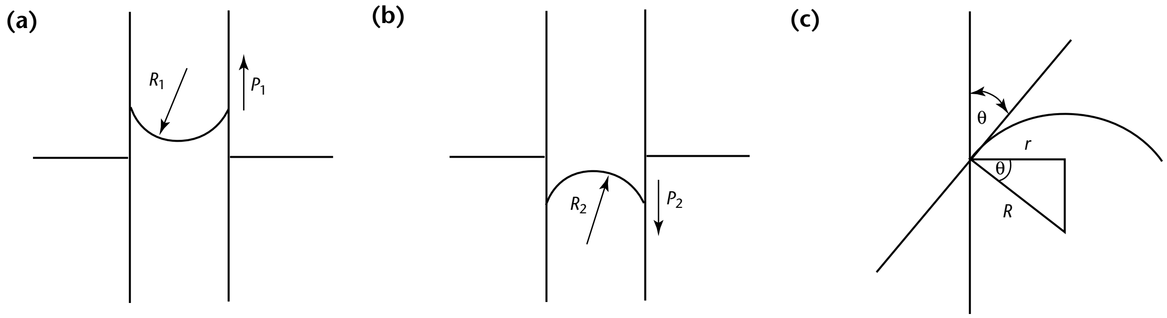
In Fig. 1a the liquid wets the capillary and the pressure P_1 is up. In Fig. 1b the liquid does not wet the capillary and the pressure P_2 is down. The ability to wet or not wet determines in which direction the surface will *curve,* whereas the degree of *wetting* determines to what extent the surface will curve. Therefore, the first requirement for penetration is its ability to wet the surface of the discontinuity.

The dimensions of the capillary are also important and the radius of the capillary can be related to the capillary pressure by examining Fig. 1c. It is found that $R = r/\cos \theta$, i.e., $\cos \theta = r/R$, where r is the radius of the tube and θ is the angle of contact of the liquid and the tube.

Equation 1 becomes:

$$P = \frac{2\gamma \cos \theta}{r} \tag{2}$$

FIGURE 1. Liquid in capillary: (a) wet capillary, pressure up; (b) dry capillary, pressure down; (c) relationship of capillary radius to capillary pressure.



Legend

P = pressure
R = radius of liquid surface curvature
r = tube radius
θ = angle of contact between liquid and tube

Using this equation and assuming θ = 0 degrees, the capillary pressure for tubes of various radii with liquids that have surface tensions of 0.025 and 0.035 N·m^{-1} (1.7×10^{-3} and 2.4×10^{-3} lb$_f$·in.$^{-1}$) can be calculated. The latter two values are taken because they span the range of most penetrants. Table 1 presents these data.

The capillary pressure increases directly with the surface tension of a penetrant and inversely with the radius of the capillary. But unless θ is less than 90 degrees ($\cos\theta > 0$), P will be zero and there will be no wetting and no penetration.

The rate at which a liquid will fill a capillary is determined primarily by its viscosity. The coefficients of viscosity η are given by:

$$\eta = \frac{\pi r^4 T P}{8VL} \tag{3}$$

where T is the time for the volume V of liquid to flow through a tube of radius r and length L under the influence of a pressure P.

Solving for T, Eq. 3 becomes:

$$T = \frac{8VL\eta}{\pi r^4 P} \tag{4}$$

and because the tube is just being filled:

$$V = \pi r^2 L \tag{5}$$

then:

$$T = \frac{8L^2\eta}{r^2 P} \tag{6}$$

Because the pressure P is given by Eq. 2, then:

$$T = \frac{4L^2\eta}{r\gamma\cos\theta} \tag{7}$$

Because L for most open voids is usually very small, T is usually very small too (a few seconds at most), unless the viscosity η is really huge. High viscosities lead to too much dragout and wastage of penetrant, besides slow penetration.

Penetrants generally do not fill a void from the top down, compressing the air within it. It is often possible to observe bubbles leaving a submerged crack, as the

TABLE 1. Capillary pressure *P* versus surface tension.

	Capillary Radius				
	1.0 mm (4×10^{-2} in.)	0.1 mm (4×10^{-3} in.)	0.01 mm (4×10^{-4} in.)	1.0 µm (4×10^{-5} in.)	0.5 µm (2×10^{-5} in.)
Surface Tension	Capillary Pressure *P*				
N·m^{-1} (lb$_f$·in.$^{-1}$)	Pa (lb$_f$·in.$^{-2}$)	Pa (lb$_f$·in.$^{-2}$)	Pa (lb$_f$·in.$^{-2}$)	Pa (lb$_f$·in.$^{-2}$)	Pa (lb$_f$·in.$^{-2}$)
0.025 (1.7×10^{-3})	50 (7)	500 (70)	5000 (700)	50 000 (7000)	100 000 (200 000)
0.035 (2.4×10^{-3})	70 (10)	700 (100)	7000 (1000)	70 000 (10 000)	140 000 (20 000)

liquid penetrant fills it. Capillary pressure is highest where the crack is narrowest; this is where the liquid penetrant enters. The bubbles exit at the widest part.

Volatility of Liquid Penetrants

Low volatility is a practical requirement of liquid penetrant; it plays only a small part in sensitivity. Low volatility has four advantages: (1) low economic loss because of evaporation, (2) low fire hazard because few flammable vapors form above the liquid, (3) low toxicity because of low hazardous vapor concentrations in the test area and (4) uniform removal and fluorescent properties. The liquid penetrant film during the liquid penetrant dwell time changes very little in composition, so that removal and fluorescent properties do not vary over the surface, where penetrant may be present in both thick (slow drying) and thin (fast drying) layers.

Volatility does not have to be as close to zero as possible. A good level is that which provides a flash point of slightly over 93.3 °C (200 °F) in a closed cup test. This puts it in the OSHA Class IIIB fire hazard range[8] yet does not force the liquid penetrant to be uneconomically viscous. Within most series of chemical solvents, viscosity increases linearly as the flash point rises. As a result, insisting on higher flash points than optimum will merely drive viscosity higher, along with its increase in dragout losses.

Viscosity

Liquid penetrants drain off surfaces at a rate that depends on their viscosities and to an extent that depends on drainage time and surface roughness. Studies in the laboratory with *nonvolatile* liquids draining from calibrated, vertical surfaces led to Eq. 8:

$$\textbf{(8)} \qquad D = S + 7.86 \times 10^{-3} \sqrt{\frac{\eta}{T}}$$

where D is dragout (volume of liquid penetrant in liter per 24.5 m^2 of surface (gallon per 1000 ft^2 of surface), S is surface volume (same units as for dragout), η is kinematic viscosity (in stokes [where 1 St = 0.0001 $m^2 \cdot s^{-1}$]) and T is time (minute).

Surface volume S expresses the amount of penetrant left behind after an unlimited drain time and is a measure of surface roughness. It is small for a mirror smooth surface, around 0.004 $L \cdot m^{-2}$ = 4×10^{-6} $m^3 \cdot m^{-2}$ (1×10^{-4} $gal \cdot ft^{-2}$ = 0.1 gal per 1000 ft^2), and much larger on rough surfaces. Aside from the constant S, dragout is proportional to the square root of the liquid penetrant's viscosity and inversely to the square root of the drain time. When penetrants are volatile, this relationship breaks down, as evaporation losses add to drainage losses and increase the measured value of D.

Equation 8 is a basis for comparing the economy of usage of low volatility liquid penetrants. On smooth surfaces, S is small and consumption of a liquid penetrant will vary as the square root of its viscosity. For example, if liquid penetrant X has a viscosity of 4 $mm^2 \cdot s^{-1} = 4 \times 10^{-6}$ $m^2 \cdot s^{-1}$ (0.04 St) and liquid penetrant Y has a viscosity of 9 $mm^2 \cdot s^{-1} = 9 \times 10^{-6}$ $m^2 \cdot s^{-1}$ (0.09 St) then on the same smooth surface and at the same drain time, 50 percent more of liquid penetrant Y will be *dragged out* or used: $\sqrt{(9/4)} = 3/2$. If drain times were adjusted to equalize consumption, liquid penetrant Y would have to drain 50 percent longer than liquid penetrant X.

PART 2. Liquid Penetrant Removal

Solvent Rinse

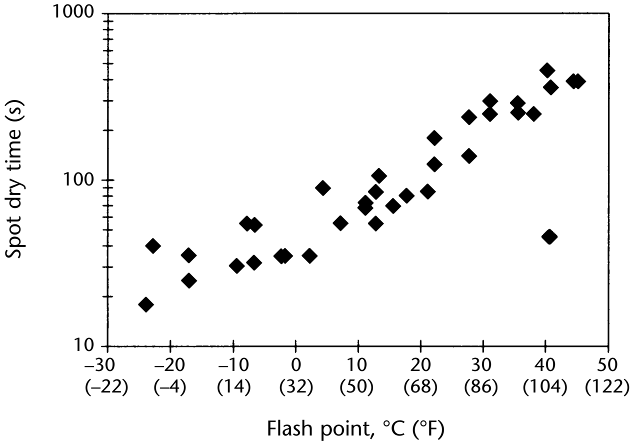
Solvent rinse or vapor degreasing have been tried in a few cases where it was very difficult to clean surfaces before applying developer and inspecting. They quickly and thoroughly remove liquid penetrant from all but the deepest of voids while leaving surfaces attractively clean. They are not recommended for liquid penetrant removal where sensitivity is important.

Solvent Wipeoff

Removing excess liquid penetrant by wiping the surface with a solvent dampened rag is the technique normally used with aerosol liquid penetrants and developers. It requires skill on the part of the inspector but has worked well for over 40 years.

The solvent must dry quickly and thoroughly so as not to dilute liquid penetrant entrapments and dim their fluorescence. Desirable properties are low toxicity, solvency for liquid penetrants and some compromise between maximum drying speed and minimum fire hazard. This is difficult because solvent dry times increase rapidly at higher flash points. Figure 2 plots data for a broad range of volatile chemical solvents. Flash point is a familiar indicator of fire hazard with limits proposed by the Occupational Safety and Health Administration (OSHA) as well as the Department of Transportation (DOT). Spot dry time is an old fashioned, rough-and-ready test for speed of drying. A droplet of solvent is placed on a filter paper circle and its disappearance is timed to the minute and second. The data are scattered but it is obvious that dry time rises exponentially with flash point.

FIGURE 2. Spot dry time versus flash point of volatile solvents.



Ordinary varnish makers' and painters' (VM&P) naphtha flashes at around 12.8 °C (55 °F) and dries in about 85 s. A *safety* solvent flashing at 37.8 °C (100 °F) will take about 5 min to dry and one that flashes at 48.9 °C (120 °F) will take nearly 10 min. Low volatility (high flash point) solvents can be used without slowing down the test time if they are applied with dampened rags and are promptly and *completely* removed with a clean, dry rag so as not to dilute indications and stain the developer films. Drying time is not important if there is nothing left to be dried.

Water Wash

The earliest commercial fluorescent liquid penetrants, dating back to the 1940s, were water washable. That is, they contained chemical emulsifying agents that forced the liquid penetrant to disperse spontaneously into a spray of rinse water or into the water in an immersion wash tank.

Water washable liquid penetrants are still widely used because of their simplicity: simply rinse with water and dry. Early water washable liquid penetrants contained sulfur bearing emulsifying agents that washed more quickly in hotter water. Modern water washable liquid penetrants, formulated to avoid the presence of sulfur, use agents that act in a slower and more controllable manner. It is a lot harder to overwash them.

However, if the test surface is hard to rinse clean, the inspector's tendency is to use a long and vigorous wash that can still remove liquid penetrant from entrapments and dim subsequent indications. Solving this drawback led to the development of postemulsifiable liquid penetrants.

Lipophilic Emulsifier

The lipophilic liquid penetrant system uses two materials, a liquid penetrant and a separate emulsifier. The liquid penetrant is not emulsifiable and cannot be easily removed by rinsing with water. The emulsifier is applied at the end of the desired liquid penetrant dwell time by dipping a part into the emulsifier reservoir. The lipophilic emulsifier is a viscous liquid that slides off the test surface and drains back into the reservoir, taking much of the surface excess of liquid penetrant with it. The emulsifier remaining on the part then slowly diffuses into the surface liquid penetrant layer, making it emulsifiable and removable with water. If the emulsifier dwell is timed correctly, it does not diffuse much into liquid penetrant entrapments, which remain inert to water rinsing.

The improved sensitivity allowed by this system made it the standard for high sensitivity testing for many years. Its disadvantages have become more obvious over the last few years and it is rapidly becoming obsolete.

The first disadvantage is the high rate of consumption of the emulsifier. It has to be viscous or it removes liquid penetrant too rapidly to control. But it drains from surfaces very slowly, causing a high dragout loss. This effect is aggravated on complex geometry parts, resulting in nonuniform removal. Lipophilic emulsifiers have a large liquid penetrant tolerance and rarely need to be discarded because of excessive liquid penetrant contamination. However, the activity or diffusion rate of the emulsifier decreases with increasing amounts of liquid penetrant contamination. Their loss through dragout is so high that users must constantly replenish the reservoir with fresh emulsifier that holds the contamination at a low level.

The excess emulsifier that does not drain off ends up, of course, in the rinse water where it becomes a heavy dose of water pollution — a second major disadvantage.

A third disadvantage became apparent when the hydrophilic emulsifier removal technique was being developed in the laboratory. At the end of the lipophilic emulsifier dwell time, emulsifier was actually beginning to diffuse into liquid penetrant filled cracks. There was not enough to make the entrapments emulsify but enough to contaminate them and dim indication fluorescence.

Hydrophilic Emulsifier

Hydrophilic emulsifiers are basically dispersant/detergent concentrates that are dissolved into water. They remove excess surface liquid penetrant by (1) preferentially wetting the test surface and literally peeling the liquid penetrant away and (2) by dispersing or dissolving droplets so that they do not redeposit on the surface. This action occurs during final rinse as well as during immersion, whether assisted by gentle agitation or not.

Hydrophilic emulsifiers yield brighter indications because they do not dissolve into and contaminate entrapped liquid penetrant. Their propensity for removal of entrapped liquid penetrant is minimal. For this reason, the hydrophilic emulsifier liquid penetrant processing technique is most often recommended for critical hardware, e.g., rotating turbine engines.

Dragout is low, as hydrophilic emulsifier solutions are nearly as thin as water. They yield brighter indications, because they do not dissolve into liquid penetrants and contaminate them. Because of their high water content, however, they cannot tolerate as much liquid penetrant contamination as the lipophilic emulsifiers. A hydrophilic emulsifier solution's tolerance for liquid penetrant contamination depends on its individual formula and also on the contaminating liquid penetrant's formula. Tolerance for a liquid penetrant with a high percentage of petroleum distillate is lower than for one with less petroleum oil or distillate. A generalization would be that a 10 percent solution will tolerate two percent liquid penetrant contamination before becoming spent; a 20 percent solution, four percent contamination; and a 30 percent solution, six percent. A tank of spent hydrophilic emulsifier solution must be emptied and recharged.

Hydrophilic emulsifiers can be applied by spray or immersion and, in rare instances, as foam. Maximum concentration for spray application is five percent and usually is applied in a much lower concentration, one or two percent. Metering pumps are available that can meter such amounts directly into a water stream. Sprayed hydrophilic emulsifiers are not collected for reuse.

For dip applications, concentrations range from five percent up to 33 percent. Specific concentrations are often mandated by specifications but also can be worked out by experiment for each application.

The hydrophilic emulsifier is a combination of solvents and dispersants (wetting or surfactant agents). The solvents remove surface liquid penetrant by dissolving action and the surface active or dispersant agent by emulsifying action, suspending and preventing the redeposit of removed surface liquid penetrants. Hydrophilic emulsifier formulations differ between manufacturers. Some are more solvent action dependent; others, more surfactant dependent.

Typically, specifications for liquid penetrant materials require an emulsifier (hydrophilic or lipophilic) and a liquid penetrant from the same manufacturer to be used together according to specific processing parameters. Otherwise, a liquid penetrant test may become desensitized.

Water pollution can be minimized by prerinsing the test piece with a plain water spray before applying the hydrophilic emulsifier. This removes the loose surface excess of liquid penetrant by mechanically emulsifying it. If the liquid penetrant is completely water repellent, entrapments within voids are not touched. If the prerinse drainage is contained, an oily liquid penetrant layer quickly migrates to the top of the of fairly clean rinse water, because the emulsion is not chemically stabilized. Further, the final removal step generates less water pollution because up to 90 percent of the oily liquid penetrant can be separated from the prerinse drainage before it becomes waste.

A prerinse decreases the necessary exposure time to the emulsifier solution very slightly. However, the prerinse greatly extends the life of solutions used in dip applications by eliminating about 90 percent of the contamination.

Experimentation has shown that the final rinseoff of the emulsifier solution can be overdone. Up to 2 min spraying on a nickel chrome test panel can noticeably dim indications. The best overall rule for liquid penetrant removal is to do just enough to clean excess fluorescence off the surface. Doing the job more thoroughly will not help but can surely hurt.

Part 3. Color of Liquid Penetrants

Movie. Visible red dye liquid penetrant bleeds out.

Nonfluorescent Liquid Penetrants

Indications from nonfluorescent (visible) liquid penetrants cannot be seen unless they contrast strongly with the test surface. The strongest contrast is dark on white, typically dark red indications on a snow white background. Thus, visible liquid penetrants must be used with a white developer and must be deeply colored.

The relative sensitivity of visible liquid penetrants can be displayed with nickel-chrome test panels, chrome plated panels with cracks having depths equal to the thickness of the plating. A panel with nickel-chrome plate of thickness of 50 µm (2.0×10^{-3} in.) contains cracks that have a volume of about 2.5×10^{-3} mm^3 per 1 mm of length (3.9×10^{-6} in.^{3} per 1 in. of length). Only this much liquid penetrant can be crammed into them. With a good liquid penetrant and developer, the indications are fairly dark, continuous and easy to see. The cracks in the 30 µm (1.2×10^{-3} in.) panels have a volume of only 9×10^{-4} mm^3 per 1 mm (1.4×10^{-6} in.^{3} per 1 in.), about a third as much. Indications are spotty, a pale pink and require a careful procedure, good lighting and a sharp eyed inspector to find. Cracks in nickel-chrome test panels with 20 and 10 µm (8×10^{-7} and 4×10^{-7} in.) deep cracks are generally impossible to find with visible liquid penetrants. Crack volumes are 4×10^{-4} mm^3 and 1×10^{-4} mm^3 per 1 mm of length (6.2 and 1.6 in.^{3} per 1 in. of length).

Deeply colored visible liquid penetrants absorb light even in microscopically thin layers. When a film of colored liquid (or visible liquid penetrant) is exposed to a beam of light (of intensity I_0), some of the light I_T is transmitted through the film and some light I_A is absorbed within it.

$$I_0 = I_T + I_A \tag{9}$$

The small amount of light that is reflected from the surface is ignored.

The amount of light absorbed depends on the light absorption coefficient e of the dye in the liquid penetrant, the concentration c of the dye and the thickness t of the liquid penetrant film. The Beer-Lambert law expresses this relationship as:

$$I_T = I_0 \times 10^{-ect} \tag{10}$$

Combining Eqs. 9 and 10, the amount of light absorbed by a film of liquid penetrant is:

$$I_A = I_0 \left(1 - 10^{-ect}\right) \tag{11}$$

where t is thickness (millimeter), the product (ec) is a constant for a particular liquid penetrant and I_A is a fraction of I_0. The relationship is presented graphically in Fig. 3.

A good visible liquid penetrant is opaque in films thicker than 0.1 mm, nearly opaque at 0.01 mm but falling off to nearly transparent (and invisible) in thinner layers. Smaller cracks yield smaller seepages that approach invisibility at the smallest sizes.

Finding the tiniest discontinuities requires sensitive fluorescent liquid penetrants.

Fluorescent Liquid Penetrants

Before a fluorescent liquid penetrant can fluoresce, it must absorb near ultraviolet radiation (UV-A). The Beer-Lambert law (Eq. 11) applies, just as with nonfluorescent liquid penetrant indications. The dye in fluorescent liquid penetrants converts the absorbed near ultraviolet radiation into visible light. The resulting fluorescent brightness F is given by Eq. 12:

$$F = Q I_A \tag{12}$$

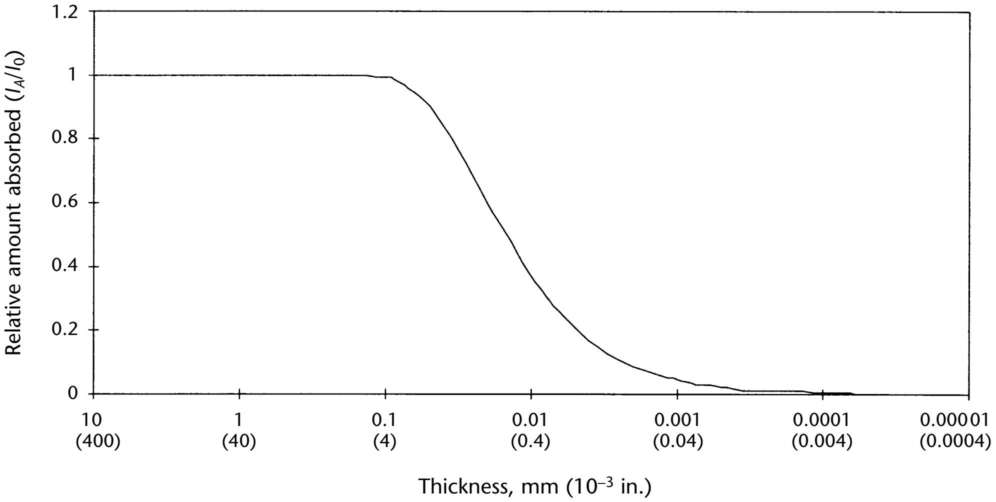
where Q is the quantum efficiency of the dye. Q can be defined as the ratio of photons emitted as fluorescence to the photons of near ultraviolet radiation absorbed. Values of Q for liquid penetrants seem to be below 0.1.

Substituting I_A from Eq. 11 gives:

$$F = Q I_0 \left(1 - 10^{-ect}\right) \tag{13}$$

With the variables Q, e and c constant for a given liquid penetrant, the brightness curve is the same shape as in Fig. 3 but

FIGURE 3. Typical light absorption characteristics of liquid penetrant films.



extends into much thinner layers to the right.

Fluorescent liquid penetrants function in very thin layers for three reasons. (1) The absorption coefficient *e* is about three times larger for fluorescent dyes than for visible ones. (2) Visual contrast is light-on-dark, much more favorable than the dark-on-light contrast of visible liquid penetrant. (3) Most importantly, the light scattering that takes place between developers and fluorescent liquid penetrants increases indication brightness by nearly an order of magnitude. The effect of this light scattering is covered below.

PART 4. Action of Developers

Developer Options

No Developer

Liquid penetrant seeps into voids without help. After excess surface liquid penetrant is removed, it can seep back out onto the surface.

Dry Developers

Fluffy dry developers contain particles ranging from 0.1 µm (4×10^{-6} in.) to about 15 µm (6×10^{-4} in.) in diameter and provide a superior capillary path to suck liquid penetrants out of voids and spread them at up to 100 times the width of the void. Figures 4 to 6 demonstrate the simple magnifying effect of developers. The developed indication is very much wider than the crack itself.

Note the increase in the area of the indication in Fig. 6 compared with Fig. 5. Like many other developers, dry developers scatter light in a way that greatly increases fluorescent output.

The trace seepage of liquid penetrants is what allows fluffy dry developers to work. Because the developer particles are very small (less than 1 µm in diameter) they easily stick to the invisibly thin liquid penetrant seepage at voids and build up in a mound of particles that pulls up most of the entrapped liquid penetrant. Before 1950, dry developers were coarse (greater than 10 µm in diameter) and showed poor sensitivity because they were too heavy to stick to seepage and build an indication.

Dry developer is nearly invisible on a test surface and hence offers no contrast to visible liquid penetrants. Therefore, even though indications develop, they are invisible. Dry developers are not approved for use with color contrast (visible) liquid penetrants.

Aqueous Particulate Developers

These were first formulated in the 1940s. Basically they are powder compositions that can be dispersed into water, containing wetting agents and corrosion inhibitors, to form a sort of

FIGURE 4. Photograph of crack under white light.

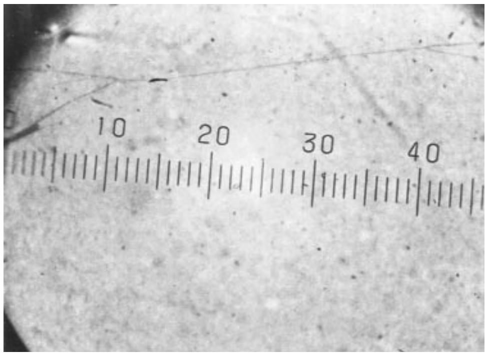


FIGURE 5. Photograph of fluorescent liquid penetrant indication of crack shown in Fig. 4 *without* developer.

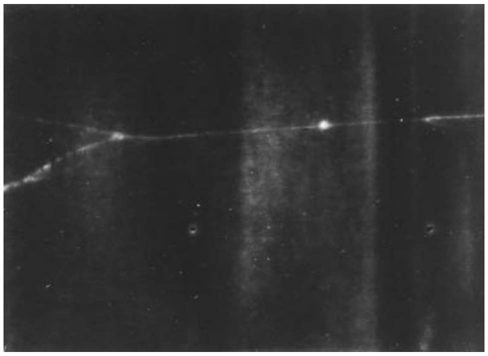
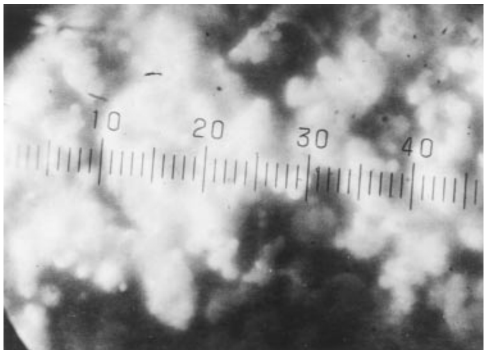


FIGURE 6. Photograph of fluorescent liquid penetrant indication of crack shown in Fig. 4 *with* developer.



whitewash. They are commonly referred to as water suspendible developers. They should be oven dried. They yield a white film that is good for both visible and fluorescent liquid penetrants. They are easy to apply in high volume testing, emit no hazardous dust or fumes and scatter light.

Solvent Based Particulate Developers

Solvent based developers are the most sensitive. The thin, volatile solvents speedily diffuse into liquid penetrant entrapments, dissolve them and quickly drag them to the surface, after which they evaporate away. The particles then spread the indications. They provide contrast for visible liquid penetrants and scatter light for fluorescent ones.

The evaporating solvents pose both a health hazard and a fire hazard. This limits their use to locations where it is not possible to use water and drying ovens in fixed installations. They are the developers of choice for portable liquid penetrant kits.

Water Soluble Developers

Water soluble developers are designed to provide an aqueous developer that does not need to be stirred up constantly and that rinses off easily. The sort of crystalline substances that dissolve readily into water usually dry to give a coarse grained film with marginal light scattering and capillarity. Like dry powder developers, they do not offer good contrast for visible liquid penetrant indications.

Unusual Developers

Solvent based lacquer developers have had a limited use, as they can (with some difficulty) be peeled off a surface and mounted in a logbook for future reference. Photography can provide a better record of both fluorescent and visible indications.

Importance of Light Scattering for Fluorescent Liquid Penetrant Testing

Partially fill a clear glass container, beaker or cylinder with fluorescent liquid penetrant, place it under a near ultraviolet lamp and look at it from above. What you see is a dim greenish fluorescent liquid surface. Next squat down and view the liquid penetrant surface from the edge. What you now see is a thin bright yellow layer at the surface with nothing but nonfluorescent green liquid beneath. All the near ultraviolet radiation is absorbed in this thin top layer. No fluorescence is possible below this layer because no ultraviolet radiation is left. Finally drop a pinch of fluffy dry developer onto the liquid surface. When viewed from above, the developer glows as brightly as the edge fluorescence. You are seeing the effects of internal reflection and of light scattering (Fig. 6).

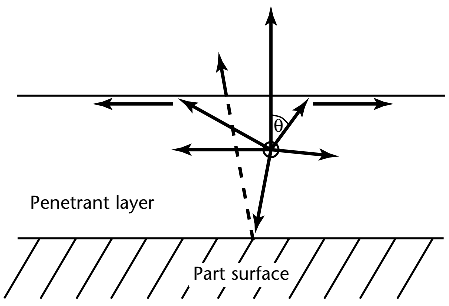
The fluorescent light that is emitted from each tiny region of a liquid penetrant film radiates in all directions (see Fig. 7). It cannot escape from the liquid surface to be seen unless it impinges on the surface at an angle less than about 45 degrees from perpendicular. The exact angle at which total internal reflection occurs depends on the liquid penetrant's index of refraction:

$$\textbf{(14)} \quad \sin\theta = \frac{1}{n}$$

where n is the liquid penetrant's index of refraction and θ is the angle at which total internal reflection begins. Most penetrants have an index of refraction of about 1.4; consequently θ is near 45 degrees. Roughly 12.5 percent of the generated fluorescence reaches the surface within this 90 degree cone. The other 87.5 percent is caught in this light trap. With a highly reflective test surface more fluorescence may be reflected up, but not reliably. The fluorescence that reaches the edge of the liquid penetrant seepage may be bright but will remain unseen unless the inspector can bring eyes within a few micrometers of the test surface.

Developers break up this light trap by scattering the fluorescent light (Fig. 8). Because of multiple reflections from particles, nearly all the fluorescent light escapes to be seen. This amounts to an eight fold increase in fluorescent brightness.

FIGURE 7. Fluorescent liquid penetrant light trap.



Legend
θ = Angle at which total internal reflection begins

Figure 8. Breaking of light trap.

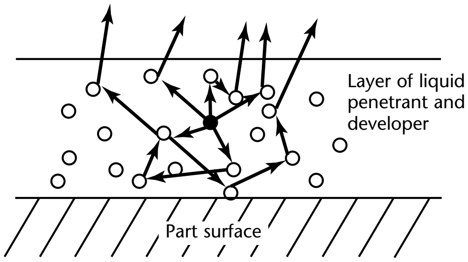


Figure 9. Ultraviolet radiation passing through thin layer of fluorescent liquid penetrant on a test surface.

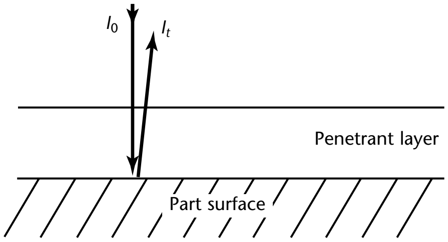
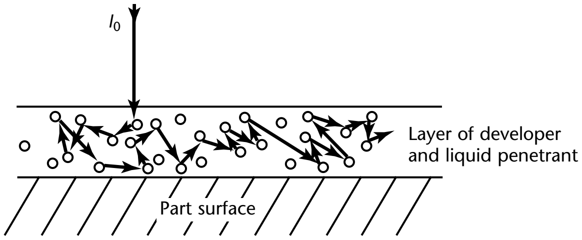


Figure 10. Multiple scattering of ultraviolet radiation among developer particles.



Light scattering plays one more role in enhancing light intensity and sensitivity. As stated by Eq. 15, the fluorescent brightness of a liquid penetrant seepage is given by:

(15) $$F = Q I_0 (1 - 10^{-ect})$$

With tiny seepages, *t* is microscopically small, which diminishes the value of fluorescent brightness *F*. Figure 9 shows that little of the exciting ultraviolet light is absorbed as it passes through the thin layer of liquid penetrant, is reflected by the test surface and passes through the layer for the second and last time. If the test surface is not reflective, the light only passes through once.

Fine developer particles embedded in the liquid penetrant seepage scatter the ultraviolet radiation throughout the layer, ensuring that it all gets absorbed by the liquid penetrant (see Fig. 10). Remember, it is not how much ultraviolet radiation is present that matters; it is how much gets absorbed. In effect, scattering the incident ultraviolet radiation makes *t* very large, maximizing visible light *F* of the indication.

PART 5. Viewing Indications

Visible Indications

Visible liquid penetrants are sometimes called color contrast liquid penetrants — not a very accurate description. The contrast of dark indications against a white background is far more striking than the contrast of, say, a green liquid penetrant against a red or purple background. Visible liquid penetrants are red because formulators can achieve much darker indications than with brighter colors such as green, yellow or orange.

Red indications appear black if viewed under green light or under white light while the inspector wears green glasses. In some test applications, this expedient might usefully increase the contrast of the indication on the background and may be worth trying.

Developers that form an even, white film are required for use with visible liquid penetrants. Most test surfaces are much too dark to provide contrast. Dry powder developers leave transparent films in normal thicknesses. If applied by electrostatic spraying or fluid bed techniques, dry developers can be built up to thick white coatings that can slide off the test surface and take indications with them. Thin developer layers are not likely to fall off.

White developers deposited from liquid suspensions have superior cohesion and adhesion; they cannot be jarred loose. Water based developers are best applied by dipping, followed by draining and oven drying. Spraying is possible but their necessary wetting agent content generates copious amounts of foam, which can obliterate indications. They can be air dried, if time is not important but then indications tend to be faint and fuzzy. The wetting agent content of aqueous developers spreads indications too much during the extended air dry time.

Solvent based developers, on the other hand, *must* be applied by spraying. Brushing or dipping dissolves and brings far too much liquid penetrant from the cracks on the test surface. This tends to deplete liquid penetrant entrapments and smear them all over the surface before drying is complete. Of course, it is possible to spray on too much solvent based developer, with the same unwanted results.

This is where operator skill is important. A good inspector does not splatter a heavy coat of developer in one or two quick, sloppy passes. Instead, he or she applies a series of thin, fast drying layers; never allowing the surface to become wet enough to get runny. Finally, the inspector stops spraying before the film becomes thick enough to be dead white and opaque. Fine liquid penetrant entrapments simply lack sufficient liquid penetrant to soak through a thick developer coat in quantities capable of being detected. A good rule of thumb is to stop spraying a developer just before the test surface texture and color become totally hidden. This requires skill and practice. At this point the indication is fully and visibly developed against a near optimum white background.

Lighting intensity for viewing is often specified. In general, lighting should be about the same as is required for reading fine print on white paper.

Fluorescent Indications

When viewed under 10 $W \cdot m^{-2}$ (1000 $\mu W \cdot cm^{-2}$) of 365 nm ultraviolet radiation, most indications fluoresce in a range of intensities centered around 54 to 108 lx (5 to 10 ftc). If visible light intensity in the test area exceeds this level, there is a loss in contrast of the indication to its background. Now the inspector is looking for bluish to greenish indications on a typically blue or white background. No brightness contrast, just color contrast. To avoid this predicament, the test area must be kept dark. It should not be greater than 10.8 to 21.6 lx (1 to 2 ftc) because this much visible purple (violet and red) radiation is emitted from the ultraviolet lamp. Actually, this amount of purplish light is necessary; without it the inspector would literally be blind, stumbling around in total darkness. What is not necessary is stray light from adjacent areas, leaky ultraviolet lamp housings, fluorescent clutter from spilled liquid penetrant and optically *bleached* white clothing from within the area.

Preliminary laboratory work has shown an approximate relationship between the intensity of visible light in an test area and the level of near ultraviolet radiation required to intensify indications enough to offset the ambient light. As can be seen from Fig. 11, near ultraviolet intensity requirements get absurdly high in well lighted surroundings.

Table 2 shows representative visible light intensities measured in various lighting environments.

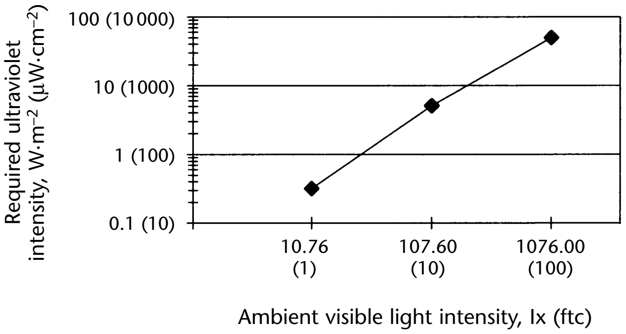
Eyesight is very important to any inspector and much has been written about the need for vision acuity and dark adaptation. Other factors exist. Cataracts can affect the ability of an inspector to see fluorescent indications. First there is a defocusing that can be partially corrected with glasses. Second, the eyes' lenses become yellow and absorb the violet (405 nm) emission peak from the visible fluorescent radiation, making it appear red. Thus acuity decreases, but because less violet radiation is seen the field of view darkens and contrast increases. Replacing cataracts with clear plastic lenses allows the 405 nm radiation to be seen. Ultraviolet lamps then seem to emit an intense violet light that washes out faint indications.

Assessing vision acuity can become very complex, as there are a wide range of eye conditions that may affect an inspector's ability to see and evaluate indications. Color blindness and ordinary ability to resolve tiny lines and spots are only the most well known conditions. None of this has much to do with liquid penetrant materials themselves but as long as human eyes are part of the liquid penetrant testing process, their performance must be anticipated in planning tests and considered in evaluating test results.

Table 2. Representative ambient visible light intensities. 10.8 lux (lx) = 1 footcandle (ftc).

	Intensity	
Light conditions	**lx**	**(ftc)**
General plant	108 to 324	(10 to 30)
General office	270 to 324	(25 to 30)
Laboratory	324 to 432	(30 to 40)
Bright interior	1080	(100)
Storage area	54 to 75.6	(5 to 7)
Ultraviolet inspection booth	10.8 to21.6	(1 to 2)

Figure 11. Intensity of near ultraviolet radiation required in liquid penetrant test viewing area versus ambient visible light in area.



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4

CHAPTER

Care and Maintenance of Liquid Penetrant Test Materials

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Part 1. Importance of Maintenance of Liquid Penetrant Materials

The quality of an inspection made with liquid penetrants can be no better than the quality of the liquid penetrant test materials used for the inspection. Recognizing this basic fact requires that liquid penetrant materials meet certain industry standards before they are purchased for use. It also requires that these materials and the liquid penetrant systems in which they are used be monitored and tested on a periodic and regular basis. To ensure the materials purchased are of desired quality and that the proper tests are made at the proper intervals during their use, a variety of specifications have been developed. A list of some of the better known nondestructive testing specifications appears in the references.[1-19]

These specifications can be broadly classified as to their origin, typically the United States military, various United States technical societies or corporate users. Many of the specifications describing the materials have common threads running through them whereas some have been specifically tailored to the specialized use of a particular industry or customer. For example, although virtually every liquid penetrant in use has had to meet the requirements of MIL-I-25135[1] (or its commercial replacement, AMS-2644[2]), liquid penetrants used in the nuclear industry must additionally have particularly low contents of certain low melting metals, as well as sulfur and halogens. Aircraft turbine engine manufacturers require products with low fluoride, sodium, chloride and sulfur content. Specifications detailing the testing of materials in use have revolved mainly around the military specification MIL-STD-6866[3] (or its commercial replacement, ASTM E 1417[4]) but other corporate specifications may also exist. These specifications, in turn, often refer to tests which are called out in other specifications. For example, MIL-STD-6866[3] refers to tests which are outlined and described in MIL-I-25135[1] or AMS 2644,[2] and NAVSHIPS 250-1500-1[20] refers to tests documented by the American Society for Testing and Materials (ASTM).

When using any specification, it is important to find out whether the latest version of the specification is used. Specifications are usually under constant review and the latest changes are often important improvements over previous issues. Using the version specified by contract is essential if the liquid penetrant test system is subject to audit, because the auditor will immediately check to see that the correct issues are being followed.

PART 2. Care and Maintenance of Liquid Penetrant Testing Materials in Storage

The following admonitions apply to the storage of all liquid penetrant materials, that is, of liquid penetrants, of emulsifiers or removers and of developers. Materials in storage can suffer either deterioration or contamination if they are not properly cared for.

Deterioration

New Liquid Penetrant Test Materials

Deterioration is largely the result of time and storage conditions. Most liquid penetrant materials are not greatly affected by time as long as they are kept in closed storage containers. Liquid penetrants stored in open or loosely covered tanks or in improperly sealed containers are subject to evaporation losses.

Hot and cold storage conditions can affect liquid penetrants adversely. Cold storage will cause freezing of many liquid penetrant materials. Freezing will not usually prevent the liquid penetrant test material from performing properly after warming to the temperature of use, but in a few cases, freezing of liquid penetrant test materials has caused irreversible separation of constituents and performance failure. This separation is rare with modern liquid penetrants and MIL-I-25135E contains liquid penetrant qualification tests designed to detect this irreversible separation.[1] Hot storage up to 65 °C (150 °F) for limited periods of time usually has little effect. However, hot storage for long periods of time (months or years) could cause internal reaction between some components and degradation of fluorescent dyes, with subsequent loss of performance.

Aerosol Containers

Materials packaged in aerosol spray containers are also not affected by normal storage conditions. Cold storage reduces the internal pressure so the can must be warmed to nearly room temperature to spray properly. Conversely, high storage temperatures raise the pressure and extremely high pressures can cause bursting of the can. Therefore, aerosol can temperatures should never exceed 55 °C (130 °F).

Aerosols do not have infinite shelf life, because there is always some slight leakage of propellant through the valve. This leakage usually does not cause a significant change in performance until a couple of years have passed. Aerosol containers can eventually become depressurized after storage for three to five years, although there are many instances where aerosol containers spray well after as long as 20 years.

Contamination

Deterioration is unlikely in storage but contamination is always a possibility if care is not taken. For example, if drums containing liquid are stored outside, they can have water cover the top if it rains. Then, if the openings are not sealed tightly, this water can be sucked into the drum as the temperature changes. If containers are stored after they have been opened and they are not properly resealed, dust, dirt or other foreign materials can possibly get into the containers. Depending on what type of contamination enters the container, the material can suffer a loss in performance or even fail completely when it is used.

For developer powders, it is especially important to use proper storage. Dry developer powders can become damp and then *clump,* rendering them less sensitive when used. Foreign material getting into dry developer could react with the liquid penetrant and cause it to lose some of its brightness. If the contamination in the dry developer is fluorescent, it can cause false calls.

Soluble and suspendible developer powders contain surfactants that are hygroscopic. If their containers are not tightly sealed, they can pick up moisture. This can cause them to become difficult to use and can also make them subject to biological decay. Microorganisms find the surfactants very tasty. They can live in the developer and eat all of the surfactant. When this happens, the developer will no longer wet the surface of the parts and the inspection will fail.

General Rules

Many tests can be performed to ensure that stored materials are still good but common sense is one of the best things to use. First, make sure that liquid penetrant products are stored properly. This means indoors and at temperatures which are not either extremely hot or extremely cold. Second, make sure that the containers are well sealed. Third, make sure that the containers are clearly labeled. When removing something from storage, first inspect the container. Look for evidence of incorrectly sealed containers. Look for evidence of water that has been on the top of the container. Look for evidence that someone has opened the container, removed some of the contents and then not resealed the container properly. If everything looks good, the contents are probably good. Nevertheless, when taking material from the container, look at it critically. If it is a liquid, it should be clear in color, without evidence of any foreign material. It should have no milky streaks in it if it is a water washable liquid penetrant or a lipophilic emulsifier. There should be no particulate matter evident. The liquid at the bottom of the container should appear no different than that that at the top.

If the container has developer in it, see that it has no clumps that are damp. Look for evidence of fungus or algae — dark spots which indicate that a colony of *bugs* is there, eating the developer ingredients. If all appears clean, dry and relatively free flowing, the developer is probably in excellent condition.

Finding any of the indications listed above should make one suspect that the material may not be in condition to use. In that case, tests should be made as outlined below for in-process materials.

PART 3. Care and Maintenance of Liquid Penetrants in Use

Liquid Penetrants in Open Tanks

Proper maintenance is more difficult with liquid penetrants used in open tanks where parts are dipped into them than when sprayed from storage cans. When expended as used, particularly in the small portable test kits, liquid penetrants are subject to very little contamination or degradation. This is particularly true of liquid penetrants that are packaged in aerosol spray cans. When used in dip tanks or open containers, contaminating materials can get into liquid penetrants quite easily.

Some materials such as certain cleaners and solvents commonly used in manufacturing plants can affect the wetting ability of liquid penetrants when present in sufficient quantity. In addition, the greater liquid surface areas exposed with dip tanks make evaporation and loss of light volatile constituents of liquid penetrants more likely. The large liquid surface can absorb or condense moisture from the atmosphere. This water can have a deleterious effect on liquid penetrant performance, as can water carried into liquid penetrant tanks on test objects.

In-Use Contamination

Effects of Water Contamination in Water Washable Liquid Penetrants

Presence of moisture in a liquid penetrant is probably the most common cause of failure in liquid penetrant testing. This is particularly true of water washable liquid penetrants, which contain emulsifiers so they can be readily removed by water washing. Water washable liquid penetrants have a definite water tolerance limit beyond which they do not function properly. Added water reduces their fluorescence and penetrating ability and also adversely affects their washability.

Water contamination in liquid penetrants may be first seen as a slight cloudiness. This increases with rising water content and is usually accompanied by an increase in liquid penetrant viscosity. With more added water, the liquid becomes somewhat striated and the liquid penetrant eventually separates into two distinct phases. The liquid may form a gel.

Effects of Water Contamination in Postemulsifiable Liquid Penetrants

Water contamination of postemulsifiable types of liquid penetrant is seldom a serious problem, because these materials are not usually compatible with water. With no emulsifier present, water in the liquid penetrant dip tank will settle to the bottom and may cause undetected corrosion at the bottom of the tank. Violent agitation may bring some water into suspension in the oil, causing slight liquid penetrant turbidity, but when the agitation ceases, the liquid will clear quite rapidly as the water settles out. Because water will not stay suspended in postemulsifiable liquid penetrants, it is seldom necessary to conduct a water test. However, if test parts are dipped to the bottom of the tank, the accumulated water can be a problem during operations.

Water is frequently introduced into liquid penetrants and processing materials from wet parts, through careless overspray from a wash station or from leaking pipes or roofs. Water can also enter a liquid penetrant from the air, if the air is very humid and the liquid penetrant temperature is below the dew point. Condensation of water from ambient air can happen during a humid morning following a night that was cold enough to chill the liquid penetrant in the immersion or storage tank.

Effects of Contaminants (Other than Water) in Liquid Penetrants

There are other contaminants that can affect the performance of fluorescent liquid penetrants. Overall tests to disclose their presence are not very practical. Such tests would involve complicated laboratory analysis and each test would have to be directed specifically to a particular contaminant. Fortunately, most of these contaminant materials have to be present in fairly large quantities before they can seriously affect liquid penetrant performance and their presence will be made evident by a change in behavior of the process material. Foreign materials such as cleaning solvents, heavy oils, acids or chromates in liquid penetrants will make their presence known by changes in liquid penetrant performance such as in wetting ability, drying characteristics or loss of fluorescent brightness.

Changes in wetting ability and drying characteristics of liquid penetrants can generally be seen by operators. Changes in fluorescent brightness can be detected during operations by placing a single drop of used liquid penetrant on a filter paper alongside a drop of new liquid penetrant and viewing the two under an ultraviolet lamp. This permits a very rough comparison but is adequate in most cases. More accurate tests can be made by use of photometers, or fluorometers described elsewhere in this volume.

Effects of Organic Contamination of Test Objects on Liquid Penetrants

Another source of contamination of liquid penetrants and processing materials is formation of organic coatings on surfaces of test objects. These organic contaminants include grease, oil, preservative, paint and residues from previous processing. These contaminants cause serious problems when not removed from the surface of test parts because they may fill cracks and prevent the entrance of liquid penetrant. The organic contaminants are usually soluble in liquid penetrant and slowly increase in concentration in the liquid penetrant. Undesired effects of organic contaminants in liquid penetrants include the following: (1) diluting the dye in the liquid penetrant; (2) absorbing ultraviolet radiation before it reaches the dye in the liquid penetrant indications; (3) changing liquid penetrant viscosity; (4) unbalancing emulsifier systems; and (5) deterioration of liquid penetrants and process materials. Most of these contaminants never get beyond the liquid penetrant tank or drain stations and do not affect the emulsifier or developer.

Effects of Organic Solvent Contamination of Liquid Penetrant Test Materials

Still another type of contaminant often encountered is the organic solvent, such as degreaser fluid, gasoline or kerosene carried on test object surfaces. These contaminants usually originate in a previous cleaning operation. Small amounts of these organic solvent contaminants are not serious but large amounts affect liquid penetrant fluorescence and ease of washing to remove excess surface liquid penetrant. Carryover of some solvent degreasing fluids can result in corrosion conditions. Residues from deburring, tumble polishing or burnishing operations may fall in this third category.

Effects of Contamination of Liquid Penetrants by Acids, Caustics and Chromates

Acids and caustics have an additional adverse effect on any type of liquid penetrant in which they can be dissolved. These active chemical contaminants cause loss of fluorescence in fluorescent liquid penetrant dyes. They have an adverse effect on nonwater washable (postemulsifiable) liquid penetrants in which they are not soluble. Sometimes, chromate residues from etching operations may become trapped in discontinuities and subsequently destroy the fluorescent response of a liquid penetrant entrapment. This effect is due mainly to the powerful ultraviolet absorbency of the chromate ion.

In-Use Deterioration

Effects of Evaporation of Liquid Penetrant Test Materials

One source of deterioration of materials is evaporation. The liquid penetrants and some of the emulsifiers often contain light oil fractions that evaporate at various rates, leaving an unbalanced liquid penetrant formula. Wet developers and water base penetrants contain water or organic solvent that will evaporate if exposed for long periods. Some evaporation is unavoidable but the rate of evaporation is increased by higher temperatures and large exposed surface areas.

The effects of evaporation of volatile constituents of liquid penetrant processing materials include increased viscosity, higher developer concentration, changes in fluorescence, changes in water tolerance and increased dragout.

Also, evaporation will either speed or slow washing characteristics, depending on the type of liquid penetrant material. Therefore, evaporation of liquid penetrant materials cannot be ignored. Evaporation of liquid materials in tanks occurs whether the material is used or not and at a rate so gradual that it is often overlooked. Periodic checks are therefore required to ensure that excessive evaporation has not occurred.

Effects of Heat on Liquid Penetrant Test Materials

Heat can be a cause of serious deterioration of liquid penetrant materials. A little heat continuously applied increases the rate of liquid penetrant evaporation. As the lighter constituents evaporate, liquid penetrant viscosity increases. This may actually upgrade the liquid penetrant material because, when lighter fractions evaporate, dyestuff becomes more concentrated in the less volatile oil that remains. However, an increase in liquid penetrant viscosity increases dragout on test parts, slows penetration into discontinuities and changes the wash characteristics. Liquid penetrants that include coupling agents that are more volatile than other constituents may separate or gel as the coupling agent evaporates. Such coupling agents are used to prevent separation of liquid penetrant constituents or to control liquid penetrant tolerance for water.

High temperatures cause all of the preceding effects and, in addition, can kill fluorescence of dyes in liquid penetrants or leak tracers. Therefore, heating of liquid penetrant materials much above room temperature, either locally or completely, should be avoided if at all possible.

PART 4. Care and Maintenance of Liquid Penetrant Emulsifiers and Removers in Use

In-Use Contamination

Deterioration of Emulsifiers by Contamination with Water or Liquid Penetrant

Whenever the washing of surface liquid penetrant from test parts becomes noticeably difficult, the emulsifier (whether lipophilic or hydrophilic) should be checked immediately. The most probable cause of deterioration of lipophilic emulsifiers is contamination of the oil base emulsifier with water. All lipophilic emulsifiers have a definite water tolerance that may vary from five percent to practically unlimited amounts of water. When water concentrations exceed the water tolerance limit, the lipophilic emulsifier is no longer effective as a liquid penetrant remover. This loss in effectiveness is generally accompanied by changes in emulsifier appearance or physical properties. The low tolerance emulsifiers usually become viscous or gel completely, whereas the high tolerance emulsifiers become cloudy or show a tendency to thicken.

Another important source of contamination of emulsifier baths is liquid penetrant carried into emulsifiers during processing. If excessive liquid penetrant contamination builds up, the effectiveness of the emulsifier will decrease noticeably.

Sources of Liquid Penetrant Contamination in Emulsifiers

The most common source of liquid penetrant contamination in emulsifiers is that carried into emulsifiers by dragout on test parts processed through a dip operation. This liquid penetrant reduces the emulsifying ability of the emulsifier, making it less effective. If the liquid penetrant contamination reaches a high enough level, it destroys the emulsifier. In many operations, the liquid penetrant content reaches an equilibrium because emulsifier is carried out on the parts and the necessary makeup emulsifier dilutes the carried-in liquid penetrant. If the liquid penetrant content does reach excessive levels, the reason is often poor test procedure. Liquid penetrant should be fairly well drained off the parts before they enter the emulsifier. Particular attention should be paid to reservoirs (openings in test objects) or recessed areas that hold more than a thin surface layer of liquid penetrant. This may mean that the parts must be turned over during the drain period but the extra effort will be justified by the reduced material loss and contamination.

Sources of Water Contamination in Emulsifiers

Any liquid penetrant testing system that uses emulsifiers also uses water to wash the parts after they have been emulsified. The close proximity of water to the emulsifier makes it relatively easy to contaminate the emulsifier with water. In any case where it has been found that water contamination has taken place, the first thing to suspect is that water from the wash operation has gotten into the emulsifier tank. In virtually every case, careful attention to procedures will reveal how contamination is happening. In one instance, the operators were steadfast in maintaining that it was not possible for water to get in the tank but when the operation was observed, the situation was very clear. The operators were holding the parts by hand and spraying them with water. They held the parts in such a position that the overspray was going directly into the emulsifier tank. It was like rain.

Other sources of water are rare and not as obvious. In one case, a night janitor found that, if he wanted to really clean his mop, all that he needed to do was to dip it into the emulsifier tank and then wash it with water. He repeated this many times each night and each time that the mop went into the tank, it put some water into it. In just a few days, the emulsifier was ruined. In another case, a new maintenance man had been hired and he was anxious to show that he did good work. The emulsifier tank was empty and he cleaned it with water, doing a very good job. However, the tank had piping connected to it and he left these pipes full of water. When the tank was refilled with emulsifier, it was almost instantly contaminated.

PART 5. Care and Maintenance of Developers in Use

There are four types of developer in common use. These are dry powder developer, water soluble developer, water suspendible developer and nonaqueous developer. Each of these has distinctly different characteristics and different susceptibilities to deterioration and contamination.

Dry Powder Developer

Dry powder developer is not prone to deteriorate. It is composed of chemically stable absorbent powders that are unlikely to decompose or otherwise change their composition in a way that would affect their performance. However, dry powder developers are prone to contamination of various types. The most obvious of these is contamination by fluorescent liquid penetrant. When parts have been dipped into the dry developer, the developer adheres to the wet opening of discontinuities because there is liquid penetrant there. The liquid penetrant then is wicked into the developer and the liquid penetrant makes the dry powder wet and fluorescent. If particles of this wet, fluorescent powder fall free from the part, they mix with the rest of the dry powder, creating spots of fluorescence that can later adhere to another part and cause a false indication.

Dry powder developer can also become damp or wet, causing it to clump. When this happens, it does not form a smooth even coat on the parts being inspected and it also may not stick to the wet openings of the discontinuities, thereby missing indications. Wetness can result from parts that are not completely dry before being put into the developer and it can occur because of excessively high humidity.

Water Soluble Developer

Water soluble developer may deteriorate in use as a result of infections of bacteria, algae or fungus, commonly termed *bugs*. In order for the soluble developer to form a smooth coat on the parts, a surfactant is included in the formulation. Surfactants are a favorite food for bacteria, algae and fungi and airborne bugs can land in the solution and infect it. Soluble developer formulations also include biocides to counteract this undesirable occurrence but they do not last indefinitely. The best practice to avoid infections is to keep the tank covered when not in use. If an infection occurs, the cure is to drain the tank, sterilize it and then refill it with fresh developer solution. The developer manufacturer has complete instructions for this procedure.

Soluble developers can also become contaminated in various ways. The concentration can go up or down depending on evaporation of water from the tank or the addition of water from wet parts being immersed. Fluorescent liquid penetrant can get into the developer bath from the parts being inspected. Also, it is possible to contaminate the developer solution through electrolytic action. The developer is a solution of chemicals that ionize in solution, creating an electrolyte. If a basket of dissimilar metals is placed into the solution, electrolysis can occur in which metal is dissolved from one of the dissimilar metals. The result can be cloudy or murky solution that reduces the developing ability of the solution.

Water Suspendible Developer

Water suspendible developers are prone to some of the same contaminants that soluble developers are, because they also contain surfactants and because they also have ionized components. This means that it is possible to have an infected developer bath and that it is possible to have electrolytic effects. It is also possible to contaminate the suspension with liquid penetrant from the parts being inspected and it is possible that the concentration of the suspension will change as a result of evaporation of water from the tank or the addition of water from the parts.

Nonaqueous Wet Developer

Nonaqueous wet developers are usually used in aerosol form. Properly used, the developer is not prone to either deterioration or contamination. If the cans are not agitated before use, the developer powder will not be properly dispersed and this improper dispersion will cause the developer coating to be either too thick or too thin. The only other failure that can occur is the loss of pressure in the can, in which case the developer may be good but cannot be expelled from the can.

Nonaqueous developers used in bulk form are prone to concentration changes because of solvent evaporation and should be kept in tightly closed containers. If applied with a spray gun, agitation must be used to keep the developer particles in suspension.

PART 6. Quality Control Tests for Liquid Penetrant Materials

The following information applies generally to the testing of liquid penetrant materials to determine whether they are still suitable for use after having been used for some period of time. Most liquid penetrant processes are run according to certain specifications or standards, such as MIL-STD-6866[3] or its replacement, ASTM E 1417.[4] These standards or specifications contain the exact requirements for testing and reference the exact test techniques to be used. Liquid penetrant users may refer to the following discussion for general information but should carefully follow the requirements of the standard or specification under which they are working. If no standard or specification is called out, it is wise to use ASTM E 1417[4] to ensure that the test process is in good condition.

Water Tolerance of Water Washable Liquid Penetrants and Lipophilic Emulsifiers

A useful property test that may be performed on liquid penetrants is the water tolerance test. This test is applicable only to water washable liquid penetrants and to lipophilic emulsifiers used with postemulsifiable liquid penetrants because these are the only materials affected by small amounts of water contamination. The water tolerance test is not usually prescribed for postemulsifiable liquid penetrants themselves as they are not water miscible in their original form. Typically, water will sink to the bottom of the postemulsifiable liquid penetrant tank and form a separate layer.

When water is introduced into water washable liquid penetrants, it will mix, up to a point, causing some characteristic changes. First, it will usually result in increased viscosity, thereby causing some of the same changes as evaporation. The peak viscosity is often reached with a relatively small amount of added water. More water then reduces viscosity, in some cases to a value lower than normal. In addition to the viscosity changes, water reduces the dye concentration, thereby decreasing the performance of water washable liquid penetrants. Further, addition of water (with its high surface tension) upsets the liquid penetrant formula's balance between adhesion and cohesion. This modifies the characteristics of a liquid penetrant, even though the penetrant-and-water mix remains clear. Also, chemicals with substantial water contents and without inhibitors will contribute to rusting of test parts as well as liquid penetrant processing equipment. A liquid penetrant with a high water content could be a source of corrosion.

Enough added water eventually causes many liquid penetrant test materials to separate into two layers. Generally, but not necessarily, the first sign of such separation is a cloudiness of the fluid. Sometimes, this cloudiness is localized in a small area of a tank, and stirring to dilute the local high water content will clear the fluid. Therefore, care must be taken to ensure that a representative sample is used. If the whole tank is cloudy, the layers will often separate by gravity. Even if they do not, the effectiveness of the liquid penetrant test material is gone. The material must then be replaced.

Visible Determination of Water Tolerance Limits

A simple test for water tolerance is to add known amounts of water to a known amount of material with mixing. When permanent cloudiness or gelling occurs, the water tolerance limit has been determined. The amount of water used to produce cloudiness or gelling is a direct indication of how much more water the material will accept before breaking down.

It is wise to know the water tolerance of new liquid penetrant test materials. This gives a base point that allows one to determine if a large variation from the base value has occurred in the test material. If such a large variation does occur, not only should one be prepared to replace the material but the probable cause of the contamination should be determined and, if possible, eliminated.

Regardless of the water tolerance of the liquid penetrant, it must be checked periodically in accordance with MIL-STD-6866[3] or ASTM E 1417[4] to determine that the maximum allowable water concentration has not been exceeded.

Quantitative Water Content Measurements

A water content measurement may be desired instead of a water tolerance test and is necessary if one must know the actual water content. This is usually done by the ASTM D 95[21] technique where a known amount of material is refluxed with the specific solvent xylene and the condensed vapors are caught in a water trap. Water and xylene boil at similar temperatures and so leave the mixture together. The condensed liquids are not mutually soluble, so they separate in the condensation trap. The water is heavier so it settles to the bottom of the trap for measurement. Most of the xylene is returned to the original mixture.

It is essential to use the specific solvent known as xylene for these water content measurements. Many liquid penetrants contain water soluble glycols or glycol ethers which, though much less volatile than water, are still distilled out to a small extent. They collect with the water and act to increase its volume. Solvents with a higher boiling point than xylene extract more of these glycols or glycol ethers and so yield higher apparent water contents. Solvents that are more volatile than xylene extract less water. Use of xylene only, in water content tests, permits equivalent results to be obtained in different facilities. One way to avoid the errors that glycols or glycol ethers can cause is to use a Karl Fischer analysis, a chemical titration technique for precise measurement of moisture.

Precautions in Selecting Samples of Liquid Penetrant Materials

When liquid penetrant materials are to be tested for contamination or deterioration, the first consideration is to ensure that a truly representative sample is taken. The product must be well mixed so that any sludge or separation layers are included in the sample. The container used to store liquid penetrant samples must be clean and made of material that is not attacked by and is not permeable to the liquid penetrant material.

Selecting Standard Materials for Evaluation of Liquid Penetrant Deterioration

Most test procedures usable for the determination of liquid penetrant material conditions do not give absolute results but rather are comparisons to some standard. Therefore, the choice and care of standard samples of liquid penetrants and processing materials for each liquid penetrant test system in use is very important. A good standard is new material saved from the original container at the time the material is put into use. This type of standard eliminates any effects of batch-to-batch material variation and previous storage. The new material standards should, of course, be stored in such a way that they will not deteriorate. Therefore, standards should be kept in tightly closed glass or metal containers (not plastic containers) and stored in a cool, dry place. Even with such proper storage, these liquid penetrant and processing material standard samples should be checked against brand new materials of the same types every two or three years to ensure that no deterioration has occurred.

Procedures for Comparing Standard Materials with In-Use Liquid Penetrant Materials

It is possible to use very sophisticated instrument analyses to check liquid penetrant materials during their use but such sophistication is rarely justified. All that is really necessary at the field level is to know whether the material is performing as required and, if not, where and how bad are its shortcomings. These can be determined with a series of relatively simple, inexpensive test procedures requiring a relatively small investment in test equipment.

The most important test is the system performance test in which the in-use materials are tested against standard liquid penetrant test materials of the same type on actual cracked reference test objects. The specimens may be parts of the type being tested and containing known, naturally occurring discontinuities or they may be test panels with synthetic discontinuities. In any case, the test parts must be clean and dry before the test. With some test specimens, half of the specimen can be treated with in-use material and the other half with standard material. With other specimens, it will be necessary to have two similar test pieces, one for in-use material and one for new.

Processing Reference Specimens with Standard and In-Use Liquid Penetrant Materials

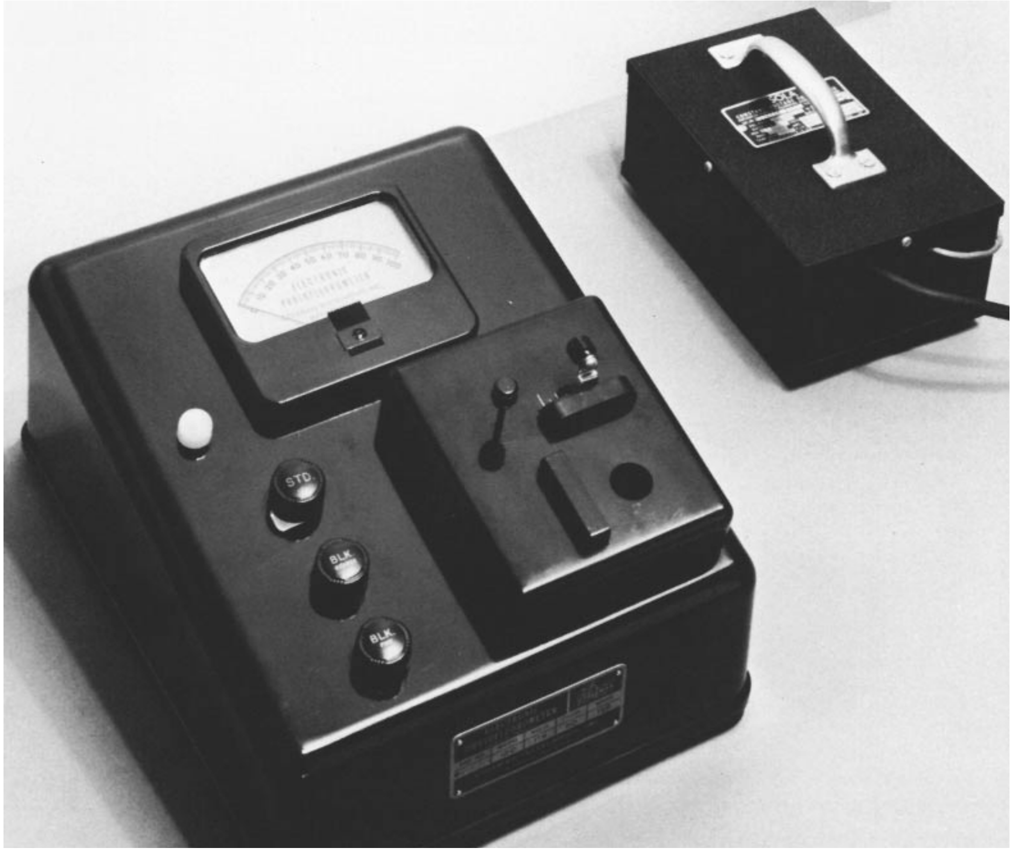
In the reference test procedure, standard materials are applied to one part of the test piece, the used materials are applied to the other part (or to a similar piece) and the two systems are processed equally. If actual cracked parts are being used, the processing should be the same as that used in normal production tests. If synthetic discontinuity test pieces are being used, procedures may have to be modified to handle the different surface and crack conditions of the synthetic discontinuity pieces. The main requirement is to ensure that standard and used material systems are processed identically.

Close comparison of test indications with standard and used material systems will show whether there is a noticeable difference between them. If there is no difference, the used material can be assumed to be acceptable and further tests are not necessary (but may be performed if a numerical status rating is desired). If a difference is noted, a decision must be made as to whether this difference (1) is significant enough to reject the used materials at this point or (2) justifies further tests to determine the cause and degree of the problem.

Laboratory Fluorometers for Fluorescent Brightness Measurements

One type of filter photometer that has been used for fluorescent brightness measurement is shown in Fig. 1. These fluorometers normally contain the photometer sample holder and the ultraviolet light source, all in one package. They are normally designed to measure test tubes full of fluorescent liquid. With a special sample holder (Fig. 2) these instruments can be used to measure

FIGURE 1. Laboratory fluorometer specified by MIL-I-25135[1] and ASTM E 1135[6] and containing built-in ultraviolet radiation source and interchangeable filters for light modification.



brightness of filter paper soaked with highly diluted liquid penetrant. ASTM E 1135[6] contains procedural details for comparing the brightness of fluorescent liquid penetrants. These instruments are no longer manufactured but many are still in use.

Figure 2 shows a sample holder that can be built to accept soaked filter paper samples. When such a sample holder is used, it must be positioned properly in the instrument or no reading will be obtained. Because most laboratory fluorometers are arranged so that the angle between the illumination source and the photometer is 90 degrees, the face of the sample must be set halfway between these devices to permit passage of light. Furthermore, the angle must be exactly the same for each sample measured if extreme measurement variations are to be avoided. Usually stops are installed on the instrument case and sample holder for this purpose or the holder may be manually rotated until a maximum reading is obtained.

Another instrument that can be used with soaked filter paper is shown in Fig. 3. The sample holder is pictured lying on its side on top of the instrument. For measurement, the sample holder is inserted in the slot in the front of the instrument.

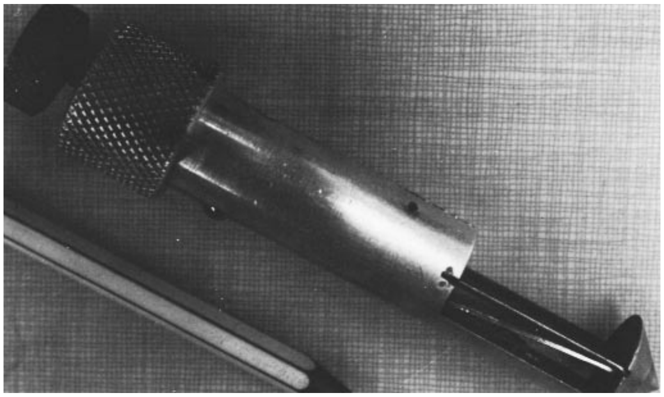
Selection of Filters for Fluorometer Measurement of Fluorescent Brightness

When fluorometers are used for liquid penetrant brightness measurement, they must be equipped with proper filters. First, of course, is the primary filter that must pass ultraviolet-A radiation but absorb visible light. Generally, this filter must be made of cobalt glass, often of a heat resistant type because it may be placed very near the hot light source.

The fluorometer must also be equipped with a secondary filter that corrects the photodetector to the desired wavelength response. The first job for the secondary filter is to remove stray ultraviolet radiation. If ultraviolet radiation is not removed, one obtains a reflectance measurement rather than a fluorescence measurement and spurious results are obtained. Many secondary filters will remove enough ultraviolet radiation to give correct measurements. An ultraviolet radiation filter may be added if excess ultraviolet radiation becomes a problem.

In addition to removing the ultraviolet wavelengths from the fluorescent brightness measurement, the secondary filter should normally cause the instrument to respond to color as the average human eye does. Most fluorometers use photodetectors with the blue sensitive response. A filter combination must be used to correct the response of these phototubes to approximate the human eye response.

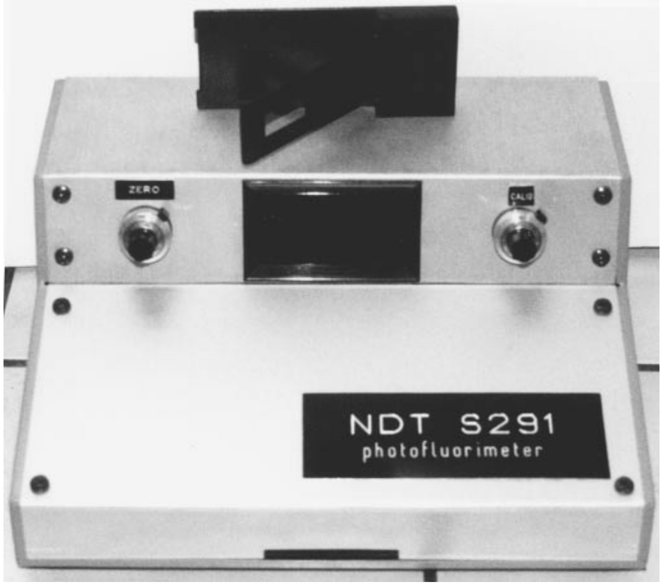
FIGURE 2. Special reflectance measuring sample holder for use with fluorescence photometer.



Test for Water Contamination in Lipophilic Emulsifier

The amount of water contamination in a lipophilic emulsifier can be easily determined by use of ASTM D 95.[21] The test procedure and apparatus are followed exactly as described in the ASTM test

FIGURE 3. Another type of fluorometer for measuring penetrant brightness.



specification but anhydrous (waterfree) xylene must be used as the solvent (instead of the general solvent specified). It is most important that only the waterfree xylene solvent material be used. If this material cannot be obtained, a satisfactory solvent can be prepared by distillation of the commercial grade of xylene by placing a suitable amount of commercial xylene in a still and boiling off ten percent by volume. Most of the water in the commercial xylene will be driven off in this first ten percent evaporation and the xylene residue will be sufficiently dry to permit a reliable test for the water content of emulsifiers. Although lipophilic emulsifiers are petroleum based, the water contamination test results are affected by the type of solvent used in the ASTM D 95 test.[21] (See above for detailed discussion of water content measurements.)

Comparison Tests for Determining Contamination of Emulsifiers by Fluorescent Liquid Penetrant

Fluorescent liquid penetrant contamination in emulsifiers can often be seen by illuminating the used emulsifier with near ultraviolet (ultraviolet-A) radiation. The actual test for liquid penetrant content in an emulsifier can be quite simple or fairly complex, depending on the amount of information desired. Essentially, the test involves preparation of a standard series of emulsifier samples contaminated with various known amounts of liquid penetrant. These are then compared with the test sample of used emulsifier to determine the approximate degree of its contamination with liquid penetrant. The comparison can be made visually or with instruments, depending on the degree of sophistication desired.

The basic procedure for evaluating fluorescent liquid penetrant contamination in lipophilic emulsifiers is to make a series of mixtures of the same types of liquid penetrant and emulsifier used in production. The mixtures should contain amounts such as 0, 5, 10, 15, 20 and 30 percent liquid penetrant. Smaller increments are only confusing. The solutions should be thoroughly mixed and placed in clear, nonfluorescing glass containers. A similar container filled with a similar amount of test sample is then, under ultraviolet radiation, visually compared side by side with the standard series. The estimation thus obtained will be approximate but close enough to confirm or eliminate liquid penetrant content of emulsifier as a cause for a performance deficiency.

Washability Test for Emulsifier Contamination Using Grit Blasted Test Panel

A practical test for emulsifier contamination is a washability test on a grit blasted stainless steel panel. A drop of in-use emulsifier is placed on the panel and is allowed to drain off to one side. Then the panel is washed in a very gentle flow of tap water. Failure of the emulsifier streak to wash clean and without any edge residues indicates the presence of excessive liquid penetrant contamination. Emulsifiers usually exhibit a sharp *washability break* at some critical concentration of liquid penetrant contamination, at which point the streak of emulsifier will not dissolve properly in water. In conducting this washability test, the panel should be examined under ultraviolet radiation for the presence of unwashed residues.

Visual Monitoring of Hydrophilic Emulsifiers Bath for Liquid Penetrant Contamination

Visual monitoring of the hydrophilic remover immersion bath, although not precise, will give clues as to the general condition and freedom from liquid penetrant contamination. For example, a solution of 20 percent hydrophilic emulsifier in water has a clear, pinkish red color in white light and exhibits a pinkish fluorescence under (near ultraviolet) ultraviolet-A radiation. A trace of fluorescent liquid penetrant contamination in the hydrophilic emulsifier bath will darken the emulsifier solution color and the fluorescence will shift to a blue-white color. Much higher levels of liquid penetrant contamination cause the hydrophilic emulsifier solution to become cloudy. With still higher levels of liquid penetrant contamination, free liquid penetrant will float on the surface of the hydrophilic emulsifier bath solution. A hydrophilic emulsifier bath that is cloudy or has free liquid penetrant on its surface is generally considered to be over contaminated. Such a bath can be used but the free-floating liquid penetrant should be skimmed from the bath surface to prevent liquid penetrant contamination of test parts as they are removed from the hydrophilic emulsifier bath.

Noticeable changes in the hydrophilic emulsifier performance, especially increased fluorescent background on the washed test parts, will accompany the visual changes in the bath described above. As the emulsifier bath becomes more contaminated with liquid penetrant, it will become less efficient in removing excess surface liquid penetrant and will require increased emulsifier contact time. The addition of hydrophilic emulsifier concentrate to a contaminated emulsifier bath is not recommended, because this leads to loss of control over the remover concentration. Properly diluted emulsifier concentrate (corresponding to the original remover bath concentration) can be added to a tank that is subject to a heavy dragout loss due to heavy use.

Concentration Control of Hydrophilic Emulsifier or Remover

The concentration of hydrophilic emulsifier in water is important to both its performance effectiveness and the economies of its use. The concentration of hydrophilic emulsifier can be estimated by comparing the color of standard dilutions to those of the freshly mixed bath. This procedure is used for spray solutions rather than for the more highly concentrated dip solutions. This color comparison technique is not usable for contaminated baths of hydrophilic emulsifier.

A useful technique for determining the concentration of specific hydrophilic emulsifiers in water baths is the measurement of the refractive index of the solution. Figure 4 shows a refractometer being used to determine the refractive index of a hydrophilic emulsifier solution. Charts relating the concentration to the refractive index are available from the emulsifier manufacturer. Figure 5 shows an example of the full range of refractive index values for concentrations varying from 0 to 100 percent of a hydrophilic emulsifier in water. This refractive index test is applicable only to fresh, uncontaminated emulsifier solutions. Therefore, the test is especially suited to solutions applied by spray. Contamination by liquid penetrants can cause the refractive index of hydrophilic emulsifier baths to shift from the values for uncontaminated baths.

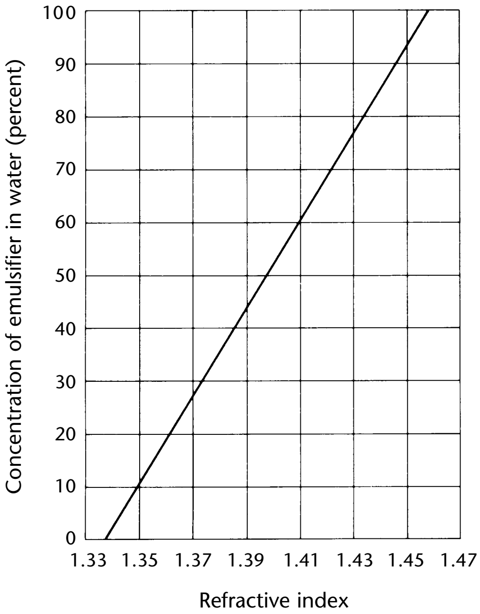
Figure 4. Refractometer test provides an immediate visual determination of hydrophilic emulsifier concentration.

Quick Tests for Performance Loss Due to Remover Contamination

Test Procedure

A quick emulsifier bath performance test uses reference panels for comparison tests to determine the loss in performance due to contamination of hydrophilic emulsifier baths. (See elsewhere in this volume for descriptions of test panels and cracked blocks used for evaluating liquid penetrant test system performance.) The background and indication brightness and definition obtained when liquid penetrant coated test panels are exposed to hydrophilic emulsifier for 15 s and 30 s time periods are compared. Two grit blasted steel test panels and two

Figure 5. Variations of refractive index of specific hydrophilic emulsifier as function of emulsifier concentration in water.



chromium plated panels with fine cracks are covered with liquid penetrant and allowed to drain in air for 5 min. The first set, including one grit blasted and one cracked chromium plated panel, is processed as follows: 15 s prerinse, 15 s drain, 15 s agitated remover dip, 15 s drain and 15 s wash.

The second set of similar panels is processed like the first set, except that the agitated remover dip is of 30 s duration. In this test, fresh hydrophilic remover at 20 percent dilution in water leaves no background residues on either grit blasted test panel. The first cracked chromium sensitivity panel has good crack indications after the 15 s dip. The second cracked chromium sensitivity panel has no indications or only faint indications after its 30 s dip in agitated remover. Fresh hydrophilic remover at 20 percent concentration leaves no background color or fluorescence on either grit blasted background test panel. All panels are dried and developer applied before inspection. These results are those for fresh, clean hydrophilic remover bath.

Interpretation of Results

As the remover bath becomes contaminated, similar test panels given similar processing show differences in performance. Background is present after the 15 s dip and faint background after the 30 s dip, on the grit blasted test panels. The cracked chromium plated test panels show poor performance after 15 s in the remover bath. Resolution on the fine crack panel may improve after the 30 s dip, reinforcing the interpretation of a loss in remover effectiveness with contamination. A sample of fresh liquid penetrant should be used periodically in these tests to determine whether contaminated liquid penetrant could be responsible for the changes observed in performance.

With a specific liquid penetrant and remover, this comparison test indicated that no noticeable change in performance occurred until the remover bath reached about four percent contamination. At four percent contamination with liquid penetrant, heavy background appears on the grit blasted test panel after a 15 s dip and faint background remains even after a 30 s dip. With about six percent contamination, the difference in background on the grit blasted test panels exposed to agitated remover for 15 and 30 s is negligible. the comparison between the two dip periods is the guide to remover condition. The test is only meant to be a quick, easy reference and is not quantitative. With different test objects and processing requirements, the user may find it beneficial to use an ideal test part for performance test or to alter the test conditions to correspond to actual liquid penetrant processing conditions in use in the specific facility.

Visual Comparison Test for Dry Developer Performance

Developers may suffer degradation, which can affect performance and thus should not be ignored. The best test of dry developer is a visual comparison with new developer material under both white light and ultraviolet-A radiation. Limits may be set if desired but the results of the performance test will normally determine whether the material is acceptable or not. Water in dry developers usually comes from incompletely dried test parts, careless overspray during washing or leaking roofs or pipes. Added water causes lumps in the dry developer tank or on the test parts, which may mask indications. If the contaminant is water, the developer material may dry eventually, particularly if heated. Liquid penetrant contamination in dry developers causes bright color or fluorescent spots that form false indications. Liquid penetrant usually enters the developer through careless handling of washing and removal of excess surface liquid penetrant. If the developer is contaminated, the dry powder developer must be replaced.

Control and Maintenance of Aqueous Wet Developer Baths

The proper consistency of aqueous wet developer baths must be maintained by replacing water lost through evaporation or powder lost through dragout. The technique for measuring the consistency of the batch will depend on the type and brand of material being used. The recommendation of the manufacturer should be followed in all cases.

Visual Examination of Applied Developer

One test involves pouring a streak of well mixed developer bath onto a glossy black plate supplied as part of a comparator kit. The appearance of this streak is then compared with the developer streaks on a standard plate. The solution or suspension can then be adjusted by adding more water or more powder until the test streak closely matches the proper standard streak. Any cracking of the developer coating during the drying operation in the normal test procedure indicates (1) a serious loss of water or (2) an excessively high concentration of developer powder. Both of these conditions can cause the developer to obscure indications of fine discontinuities.

Hydrometer Test for Concentration of Aqueous Wet Developer Baths

Another technique of checking the bath concentration is by means of a hydrometer with a suitable range. Before checking the concentration with the hydrometer, the developer bath should be at least 24 h old, soluble powders should be completely dissolved and suspensions should be thoroughly stirred. The hydrometer can be floated directly in the bath or in a small vessel containing a sample of the bath. Manufacturers of the developer will supply information as to the correct hydrometer range for the developer and will furnish tables relating the developer bath concentration and specific gravity. A high specific gravity reading can be lowered by adding water to the mixture. If the specific gravity is too low, add powder and stir thoroughly.

Table 1 compares typical hydrometer readings to developer bath particle concentration. Generally, the powder concentration in water suspension ranges from 40 to 240 g (1.4 to 8.5 oz_m) of dry powder concentrate per 1 L (0.25 gal) of water. This corresponds to 152 to 907 g (0.33 to 2.0 lb_m) of powder per 3.8 L (1 gal) of water (4 to 24 percent by weight).

Evaluating Developer Wetting and Evenness of Coating

The coating test is simply to pour or otherwise apply some of the material and some standard mixture to a smooth hard-to-wet metal surface and inspect for signs of *pulling apart* or *balling up* of the wet developer coating material. A convenient surface for this test is a new, clean, tin-plated lid from a gallon can. If pulling apart or balling up of the coating occurs, the surface should be dried and then checked for even, complete developer coverage.

TABLE 1. Aqueous developer concentrations of dissolved or suspended particles as function of specific gravity hydrometer readings of the bath.

Typical Developer Concentration		Specific Gravity Hydrometer Readings
$g \cdot L^{-1}$	($lb_a \cdot gal^{-1}$)	at 22 °C (72 °F)
120	(1.0)	1.052
96	(0.8)	1.042
72	(0.6)	1.032
48	(0.4)	1.021
24	(0.2)	1.011

Evaluation of Fluorescent Contaminants in Developer Coatings

Another test that should be applied to wet developers is a check for fluorescence. This is easily done by examining the two developer coatings prepared for the evenness test under ultraviolet-A radiation. Increased fluorescence of the test material will be obvious. Whether the fluorescence has reached a rejection level must be determined by the performance test.

Wet developer becomes fluorescent mainly from liquid penetrant carried into it on test parts or that otherwise enters the developer. There is no way to reclaim liquid penetrant contaminated developer, so replacement is the only answer to such a problem. Developer should not normally become fluorescent; therefore, the cause of the problem should be determined and procedures should be altered to prevent recurrence.

Care and Maintenance of Nonaqueous Wet Developers

Most of the developers used with portable liquid penetrant test kits are of the nonaqueous wet type. The developers are procured in a ready-to-use form and contain the necessary developer powder suspended in a volatile liquid medium. With flammable solvent types, operators must avoid smoking or other source of ignition while spraying developer from pressurized spray cans. Solvent developers in bulk should be kept in covered or closed containers to limit evaporation or spreading of flammable vapors. If solvent developers lose appreciable liquid through evaporation, the quality and effectiveness of the developer will decrease significantly. The solids must be in suspension, before use, to obtain proper developer performance. Solvent developers in pressure spray cans or other portable containers must be thoroughly agitated before use to ensure the proper suspension of developer in solvent when applied to test parts. Developers in pressurized spray cans generally do not require maintenance precautions, because they are primarily intended for use only once. When developer is sealed in a spray can, there is no way for it to become contaminated with liquid penetrant or other foreign materials.

If it is necessary to check the content of solids in nonaqueous solvent developers, this can best be done by weighing a well agitated sample of developer, filtering out the solids and then weighing the dried solids content. Older techniques of allowing the solids to *settle out* of a developer suspension have fallen into disrepute.

PART 7. Quality Control Tests for Test Systems and Procedures

Maintenance Checks for Expendable Liquid Penetrant Process Materials

Expendable materials, once placed in service in a liquid penetrant nondestructive test system, are not particularly susceptible to change or variation. Most of the changes that do take place will be apparent to experienced operators by variation in the performance of the liquid penetrant or of the processing materials. In most installations, alertness on the part of the operator may be all that is required to maintain all materials in satisfactory condition. However, it is advisable to carry out a routine check on the test materials to ensure that reliable and consistent performance is being attained with the test system.

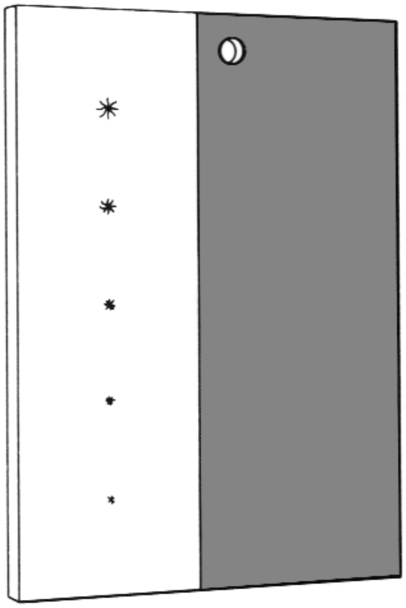
Selection of specific tests will depend on the make and type of liquid penetrant process materials being used. Tests recommended by the manufacturer or supplier of the expendable liquid penetrant process materials may be used as a guide. There are some generally applicable tests, however, that can be applied advantageously, as described here and elsewhere in this volume. Note that these tests described are comparison tests only; that is, a current result is compared to a previous result or results obtained with in-use materials are compared to results obtained with retained unused materials.

Checking Test System Performance with Combination Test Panel

The quality of indications on processed test parts depends on proper functioning of all phases of the entire liquid penetrant test system, including the following: effectiveness of precleaning of test objects; condition of the liquid penetrant, emulsifier and developer (all of which can easily become contaminated or *spent*); liquid penetrant and emulsifier dwell times; temperature, pressure and cleanliness of the wash water; drying time and temperature; lighting in the inspection area.

Figure 6 is a drawing of a combination test panel devised to verify the functioning of the liquid penetrant test system. Proper performance of the test system can be ensured by processing this performance test panel through all cycles of the system, from precleaning to readout of indications, at the beginning of each work shift. One half of the combination test panel consists of a metal strip that has a rough, grit blasted, stainless steel surface. The other half of the combination test panel has a smooth chrome plated surface with five dimple crack patterns imposed on it by a hardness tester. The five dimple crack patterns range in size from very fine to coarse. The combination panel can be used for judging both rough surface washability and smooth surface washability, as well as for judging relative sensitivity of the liquid penetrant test process conducted with a given test system at specified intervals. To remain useful, the combination test panel must

FIGURE 6. Penetrant system monitor panel with rough, grit blasted section (at right) for washability check and five crack centers in chrome plated section (at left) for sensitivity evaluation.



be thoroughly cleaned immediately after each use to remove all residues of liquid penetrant processing materials and water. (See elsewhere in this volume for descriptions of additional artificial reference panels of various types).

Checking Test System Performance Using Test Parts with Known Discontinuities

Test parts with known typical discontinuities and known washability levels can be retained as reference specimens and processed at the beginning of each shift or when inadequate system performance is suspected. These test parts serve a function similar to that of the combination test panel. The experienced inspector will quickly spot a radical change in the liquid penetrant testing system performance by use of either the combination panel or retained anomalous test parts. A problem that must be recognized is that, even after discontinuities in test panels or test parts are cleaned, they may retain residues of liquid penetrants or processing materials from previous liquid penetrant tests or inspections of other types. The gradual buildup of retained processing materials will then reduce the apparent size of the liquid penetrant indications and the test panels/parts must be replaced.

Frequency of Comparison Tests of Liquid Penetrant Materials

In all probability, liquid penetrant materials’ deterioration due to evaporation, contamination and other causes will be gradual. The rate will vary with such conditions as the work load, type of test parts, climatic conditions or prior processing. The need for a comparison test between materials in use and retained standards will not be the same for all liquid penetrant installations. The frequency of tests may vary from as often as twice daily to weekly or even monthly.

Detecting Sudden Performance Shifts in Test System Operation

It should be remembered that, in addition to gradual deterioration, there is always the danger of sudden deterioration of materials or sudden change in the functioning of a processing stage. The sudden change can be guarded against by processing known anomalous parts or special test panels with which the technician is familiar at the beginning of each shift or at other selected intervals. An experienced inspector will detect a change in familiar parts or test panels by noting the following: whether the known discontinuities appear; the contrast of the discontinuity indications; the degree of background color or fluorescence left on test object surfaces after removal of excess surface liquid penetrant and application of developer. The stainless steel combination grit blasted and chrome plated test panel (Fig. 6) has been used for several years to monitor for sudden changes. Another suitable test panel is an unglazed ceramic plate or disk having a surface porosity condition.

Processing special test panels such as these can alert the inspector to a sudden shift in performance caused by the following: sudden increase in oven temperature; failure of developer dust chamber; wash water temperature increase; solvent contamination of emulsifier; and other changes from normal conditions

Though these monitoring panels do not measure the gradual shift in performance and do not replace the comparison test, they protect against the sudden failure and they can be processed quickly and easily.

Tests for Effectiveness of Liquid Penetrant Removal

A removability test, or washability test, often follows the fluorescence test (see elsewhere in this volume for step sequence). These tests measure the removability performance of the individual process materials. Removal performance is very important because surplus liquid penetrant must be removed from the surface of the part or the entire part will have a high background fluorescence. This will greatly reduce the contrast between the discontinuity indication and the rest of the surface area. On the other hand, if the liquid penetrant can be removed too easily, it will be washed out of the discontinuities. This will cause greatly reduced discontinuity detection sensitivity capability, particularly for the shallower discontinuities.

The test for effectiveness of removal of surface liquid penetrant may be performed in a variety of ways but, with present procedures, it must always be done as a comparison to standard materials; this is because there is so much variation of the test parameters even when rigorous controls are applied. An accurate comparison can be made only if standard and test materials are handled side by side.

Selection and Renewal of Removability Test Panels

Removability is probably best tested on a fairly rough surface such as the stainless steel test panels sand blasted with 165 µm mesh aperture (100 lines per 1 in. mesh) grit as specified by MIL-I-25135[1] or AMS 2644.[2] Rough surfaces on test objects are harder to wash than smooth surfaces, so they allow a better evaluation of wash capability. A problem with wash test panels is that, once used, a very slight residue remains on the surface and affects future tests. An effective procedure for cleaning removability test panels for reuse includes the following processing steps: (1) use a soft brush under running water to remove the developer, (2) dry, (3) dip in alcohol, (4) dry, (5) immerse in a solvent and ultrasonically clean and (6) dry. This entire cycle can be repeated if necessary to remove all traces of prior processing materials. If this procedure does not completely clean the panels, they can be sandblasted again and probably should be after five or ten uses.

Procedures for Performing Removability Tests

When performing removability tests, standard and test materials should be applied to separate panels that were grit blasted simultaneously or adjoining areas on a single test piece, being careful not to allow the liquid penetrants to mix. The test should actually be run twice: once with a minimum removal effort (short emulsification or wash) that will not quite completely remove the standard materials and once with a fairly strong removal effort that will completely remove liquid penetrant from the standards.

Interpretation of Liquid Penetrant Removability Tests

If the test materials are more completely removed than the standards, the test materials are being removed too easily and performance will suffer. This loss of performance usually shows up on the performance test, so the purpose of removal test is to point out any poor removability performance. This may be obvious from the results being obtained in the actual test operation where parts being tested may be showing sufficiently high residual background that complaints arise. If so, the main use of this test is to locate which material or materials are causing the poor removability.

Purpose of Cracked Sample Tests

A practical test of a liquid penetrant test system uses a test object or part of the type actually being inspected that contains the smallest allowable discontinuity. If this discontinuity is detected, the liquid penetrant test system is doing the minimum required job. How well this smallest discontinuity is detected can be determined by the brightness of the indication as measured with a photometer (Fig. 7), if such an instrument is available and the information is required. However, because each user's test parts and minimum allowable discontinuity size will be different, there is no way that individual ratings will be comparable when using different parts.

Synthetic Crack Specimens for Comparison Evaluations

In practice, there is a great need for reproducible, synthetically produced discontinuities that can be used to rate and compare liquid penetrant test systems and materials. Many attempts to produce such devices have been made over the years. Unfortunately, none of these attempts has produced the ideal synthetic discontinuity. The big problem is reproducibility. To rate liquid penetrant materials properly in different locations,

FIGURE 7. Narrow angle photometer with digital readout and optical finder.

the test parts must be identical and no two parts of any current synthetic discontinuity sample are identical. Without identical test discontinuities, there is no way to cause the rating of a system done at one location to equal that done at another. Even at one location any rating of a test system, process or material is a comparative rating only.

Over the course of many years, two types of synthetic discontinuity test panels have found wide use despite their inadequacies; the cracked chrome plated brass panel and the quench cracked aluminum block. These are briefly described below and discussed in detail elsewhere in this volume. The normal procedure for checking a complete system by means of cracked specimens is to treat one half of each specimen with all new materials and the other half with all in-use materials. After processing is complete, the specimen is examined closely under the appropriate light, according to the types of materials used.

If a careful comparison reveals no outstanding difference between the two halves of the specimen, it can be assumed that all materials are in usable condition. If the half that was processed with in-use materials bears indications that are definitely inferior, it indicates that at least one of the in-use materials is not up to standard. The actual material(s) at fault can be pinpointed by carrying out further tests, substituting new materials, one at a time, for the in-use ones. This should be continued until the block shows equal indications on the two halves, whereupon the last used material replaced by the new material may be considered at fault.

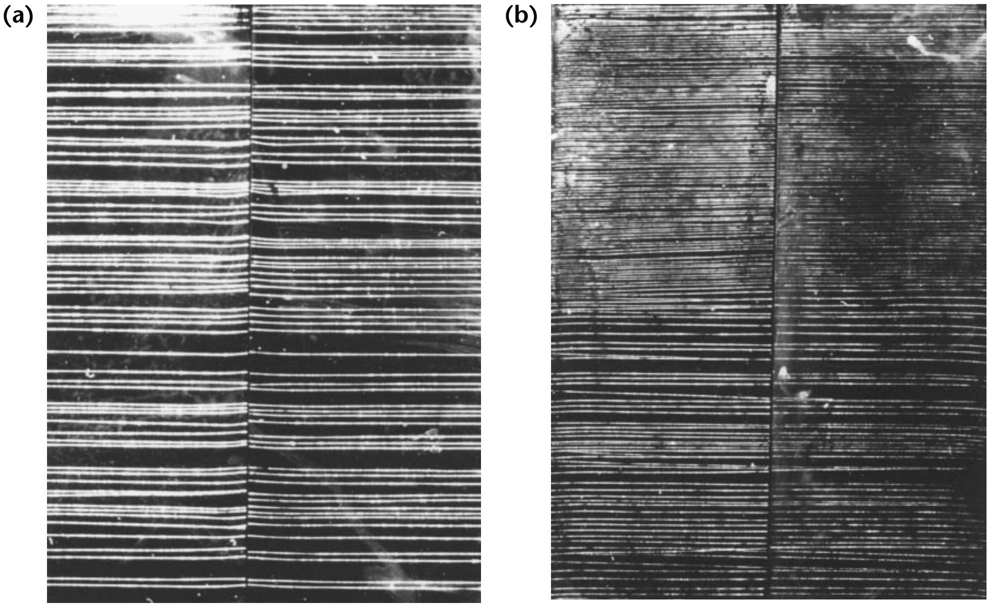
Once the faulty material is found, the necessary corrective measure may be obvious. If not, further tests may be necessary but need be carried out on the inferior material only. If no material is found faulty, one or more processing parameters or procedural steps may be at fault. An audit of the test process or having a different operator process the cracked specimens may help reveal the problem.

In most cases comparable crack patterns appear immediately adjacent to each other on the two halves of a specimen. The patterns should be observed not only for brightness but also for crack definition as well. Photographic records of crack patterns can aid observers to make valid conclusions. Some contaminants, particularly in liquid penetrants, can cause bleeding of indications to such a degree that, although the indications may be larger, they are less well defined and may even obscure other fine indications. In such a case, indications are usually less bright.

Cracked Nickel-Chromium Plated Specimens for Evaluating the Performance of Test Systems

One synthetic discontinuity test panel is the cracked nickel-chrome plated panel. In this case the two halves are two

FIGURE 8. Two examples of matched halves of chrome plated, cracked panels for evaluating liquid penetrant system performance: (a) *coarse* cracks, relatively deep; (b) *fine* cracks, relatively shallow.



separate panels made by cutting the originally prepared panel completely in half. Two examples of this type are shown in Fig. 8.

The cracks extend entirely through the brittle nickel-chrome plating to the brass below, so the depth of the cracks is controlled by the plating thickness. Variation of the coating thickness thus allows the production of different ranges of crack size that can be used to test liquid penetrant test systems with different sensitivity levels. The nickel-chrome plated crack specimens, especially the fine grade, contain some of the smallest discontinuities normally detectable by the liquid penetrant method. Thus, they can be used as *go/no-go* standards for the rating the relative performance of a liquid penetrant test system over a period of time.

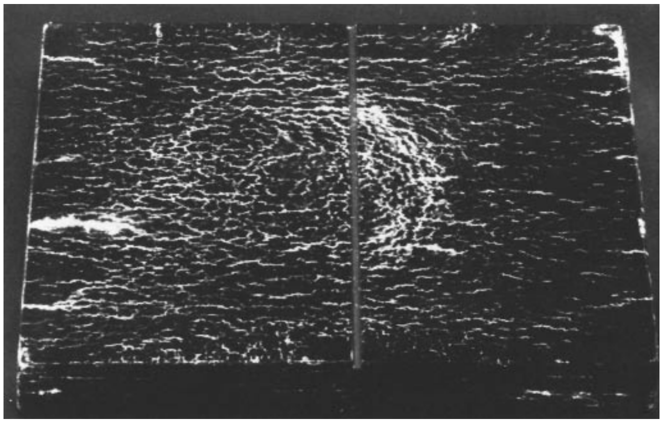
A further advantage of these panels is that they may be easily and completely cleaned for reuse, by washing and brushing off the developer coating and then by soaking the panel in solvent overnight.

Quench Cracked Aluminum Specimens for Evaluating the Performance of Test Systems

A second type of synthetic discontinuity sample in common use, especially for visible dye liquid penetrant test systems, is the quench cracked aluminum block specified in AMS 2644[2] and elsewhere.[1,22] This sample is produced by nonuniformly heating a piece of rolled 2024-T3 aluminum alloy to nearly its melting point, then by quenching the piece quickly in cold water. This produces a network of cracks of various sizes, as seen in Fig. 9. Naturally, there is considerable variation in crack patterns from piece to piece and no two pieces are exactly alike. Therefore, these samples also must be used strictly for comparison of two liquid penetrant test systems or materials on the same piece at the same time.

These samples are suitable only for systems of low sensitivity. To clean them for reuse, it is necessary to wash and brush off the developer, soak the panels in solvent at least overnight and then reheat them to about 30 °C (50 °F) less than the original temperature. This procedure can be repeated only three or four times for a panel before it must be replaced.

FIGURE 9. Quench cracked aluminum test panel specified by MIL-I-25135,[1] AMS 2644[2] and *ASME Boiler and Pressure Vessel Code*.[22]



Need for Improved Synthetic Crack Specimens

Various other liquid penetrant test reference samples have been tried over the years but none has survived in general use except the cracked aluminum blocks and the cracked nickel-chromium plated panels. All others were too difficult to make, not reproducible enough or not sufficiently indicative of performance. There is still need for a better synthetic discontinuity sample than those presently available.

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5
CHAPTER

Interpretation of Liquid Penetrant Indications

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PART 1. Inspector Functions and Terminology for Interpretation and Evaluation of Liquid Penetrant Test Indications

Interpreting Results of Liquid Penetrant Tests

All nondestructive testing methods, including liquid penetrant testing, produce indirect indications of conditions but do not by themselves tell exactly what these material conditions are. The test indications must be correctly interpreted before they give any useful information as to the actual conditions that exist in a material.

Definitions of Liquid Penetrant Interpretation and Evaluation

There is often a tendency on the part of an inspector to confuse the terms *interpretation* and *evaluation* and to fail to recognize that there is a significant distinction between them. Actually, the terms refer to two entirely different steps in the test process and require entirely different categories of knowledge and experience. To *interpret* an indication means to give a decision as to what material condition is causing the indication. There may be many possible conditions: cracks, porosity, lack of results from the assembly of parts, such as a forced fit. Evaluation then follows interpretation. If it has been decided that a crack of given size and direction exists, the extent of its effect on the usefulness of the part must be evaluated before the part can be disposed of: either accepted as is, reworked or scrapped.

Experience Needed for Liquid Penetrant Interpretation

To interpret liquid penetrant indications correctly, the inspector must first of all be thoroughly familiar with the test method in use. The inspector must know that liquid penetrant processing has been correct. In the case of fluorescent liquid penetrants, for example, the inspector must be certain that washing has been thorough, so that the indication the inspector sees can be accepted as that of a *bona fide* discontinuity. The inspector must further be able to derive all possible significant information from the appearance of the indication itself. From this, the inspector may be able to declare that a crack or porosity or some nonrelevant condition is present.

The task, however, becomes easier and the declaration more authoritative if the inspector knows the background of the part being tested. The inspector should know the material, the process by which it is made and the various processes it has been through. The inspector should know the kinds of discontinuities characteristic of the material and should be aware of what discontinuities various processes are likely to introduce. The inspector should know enough about failure of parts in service to know where fatigue cracks are most likely to occur. In addition, of course, the inspector must be familiar, from past experience, with the appearance of indications of these discontinuities in similar parts or materials.

Experience Needed for Evaluation of Liquid Penetrant Indications

Once it is known that a crack or porosity or other discontinuity of given size or direction is present, a decision as to the disposition of the test parts depends on an evaluation of the significance of the discontinuity to the serviceability of the part. This is a question of stress and stress distribution or environmental requirements and calls for the knowledge of the designer and engineer responsible for the performance of the part. For a given service, one direction of discontinuity may be harmless but the same discontinuity that may be at right angles to the tensile stress may be highly objectionable. In the same way, a discontinuity in an area of low stress can perhaps be tolerated but a similar discontinuity in an area of high stress would cause rejection of the part. The usual way of expressing this idea is to evaluate a *discontinuity* as a *defect* only when it will interfere with the usefulness of the part in service.

Importance of the Inspector's Evaluation

Because correct liquid penetrant evaluation depends on accurate interpretation, the inspector is the key person in the test process. In some mass inspection operations, the person who operates the test equipment merely segregates the parts that show indications. Others decide their disposition. In most cases, however, the inspector who first sees the indication is also expected to interpret it. Actually, if the inspector has any of the qualifying background, he or she is the one best able to do this, because the inspector is most familiar with all kinds of indications as they occur on the parts the inspector handles. Also, the inspector is best able, because he or she performed the tests, to know that the process has been properly carried out or to know and assess any variations from normal behavior during the test. The inspector therefore must be thoroughly honest and dependable. The inspector must be fully alert to the importance of the work he or she is doing.

Discontinuity detection with liquid penetrants is more art than science. This is necessarily true unless or until some successful means is evolved that can automatically see and accurately interpret liquid penetrant indications. In the meantime, the inspector must be relied on to perform these functions. Skill and proficiency in developing and then interpreting indications must be acquired by experience. A skilled and experienced inspector can add greatly to the inherent effectiveness of liquid penetrant testing.

Assuming that the inspector knows how to operate the instruments and carry out the techniques, it is almost self evident that the inspector cannot do a competent job unless he or she also knows the materials under test. The inspector must know what they are, how they are made and how they have been processed. This knowledge must include an understanding of what discontinuities may be introduced during manufacture and processing. If the inspector knows what discontinuities to look for and where they are likely to occur, the inspector can select the techniques available for their detection much more effectively.

General Classification of Discontinuities by Their Origination

Discontinuities are most commonly classified on the basis of the progress of material from its raw state to finished form and on into its service life. This classification is as follows.

1. Inherent discontinuities are discontinuities introduced into the basic materials as the result of its initial production from ore to raw components up to the point where it is ready for initial processing.
2. Processing discontinuities fall readily into two groups: (a) discontinuities introduced during primary processes such as casting, rolling, forging, drawing, welding etc. and (b) discontinuities introduced during finishing processing, such as machining, heat treating, grinding, plating etc.
3. Service discontinuities are those discontinuities that develop as the result of the material or part being in service. This group includes fatigue, corrosion and damage from impact, overloads and environment.

Testing in Primary Metals Production

By far the largest field of application of nondestructive tests is in the metal making industry, including ferrous alloys and the growing list of nonferrous metals and alloys now being produced and used. Time and space do not permit discussion of all the types of discontinuities that are special to many of these materials or consideration of the many special processes used to work them and the test problems they present. However, for the usual metals and alloys, there is a considerable similarity both of processes and discontinuities that are encountered. Describing the production of basic metals and pointing out the sources of discontinuities covers, by analogy except for detail, the discontinuities found in many of the common metallic materials as well. The problems of nondestructive testing are still overwhelmingly concerned with the more common metals.

Methods for Producing Metals and Alloys

Iron and the nonferrous metals are refined from their ores by a variety of processes but most of them are ultimately produced in molten form and the molten metal is poured into molds and allowed to solidify. These molds may be ingot molds from which the solidified ingot is taken through a variety of forming processes or they may be molds for casting the metal into final shape, with little or no physical deformation to be made on the product subsequently.

Sources of Impurities in Molten Metal

All care is taken and elaborate techniques have been devised to ensure that the metal be as free as possible from unwanted foreign materials when it solidifies. Inevitably, however, the metal does contain amounts of (1) dissolved or entrapped gasses; (2) various nonmetallic materials such as oxides and sulfides of the metal; and (3) finely dispersed particles of slag. To some extent the behavior of the metal during cooling can be controlled by size and shape of the mold, the technique of pouring and the addition of suitable materials to assist in the removal of gasses.

Sources of Discontinuities Related to Metal Solidification

In spite of all precautions to produce and solidify metal sound and free of foreign materials and gasses, the solidified product invariably contains a greater or less quantity of such nonmetallic materials. Most metals contain nonmetallic inclusions of one sort or another. Their presence is not in itself an indication of poor quality; this is true of steel, copper, brass, aluminum and other metals. However, if not well distributed or if the segregates are large, they may be very objectionable. They will appear as stringers or discontinuities in the final rolled or forged product, which may seriously affect the suitability of the metal for many purposes.

Discontinuities in Metal Ingots

In solidifying and cooling, the metal shrinks. This shrinkage may cause shrink cavities in the center of the ingot, usually mostly confined to the top or last-to-freeze portion. This section of the ingot is normally cropped and discarded. If it is not completely eliminated, such internal discontinuities may show up in the finished product as pipe in rolled bars or as laminations in plate or strip.

Cracking also may occur on the surface of ingots. These cracks are removed as completely as possible by chipping or scarfing so that they will not show up as seams on the finished product.

Sources of Discontinuities in Metal Castings

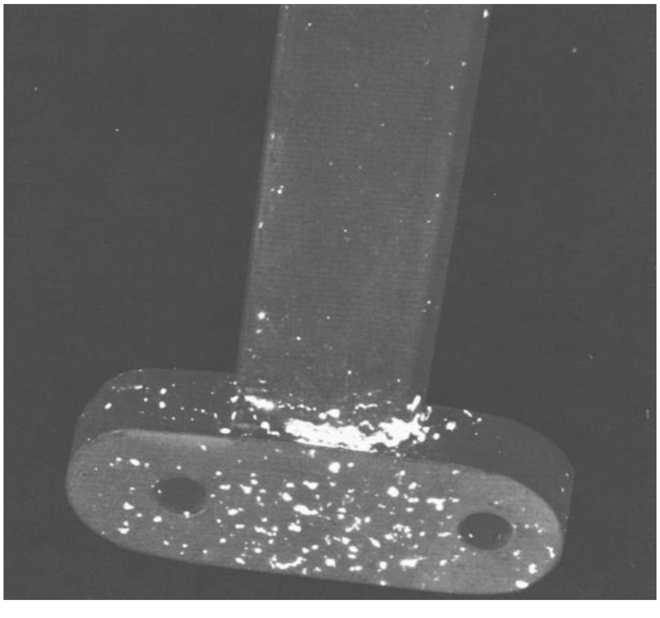
In the case of castings, where the metal solidifies in final form, great care is taken to place gates and risers by which surplus metal is provided at favorable locations so that impurities can float out of the casting proper and gas can have a chance to escape. Porosity and gas pockets along with slag inclusions are still a major source of discontinuities in castings and much testing focuses on the location of these undesirable conditions (Figs. 1 and 2). This is true of nonferrous castings as well as steel, and special types of porosity are related to individual metals and casting processes, as for instance surface porosity in die cast magnesium alloys.

Shrinkage on cooling results in thermal cracks in castings, most often on the surface and related to the shape of the casting but sometimes internal (see Figs. 3 and 4). Other casting discontinuities are hot tears and cold shuts, both being surface discontinuities.

Movie. Fluorescent bleedout reveals shrinkage.

Figure 1. Fluorescent liquid penetrant indications of porosity and shrinkage cracking in cast light alloy aircraft fittings.

Figure 2. Fluorescent liquid penetrant indications of porosity in light alloy aircraft casting.



Sources of Discontinuities in Blooms and Billets

When cast into ingots, the metal is then further worked down into usable forms by forging, rolling or pressing. The steel ingot, for example, is reheated to the proper temperature and passed between heavy rolls to form blooms or billets. The size of ingots varies widely, depending on the ultimate product to be made from them. Ingots of alloy and tool steel may be quite small, weighing perhaps 100 kg (220 lb_m), whereas ingots from which large forgings or large thick plate are to be made may weigh many tons. Blooms and billets are formed in an intermediate step between the ingot and the finished size or product.

FIGURE 3. Fluorescent liquid penetrant indication of crack at attachment lug in cast light alloy aircraft part.

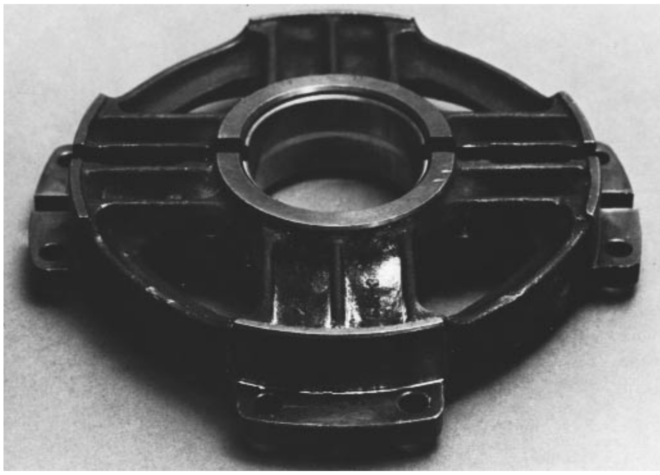
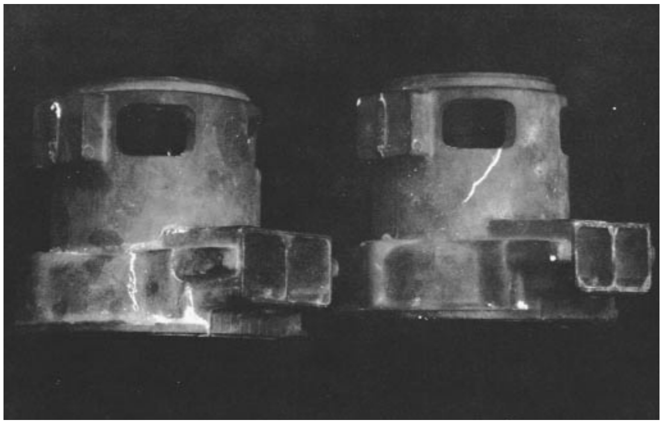


FIGURE 4. Thermal cracks and shrinkage in cast motor housings.



The surface of blooms and billets may contain seams due to rolled out ingot cracks resulting from cooling stresses or bursts or tears or rolled-in scale or metal particles. All of these surface imperfections should be removed before the final finishing operation. Unless they are completely removed, the end product will contain seams or other surface discontinuities that would be objectionable. The surfaces of blooms and billets may be freed of such objectionable conditions by chipping, grinding or flame scarfing. Billets, especially when intended for seamless tube piercing, are often cleaned up by scaling, i.e., by taking a cut off the surface in a lathe if the billet is round or by planing the surface if the billet is square.

Sources of Discontinuities in Hot Rolled Bars, Shapes, Plate or Strip

The blooms or billets are often reheated to proper working temperature and rolled into bars, shapes, plate or strip. As has been pointed out, seams, stringers and laminations may appear in the finished product as a result of rolling, forging or extrusion. The rolling operation itself may introduce certain discontinuities, of which the most common are laps resulting from too much or too little metal to fill the rolls. Too rapid reduction of cross section, especially if the metal is at too low a temperature, may produce tears and internal rupture called cupping.

Internal shrinkage cavities from the ingot or gas pockets not completely welded shut in the rolling operation may result in laminations in plate or strip or in pipe, bars or other shapes. Uneven cooling of some types of steel may cause cooling cracks to appear in bars and shapes — a type of damage that may be very severe.

Sources of Discontinuities in Forgings

If the ingot or billet is used for forging, a variety of discontinuities can be produced, usually because of improper handling of the metal under the hammer or to working at too low a temperature. Common discontinuities are laps and folds. Forging bursts, both external and internal, can also occur. Figure 5 shows a forging lap.

In the case of die or drop forging, laps and surface tears and bursts may be produced. In die forgings, excess metal is forced out between the two halves of the die forming the flash and this excess metal is subsequently trimmed off. If not properly done, flashline cracks or tears may be formed. Another type of forging discontinuity is the internal rupture usually called flake, which occurs in the process of cooling relatively large forgings. These may be very severe and extremely objectionable.

Sources of Discontinuities in Rolled and Pierced Products

In the production of seamless tubing, the billet is pierced. Discontinuities on the inside surface of the pierced billet may take the form of tears. Seams may occur on the outside surface, especially if the surface of the billet or blank had not been properly cleaned.

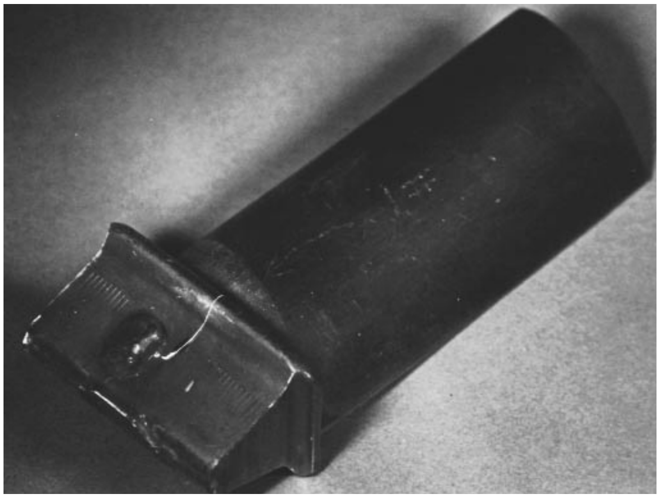
Sources of Discontinuities in Extrusions

Nonferrous seamless tubing is often made by extrusion, starting with hollow or pierced billets or from solid ingots. Discontinuities that occur may be checks and tears or imperfections may result from uncovering or bringing to the surface internal discontinuities of the billets or ingots. In addition to tubing, many shapes and products are made today by various extrusion processes. Because of flow of the metal of the original ingot during extrusion, oxide and surface skin sometimes becomes folded into the interior. A form of pipe also results from this action, which is most objectionable when it appears in a finished shape.

Sources of Discontinuities in Cold Worked Metal Products

Cold rolling and cold drawing of strip, rod and wire is a process for improving the surface finish of steel products. Close dimensional tolerances can thus be maintained and the metal becomes somewhat work hardened. Die marks, scratches and surface imperfections sometimes make their appearance in this process. Of course, the process does not remove any seams or other discontinuities present in the material before the cold finishing is applied.

Figure 5. Fluorescent liquid penetrant indication of forging lap in aircraft turbine bucket (shown on as-forged surface which has not been machined).



Sources of Discontinuities in Fusion Weldments

Welding is a process that has its own group of typical discontinuities that must be guarded against. In fusion welding processes, where liquid metal solidifies in the weld, the same sort of discontinuities may occur as in castings — namely, slag inclusions, gas porosity and thermal cracks. In addition, cracking in the parent metal may occur because of thermal stresses or as a consequence of hydrogen pressure. There are also discontinuities due to lack of penetration of the weld and failure to get proper fusion of the weld metal to the parent metal.

Sources of Discontinuities in Heat Treating Processes

Looking now at the various finishing processes, most metal products undergo some form of heat treatment to produce desirable physical properties. In the course of heat treatment, discontinuities may be produced, most often as the result of warping or cracking. Quenching cracks occur in steel when the process is not properly carried out or when the design of the part or the steel used is not adapted to the operation. Quenching cracks are apt to appear in connection with changes in cross section of the material that cause excessive cooling stresses or at locations where the contour of the surface permits stress concentrations to occur. Sometimes hardened parts are cracked when an attempt is made to straighten those that have warped slightly out of shape.

Movie. Quenching cracks.

Special nondestructive test techniques have been devised for checking hardness against specification tolerances and for such unwanted conditions as abnormal grain size, segregations etc.

Sources of Discontinuities in Machined and Ground Surfaces

Sometimes machining operations, as for instance too heavy a cut with improper tools, may cause surface damage, leaving discontinuities in the form of surface tears. Grinding of surfaces for accurate dimensions or for finish is a prolific source of surface cracking, especially on hardened steel surfaces. Parts that have been hardened may have residual internal stresses, produced in the quenching process and not subsequently removed by drawing or stress relieving. Such parts are particularly sensitive to the formation of grinding checks.

Sources of Cracks during Plating or Chemical Treatment

Parts containing residual stresses from heat treatment or perhaps simply from cold working may crack during plating processes or during the pickling that precedes plating. This is because the pickling etch removes some of the metal surface containing compressive stresses, permitting the internal tensile stress to be relieved through cracking. Embrittlement by absorbed hydrogen during pickling may sometimes be a factor in such cracking.

Sources of Fatigue Cracks Incurred during Service Operation

The last group of discontinuities are those that occur after the part or material has been placed in service. Of this group, fatigue cracking and failure resulting from fatigue is by far the most important group. Fatigue occurs during repeated or cyclic loading or stressing of materials (see Figs. 6 and 7).

A fatigue failure starts with a crack initiated by a variety of causes. Under cyclic loads, this crack progresses through the cross section of the metal until only a small portion of the original section remains sound. Finally failures occur even when calculated or average stresses are far below the elastic limit and do not depend directly on whether the tensile strength of the metal, as determined by static tests, is either high or low.

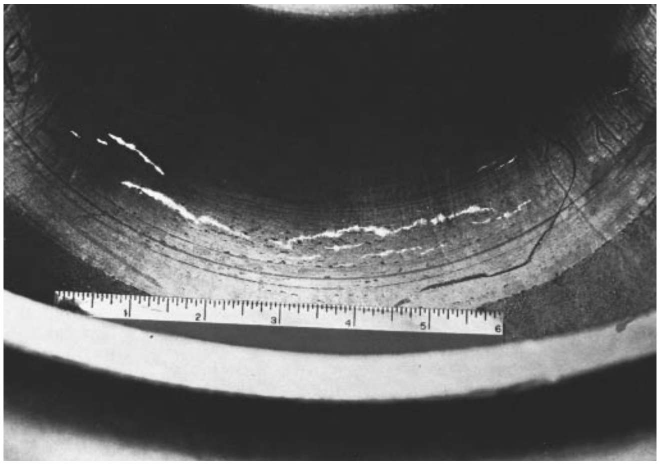


Figure 6. Fluorescent liquid penetrant indications of fatigue cracks in aircraft wheel.

Significance of Surface Discontinuities under Repeated Loading or Vibration

Fatigue cracks almost invariably start at the surface and are initiated by conditions that bring about locally high stresses. These stress concentrations involve stresses above average for the part. The stresses may, in their local area, be above the fatigue strength of the metal. Surface scratches, cracks or other discontinuities may cause these local areas of high stress (Fig. 7). Localized high stresses may also be caused by design features of the part — for example, high stresses occur around holes, fillets and stiffening members.

Prevention of Fatigue Failures in Service

One of the main purposes of liquid penetrant nondestructive testing is to locate and eliminate discontinuities likely to lead to fatigue failures. However, fatigue cracking still occurs and is a serious indication sought by nondestructive techniques when the

Figure 7. Example of working standard and interpretation guide for 356-T6 aluminum alloy casting with line of porosity that will propagate into a fatigue crack and cause failure. This condition is in stressed area, so fan casting should be rejected.

machine or structure is inspected at intervals during its service life. Fortunately, fatigue cracks do not often propagate so rapidly that they cannot be located early in their existence and the part replaced before failure.

Sources of Failures Related to Corrosion

If a part that is subject to frequent stress reversals or fluctuations is at the same time subject to corrosion, fatigue cracks may appear very rapidly and may progress to failure in a very short period of time.

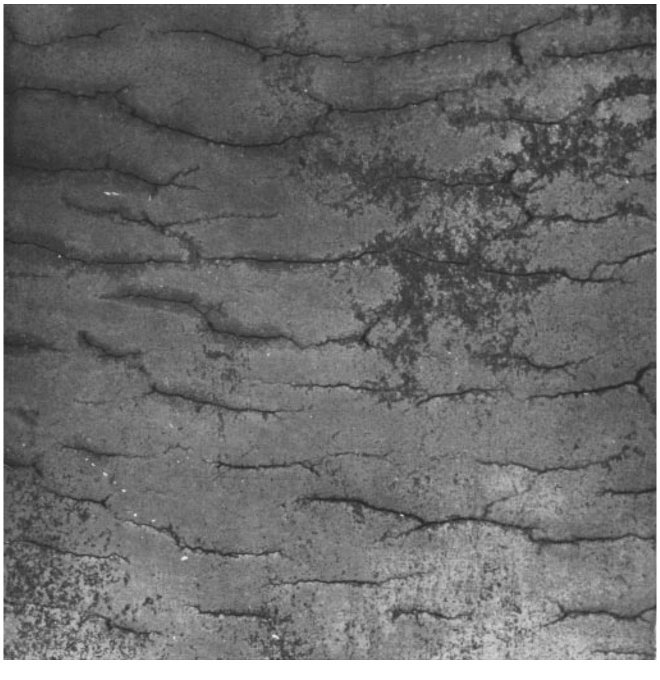
Corrosion leads to another type of service failure through cracking of metal subject to corrosion at the same time it is under tensile stress. Stress corrosion cracking of steel beams around bolt holes, leading to bridge collapse, is an example. Such cracking is analogous to cracks in the surface of heat treated or cold worked parts produced in pickling before plating, where residual tensile stresses are left from some previous operation. The corrosion allows the tension stress at the surface to be relieved by cracking (Fig. 8).

Other Causes of Service Damage

Other sources of service damage causing cracking that can be located by nondestructive techniques are abnormally high stresses caused by vibration, as in steam turbine blades and jet engine buckets; impact due to wrecks and other sudden stoppages; and overloads due to abnormal service conditions or simple abuse of the engine or machine.

On the subject of sources of discontinuities in all kinds of materials on which nondestructive testing techniques are commonly used, books have been written that give useful references for those in the field of nondestructive testing.[1-3] The material in the present chapter gives merely a general idea of how many typical and often encountered discontinuities are produced and to provide background for later discussions of nondestructive testing techniques designed to locate such discontinuities.

FIGURE 8. Visible dye liquid penetrant indications (without developer) of stress corrosion cracking of metallic sheet.



PART 2. General Interpretation of Liquid Penetrant Indications

Mechanism of Formation of Liquid Penetrant Indications

Any liquid penetrant indication marks the location of a discontinuity on the surface of the test object. There must be a surface opening; liquid penetrants cannot detect inclusions, chemical segregation, the presence of foreign material or any other abnormality unless an opening is present. Because of the nature of liquid penetrant testing, even a crack or void will remain undetected unless open to the part surface. Liquid penetrants work equally well on any nonporous metal, regardless of magnetic properties, size, shape or chemical composition.

Even ferromagnetic metals, which are usually checked by magnetic particle testing, are sometimes more easily inspected for surface cracks by liquid penetrants. For example, the sudden change in section in sharp fillets or in the roots of threads may cause a nonrelevant magnetic indication. Because liquid penetrant testing deals only with the surface, it can be used with equal accuracy in sharp corners or on wide, flat areas.

Evaluation of Liquid Penetrant Indications

The presence of an indication poses three questions.

1. What type of discontinuity causes this indication?
2. What is the extent of this discontinuity?
3. What effect will this discontinuity have on the anticipated service of the part?

On the answers to these three questions depends the fate of the part — acceptance or rejection.

Quantitative information on the type and size of discontinuity is not always obtainable from surface inspection alone. Liquid penetrant indications do, however, provide the experienced inspector with qualitative data on which to base a decision in all obvious cases. The inspector must know the kind of discontinuity and its approximate magnitude before attempting to solve the third problem, that of estimating probable damage to the part.

Appearance of Liquid Penetrant Indications

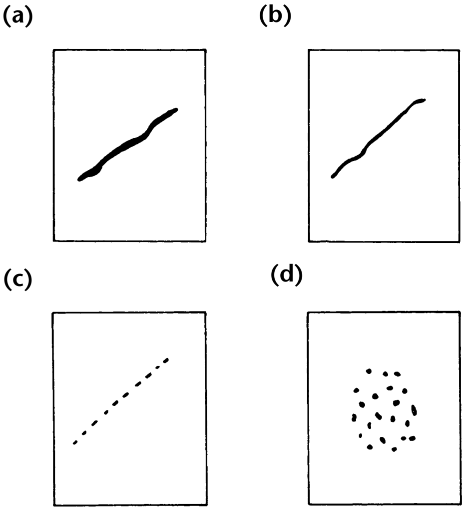
If fluorescent liquid penetrant is used, the examination is made under ultraviolet radiation, sound areas appear as deep violet-blue, whereas discontinuities glow with a brilliant, generally yellow-green light. The intensity of the fluorescence is associated with the volume and concentration of liquid penetrant retained in the discontinuity. If visible dye liquid penetrant is used, the examination is made in ordinary white light. The developer forms a white background and discontinuities are made visible by a red color indication, whose richness is closely related to the volume of entrapped liquid penetrant.

Several factors influence the exact appearance of individual liquid penetrant indications. However, there are certain general trends that hold true for all sorts and forms of materials.

Interpretation of Continuous Line Liquid Penetrant Indications

A crack usually shows up as a continuous linear liquid penetrant indication, as shown in Fig. 9. The width and brightness

FIGURE 9. Typical liquid penetrant indications: (a) large crack or opening; (b) tight crack or cold shut; (c) partially welded lap; (d) pits or porosity.



MOVIE. Linear discontinuity.

MOVIE. Open and partially open cracks.

MOVIE. Pitting and porosity.

of fluorescence or color depend on the volume of the crack. The line may be fairly straight or jagged, because it follows the intersection of the crack with the surface. A cold shut on the surface of a casting also appears as a continuous line, generally a relatively narrow one. Because cold shuts are caused by imperfect fusion where two streams of metal meet but do not merge, the liquid penetrant indication is likely to be smooth in outline rather than jagged. A forging lap may also cause a continuous line liquid penetrant indication.

Interpretation of Intermittent Line Liquid Penetrant Indications

Many forging laps are partially welded during subsequent blows of the forging hammer. The liquid penetrant indication caused by such forging laps is therefore an intermittent linear indication. A subsurface crack that does not reach the surface for its entire length or a seam that is partially filled also produces an intermittent line or liquid penetrant indication, as shown in Fig. 9c.

Interpretation of Rounded Areas of Liquid Penetrant Indications

Rounded areas of liquid penetrant indication signify gas holes or pin holes in castings or relatively large areas of unsoundness in any form of metal. The indications appear rounded because the volume of liquid penetrant entrapped; the actual discontinuities may be irregular in outline. Deep crater cracks in welds frequently show up as rounded indications also, because a large amount of liquid penetrant is entrapped and the individual crack indications merge.

Interpretation of Small Dot Liquid Penetrant Indications

Liquid penetrant indications in the form of small dots, as in Fig. 9d, result from a porous condition. Such indications may denote small pin holes or excessively coarse grains in castings or may be caused by a shrinkage cavity. In the latter case, an overall indication pattern of fernlike or dendritic outline is usually noted.

Interpretation of Diffuse Liquid Penetrant Indications

Sometimes a large area presents a diffused appearance. If fluorescent liquid penetrants are used, the whole surface may glow feebly; if visible dye liquid penetrants are used, the background may be pink instead of white. This diffused condition may result from very fine, widespread porosity, such as microshrinkage in magnesium. Or it may be caused by insufficient cleaning before testing, by incomplete removal of excess liquid penetrant, by too thick a coat of developer. Weak indications extending over a wide area should be regarded with suspicion. It is usually wise to repeat the liquid penetrant test and to eliminate any false indications due to faulty technique, rather than to attempt immediate evaluation of a diffused indication.

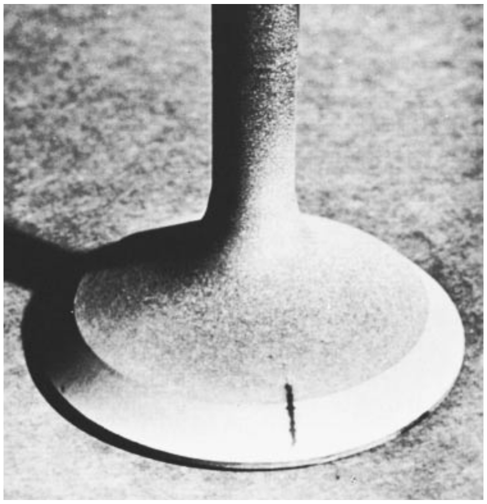
Edges of Indications

The sharpness of liquid penetrant indications is affected by the volume of liquid retained in the discontinuity, the test conditions such as temperature and time allowed for indications to develop and the type of liquid penetrant used. Generally, clear cut indications come from narrow linear discontinuities.

Brilliance and Extent of Liquid Penetrant Indications

The color or fluorescent brightness of liquid penetrant indications can be useful in estimating the seriousness of the discontinuity. Brightness is directly related to the amount of liquid penetrant present and therefore to the size of the discontinuity. It is difficult for the human eye to detect slight differences in color of dye or brilliance of fluorescence. Tests show that although instruments can record four percent difference in brightness, the eye cannot see less than 10 percent difference. It is fortunate that larger discontinuities nearly always produce larger indications in addition to the increased brightness.

FIGURE 10. Visible dye liquid penetrant indication of crack in heat resistant alloy diesel valve.



Time for Liquid Penetrant Indication to Develop

Other things being equal, the time required for an indication to develop is inversely proportional to the volume of the discontinuity. The larger the discontinuity, the more quickly will liquid penetrant entrapped therein be pulled out by the developer. The crack in the railroad diesel engine valve in Fig. 10 appeared immediately, showing that it was a discontinuity of significant size. It is important to allow sufficient time for the appearance of minute indications from fine discontinuities, such as tight fatigue cracks. To use the time required for an indication to develop as a measure of the extent of the discontinuity, other variables such as type of liquid penetrant, sensitivity of technique, temperature of part, dwell time and condition of examination must be controlled.

Persistence of Liquid Penetrant Indications

One good way to estimate the size of discontinuity is by the persistence of the indication. If it reappears after the developer has been removed and reapplied, there must be a reservoir of liquid penetrant present. In case of faint or weak indications where there is some doubt as to the type or even the existence of a discontinuity, it is good practice to repeat the entire liquid penetrant test. If the indication reappears, it is probably due to a small discontinuity rather than to incomplete cleaning.

PART 3. Processing Effects Influencing Liquid Penetrant Indications

Influence of Liquid Penetrant System Selection on Interpretation

Various commercial materials are available for liquid penetrant testing, each of which has its special field of optimum application. To a large extent, the sensitivity of the liquid penetrant test process can be varied at will by the proper selection of liquid penetrant and developer. It is important for best results to discuss with the manufacturers the type of discontinuity that should be found by liquid penetrant testing. Very high performance liquid penetrant systems may cause unnecessary rejections due to indications from discontinuities that do not adversely affect that particular part.

Effects of Metals Manufacturing Processes on Liquid Penetrant Indications

Liquid penetrant indications can be influenced seriously by previous processing during manufacturing, inspection or surface treatments of test parts. Although the chemical composition or form of material does not affect the indications obtained from liquid penetrant testing, it is true that the same technique will produce varying indications on rough castings, finish machined parts or die forgings because the various manufacturing processes result in characteristic surface conditions that frequently have individual types of discontinuities. Furthermore, some operations may interfere with accurate liquid penetrant testing. Table 1 gives the effects of metals manufacturing processes on liquid penetrant indications.

Therefore, any interpretation of liquid penetrant indications should include consideration of the test part and its history. Is the surface porous? Is there a possibility of embedded material that would clog openings, say, in lapped parts? Can the production techniques obscure a discontinuity, such as a seam or forging lap, by further working that tends to close the discontinuity? Or does the shape of the surface tend to produce an irrelevant indication, perhaps by trapping liquid penetrant in the undercut area of a weld? Obviously, paint or plating films interfere with the entrance of liquid penetrants into discontinuities. Anodic or chromate treatments reduce the detectability of many fluorescent liquid penetrant indications, primarily because the porous oxide absorbs penetrants and creates a bright fluorescent background. However, special fluorescent liquid penetrants can be used successfully after anodic or chromate treatments. It is essential that the fabrication methods be considered when interpreting liquid penetrant indications.

TABLE 1. Effects of metals manufacturing processes on liquid penetrant indications.

Process	Obscured Discontinuities	Irrelevant Indications
Casting	———	rough surface retains liquid penetrant
Honing, lapping	compound clogs openings	oils and greases may fluoresce
Forging	partially seals laps	scale holds liquid penetrant
Shot blasting	seals openings	———
Polishing	metal flows over discontinuities	———
Heat treating	———	scale holds liquid penetrant
Painting or plating	fills openings	———
Anodizing	reduces fluorescence	porous oxide absorbs liquid penetrant
Chromate treatment	reduces fluorescence	———
Rough machining in blind holes	———	hard to remove excess liquid penetrant
Welding	———	rough surface retains liquid penetrant

Effects of Previous Testing on Liquid Penetrant Indications

Test processes, like fabrication, can change the surface condition. It is not possible to determine the relative efficiency of various test processes by subsequent checks of the same part because many of the materials used in magnetic particle, fluorescent liquid penetrant and visible dye liquid penetrant techniques are incompatible.

Discontinuities may remain undetected by liquid penetrant testing. If magnetic particle testing has been previously used, the residual iron oxide may fill or bridge the discontinuity. Similarly, fluorescent liquid penetrant will often fail to show discontinuities previously found by visible dye liquid penetrant because the dye absorbs incident ultraviolet radiation or perhaps reduces or even kills fluorescence. Subsequent visible dye liquid penetrant testing may miss discontinuities indicated by fluorescent liquid penetrant, because the later affects the visible color dye. Therefore, in judging the presence or absence of liquid penetrant indications, the inspector must know whether the parts have been subjected to other test processes. If such is the case, extreme care must be taken to clean parts thoroughly before the additional liquid penetrant testing.

Chromic Acid Anodic Treatment to Provide Acid Stain Indications

Anodic treatment interferes with fluorescent liquid penetrant testing. However, chromic acid anodization serves both manufacturing and inspection needs. Although its primary purpose does not include the detection of cracks, laps or other surface discontinuities, experience has shown that chromic acid anodization does render such discontinuities more visible. Any surface connected void retains some of the acid, which then produces a directional chromic acid stain on the surface. Although not so sensitive as liquid penetrant testing, chromic acid anodization is accepted by some as an alternate method for detection of surface discontinuities in aluminum alloy forgings.

Other Variables Affecting Indication Appearance

The following variables have a marked effect on the size, brilliance and appearance of liquid penetrant indications: condition of surface, temperature of the part or the liquid penetrant, dwell times, amount of washing, developer and conditions of examination.

Effects of Test Object Surface Condition on Liquid Penetrant Indications

Surface conditions that influence liquid penetrant indications are given in Table 2.

There are four general ways in which the condition of the surface can interfere with the proper results from liquid penetrant testing.

1. Surface openings may be closed. This can occur when lubricants, polishing compounds, dirt, scale or other contaminants are forced into cracks or holes. Or metal can be peened over surface discontinuities by forging, polishing or shot blasting.
2. Rough or porous areas may retain liquid penetrant, producing irrelevant indications. Or naturally fluorescent materials (such as many oils and greases) may cause confusing indications.
3. Deposits on the surface or in openings may dilute the liquid penetrant and thus reduce its effectiveness, or such materials may react with the liquid penetrant, destroying fluorescence or dye color.
4. Water or moisture within crack discontinuities can prevent the liquid penetrant from entering the crack.

Proper cleaning before liquid penetrant testing will remove any dirt or other contaminants, leaving surface openings free to receive the liquid penetrant. For correct evaluation of the discontinuities found by liquid penetrant testing, it is essential that the surface be adequately

Table 2. Effects of surface conditions on liquid penetrant indications.

Surface Condition	Possible Result
Oily or greasy	no indications (openings closed) or false fluorescence
Dirty	no indications (openings closed)
Shot blasted	no indications (openings closed)
Acid	weak indications (reduced fluorescence)
Caustic	weak indications (reduced fluorescence)
Wet	weak indications (diluted penetrant)
Scale or rust	no indications (openings closed) or false indications
Excessively rough weld	false indications
Rough castings surface	false indications
Clean	excellent

clean and dry. If it is impossible to attain satisfactory cleanliness, the inspector must try to take this fact into account when weighing the importance of liquid penetrant indications.

Effects of Temperature of Part or Liquid Penetrant on Indications

The viscosity of most liquids increases at low temperature and liquid penetrants are no exception. If a part is quite cold, say under 16 °C (60 °F), the liquid penetrant may be chilled and thickened so that it does not enter very fine discontinuities in the same dwell time as for higher temperatures. If the part or liquid penetrant is too hot, the volatile components of the liquid penetrant may evaporate, changing the capability for revealing small discontinuities. Material temperatures from 10 to 52 °C (50 to 125 °F) produce optimum results with conventional liquid penetrants.[4] However, special liquid penetrants developed for aerospace and nuclear power programs can be used in extremely cold temperatures and others at relatively high temperatures.

Effects of Dwell Time and Washing on Liquid Penetrant Indications

Fine liquid penetrant indications usually denote fine discontinuities. However, fine indications may be caused by insufficient liquid penetrant dwell time. A diffused indication may mean a generally porous condition but may also imply incomplete washing. If excess liquid penetrant is not removed, false indications are evident. On the other hand, washing too long and too hard can remove liquid penetrant from large or shallow discontinuities, resulting in less intense indications. Problems resulting from poor washing are discussed elsewhere in this volume.

Effect of Developer on Liquid Penetrant Indications

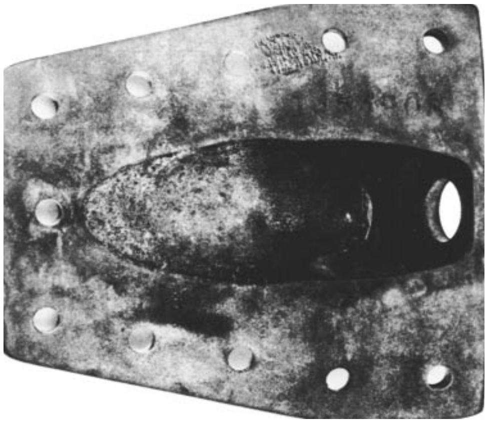
The developer renders indications more easily visible by (1) providing a contrasting background, (2) pulling liquid penetrant out of openings by a blotting action and (3) reducing glare from reflected light during observations of fluorescent indications. A thick film of developer may absorb liquid penetrant, resulting in faint indications or even masking very fine discontinuities. The net result of most faulty liquid penetrant processing techniques is loss of indications, as indicated in Table 3.

Effect of Examination Conditions on Visibility of Liquid Penetrant Indications

The correct interpretation of indications from liquid penetrant testing is up to the inspector. In addition to a knowledge of the meaning of indications and the

FIGURE 11. Heat treatment cracks in forging: (a) fluorescent indications; (b) cross section.

(a)



(b)

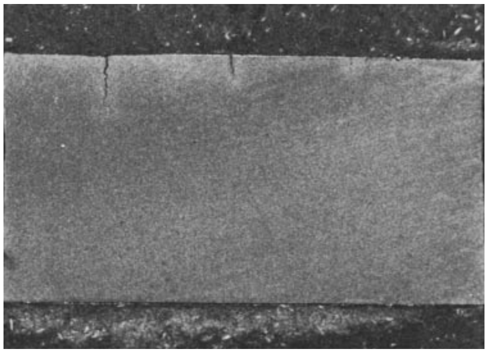


TABLE 3. Results of faulty liquid penetrant processing techniques.

Operation	Too Low or Too Little	Too High or Too Much
Temperature of part or liquid penetrant	fine defects missed	fine defects missed
Dwell time	fine defects missed	removal difficult
Washing	false indications	liquid penetrant removed from shallow defects
Developer	poor contrast	hide fine defects

variables affecting them, a good inspector must have good eyesight and proper lighting. The latter is especially important for fluorescent liquid penetrants, which should be viewed in a darkened area with ultraviolet illumination.

An inspector whose eyesight was below average because of a vitamin A deficiency or whose eyes had not properly adjusted to the darkened examination booth could not have detected the fine heat treatment cracks shown in Fig. 11a. As shown in Fig. 11b, these cracks could be very serious in this highly stressed aircraft forging.

PART 4. Establishing Acceptance Standards for Liquid Penetrant Indications

Types of Specifications for Liquid Penetrant Testing

Specifications and standards applicable to liquid penetrant testing may be divided into two broad classes: (1) those dealing with techniques and (b) those dealing with materials. Each of these groups can be broken down further. Some of the subgroups are below.

Techniques

Specifications and standards may apply to the following types of techniques:

1. broad procedural guidelines;
2. company procedural guidelines;
3. procedural guides for specific types of products or for industries;
4. procedures for testing specific articles, specified by a purchaser or by process specifications internal to the company;
5. procedures specified for overall inspection of a company's products;
6. specifications for certification of operators;
7. standards for acceptance or rejection, set up by buyer or by company for quality control;
8. repair station requirements;
9. equipment specifications; and
10. instructions for operating specific types of equipment or individual special units.

Materials

Specifications that apply to materials may be of the following types:

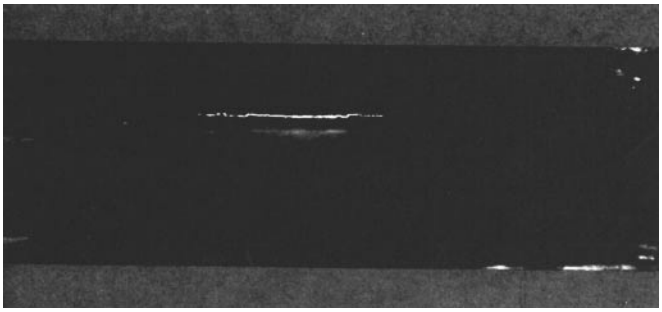
1. specifications designed for use in purchasing liquid penetrants and other materials and
2. specifications designed for testing and evaluating performance of liquid penetrants and other materials.

Lack of "Standard" Liquid Penetrant Indications

There are as yet no "standard" liquid penetrant indications for comparison. Radiographers can judge the seriousness of a discontinuity revealed on X-ray film by comparing it with standard film but the many factors affecting liquid penetrant testing have retarded the establishment of standards for this process. Differences in indications may be due to personnel or technique, as well as to variations in discontinuities. The inspector must know the technique used and its effect on liquid penetrant indications. Possible causes of inadequate liquid penetrant indications are shown in Table 4.

FIGURE 12. Crack in stainless steel tube: (a) fluorescent liquid penetrant indication; (b) cross section.

(a)



(b)

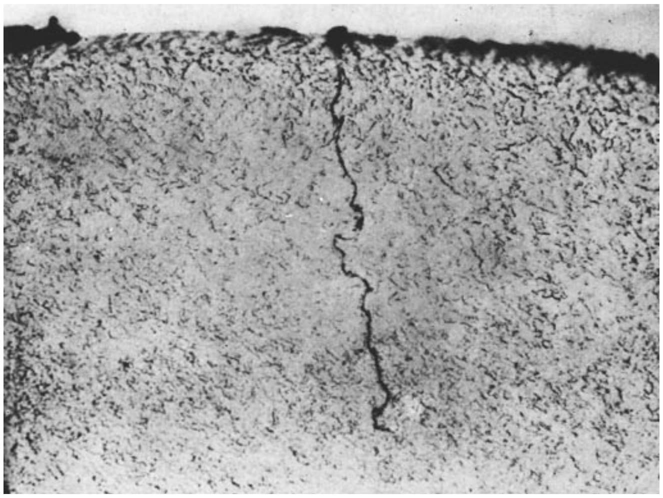


Table 4. Possible causes of inadequate liquid penetrant indications compared to valid indications from defects.

Cause	Indications			
	Weak Faint Line	Diffused	Many, Small	Heavy
Defect	fine crack or cold shut	general porosity	porosity	large flaws
Fabrication	prior anodize or chromate	embedded grease	rough surface	———
Cleaning	wet, acid, or caustic	oily or greasy	scale or rust	———
Temperature	too low	———	———	———
Washing	inadequate	inadequate	———	———
Lighting	inadequate	———	———	———
Inspector	poor sight[a]	poor sight[a]	———	———

[a] Inadequate vision of inspector may be due to (1) inattention, (2) maladaption to darkness or (3) poor vision acuity, which may be due to vitamin A deficiency.

Liquid Penetrant Reference Standards for Repetitive Testing

Companies performing repetitive testing of the same or similar parts make their own standards by photographing the indications and the sectioned parts. A series of such indications produced by exactly the same technique, together with the discontinuities that were thus located, help the inspector estimate both the type of discontinuity present and its seriousness. For example, the indication on the stainless steel tube shown in Fig. 12a was caused by the crack pictured in Fig. 12b. Where it is possible to display actual sectioned parts instead of photographs, this has proved even better. As in any other nondestructive test, liquid penetrant test standards must be corroborated by destroying the part and confirming the existence of the discontinuity. The time and money spent in selecting, photographing and sectioning typical parts is a good investment in quality control.

Indications of Miscellaneous Parts

Many test laboratories handling a wide variety of work do not have the advantage of inspecting large quantities of any one item. Most of these commercial laboratories are performing tests to government specifications and consequently, the liquid penetrant inspectors are trained and tested. There is no substitute for experience, which is gained only by seeing which discontinuities caused which indications.

Liquid Penetrant Indications of Leaks

In any part such as a gas tank, tubing, fitting, flange or cylinder that must maintain pressure, a liquid penetrant indication through the wall is considered to be cause for rejection. It makes no difference whether the discontinuity is a crack, a hole, lack of penetration in a weld or a porous area. The fact that a liquid penetrant can pass through the wall proves that the vessel cannot hold pressurized fluids without leakage.

PART 5. Interpretation of Liquid Penetrant Indications of Cracks

Cracks Occurring on Solidification

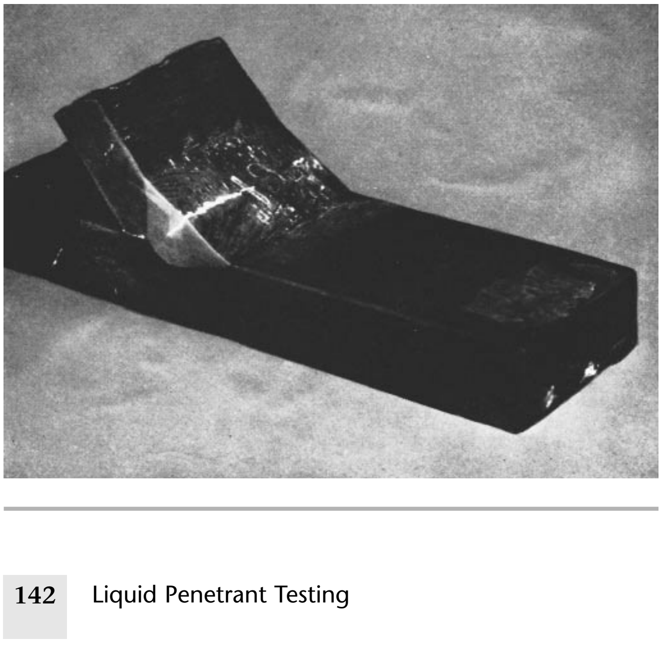
Cracks may occur in castings during the solidification and cooling of the metal, because of contraction. Indications of cracks are considered a basis for rejection in almost all cases. Cracks not only reduce the strength of a part but they also may propagate, especially under alternating or fatigue loads and they afford entrance for corrosive media. Shrinkage cracks in castings are usually found in areas where there is an abrupt change in the thickness of metal. They are caused by internal stresses that develop because of the unequal cooling of the area between the heavy metal and the thin wall. Vibration and external stress would cause these cracks to become more extensive, resulting in failure of the part.

Cold shuts are often confused with cracks but the indications from cold shuts are usually narrow lines of smooth, curving outline.

Cracks in Fusion Welds

Fusion welds may have cracks in the weld metal like that shown in Fig. 13. Crater cracks may produce rounded indications because so much liquid penetrant is retained. These cracks are usually rejectable. Liquid penetrant testing has made possible the successful repair of many fusion welds because discontinuities are located immediately and accurately and small cracks can be ground out and the area rewelded. Cracks in the parent metal adjacent to the weld are nearly always cause for rejection. Welds may give straight line indications that look like cracks but which are actually caused by lack of penetration or lack of fusion. Whether or not this is a harmful discontinuity depends on the design and the service expected of the part.

FIGURE 13. Fluorescent liquid penetrant indication of crack in stainless steel weldment.

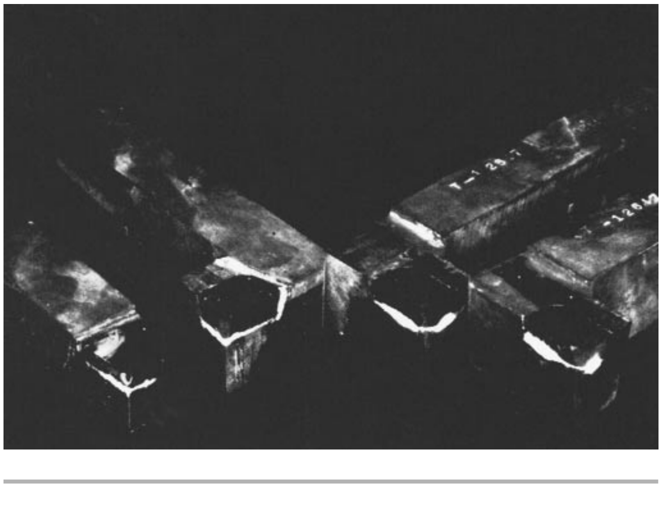


Cracks in Brazed Bonds

Brazed assemblies, like welds, may have cracks or lack of adhesion. Cracks are rejectable, mainly because of their tendency to spread. A certain amount of lack of adhesion is tolerated in brazed joints; only in very critical assemblies would 100 percent braze be required. The inspector must observe liquid penetrant indications closely to differentiate between the straight line from lack of adhesion and the uneven meandering of a crack.

Fluorescent liquid penetrant indications on tipped cutting tools are shown in Fig. 14. These indications show a lack of bond between the shank and the hard metal insert. Lack of bond in this area would shorten the life of the tools because there would not be sufficient support for the tip. The broad, smudgy indication in the illustration results from

FIGURE 14. Lack of bond on tools tipped with hard metal.



the large amount of liquid penetrant trapped in the void between the two pieces of metal.

Cracks Occurring during Processing of Metals

Hot and cold working of metals and alloys can induce cracking. “Hot short” materials can crack when hot working stresses exceed loads that can be supported at grain boundaries. Cold working to excess leads to cracking as well as work hardening. Heating and cooling (as when hardening by quenching parts in water after removal from hot furnaces) can lead to thermal stress and quench cracking.

Forging Cracks

Forgings may have indications of cracks, often at the juncture of light and heavy sections or in thin fins. As in castings, cracks are regarded as rejectable. Indications similar to those from cracks are produced by forging laps, discussed elsewhere in this chapter.

Cracks in Sheets or Tubing

Formed parts such as sheet or tubing or castings that have been straightened may crack at the point of maximum stress. Such cracks may be very small; there are usually several in close proximity and they are generally considered rejectable discontinuities.

Heat Treatment Cracks

Heat treatment cracks should be looked for at the meeting of light and heavy sections. They are nearly always deemed detrimental and therefore a cause for rejection.

Machining Marks

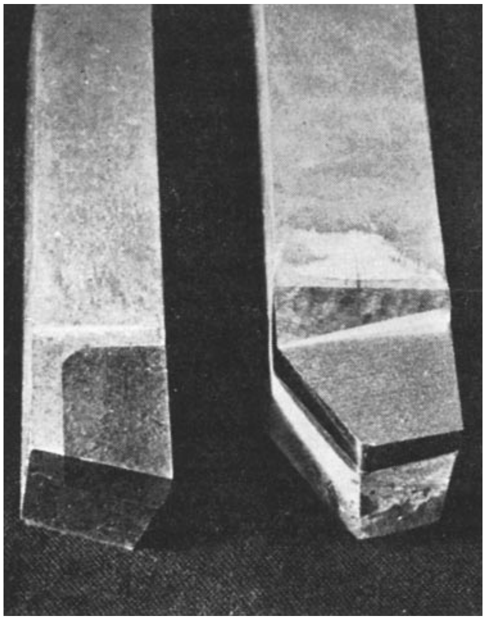
Machining practice may produce cracklike indications from dull tools, chatter marks and similar tool marks. Such indications are ordinarily not intense and are not considered sufficient cause for rejection.

Grinding Cracks

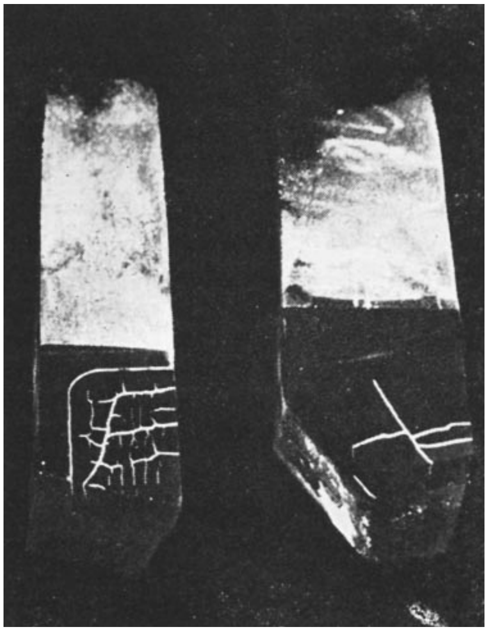
Grinding cracks are minute, often invisible to the unaided eye and are cause for rejection. The type of precision part that must have a ground surface cannot tolerate any surface cracks, however small. While grinding cracks are extremely fine and may be shallow, they usually occur in a definite network that is easily identified. Extensive grinding cracks are shown in the two carbide tipped cutting tools illustrated in Fig. 15. The photographs in Fig. 15a were taken under normal light; the photographs in Fig. 15b show the same tools, processed with water washable liquid penetrant, under ultraviolet radiation. These cracks would soon progress to failure if the tools were used. Notice that the indications are bright and well defined because the cracks are deep and rather tight lipped.

Figure 15. Carbide-tipped tools:
(a) photographed with white light;
(b) fluorescent indications of grinding cracks.

(a)



(b)



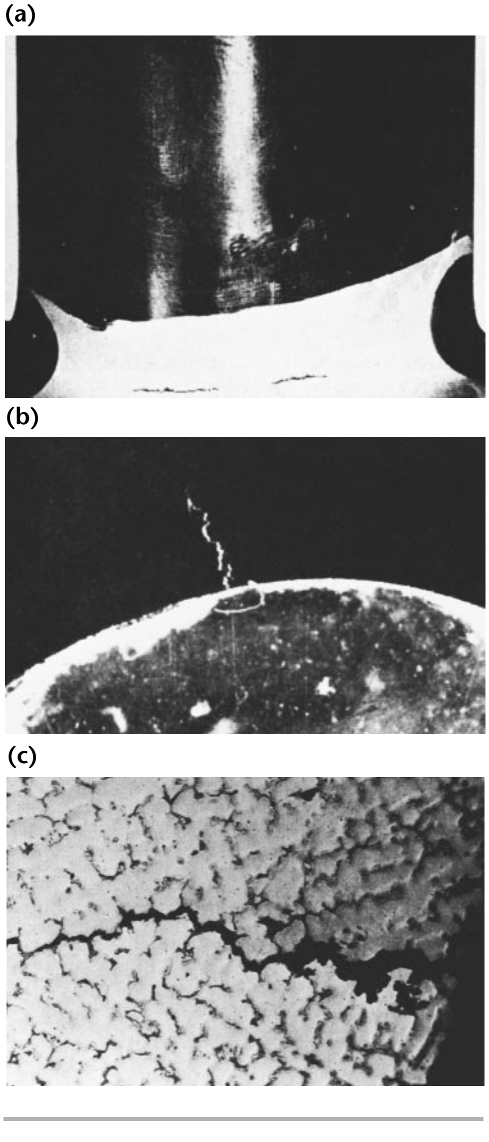
Cracks Occurring during Service

Cracks can develop in service as a consequence of fatigue under repeated loading, thermal cycling, heat checking or stress corrosion.

Fatigue Cracks in Turbine Blades

One very serious type of crack occurs during service as the result of fatigue or intermittent loading. Fatigue cracks often start at a stress raiser such as a sharp tool mark, a nonmetallic inclusion or a scratch. However, even in carefully prepared parts such as turbine blades, interrupted loading produces fatigue. Figure 16a shows a faint liquid penetrant indication on a cobalt base superalloy turbine blade. The original indication had been removed with a pencil grinder in the hope that it would be a shallow surface discontinuity. When developer was reapplied, the indication again appeared, showing that all the crack had not been ground out. Figure 16b shows a cross section through that crack and Fig. 16c illustrates the path of the crack (about 100× magnification). A fatigue crack is a rejectable discontinuity.

FIGURE 16. Crack in superalloy turbine blade: (a) visible dye liquid penetrant indication; (b) cross section through indication; (c) photomicrograph of crack.



Two of the rotor buckets shown in Fig. 17 have fatigue cracks that would grow in size if the rotor were left in service. The *Christmas tree* dovetails where the blades are fitted into the wheel are sharply visible because liquid penetrant has lodged in space between the dovetails and the wheel. This latter indication is normal in such a part, because the blades and wheel, although a press fit, are not intended to be bonded to each other.

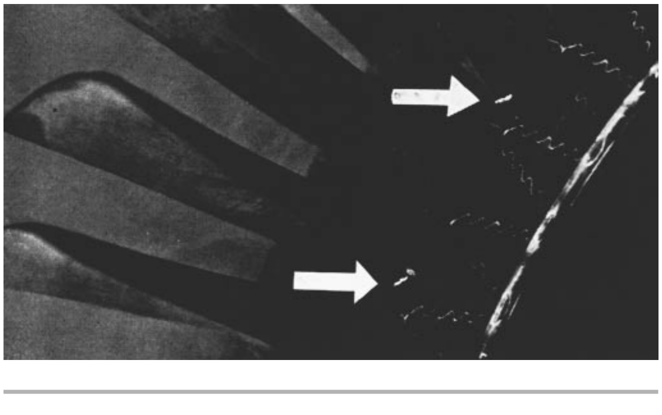
Fatigue Cracks in Aluminum Pistons

The aluminum piston in Fig. 18 clearly shows the difference between tight and broad cracks. The crack between the fins in the top of the piston is broad; the liquid penetrant has bled out of this crack. This is a condition that usually occurs in wide, deep discontinuities. In contrast, the cracks at the base of each boss are much finer, indicating a crack of smaller dimensions.

Fatigue Cracks in Light Alloy Castings

Six of the eight spokes in the magnesium wheel in Fig. 19 have fatigue cracks, four of them almost to the web. Notice also the start of cracks in the spokes near the rim. There are also several generally fluorescent areas indicating some porosity but because no cracks seem to have grown

FIGURE 17. Fatigue cracks in assembled rotor buckets.



from these areas, this porosity is probably harmless.

Cracks in Valve Heads

Some valves are faced with special alloys to increase their resistance to heat and wear. Because this facing is nonmagnetic, cracks can be detected only by liquid penetrant testing (Fig. 20). Such cracks are cause for rejection unless they can be lapped out within the acceptable dimensional tolerance.

FIGURE 18. Fatigue cracks in aluminum piston head.

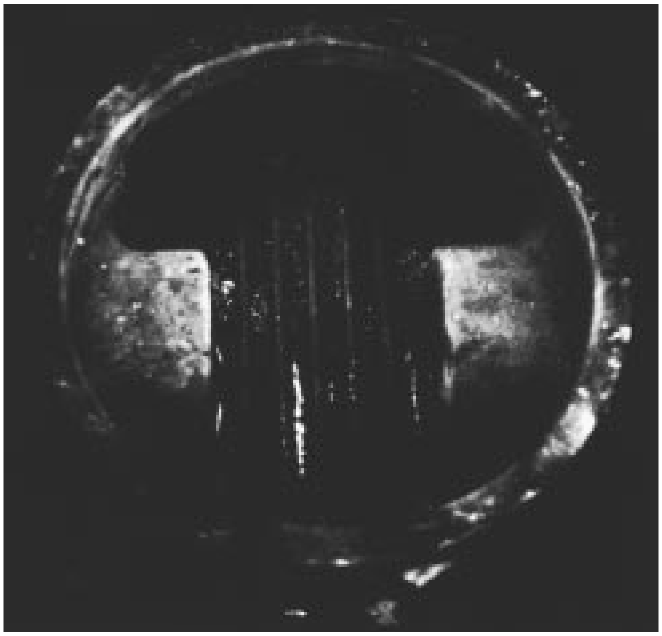
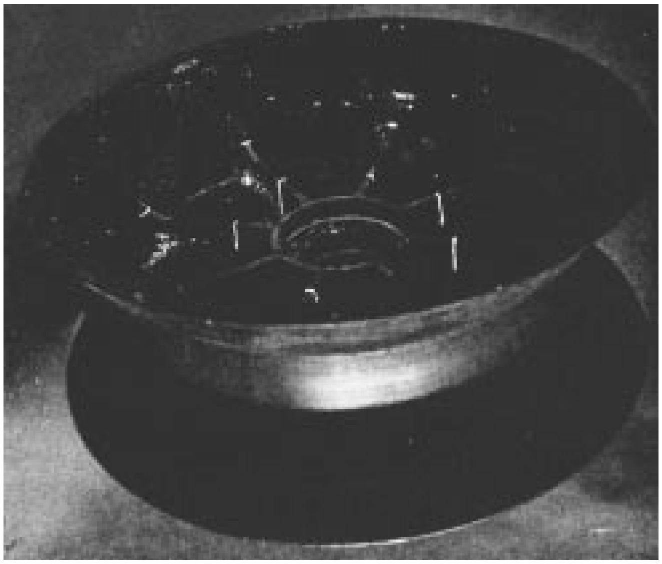


FIGURE 19. Fatigue cracks in magnesium wheel.



Stress Corrosion Cracks

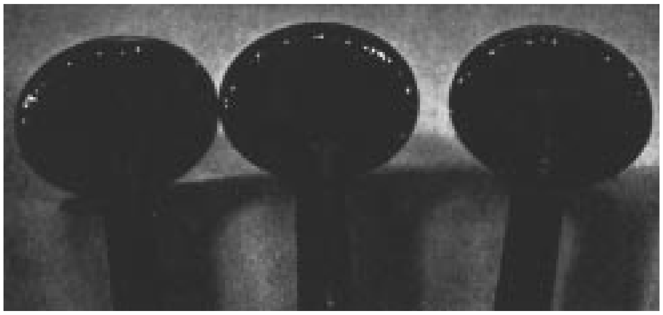
Another crack that is caused by operating conditions is stress corrosion cracking. Deep drawn parts used to contain chemicals and items for maritime service are especially likely to crack from stress corrosion. Stress corrosion cracking does not necessarily start from an edge or stress raiser. Indications of these cracks often appear in a pattern at the area of maximum stress and are easily identified. Stress corrosion cracks are considered cause for rejection.

Heat Checks

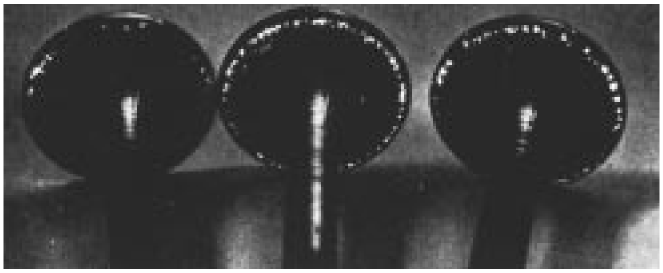
The third type of crack that may show up on maintenance overhaul is the heat check, occurring when surfaces are overheated. Like grinding cracks (which are initiated in the same way by local overheating), heat checks are usually quite shallow but occur in definite, recognizable network. These indications may or may not, be cause for rejection, depending on the use of the part.

FIGURE 20. Comparison of cracks in diesel valves: (a) water washable liquid penetrant indications; (b) postemulsification liquid penetrant indications.

(a)



(b)



Cracks in Plastics and Glass

Liquid penetrant testing can be used on any nonporous material. It should not be used on materials that might be adversely affected by the liquid penetrant. Some plastics are attacked by certain oil base liquid penetrants but many plastics are not affected. A water base liquid penetrant should be used where it is found that the usual oil base liquid penetrants react with the plastic. Before inspecting plastics with liquid penetrant techniques, it is wise to try out the reaction of the test materials on material similar to that of which the part is made. Fatigue cracks may be found in plastics as well as in metals. Liquid penetrant testing can also be used on glass, because it is nonporous. Electrified particle testing in preferred for inspection of glass and glazed ceramics; however, liquid penetrants are more suitable for determining leaks and lack of bond between glass and metal.

PART 6. Interpretation of Liquid Penetrant Indications of Laminar Discontinuities

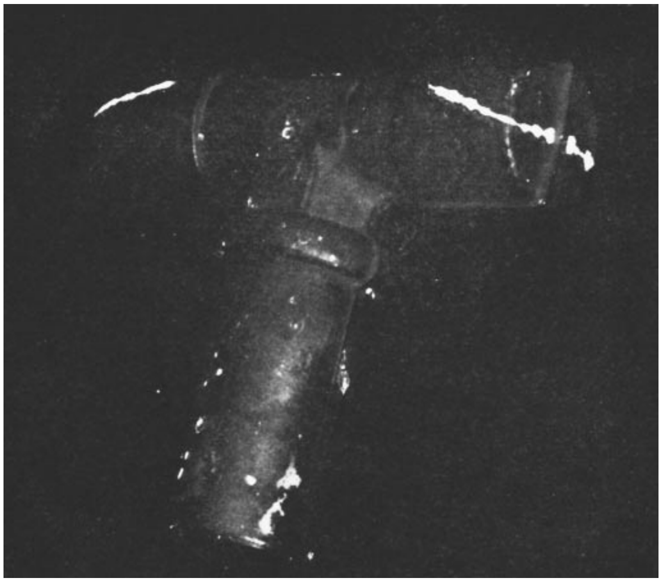
Cold Shut or Fold

As mentioned in the discussion of cracks, cold shuts or folds give liquid penetrant indications that are definitely lines, usually curving in a smooth outline. In highly stressed castings, a cold shut is a rejectable discontinuity because, like a crack, it lessens the strength of the part and is a point of high stress concentration. If the surface is to be machined and the cold shut can be removed, it may be accepted on condition that an additional liquid penetrant testing be performed after machining.

Die Castings

In die castings, however, slight cold shuts or skin folds, less than 0.1 mm (0.004 in.) in depth, are common. Because die castings are seldom used for applications requiring very high strength, faint indications of cold shuts or skin folds are not causes for rejection. The usual practice is to remove some of the worst looking discontinuities and estimate how deep they were, then make the decision of acceptance or rejection.

FIGURE 21. Forging laps in aluminum forging.



Forging Laps

Forging laps, like cracks, produce linear liquid penetrant indications and are considered equally detrimental. It is especially hard to estimate the significance of a lap from the liquid penetrant indication because (1) forging tends partially to seal the lap on the surface and (2) embedded scale and/or die lubricant may partially fill a lap. In either of these cases, the resultant indication would not denote the true degree of severity of the discontinuity. Forging laps are serious discontinuities and are cause for rejection unless it is definitely known that they will be removed during subsequent machining. Figure 21 shows such laps in an aluminum forging. It is doubtful that the machining operation would remove these laps, so the part would probably be rejected. The brightness of the indication and the bleeding out of liquid penetrant show that these laps have considerable depth because they harbor so much liquid penetrant.

Seams

Seams in bar stock, laminations in sheet or plate and seam conditions in forgings give liquid penetrant indications similar to those from extrusion discontinuities. Seams are often extremely narrow, having been compressed and elongated in manufacture. Indication lines are usually quite straight, easy to recognize and in the longitudinal direction. They may be only short lines when examined transverse to the direction of rolling. Seams are usually bases for rejection (Fig. 22).

FIGURE 22. Fluorescent liquid penetrant indications of prominent seam in bar stock.

FIGURE 23. Liquid penetrant indications of discontinuities in extruded, milled, aircraft wing spar.

Extrusion Discontinuities

Depending on the orientation of the surface being examined, an extrusion discontinuity may cause continuous or dotted liquid penetrant indications. A typical *extrusion discontinuity* is an internal unsound area, longitudinally squeezed during extrusion and sometimes breaching the surface (Fig. 23). If the extrusion is sectioned and a longitudinal surface examined, the extrusion discontinuity will show up as a line, like a crack. If a cross section is inspected, liquid penetrant indications will appear as short lines or dots. An extrusion discontinuity is usually considered a basis for rejection in aircraft applications but may be acceptable for other service where only longitudinal strength is required.

PART 7. Interpretation of Liquid Penetrant Indications of Porosity and Leaks

Gas Holes

Liquid penetrant indications of gas holes are round blobs of rich color or fluorescence. Large gas holes are bases for rejection, not only because they reduce strength but also because they produce a rough surface. Small gas holes may not be rejectable discontinuities, because they do not have the serious effect on strength that a crack or a lap does. If pressure tightness or smooth surface is required, then even tiny pinholes are considered a basis for rejection. Figure 24 shows fluorescent liquid penetrant indications of extreme porosity in a casting.

Shrinkage Cavities

Porosity resulting from shrinkage cavities may produce rounded liquid penetrant indications or may give the appearance of cracks. Usually, shrinkage cavities have a dendritic pattern that helps the inspector identify them. For high stress applications, shrinkage cavities are rejectable discontinuities. These are cases where the amount of shrinkage and its location on the part do not detrimentally affect service; in such cases the part is acceptable.

MOVIE. Porosity in casting.

FIGURE 24. Fluorescent liquid penetrant reveals extreme porosity in casting.

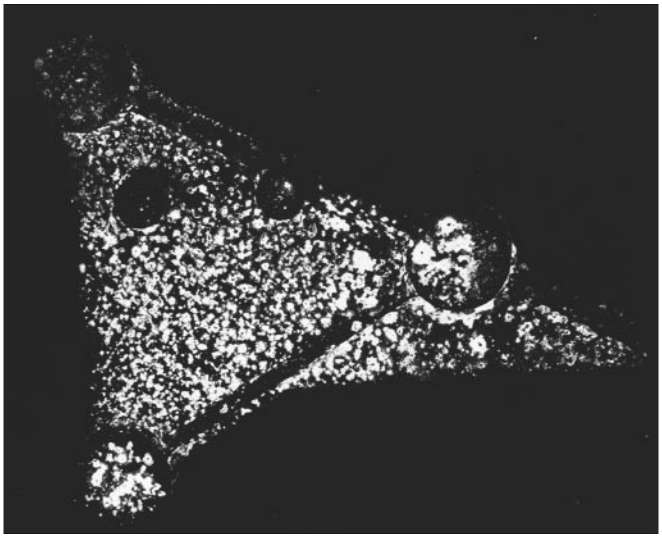
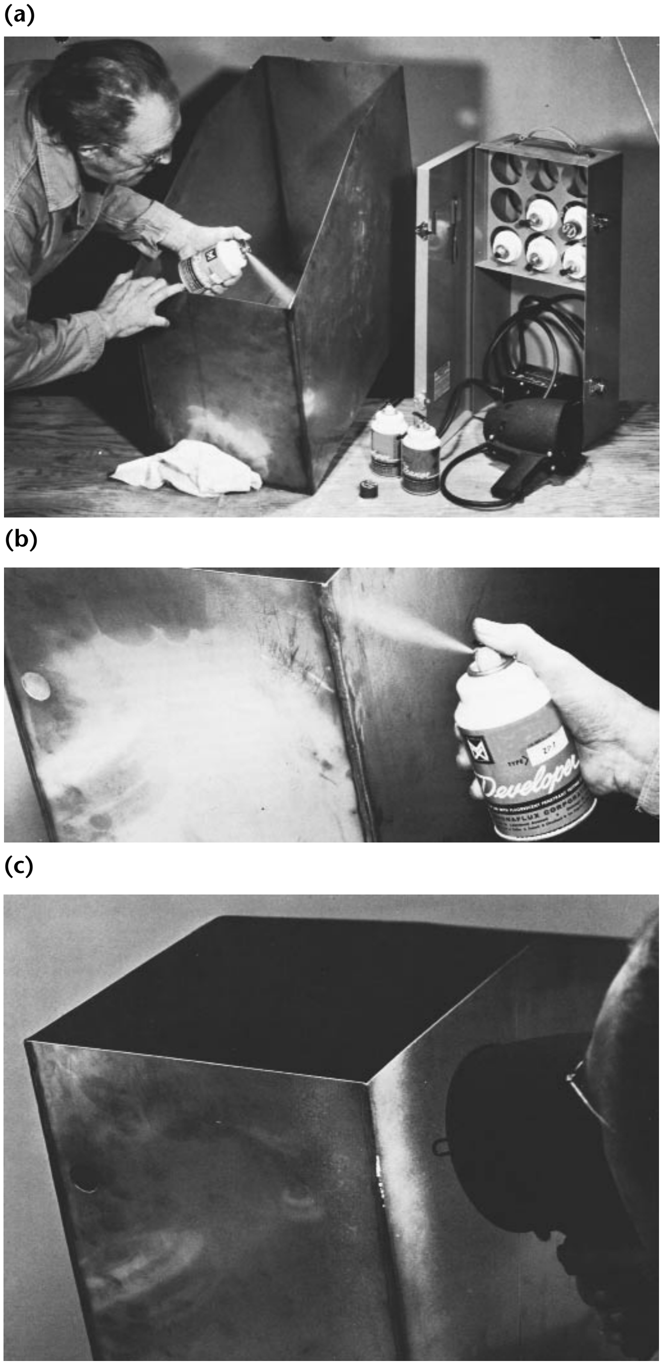


FIGURE 25. Leak testing of welded seam with fluorescent liquid penetrant: (a) spray application of liquid penetrant to interior wall at weld seam; (b) spray application of developer to exterior wall at weld seam; (c) leak indications in welded seam shown by fluorescence.



Microshrinkage

Some materials, especially magnesium castings, have shrinkage cavities so fine that they are almost invisible. These openings are so tiny that instead of getting a speckled condition with a number of small spots, the liquid penetrant indication is more likely to be a generally diffused condition. To confirm the actual presence of microshrinkage, it is best to clean and reprocess the part. Microshrinkage is not always a rejectable discontinuity; rejection depends on size and severity of microshrinkage, its location and the end use of the part.

Porosity in Ceramics

Liquid penetrant testing is a good way to locate porosity in ceramics. The appearance and interpretation of indications are the same as in metals, with the one extra caution that special attention must be paid to cleaning because most ceramics are somewhat porous.

Leak Testing of Welded Seams

Liquid penetrants are often effective tracers for detecting leaks that would allow gases or liquids to pass through the walls of welded containers such as pipes, cans, boxes or other containment systems. Figure 25 shows typical procedures and indications produced by fluorescent liquid penetrants on a corner welded sheet metal box. Liquid penetrant is applied to seams or other suspect areas on the outside (or inside) surface of the containment. After allowing dwell time sufficient to permit liquid penetrant to seep through leaks, examination for liquid penetrant indications is carried out on the opposite surface of the containment wall (with or without developers, as appropriate). Either visible dye or fluorescent liquid penetrants can be used as leak tracers, as convenient for visual examination.

Part 8. Nonrelevant and False Liquid Penetrant Indications

Movie. Process control can mask discontinuities.

Movie. False indications.

Common Causes of Nonrelevant Liquid Penetrant and False Indications

Nonrelevant indications may be due to misapplied or improper testing procedures or to actual discontinuities that do not affect the usability of a part. *False* indications, a subcategory of nonrelevant indications, are best defined as indications that distract from the quality of the inspection but do not indicate a discontinuity in a part. False indications are due to several causes but the primary cause is usually a deficiency in process control.

Poor Process Control

Regardless of the liquid penetrant technique used, the level of sensitivity can be adversely affected by poor process control, such as improper application of liquid penetrant, improper removal of liquid penetrant, lack of cleanliness in the inspection area and poor handling of parts being processed. Any of these can cause false indications that will interfere with or cause a distraction during the visual detection and interpretation of indications.

Improper application of liquid penetrant can cause pooling of the liquid penetrant. This produces an uneven coating of liquid penetrant on the surface of a part and, on certain types of materials, results in areas of high background bleedout.

Improper removal of liquid penetrant can cause either an overremoval or underremoval of excess surface liquid penetrant. Overremoval is indicated by a complete lack of background or indications; a slight background is normal. Overremoval will not result in a false indication but increases the chances of removing a valid discontinuity indication. However, underremoval of excess liquid penetrant can cause a high background intensity and decrease the contrast needed to reveal small indications. Another problem with underremoval is that the remaining liquid penetrant background may mask a relevant discontinuity indication. In either case, a part that has been subject to improper removal of excess surface liquid penetrant must be cleaned and reprocessed.

Movie. Nonrelevant indications can mask relevant ones.

Lack of cleanliness in the inspection area is often a cause of false indications. Except for the liquid penetrant containers, an inspection area should be free of all liquid penetrant. Liquid penetrant on roller assemblies, dryer shelves or inspection tables should be cleaned up before parts are processed. Otherwise this liquid penetrant can be absorbed by the developer and cause nonrelevant indications.

Proper handling of parts during all phases of the liquid penetrant process is important. Rubber gloves should be cleaned between processing steps. Small parts processed together should be handled in a manner to prevent their rubbing against each other. Towels or rags that are not lint free will leave lint on a part that will fluoresce under near ultraviolet radiation and give the appearance of a crack. False indications due to improper handling of parts can be easily prevented.

Part Geometry and Surface Condition

Movie. Nonrelevant indication from part geometry.

The geometry of a part or assembly can cause nonrelevant indications. The indication of an interface between a turbine blade and a disk can not only produce a nonrelevant indication but also mask possible small indications if the bleedout from the interface is excessive. Figure 17 shows an example of assembled rotor buckets being liquid penetrant inspected. Note the liquid penetrant indications of the *Christmas tree* junctions of the rotor (disk) and turbine blades. One aid to the inspector is that the regular pattern of the indications make them easy to identify. However, in many cases inspection procedures will require that an assembly be completely disassembled before inspection.

Press fittings, like the example of turbine blades and disks above, are a source of nonrelevant indications caused by part geometry. It is sometimes impossible to completely disassemble a part that must be inspected. The bleedout of the liquid penetrant around press fittings can be considerable and can mask relevant indications. In these situations inspectors must monitor the part very closely during the developer dwell time to properly evaluate the indications as they are forming.

Another cause of false and nonrelevant indications is a rough part surface. Welds are very difficult to inspect, especially with solvent removable method, because of rough weld bead surfaces and weld spatter. The major concern on a weld bead is masking of relevant indications. As-cast and as-forged surfaces may also lead to nonrelevant indications due to surface roughness or other irregularities. Machined parts may have machining grooves or marks or may have scratches due to rough handling.

Evaluation of Nonrelevant Indications

One technique that an inspector can use to help identify a nonrelevant indication is wiping off the indication with a solvent dampened lint free swab or cloth and reapplying the developer. The original developer dwell time must be repeated; however, the inspector should monitor the bleedout to help evaluate the indication. If there is no bleedout, the original indication can be considered nonrelevant or false. This technique may also reveal multiple relevant indications that had previously merged into one or had been hidden by excessive bleedout from an adjacent nonrelevant indication during the developer dwell.

PART 9. Recognition Training of Liquid Penetrant Inspectors

Sample Anomalous Parts

The most effective means for training liquid penetrant inspectors to recognize and identify discontinuities is frequent reference to a collection of parts with typical discontinuities. Parts that have been rejected because of discontinuities should be clearly marked or partially damaged so that they will not be confused with acceptable parts.

The parts with known discontinuities could be processed with regular production parts. This would serve two purposes: the inspector in training could be judged for discontinuity recognition and at the same time, the inspector could be familiarizing himself with the type of discontinuity indication considered to be cause for rejection. However, with continued processing, the known discontinuities will clog with liquid penetrant and developer residues. Special cleaning of these parts with clogged discontinuities will be necessary to continue their use in recognition training.

Visible liquid penetrants tend to kill the fluorescent qualities in fluorescent liquid penetrants. After a part has been inspected by using visible liquid penetrant, it is not desirable to attempt to reprocess with fluorescent liquid penetrant. The results will not be reliable. In all cases, parts should be cleaned thoroughly and degreased before reprocessing.

Evaluating Indications to Determine Causes of Discontinuities

It is possible to examine an indication of a discontinuity and to determine its cause as well as its extent. Such an appraisal can be made if something is known about the manufacturing processes to which the part has been subjected. The extent of the indication or accumulation of liquid penetrant, will show the extent of discontinuity and the breadth and brilliance will be a measure of its depth. Deep cracks will hold more liquid penetrant and therefore will be broader and more brilliant. Very fine openings can hold only small amounts of liquid penetrant and therefore will appear as fine lines.

Although many factors influence the exact size and shape of indications from liquid penetrant testing, most typical discontinuities are easy to recognize. A line of liquid penetrant signifies a crack, lap, cold shut, seam or other long discontinuity. A spot or blob denotes a hole, large or small.

By photographing typical indications and pairing them with sectioned parts showing the discontinuities causing those indications, standards for acceptance or rejection can be established in terms of the photographic appearance of liquid penetrant indications.

PART 10. Specifications and Guides for Evaluation of Liquid Penetrant Indications

Specifications and References Applicable to Liquid Penetrant Interpretation

Some industries have prepared standards for evaluation and acceptance/rejection of hardware on the basis of liquid penetrant indications. These can be anything from quite general to very detailed. Liquid penetrant users may find some of these helpful or may prefer to prepare their own. If liquid penetrant inspectors are working under a contract, it is mandatory that they determine and conform to the specifications to which the contracting agency intends to hold them.

Commonly, a general statement may be encountered, such as "The inspection department shall pass only those parts that are free of liquid penetrant indications. Parts showing liquid penetrant indications should be referred to the metallurgy or design departments for disposition. The metallurgy or design department shall decide which parts shall be accepted, reworked or rejected".

ASTM E 433, *Standard Reference Photographs for Liquid Penetrant Inspection,* contains reference photographs to be used as a means of establishing and classifying types and characteristics of surface discontinuities detectable by liquid penetrant testing.[5] They may be used as a reference for acceptance standards, specifications and drawings. However, no attempt has been made to establish limits of acceptability or the extent of the metallurgical discontinuity.

Blueprint Notations Controlling Interpretation of Liquid Penetrant Indications

Ideally, the manufacturer's drawing or print for the test part or surface under examination will specify the nondestructive test method or methods required for acceptance. Moreover, it will either specify the acceptance or rejection criteria or refer the inspector to supplemental documents such as acceptance/rejection specifications. If critical parts are involved (such as nuclear hardware or jet engine components), an expert in evaluation of indications may have to be called on for a judgment.

Establishing Criteria for Acceptance or Rejection in Liquid Penetrant Testing

To establish acceptance/rejection criteria, it may be necessary to conduct an extensive correlation study between nondestructive test indications and destructive test results. This is the ultimate procedure but even it may leave some doubt because discontinuities or indications do not always occur in exactly the same place, with the same frequency or to the same extent.

It should be obvious that a number of factors enter into the final judgment of acceptability of test parts during liquid penetrant testing, including: (1) the metal or metal alloy involved; (2) if a nonmetallic surface, the composition of the nonmetal; (3) locations of the liquid penetrant indications, for example, in critical radii, on edges that will be ground off, in parts designed for high strength applications or in thick sections that may allow for removal without sacrifice of function; (4) whether or not the surface or surfaces are repairable by welding or other means; and (5) the cost of the part. It may be that the cost of a new part is so low that the expense of repair or rework of an anomalous part is not warranted. Conversely, of course, one would not want to discard an expensive piece of hardware that could be reworked at a considerable saving over the cost of a new part.

In summary, it can be seen that liquid penetrant evaluation is dependent on several factors that are not easily standardized. Further work in detecting, defining, describing and evaluating indications could be very helpful to the science of liquid penetrant testing.

Examples of Interpretation Guides Based on Appearance of Liquid Penetrant Indications

In some cases, specifications provide a guide to parts evaluation based primarily on the size, shape or location of liquid penetrant indications. For such purposes, a *linear* liquid penetrant indication is defined as having a length greater than three times the width. Rounded liquid penetrant indications are those indications that are circular or elliptical with the length less than three times the width. In some code applications, unacceptable discontinuities are then defined in terms such as (1) any crack or linear indication; (2) rounded indications greater than 5 mm (or 0.2 in.) in dimension; (3) four or more rounded indications in a line separated by 1.5 mm (or 0.06 in.) or less, edge to edge; and (4) ten or more rounded indications in any 37.5 cm^2 (6.0 in.^2) of surface with the major dimension of this area not to exceed 150 mm (6.0 in.). The area must be taken in the most unfavorable location relative to the indications being evaluated.

Representative Aerospace Manufacturer's Liquid Penetrant Test Interpretation Guide

A typical aerospace manufacturer's process specification requires that visual inspection areas shall be illuminated with essentially white light. The intensity of white light at the visual test level shall be equivalent to at least 750 lx (70 ftc). Fluorescent liquid penetrant testing shall be conducted in a suitable darkened area (with an ultraviolet radiation intensity of at least 10 W·m^{-2} (1000 $\mu\text{W·cm}^{-2}$) and background illumination preferably not exceeding 20 lx (2.0 ftc). The following lists the criteria for parts acceptance or rejection in accordance with the aerospace company's quality requirements.

1. Propagating discontinuities, regardless of location, are cause for rejection unless completely removed within drawing tolerances. Propagating discontinuities are those discontinuities that, because of their nature or geometry, may enlarge in any way during service life. Included are linear porosity, laps, seams and cracks.
2. Any indication discernible as a crack when observed with 10× magnification shall be rejectable.
3. Nonpropagating imperfections are acceptable and do not require removal if the dimensional and smoothness requirements established on the engineering drawing can be met.

Table 5 lists one company's acceptance and rejection criteria for commonly used aerospace materials and conditions. Questionable conditions are required to be referred to quality control engineering for resolution. Rejected parts shall be disposed of in accordance with the applicable procedures.

Acceptance/Rejection Criteria for Liquid Penetrant Testing of Cast Turbine Blades

An example of how one manufacturer handles the liquid penetrant test requirements for gas turbine engine turbine blades and vanes is to issue a specification that covers the acceptance/rejection criteria for visual, radiographic and liquid penetrant indications. The specification indicates that drawings shall designate zones on the casting identified by letters A, B, C etc. Each of these letters (or grades) as defined in this specification establishes different degrees of allowable discontinuities for visual, fluorescent liquid penetrant and radiographic testing. The zones for each casting are established by the manufacturer's materials engineering and stress analysis group.

The specification emphasizes the importance of carefully controlled liquid penetrant testing and the necessity to record on the technique card or other applicable document the exact techniques used to process the parts. In a number of specifications, porosity bleedout diameters are specified as accept/reject criteria. These maximum acceptable size limits for liquid penetrant indications apply to the bleedout indication, viewed immediately after wiping the indication only one time with a swab or cloth dampened with a suitable solvent. The recurrence of the fluorescent liquid penetrant indication after once wiping clean is referred to as *bleedback*.

Positive surface discontinuities (excess metal), such as mold ridge, fins, bumps etc., generally are not considered potential stress raisers when not associated with severe undercutting at their bases. These discontinuities are permissible on turbine blade and vane castings provided they can be removed

Table 5. Typical aerospace manufacturer's liquid penetrant testing acceptance and rejection criteria.

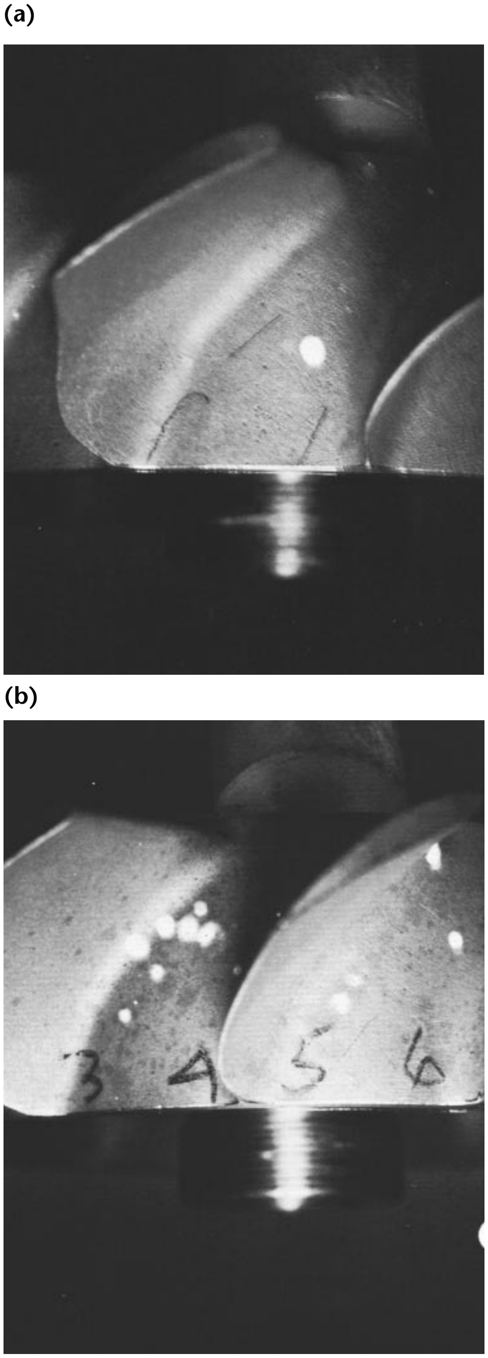
Material and Discontinuity	Aluminum	Copper	Magnesium	Nickel	Stainless Steel	Iron Alloy	Titanium	High Temperature Alloy
Bar Stock								
cracks	N	N	N	N	N	N	N	N
seams	N	N	N	N	N	N	N	N
Castings								
cold shuts	Q	Q	Q	Q	Q	Q	Q	Q
cracks	N	N	N	N	N	N	N	N
porosity	A	A	Q	A	A	A	A	A
sand blisters	A	A	A	A	A	A	A	A
shrinkage	Q	Q	Q	Q	Q	Q	Q	Q
Extrusions								
blisters	N	N	N	N	N	N	N	N
broken surface	N	—	N	—	N	N	N	N
deep scratches	Q	Q	Q	Q	Q	Q	Q	Q
die drag	Q	Q	Q	Q	Q	Q	Q	Q
die weld cracks	N	N	N	—	—	—	—	—
cracks	N	N	N	N	N	N	N	N
inclusions	Q	Q	N	Q	Q	Q	N	Q
metal pick up	A	A	A	A	A	A	A	A
pitting	A	Q	N	Q	Q	A	N	Q
Forgings								
cracks	N	N	N	N	N	N	N	N
inclusions	Q	Q	N	Q	Q	Q	N	Q
laps	N	N	N	N	N	N	N	N
Formed Part								
cracks	N	N	N	N	N	N	N	N
inclusions	Q	Q	N	Q	Q	Q	N	Q
metal pick up	A	A	A	A	A	A	A	A
orange peel	Q	Q	Q	Q	Q	Q	Q	Q
Heat Treated								
cracks	N	N	N	N	N	N	N	N
scale	A	A	A	—	—	—	—	—
Machined parts								
cracks	N	N	N	N	N	N	N	N
grinding cracks	N	N	N	N	N	N	N	N
tool marks	Q	Q	N	Q	Q	Q	N	Q
Plate								
cracks	N	N	N	N	N	N	N	N
inclusions	Q	N	N	Q	Q	Q	N	Q
laminations	N	N	N	N	N	N	N	N
pitting	A	Q	N	Q	Q	A	N	Q
scratches	A	A	N	A	A	A	N	A
Sheet								
cracks	N	N	N	N	N	N	N	N
inclusions	Q	Q	N	Q	Q	Q	N	Q
laminations	N	N	N	N	N	N	N	N
pitting	A	Q	N	Q	Q	A	N	Q
scratches	A	A	N	A	A	A	N	A

A = Acceptable.
N = Not acceptable.
Q = Questionable.

TABLE 6. Example of acceptance standards for nondestructive testing of cast turbine blades and vanes.

Grade	Visual Testing	Liquid Penetrant Testing	Radiographic Testing
Grade A	No defects allowed	No bleedback allowed	No defects allowed
Grade B	Negative flaw of diameter ≤ 0.4 mm (0.016 in.) and estimated depth ≤ 0.2 mm (0.008 in.) or 20 percent of local drawing minimum thickness, whichever is less Any number allowed if clearly spaced ≥ 3 mm (0.12 in.) apart	Bleedback of diameter ≤ 0.4 mm (0.016 in.) Any number allowed if clearly separated a distance ≥ 3 mm (0.12 in.) apart	Diameter ≤ 0.4 mm (0.016 in.) Any number allowed if clearly separated a distance ≥ 3 mm (0.12 in.) apart, and each does not exceed 20 percent of the local drawing specified thickness
Grade C	Allows same flaws as Grade B, plus four negative flaws per side of 0.4 to 0.8 mm (0.016 to 0.032 in.) diameter and estimated depth ≤ 0.2 mm (0.008 in.) or 20 percent of local drawing minimum thickness, whichever is less, if clearly separated a distance ≥ 3 mm (0.12 in.) apart	Bleedback ≤ 0.4 mm (0.016 in.) diameter Allows any number, plus four 0.4 to 0.8 mm (0.016 to 0.032 in.) diameter indications per side if all indications clearly separated a distance ≥ 3 mm (0.12 in.)	Allows same indications as in Grade B, plus 0.4 to 0.8 mm (0.016 to 0.032 in.) diameter limited to four places per area designated, if clearly separated a distance ≥ 3 mm (0.12 in.), none exceeding 20 percent of local drawing specified thickness
Grade D	This grade is usually assigned to blade root serrations and allows essentially same flaws as under Grade C except that there shall be no 0.4 to 0.8 mm (0.016 to 0.032 in.) indications in serration root radii; not more than two 0.2 to 0.8 mm (0.008 to 0.032 in.) indications per serration; and not more than four 0.2 to 0.8 mm (0.008 to 0.032 in.) indications in all serrations on each side of blade	Bleedback allowed same as in grade C except that there shall be no 0.4 to 0.8 mm (0.016 to 0.032 in.) indications in serration root radii; not more than two 0.4 to 0.8 mm (0.008 to 0.032 in.) indications per serration; and not more than four 0.4 to 0.8 mm (0.008 to 0.032 in.) indications in all serrations on each side of blade	Same as Grade C
Grade E	Allows same flaws as Grade B, plus four negative flaws per side of 0.4 to 1.5 mm (0.016 to 0.06 in.) diameter and an estimated depth ≤ 0.5 mm (0.02 in.) or 25 percent of the local drawing thickness, whichever is least, if clearly separated a distance ≥ 6 mm (0.24 in.) apart Negative flaws of diameter ≤ 0.8 mm (0.032 in.) allowed if spaced ≥ 3 mm (0.12 in.)	Allows same bleedback as in Grade B, plus four bleedback indications per side of 0.4 to 1.5 mm (0.016 to 0.06 in.) diameter if clearly separated a minimum of 6 mm (0.24 in.) apart Allows indications ≤ 0.8 mm (0.032 in.) diameter if spaced 3 mm (0.12 in.) apart	Allows same indications as in Grade B, plus diameter ≥ 0.4 to 1.5 mm (0.016 to 0.06 in.) limited to four places per area designated if clearly separated a distance ≥ 3 mm (0.12 in.) apart and each does not exceed 20 percent of the local drawing specified thickness Allows indications of diameter ≤ 0.8 mm (0.032 in.) if spaced ≥ 3 mm (0.12 in.) apart
Stock surfaces, all grades	Negative defects allowed to depth of machining stock Negative flaws of ≤ 0.1 mm (0.004 in.) diameter shall be considered not interpretable and shall be acceptable regardless of location if clearly separated by ≥ 2.5 mm (0.1 in.) Cracks, folds, cold shuts, or linear flaws (width 1/3 its length) are not allowed	For any grade, bleedback allowed to depth of machining stock Negative flaws of ≤ 0.1 mm (0.004 in.) diameter shall be considered not interpretable and shall be acceptable regardless of location if clearly separated by ≥ 2.5 mm (0.1 in.) Cracks, folds, cold shuts or linear flaws (width 1/3 its length) are not allowed	Unlimited flaws allowed to depth of machining stock Negative flaws of ≤ 0.1 mm (0.004 in.) diameter shall be considered not interpretable and shall be acceptable regardless of location if clearly separated by ≥ 2.5 mm (0.1 in.) Cracks, folds, cold shuts, or linear flaws (width 1/3 its length) are not allowed

Figure 26. Example of working standard and interpretation guide for shop personnel inspecting 356-T6 aluminum fan casting for porosity bleedout diameter: (a) indications in fan blade fillet area (cause for rejection because area is highly stressed so indications propagate through part thickness); (b) indications in rim of fan, which has heavy wall thickness and is subject to lower stress levels. Probing indicates depths of about 0.3 mm (0.01 in.). Experience has indicated that these have never extended through fan rim and therefore will not be detrimental to use of fan.



without exceeding the minimum dimensions on the drawings and are removed by approved techniques of grinding and polishing.

Negative discontinuities may be either propagating (cracks, cold shuts, folds) or nonpropagating (oxide pits, small gas holes, shallow smooth bottomed depressions). Propagating discontinuities are not acceptable regardless of location. Negative discontinuities of the nonpropagating type are acceptable to the limits set forth in Table 6. Any of the above listed discontinuities that occur in areas with stock to be removed in later operations shall not be immediate cause for rejection. Such discontinuities may be removed within the stock allowance limits to ascertain that the requirements of this company's standards are met. Figure 26 shows examples of working standards and interpretation guides provided for shop personnel for the case of a 356 aluminum fan casting.

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6

CHAPTER

Surface Preparation and Cleaning

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PART 1. Effects of Test Object Surface Contamination or Irregularities

Other than removing loose dirt with nonabrasive techniques and cleaning with a simple solvent wipe, a nondestructive testing inspector is unqualified to perform most cleaning operations. However, the inspector needs to know (1) what contaminants and surface conditions adversely affect the liquid penetrant test, (2) the cleaning techniques or other processes required to eliminate the adverse conditions and (3) the consequences of using those techniques and processes. Knowledge of these conditions and techniques enables the inspector to request the proper operations and be assured that the surface is properly prepared for liquid penetrant testing.

The mesh numbers used in this chapter to express the coarseness of grit used in mechanical processing correspond to particle diameters, as explained in this volume's discussion of measurement units.

Test Object Preparation for Liquid Penetrant Testing

The first step of the liquid penetrant test process is the preparation and cleaning of the test surface and any surface connected discontinuities. Surface preparation aids wetting and flow of the liquid penetrant. Surface conditions, e.g., soil contamination or surface irregularities, can reduce the effectiveness of the test process by interfering with (1) wetting of the test surface by the liquid penetrant, (2) entry of the liquid penetrant into discontinuities and (3) subsequent bleedout of liquid penetrant to form discontinuity indications.

Such interfering surface conditions must be eliminated by surface preparation before application of liquid penetrant. The surface preparation technique selected must effectively remove the potential sources of interference without damaging the parts being processed. Reliable liquid penetrant testing cannot be expected unless the parts to be tested are free from contamination. Foreign material adhering to the surface or contained within the discontinuities or leak passageways, as well as the surface effects cited above, can produce erroneous test indications or prevent indications from forming.

After surface preparation and cleaning, any residues of cleaning agents, including water, must be removed. The part and discontinuity surfaces must be not only clean but also dry.

Surface Conditions Interfering with Liquid Penetrant Testing

Test material surface conditions that may interfere with the application of liquid penetrants or their entry into surface connected discontinuities may be classified into two groups: (1) contaminants on the surface or within discontinuities that prevent surface wetting and capillary flow of the liquid penetrants; (2) contaminants or surface conditions that physically block the entrances to discontinuities so that liquid penetrants cannot enter.

Similarly, surface conditions or contaminants that trap liquid penetrant or tracer liquids to produce false indications or inhibit or prevent extraction of liquid penetrant retained in leaks or discontinuities during development, can be classified into two groups: (1) porous, adherent coatings or contaminants providing interstices that retain liquid penetrants on test object surfaces or impede their entry into underlying discontinuities or leaks; and (2) coatings on interior surfaces of discontinuities or leaks that have high surface energies and resist extraction of the liquid penetrant from the discontinuities into the developer coating.

Types of Surface Contamination Found on Test Objects

Surface contamination and contamination within leaks or surface connected discontinuities can be of many types, including (1) preservative, forming, machining or lubricating oils and other liquids containing organic constituents; (2) carbon, varnish and other tightly held soil; (3) scale, rust, oxides, corrosion products and weld metal and weld flux residues; (4) paint and organic protective coatings; (5) water, hydrates or other residues left after evaporation of water; (6) strong acids, alkalis or other chemically active residues, including halogens; (7) polishing, forming, drawing or buffing lubricants; (8) residues from previous liquid penetrant testing or liquid leak testing; and (9) surface treatments such as phosphate, chromate conversion coatings, black oxide or temper colors.

In some cases, sources of contamination can be very subtle and difficult to identify. For example, one aerospace manufacturer encountered problems resulting from contamination by the adhesive backing on sanding disks that came off and adhered to weld surfaces during mechanical cleaning. The effects of each of these types of contaminant will be discussed below. Tables 1 and 2 summarize examples of conditions interfering with penetrant action and suggest treatments for removal or correction of interfering conditions.

Effects of Contamination by Oils, Grease, Organic Fluids or Residues

The performance of liquid penetrants can be affected by contamination of test surfaces and surfaces within discontinuities by various processing substances. Typical examples of such contaminants include preservative, forming, drawing, cutting, machining or lubricating oils; wax or crayon marks; dyes; greases; and ultrasonic test couplants such as glycerine. Many analogous contaminants can result from shop environments or industrial pollution.

Oily or greasy surfaces tend to impair the action of liquid penetrants (1) by preventing formation of a continuous layer of liquid penetrant over the surface area being tested or (2) by filling or blocking leaks and surface connected discontinuities so that the liquid penetrant cannot enter and fill their cavities. Contamination by addition of a

Table 1. Contaminants that are on the test object surface or contained in voids or discontinuities and that interfere with liquid penetrant action during processing, with removal procedures or corrective treatments.

Types of Contaminants	Interference Effects	Removal Procedure or Treatment
1. Preservative, forming, machining or lubricating oils	Most oils fluoresce under ultraviolet radiation. This fluorescence can obscure fluorescent liquid penetrant indications or produce false indications. Oily surfaces also tend to impair the action of the liquid penetrant.	1. vapor degreasing 2. hot tank alkaline cleaning 3. steam cleaning 4. solvent emulsion cleaning 5. water emulsion cleaning 6. solvent washing
2. Carbon, varnish or other tightly held soil	Surface soils tend to adsorb or absorb penetrant, resulting in background color or fluorescence. These contaminants may also obstruct penetration into defects, impede wetting action or bridge discontinuities.	1. solvent type carbon remover[a] 2. alkaline type removers[a] 3. wire brushing (caution)[a,b] 4. vapor or sand blasting[a,b]
3. Scale, rust, oxides and corrosion	Surface soils tend to adsorb or absorb penetrant, resulting in background color or fluorescence. These contaminants may also obstruct penetration into defects, impede wetting action or bridge discontinuities.	1. alkaline or acid type removal procedures 2. wire brushing[b] 3. vapor or sand blasting[b] 4. electrocleaning
4. Paint coatings	Paint coatings impede wetting. Paint coatings may also obscure or bridge surface discontinuity openings.	1. solvent type paint removers 2. alkaline type paint removers 3. abrasive removal procedures[b] 4. burning
5. Water	Water impedes wetting and penetration.	1. air dry 2. force dry with dry air 3. oven dry at elevated temperature
6. Strong acids or alkalines	Strong acids or alkalines impede wetting and penetration. These contaminants may also also may react with penetrant to decompose or degrade dyes or other constituents.	1. rinse with fresh water 2. use neutralizing rinse, fresh water rinse and dry

a. Agitation such as used in ultrasonic cleaning may be beneficial with this surface treatment.

b. Mechanical processes that peen or smear surface material may act to close openings into discontinuities so that liquid penetrant indications cannot form. Such abrasive cleaning techniques are often prohibited or require a subsequent acid etching treatment to reopen the discontinuity to the part surface so that penetrant can enter.

TABLE 2. Test object surface irregularities and conditions interfering with liquid penetrant action during processing, with removal procedures or corrective treatments.

Types of Contaminants	Interference Effects	Removal Procedure or Treatment
1. Surface roughness	reduces ease of rinsing; increases difficulty of hand wiping	1. abrasive polishing[a] 2. electropolishing
2. Smeared metal resulting from forming operations of surface abrasion	may cover flaws and prevent liquid penetration	1. acid etching 2. electropolishing

a. Mechanical processes that peen or smear surface material may act to close openings into discontinuities so that liquid penetrant indications cannot form. Such abrasive cleaning techniques are often prohibited or require a subsequent acid etching treatment to reopen the discontinuity to the part surface so that penetrant can enter.

second liquid to a liquid penetrant will modify the surface tension and change the wetting characteristics of the liquid penetrant, typically with undesired results. When a crack is coated with a material that has a surface energy differing from that of the liquid penetrant, the penetrating action can be changed.

Many oils can fluoresce under ultraviolet radiation. This fluorescence of oil may obscure a true liquid penetrant or leak indication or result in a false indication. Removal of all contamination by oils or greasy fluids from the surfaces of the test object and any surface connected discontinuities is essential before liquid penetrant testing. A check can be made with ultraviolet radiation to ensure proper removal of fluorescing oils.

Effects of Contamination by Carbon, Engine Varnish or Tightly Held Soil

Tightly bonded contaminants such as layers of carbon, engine varnish and other soils are difficult to remove from test surfaces. They can interfere seriously with liquid penetrant testing. They typically impede surface wetting by liquid penetrant and may bridge over or obstruct entry of liquid penetrant into discontinuities. Such contaminant layers on the test part surface tend to absorb or collect liquid on their surface; they may also absorb or assimilate liquid into the interior of the contaminant layer. This leads to background fluorescence or visible dye staining of the surfaces of test objects, reducing indication contrast and visibility. For these reasons such contaminants should be removed from test parts before application of liquid penetrant.

Effects of Scale, Rust, Oxides, Corrosion Products and Weld Residues

Scale, rust, oxides and corrosion products must also be removed from test surfaces before application of liquid penetrants. These surface layers tend to cover discontinuities so as to block entry of liquid penetrant. They may also cause confusing test indications by trapping and holding liquid penetrant on the surface of the parts. The removal of scale, rust and oxides should be accomplished by techniques that do not close entrances to the discontinuities that may be present and that will not impair the ultimate serviceability for which the part is intended. In particular, it is desirable to avoid techniques that will cover leak or discontinuity openings by peening, smearing or cold working the surfaces. Where the surface is suspected of having been adversely affected, a treatment to reopen the discontinuities is required before liquid penetrant testing (see elsewhere for metal removal techniques). Care is also required to ensure that residues left from cleaning processes are not retained to affect liquid penetrant processing or evaluation.

Effects of Paint, Organic Coatings, Carbon and Varnish Contamination

Paint, varnish, organic coatings, enamels or carbon contamination can completely prevent detection of discontinuities by liquid penetrant testing. Although some conventional paints are readily removed with standard procedures, recent advances in paint technology have resulted in finish systems with unique adherence and durability. Total removal of such adherent coatings can be very difficult, even with special products and processes developed for this purpose. Even after removal of the major part of such coatings, residues may be left that obscure or bridge discontinuities in the underlying metal or test material. Particular problems can arise when paint, other coating material or residues from paint removal are firmly lodged within surface connected discontinuities. In these cases, no cavity is left for entrapment of liquid penetrant. To ensure reliable liquid penetrant testing, surface layers including materials imbedded within the discontinuities must be removed completely before application of the liquid penetrant.

Effects of Water Contamination of Test Surfaces, Leaks and Surface Discontinuities

Special precautions are needed when test parts may have been in contact with water, such as during water rinsing after chemical cleaning, before liquid penetrant testing and leak testing. It is important that all traces of water be completely removed before application of liquid penetrants. Water must be removed not only from the surface of the parts but also from any surface connected discontinuities that may be present; otherwise, water within discontinuities will minimize or prevent the penetrant's entry into surface discontinuities. Generally, oil based liquid penetrants tend to be immiscible with water.

An excellent means for drying smaller parts before application of liquid penetrants is with the dryer normally used to dry test parts. However, in many cases, drying at room temperature until the surfaces appear dry will be adequate for liquid penetrant testing if time is not a factor. It is desirable to perform tests to determine the effects of drying for each specific liquid penetrant testing system. However, much greater difficulty is involved in removal of water from leak passageways before leak testing. Vacuum drying before leak testing is helpful where it is feasible. A preferred procedure is to prevent water from contacting test objects before leak testing.

Effects of Contamination by Strong Acids or Alkalis

Strong acids or alkalis used to clean test parts before liquid penetrant or leak testing can impede surface wetting and penetration of test media into surface discontinuities if proper water rinsing and drying are not performed. These acids and alkalis may react to decompose or degrade dyes or other active constituents of liquid penetrants. In particular, acid and chromate residues may adversely affect the dyes by decomposing them, resulting in weak or faint test indications. Chromate residues also absorb ultraviolet radiation, which leaves less radiation to excite fluorescence in the liquid penetrant. For this reason, it is desirable to rinse thoroughly any test object surfaces that have been exposed to acids or chromates before liquid penetrant testing. All residues of acidic etching solutions such as those applied to remove smeared surface metal must be eliminated by thorough washing.

Effects of Surface Contamination by Fingerprints

The effects of fingerprints from manual handling of tests parts are not always recognized as sources of contamination. Some individuals' fingerprints are acidic to the extent that they can etch or corrode a highly polished surface. Even when etching does not occur, the oils associated with fingerprints can inhibit wetting by a liquid penetrant. Cotton or rubber gloves are recommended for parts handling where fingerprints are a known problem or where it is suspected that they could cause trouble during liquid penetrant testing. This can be particularly important on critical surfaces of machine parts, aircraft components or nuclear components.

Effects of Residues from Prior Visible Dye Liquid Penetrant Testing or Leak Testing

Residues retained from previous liquid penetrant or leak tests must be classified as contaminants that may affect subsequent tests adversely. If further liquid penetrant testing will be performed on the part (either as further processing takes place or when it is in service), thorough and prompt postcleaning should be practiced (see elsewhere about cleaning techniques after testing).

Visible dye liquid penetrant residues containing red dyestuffs act as ultraviolet radiation filters. When mixed with fluorescent liquid penetrants, these residues can appreciably diminish or destroy fluorescent indication brightness. Consequently, visible dye liquid penetrant testing should be prohibited when fluorescent liquid penetrant tests will follow. When reinspection of a test object is essential and preceding tests have used visible dye penetrants, the reinspection should also be made with visible dye liquid penetrant, if possible. If such reinspection is not possible, tests using cracked reference specimens and the liquid penetrant systems in question should be performed to verify the effectiveness of any planned subsequent fluorescent liquid penetrant testing.

Effects of Lack of Cleanliness in Liquid Penetrant Processing Areas

Lack of cleanliness in liquid penetrant testing areas is a potential source of test object contamination. If test objects are placed on surfaces or in containers that have previously been used for parts in process, they may be contaminated by liquid penetrants, emulsifiers, solvents, water or developers. If, before the test process, the test operator handles test parts with hands contaminated with materials used in the liquid penetrant testing, these contaminants may be deposited on the surfaces of the previously cleaned test parts. Any such prior contamination of the test objects can interfere with the proper functioning of the liquid penetrants and either can lead to false indications or can obscure valid indications. When doubt exists, it may be preferable to subject test objects suspected of being contaminated to thorough recleaning and retesting.

PART 2. Procedures for Cleaning Surfaces before Liquid Penetrant Testing

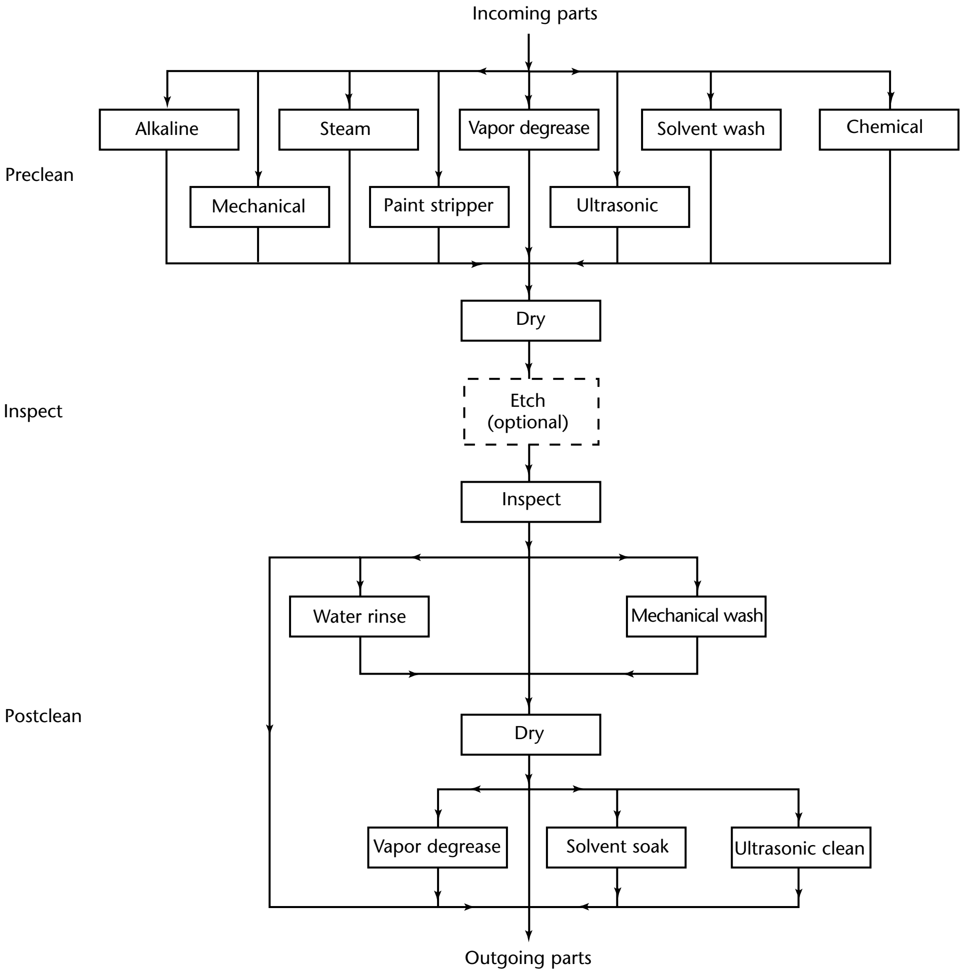
Techniques of Precleaning Test Objects for Liquid Penetrant Testing

Both precleaning (before testing) and postcleaning (following liquid penetrant testing) are vital steps in the test process (Fig. 1). Methods for precleaning of test objects include (1) detergent cleaning, (2) vapor degreasing, (3) steam cleaning, (4) solvent cleaning, (5) acid or alkaline cleaning, (6) abrasive cleaning, (7) paint, varnish and carbon removal, (8) electrocleaning, (9) agitation or ultrasonic cleaning, (10) salt bath descaling, (11) etching and (12) combinations of these techniques.

The cleaning process selected must be effective in removing soil or contaminants but must not damage the test objects. Different cleaning processes may be required for different metals, alloys or nonmetallic objects and for different types of contaminants and surface conditions.

Surface preparation by nondestructive test personnel is usually limited to removal of water or loose dirt and removal of oils and greases with solvents. However, test personnel should be alert to

FIGURE 1. Flowsheet for cleaning processes used with liquid penetrant testing.



all surface contamination and request that appropriately skilled personnel perform more thorough cleaning as required.

Selection of Cleaning Processes

Selection of cleaning processes for removal of soils and other contaminants from metallic test objects is influenced by the following factors: (1) types of contaminants to be removed (2) composition or alloy of the test object, (3) degree of cleanliness required for proper operation of liquid penetrant tests and (4) cost and time factors.

In addition, the quantity of similar test objects to be cleaned, their size and shape and the ease with which they can be handled are factors to be considered.

Multiple small test objects can often best be cleaned by immersion in liquid cleaners or by mechanized processes such as vapor degreasing, dipping or spraying of parts carried by conveyor lines. Large parts that cannot be placed in cleaning tanks may be cleaned by spraying both cleaners and rinsers onto part surfaces.

Parts to be cleaned in the field or at fixed locations in shops or test laboratories can often be handled by wipe-on, wipe-off techniques. In wiping techniques, cleaning or removal fluids are applied by lintfree rags moistened or wetted and wiped over test surfaces. Excess fluids and contaminants are removed by wiping with dry rags or lintfree paper towels. In each case, caution is required to ensure that cleaning and rinsing fluids are free from excessive contamination that could reduce their effectiveness. Hazards to personnel from toxic or flammable materials must be controlled or prevented. The cleaning agents must also be selected to be nondamaging to test object materials and surfaces. Wiping material that is lint free or has lint that does not fluoresce should be used.

Precautions in Cleaning of Metallic Surfaces

Although liquid penetrant testing is applicable to a wide variety of test materials, metal surfaces are by far the most commonly tested. Various metals may be involved, including aluminum, magnesium, titanium, carbon and low alloy steels, stainless steels, high temperature nickel base alloys and copper alloys. The choice of cleaning chemicals should be specific to the method to be cleaned. For example, a highly alkaline or caustic solution may be effective for cleaning magnesium or magnesium alloys but can act as a strong etchant on aluminum alloys. Alternatively, mechanical procedures (such as grit blasting) recommended for removing scale from some steels may cause excessive smearing of softer metals such as aluminum, magnesium or titanium.

Cleaning by polar inorganic chemicals, as in alkaline cleaning or acid etching, is not generally recommended for assemblies that contain exposed joints or junctions that could entrap the cleaning materials. The entrapped materials can not only contaminate liquid penetrant materials used later but can also cause corrosion of parts after liquid penetrant testing.

Precautions in Cleaning and Processing of Nonmetallic Surfaces

Nonmetallic surfaces such as plastics and elastomers or ceramics and glass can have different wetting characteristics than surfaces of metals. The nonmetallic chemistry may resist removal of contaminants. In addition, damaging effects can occur from the liquid penetrant materials. For example, liquid penetrant testing of acrylic plastics might result in crazing. Preliminary trials on reject or scrap surfaces and/or consultation with the supplier of the test object materials or the liquid penetrant test materials is advisable in questionable cases. The same precautions for cleaning metallic surfaces apply to cleaning of nonmetallic surfaces because cleaning techniques used for metallic surfaces may be ineffective or may damage the nonmetallic material. Because liquid penetrant testing of nonmetallics is a minor application, the following discussion deals with metals.

General Sequence of Steps for Precleaning Test Surfaces

Cleaning before liquid penetrant testing of production parts generally has the following sequence: (1) removal of light oil or grease by treatments such as degreasing, emulsion cleaning, solvent wiping, alkaline cleaning or steam cleaning; (2) rinsing if water base materials are used in the previous step; (3) removal of oxide, scale or rust by mechanical means such as grit blasting or by chemical means such as acid pickling or alkaline descaling; (4) etching if metal might be smeared; (5) rinsing to remove all residues left from cleaning; and (6) drying to remove all traces of water left from rinsing.

However, it should be noted that many inservice parts have an accumulation of dirt mixed with oils that is not removable by the techniques listed above.

Problems Requiring Complex Cleaning Procedures

Complex problems encountered in precleaning of test objects for liquid penetrant tests may require several contaminant removal techniques. For example, scale removal by acid treatment must normally be preceded by alkaline cleaning or by some other technique that removes the oil so that the acid can react with surface contamination. Acids are not generally good cleaners for oily soils.

The removal of scale and carbonaceous deposits such as those on used jet engine blades usually requires a multistage cleaning process. Procedures for cleaning highly critical products may necessitate careful processing with pure cleaning products, followed by rinsing with deionized or distilled water. Such critical applications are best considered on an individual basis.

Types of Soil

The term *soil* refers to undesired material on a surface that is not an integral part of the surface. Oil, grease, dirt and loose scale are soils. On the other hand, a decarburized skin or excess hard chromium are not considered to be soils. Soil can be classified into seven broad groups: (1) pigmented drawing compounds, (2) unpigmented oil and grease, (3) chips and cutting fluids, (4) polishing and buffing compounds, (5) rust and scale, (6) carbonaceous deposits and (7) miscellaneous compounds such as lapping compounds, ultrasonic test couplants and residue from magnetic particle testing.

Removal of Pigmented Drawing Lubricants

All pigmented drawing lubricants are difficult to remove from metal parts. They usually contain substances such as whiting, mica, graphite, white lead, zinc oxide, bentonite, flour, molybdenum disulfide and soaplike materials. Graphite, white lead, molybdenum disulfide and soaps are the most difficult soils to remove from metallic test objects. Vapor degreasing or solvent cleaning can remove common unpigmented oils and greases from hot metals and alloys. Animal and vegetable oils that saponify at slow rates and are insoluble in water can be removed by soaking or spraying with 80 °C (180 °F) alkaline solutions.

Removal of Oily Soils Containing Hard Particles

Soils containing metal or abrasive particles in an oil phase offer special removal problems. The oil phases are readily removed with solvent or vapor degreasing but the solid particle residues are difficult to remove from metallic surfaces except by agitation. When soils contain solid particles, the baths of cleaning compounds must usually be agitated by a mechanical device, excited by ultrasonic vibrations (ultrasonic cleaning) or applied by pressure spraying.

Difficulties in Removing Residues of Magnetic Particle Testing or Ultrasonic Testing

Residues left on test surfaces by wet magnetic particle testing are difficult to remove and can interfere with subsequent liquid penetrant testing. It is essential to demagnetize the parts before attempting to clean off these residues. Vapor degreasing acts to set the magnetic particles rather than to remove them. The extremely powerful magnetizing fields used in magnetic particle testing result in restricting the openings of surface discontinuities with magnetic particles. It is so difficult to remove the magnetic particles that it is better not to try to reinspect the part with liquid penetrants. If both test methods are to be used, the liquid penetrant test should be used first.

Liquid penetrant testing should also precede ultrasonic testing. The fluid couplants used with ultrasonic transducers can also block or fill surface discontinuities and may be quite difficult to remove.

Avoidance of Abrasive Methods That Peen, Smear or Cold Work Metals

Surface preparation by severe abrasion that peens, smears or cold works metallic surfaces should be avoided in precleaning. Peening or cold working of metal surfaces tends to close discontinuities. Thus techniques such as grit blasting, sand blasting, emery cloth, wire brushing or metal scraping should be used only with caution and only when no other technique will suffice. Specifications usually prohibit such abrasive cleaning techniques, particularly on soft materials such as aluminum.

When abrasive treatments are unavoidable and the metal surface is suspected to having been adversely affected, a treatment such as etching to reopen the surface discontinuities is mandatory.

Restrictions on Grit Blasting or Soft Wire Brushing

Aerospace industries frequently prohibit grit blasting or wire brushing of parts before liquid penetrant testing. In other applications, grit blasting with soft grit or gentle brushing with soft wire brushes may be used. These soft abrasion techniques are not so objectionable when used on metallic materials with Rockwell C hardness of 40 or greater. However, soft wire brushes may cause smearing when the brush material wears off and is deposited on the hard metal surface. Wire brush residue is also objectionable because it is a source of metal contamination. Carbon steel wire brushes are allowed only on carbon and low alloy steel. Austenitic stainless steel wire brushes that have not been used previously on other materials may be used manually on austenitic stainless steel to prepare its surface for liquid penetrant application.

Restrictions on Halogen, Sulfur, Potassium or Sodium Cleaning Compounds

Some metals and alloys are sensitive to certain elements such as halogens, sulfur, sodium and potassium. The aerospace and nuclear industries have been concerned about effects of halogenated solvents such as have been used in vapor degreasing, which can have damaging effects on halide sensitive materials, particularly titanium and its alloys. (Some companies forbid vapor degreasing with halogenated solvents to eliminate any possible effects of chlorides or fluorides from the decomposition products.) Cleaning compounds that contain sulfur should not be used with nickel or nickel base alloys. Restrictions are placed on halogen containing compounds on stainless steels and on both halogen and sulfur containing compounds for use on nickel base alloys for nuclear power industrial applications. Restrictions on surface treatments of metals for military equipment are cited in applicable specifications.

In the United States, precautions on halogenated solvents are moot in light of regulations prohibiting the production and use of ozone depleting substances.

Removal of Soluble Oils and Greases

The removal of unpigmented oil and grease such as common shop oils and greases, rust preventive oils, lubricating oils, drawing lubricants and quenching oils can be effected by several different cleaning processes, including (1) vapor degreasing, (2) hot tank alkaline cleaning, (3) steam cleaning, (4) solvent emulsion cleaning, (5) water emulsion cleaning, (6) solvent washing or wiping, (7) high pressure spray or air assisted spray and (8) combinations of above cleaning techniques.

The spray cleaning techniques may be used either in an automated cleaning system or by using hand held hoses or wands. Agitation is beneficial in tank application and ultrasonic agitation is particularly effective in certain applications.

Protection of Cleaned Test Surfaces against Corrosion

After cleaning to remove surface oils and grease, test objects that are thoroughly clean and dry should (1) have the liquid penetrant applied immediately or (2) be placed in clean, dry temporary storage and (3) possibly be treated with corrosion preventive materials. Clean steel parts can rust in a few hours in a humid atmosphere. If rust preventives are used after precleaning, another cleaning operation is required before liquid penetrant testing. Magnesium is also susceptible to corrosion if not treated.

Vapor Degreasing

One of the most common techniques of preparing test parts for liquid penetrant testing is vapor degreasing. This process is particularly suitable for removal of soluble organic contaminants such as mineral oils and greases. Unfortunately, vapor degreasing is not effective for removal of solid contaminants such as carbon, varnish, paints, scale, corrosion products or oxides. Other means of removal are required. In some cases, restrictions are placed on vapor degreasing of chloride sensitive metals and alloys with halogenated solvents (see discussion elsewhere on restrictions on halogen, sulfur, potassium or sodium compounds).

When steel or other ferrous metal parts are vapor degreased, the metal is usually highly susceptible to atmospheric corrosion if the air has high humidity or contains acid vapors, combustion products or other corrosives. All acids, cyanides or oxidizing agents should be prevented from contaminating the solvent used for cleaning steels. If the solvent should become acidic, it can attack steel, aluminum and magnesium alloys, which can lead to solvent decomposition and formation of contaminants that can affect stainless steels adversely.

Mechanism of Soil Removal in Vapor Degreasing

In vapor degreasing the hot vapors of a volatile solvent are used to remove oils, greases or waxes from metallic test objects in preparation for liquid penetrant testing. A steel tank fitted with a heater, solvent reservoir, condensing coil and removable cover is used to heat the solvent to boiling, generating a vapor zone above the solvent. The vapor condenses on the relatively cool metal surface of parts placed in the vapor zone. The condensed solvent dissolves the organic contaminants on the part. Contaminated solvent condensate then drips back into the tank reservoir, carrying the contaminates into the bath. During evaporation only clean solvent vapors are produced so that test parts are given adequate exposure to clean soilfree solvent. The test objects come out of the vapor degreasing operation clean and dry, but warm. After cooling, the test objects are ready for application of the liquid liquid penetrant if no other forms of contamination exist.

For many years, the preferred solvent for vapor degreasing was 1,1,1-trichloroethane (methyl chloroform), which was considered less toxic than trichloroethylene or perchloroethylene). All three have been widely used because they are nonflammable. More recent studies have found that there are significant health risks with the latter two and 1,1,1-trichloroethane is an environmental hazard as an ozone depeleter. Vapor degreaser manufacturers have developed equipment that can more safely use flammable solvents as vapor degreasing fluids. Chemical manufacturers continue to try to develop safer solvents for this cleaning method.

Personnel Hazards and Safety with Vapor Degreasing

Personnel using vapor degreasing systems should be aware of health hazards resulting from excessive inhalation of chlorinated hydrocarbon vapors, which adversely affect the mucous membranes of the respiratory system. Symptoms of excessive inhalation or absorption include headaches, fatigue, coughing, nausea, loss of appetite and loss of sense of balance. Long term exposure may result in kidney and liver damage.

High temperatures and high intensity ultraviolet radiation, such as produced by arc welding, can oxidize or decompose chlorinated hydrocarbon vapors to produce the highly toxic and dangerous gas phosgene (a poison gas once used in warfare). Other products of decomposition include hydrochloric acid, carbon dioxide and dichloroacetyl chloride, which aid corrosion and are strong irritants as well.

Like other fluids used in liquid penetrant testing, prolonged exposure of the skin to vapor degreasing solvents can extract oils from the skin, resulting in cracking of the skin and dermatitis. Vapor degreasing work areas should be ventilated properly. Chlorinated hydrocarbons should not be used in areas close to welding or heat treating operations or other sources of high temperatures. Smoking should be prohibited in areas used for vapor degreasing because phosgene gas may be formed inside the burning tobacco and the smoker will be exposed to it.

Disposal of sludge residues from cleaning operations must follow federal, state and local regulations and should not be burned or discharged into steams or sewers (see discussion elsewhere on liquid penetrant effluent). The sludge residue is toxic and may be flammable because it contains oil and grease collected during the degreasing operations. Direct contact with hot residue is dangerous. Sludge residues should be disposed of in covered containers that should not be airtight.

Solvent Precleaning of Test Objects

In some field applications an inspector may be able to clean small areas with a rag dampened with solvent. The solvent cleaner usually supplied with the hand wipe penetrant system for removal of excess penetrant may also be adequate for precleaning oil and grease residues from test objects before the liquid penetrant is applied. The operator should make certain that sufficient time has elapsed after use of solvent precleaners for the cleaner to have evaporated completely from any discontinuities that may be present, as well as from the exposed surfaces, before applying liquid penetrant to test parts.

For more extensive solvent cleaning, test objects are immersed and soaked in tanks of common organic liquid solvents. The solvents are normally used at or near room temperature. Oil, grease and loose metal chips are removed from metal surfaces, with or without agitation. Ultrasonic vibration is sometimes used to loosen soils such as abrasive compounds from deep recesses or test object discontinuities open to the part surface.

After solvent cleaning, parts are dried at room temperature or by external heat (such as that from a steam coil). Because contamination removed from test parts is retained in the solvent, both cleaning efficiency and the final cleanliness of test objects can decrease with continued use. Cleanliness requirements dictate when the used solvent must be replaced with new or reclaimed solvent.

Cleaning inconsistency is a problem with solvent tank cleaning because the rate of resoiling of part surfaces increases with greater contamination of the solvent. Most metals can be cleaned in common solvents unless acid or alkali contamination is introduced into the solvents. Solvent cleaning is often used in combination with separate acid or alkaline cleaning procedures for removal of complex soils.

Common organic solvents include aliphatic petroleum or chlorinated hydrocarbons (similar to those used in vapor degreasing) or blends of two or more solvents. Aliphatic petroleums include such familiar fluids as kerosene, naphtha, mineral spirits and Stoddard solvent. Other solvents include alcohols (ethanol, isopropanol or methanol), ketones, benzol, toluol and glycol ethers.

Precleaning by Spraying or Wiping of Solvent Cleaners

Test objects that are located in the field or are too large to be immersed in tanks can be cleaned by spraying or wiping the surfaces with solvent.

Caution. When spraying a flammable solvent, dispersion of low flash point liquids creates an explosion hazard. Spraying is typically done with conventional paint spraying equipment, airless spray, small bench type sprayers or by aerosol spray cans. Where feasible, the sprays should be directed into a vented fume collecting hood. Solvent cleaning is also often used as a preliminary step before acid or alkaline cleaning to remove soils that could interfere with the action of these chemical means of decontamination.

Field Use of Pressurized Spray Cans of Cleaner/Remover Solvents

Portable liquid penetrant kits for field use usually contain spray cans of liquid penetrant, developer and cleaner/remover. The cleaner/remover serves a dual purpose. It may be used to (1) clean the surface before liquid penetrant application, although other stronger solvents are also used for precleaning in the field or (2) remove excess surface liquid penetrant on completion of the liquid penetrant dwell.

When used to preclean, the spray solvent should be applied liberally and directly on the surface to be cleaned. Contaminants and excess solvent can then be removed with dry, lintfree cloth or paper towels. Adequate time for evaporation of remaining surface solvent must be allowed to dry before liquid penetrant application.

When solvent removers are used for removal of excess liquid penetrant, caution must be excercised to prevent removal of the liquid penetrant from shallow flaws. The solvent should be applied sparingly to a cloth that is then used to wipe off the excess surface liquid penetrant. Never spray solvent directly on the part surface to remove excess liquid penetrant.

Personnel Hazards and Safety with Solvent Cleaning

Personnel using solvent cleaning techniques should be aware of the hazards of fire (with flammable solvents) and toxicity (with chlorinated hydrocarbon solvents and ketones). The flash points and permissible toxicity concentrations are given in Table 3.[1,2] Areas used for solvent cleaning should have adequate ventilation to remove fumes and prevent accumulation of vapors in explosive or toxic concentrations. Flammable solvents should be stored in safety cans or closed metal containers. Open flames or heaters with exposed coils must not be used in areas where solvent cleaners are available. Smoking should be prohibited in solvent cleaning areas, including areas used for solvent wiping and drying.

Operators should be warned not to expose hands or skin to solvents because they dissolve skin oils and can lead to dermatitis or cracking of the skin. Protective gloves and ointments to restore skin oil should be used, when operators must be in contact with solvents. Vapors of chlorinated hydrocarbons and alcohol can have potentially lethal anesthetic actions when they are inhaled. Use in closed areas, as within tanks, can be dangerous with high concentrations of trichloroethylene or perchloroethylene, both of which have a strong narcotic effect.

Hand Wiping in Solvent Cleaning of Test Objects

Solvent application by hand wiping or spray wand can be used, in lieu of vapor degreasing, in precleaning of test objects for liquid penetrant testing. In many instances, the nature of the test object surface, the test object size and location (as in the case of inservice testing) or other considerations dictate solvent cleaning by hand wiping. This is time consuming but may be unavoidable in some cases.

Table 3. Flash points and relative toxicity values of common cleaning solvents.[1,2]

Flash Point[a]			Threshold Limit Values[b,c]	
Solvent	**°C**	**(°F)**	**μL·L^{-1}**	**mg·m^{-3}**
Aliphatic Petroleums				
Kerosene	65	(150)	___	___
Mineral spirits	15	(59)	___	___
Naphtha, high flash	45	(110)	___	___
Naphtha, VM&P[d]	10	(50)	300	2000
Stoddard solvent	40	(105)	100	525
Chlorinated Hydrocarbons				
Chloroform	none	none	10	49
Methylene chloride	none	none	50	174
Perchloroethylene	none	none	50	339
1,1,1-Trichloroethane	none	none	350	1900
Trichloroethylene	none	none	50	269
Trichlorotrifluoroethane	none	none	1000	7600
Alcohols				
Ethanol, specially denatured	14	(57)	1000	1900
Isopropanol	12.7	(54)	400	980
Methanol	12	(54)	200	260
Other Solvents				
Acetone	–18	(0)	750	1780
Benzol (benzene)	–11	(12)	1[f]	___
Ethyl cellosolve	44	(110)	5	18
Toluol (toluene)	8	(46)	50	188

a. Tag closed cup.

b. Key, M.M. et al. *Occupational Diseases — A Guide to Their Recognition.*[1]

c. Permissible exposure limits given as threshold limit values (TLVs) by American Council of Government and Industrial Hygienists[2] in parts per million and in milligram per cubic meter of air atmospheric pressure refer to time-weighted average (TWA) values of concentrations per normal 8 h work day. Warning — check against local regulations and most recent federal and state regulations.

d. Varnish makers' and painters' naphtha.

e. Manufacture and use both illegal in the United States.

f. 1 μL·L^{-1} per 8 h day.

Precautions in Safe Use of Flammable Solvents during Hand Wiping

Generally speaking, hand wipe solvents are either flammable or toxic or both. The levels of flammability and toxicity can vary with various types of solvents but in all cases it is essential that precautions be taken to *ensure adequate ventilation* and to *observe fire safety precautions*. The extremely flammable ketone solvents such as acetone and methyl ethyl ketone and aromatic solvents such as benzene and toluene and their vapors are potentially explosive. They should be treated with the same precautions as gasoline.

Generally speaking, petroleum solvents, although flammable, are relatively less dangerous. Observance of fire precautions and assurance of adequate ventilation are nevertheless warranted. Some solvents such as ketones are water miscible whereas petroleum solvents, chlorinated solvents and aromatic solvents are water immiscible. Thus, this water miscibility characteristic may be of concern for some solvent wiping applications. Water miscible solvents can quickly remove water and many organic substances from surfaces, thus providing a more thorough cleaning. However, some soils and contaminants are not soluble in water but are soluble only in water immiscible solvents.

Precautions in Safe Use of Toxic Solvents during Hand Wiping

Chlorinated solvents are generally toxic and, although they are generally nonflammable, adequate ventilation must be provided to avoid any physiological effects from breathing their vapors. These solvents are also of concern in some applications because they contain chlorine that can react to form chlorides, with detrimental effects on certain alloys. The fast evaporating solvents fall into either the chlorinated or highly flammable class, so the property of fast drying can be realized only through a compromise on safety. The petroleum solvents, although relatively less flammable, are also slower drying. However, this loss in drying time may be more than compensated for by the added safety factor.

Fluorinated solvents are relatively less toxic than chlorinated solvents. However, they are halogenated and contain fluorine and chlorine and their use is undesirable for cleaning metals sensitive to halides. The fluorinated solvents are also more expensive but have the advantage of leaving no residue following evaporation.

Removal of Paint

Paint can obscure or bridge surface discontinuities in underlying metals of test objects and must be removed before liquid penetrant testing to obtain effective liquid penetrant test indications. Paint removers are commercially available from various manufacturers for both in-place and dip tank application. Because paint removal technology is somewhat complex, the recommended approach is to enlist assistance from a supplier of good paint removers. Recent advances in paint technology have resulted in finished systems removable only with special products. Factors that influence the ease of paint removal include (1) surface preparation before painting, (2) type of paint primer, (3) type of paint used, (4) number of paint coats, (5) age or cure of the paint finish, (6) type of paint removers used and (7) nature of the substrate.

The treatments for paint removal from test objects before liquid penetrant testing include (1) solvent type paint removers, (2) alkaline or acid type paint removers, (3) abrasive removal procedures and (4) burning or ignition.

Critical structures cannot tolerate the use of any products or paint removal procedures that may be damaging to their metals or alloys. This requires careful attention when abrasive techniques are used for paint removal. Ignition or burning off of paint layers should never be used on aircraft. When solvent cleaning techniques are used, it is essential to remove traces or residues from solvents and other contamination by techniques such as have been recommended for unpainted metallic parts.

Removal of Carbon, Varnish and Other Tightly Held Soil

Carbon and varnish removal is similar to paint removal and many of the procedures and products used for removal of paint are also used for removal of carbon and varnish. Solvent carbon removers are available for brush or spray application or for use in dip tanks. Dip tank carbon removers are available that operate at ambient or elevated temperatures. Carbon can also be removed by alkaline products, depending on the conditions and the nature of the carbonaceous deposits. Mechanical means are also used for removal of this type of soil.

The treatments for removal of carbon, varnish and other tightly held solids include (1) solvent type carbon removers, either brush-on, spray-on or tank types, (2) alkaline or acid based removers, either brush-on, spray-on or tank types, (3) wire brushing or other abrasive cleaning, (4) blasting with vapor, sand, seed or glass beads (see cautions cited elsewhere on grit blasting), (5) electrocleaning and (6) combinations of these techniques.

Removal of Scale, Rust, Corrosion Products and Oxides

Scale, rust, corrosion products and oxides can usually be removed from test surfaces by chemical means, provided the surfaces are accessible. Acid scale removal is commonly used, with the type of acid or acids selected with consideration of factors such as (1) the type of metal or alloy surface, (2) the severity of the scale, (3) the dimensional tolerances permitted and (4) other limiting factors.

Alkaline type rust removers or descaling products are often effective and may be preferable to acid cleaning, depending on the circumstances. After the use of either alkaline or acid products, it is necessary to rinse the test objects thoroughly to ensure that acid or alkaline residues are not retained on test object surfaces where they might later affect the performance of the liquid penetrant.

Removal of High Temperature Alloy Oxides

Unique high temperature alloys are used in the hot sections of aircraft jet engines and rocket chambers and in nuclear applications. These alloys operate under conditions that result in deposits of complex oxides on the surface of metallic parts. Removal of these oxides requires special procedures that usually involve several cleaning stages. Among those commonly used are (1) high temperature alkaline cleaning processes, (2) fused salts descaling processes, (3) acid cleaning processes, (4) processing in alkaline oxidizing solutions, (5) electrocleaning and (6) combinations of above processes. Vapor or dry abrasive blasting (used with due caution, where permissible) is commonly required as a final step in removal of tenacious oxides that are integrally bonded to the alloy surfaces. High temperature alloys sensitive to certain elements such as chloride, sulfur, sodium and potassium are subject to restrictions that must be considered.

Removal of these oxides is mandatory if liquid penetrant testing of the high temperature alloy parts is to be successful. It is recommended that specialists in removal of high temperature oxides be consulted for recommendations and assistance in selecting and controlling the cleaning processes.

Alkaline Cleaning

Alkaline cleaners remove oily soils from metals by detergent action that reduces surface and interfacial tensions and permits the cleaning compound to wet the soils, seep under them and displace them. This action is attributed to *builders* (usually sodium compounds) that provide alkalinity. They loosen, disperse and emulsify soils removed from the metal surface. In water solution, alkaline cleaners reduce the viscosity of the soil and the water transmits agitation to the work surface and flushes away the soils. Cleaning action is provided by soaps and detergents added to the cleaning compounds that act as surface active or wetting agents.

The cleaner may function by the mechanism of high alkalinity needed for saponification reactions and must dissociate to provide ions. Most soaps or synthetic detergents are more efficient at pH values from 7 to 13. This active alkalinity is one of the working agents and is continually lost by saponification and neutralization reactions and by dragout on parts removed. This type of cleaner should provide alkalinity that is continuously available and ionized to replace the losses in active alkalinity.

The alkaline cleaner must also disperse soils removed from the test objects so that fluid close to the part surface does not become so highly contaminated as to redeposit soils on the surfaces being cleaned. The builders should be soluble in cold water and have no affinity for the object being cleaned. Traces of cleaner or alkali remaining on test objects after rinsing are objectionable because they might cause dermatitis or other health hazards or interfere with the action of liquid penetrants during the later test operations.

Acid Precleaning of Test Objects

Acids are not generally good cleaners for oily soils, so oxide or scale removal by acid means must normally be preceded by alkaline cleaning or by some other technique that removes the oil so that the acid can react at the test object surfaces. Acid cleaning processes use solutions of mineral acids, organic acids or acid salt and a combination of wetting agents and detergents, with or without heating, to remove oxides, shop soil and other contaminants from metal surfaces.

Acid solutions with 40 to 60 percent hydrochloric acid or 6 to 8 percent sulfuric acid can be used at room temperature for removing soil and light rust. Phosphoric acid mixed with ethylene glycol monobutyl ether is widely used for removing grease, oil, drawing compounds and light rust from ferrous alloys. Citric acid is used to clean rust from iron and steel without attacking the metal; it is also used in small concentrations in combination with sulfuric, phosphoric and other common acids to clean rust without attacking base metal.

Many proprietary acid compounds are available and consultation with the suppliers is recommended in selection of acid cleaners for various test object materials and contamination conditions. Inhibitors may be added to cleaners used on ferrous metals to reduce acid consumption and attack on base metal.

Salt Bath Descaling and Deoxidizing

Salt bath descaling and deoxidizing with reducing and electrolytic processes are effective in attacking heavy, tightly adhering scale that can form on carbon and alloy steels, nickel and cobalt base alloys and some grades of stainless steel. The test objects are typically immersed in a 370 °C (700 °F) bath of molten sodium hydroxide containing 1.5 percent sodium hydride. Immersion into the hot salt bath results in unequal thermal expansion of scale and base metal that cracks the scale. The molten salt then penetrates through the cracks and chemically reduces the oxides to lower oxides or metal. Following the salt bath treatment, the test parts are water quenched. Thermal shock may cause the cracks to open further. Various amounts of scale can be *blasted* off the metal surface during quenching. Following quenching, the parts can be rinsed in water to reveal a bright, clean metal surface.

Advantages of salt bath descaling include the following.

1. It can be used for all carbon and alloy steels, tool steels, stainless steels, nickel or cobalt alloys and refractory metals and alloys based on copper, nickel, cobalt, molybdenum and other refractory metals.
2. It provides very efficient removal of scale from surface discontinuities.
3. It decreases the time required for descaling all grades of stainless steel.

4. It is less destructive to smooth finishes than mechanical descaling.
5. It virtually eliminates metal loss and avoids surface pitting and etching.

Disadvantages of salt bath descaling include the following.

1. It uses high operating temperatures of 370 to 540 °C (700 to 1000 °F), which require special heating equipment and means for parts handling.
2. It results in distortion of thin gage materials of 0.8 mm (0.03 in.) gage and thinner.
3. It is not usable with aluminum, magnesium, zinc, cadmium, lead and tin, because of either their reactivity or low melting points.
4. It can embrittle titanium and titanium base alloys and can actually ignite titanium materials.

Emulsion Precleaning

Emulsion cleaning can remove many types of soils from test objects, including pigmented drawing lubricants, unpigmented oils and greases, cutting fluids and residues from polishing, buffing or magnetic particle testing. Emulsion cleaning provides rapid superficial cleaning and typically leaves on the work a thin film of oil that provides some protection against rusting. This oil can be removed by subsequent vapor degreasing or by two stage rinsing with an initial rinse (typically in agitated cold water) and a final rinse with hot water at 65 to 95 °C (150 to 200 °F) to preheat the test objects and aid in drying.

In some cases, emulsion cleaning following alkaline cleaning is used to provide temporary protection against rusting of ferrous parts. However, unless the residual oil film is completely removed before liquid penetrant testing, careful tests might be required to ensure that it could not interfere with liquid penetrant action.

The emulsion cleaner system typically involves stable emulsions of two immiscible liquids, such as a hydrocarbon and water, whose stability is aided by addition of a suitable emulsifying agent. Depending on the nature of the hydrocarbon solvent, the cleaning is done at temperatures of 60 to 80 °C (140 to 180 °F). The solvent is often of petroleum compounds of naphthenic, paraffinic or aromatic types. The low boiling solvents are usually more effective in removing soils but increase hazards of fire or evaporation loss as boiling and flash points are approached. Both stable single phase and unstable multiphase emulsion cleaners exist. The latter are used for the most difficult to remove hydrocarbon oils such as lapping or buffing compounds or oxidized oils. Cleanliness of the emulsion solution must be considered. The solution should be replaced when it leaves smut or deposits on the test objects or its cleaning action has diminished noticeably.

Removal of Strong Acids or Alkalis from Test Surfaces

Strong acids or alkalis might be present on test object surfaces if rinsing was inadequate following cleaning by acids, salt baths or alkaline solutions or if contamination with such materials had occurred during handling, storage or use. Acids or alkalis act to impede wetting and penetration of liquid penetrants into discontinuities. They may also react with liquid penetrant materials to decompose or degrade dyes or other active constituents. Removal of acids or alkalis can be achieved by (1) rinsing with fresh water or (2) rinsing with a neutralizing rinse followed by a fresh water rinse. After either of these treatments, the test objects should be thoroughly dried by the techniques described for removal of water.

Removal of Water from Test Surfaces

If test parts have been in contact with water, it is important that all traces of water be removed before liquid penetrant testing or leak testing. Water must be removed not only from the surface of the part but also from surface discontinuities that may be present; otherwise, liquid penetrant will be prevented from entering the discontinuities. The dryer customarily used with liquid penetrant testing (to dry parts after water washing to remove surface liquid penetrant or to dry parts to which wet developer has been applied) is an excellent means for drying test parts before testing. Water can also be removed by blowing it off with clean air (oil contaminated air should not be used). The surface could also be allowed to air dry, though air drying under static conditions can take an excessively long time; auxiliary drying techniques are usually used for this reason.

Alternative drying techniques include wiping of the test objects with clean, absorbent rags or rinsing test objects with fast drying, water soluble solvents, e.g., volatile alcohols, followed by drying. Heat lamps and other radiant heat sources can also be used. Warning: Most fast drying, water miscible solvents are flammable or toxic and should be used with caution.

Smoking and open flames should not be permitted in areas where such solvents are used. Good ventilation is always essential.

Removal of Fingerprints from Test Surfaces

Most cleaning techniques will remove fingerprint contamination on test objects. However, in critical applications, it may be necessary to use special procedures such as electrocleaning or special fingerprint removal products. The mandatory use of cotton gloves for handling test parts may be justified where contamination from fingerprints, during test handling or operations, is suspected of causing trouble.

Special Surface Treatments

Surface treatments such as phosphate, chromate conversion coating and black oxide are typically very adherent and tend to become integral portions of the test object metal surface. Some of these coatings can act physically to impede surface wetting and entry of liquid penetrants into leaks or discontinuities. Some phosphate and chromate coatings can react with the liquid penetrant and suppress fluorescent brightness. In general, it is recommended that the test be performed before the process that applied the coatings, if practicable. When the coatings are already in place, suppliers of the coatings process should be consulted for recommendations on removal of the surface coatings.

PART 3. Procedures for Postcleaning Test Objects after Liquid Penetrant Testing

Need for Cleaning of Test Objects after Liquid Penetrant Testing

Some form of posttreatment of test parts is generally required on completion of the liquid penetrant test process. For example, rust preventive steps may be required for carbon steel, because surfaces are left relatively clean and free of light oils by the liquid penetrant process. Exacting surface cleanliness may be required if the test object is to be installed in a liquid oxygen system. Whether or not the post treatment of the test object surface should be the responsibility of the inspection department or of the production department would depend on factors such as the need for swift action to prevent corrosion of test objects and the physical location of the available cleaning facilities. Regardless of where responsibilities lies, personnel responsible for liquid penetrant testing should be thoroughly cognizant with posttreatment criteria. They should know the effects of liquid penetrant processing on the subsequent deterioration, processing or serviceability of test parts. Also, at the minimum, test personnel should be responsible for removal of residues left on the surface by the liquid penetrant process. This would apply especially to residues conducive to corrosion and would include developer coatings under many test conditions.

Questions to be asked in determining whether or not posttreatment is necessary and in selecting the cleaning procedures and materials to be used include the following.

1. Is the condition of surface on conclusion of the liquid penetrant process likely to interfere with a subsequent process?
2. Is it conducive to corrosion or similar effect?
3. Does the ultimate use of the test object demand cleanliness?

After completion of the liquid penetrant test process, including interpretation of test indications and sorting of test objects into acceptable, salvageable and reject categories, all traces of liquid penetrant materials or other contaminants should be removed from test objects that are acceptable for service. As a general rule, the sooner the liquid penetrant and developer residues are removed by a cleaning process after testing, the easier it will be to remove them.

MOVIE. Postcleaning.

The purpose of postcleaning is to ensure that no deterioration of or damage to the test objects can occur later as a consequence of the liquid penetrant test process and to remove any residues that might interfere with subsequent processing. In the event that repair welding is required, liquid penetrant residues can have detrimental effects on weld areas. Special care is required if the test objects will be used in nuclear service or with liquid oxygen (LOX) systems. Traces of hydrocarbons can lead to violent explosions when the test parts come into contact with liquid oxygen. Extreme cleanliness is also essential for nuclear components.

In general, care should be taken to protect the test objects from corrosion or damage during parts handling, storage or assembly. In some cases, by mutual agreement with the user or customer, protection against rusting or corrosion may be applied to preserve parts until ready for use.

Procedures for Cleaning Test Objects Following Liquid Penetrant Testing

Whether or not post treatment other than developer coating removal is required or desirable following completion of the liquid penetrant process must be determined by conditions including (1) likelihood of corrosion, (2) texture of the surface, (3) intended use of the test object and (4) subsequent processing scheduled. Cleaning following liquid penetrant testing can generally be accomplished by one or more of the procedures discussed elsewhere in this chapter. Developer residues tend to be somewhat tenacious at times. Part of this tenacity may be caused by electrostatic attraction between the developer particles and the metallic surface of the tested parts. The longer the developer coating — aqueous or nonaqueous — remains on test parts, the more difficult it will be to remove. Developer coating removal should be done as soon as practical after completion of liquid penetrant testing. Combinations of one or more cleaning techniques may be necessary during post cleaning, depending on (1) the types of liquid penetrant test resides involved, (2) the length of time these residues have been left on the test objects and (3) the cleanliness required or specified.

Ultrasonic agitation of cleaning fluids may be especially beneficial for removing liquid penetrant process residues, particularly for tight clearance crevices, blind holes and other surface conditions that tend to trap and hold residues. However, the user is cautioned that ultrasonic cleaning has certain limitations and it is advisable to explore these before adopting this method. Care must also be exercised to ensure removal of all masking and plugging materials.

Cleaning Action of Liquid Penetrant Testing Processes

The liquid penetrant process is itself a cleaning operation. Liquid penetrant *oils* do a job of dissolving organic soils, especially if the contact time or liquid penetrant dwell time is extended. These liquid penetrant dissolved soils will be removed. Further, developer particles are absorbent and soak up oils, solvents and similar contaminants. Thus, on completion of the liquid penetrant process and removal of the developer coat, the surface of the test object may be more nearly free of certain contaminants than when the test process began.

Postcleaning to Remove Liquid Penetrant Residues

The cleanliness condition following testing will vary with processing techniques, liquid penetrant materials and surface texture. Some liquid penetrants such as water washable liquid penetrants with a low level of water solubility may be apt to leave a film of surface liquid penetrant on test objects. However, some water washable liquid penetrants, when properly washed off, leave a cleaner surface than lipophilic (oil base) emulsifiers. Rough surfaces such as sand casting surfaces tend to retain liquid penetrant in a multitude of pores. Some test processors, fearing washout of liquid penetrant from relevant wide open discontinuities, favor underwashing. They intentionally leave a surface film of liquid penetrant. However, where the test involves either self-development (using no developer) or a dry powder developer system, there will be little absorbent particle action to remove this liquid penetrant residue. So, in addition to removal of the developer coat, postcleaning (or posttreatment) is more often than not required to remove liquid penetrant residues.

Liquid Penetrant Emulsifiers in Postcleaning of Liquid Penetrant Residues

Although not a common practice and not as thorough as many other procedures, the emulsifier used to remove postemulsifiable liquid penetrants can be used for removing residual surface liquid penetrant during postcleaning. The parts are subjected to a prolonged emulsifier dwell time. This procedure may be relatively inexpensive, depending on the cost of the emulsifier and the rate at which it becomes contaminated. In some instances, such as in field testing of only a few parts, emulsification may be the most practical postcleaning technique. When the volume of testing is low and the requirement for a special cleaning procedure is absent, the emulsifier approach may be preferable.

Postcleaning of Test Parts to Be Plated, Anodized, Painted or Coated

If the test object is to be plated, anodized, painted or treated with similar coating, any oil film or developer particle surface contamination will interfere with the adhesion of the applied coating. Normally, the department responsible for application of such coatings will have a cleaning process. This cleaning would precede the coating application whether the part arrived from the liquid penetrant station or from some other source. The liquid penetrant test department will seldom be responsible for delivering the test objects in a condition ready for anodizing, plating or even painting.

Prevention of Corrosion of Carbon Steel or Magnesium Parts

Very often, on completion of the liquid penetrant testing process, the test surface is cleaner than when the parts were received for testing. Rust on carbon steel surfaces and corrosion on magnesium surfaces will appear almost instantaneously under most climatic conditions. Immediate rust prevention is required. There are several approaches to this problem. A rust inhibitor additive may be put into the final rinse water for postinspection cleaning to remove developer. Following final cleaning, the part may be treated with light oil, a temporary protective coating or a commercial corrosion inhibitor. Additives like sodium nitrite and sodium chromate are environmental hazards and their use is restricted.

Reasons for Removing Developer from Parts after Testing

The developer is the last material applied in the liquid penetrant process. It may be one of several types: dry powder, nonaqueous, aqueous suspension, aqueous soluble or one of the less common types such as resin developer. After completion of the liquid penetrant test process, including interpretation of the test indications and sorting of test objects into acceptable, salvageable and rejectable categories, the developer coating should be removed. If the coating is not removed, the developer may interfere with subsequent processing such as anodizing or act to absorb and hold corrosion conducive moisture. Even if there is not subsequent processing and no corrosion concern, the developer residue may interfere with the proper function of the parts. There is generally at least a cosmetic need to remove the developer coating before delivering the part.

Removal of Dry Powder Developers

Developer removal techniques must fit the developer type. For example, the fluffy dry powder developer, unless applied by an electrostatic spray technique, will only adhere to areas that are wet with liquid penetrant (or other liquid substances), although powder may lodge in crevices. So, dry powder removal is either unnecessary or can be accomplished by a plain water wash, an air blast or similar uncomplicated means.

Removal of Aqueous Suspendible Developers

Aqueous wet suspendible developers are more difficult to remove than dry powder developers are. Typically, the aqueous wet suspendible developer is dried on the test part surface by means of an oven. Removal is best accomplished by a pressure spray water wash that contains detergent. Hand wiping with a nonabrasive medium, water and detergent is also effective.

Removal of Aqueous Soluble Developers

The aqueous soluble developer is a combination of white powders, wetting agents, corrosion inhibitors and similar ingredients, all of which dissolve in water. Cleaning is not complicated, because all of the developer ingredients are water soluble. Plain water will quickly flush most water soluble developers from the test object surface. The mechanical action of a pressurized spray will facilitate removal.

Removal of Nonaqueous, Solvent Suspendible Developers

The nonaqueous developer, typically a mixture of suspendible absorbent particles such as calcium carbonate in a volatile solvent such as alcohol, is usually sprayed on the test object surface. In a high percentage of applications, this developer is applied to relatively small areas, such as a weld, from an aerosol spray can.

Small areas lend themselves to hand wiping. Most nonaqueous developers wipe readily from the surface with a dry, clean cloth or soft bristle brush sufficiently clean to meet requirements. However, for more thorough removal, a wipe with water moistened toweling, followed by a dry wipe, may be in order.

Also, even though the area may be small, there may be threads, crevices and surface recesses where trapped nonaqueous developer particles cannot be reached by wiping. A forceful water spray, plain or reinforced with detergent, will be effective in removing trapped developer under these conditions. Where the test object is too large for manual wiping, this same water spray technique is the logical answer for removal of the nonaqueous developer coating. Ultrasonic cleaning would also be very effective.

PART 4. Cleaning Requirements for Fluorescent Liquid Penetrant Testing in Aircraft Overhaul

Precleaning Inservice Aircraft Components for Liquid Penetrant Testing

In liquid penetrant testing, during overhaul of aircraft, cleaning is the most important process if the test is to be valid. Where aircraft are returned from a service tour for rework or repair, the cleaning and its effect take on a special significance. On a returned aircraft, the airframes and engines with their related components will all vary in surface conditions. These part surface conditions affect the test as well as the cleaning requirements before liquid penetrant testing. Other factors that must be considered include (1) the amount of disassembly required, (2) part configuration, (3) material composition and (4) surface coating previously applied.

Disassembly of Aircraft and Engine for Rework and Inspection

Aircraft returning for rework or repair are disassembled to the degree necessary to provide an airworthy product for another service tour. This disassembly includes both the aircraft and engines. The amount of disassembly an aircraft component receives will govern its techniques of precleaning for the fluorescent liquid penetrant test. In general, the precleaning may be divided into two major categories: (1) precleaning of components that are completely disassembled and processed through feeder shops and their fluorescent liquid penetrant test stations; (2) precleaning of components and structures that are fluorescent liquid penetrant tested only in selected areas. Each of these categories entails different precleaning processes.

Preparation of Components for Inspection

Before induction into rework facilities, the aircraft and engines(s) are cleaned by detergents, solvents, steam or other techniques to remove soils, greases etc. that accumulate on inservice equipment. Following induction into rework facilities, those parts requiring liquid penetrant testing begin precleaning processes that vary with the alloys, surface coatings and general condition of the part and whether it is to be processed through feeder shops, remain on the aircraft or be part of a component. Those parts to be processed through feeder shops will be discussed next.

With cleaning techniques where parts are processed literally from tank to tank, precleaning is tailored to the parts. These parts being disassembled have very few rivets or fasteners to cause entrapment and usually offer good smooth surfaces. Structures and components that remain on the aircraft or are not disassembled require a different approach.

Chemical Cleaning of Components Scheduled for Feeder Shops

Components scheduled for feeder shops are removed from the engine or aircraft and disassembled and their parts are cleaned and tested separately. Chemical cleaning is a preferred technique and is used as much as practical for paint stripping, derusting and descaling of parts. However, mechanical cleaning is required on some parts.

As most parts and components on aircraft are painted as protection against the operating environment, paint stripping is usually the first precleaning process used. Parts are then chemically cleaned to remove corrosion products, grease, carbon, dirt etc. This aids in ensuring that surfaces are free of any foreign materials that would either prevent the liquid penetrant's entry into discontinuities or would hold the liquid penetrant on the surface, causing false indications or masking relevant indications. Etching of turbine blades is but one example of the variety of precleaning required to condition a part for liquid penetrant testing.

Restrictions on Mechanical Cleaning of Components of Inservice Aircraft

Even though chemical cleaning is the preferred technique, mechanical cleaning is required at times. Whenever mechanical precleaning is used, the following restrictions are imposed.

1. Rotary disks and wheels are acceptable only when used at low speeds.
2. Small areas are cleaned by hand sanding. The sanding motion follows a back and forth pattern in the same direction as a suspected discontinuity.
3. Abrasive blasting may be used only to the extent that the surface does not become peened to a degree that could seal a discontinuity or contaminate the opening with abrasive residue. The blast dwell is kept to the absolute minimum required to clean the metal surface. The area blasted is restricted to the proximity of that area to be tested.
4. Steel wire brushes, either flat or rotary, are not used on nonferrous metals.

Etching is at times used to assist in opening the discontinuities. However, etchants and the etching procedure are authorized only by the materials or quality laboratory having cognizance of the test procedures.

Final Precleaning by Vapor Degreasing

Vapor degreasing is a good technique of final precleaning. The use of chlorinated solvents to vapor degrease titanium is prohibited. The final precleaning of titanium parts is with a Stoddard or specialty solvent followed by oven drying at 50 °C (120 °F). Drying is necessary as the less volatile solvent could become entrapped in cracks even though the surface may appear dry.

Precleaning of Selective or Localized Areas of Aircraft or Components

Preparation of selected, localized surface areas can range from cleaning a complete wing spar to a small attach fitting. Some large helicopter transmission housing and engine accessories cases also fall into this category. Because these parts cannot be taken into the cleaning tanks, the precleaning techniques are much more restrictive.

Again, precleaning usually starts with paint stripping. Chemical stripping is generally used but mechanical stripping is substituted for some components having phenolic resins or baked enamels. Mechanical stripping is usually grit blasting of the approximate area to be tested. Many areas will have sealants applied that must be removed, usually by scraping with a nonmetallic scraper followed by chemical removal.

Assembled aircraft parts and structures will contain fasteners, overlapping joints and a myriad of other protrusions that make precleaning difficult. Extreme care must be used to remove the residue from around abutting surfaces and protrusions. A fiber brush is used for this operation.

Following the paint stripping, the areas are washed with a safety solvent and dried. Drying is at times assisted by air blasting with clean air. Oil contaminated air is prohibited. The final precleaning is done by the liquid penetrant inspector. The entire area is precleaned with a liquid penetrant precleaning solvent and dried.

Causes and Prevention of Improper Preparation of Aircraft Structures

The results of the fluorescent liquid penetrant test for either of the two precleaning categories depend on the thoroughness of the precleaning. Laxity in any of the above processes can be dangerous. Improper or incomplete precleaning may be the result of many factors; time is a major one. Sufficient dwell time is required to dissolve or remove the extraneous materials that can interfere with the test procedures. Trying to rush parts or areas through precleaning will probably account for more poor tests than any other factor.

Incomplete paint removal is an example of hurrying the precleaning. The items are coated with stripping compounds, the compounds and residue are removed and the item is processed to its next station. Many times a part will appear clean to a casual observer but the item will still have traces of primer intact. These minute traces are often mistaken for stains caused by anodizing or other treatments. In some cases, residues of softened paint and/or paint removers are fluorescent. Other examples include inadequate derusting (or corrosion removal) and descaling.

In addition to the problems previously mentioned, there are those encountered where cleaning is required around fasteners, attachments etc. After stripping the areas around these, protrusions usually contain small amounts of paint residue softened by the stripper. They also typically have scratches and tooling marks which, through a period of time, have become corroded. This paint residue and corrosion serve as a blotter for the liquid penetrants, leading to unwanted fluorescent background.

Conditions Interfering with Liquid Penetrant Testing of Inservice Aircraft

Conditions listed below and many others interfere with fluorescent liquid penetrant testing for the reasons given.

1. Remaining scale, rust and paint residue will absorb liquid penetrant and thereby give false indications or mask relevant indications.
2. Residue remaining around fasteners presents an additional masking problem and causes such excessive bleedout that cracks extending from these areas have to propagate from 3 to 6 mm (0.125 to 0.25 in.) to be identified.

These conditions also tend to cause overcleaning and overremoval of liquid penetrant by inspectors with limited experience. This is especially true of solvent removable liquid penetrant process, referred to as Method C in SAE AMS 2644[3] and ASTM E 1417.[4] When improper cleaning conditions are detected by the inspector, the parts or areas must be recycled through the precleaning process and all subsequent liquid penetrant processing steps. This is costly in both time and production delay.

Other factors affecting the test system are the maintenance of the liquid penetrant tanks. Liquid penetrant contamination is one concern; another concern is a production line where parts are continually fed into the liquid penetrant tanks. Hot parts out of degreasers, hot alkaline cleaners or ovens can eventually heat the liquid penetrant sufficiently to possibly change the liquid penetrant's solvent system, with a resultant change of sensitivity. This possibility, even though remote, should be considered.

Quality Control during Precleaning for Liquid Penetrant Testing

To provide adequate precleaning, quality control must start at the first cleaning process and continue throughout. With proper quality control, parts with residual paint, corrosion etc. will be stopped and properly precleaned before proceeding to the next process. A savings in both time and money is realized by this technique, as the item does not have to back track through the system.

A little extra time to test each protrusion and fastener area for residue will, in the end, save time. These areas can be readily cleaned with a little solvent and a fiber brush. This little effort will provide much better testing of these critical areas and also can avoid recycling due to excessive bleedout. To summarize, fluorescent liquid penetrant can provide economical and reliable testing after the items to be tested are properly precleaned and processed. There are no short cuts in precleaning for a reliable test.

PART 5. Influence of Mechanical Processing on Effectiveness of Liquid Penetrant Testing

Liquid penetrant testing can be an effective test method only if the discontinuities are open to the surface so that liquid penetrant can enter. When performed before liquid penetrant testing, some mechanical processes mask discontinuities by causing surface material to deform plastically and seal discontinuities. The so called *soft* metals such as aluminum and titanium are especially susceptible to deformation by mechanical processing. This problem is of special concern to aircraft manufacturing and transportation industries that use these metals.

Types of Mechanical Processing Preceding Liquid Penetrant Testing

During the fabrication of components such as in aircraft, a number of mechanical processes may be applied to the part. Titanium and aluminum parts are frequently machined to their final configuration. Steel parts are often grit blasted to remove heat treat scale. Titanium and aluminum parts are commonly tumble deburred or liquid honed to improve the surface condition and remove burrs resulting from previous operations. Shot peening is used to induce a favorable stress pattern in the surface of some parts. Many parts are machined and then sanded to remove machining marks. Liquid penetrant testing often is applied at several stages in the fabrication sequence and may directly follow any of the above mechanical processes.

Need for Chemical Removal of Surfaces Damaged by Mechanical Processing

The examples described elsewhere demonstrate the importance of chemical removal of surface material that has been plastically deformed by mechanical processing before liquid penetrant testing of titanium, aluminum and steel. If chemical removal (etching) of surface metal is not feasible, liquid penetrant testing should be carried out before the mechanical process in question or a different test method should be used. In addition, for a single mechanical process such as grit blasting, the required amount of chemical removal can vary, depending on the operating parameters chosen for the mechanical processing. Consequently, further investigation is needed for those processes or operating parameters not specified in the following examples.

Examples of Mechanical Obliteration of Crack Indications in Aluminum Alloys

McFaul has reported unique photographic evidence of obliteration of liquid penetrant indications of surface cracks in aluminum alloys.[5] These tests indicated that obliteration of cracks by mechanical surface processing (except for shot peening) can be overcome by a mild etch, if a postemulsifiable liquid penetrant system is used. The postemulsifiable liquid penetrant, compared to a water washable liquid penetrant, is more impervious to the nullifying effects of possible residual acids and other contaminants.

To conduct the tests, patterns of tight cracks with depth of 0.2 to 3 mm (0.01 to 0.125 in.) were generated in 10 mm (0.375 in.) thick blocks sliced from 75 × 100 mm (3 × 4 in.) aluminum alloy bars by repeated heating to 540 °C (1000 °F) and quenching in ice water. After about the fifth quench, a network of high thermal stress, low cycle fatigue cracks appeared. These crack specimens were milled sufficiently to clean up both top and bottom surfaces of the blocks to a 0.8 mm (0.03 in.) root mean square (rms) surface finish.

Liquid penetrant tests were made with a lipophilic postemulsifiable liquid penetrant system and a nonaqueous developer. Liquid penetrant dwell time was 15 min. Excess liquid penetrant was then flushed off with water to reduce the subsequent emulsification time, established at 1 min. After emulsification, the parts were again thoroughly washed with a spray rinse and checked with ultraviolet radiation. Specimens were then dried for 10 min in an 80 °C (180 °F) circulating hot air oven, allowed to cool and sprayed with a very light coat of nonaqueous developer. A minimum of 5 min developing time occurred before photographing the fluorescent indications under ultraviolet radiation. Where there was no initial evidence of a returning crack pattern, as much as a half hour of developing time was allowed.

Recovery of Crack Test Specimens for Further Tests

To remove residual liquid penetrant and reuse the specimens, they were cleaned for about 18 h, in a vapor degreaser. To probe the effectiveness of the cleaning techniques, these specimens were again sprayed with nonaqueous developer, allowed a development time of 3 h and again examined under ultraviolet radiation. This technique of cleaning for removal of residues from prior liquid penetrant processing proved satisfactory, because no evidence of liquid penetrant remained. The cracked test blocks were then given various mechanical surface treatments and again subjected to the liquid penetrant test procedures. Results of obliteration of liquid penetrant indications by mechanical treatments and their restoration by chemical etching are shown in the photographic sequences of Fig. 2 through 11.

Effect of Honing or Lapping on Liquid Penetrant Crack Indications in Aluminum Alloys

Figure 2 simulates the effects on visibility of fluorescent liquid penetrant crack indications of final honing or lapping of the inside diameter of an aluminum hydraulic cylinder. As shown in Fig. 2c, honing completely obliterated all evidence of cracks. Because an etch of the lapped cylinder surface would destroy the hydraulic seal effect of the lapped surface, it was necessary to conduct liquid penetrant testing before honing or lapping. Note in Figs. 2d and 2e that anodic etching or milling restored the crack indications on the cracked test block.

Effects of Sanding on Liquid Penetrant Indications of Cracks in Aluminum Alloys

Figures 3 through 5 show effects of power and hand sanding on fluorescent liquid penetrant indications of cracks in aluminum alloys. In Figs. 3b, 4b and 5b, it is evident that the finer the grit size used in sanding, the more severe the masking of crack indications becomes. Scraping, whose effects are shown in Fig. 6, can be used to avoid etching after sanding. If sanding and subsequent etching are used, one of the several mild aluminum alloy

Figure 2. Effect of honing or lapping on liquid penetrant indications in cracked aluminum test specimens: (a) original crack pattern of standard quench cracked block; (b) crack pattern after removal of 0.06 mm (0.0025 in.) of material using 30 grit wheel with coolant and controlled feed and speed; (c) crack pattern after removal of 25 µm (0.001 in.) by simulated cylinder honing operation; (d) crack pattern after removal of 0.008 mm (0.0003 in.) per side by standard preanodic etch method; (e) crack pattern after removal of 0.06 mm (0.0025 in.) by milling.

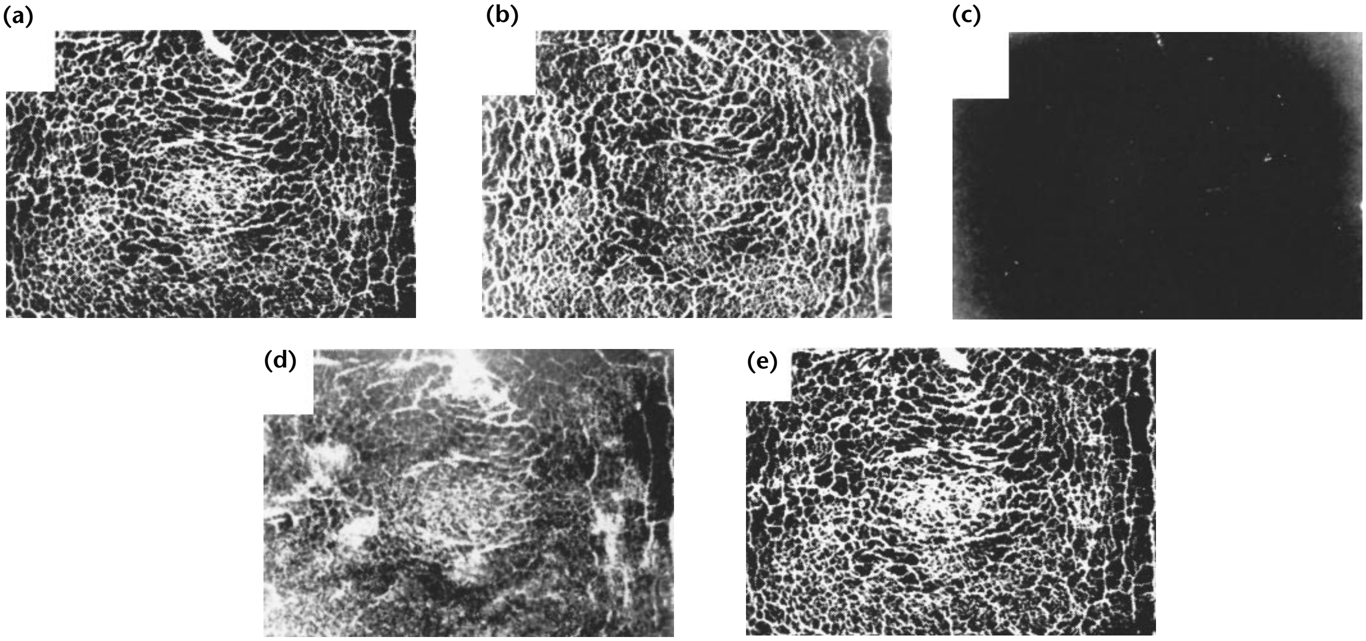


Figure 3. Effect of hand sanding using 180 grit on liquid penetrant indications in cracked aluminum alloy test block: (a) original crack pattern of standard quench cracked block; (b) crack pattern after removal of 0.05 mm (0.002 in.) by hand sanding using 180 grit aluminum oxide paper; (c) crack pattern after 10 min preanodic etch, removing about 0.005 mm (0.0002 in.) per side; (d) crack pattern after additional 5 min etch, making total of 0.008 mm (0.0003 in.) material removed per side; (e) crack pattern after 0.06 mm (0.0025 in.) was removed by milling.

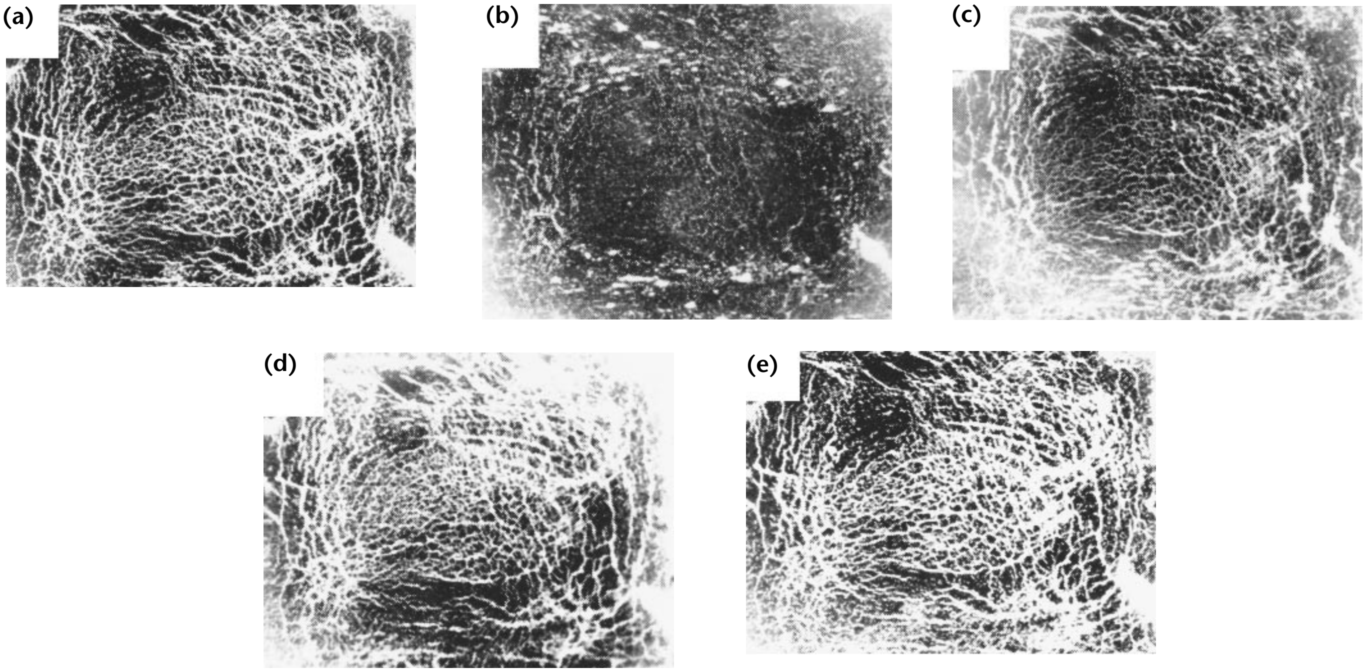
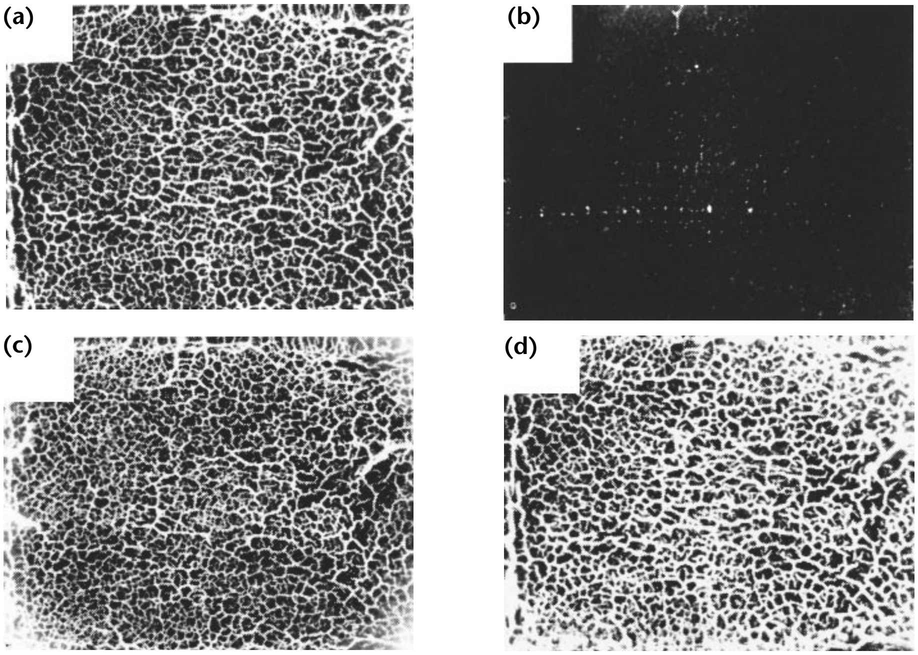


Figure 4. Effect of hand sanding using 240 grit on liquid penetrant indications in cracked aluminum alloy test block: (a) original crack pattern of standard quench cracked block; (b) crack pattern after removal of 0.05 mm (0.002 in.) material by hand sanding using 240 aluminum oxide grit paper; (c) crack pattern after removal of 0.008 mm (0.0003 in.) per side by standard preanodic etch method; (d) crack pattern after removal of 0.06 mm (0.0025 in.) material by milling. Note that crack obscuring effect of 240 grit is noticeably more than that indicated by use of coarser 180 grit.



etchants can be used. As seen in Figs. 3c and 3d, a 15 min etch in a preanodized cleaning etch bath restored the crack pattern.

Effects of Shot Peening on Liquid Penetrant Indications of Cracks in Aluminum Alloys

Figures 7a and 7b show that all liquid penetrant indications were masked by peening. A 15 min etch partially restored the crack pattern, as shown in Fig. 7c. Figure 7d shows that milling 0.1 mm (0.004 in.) from the aluminum surface fully restored the center portion of the crack pattern (where peening was less severe). By milling to remove 0.1 to 0.25 mm (0.004 to 0.010 in.) from the surface, the entire crack pattern was restored, as shown in Fig. 7e.

Effects of Vapor Blasting on Liquid Penetrant Indications of Cracks in Aluminum Alloys

Figures 8a and 8b show that nearly all liquid penetrant indications were masked by vapor blasting (liquid honing). As shown in Fig. 8c, the crack pattern was nearly restored by a 15 min etch.

FIGURE 5. Effect on liquid penetrant indications from combination of hand sanding of cracked aluminum alloy test block with 80 grit paper and finish grind using motor driven 240 grit quill: (a) original crack pattern of standard quench cracked block; (b) crack pattern after finish grind; (c) crack pattern after removal of 0.008 mm (0.0003 in.) material per side by standard preanodic etch; (d) crack pattern after removal of 0.06 mm (0.0025 in.) material by milling.

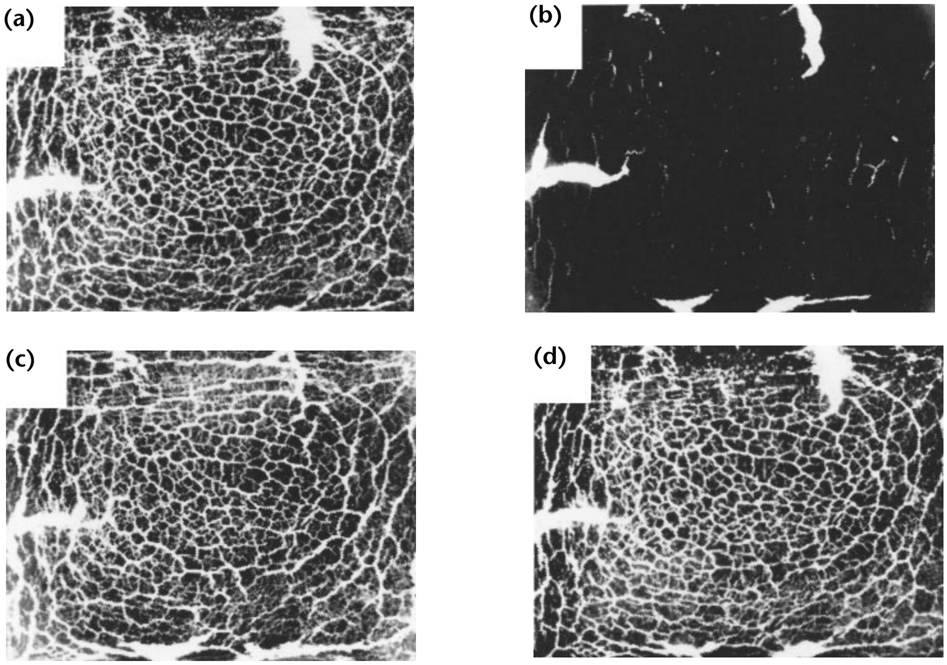
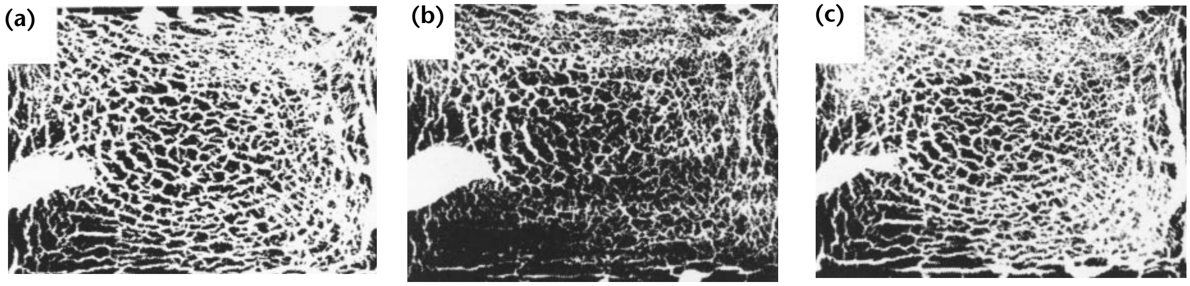


FIGURE 6. Effect of hand scraping using carbide tip scraper on liquid penetrant indications in cracked aluminum alloy test block: (a) original crack pattern of quench cracked block; (b) crack pattern after removal of 0.12 mm (0.005 in.) by hand scraping entire surface; (c) crack pattern after removal of 0.008 mm (0.0003 in.) per side by preanodic etch. Note that some streaking and slight loss of crack pattern is evidenced in Fig. 5b due to variations in scraping technique.



Effects of Tumble Deburring on Liquid Penetrant Indications of Cracks in Aluminum Alloys

Figure 9 illustrates that tumble deburring, like shot peening, masked nearly all liquid penetrant indications (Fig. 9). A 15 min etch restored most of the largest crack indications as shown in Fig. 9c but failed to restore the multitude of cracks in evidence after a mill cut removed 0.06 mm (0.0025 in.) of surface, as shown in Fig. 9d.

Effects of Grit Blasting on Liquid Penetrant Indications of Cracks in Aluminum Alloys

Figures 10a and 10b show that nearly all of the liquid penetrant indications were masked by grit blasting with 150 mesh alum oxide grit. In aerospace industries, grit blasting of spar caps is often considered to be a suitable technique for the blending of surface irregularities after machining. However, as with sanding of aluminum surfaces, a 15 min etch after grit blasting was required to restore the total crack pattern shown in Fig. 10c.

Comparison of Chromic Acid Bleedback and Fluorescent Liquid Penetrant Crack Indications in 7075-T6 Aluminum Alloy

Figure 11 compares two types of crack indications on the same 7075-T6 aluminum alloy test block. Figure 11a shows the original crack pattern revealed by fluorescent liquid penetrants. Figure 11b shows the crack pattern produced by the old technique using chromic acid bleedback for detection of cracks and discontinuities open to part surfaces. The chromic acid stain is light brown in color and low in contrast compared to the bright fluorescent liquid penetrant indications.

Figure 11c shows that use of postemulsifiable fluorescent liquid penetrant on anodized aluminum alloy surfaces is quite satisfactory in this case where the cracks are relatively wide. Fluorescent liquid penetrant indications of tight cracks may be obscured by fluorescent background generated by the porous anodized surface.

Investigation of Mechanical Processes Reducing Liquid Penetrant Sensitivity

An investigation has been reported[6] whose objectives were to (1) identify several mechanical processes that reduce the effectiveness of subsequent liquid penetrant testing of aluminum, titanium and steel and (2) determine techniques to restore liquid penetrant sensitivity after those mechanical processes. Quench cracked steel and stress corrosion cracked

Figure 7. Effect of standard shot peen process on liquid penetrant indications in cracked aluminum alloy test block: (a) original crack pattern of standard quench cracked block; (b) crack pattern after shot peen; (c) crack pattern after removal of 0.008 mm (0.0003 in.) material per side by standard preanodic etch process; (d) crack pattern after removal of 0.12 mm (0.005 in.) material by milling; (e) crack pattern after removal of an additional 0.12 mm (0.005 in.) by milling.

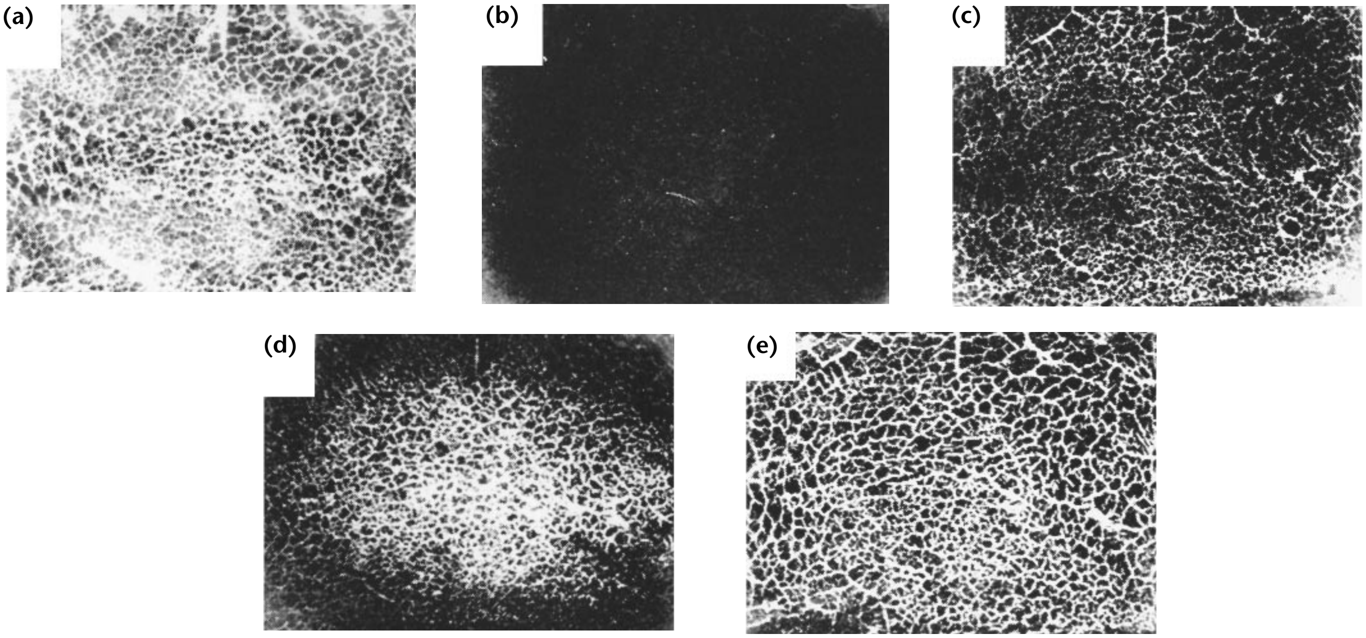


FIGURE 8. Effect of standard vapor blast operation on liquid penetrant indications in cracked aluminum alloy test block: (a) original crack pattern of standard quench cracked block; (b) crack pattern after vapor blast; (c) crack pattern after 0.008 mm (0.0003 in.) was removed per side by standard preanodic etch; (d) crack pattern after removal of 0.06 mm (0.0025 in.) material by milling.

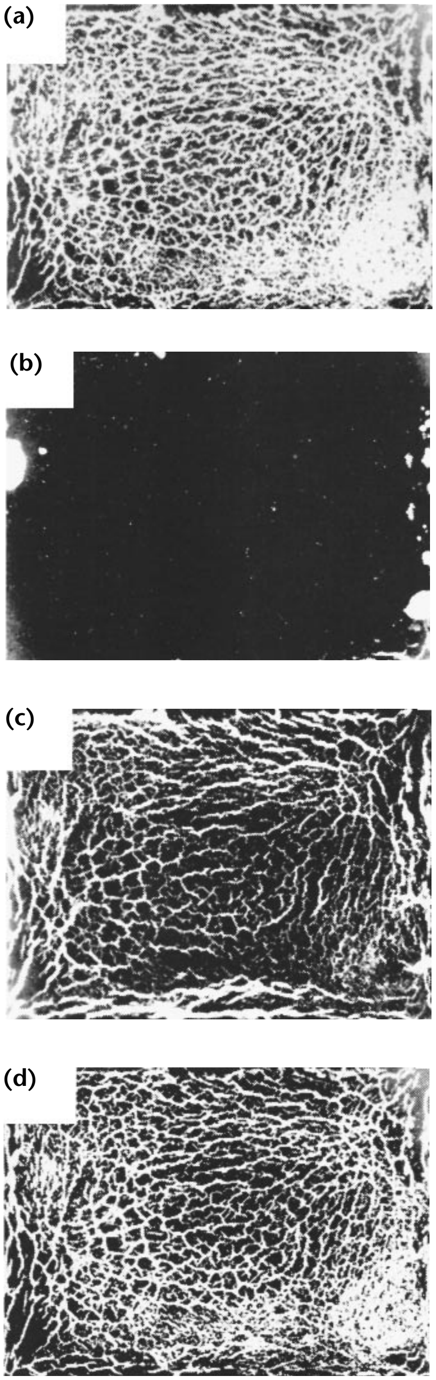
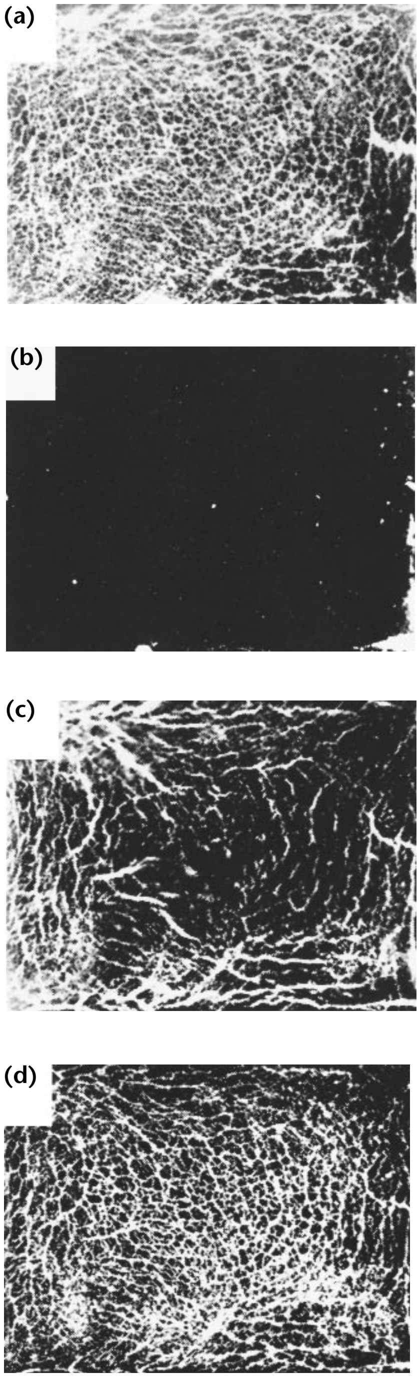


FIGURE 9. Effect of standard tumble deburr process on liquid penetrant indications in cracked aluminum alloy test block: (a) original crack pattern of quench cracked block; (b) crack pattern after tumble deburr operation; (c) crack pattern after 0.008 mm (0.0003 in.) material per side was removed by standard preanodic etch; (d) crack pattern after 0.06 mm (0.0025 in.) was removed by milling. Note that crack specimen was tumbled with another group of production parts of about same weight.



titanium were subjected to grit blasting, shot peening, liquid honing, tumble deburring and sanding and the resultant effect on liquid penetrant effectiveness was noted. In addition, quench cracked aluminum was machined, tumble deburred, sanded and subsequently tested with liquid penetrant. Following this, chemical etching was used in incremental steps on each of the materials to determine the amount of material required to be removed to restore the original liquid penetrant indications. The required amount of surface material to be removed by etching listed in Table 4 summarizes their recommendations. This

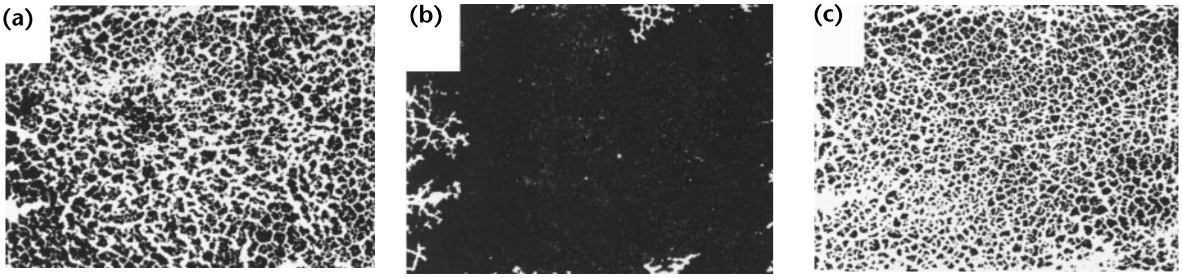


FIGURE 10. Effect of grit blasting using 150 alum oxide grit on liquid penetrant indications in cracked aluminum alloy test block: (a) original crack pattern of quench cracked block; (b) crack pattern after grit blast; (c) crack pattern after 0.008 mm (0.0003 in.) per side was removed by standard preanodic etch. Note that textured surface of block in Fig 5c definitely affected spread of liquid penetrant during development period. Because liquid penetrant pattern was returned in its entirety, no further work was done with this example.

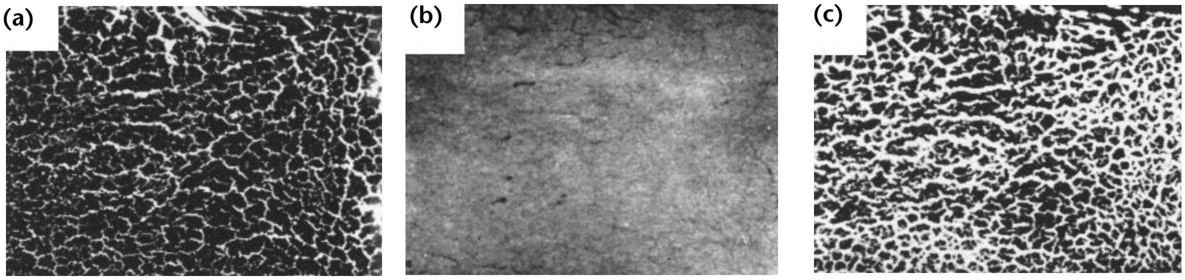


FIGURE 11. Effect of chromic anodic anodize treatment on liquid penetrant indications in cracked aluminum alloy test block: (a) original crack pattern as developed in 7075-T6 block by quench crack method; (b) chromic acid bleed back stain after anodizing; (c) crack pattern as developed by liquid penetrant process after anodizing. Note that here, as in grit blasted specimen, surface texture promoted increased spreading of liquid penetrant during development.

TABLE 4. Amount of surface material to be removed by etching to restore liquid penetrant indications.

	Surface Material to Be Removed							
	Titanium		4340 Steel		300M Steel		Aluminum	
Process	µm	(in. × 10^{-6})	µm	(in. × 10^{-6})	µm	(in. × 10^{-6})	µm	(in. × 10^{-6})
No. 120 aluminum oxide grit blasting	7.5	300	1.8	70	0.8	30	___	___
No. 50 aluminum oxide grit blasting	100.0	4000	1.5	60	0.5	20	___	___
Liquid honing	2.5	100	1.8	70	0.8[a]	30	___	___
Shot penning	100.0	4000	4.5	180	2.5	100	___	___
Tumble deburring	2.5	100	1.5	60	1.0[a]	40	5	(200)
Sanding, 100 grit	no effect		1.5[a]	60	no effect		5	(200)
Sanding, 180 grit	2.5	100	1.8[a]	70	no effect		5	(200)
Finish sanding of O-ring grooves	___	___	___	___	___	___	1.3	(30)
Conventional machining	___	___	___	___	___	___	5	(200)

a. Process reduced the strength of the indications only.

required amount was shown to vary with the mechanical cleaning process and with the test object materials.[6]

Evaluation of Effect of Mechanical Processing of Aluminum on Liquid Penetrant Sensitivity

Quench cracked 2024 aluminum alloy specimens were investigated using the procedures shown in Figs. 12 and 13. The liquid penetrant materials used in the evaluation were (1) a water washable fluorescent liquid penetrant and (2) a lipophilic fluorescent postemulsifiable liquid penetrant system used with two types of wet developer. The specimens were cleaned after each liquid penetrant test by vapor degreasing to remove residues of liquid penetrants and processing materials before retesting.

The effects of four mechanical processes were investigated: (1) tumble deburring, (2) sanding with 100 grit emery cloth sanding disks with an air motor unit in the same manner as standard milled part, (3) sanding with 180 grit butterfly type sanding air motor units and (4) machining. Quench cracked specimens were processed, liquid penetrant tested, etched and again liquid penetrant tested to determine the extent of etching necessary to restore liquid penetrant indications lost during mechanical processing.

Techniques for Measuring Extent of Etching

Coupons to be used for measuring the extent of metal removal by etching were cut from each specimen containing cracks. The coupon surfaces were machined to a 0.8 µm root mean square (3.2×10^{-5} in. root mean square) finish and opposite surfaces were machined parallel to 0.01 mm (0.0004 in.) across the length of the coupon. Then the coupons and parent specimens were etched according to the procedures indicated in Figs. 12 and 13. The thicknesses of material removed by etching were measured in millionths of an inch and capable of readings accurate to five decimal places. The measured values have been converted to micrometer in Table 4 and Figs. 12 and 13. Before being measured, the specimens were held in a temperature controlled environment overnight.

Figure 12. Etching sequence after tumble deburring crack aluminum panels.

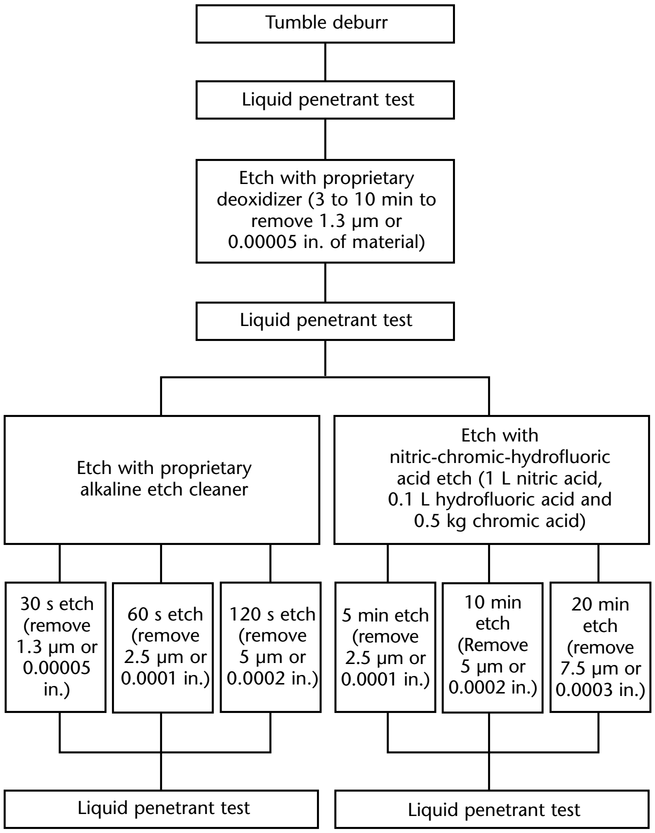
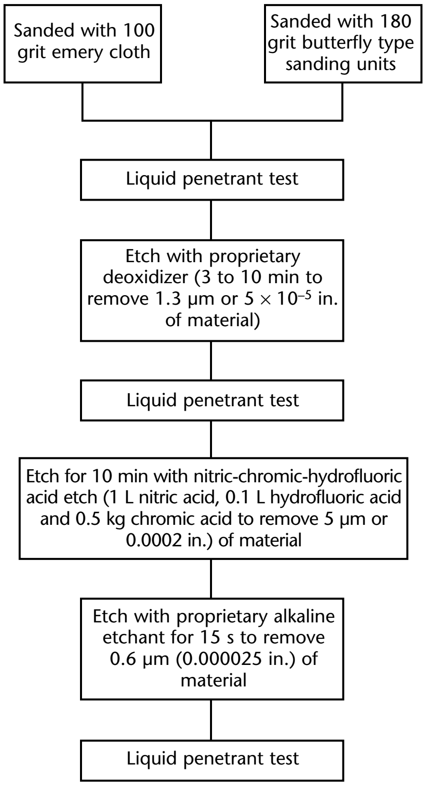


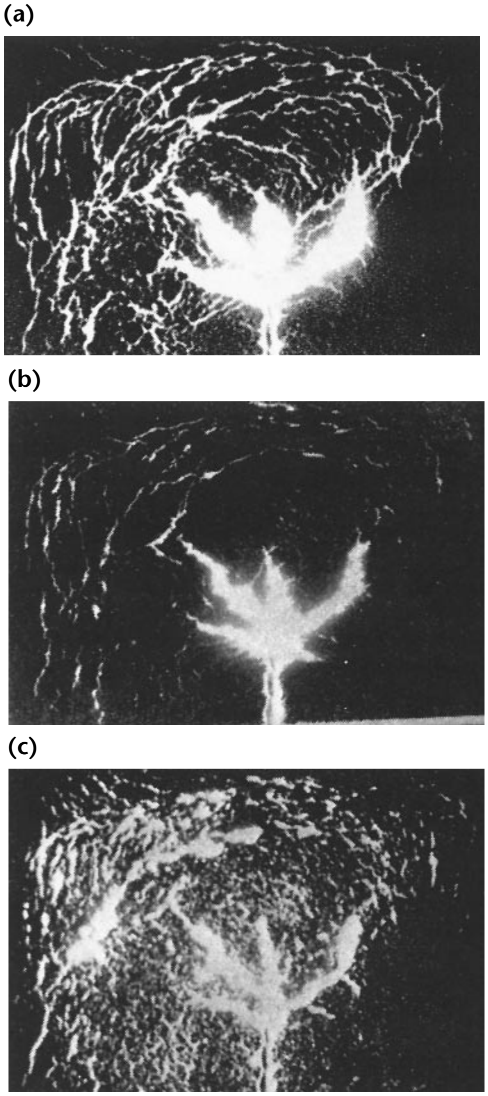
Figure 13. Etching sequence after sanding of cracked aluminum panels.



Effects of Etching of Tumble Deburred or Sanded Aluminum Alloys

Some of the liquid penetrant indications, particularly those of fine cracks, were obliterated when the 2024 aluminum alloy specimens were either tumble deburred or sanded. After etching with a proprietary alkaline etch cleaner for 60 s or with a nitric-chromic hydrofluoric acid etch cleaner for 5 to 10 min, the water washable liquid penetrant indications obtained without developer were restored as shown in Fig. 14. It was necessary to remove 5 µm (0.0002 in.) of material to restore the cracks that were obliterated (see Table 4). The proprietary alkaline etch cleaner produced a better surface condition than the nitric-chromic hydrofluoric acid etch cleaner. The acid etch cleaner pitted the surface somewhat. This increased the fluorescent background on part surfaces during subsequent liquid penetrant testing. In addition, the acid etch cleaner discolored the surface and it was necessary to etch with the proprietary alkaline etch cleaner for 15 s to remove the discoloration. This discoloration might have had no effect on the liquid penetrant process.

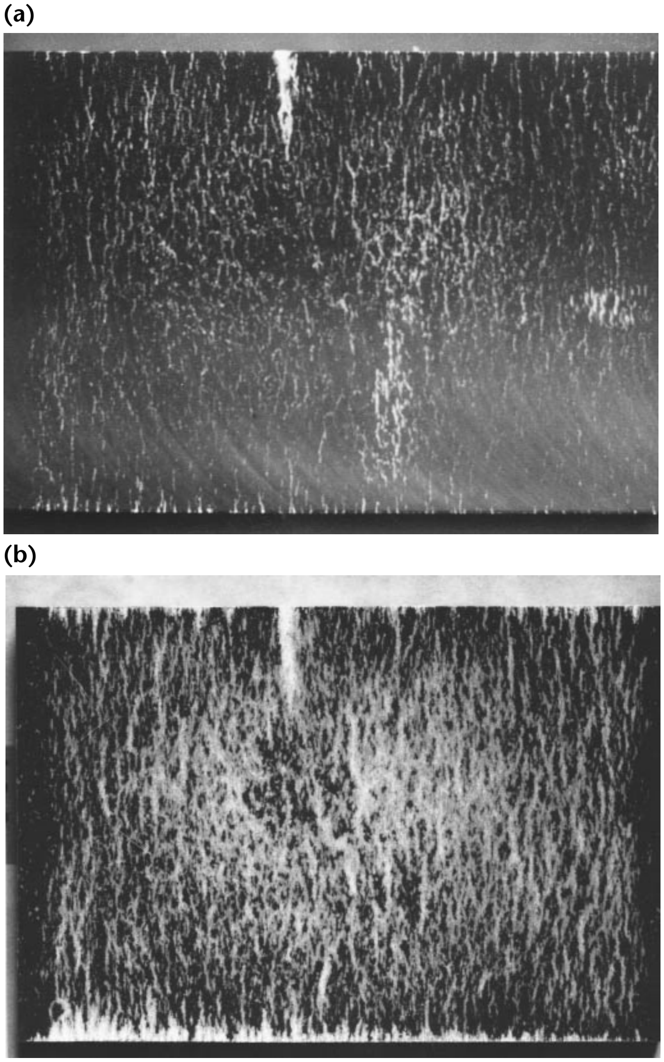
Figure 14. Effect of sanding and etching on liquid penetrant indications in 2024 aluminum specimens (water washable liquid penetrant without developer): (a) after cracking; (b) after sanding; (c) after sanding, etching with deoxidizer, and nitric-chromic-hydrofluoric acid etch.



Effects of Etching Conventional and High Speed Machined Aluminum

Conventional machining is used in many industries to reduce plate and

Figure 15. Effect of conventional machining on liquid penetrant indications in 2024 aluminum specimens (water washable liquid penetrant with dry powder developer): (a) after machining, (b) after etching.



forging material to the final part configuration. To determine the effect of machining of aluminum on the sensitivity of a subsequent liquid penetrant test, quench cracked 2024 aluminum specimens were produced using the method previously described. The specimen surfaces were machined and liquid penetrant tested with a water washable liquid penetrant and dry powder developer. Next, the specimens were etched and again liquid penetrant tested. As indicated in Fig. 15, it was determined that it was necessary to remove 5 µm (2×10^{-4} in.) to restore the liquid penetrant indications after conventional machining.

High speed machining is a machining approach designed to minimize tool vibrations and maximize metal removal rate. For high speed machining of aluminum, the surface speed of the cutter typically exceeds 12.7 $m \cdot s^{-1}$ (2500 $ft \cdot min^{-1}$). Quench cracked 2024 aluminum specimens were produced using the method previously described. The specimen surfaces were then high speed machined with a spindle speed of 34 000 rotations per minute and a feed rate of 219 $mm \cdot s^{-1}$ (518 $in. \cdot min^{-1}$). After machining, the specimens were liquid penetrant tested with a water washable liquid penetrant and dry powder developer. Next, the specimens were etched to remove 5 µm (2×10^{-4} in.) of material and liquid penetrant tested again. As indicated in Fig. 16, it was determined that high speed machining did not degrade liquid penetrant indications in aluminum and that etching is unnecessary.

Effects of Etching of Finish Sanded Aluminum O-Ring Grooves

To investigate the effect of finish sanding of O-ring grooves, two aluminum specimens were tested as indicated in Fig. 17. The specimens were liquid penetrant tested with water washable liquid penetrant and nonaqueous wet developer. Sanding obliterated most of the crack indication in the O-ring grooves. The indications were restored by etching with a proprietary deoxidizer to remove 1.3 µm (5×10^{-5} in.) of material (Fig. 18).

Recommended Metal Removal by Etching of Sanded Aluminum Parts

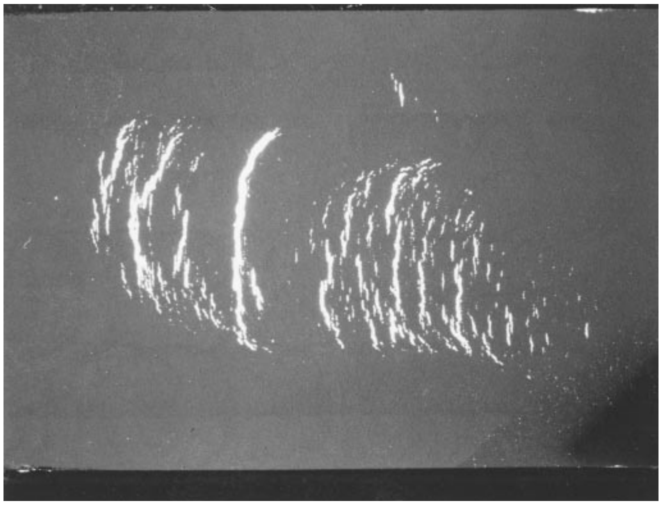
These results indicate that aluminum parts subjected to (1) a sanding operation with 180 grit butterfly type sanding units or (2) a sanding operation with 100 grit emery cloth sanding disks or (3) tumble deburring, should be etched to remove about 5 µm (2×10^{-4} in.) of material before any liquid penetrant test. Also, aluminum parts subjected to a finish sanding operation with 320 to 400 grit paper should be etched to remove at least about 1.3 µm (5×10^{-5} in.) of material before performing any liquid penetrant test.

Evaluation of Effect of Mechanical Processing of Steel on Liquid Penetrant Sensitivity

Specimens of AISI 4130 and AISI 1018 steels were cracked by carburization and

FIGURE 16. Effect of high speed machining on liquid penetrant indications in 2024 aluminum specimens (water washable liquid penetrant with dry powder developer): (a) after machining, (b) after etching.

(a)



(b)

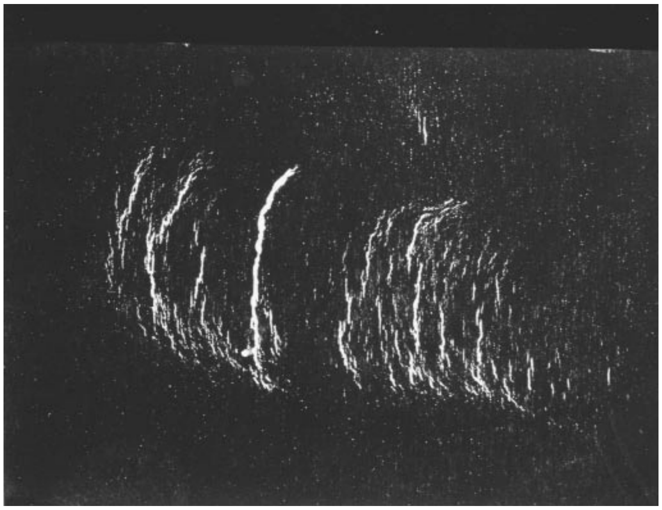
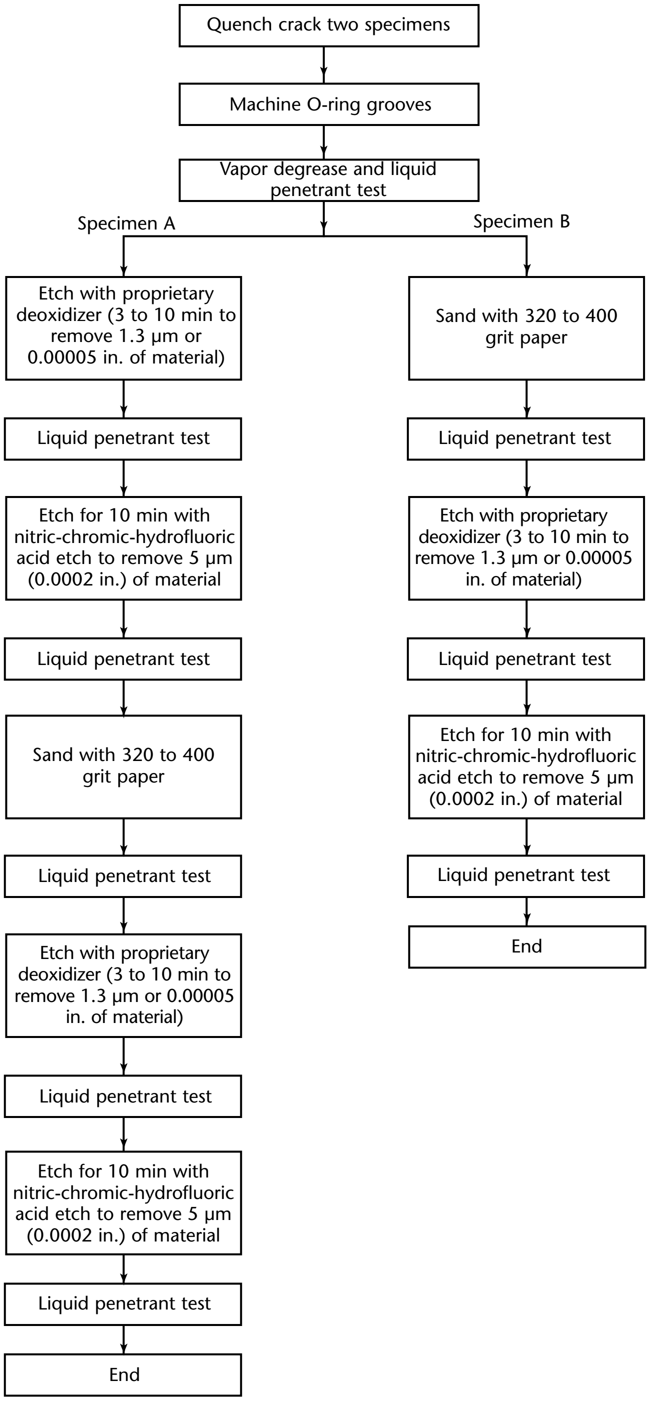


FIGURE 17. Etching sequence after sanding of cracked aluminum O-ring grooves.



grinding (see Fig. 19). AISI 4340 and 300M steels were intentionally quench cracked (see Fig. 20). Thereafter, the 4340 steel was heat treated to the 1400 to 1550 MPa (2.0×10^5 to 2.2×10^5 $lb_f{\cdot}in.^{-2}$) strength range and the 300M steel was heat treated to the 1850 to 2050 MPa (2.7×10^5 to 3.0×10^5 $lb_f{\cdot}in.^{-2}$) strength range. The specimens were then tested with a water washable fluorescent liquid penetrant. A 5 min liquid penetrant dwell time was used and excess liquid penetrant was removed using tap water with a spray nozzle operating at 280 kPa (40 $lb_f{\cdot}in.^{-2}$). After washing, the specimens were oven dried at 60 °C (140 °F) for about 5 min. A

FIGURE 18. Effect of sanding and etching on liquid penetrant indications in aluminum O-ring grooves (water washable liquid penetrant with nonaqueous wet developer): (a) after sanding; (b) after sanding and etching with proprietary deoxidizer.

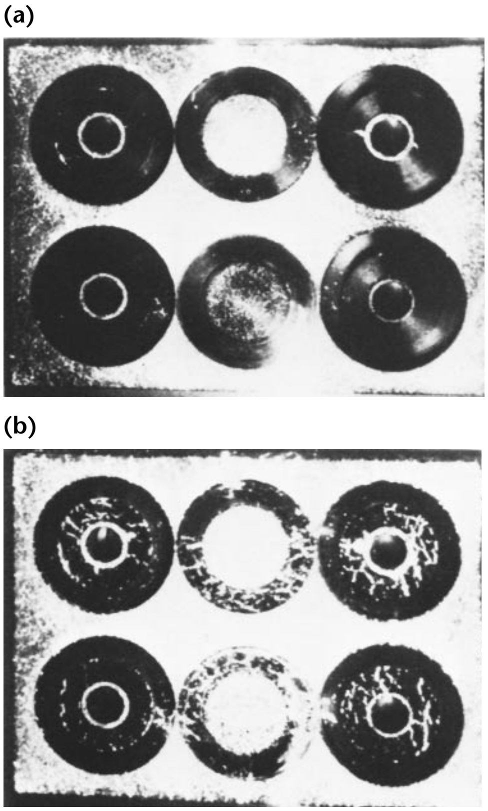
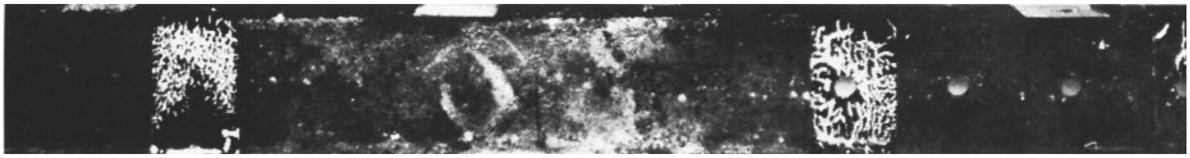


FIGURE 19. Typical grinding crack pattern in carburized AISI 1018 steel.



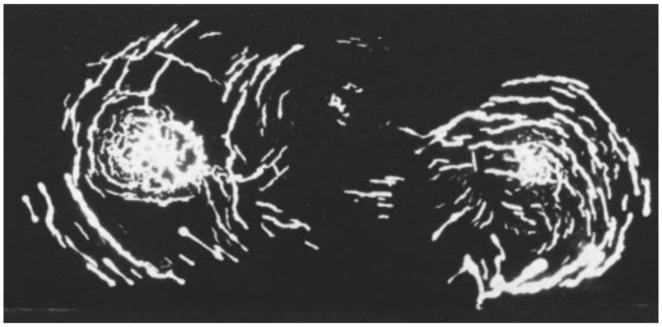
nonaqueous wet developer, applied with spray cans to the AISI 4340 and AISI 300M steels, remained in contact with the specimen for 15 min. No developer was used on the AISI 4130 and AISI 1018 steels. Following the initial liquid penetrant testing, the specimens were subjected to a trichloroethylene vapor degrease to remove residual liquid penetrant.

After the initial liquid penetrant test, the test specimens were subjected to various mechanical surface processing operations, details of which are given in Table 5. After the mechanical processing the specimens were cleaned and retested using the initial liquid penetrant procedure.

Technique for Measuring of Extent of Etching

The AISI 4340 and AISI 300M steel specimens where chemically etched after the second liquid penetrant test if the mechanical processing operation was found to have affected the intensity or the number of crack indications. Etch rate coupons were used to monitor the etching procedure as described previously for aluminum. The etching was accomplished in incremental steps using a hydrochloric acid pickle solution. After each etching step, the specimens were liquid penetrant tested using the initial procedure to note the change in the liquid penetrant indications.

Figure 20. Typical quench cracks in 6.3 mm (0.25 in.) thick AISI 4340 steel (water washable liquid penetrant with nonaqueous developer).



Effects of Mechanical Processing of Steels on Liquid Penetrant Indications

The effects of mechanical processing on liquid penetrant indications are summarized in Table 6. The effect on the

Table 5. Mechanical processing parameters for steel.

Operation	Parameters
Tumble deburring	1.5 to 2 h with triangular aluminum oxide chips[a]
Sanding (air motor units)	100 grit emery cloth sanding disk[a]; 180 grit butterfly type[a]
Grit blast	500 kPa (75 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) 120 grit aluminum oxide[a]; 500 kPa (75 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) 50 grit aluminum oxide[a]
Liquid hone	700 kPa (100 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) 220 grit aluminum oxide[a]; 550 kPa (75 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) 220 grit aluminum oxide[b]
Shot peen	peening intensity of 0.008 Almen (steel shot)[a]

a. Quench cracked 4340 and 300M steel.

b. Grinding cracked 4130 and 1018 steel.

Table 6. Summary of mechanical processing effects on liquid penetrant indications. Blank boxes indicate that tests were not performed under those conditions.[a]

Operation	Aluminum	4340 Steel	300M Steel	1018 and 4130 Steel	Titanium (6Al-4V)
Grit blasting, 120 grit aluminum oxide	not performed[a]	masked some[b]	masked some[b]	not performed[a]	masked most[c]
Grit blasting, 50 grit aluminum oxide	not performed[a]	masked some[b]	masked some[b]	not performed[a]	masked most[c]
Liquid honing	not performed[a]	masked some[b]	reduced strength[d]	masked most[c]	masked some[b]
Shot peening	not performed[a]	masked most[c]	masked most[c]	not performed[a]	masked most[c]
Tumble deburring	masked some[b]	masked some[b]	reduced strength[d]	not performed[a]	masked some[b]
Sanding, 100 grit	masked some[b]	reduced strength[d]	no effect[e]	not performed[a]	no effect[e]
Sanding, 180 grit	masked some[b]	reduced strength[d]	no effect[e]	not performed[a]	masked some[b]
Finish sanding O-ring grooves	masked most[c]	not performed[a]	not performed[a]	not performed[a]	not performed[a]

a. Test not performed under indicated condition.

b. Masked some indications.

c. Masked most or all indications.

d. Reduced strength of indications only.

e. No effect.

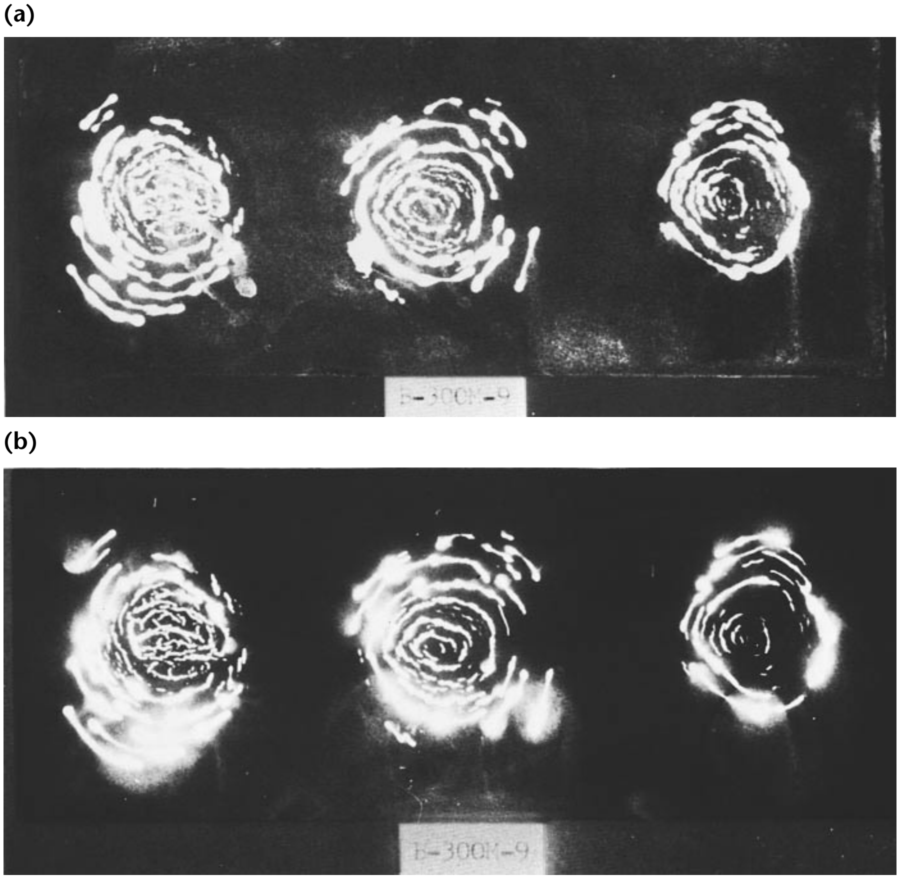
liquid penetrant indications varied depending on the mechanical process and the particular steel. For example, liquid honing of AISI 1018 and AISI 4130 steels resulted in a total loss of liquid penetrant indications. However, liquid honing of 300M steel only reduced the strength of the indications (Fig. 21). The most detrimental mechanical processes were shot peening (in the case of AISI 4340 and 300M steels) and liquid honing (in the case of AISI 4130 and AISI 1018 steels). These treatments resulted in a total loss of indications (see Fig. 22). The effectiveness of the liquid penetrant testing was reduced to a lesser degree by grit blasting and tumble deburring (in the case of AISI 4340 steel) and by grit blasting (in the case of AISI 300M steel). For those processes, finer indications were lost but the larger indications remained (see Fig. 23).

Several of the processes only reduced the strength of the liquid penetrant indications as opposed to masking all or some of them completely. These processes were sanding (both 100 and 180 grit) in the case of 4340 steel and liquid honing and tumble deburring in the case of 300M steel. Finally, both 100 grit and 180 grit sanding had no observable effect on 300M steel relative to either the number of liquid penetrant indications or their strength.

Recommended Metal Removal by Etching to Restore Indications in Steel

The amount of etching required to restore masked liquid penetrant indications also varied depending on the mechanical process and the material (see Table 4). For example, the average required amount of etching varied from 0.5 to 5 µm (7×10^{-5} to 2×10^{-4} in.) for 300M steel. Etching of high strength steels is not always feasible because of the possibility of embrittlement. Consequently, when it is not feasible to etch, these test results indicate that it may be necessary to use a supplementary testing such as magnetic particle testing along with liquid penetrant testing if parts are to be tested after grit blasting or liquid honing.

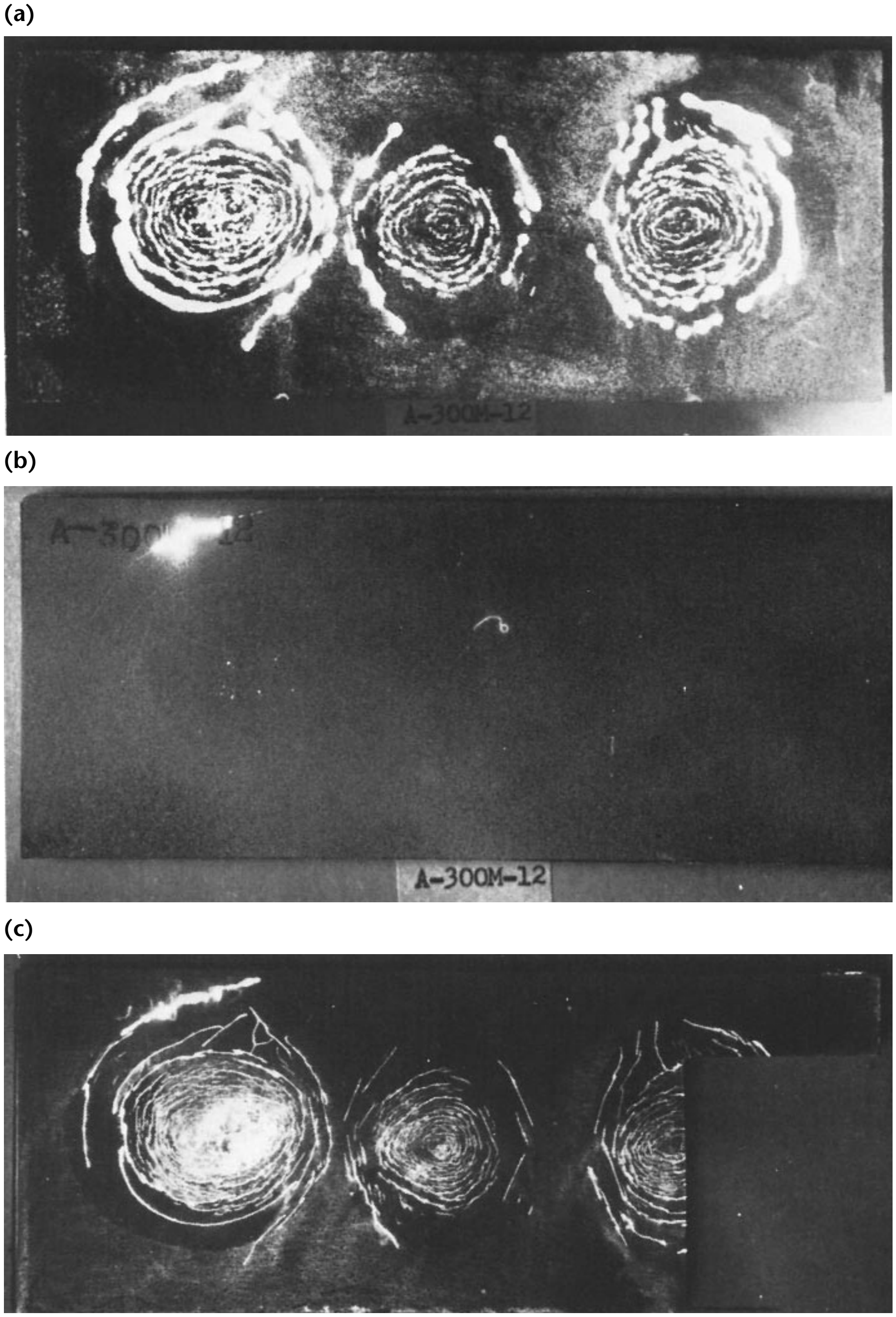
FIGURE 21. Effect of liquid honing on liquid penetrant indications in 300 M steel (water washable liquid penetrant without developer): (a) before liquid honing; (b) after liquid honing.



Evaluation of Effect of Mechanical Processing of Titanium on Liquid Penetrant Testing Sensitivity

Stress corrosion cracked specimens of annealed Ti-6Al-4V titanium alloy were also investigated for effects of mechanical processing on liquid penetrant test sensitivity. Half of the specimens were fabricated with the principal grain flow parallel to the thickness of the specimen; the remaining half were fabricated with the principal grain flow perpendicular to the thickness of the specimen. Each specimen was initially liquid penetrant tested using the parameters described for steel, except that a 10 min liquid penetrant dwell time was used. A

Figure 22. Effect of shot peening on liquid penetrant indications in 300M steel: (a) as cracked; (b) after shot peening; (c) after etching.



nonaqueous wet developer was used on the specimens.

After the initial liquid penetrant test, the test specimens were subjected to the mechanical processes described in Table 7. After the processing the specimens were cleaned to remove residual liquid penetrant, then retested using the initial liquid penetrant procedure.

The specimens were chemically etched after the second liquid penetrant test if the mechanical processing operation was found to have affected the intensity or the number of crack indications. Etch rate coupons were used to monitor the etching, as previously described for aluminum and steel. The etching was accomplished in incremental steps using a

Table 7. Mechanical processing parameters for titanium.

Operation	Parameters
Tumble deburring	deburred for 1.5 to 2 h using triangular aluminum oxide chips (No. 3)
Sanding (air motor units)	100 grit emery cloth sanding disk, 180 grit butterfly type
Grit blast	620 kPa (90 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) 120 grit aluminum oxide
	620 kPa (90 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) 50 grit aluminum oxide
Liquid hone	550 kPa (80 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) 220 grit aluminum oxide
Shot peen	peening intensity of 0.008 Almen (steel shot)

Figure 23. Effect of grit blasting on liquid penetrant indications in 300M steel: (a) as cracked; (b) after grit blasting; (c) after etching.

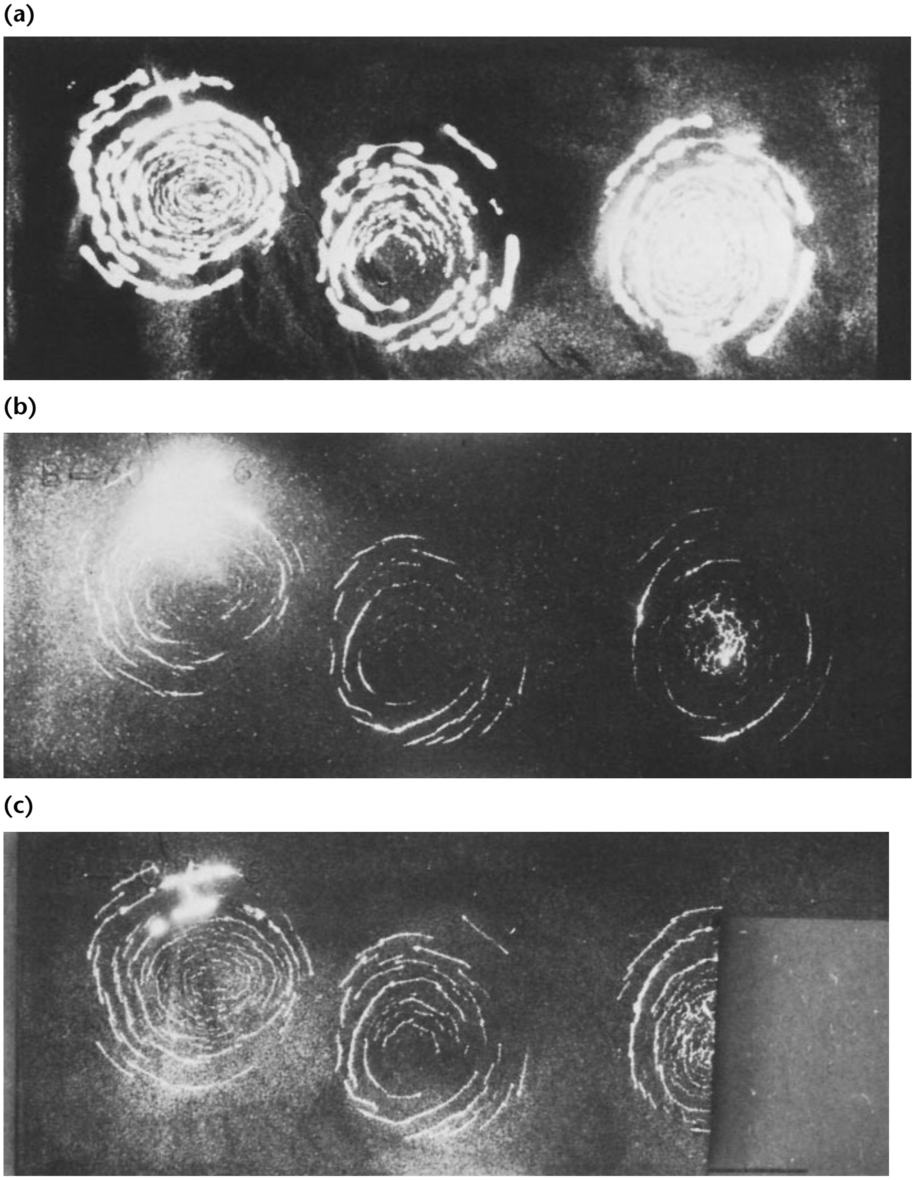
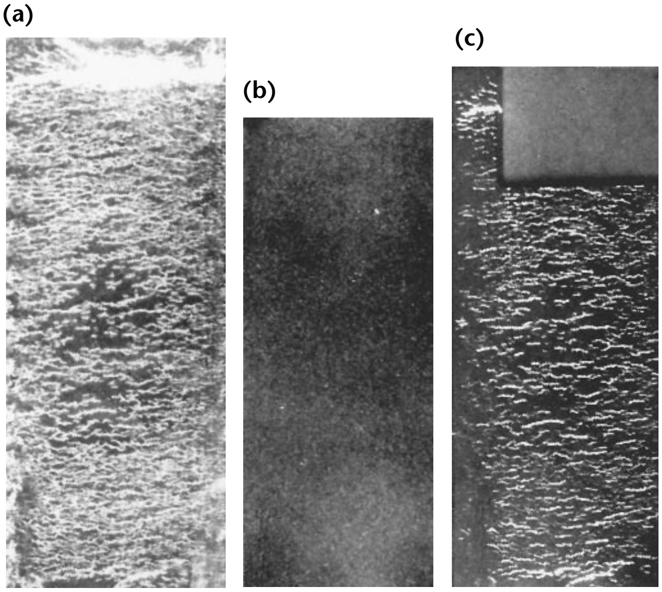


FIGURE 24. Effect of grit blasting on liquid penetrant indications in titanium (Ti-6Al-4V) alloy: (a) as cracked; (b) after grit blasting; (c) after etching.

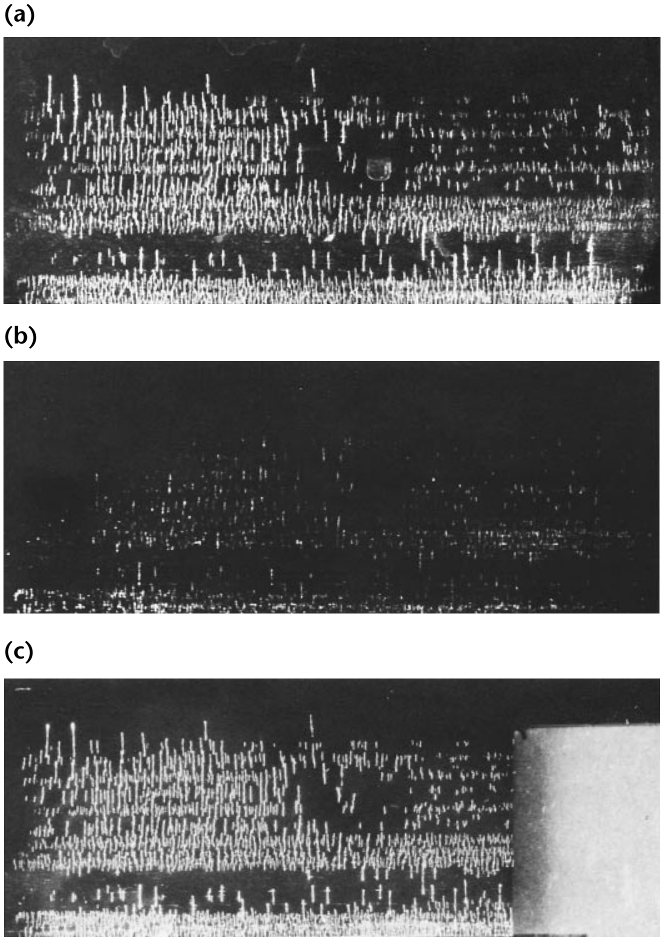


modified nitric-hydrofluoric acid pickle solution. After each etching step, the specimens were liquid penetrant tested using the initial liquid penetrant procedure to note the change in the liquid penetrant indications.

Effects of Mechanical Processing of Titanium on Liquid Penetrant Indications

The effect of mechanical processing on titanium can be seen in Table 6. The effect on the liquid penetrant indications varied depending on the mechanical process. For example, grit blasting and shot peening resulted in a total loss of liquid penetrant indications (see Fig. 24) and were the most detrimental processes. Consequently, it can be seen that if liquid penetrant testing of titanium is performed immediately after grit blasting or shot peening without etching, the test would be highly ineffective. The effectiveness of the liquid penetrant testing was reduced to a lesser degree by liquid honing, tumble deburring and 180 grit sanding (see Fig. 25). For those processes, finer indications were lost but the larger indications remained. Finally, 100 grit sanding had no observable effect on either the number of liquid penetrant indications or their strength.

FIGURE 25. Effect of liquid honing on liquid penetrant indications in titanium (Ti-6Al-4V) alloy: (a) as cracked; (b) after liquid honing; (c) after etching.



Recommended Metal Removal by Etching to Restore Indications in Titanium

The amount of etching required to restore masked liquid penetrant indications also varied depending on the mechanical process and the material (see Table 4). The average required amount of etching for Ti-6Al-4V alloy varied from 2.5 to 100 µm (0.0001 to 0.004 in.).

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7

CHAPTER

Liquid Penetrant Testing Equipment

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PART 1. Processing Equipment for Liquid Penetrant Testing

General Classification of Liquid Penetrant Test Equipment

In many cases, when large numbers of production parts are to be tested, the choice of equipment to be used for liquid penetrant testing determines whether or not the test method will be economical and productive. Inadequate or improper equipment could be costly and wasteful, leading either to discarding of parts that may not be anomalous or to retaining and using anomalous parts. In the broadest sense, liquid penetrant test equipment may be classified in one of three categories: (1) simple, hand operated, portable equipment that can be moved about easily as needed, (2) larger and more complete stationary equipment, somewhat universal in the variety of parts it can accommodate, and (3) specialized units built to accommodate specific types of parts and generally designed to function as an integral part of a production line.

Portable Liquid Penetrant Test Equipment

Where only an occasional check is to be made, no equipment may be needed other than the containers in which the processing materials are obtained. An example is a job shop in which there is no necessity for liquid penetrant testing of the parts actually manufactured but where it is felt desirable to use liquid penetrant for maintenance testing of some of the shop equipment. Here it is quite feasible to keep a small supply of liquid penetrant test materials on hand and to use them in the simplest way.

An absolute minimum supply would be spray cans of suitable visible dye liquid penetrant, cleaner/remover and developer. These materials could be taken to the machine or part to be tested and the materials are applied or removed by means of sprays, cloths and swabs. Because visible dye liquid penetrants require no special illumination, the actual test could be carried out under good shop illumination or, if necessary, with auxiliary light from a flashlight, trouble lamp or other source. Where fluorescent liquid penetrant is desirable, the same procedure can be carried out by substituting the proper fluorescent test materials and by providing a portable ultraviolet lamp and a screen or hood that can be used to darken the test area.

Liquid Penetrant Testing Kits

To make portable applications convenient, liquid penetrant test kits are available at low cost. These are small in size and weight and can be carried easily to any location. Fluorescent and visible liquid penetrant materials are available in kits. All items necessary for testing are included. The cases provide storage space for application brushes or swabs, cleaning rags and a brief instruction book. In some kits, the liquids are in containers with broad screw tops, to make application by brush or swab convenient during spot checks. In others, the liquid materials are provided in pressurized cans so that the materials can be applied by spraying.

Fluorescent liquid penetrant kits generally include an ultraviolet radiation source. The portable ultraviolet lamp can be hand held and moved to any test location or position quite easily. It is often possible to use such a portable fluorescent liquid penetrant test kit in subdued shop light by using shades to prevent the ambient light from falling onto the test area irradiated by ultraviolet radiation. However, fluorescent liquid penetrant testing is not recommended in shop light or daylight and should be used only under proper lighting conditions. Many specifications prohibit liquid penetrant testing under improper lighting conditions. (See below for precautions and recommendations concerning ambient and ultraviolet radiation intensity levels required for good viewing.)

General Purpose Stationary Liquid Penetrant Test Equipment

General purpose stationary test equipment includes small units that handle only a few parts per hour as well as combinations of larger test units through which production quantities of parts can be processed. The equipment, regardless of size or capacity, is generally characterized by the following attributes.

1. All functions of the testing technique are provided in a single piece of equipment or a collection of single function units that can be arranged in various sequences.
2. Processing is primarily carried out manually or with the assistance of simple handling devices such as roller conveyors and hoists.
3. Within the dimensional limitations of a particular unit, the number of shapes or types of parts that can be inspected is almost unlimited.

Small Self-Contained Liquid Penetrant Test Units

Typical of a smaller, completely self-contained test system is the unit shown in Figs. 1 and 2. This unit provides accommodations for carrying out the five steps of the liquid penetrant testing method where a water washable liquid penetrant is to be used. By the addition of one extra tank and drain rack, the postemulsifier process can be used. The main unit, without the added emulsifier tank, occupies about 3 m^2 (35 ft^2) of floor space.

Liquid Penetrant Dip-and-Drain Station

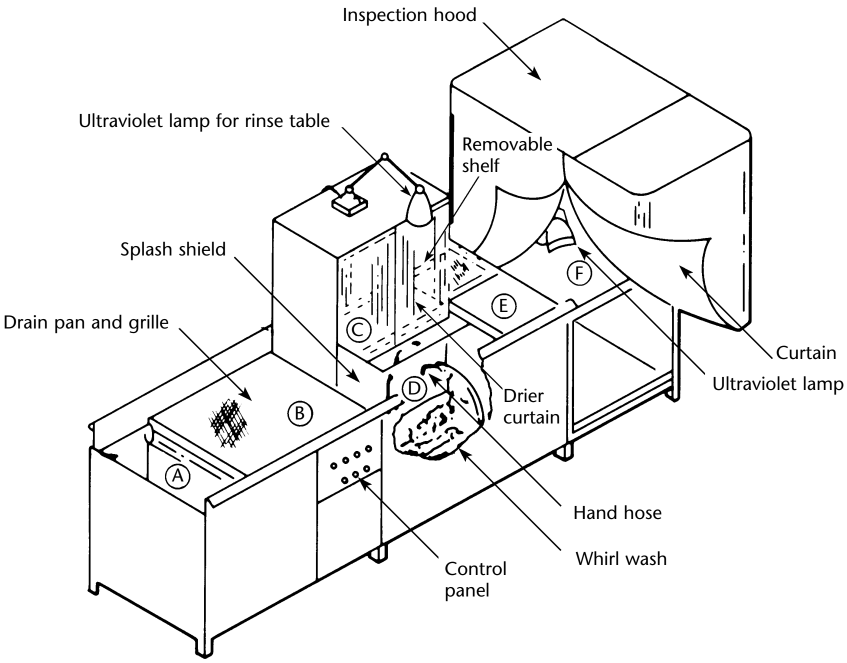
The liquid penetrant is contained in a dip tank located at the left end of the unit and is usually applied to the part by dipping or brushing. A grilled drain section is located adjacent to the liquid penetrant tank. After test parts have been covered with liquid penetrant, they can be placed on this grill to allow excess surface liquid penetrant to drain back into the liquid penetrant tank for reuse. The test parts should be left on the grill for a dwell time sufficiently long to allow liquid penetrant to enter all surface discontinuities.

Wash Station

The wash station is located adjacent to the liquid penetrant drain grill at the front center part of the unit. This station

Figure 1. Small self-contained water washable fluorescent liquid penetrant testing unit.

FIGURE 2. Schematic diagram of water washable fluorescent liquid penetrant testing unit.



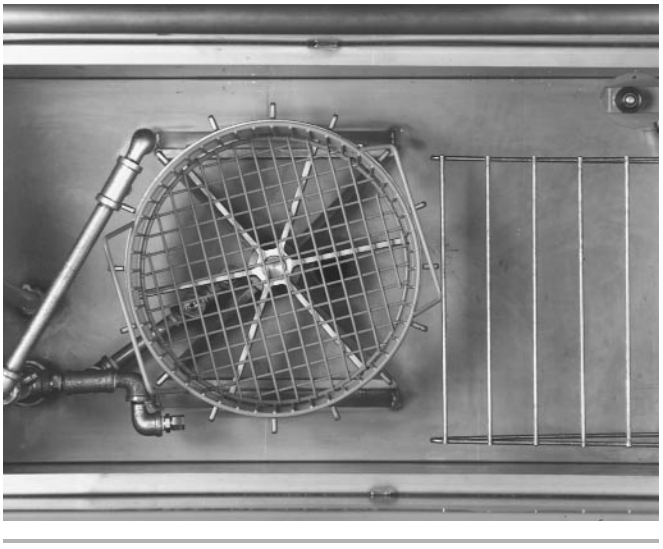
Legend
A = liquid penetrant tank
B = drain area
C = rinse tank
D = drier
E = developer tank
F = inspection table

is equipped with a drain, hose and spray nozzle for washing parts by hand. An ultraviolet radiation source is mounted over the wash tank so that the operator can see when all excess liquid penetrant has been removed in fluorescent liquid penetrant testing. An automatic washer is often incorporated into this wash tank, as shown in Fig. 3. This feature is desirable when large numbers of parts are inspected. With an automatic washer, no personnel are required for the washing operation. Parts are cleaned by multiple water sprays as they rotate on the automatic turntable located at the bottom of the tank. Washing time can be regulated to suit the application. The wash station is plumbed with inline pressure and temperature control devices.

Parts Drying Station

A warm air recirculating parts drier is located at the center rear. Drying temperature is thermostatically controlled to avoid excessive temperatures and there is provision for dry air replenishment and temperature recovery. Even large and complicated parts are dried quickly. A removable center shelf accommodates large pieces. Curtains to close the front of the drier retain heat and maintain proper air circulation inside the cabinet but are still convenient for in-and-out handling of parts.

FIGURE 3. Automatic washer inserted in wash tank, as seen from above.



Developer Application Station

The developer tank next to the wash and dry station is designed for use either with dry power developer or aqueous types of developers. When dry developer powder is used, parts are washed to remove excess surface liquid penetrant and then are dried thoroughly before the dry powder developer is applied. Dry powder developer is usually applied by dipping dry test parts into the tank of powder or by the preferred technique of dusting with dry powder. When wet aqueous suspendible developer is used, the test parts need not be dried before application of the wet developer. In this case, the clean, wet test parts are usually dipped into the wet developer tank. A removable grill placed over part of the developer tank can be used to drain excess developer from parts after dipping. Following application of the wet developer, the developer coated parts are dried in the drying oven described previously. After drying, test parts can be placed on a suitable clean grill to cool to temperatures comfortable for further handling and testing. Note that following drying of developer coatings or after applying dry developer to dried test parts, a sufficient period of time is required for liquid penetrant indications to develop. This time period is often known as the developer dwell time.

Inspection Station

The inspection station of the self-contained test unit is a booth on the right side of the unit shown in Figs. 1 and 2. This booth is enclosed with lightproof curtains for fluorescent liquid penetrant testing. The curtains overhang the front of the unit to give the inspector plenty of room. Ventilation is provided. A source of near ultraviolet radiation, white light or both, is provided. The light source is normally mounted on an adjustable bracket above the test table. Light sources are typically removable for manually directing the radiation around larger objects.

Limitations of Small Stationary Self-Contained Units

Although the small, stationary general purpose liquid penetrant test unit of Figs. 1 and 2 provides a means for liquid penetrant testing at a small production rate, it has certain limitations. Because of the physical size of the immersion tanks used, test parts with dimensions greater than the tank permits cannot be immersed into the processing materials. In processing oversize parts, it is sometimes feasible to apply the processing liquids by pouring them over the test objects and collecting the excess fluid that drains off test parts in the tanks. The small size of the typical self-contained stationary system also limits the number of test operators and inspectors that can be used efficiently on one unit. Multiple general purpose test stations are sometimes used, particularly when more than one type of liquid penetrant is required in day-to-day testing.

Multiple Component Stationary Liquid Penetrant Testing Systems

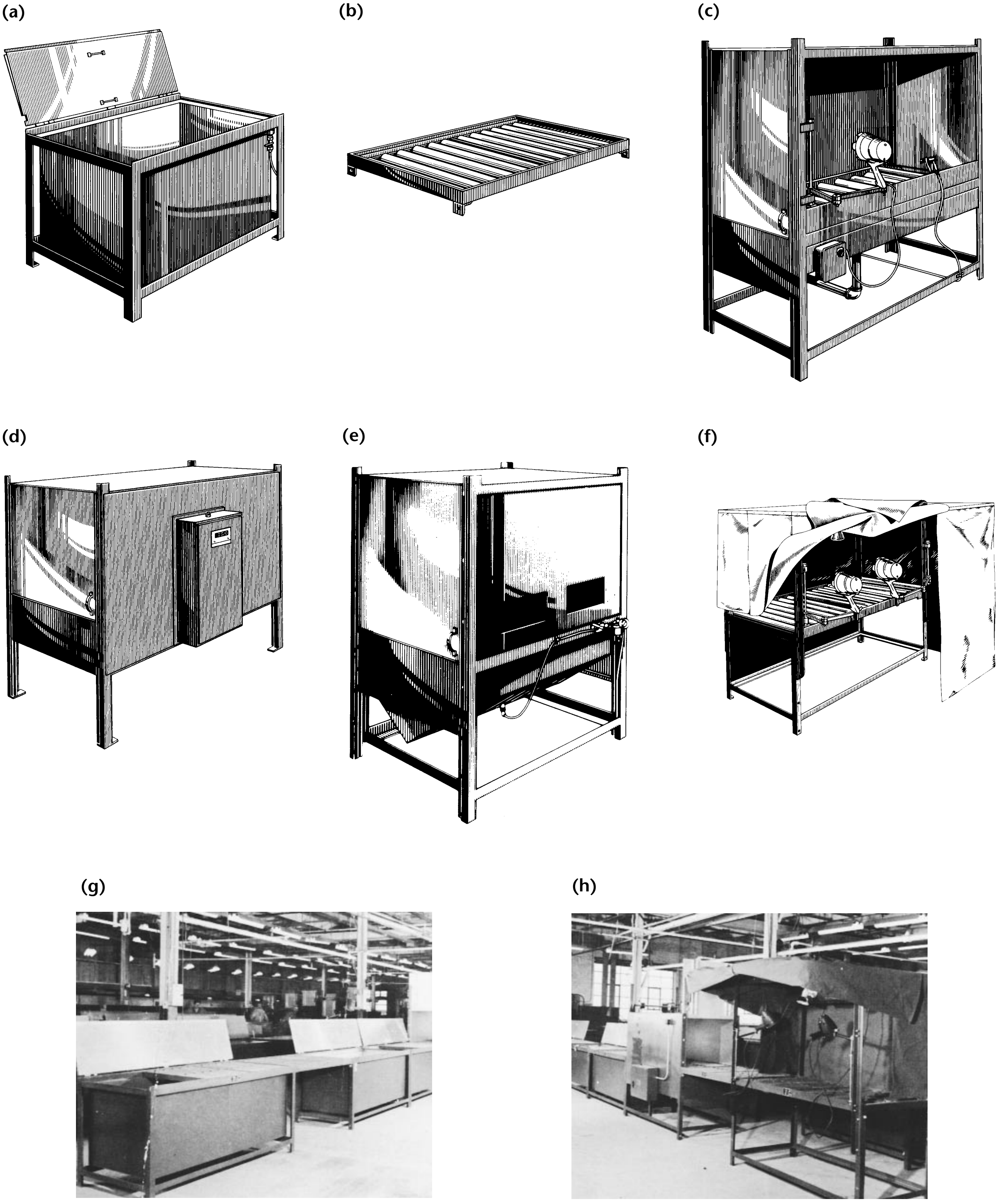
Where high production test rates or tests of large test objects are required, multiple component stationary liquid penetrant testing units offer advantages. Figure 4 illustrates the several components of a typical multiple component liquid penetrant testing station. Figures 4g and 4h together constitute an in-line arrangement of test equipment made up of several individual components. Such installations are not usually purchased as single items; actually, they are an assemblage of individual liquid penetrant processing units, each designed for a single phase of the testing procedure. Multiple component test systems thus offer extreme flexibility and permit the user to combine needed components into many combinations of optimum sizes. The liquid penetrant test system can then be tailored to meet specific needs or plant layouts. In Figs. 4g and 4h, the multiple unit equipment is set up for liquid penetrant testing using water washable liquid penetrant and dry developer. As shown in Figs. 4g and 4h, the flow of test parts being inspected is straight through the equipment line, starting at the left end. Inspected test parts finally emerge from the test booth at the right end of this arrangement.

Liquid Penetrant Dip-and-Drain Stations

Figure 4a shows a large tank for holding liquid penetrant. The open grill of Fig. 4b serves as the liquid penetrant drain and dwell station in multiple component liquid penetrant test systems. Liquid penetrant tanks can be obtained in a wide range of sizes including those large enough to permit immersion of relatively large test parts.

Liquid penetrant application is generally by dipping. A small hoist can be used to help the operator to handle heavy test parts. For test parts too large to be

FIGURE 4. Modular construction of multiple component liquid penetrant test system permits straight line, L or U arrangement: (a) liquid penetrant tank with cover; (b) drain and rest station; (c) wash station; (d) drying oven; (e) dry developer station; (f) inspection station; (g, h) multiple component inline liquid penetrant testing system consisting of assembled units.



immersed in the tank, an alternative technique of *flooding* or flowing liquid penetrant over the parts can be used. A small pump and hose for flowing liquid penetrant over parts can be installed so as to use liquid penetrant from the dip tank. In addition, application of liquid penetrant by spray guns is very effective, where suitable ventilating facilities are provided for removal of vapors from spray and part surfaces. Hazards also exist if flammable liquid penetrant vapors are allowed to accumulate above the liquid penetrant in closed tanks, as when the cover is closed in the unit shown in Fig. 4a. Good ventilation is appropriate wherever volatile liquids capable of supporting combustion are used in industry.

A roller top liquid penetrant drain or parts storage station is shown in Fig. 4b. The drain is equipped beneath the rollers or grill with a sloping tray that catches liquid penetrant draining from test parts. Because of the possibility of contamination of liquid penetrant in the dip tank, it is recommended that the drain not be plumbed back to the liquid penetrant application tank. Care is required to prevent dripping of liquid penetrants or processing materials onto work surfaces, floors or testing personnel. Such oily wastes can lead to slipping and hazards to personnel, as well as the possibilities of fires or explosions of flammable vapors. Another result of contaminated work surfaces or test operator hands and clothing can be smears of liquid penetrant on test objects. These smears could obscure relevant liquid penetrant indications or confuse inspectors during interpretation of liquid penetrant indications.

Washing Station

Figure 4c shows a typical washing unit used to remove excess water washable liquid penetrant from test objects. This wash station may use either a hose and spray nozzle manipulated by hand or it may be an automatic washer (see Fig. 3).

Drier and Cooling Station

The parts drier shown in Fig. 4d is an electrically heated, thermostatically controlled, recirculating warm air oven. This drier has a roller grill to support test parts during drying. Counterbalanced doors that open by sliding upward are located at each end of this drier, so it is easy to move baskets of small parts or individual large test parts into or entirely through the drying unit. A cooling table with roller top similar to that shown in Fig. 4b permits parts emerging from the drying oven to air cool to comfortable handing temperatures before entering the inspection booth or the dry developer station.

Dry Developer Station

Figure 4e shows the dry developer application station. Test parts must be thoroughly dry before application of dry powder developer. Test parts are dipped or *swirled* through a cloud of light, fluffy powder that adheres to the part surface.

Inspection Station in Multiple Component Liquid Penetrant Test System

The inspection station in which processed test parts are examined is shown in Fig. 4f and at the right end of the assembly of Fig. 4h. This liquid penetrant inspection booth may also have a roller table top and is equipped with one or more sources of ultraviolet radiation or white light, as appropriate. These directional ultraviolet radiation sources can be supported on brackets and focused on specific areas or removed from the brackets and directed by hand to illuminate hard-to-get-at locations. Some inspection booths have high wattage flood overhead ultraviolet lamps built into the ceiling of the inspection booth for overall ultraviolet illumination. Even with fluorescent liquid penetrant, a white light fixture should also be provided for detection of visible discontinuities that may not necessarily have been revealed by means of liquid penetrants or for checking the part surface, to aid in interpretation of indications. A ventilating fan can be built into the ceilings of test booths for operator comfort during warm weather and to minimize operator exposure to dust and fumes.

Varieties of Multiple Component Liquid Penetrant Testing Systems

The individual components of multiple component liquid penetrant test system can be rearranged, removed or replaced with other components with special functions suitable for other liquid penetrant processes. The combination can be adapted for use with the postemulsifiable liquid penetrant test techniques by inserting dip-and-drain tanks or additional apparatus for emulsifier immediately after the liquid penetrant tank — similar to but larger than the additional stations described above for postemulsifiable liquid penetrant testing with self-contained units. This tank could be of the same type as that shown in Fig. 4a.

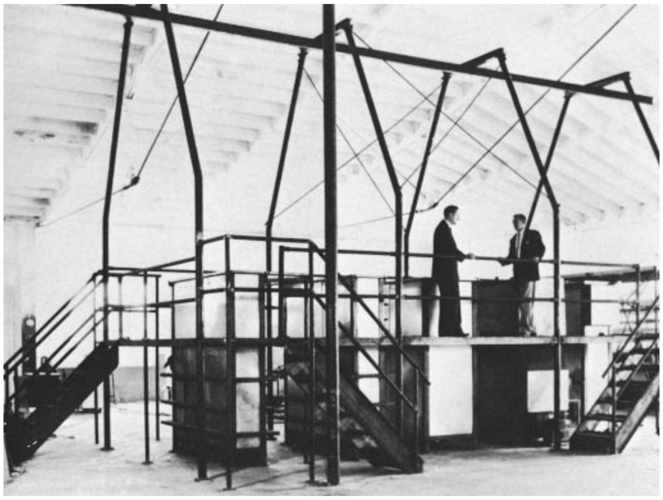
Large Custom Designed Dip Tank Stations

Special dip tanks for liquid penetrant, emulsifier and wet developer can be made to almost any size requirements (Fig. 5). A typical large unit might be 30 m (100 ft) long, 1 m (3.5 ft) wide and 2.5 m (8 ft) deep. Large tanks operate on the same principle as those on smaller systems but may have many times the capacity when used to process airframe components. Such a tank may contain more than 60 m^3 (1.5×10^4 gal) of fluid. Shown in Fig. 5 is a custom facility with an overhead rail for traveling hoists to carry large test objects or racks containing several smaller test parts.

Specialized High Volume Liquid Penetrant Test Units

In manufacturing operations where parts are made in high volume on conveyorized production lines, testing of parts at production line speeds may be desirable. The liquid penetrant method lends itself to mechanization. In such cases, it is necessary to design special equipment so that test rates can be coordinated with production manufacturing rates. Conveyorized equipment is generally designed with moving part supports provided with holding fixtures. These require only the services of an operator to load parts onto the carrier. The parts then proceed unattended through the entire processing operation and are finally presented for examination to an inspector in a suitable booth.

FIGURE 5. Custom liquid penetrant dip tank facility to accommodate relatively large components.



This special production equipment may be designed to handle only one or a few similar types of parts or a multitude of shapes and sizes. If properly designed and built, it is capable of yielding the most productive uniform liquid penetrant testing attainable. Actual speed of testing is determined by the requirements of the production line; inspection booth size is determined by the number of inspectors needed. Test speed must also be compatible with requirements for liquid penetrant and emulsifier dwell times and for developing time. Speed can also be limited by the capacities of the testing line process equipment. Test time on repetitive test parts can be reduced to a minimum by devices that make it necessary only for the inspector to view each test object as it revolves and to press a *pass* or *reject* button that will cause the machine to segregate the parts.

Automated Processing for Production Line Liquid Penetrant Testing

Production line testing can obviously be improved through automation when production capacity requirements reach a point where manual testing operations can no longer match the production rates. There are many examples where several basic manual lines have been made obsolete by an automatic system with greater productive yield. In the aircraft industry, for example, turbine blade testing uses test systems capable of handling several thousand blades per hour, depending on part size and configuration. There are many high volume liquid penetrant testing requirements in the general metalworking industry.

There are many other benefits to be gained that contribute to increased productivity through automating production line testing. In addition to the increase in production test capacity, positive control over liquid penetrant test processing is attained. Each phase of the production line testing can be controlled through proper handling equipment on an automatic basis. Automatic sequencing minimizes the possibility of overprocessing or underprocessing, which are constant concerns of nearly every quality assurance group throughout industry.

Much consideration has been given to automating existing manual liquid penetrant test equipment wherever possible to increase production test capacity and gain improved process control. There are many instances where funds are not available for capital equipment but such funds can often be justified and made available for modification and updating of existing equipment. This approach has worked very well in increasing production line test capabilities over manual operations.

Possibilities for Automating Detection of Discontinuity Indications

Future improvements in production line testing can be expected, particularly in the area of automatic testing. All parts going through a liquid penetrant testing line obviously must be examined for discontinuity indications and the labor cost associated with this visual examination by human operators is one of the largest cost factors of the entire process. Automatic discontinuity reading may play a major role in further reducing production line testing costs (see discussion of automated scanning, below).

Limitations Involved with Automated Liquid Penetrant Test Systems

There are many considerations in the selection of fluorescent liquid penetrant testing equipment that can affect the productive yield of the process. A common pitfall in the selection of processing equipment is to assume that a simple arrangement of dip tanks, rinse tanks, driers and inspection booths will suffice in all cases. It is usually better to build versatility into the test system, rather than to limit it to present needs. Limitations of automated systems are determined by factors such as (1) volume of work and economics of the system, (2) variations in test object sizes, shapes and surface conditions, (3) flexibility of the system as compared with systems using human operators, (4) space available for installation and (5) risk that changes in processing specifications will make the system obsolete.

Factors Influencing Selection of Liquid Penetrant Test Equipment

One logical approach to determining processing equipment requirements that will determine the production line capability would be to consider factors such as the following.

1. The type of part to be inspected must be considered: the type of material (titanium, aluminum etc.); the size, shape and weight of test objects; the stage in manufacturing process where testing is performed; and the criticality of the part application.
2. Different types of anomalies sought during testing: nature of anomalies sought and processing specification requirements.
3. Certain factors affect production rate: how parts arrive for processing; reloading or repositioning of parts required for liquid penetrant processing; part handling equipment presently available; number and level or skill of operators and inspectors available; unloading facilities required, if any.
4. Particular processing requirements include maximum part temperature and precleaning treatments.
5. Equipment and facilities need to comply with the requirements of various industrial safety or health physics codes or standards, for the sake of pollution control, environmental safety requirements and electrical hazards protection.
6. Special operating conditions influence selection of the installation site: available space (length, width, overhead); noise level requirements in the general area; height of waste table (which could obviate pits); access for rail or truck movement or to conveyors; and suitable utilities.
7. Liquid penetrant test materials must be practical for use in intended equipment. For example, highly volatile material would not be used in open tanks; instead, this type of material would be handled by enclosed spray systems.
8. Extent of postcleaning of test objects required following completion of liquid penetrant testing must be considered.

Example of Mechanized Conveyorized Liquid Penetrant Test System

Figure 6 shows a machine that has been used for liquid penetrant testing of castings in a large tractor plant. After being loaded onto the conveyor, the castings are automatically carried through six processing operations and are finally delivered into the inspection booth for examination of the liquid penetrant indications. Detailed descriptions of each station used in this mechanized liquid penetrant test system are given below.

Conveyor System for Transporting Castings through Mechanized Liquid Penetrant System

A conveyor belt carries castings through all stations of the mechanized liquid penetrant testing system shown in Fig. 6. Precleaned castings are loaded onto this conveyor belt at the extreme left of the unit. The conveyor belt system, moving from left to right, extends continuously through the entire length of the unit. The belt is of open wire mesh and may consist of a single length of belting or a number of sections arranged so that parts will transfer from a given section on to the next without manual assistance. In a typical machine, belt speeds are variable between 0.15 and 0.6 m (6 and 24 in.) per minute to permit selection of proper time cycles for the various processing steps. The conveyor belt carries the completely processed castings, after cooling, into the inspection booth shown at the extreme right of the unit for viewing and evaluation under ultraviolet radiation.

Liquid Penetrant Spray Application Station for Castings in Mechanized System

Water washable fluorescent liquid penetrant is used for testing of tractor castings in the mechanized processing system of Fig. 6. Rough sandcast surfaces are often inappropriate for postemulsifiable liquid penetrants because it is difficult to remove background residual fluorescence. After traveling a short distance, castings enter a cabinet in which the liquid penetrant is sprayed over the entire surface. To obtain this complete surface coverage, liquid penetrant is permitted to fall in a curtain or shower from troughs in the top of the cabinet. This falling curtain of liquid penetrant covers the top surface of the part and in most instances also wets the sides. If the part is not completely covered, auxiliary sprays may be located at either side of the conveyor to ensure complete coverage. Additional sprays are located beneath the belt to cover the underside of the part. These sprays are generally pipes or tubes located below the conveyor belt. Holes along the tops of these pipes serve as jets through which liquid penetrant is sprayed.

Circulation of liquid penetrant through the spray system is by means of a motor driven pump built into the tank. Because a rather large volume of material is being circulated and velocity at the jets is quite high, a certain amount of vapor or spray may be formed and may become objectionable in the operating area. To permit removal of fumes, a vent stack is located in the top of the liquid penetrant application cabinet for connection to an exhaust system.

Mist collectors create the negative pressure required to contain the fumes and mist and also let the air be returned to the factory. A series of filters in the mist collector ensure that all liquid penetrant is removed from the air. An alternative is to use a mist collector.

On emerging from the liquid penetrant spray cabinet, the parts progress into an open area where excess liquid penetrant drains back into the sump and is reused. This open area of the conveyor serves for liquid penetrant dwell time.

FIGURE 6. Mechanized liquid penetrant testing of castings in tractor factory.

Water Wash Station for Castings in Mechanized Liquid Penetrant Test Systems

Following the liquid penetrant dwell time, the castings enter the water wash station for removal of excess surface liquid penetrant. This water wash station is a completely closed cabinet with solid sides and top. The ends are closed by special rolling curtains that permit the wet castings to enter and leave on the conveyor but that prevent wash water from splashing outside the enclosure. Washing is accomplished by streams of water from moving spray nozzles. These spray nozzles, located above, below and at the side of the conveyor, oscillate continuously back and forth through an angle of about 45 degrees. This oscillatory motion of the spray heads, in conjunction with the forward motion of the conveyor belt, ensures that the surface of the part is completely covered and that a thorough washing job is accomplished.

Air Blowoff and Drier Stations of Mechanized Liquid Penetrant Test Systems

To lighten the load on the drier and to reduce its size, a major portion of the water remaining on the part as it emerges from the wash station is removed by an air blowoff section located at the exit end of the wash station. Inside the cabinet are multiple jets that direct steams of air over the part and remove a major portion of the water left on the surface. When fluorescent liquid penetrants are used, the blowoff cabinet is often equipped with an ultraviolet lamp to permit the operator to check on the thoroughness of the washing operation.

Parts pass directly from the blowoff station to the drier, which is another closed cabinet with the ends left open for passage of the conveyor. The cabinet walls are insulated and the interior is electrically heated, with temperature controlled by an adjustable thermostat. To ensure even drying, the air inside the cabinet is continually recirculated by fans built into the unit. Provision is made for the expulsion of a portion of the circulating air and the intake of dry air for its replacement. The test parts should be free of liquid penetrant so that only water is being evaporated within the drier; otherwise, evaporation of liquid penetrant could contribute to air pollution. Note that air pollution is measured for the entire liquid penetrant testing system and includes evaporation from parts, tanks, spray booths and drain stations. Water pollution could result from effluent wastes containing liquid penetrant and processing materials that flow into sewers or streams. Both oily and fluorescent components of liquid penetrants are objectionable and readily traceable to their sources.

Omission of Developer Application Station in Mechanized Casting Testing

In the machine illustrated in Fig. 6, no provision is made for the application of a developer. This specific unit was designed for testing of parts for large cracks and in this particular situation developer is not required. If developer were necessary, a station somewhat similar to the liquid penetrant application station would be charged with wet developer to be applied onto the parts. Such a developer station would be located between the rinse station and the drier. The air blowoff would not be used with the wet developer system.

Parts Cooling Station in Mechanized System for Inspecting Castings

In the system of Fig. 6, examination of castings follows immediately after the drying operation (because no developer is used). Because test parts move steadily along the conveyor system, it would be possible for these test objects to reach the inspector at a temperature too high for comfortable handling. Therefore, a short parts cooling section is designed into the unit between the drying oven and the evaluation station. This cooler is merely a small enclosed cabinet with an exhaust vent, equipped with fans below the conveyor. These fans draw in outside air and force it through the open meshes of the conveyor belt and up and around the test parts.

Ultraviolet Inspection Station in Mechanized Liquid Penetrant Test System

In the system of Fig. 6, examination of processed castings for indications is done visually by one or more inspectors in the curtained booth located immediately following the cooler station. The conveyor belt continues entirely through the examination area. The viewing and evaluation booth of Fig. 6 is equipped with large ultraviolet lamp fixtures arranged to flood the entire test area with sufficient near ultraviolet intensity for evaluation of fluorescent indications. In addition, an ultraviolet lamp bulb in a portable fixture can be used to direct ultraviolet radiation into blind holes or other inaccessible places. A white light is located in the ceiling of the booth for general illumination when needed.

Procedure for Inspection of Castings in Mechanized Liquid Penetrant System

Examination of the processed castings for fluorescent liquid penetrant test indications is done visually by one or more inspectors in the curtained darkened booth of the mechanized liquid penetrant testing system of Fig. 6. Processed parts emerge from the cooling station and are then carried through the inspection booth on the conveyor belt. Ultraviolet radiation illuminates all accessible surfaces, which are examined for fluorescent indications of discontinuities. Each casting is then rotated or turned over to reveal remaining surfaces for examinations.

In most installations, sound parts are permitted to pass out the right side of the inspection booth and are deposited on another conveyor that takes them to the postcleaning operation. Here, all traces of liquid penetrants or processing materials are removed. In some cases, further treatment is provided to prevent corrosion of parts in storage or service. However, in the case of the tractor castings, the conveyor takes the parts to the next manufacturing operation where further machining or finishing operations eliminate the need for postcleaning of liquid penetrant residues from the castings.

Limitations of Conveyorized Liquid Penetrant Processing Systems

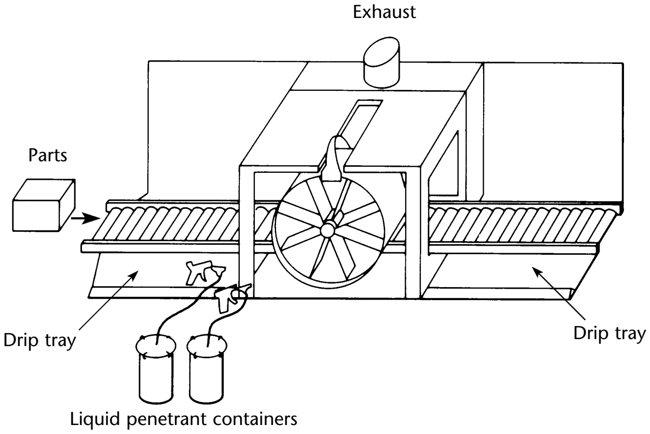
Dwell times in a conveyorized automatic test system are usually determined by the conveyor speed and travel distance. Increasing the time of one processing step by reducing conveyor speed will lengthen the time of other process steps. For example, a change in specifications may require a longer liquid penetrant dwell. Bringing this about by slowing the conveyor will lengthen the wash cycle and the chance of overwashing and the drying cycle and the chance of overheating the part. Lack of flexibility is one of the drawbacks of those completely automated processing systems whose processing dwell times are controlled by conveyor belt speeds. More advanced process systems permit individual adjustment and control of each dwell time and processing time interval. Modern microprocessor control systems allow mechanized systems to respond automatically to many operating conditions and other variables that can affect processing operations in liquid penetrant testing.

Conventional Spray Application of Liquid Penetrants

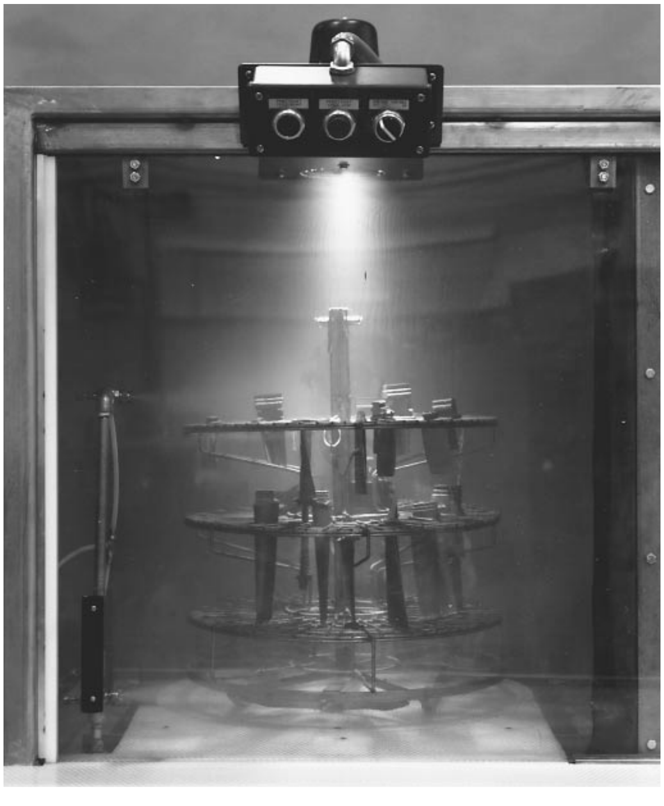
Conventional or electrostatic techniques of spray application of liquid penetrants, emulsifiers, removers and developers provide effective ways of applying these liquids with complete coverage of the surfaces of test objects. Spraying is usually more economical than immersion dip tanks, primarily because of reduced formation of pools of liquid penetrant in cavities. Pooling often results in substantial dragout losses of liquids. The conventional liquid penetrant spray station sketched in Fig. 7a is typical of the various liquid penetrant process spray stations in common use. It can spray a variety of part sizes and can be equipped for quick changeover from one liquid material to another. In contrast to immersion tanks with their liquid dragout and transfer on part surfaces, spray systems virtually eliminate contamination of the reservoirs of liquid penetrants or processing materials. The liquids are pumped directly from sealed containers and no contaminated materials are returned to these source containers. Figure 7b is a photograph of a smaller, semiautomatic spray station.

FIGURE 7. Liquid penetrant spray station: (a) schematic diagram of conventional configuration; (b) photograph of carousel design.

(a)



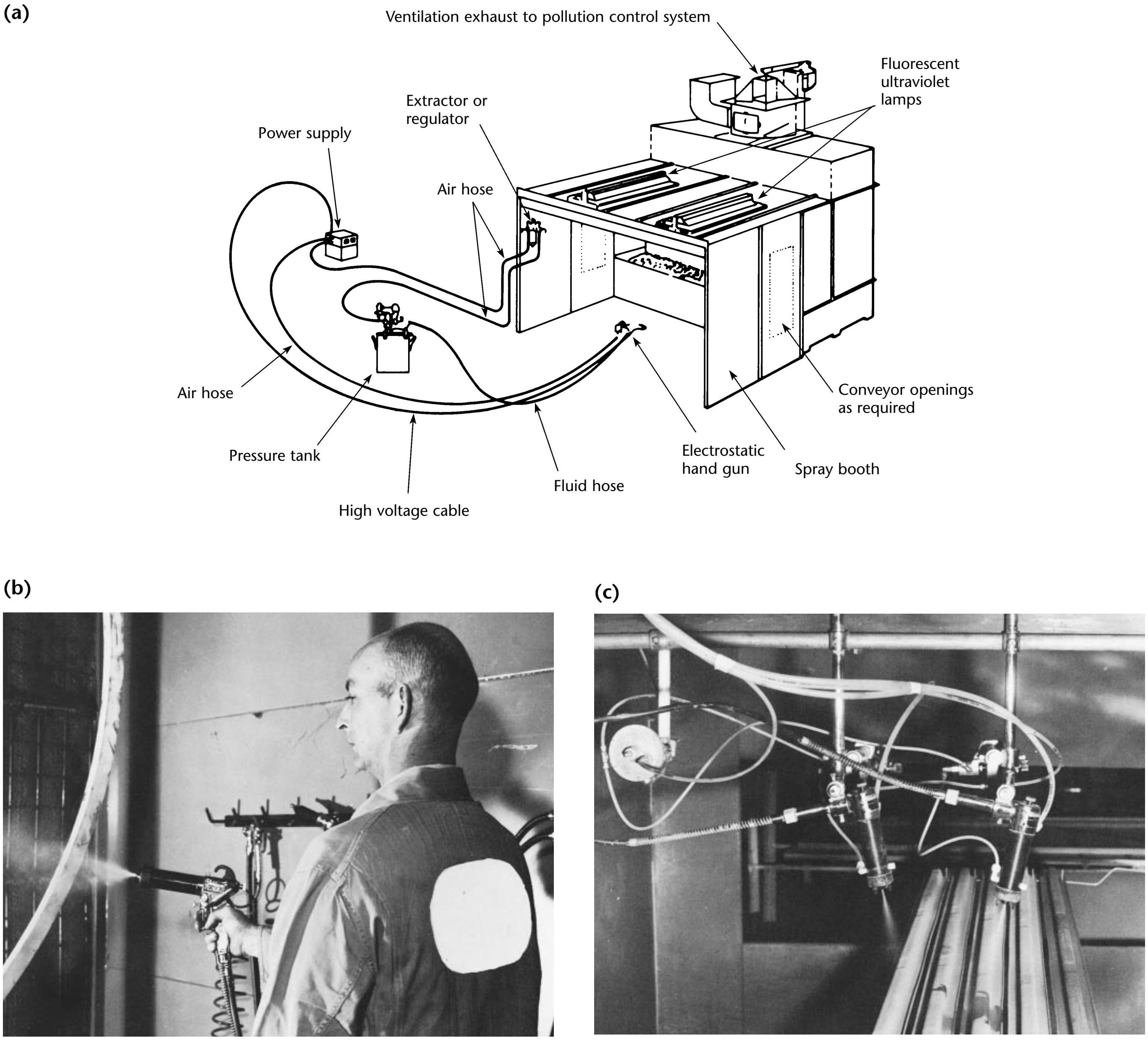
(b)



Electrostatic Spray Application of Liquid Penetrants and Processing Materials

Figure 8a shows typical components of an electrostatic spray system used to apply liquid penetrants and developers. Figure 8b shows a technician manually controlling an electrostatic spray of fluorescent liquid penetrants to parts with complex shapes. Figure 8c shows an automatic reciprocating assembly of electrostatic spray guns applying liquid penetrant to both sides of conveyor borne parts. Users indicate that liquid penetrant material usage with atomized and electrostatic spray systems is only about 10 percent of that used in a dip tank application system. This economy of application results in other advantages because less excess liquid material is

FIGURE 8. Application with electrostatic spray system minimizes consumption of liquid penetrant material and helps ensure coverage of complete surface: (a) diagram shows arrangement of system components; (b) technician applies fluorescent liquid penetrant with hand held electrostatic spray gun that makes atomized particles attracted to part; (c) two reciprocating automatic electrostatic spray guns in conveyorized installation are used to apply liquid penetrant to one side of parts while other guns (not illustrated) operate from opposite side further down line.



available to add to evaporation or drainage losses. The restricted dispersion of liquid penetrant materials also aids in limiting air and water pollution resulting from liquid penetrant processing. Quick changeover (as from low to high performance liquid penetrants) is possible in production test systems by use of a quick changeover device that selects the drum of liquid material required.

Dual Immersion Tank Application of Normal and High Performance Liquid Penetrants

Selection of liquid penetrant application techniques and associated processing equipment such as dip tanks or spray booths depends on several factors such as specification requirements, part size and configuration, production rates and available space. Production liquid penetrant requirements in industry often specify different types of liquid penetrants (normal and high sensitivity) on different test parts. Maintaining this processing capability has required duplicate liquid penetrant processing lines in many cases, especially where different emulsifiers are also required. An effective space savings approach uses an arrangement of two liquid penetrant tanks either adjacent to each other or in tandem. With this arrangement, incoming parts can be processed directly through the required liquid penetrant and then through the remainder of the common processing line.

Conversion of Existing Lipophilic to Hydrophilic Emulsifier Processing

Where major aircraft engine manufacturers and other industries have converted to hydrophilic liquid penetrant removers, spray application of liquid penetrants and processing materials greatly simplifies test system requirements. Existing postemulsifiable liquid penetrant test lines can be converted to accommodate the hydrophilic emulsifier technique by (1) adding a prerinse station, (2) providing a hydrophilic emulsifier dip station with air or mechanical agitation for immersion tanks or a spray application station and (3) adding a clarifying station to the final rinse station where necessary.

In a simple conversion, the existing lipophilic emulsifier tank can be cleaned out and converted into a hydrophilic emulsifier station. If carbon steel tanks are to be converted, it is advisable that the tanks be sand blasted and coated with a suitable epoxy or polyvinyl chloride coating to prevent corrosion from the water in the water base emulsifier. The prerinse station and associated liquid penetrant separator and recycling hardware can be added in line directly after the liquid penetrant drain/rest station. The hydrophilic emulsifier station then follows. Next in line is the water rinse station to which a liquid penetrant rinse water effluent collection storage tank or water treatment unit clarifier can be added, if required.

Manual Liquid Penetrant Test Installations Using Hydrophilic Emulsifiers

Postemulsifier fluorescent liquid penetrant systems using hydrophilic emulsifiers are equally suitable for manual or automatic processing. A typical small, manual liquid penetrant test installation would include a liquid penetrant immersion or flow-on booth equipped with a suitable drain area feeding back to the main liquid penetrant reservoir. First stage rinsing is accomplished in a spray area equipped with a water gun. The next station is a hydrophilic remover tank where both immersion in an agitated bath and draining take place. This is followed by water rinsing. Normal drying and powder development stages follow and a suitable darkened area is provided for inspection under a high intensity ultraviolet radiation. It is important in a manual plant of this kind to make sure the requisite processing times are maintained carefully. A clock timer should be provided for operator use in checking consistency in process timing.

Various modifications of liquid penetrant processing lines are possible. With low rates of testing, it may be possible to eliminate one of the water rinse areas. A spray tank using fixed or moving jets may be convenient for washing certain classes of components. It may be economically convenient or environmentally essential to use recirculating rinses with appropriate separation and purification equipment. In some cases, air agitated water rinses have been found to give good results, particularly at the postemulsifier rinsing stage.

Roller tracks may be convenient for moving larger loads of test parts. If necessary, sections can be arranged so parts descend into processing tanks for specified periods for semiautomatic operation.

Equipment for Dip Tank Hydrophilic Emulsifier Station

The removal of excess surface liquid penetrant through hydrophilic emulsifiers can be accomplished either through the immersion technique or through spray removal techniques. Either type of rinse station should be of corrosion resistant construction, such as stainless steel, when using these water base emulsifiers. The nominal concentration range for hydrophilic emulsifiers used in the dip mode is 5 to 30 percent in water. Test parts are immersed in the hydrophilic emulsifier dip tank. This remover bath is continuously and mildly air agitated to provide the necessary scrubbing action to strip the liquid penetrant from the surface of each part. It is important that agitation be gentle; vigorous agitation will cause too much foaming of the emulsifier. The excess liquid penetrant floats to the bath surface and is skimmed off the surface through skimming weirs.

Equipment for Hydrophilic Emulsifier Spray Application Station

In the spray mode, hydrophilic emulsifiers remove surface liquid penetrant effectively when used in the manual, semiautomatic or automatic modes, depending on the operational and testing requirements. Metering devices are used to control concentration of hydrophilic emulsifier in the water spray. The nominal concentration range for hydrophilic emulsifiers used in the spray mode is from 0.05 to 5 percent of emulsifier in water. The duration of the spray removal cycle will depend on the concentration of the emulsifier and on the surface condition of the test parts. Spray rinsing is continued until no interfering fluorescent background remains on the surfaces of test parts when examined under intense near ultraviolet light.

Theoretically, when using the spray technique of applying the hydrophilic emulsifier, all three stations (prerinse, hydrophilic emulsifier spray scrubbing and final rinse) could be combined into one station. Suitable controls would ensure proper sequencing and timing of the spray cycles. Where rinsings cannot be returned to waste, programmed valving is then required to direct rinsings to the necessary storage or separation facilities to permit recycling. Practical considerations, however — such as production requirements, equipment complexity, ease of maintenance or recycling — may dictate three separate stations.

Spray Application of Foamed Hydrophilic Removers on Large Test Objects

During liquid penetrant testing of large components or fixed test objects, it may become desirable to apply hydrophilic removers by spraying to avoid the necessity for large, heavy immersion tanks used for dip application. Spray application works in practice only where complete coverage of all test surfaces with the hydrophilic emulsifier is attained. However, complete part coverage is not always easy to achieve with manual spraying operations. A preferable technique may be to spray hydrophilic emulsifier onto large parts as a foam so that complete coverage of test surfaces can be verified by visual observation. Foam application of hydrophilic emulsifier is followed by normal spray washing, drying and development of test indications. Foamed hydrophilic emulsifiers have also been used in static installations. Such systems are capable of very high performance and they are particularly suitable for detection of wide, shallow surface discontinuities.

Atomized and Electrostatic Spray Application of Liquid Penetrant Processing Materials

Atomized and/or electrostatic application of liquid penetrant, hydrophilic emulsifiers and developer offers advantages of reduced dragout of materials on test parts and less pollution by wastes. However, for safety reasons, most hand held electrostatic spray guns will not handle water base (polar solvent) compositions such as water diluted hydrophilic emulsifiers. More elaborate automatic electrostatic spray equipment is required to accommodate water diluted hydrophilic emulsifiers. Atomized and electrostatic spray application systems are particularly suitable for small components such as air cooled turbine blades where solution bleedout from the drillways is a problem when immersion processes are used. An added advantage of these spraying techniques is that liquid penetrant, removers and developers are used directly from the supply containers so that progressive contamination of the working solutions cannot occur.

Water Recycling Techniques Used with Hydrophilic Removers

Applications of liquid penetrant test systems embodying hydrophilic emulsifiers are preferred for reasons of performance, flexibility, reliability and economy. The exorbitant water demand of large plants operating on the *straight through to waste* system and the increasing pressure for ecologically acceptable waste water means that water recycling is essential for modern installations. With hydrophilic emulsifier systems, water recycling can be achieved readily.

Recycling the first stage (preemulsifier) rinse can be simply accomplished. A rough separation of the liquid penetrant is adequate in many cases. This may be accomplished by gravity separation in weirs, coalescers or other separating devices. Centrifugal separation has also been used with limited success. In some cases the liquid penetrant separated from the rinse water can also be reused. Water recycling loops can be made to operate with little need for additions of water, if growth of bacteria in the rinse water can be prevented.

Recycling is also possible on the second stage (postemulsifier) wash. Here the contamination is a mixture of a smaller amount of liquid penetrant and some dragout from the hydrophilic emulsifier tank. Purification means that have been used include carbon filtration, ultra filtration, nanometer scaled filtration and reverse osmosis. This enables a constant sensitivity level to be maintained and prevents rinse marks that would occur if liquid penetrant traces were allowed to build up in the rinse circuit. Practical experience with such systems has again shown that several months of reliable operation can be achieved without replacement of the circulating water or filter media.

Hydrophilic Liquid Penetrant Removal System for Automatic Testing of Jet Engine Blades

The flow-line sequence can be used in an automated liquid penetrant testing line for jet engine blade production capable of processing several baskets of blades per hour. In this system, the baskets of blades are placed on hooks of the continuously moving overhead conveyor. The basket then moves through the precleaning system and to the liquid penetrant dip tank. The conveyor dips the basket into and out of the tank as it moves along. The basket is carried over the liquid penetrant drain area to the water spray wash station where most of the liquid penetrant is stripped from the surface of the blades. The basket moves on to the hydrophilic remover dip station where the blades are immersed in agitated remover, after which they move on to a water dip where the blades are immersed before passing through the final water spray rinse. The baskets then travel through a recirculating warm air drier where all traces of moisture are removed from the blade surfaces before they pass through the developer chamber. A light coating of dry developer is automatically applied to the blade surfaces in the dry developer station. The baskets are removed from the conveyor on emerging from the developer station. Testing is carried out in a separate station.

Equipment for Final Water Rinse Station of Liquid Penetrant Processing System

Direct water spray rinsing, without immersion rinsing, is commonly used to remove liquid penetrants and processing materials from test parts after completion of testing. However, a water rinse combining both initial immersion and a later spray application does a superior job of flushing the emulsified liquid penetrant from within cavities in test parts, especially for hollow parts such as jet engine blades and vanes.

Final water rinse stations should be constructed of corrosion resistant materials such as stainless steel because they are constantly exposed to water. Furthermore, where immersion rinse tanks are used, provisions should be made for skimming undesirable excess foaming from the liquid surface in tanks of liquid penetrant processing materials. Such foaming can occur if the rate of air agitation in the tank is too high.

Disposal of Waste Liquid Penetrant Processing Materials

Control of effluents from liquid penetrant test processing systems constitutes a unique waste treatment and environmental protection problem area. Local ordinances may not permit discharge of these waste materials into municipal sewer systems or open streams.

More information on control of effluents is provided elsewhere in this volume.

Part 2. Large Scale Automated Aerospace Liquid Penetrant Test Equipment

Typical Sequence of Operations in Automated Liquid Penetrant Test System

Automated systems for performing liquid penetrant tests of production aircraft and aerospace parts has become more common in recent years. Such systems have been installed at several aerospace companies to solve handling and testing problems peculiar to their own situations. The following discussion outlines the basic components of a representative automated liquid penetrant system for use with a fluorescent water washable liquid penetrant.

Techniques for Handling of Test Parts

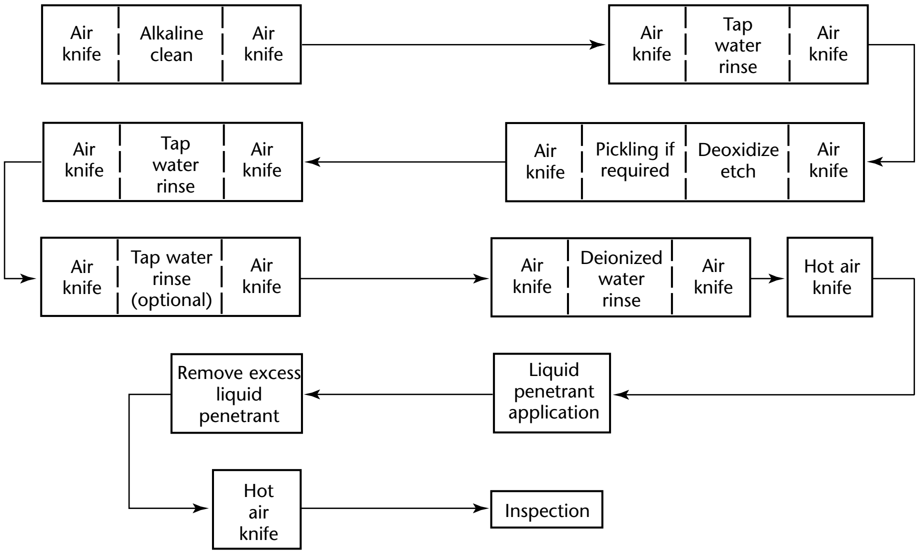
In a typical automated liquid penetrant system, the parts to be inspected are initially racked on a load bar attached to an overhead conveyor system. The way in which the parts are racked is important in order for full coverage by the cleaning solutions, liquid penetrant, water and developer to take place. Such factors as part size and geometry must be considered. If large varieties of parts are to be inspected in a typical testing facility, it may be useful to develop technique cards for racking the parts to ensure that the test personnel rack a particular part the same way each time. The automated process is particularly effective for testing of large numbers of simple geometry parts such as stringers but more complex parts can be accommodated.

Automated Precleaning, Rinsing and Drying of Parts

To prepare for application of the liquid penetrant, the parts are first moved through a series of modules that apply the appropriate cleaning solutions. A typical sequence might be alkaline cleaning, tap water rinse, pickling, tap water rinse and deionized water rinse, as shown in Fig. 9.

Each chemical processing module is preceded and followed by an *air knife*. The function of the air knife is to prevent solutions from contaminating the next processing solution. After cleaning and rinsing, a hot air knife with typical air temperature of about 66 °C (150 °F) is used to dry the parts thoroughly. For some parts, such as those with a waffle pattern on the surface, it may be necessary to hand dry some areas. Within each processing module, the chemical solutions and rinse water are power

Figure 9. Automated liquid penetrant testing sequence.



sprayed by a series of nozzles. The power spraying assists the cleaning by mechanical force that helps to loosen and remove surface contaminants. The location and number of the nozzles and the resultant spray pattern can be an important factor when cleaning parts with complex geometries by spray techniques because the solution should reach all surfaces of the test parts. The parts can be moved through the processing modules at a controlled rate using continuously moving, motor driven, speed adjustable overhead conveyors or a more complex overhead conveyor system that can engage and disengage the carriers or racks, letting them stop in each processing area. Automatic controls actuate the spraying systems of each module when the parts are positioned to use the sprays.

Automated Electrostatic or Atomized Spray Application of Liquid Penetrants to Parts

After the cleaning process, the parts are automatically moved into the module where the liquid penetrant is applied. Reciprocating spray guns fed with liquid penetrant pumped directly from its shipping barrel provide consistent coverage with minimum waste of liquid penetrants. The spray guns might be installed to oscillate vertically or in any other suitable paths. The liquid penetrant spray module is kept under negative pressure by the adjacent air knives and/or a mist collector to eliminate drifting of the liquid penetrant out of the spray application module. The liquid penetrant dwell time is controlled by the distance and the rate of movement of the overhead load bar during transit from the liquid penetrant spray modules to the water spray module.

Automated Water Spray for Removal of Excess Surface Liquid Penetrant

The parts rack automatically moves into a water spray module that removes excess liquid penetrant from the parts. A series of adjustable water nozzles are commonly used in the module while air knives act to keep the water in the module. To prevent overwashing, it may be necessary to conduct experiments to determine the proper wash water temperature, spray nozzle water pressure, time of washing and positions of nozzles. Production parts with known cracks or discontinuities or cracked reference panels could be used for this type of development program.

Automated Hot Air Drying, Developing and Inspection of Parts

After the excess liquid penetrant has been removed, the rack of parts is moved automatically into a hot air drying module where the air temperature is typically 66 °C (150 °F). Then, after application of developer, if desired, the parts are moved into a totally enclosed dark, viewing room that has near ultraviolet lamps as well as hand held spot lamps. Large parts can be lowered into a floor pit or inspectors can be elevated for ease of examination. Note the absence of a developer station. In product manufacturing, this may be appropriate and, with customer approval, acceptable.

Advantages and Limitations of Automated Liquid Penetrant Testing Lines

In summary, there are a number of advantages to an automated liquid penetrant testing system such as that just described. Possibilities of human error can be minimized by the automatic movement of the parts through each phase of the liquid penetrant system. Large parts as well as small parts can be inspected efficiently. Waste of cleaning solutions and liquid penetrant materials can be held to a minimum. Production testing rates can be more easily controlled.

Precautions in Large Scale Automated Liquid Penetrant Testing Systems

Despite the many advantages of an automated liquid penetrant system, a number of cautions should be observed to maintain its consistent and optimum performance. The manner in which the parts are initially racked must be carefully considered to allow adequate cleaning, drying, liquid penetrant application and dwell, removal and drying. The application of emulsifiers or removers and application of developers must also be considered. In some cases, the only adequate way to arrive at the best technique is through a development program with cracked production parts. By observing these precautions, an efficient and effective automated liquid penetrant system can be developed to improve the production liquid penetrant testing of aerospace components.

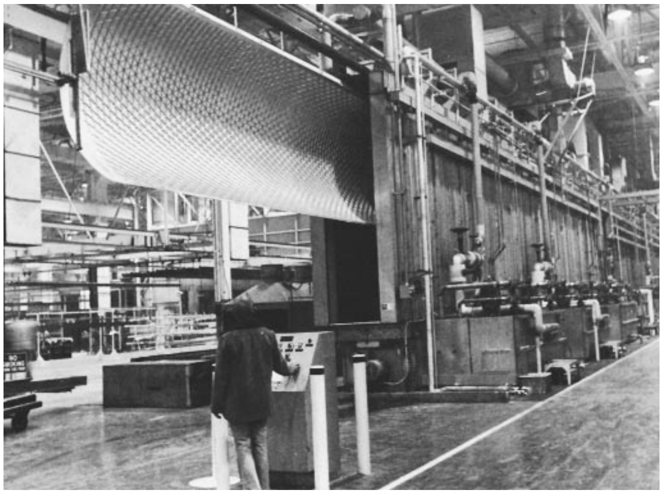
Example of Automated Liquid Penetrant Spray Processing System in Aircraft Manufacturing

The automated aerospace liquid penetrant spray processing and testing system developed for a major aircraft company, shown in Figs. 10 to 15, is an installation 60 m (200 ft) long, stands 6 m (20 ft) high and is 4.5 m (15 ft) wide. It uses the electrostatic liquid penetrant spray technique and consists of spray, wash, drying and near ultraviolet radiation viewing modules. A semidarkened observation area with near ultraviolet radiation is located on the outlet end of the liquid penetrant spray module to view parts for full liquid penetrant coverage. When developer is required, the nonaqueous wet aerosol developer is applied in the ultraviolet radiation viewing booth. The viewing booth is equipped with an exhaust system to protect personnel during the application of developer.

Part Conveyance in Automated Liquid Penetrant Test System

Parts are moved through the system on load bars hung from a motorized overhead monorail conveyor. Parts are mounted on special designed hangers that are hung, as applicable, on the overhead load bars (see Fig. 11). Parts hangers are designed for a minimum of liquid penetrant entrapment areas to preclude bleedout of liquid penetrant on parts after washing. The conveyor is equipped with a variable speed control for speeds from 5 to 43 mm·s^{-1} (1 to 8.5 ft·min^{-1}). Normal conveyor speed is 1.5 m·min^{-1} (5 ft·min^{-1}).

Figure 10. Automated aerospace liquid penetrant spray processing and inspection system.



Automated Spray Equipment for Precleaning of Test Parts

Adjacent and parallel to the liquid penetrant system is an automated spray chemical cleaning system (Fig. 12) that operates as an integral part of the liquid penetrant system by precleaning and postcleaning parts. It consists of two tandem alkaline cleaning modules, followed by rinse, deoxidizer, rinse,

Figure 11. View of load bars and hangers at part loading area.

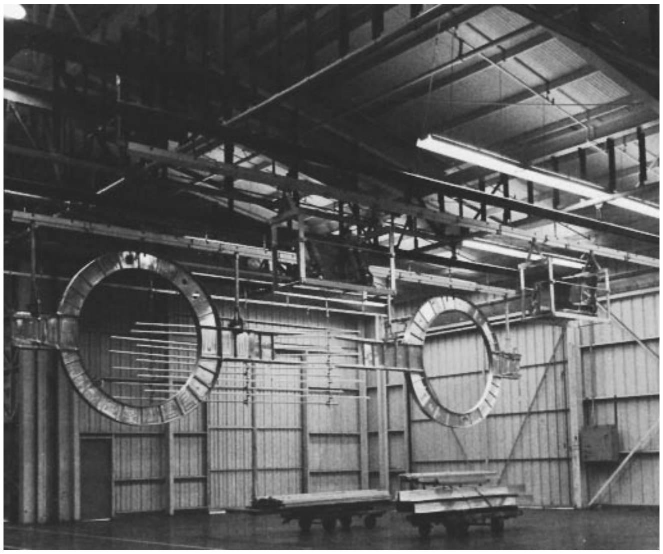
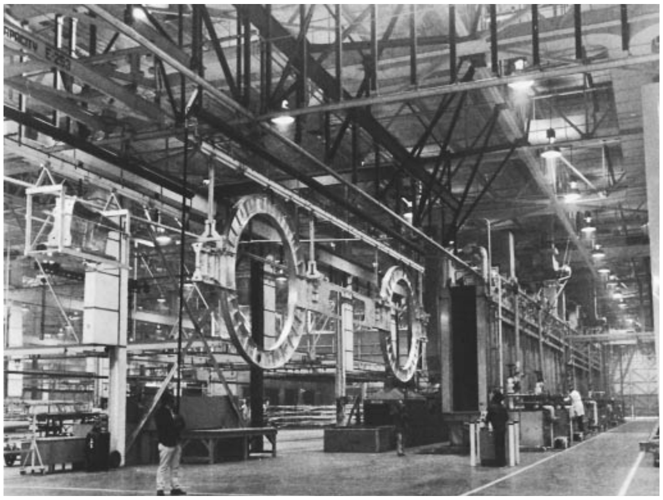


Figure 12. Overall view of chemical cleaning system. Vertical stabilizer spars measuring 5.4 m (18 ft) long and 2.7 m (9 ft) wide are ready to proceed through system.



protective coating, hot water rinse, deionized rinse and hot air knife modules. The conversion coating application module is only operated after postcleaning, as applicable. Turntable conveyor systems with pneumatic lowering platforms (*lowerators*) are located on both ends of the system to permit the feeding of parts from cleaning to liquid penetrant or reverse and the loading, unloading and temporary storing of parts, whichever is needed.

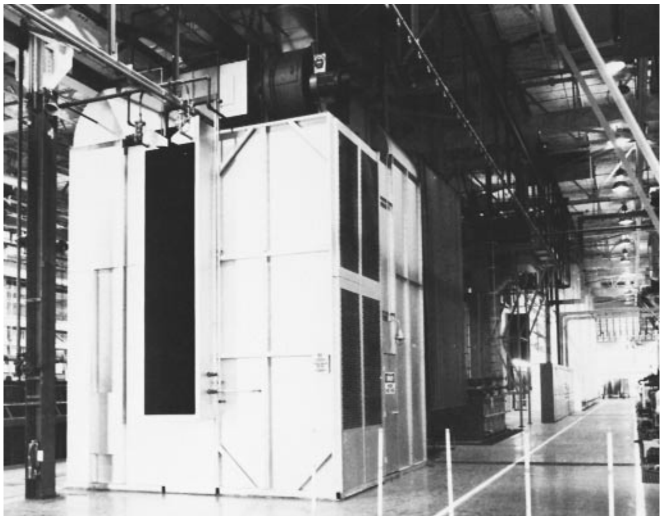
Emergency Stops for Automated Liquid Penetrant Test System

The automated liquid penetrant processing system of Fig. 10 is equipped with an alarm bell and emergency spot control located in the testing module. If parts are stalled in the system because of conveyor problems, the alarm rings, notifying the inspector to activate the *stop* control that shuts off all systems. This prevents overwashing and overdrying of parts while stalled in the system as well as preventing waste of liquid penetrant material. Emergency shutoff controls are also located on the central control panel and the liquid penetrant control panel.

Operation of Automated Aerospace Liquid Penetrant Test System

During loading of parts, electrical jumpers are connected from load bar suspension straps to conductor lugs to provide the necessary ground potential for the electrostatic liquid penetrant spray. Cracked test specimens are loaded on the first load bar through the liquid penetrant system after every shutdown, no matter how brief. Testing of these known anomaly specimens confirms proper system operation. The conveyor speed through the liquid penetrant system of Figs. 13 and 14 is set at 25 mm·s^{-1} or 1.5 m·min^{-1} (5 ft·min^{-1}). This speed permits the liquid penetrant dwell time on the material to be within specification.

FIGURE 13. Overall view of liquid penetrant spray system viewed from liquid penetrant spray application module end.

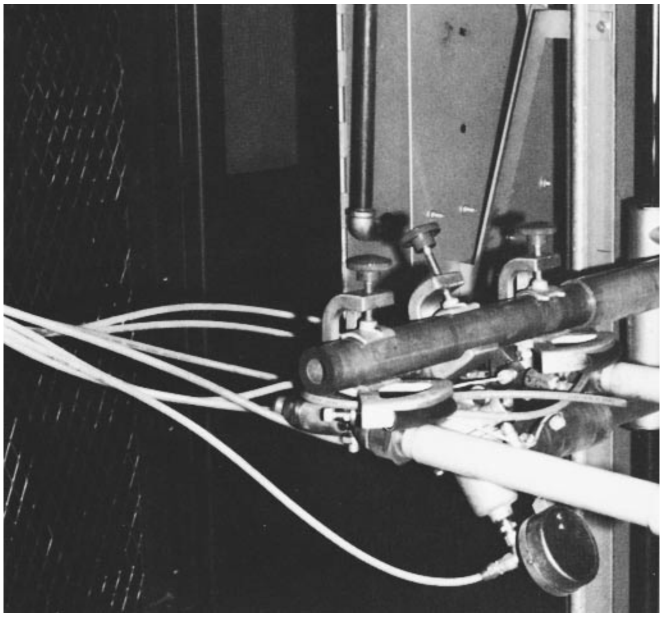


Techniques for Control of Spray Liquid Penetrant Application and Surface Coverage

The liquid penetrant reciprocator air spray pressure gage is set at 125 to 140 kPa (18 to 20 lb$_f$·in.$^{-2}$). This provides a light uniform coating of liquid penetrant on the parts and yet covers cavity areas adequately. Two liquid penetrant reciprocators operate up and down vertically for a span of 3.6 m (12 ft) inside the spray module (see Fig. 14). They can each be at full vertical span or half span (top half) depending on the volume of parts on the load bar. The liquid penetrant spray nozzles are activated by photoelectric load sensors as the end of the load bar enters the spray module.

A curtained observation area with near ultraviolet radiation is located at the part exit end of the liquid penetrant application module for the examination of parts for adequate liquid penetrant coverage. Observation platforms and six banks of tubular ultraviolet lamps are provided for this examination.

FIGURE 14. Liquid penetrant spray applicators mounted on vertical conveyance system inside liquid penetrant spray module.



Techniques for Control of Liquid Penetrant Removal and Parts Drying

The water wash module is equipped with several banks of water nozzle that provide a mild water spray. Nozzles are adjustable from the outside for different types of parts. The wash water pressure is set at a mild 140 kPa (20 $lb_f \cdot in.^{-2}$) to prevent overwashing of parts. Parts exit the water wash module through forceful air knives that remove much of the surface wetness.

The drier consists of two hot air knives mounted vertically inside the module for a 3.5 m (12 ft) span. The heaters are set to produce a maximum 66 °C (150 °F) temperature inside the module. Forceful blowers enhance adequate drying of parts.

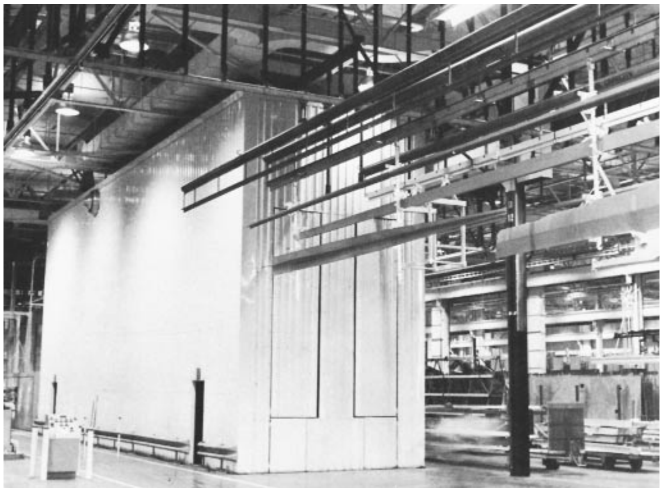
Intermediate Part Storage before Testing

Between the drier and the inspection module is a storage station where several load bars may be stored while waiting entrance in the viewing booth. Audible and visible signals are emitted inside the viewing booth when load bars are exiting the drier to alert inspectors that load bars may be moved transversely (on overhead tracks), clearing the way for additional load bars.

Inspection Booth Operations

Parts on the conveyor are moved with long hooked poles into the viewing booth (see Fig. 15). The load bar is moved into place on one of the two pneumatic lowering platforms directly above two parallel pits. Parts are lowered into the pits gradually as viewing with near ultraviolet radiation is performed longitudinally along the load bar. Cracked test coupons are examined for system performance before viewing of parts.

FIGURE 15. Outside view of ultraviolet radiation inspection module from part exit end.



Postcleaning of Test Parts Following Liquid Penetrant Testing

Following viewing, load bars carrying acceptable parts are routed back through the cleaning process to remove any liquid penetrant or developer residue. If required, a protective coating is applied during this cycle.

Advantages of Automated System in Liquid Penetrant Testing

Automation of parts handling during liquid penetrant testing produces uniformity of processing. All systems are adjusted to uniform and consistent part travel speed, which provides uniformity in liquid penetrant coverage, liquid penetrant dwell time, wash time and drying time. This precludes inadequate dwell periods, overwashing and overdrying — common discrepancies of manually operated systems. The automated chemical spray system can handle large parts in less space than is required in open tank systems. Parts of unrestricted length can be processed. Long spars of 24 m (80 ft) lengths are readily processed through the system of Fig. 13. This system can handle part widths up to 3.5 m (12 ft) and part thicknesses up to 0.9 m (3 ft).

Even though liquid penetrant is not reclaimed, the spray system uses about one eighth of the volume of liquid penetrant used in open tank systems for an equal number of test parts and minimizes potential contaminations. The system is capable of handling tremendous numbers of test parts. Two men can operate the system and perform many times the volume of viewing that can be handled through open tank systems. The system contains its own motorized conveyor system, thus eliminating overhead crane systems and reducing ceiling height and loading area requirements.

Second Example of Automated Liquid Penetrant Testing System for Aircraft Manufacturing

Figures 16 and 17 show another example of an automated liquid penetrant testing system installed in an aircraft manufacturing company plant. Aluminum extrusions and sheets up to 2.4 m (8 ft) wide and 8.5 m (28 ft) long can be handled by this fully automated fluorescent liquid penetrant testing system. Figure 18 shows the control panel, which is the brain of the system. With its help, one man can operate the automated part of the testing process. A computer controls the speed of the conveyor, automatically turns each station on and off and, if a malfunction occurs, shuts down the whole system. One glance at the board tells the operator where the malfunction is located. The sequence of processing steps for this system includes the following.

1. Preclean and dry test parts.

FIGURE 16. Schematic diagram of automated conveyorized liquid penetrant system layout. Cleaned parts are located on conveyor; loaded parts travel through liquid penetrant spray booth; drain dwell time is consumed in travel to rinse station. Following rinse, parts are dried in drier and nonaqueous developer is sprayed on parts in developer spray booth. Developing time is consumed in travel to ultraviolet radiation inspection booth; white light inspection follows before parts unloading.

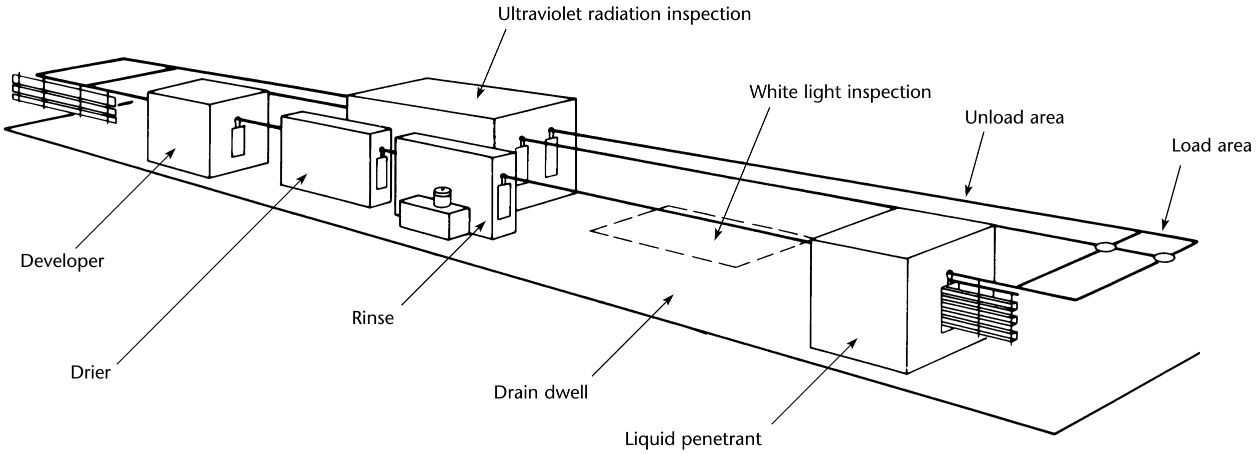


FIGURE 17. Area for liquid penetrant testing of aviation components includes dip tank operation (left) and automated spray system (right). The spray system is painted in bright reds, blues, yellows and oranges.

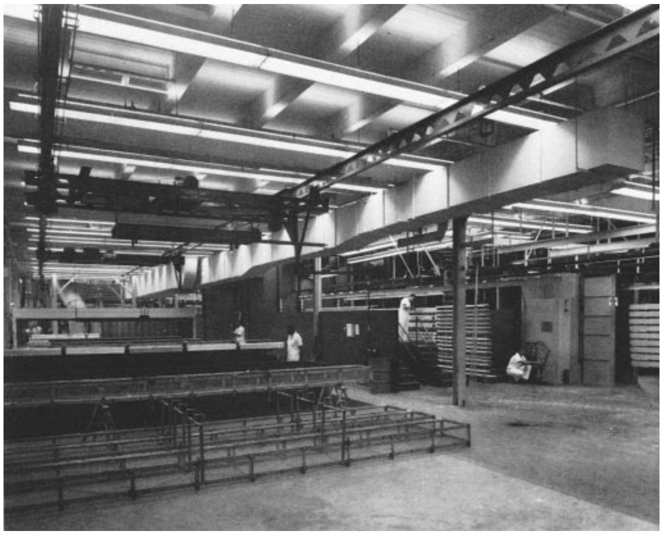
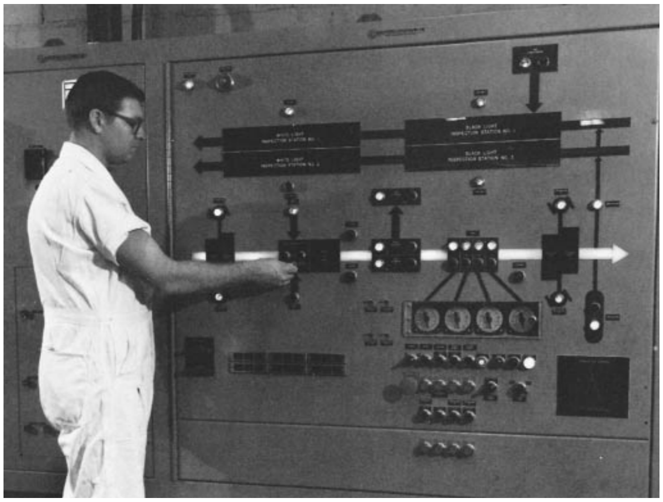


FIGURE 18. Supervisory control panel for liquid penetrant testing system.



2. Apply high performance water washable fluorescent liquid penetrant.
3. Allow dwell time.
4. Rinse with water.
5. Dry.
6. Apply nonaqueous wet developer.
7. View under ultraviolet radiation.

This automated liquid penetrant testing system has had a significant beneficial impact on cost, schedule and quality assurance.

Liquid Penetrant Spray Application Station

Figure 19 shows parts entering station where liquid penetrant is applied with electrostatic spray guns. The guns are triggered by photocells and, at this point, the length of the part or parts rack is recorded by a photoelectric cell at the controls. This cell automatically turns on the successive stations as the parts reach them and turns them off when the parts leave. Electrostatic spray application of liquid penetrant offers several advantages.

1. Initial product outlay is low because liquid penetrant reserves can be stored in a small feed tank. No large dip tanks of any type are required.
2. Liquid penetrant waste is minimized by eliminating overspraying. For example, only one eighth the normal volume of liquid penetrant materials and about half of the nonaqueous liquid penetrant developer are required.
3. Waste through drainoff is virtually eliminated.
4. No manual handling is required during the automated part of the processing cycle.

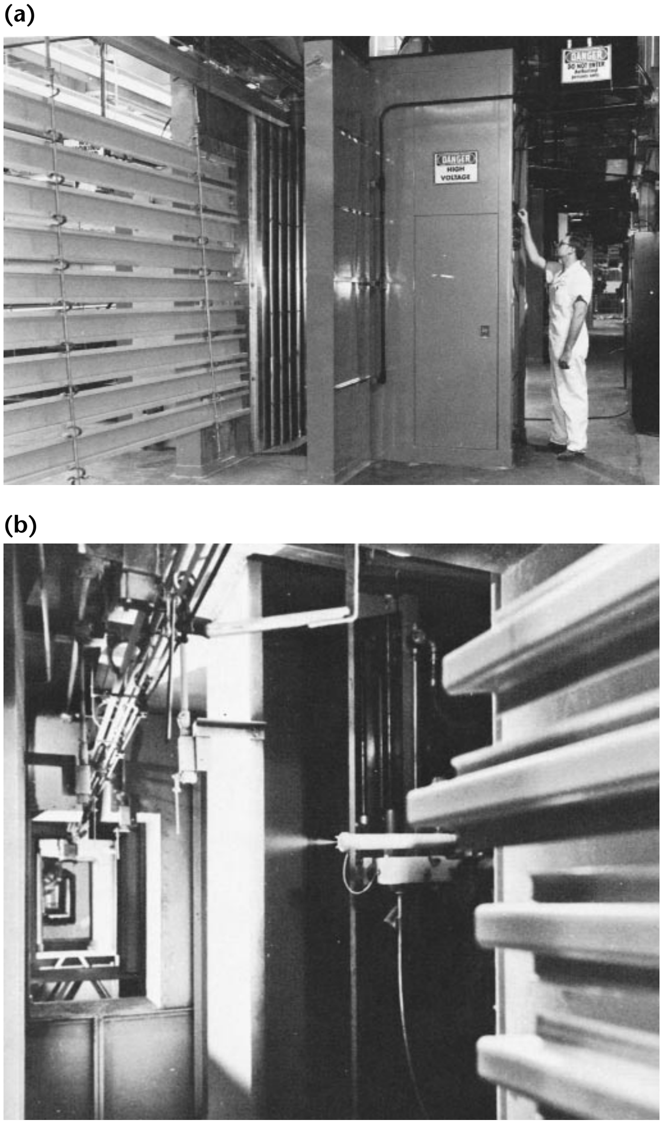
The actual viewing of parts under near ultraviolet radiation is performed with a manually controlled system, allowing adequate inspection time on the parts in process. The electrostatic spray system automatically adjusts for part size. Spray guns are arranged in three banks over the 2.4 m (8 ft) chamber height (Fig. 19b). Each bank is controlled separately with photoelectric actuation so the width of the entering part determines how many spray banks are actuated. The information recorded by the photoelectric cell is fed into a memory computer that actuates each of the successive work stations as the rack of parts enters it.

When the part enters the water rinse booth, the water is turned on; when the part leaves, the water is turned off. The process is similar when parts go through the oven. In the same way, as the parts enter, the developer station electrostatic sprays are triggered like those in the liquid penetrant station.

Water Spray Wash Station

Conveyor speed can be adjusted from a minimum of 10 mm·s^{-1} (2 ft·min^{-1}) to a maximum of 60 mm·s^{-1} (12 ft·min^{-1}), depending on the complexity of parts to permit adjustment of the liquid penetrant dwell time. The water spray station of Fig. 20 is designed so spray heads vary in impingement force and flow rate, guaranteeing an adequate washoff for most parts. The second part of this booth is equipped with near ultraviolet lamps so operators can examine parts to ensure adequate washing. Some complicated parts may not be adequately washed and hand hoses are provided to permit manual touchup washing of parts.

FIGURE 19. Electrostatic spray system: (a) parts enter station where electrostatic sprays apply liquid penetrant; (b) spray guns turn on only while parts move through their position.



Air Knife and Parts Drying Oven

The next station is an air knife that flows surface water from parts before they go into the drying oven (shown in Fig. 21). Parts are not heated beyond 66 °C (150 °F) skin temperature. Heating elements of the drier are interlocked electrically with the memory system at the main control panel so that as monorail speed increases, heat input to the oven increases. Regardless of speed, parts are heated to the proper temperature without being overheated.

Electrostatic Spray Application of Developer

After drying, developer (nonaqueous type) is applied by electrostatic spray guns as was done with the liquid penetrant. Spray guns are shown in foreground of Fig. 21. This permits a thin uniform developer film, essential for maximum sensitivity testing. Parts move from the developer station to holding area, shown in Fig. 22, before entering a darkroom inspection booth. The holding area can accommodate a backlog of at least 30 min ahead of the inspection station.

Figure 20. Water spray wash station for removal of surface liquid penetrant.

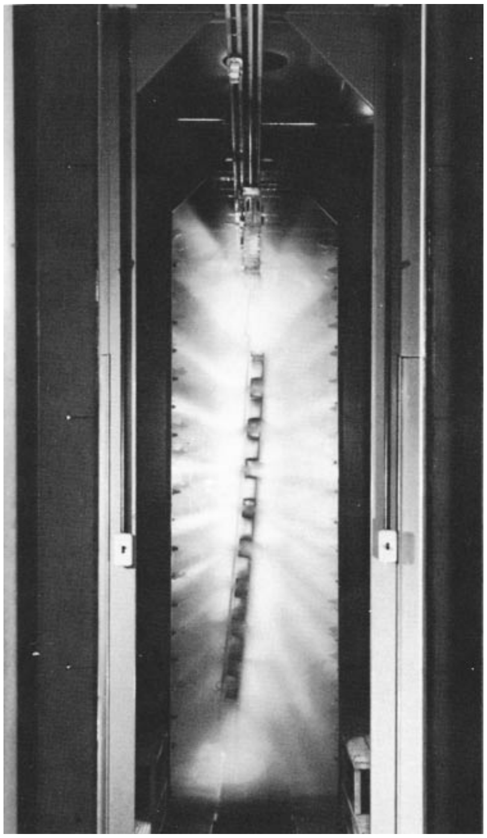


Figure 21. Parts rack is shown in drying oven, which is designed to dry parts thoroughly without heating the skin temperature over 66 °C (150 °F).

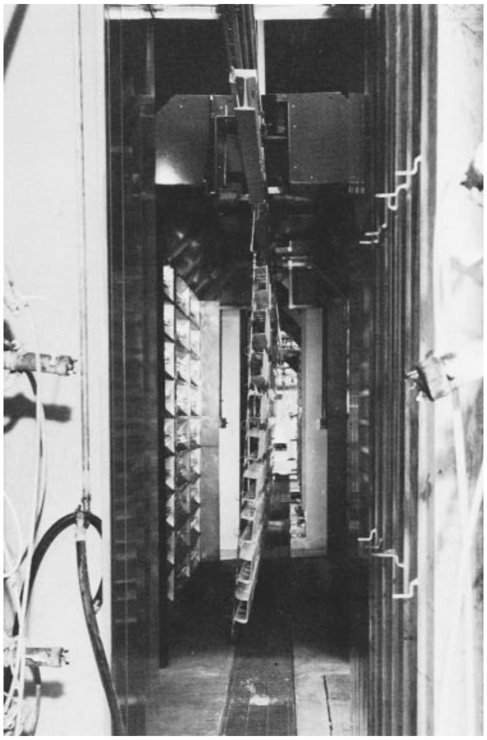
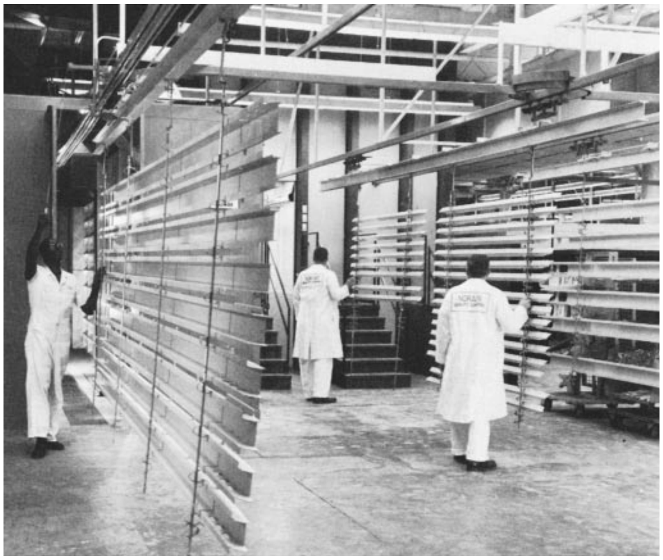


Figure 22. Developer station and holding area.



Inspection with Near Ultraviolet Radiation in Darkened Room

To speed up testing, two monorail systems run through the darkened room, where eight inspectors can work on parts simultaneously. Inspectors stand on platforms to view the top edges of parts passing through vertically, as shown in Fig. 23. The monorail is lifted into the ceiling so bottom portions of parts are brought to the eye level of the inspectors. After parts are inspected, they are moved into a white light viewing area where similar hoists are provided for inspectors (see Fig. 24).

FIGURE 23. Darkroom inspection station.

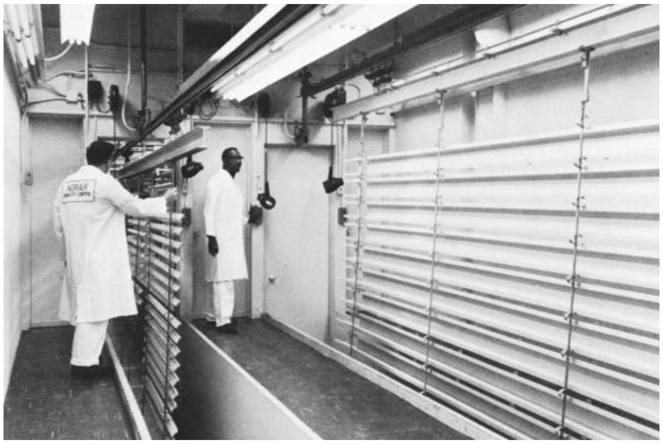
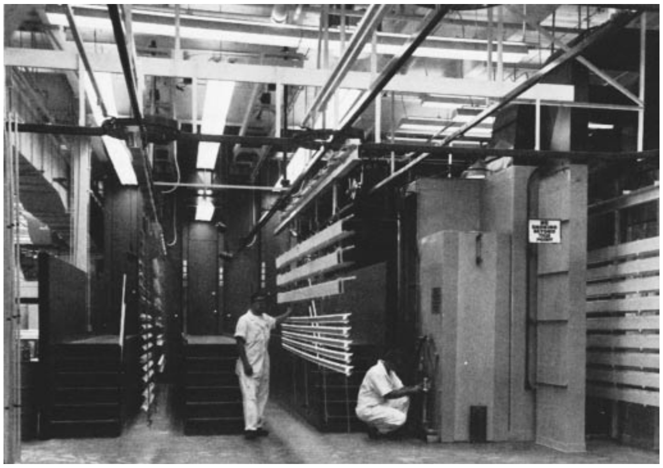


FIGURE 24. After parts have been completely inspected in dark room and monorail is lowered to down position, parts continue to white light inspection area where flawed parts are either passed or rejected. This photograph shows parts in white light station and other parts entering into liquid penetrant station.



Built-in Safety Features of Automated Testing System

If the monorail stops for any reason, the complete system is shut down. If any component malfunctions, the monorail stops and all stations shut off (except exhaust blowers). If a major problem such as a fire occurs, the entire system shuts down, including exhaust blowers. Trouble lights on the main control panel indicate minor malfunctions. These features provide for minimum downtime and prevent parts from being damaged.

PART 3. Lighting for Liquid Penetrant Testing

Sources of White Light for Visible Liquid Penetrant Testing

Because liquid penetrant testing techniques normally rely on the inspector to see test indications, the lighting provided for this examination is extremely important. It not only affects the sensitivity of the technique but also is an important factor in reducing inspector fatigue. White light sources for visible liquid penetrant testing are no different from those used for other test applications. Sunlight, incandescent lamps, fluorescent tubes or vapor arc lamps are generally quite satisfactory.

Spectral Characteristics of White Light Sources for Viewing Visible Liquid Penetrants

Spectral characteristics are usually not too important when using white light sources but it may be better to use a light source that is deficient in the light reflected by the liquid penetrant but rich in the other components of the visible spectrum. When such a light is used on a part having a good white developer background, the liquid penetrant indication will look black and maximum contrast will be obtained. Floodlights are advantageous for large and relatively flat surfaces, because of the greater area made visible. On intricate parts where areas are accessible with difficulty, hand held spot lamps may be even more effective.

Illumination Level for Visible Liquid Penetrant Testing

The proper intensity of white light illumination is determined by the nature of the testing being carried out. For gross anomalies where indications are large, a brightness level of 300 to 550 lx (30 to 50 ftc) at the surface of the part is generally sufficient. For extremely critical testing, higher intensities are required. Then, light levels should be at least 1000 lx (100 ftc).

Photometers are used to measure the intensity of electromagnetic radiation in the visible range. One of these instruments is often combined in the same package with a radiometer used to measure the intensity of near ultraviolet radiation. Further discussion on this instrumentation can be found elsewhere in this chapter.

Ultraviolet Lamps for Fluorescent Liquid Penetrant Testing

For best results, fluorescent indications should be evaluated in a darkened area. The darker the area of testing, the more brilliant the indications appear. This is extremely important, particularly when testing is being performed for very fine, cracklike anomalies that may have trapped only a small amount of liquid penetrant. It is also desirable that the test table or darkened area should be free of random fluorescent materials. If liquid penetrant has been spilled in the test area, on the table or on the operator's hands, it will fluoresce brilliantly and is likely to distract the operator's attention from anomalies. Table 1 contains examples of ambient visible light intensities for typical situations.

TABLE 1. Ambient visible light intensity.

lx	(ftc)	Remarks
10	(1)	best ultraviolet radiation booth
100	(10)	dim interior lighting
1000	(100)	bright interior; deep shade outdoors
10 000	(1000)	open shadow, bright day

Interference by White Light Illumination during Fluorescent Liquid Penetrant Testing

The visible light intensity in a test area has a dramatic effect on testing performance and reliability. More visible light makes fluorescent indications harder to see, requiring higher ultraviolet radiation intensity to permit detection of indications.

Ultraviolet lamps (with filters) have some visible light output and because of the induced fluorescence from the test parts, the inspectors' clothing and spills of fluorescent material within the test booths also add to the ambient light.

The intensity of ultraviolet radiation at the test surface can be altered by adjusting the distance between the ultraviolet radiation source and the surface. A typical filtered 100 W ultraviolet lamp bulb with recommended filters will produce 5.5 W·m^{-2} peak intensity at 380 mm (15 in.) from the test surface. Bringing the ultraviolet radiation source to a point closer to the surface will increase the intensity. About 50 mm (2 in.) is the shortest usable distance because test surfaces would be blocked out by the lamp housing and could not be viewed by the inspector if the lamp were closer than 50 mm (2 in.).

Darkness Adaptation by Inspectors

The eye normally adjusts itself to changes between light and darkness or degrees of light intensity by varying the size of the pupil. This adaptation is a natural adjustment in normal vision and is not a factor peculiar to fluorescent liquid penetrant testing. However, the change from bright, white light to the desirable darkened area necessary for reliable ultraviolet radiation testing requires at least a minute for the eyes of the inspector to adjust themselves. The time required for dark adaptation generally increases with increasing age of the inspector. The inspector should become accustomed to the darkened area before looking for indications and should avoid going from the dark to the light and back, without allowing sufficient time for eyes to adapt to the dark.

Response of Human Eye to Ultraviolet Radiation

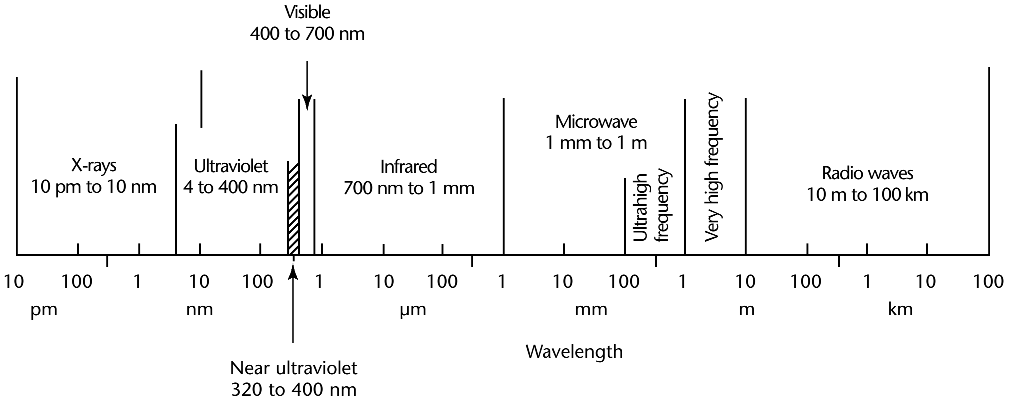
Ultraviolet radiation is electromagnetic radiation located in the 320 to 400 nm region. This is just below the visible light range and is part of the larger ultraviolet range, which extends down to about 100 nm in wavelength. Figure 25 shows the relative position of this radiation in the electromagnetic spectrum.

The eye is relatively unresponsive to ultraviolet radiation, particularly if there is visible light present. However, in the absence of significant amounts of visible light, the sensitivity of the eye greatly increases and large amounts of ultraviolet radiation, particularly of the longer wavelengths, may be visible.

Figure 26 shows the response of the average human eye under various lighting levels. Curve A depicts the highest level shown as 340 cd·m^{-2} (100 footlambert), which is a normal, bright light viewing condition. Here, the eye is almost totally insensitive to ultraviolet radiation. The second highest light level shown by Curve B in Fig. 26 is the 3.4 cd·m^{-2} (1 footlambert) level, which is about the average found in a well darkened inspection booth. In such a booth, total darkness is never achieved because (1) the light sources used to produce the ultraviolet radiation also put out some blue and violet visible light and (2) most booths contain some sources of fluorescence, often the inspector's clothing. In any case, at the 3.4 cd·m^{-2} ambient light level, the eye becomes almost 30 times as sensitive as under bright light in the 380 to 400 nm range. This light will appear deep blue to the eye and is not all bad because it allows the inspector to move around the booth safely and locate objects in the booth, all of which would otherwise have to be done by touch.

The top response curve (Curve C) in Fig. 26 is the 0.03 cd·m^{-2} (0.01 footlambert) level. This is almost total darkness and is seldom encountered in liquid penetrant testing. It should be

FIGURE 25. Electromagnetic spectrum showing narrow range of ultraviolet radiation used for inspection of fluorescent liquid penetrant indications.



noted that the eye is over 800 times as sensitive under these conditions, compared to normal levels and can detect large amounts of ultraviolet radiation, even down to 350 nm. The eye will also detect visible light much more easily at low background levels.

Response of Human Eye to White Light and Colored Light

The vision acuity of inspectors using white light illumination is affected by the working environment and must be sufficient for evaluation of visible dye liquid penetrant indications. Vision acuity drops as the illumination (brightness

Figure 26. Relative average response of human eye to various wavelengths in visible range, at three different levels of ambient light: curve A, 340 cd·m^{-2} (100 footlambert); curve B, 3.4 cd·m^{-2} (1 footlambert); curve C, 0.03 cd·m^{-2} (0.01 footlambert). Maximum response for curve A is set arbitrarily at 1.0 on vertical scale for relative eye response, corresponding to photopic eye at maximum sensitivity.

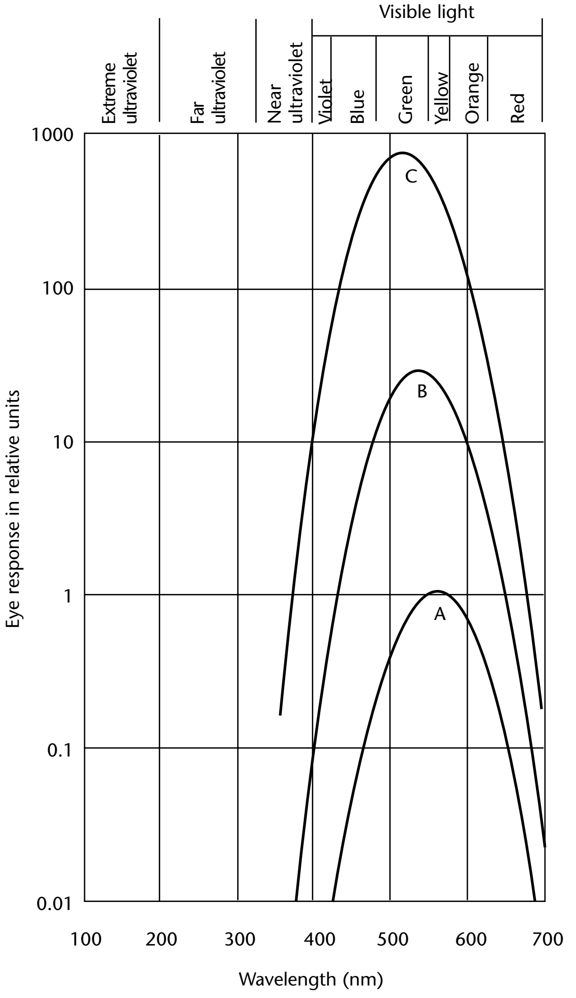


Figure 27. Threshold of vision. The minimum brightness perceptible drops sharply with time as eye adapts to darkness. Upper and lower dashed curves show effect of high and low illumination levels, respectively, before adaptation begins. For areas subtending more than 5 degrees, threshold is almost constant but rises rapidly as target size is reduced. Curves shown below are for target subtending above 2 degrees.

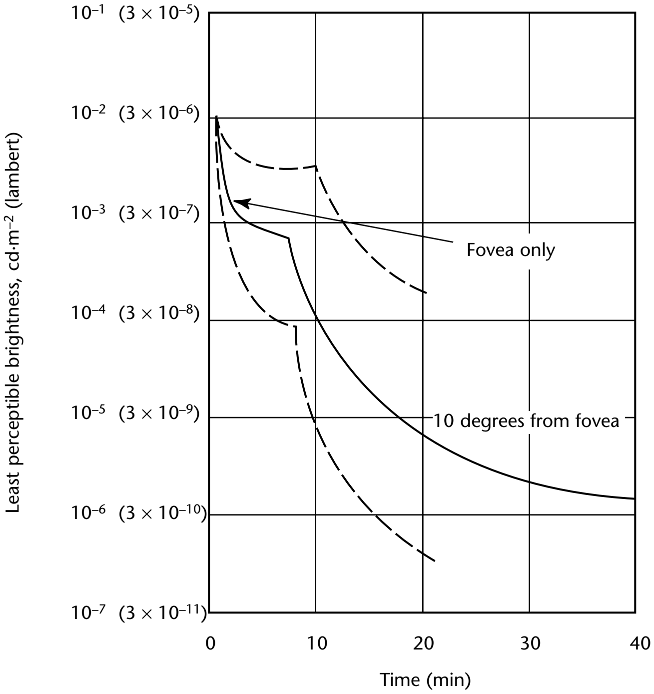
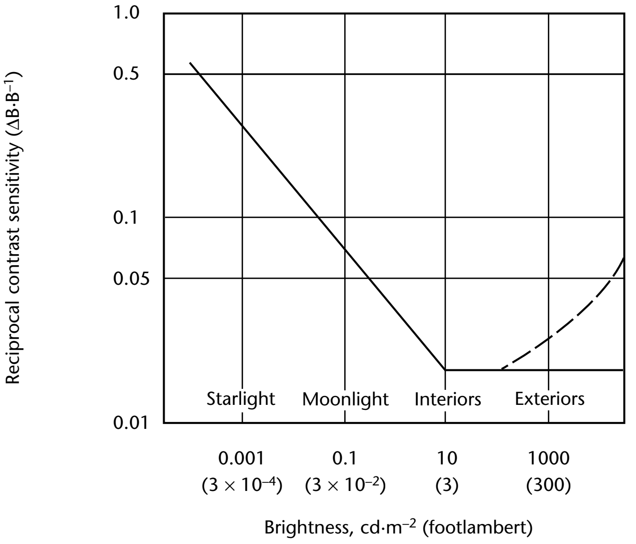


Figure 28. Contrast sensitivity of eye as function of field brightness. Smallest perceptible difference in brightness between two adjacent fields Δ*B*, as fraction of field brightness *B*, remains quite constant for brightness above 1 cd·m^{-2} (3 footlambert) if field is large. Dashed line indicates contrast sensitivity for field surrounded by dark. (One cd·m^{-2} is approximately equal to brightness of perfect diffuser illuminated by 3.4 lx).



level) decreases, as shown in Fig. 27. As the brightness of a scene is diminished, the iris of the eye opens wider. The rods take over the seeing task from the cones in the retina of the eye. At low levels of illumination, the eye is color blind because the rods are not color sensitive and the cones lack the sensitivity necessary for it to respond to low levels of illumination.

The brightness of the area surrounding the test surface or target of vision affects vision acuity. Reducing the contrast of the target (an indication) with respect to the background area reduces vision acuity, as shown in Fig. 28. Normally, vision acuity is determined for white light illumination. Monochromatic light vision acuity is very slightly higher for the yellow and yellow-green wavelengths. It is slightly lower for red wavelengths, 10 to 20 percent lower in the blue or far red regions of the visible spectrum and 20 to 30 percent lower in violet wavelengths.

Dark Adaptation of Human Eye

The lowest level of brightness that can be seen or detected is determined by the light level to which the eye has become accustomed. When the illumination level is reduced, the pupil of the eye expands in diameter, admitting more light. The retina of the eye becomes more sensitive during the process of dark adaptation. Adaptation occurs as the eye switches from cone vision to rod vision and is assisted by an electrochemical mechanism involving *rhodopsin,* the visual purple pigment. To illustrate this effect, everyone has experienced the phenomenon of *not being able to see a thing* on passing from a brightly lighted area into a dark room. After a short time, the eyes adjust or adapt to the lower light level and objects in the dark room become visible.

Need for Adequate Dark Adaptation Period for Fluorescent Liquid Penetrant Inspectors

Photopic vision refers to vision under normal levels of illumination. *Scotopic vision* is a term used to describe vision under conditions of dark adaptation. The change in perception by the human eye for varying conditions of illumination is shown schematically in Fig. 29. The dark adaptation gap is that period of time during which the eye is adapting and is not capable of performing at maximum sensitivity in either vision condition. The time required for dark adaptation before testing can be performed varies with the individual and depends on the overall health and age of the individual operator. A dark adaptation time of 1 min is usually sufficient for fluorescent liquid penetrant testing with satisfactory ultraviolet radiation illumination. Complete dark adaptation may take as long as 20 min.

The maximum sensitivity of the eye shifts in wavelength during dark adaptation. Figure 30 shows the sensitivity of the eye as a function of light

FIGURE 29. Vision acuity as function of object brightness. Pupil diameters are larger in young and smaller in old, especially at lower brightnesses.

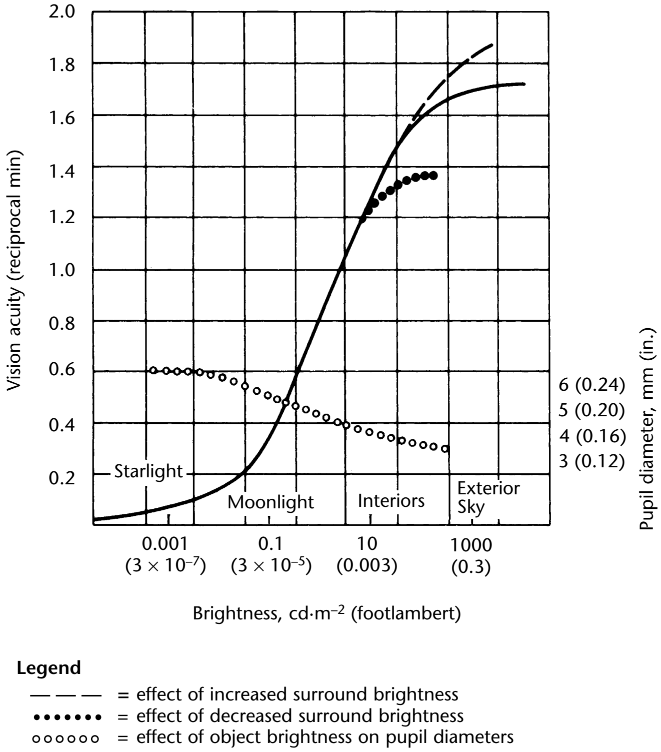
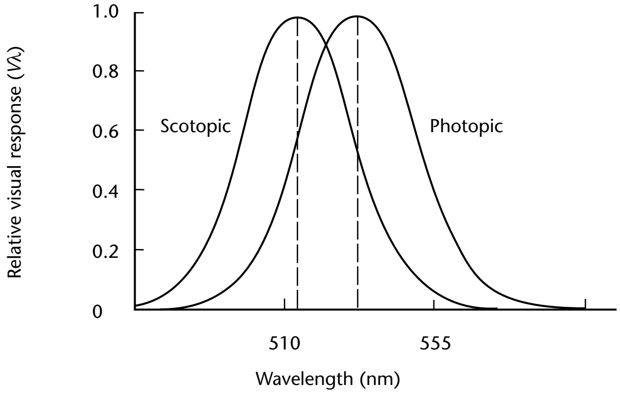


FIGURE 30. Relative luminous efficiency curves for human eye showing response as function of wavelength of light: photopic vision with adequate illumination levels and scotopic vision with dark adapted eye and low illumination.



wavelength for normal levels of illumination and also for the dark adapted eye. As dark adaptation progresses, the peak sensitivity of the eye shifts toward the blue end of the visible spectrum. This *Purkinje shift* is due to the different chromatic sensitivities of the rods and cones of the retina.

Avoidance of Photosensitive Eye Glasses during Fluorescent Inspection

Photosensitive eyeglasses have become available in recent years. They darken in the presence of ultraviolet radiation. Lens darkening is proportional to the amount of incident daylight radiation. Although this type of lens has advantages under sunlight conditions, such glasses can decrease the ability of an operator to perform fluorescent liquid penetrant testing if they are worn during viewing in a dark booth. Liquid penetrant test operators should not use photosensitive eyeglass lenses during examination of fluorescent indications.

On the other hand, wearing of suitable red eyeglasses while in lighted areas may aid dark adaptation. These glasses must be removed after entry into the darkened viewing booth, before viewing of fluorescent liquid penetrant indications. Eyeglass frames that fluoresce can cause glare or unnecessary fluorescent background illumination and their use is not recommended in the inspection booth.

Eyeball Fluorescence under Ultraviolet Irradiation

It is possible that the operator may experience a clouding of vision if the ultraviolet radiation is permitted to shine into the operator's eyeball or if ultraviolet radiation is reflected into the operator's eye from highly reflective surfaces. This is because the liquid in the eyeball fluoresces and causes a cloudy sensation in the eye. As soon as the light no longer enters the eye, the sensation will disappear. For this reason and for safety, it is desirable to arrange ultraviolet lamps in the inspection areas so that neither direct nor reflected light shines into the operator's eye. Yellow filter eyeglasses may be worn if this fluorescence is a serious problem. Ultraviolet protective eyewear is recommended.

Sources of Near Ultraviolet Radiation

Fluorescent materials used in nondestructive testing generally respond most actively to radiant energy with a wavelength of about 365 nm. This wavelength represents *near ultraviolet radiation,* light just outside the visible range on the blue or violet side but not sufficiently far removed to be in the chemically active ultraviolet range.

Some people wrongly suppose that the glow emitted by fluorescing materials is ultraviolet radiation. In fact, it is visible light that is emitted by a fluorescent material and that has been excited by ultraviolet radiation. Ultraviolet radiation is invisible.

Because it is invisible, radiation at this frequency has sometimes been referred to as *black light.* Common sources of near ultraviolet radiation include (1) enclosed mercury vapor arc lamps, (2) metal halide or halogen lamps, (3) integrally filtered tubular fluorescent lamps, (4) tubular fluorescent lamps, (5) metallic or carbon arcs and (6) incandescent lamps.

Because of insufficient output, instability or other reasons, neither of the first two is practical for test use. Because the tubular fluorescent lamps are quite low in output, they are only usable in a very few special applications. The integrally filtered tubular fluorescent lamps are similar to other ultraviolet tubular lamps except that they are integrally filtered. Because integrally filtered tubular fluorescent lamps also tend to have low near ultraviolet intensity, their use is limited. The metal halide or halogen lamp is a relative newcomer for high intensity sources of ultraviolet radiation. The most widely used ultraviolet source has been the mercury vapor arc lamp.

Mercury Vapor Arc Lamp Sources of Ultraviolet Radiation

Mercury vapor lamps are gaseous discharge devices in which an electric arc takes place in a controlled atmosphere and emits light whose characteristics depend on the nature of that atmosphere. The construction of a typical mercury vapor bulb is shown in Fig. 31. A quartz or hard glass cartridge contains the mercury. The two main electrodes carry current to the arc stream that takes place along the length of the cartridge. An auxiliary starting electrode is in series with a current limiting resistor. The entire assembly is sealed in an outer protective bulb, which may be either evacuated or filled with air or an inert gas, depending on the design of the bulb. The lamp is fed from a current regulating ballast reactance or transformer. This is required because the arc tube shows negative resistance characteristics and would quickly destroy itself if not throttled by an external device.

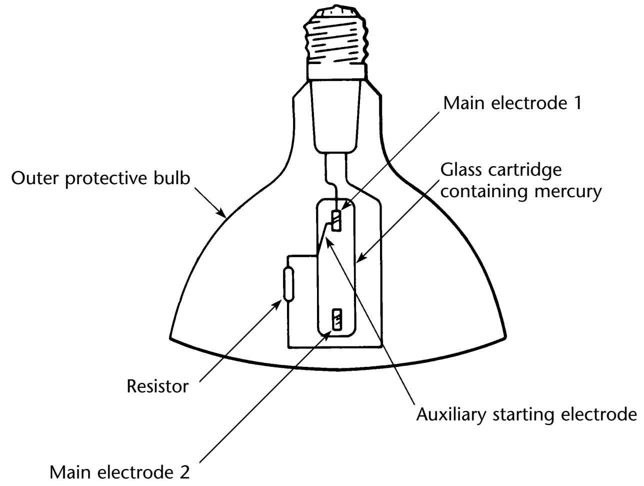
Starting of Mercury Vapor Arc Lamps

When the lamp is first turned on, the mercury in the cartridge is not in vapor form but is condensed in droplets on the inside of the tube. Under this condition, it would be difficult or impossible to strike the arc. To facilitate starting, a small amount of neon gas is incorporated into the cartridge and a starting electrode is sealed through one end of the tube near one of the main electrodes. When voltage is first applied, a discharge will take place from the starting electrode through the neon. This glow discharge carries a small current, limited by the protective resistor but sufficient to vaporize and ionize the mercury and eventually cause an arc to strike between the main electrodes. This heating and ionization process requires from 5 to 15 min of starting time when the lamp is first turned on.

Spectral Characteristics of Mercury Vapor Arc Sources of Ultraviolet Radiation

One of the advantages of the mercury vapor lamp is that its light output can be controlled by design and manufacture. By proper choice of vapor pressure, spectral output can be varied from a few intense but widely scattered lines (when the pressures are near 1 mPa (1×10^{-8} atm) to an almost continuous spectrum at about 10 MPa (100 atm). At medium pressures from 100 to 1000 kPa (1 to 10 atm), the light output is about evenly distributed between the visible, ultraviolet radiation and hard ultraviolet ranges. These medium pressure lamps are ordinarily used for test purposes. Figure 32 shows the spectral emission of two ultraviolet radiation sources.

FIGURE 31. Mercury vapor lamp construction (see Fig. 38 for effect of operating voltage on ultraviolet radiation output).



Transmission Characteristics of Ultraviolet Radiation Filters

Because only the ultraviolet radiation portion is desired for testing, the remainder of the radiation spectrum must be removed by filters. The most satisfactory is a red-purple glass filter, generally of the heat resistant variety. A typical transmission curve peaks rather sharply at slightly over 360 nm and starts to rise again in the neighborhood of 700 nm. Because this second peak comes at the very bottom of the visible red and in the invisible infrared region, the filter transmits little radiation other than the invisible ultraviolet radiation desired.

Inspection Fixtures for Mercury Arc Ultraviolet Radiation Sources

A ultraviolet lamp mercury arc bulb requires a housing and fixture (1) to support the filter, (2) to prevent leakage of unwanted visible light and (3) to permit the operator to direct the beam onto the area to be inspected. Various ultraviolet lamp fixtures are commercially available. Some of these are small and portable, whereas others are mounted permanently inside an inspection booth or on a

FIGURE 32. Spectral emission of mercury arc and fluorescent tubular types of ultraviolet radiation sources. The radiation intensity of the fluorescent lamp is actually much less than that of the mercury arc lamp.

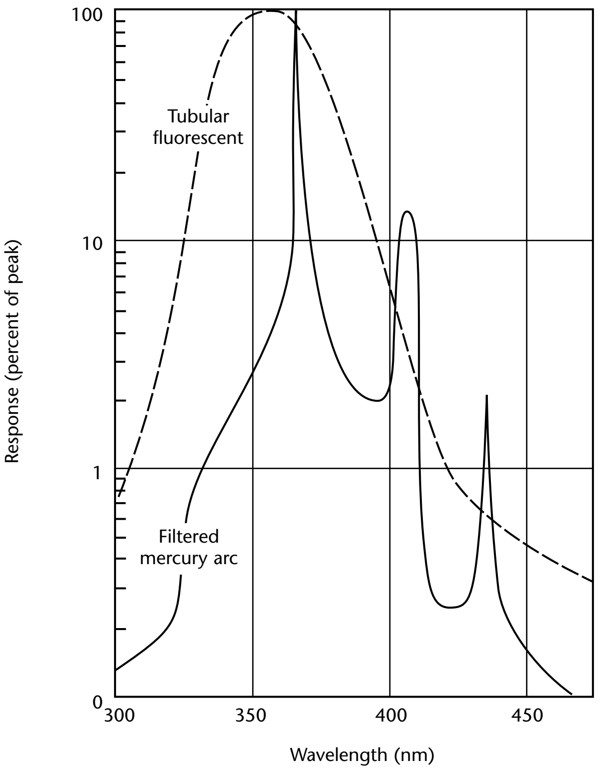


FIGURE 33. Ultraviolet radiation sources: (a) 100 W ultraviolet lamp with ballast transformer; (b) self-ballasted ultraviolet lamp; (c) 12 V battery operated portable ultraviolet lamp with plastic housing; (d) portable, battery operated, tubular ultraviolet lamp; (e) 400 W ultraviolet flood lamp; (f) low intensity, tubular ultraviolet lamp.

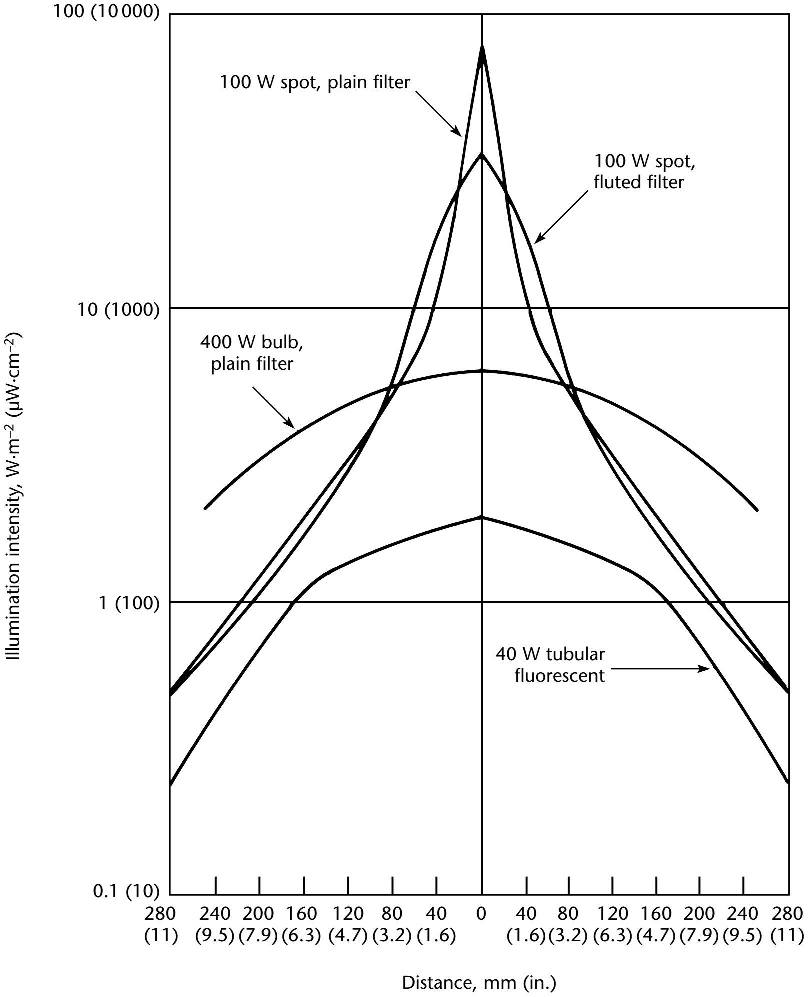
production machine. Figure 33 shows examples of ultraviolet radiation sources.

The 400 W lamp is quite large and therefore limited to stationary mounting. It puts out a large amount of light over a large area and so is well adapted to flooding a large area with ultraviolet radiation for quick location of large or medium sized indications. It does not have a high maximum intensity in any one area as the 100 W bulb, however. Figure 34 shows the relative output of several ultraviolet radiation sources measured at various distances from the center of the beam.

The 100 W lamp is small enough to be portable, although it is often mounted more or less permanently in a test unit. These lamps come in a variety of configurations from various manufacturers and all cannot be detailed here. The bulbs themselves come in *spot* and *flood* lamp types. The spot lamps are used almost exclusively to attain the high intensities required for local use. In fact, the lamps produce a very intense but very narrow beam, as seen in Fig. 34. For general testing work, this beam may be too narrow to provide adequate coverage of any but the smallest parts. For this reason, 100 W lamps are commonly supplied with ribbed or fluted filters, which partially disperse the narrow beam to cover a slightly larger area with a slightly lower intensity. This effect is also shown in Fig. 34. In the 1990s, several manufacturers introduced 120 W and 150 W lamps that require no transformer.

There are also many smaller mercury arc lamps ranging down to a 2 W pencil size. These may find certain very specialized uses in testing but are not often suitable. They usually do not have built in reflectors, so their usually lower power is widely and unusably dispersed. Note — care should be taken to avoid breaking mercury arc or vapor lamps. Mercury constitutes a significant health hazard. It may also lead to cracking of aluminum and other metallic components that it contacts.

FIGURE 34. Ultraviolet radiation intensity varies in intensity as function of distance from center of beam.



Tubular Fluorescent Cold Discharge Ultraviolet Radiation Sources

Electrically and mechanically, these standard fluorescent bulbs come in sizes from 2 to more than 60 W input. These cold discharge tubular lamps contain low pressure mercury vapor glow discharges. Their primary radiation is hard ultraviolet radiation of 253.7 nm wavelength. This is used to excite a special cerium activated calcium phosphate phosphor coated on the inside of the tube. This phosphor, when activated by ultraviolet radiation, emits ultraviolet radiation with a range of 320 to 440 nm, peaking at 360 nm. Because a significant amount of visible light is emitted along with the ultraviolet radiation, these bulbs are often made of a purple-red filter glass similar to that used over the high pressure arc lamps previously described. This greatly reduces the ultraviolet radiation emitted but still leaves what is often an excessive amount of visible blue light, considering the relatively low intensity of the ultraviolet radiation produced. Figure 32 shows the spectral emission of the fluorescent bulb ultraviolet lamp as compared with that of the high pressure mercury arc.

Advantages and Limitations of Fluorescent Tubular Ultraviolet Radiation Sources

Fluorescent ultraviolet lamp bulbs put out reasonable amounts of ultraviolet radiation but because of their configuration they cannot be easily focused. Therefore, their intensity per unit area illuminated is much lower than that provided by the high pressure mercury arc lamps. Thus, fluorescent ultraviolet lamps are not usually considered adequate for critical fluorescent liquid penetrant tests.

Fluorescent lamp sources of ultraviolet radiation for fluorescent liquid penetrant testing offer the significant advances of instant starting, cool operation and low cost (as compared to the commonly used mercury arc lamps). Used in typical four lamp fixtures, the 40 W integrally filtered tubular fluorescent lamps add up to 160 W and produce near ultraviolet radiation intensities of 1 to 5 W·m^{-2}. Although tubular ultraviolet radiation sources may not quite meet the stringent specifications of ASTM E 1417,[1] they are commonly used in industrial applications where extreme performance of liquid penetrant testing is not required. In large inspection rooms, overall ultraviolet irradiation is often provided by several ultraviolet radiation fluorescent fixtures with four lamps.

Fluorescent ultraviolet lamps, especially in the smaller sizes, are, however, the most practical source for battery powered, portable ultraviolet lamps. They are more efficient in use of electricity than high pressure arc lamps; even more important, they start and reach full output in a few seconds rather than the 15 min required by the high pressure arc.

Limitations of Incandescent Filament Ultraviolet Radiation Sources

Another ultraviolet radiation source is available but is not suitable for testing use. This is the incandescent ultraviolet lamp bulb, which comes in 75 and 150 W sizes. The bulbs come as standard incandescent bulbs with a filter glass envelope. They put out very little ultraviolet radiation and a large amount of visible light, so they are even less usable than fluorescent ultraviolet radiation sources. Measured on the standard ultraviolet radiation meter, these sources put out ultraviolet radiation intensity similar to that produced by 4 W fluorescent tubular ultraviolet lamps. However, they put out up to 30 times as much visible light as the fluorescent tubular ultraviolet lamps that are themselves borderline on this property. Experiments show that fine indications cannot be detected with incandescent ultraviolet radiation sources whereas they can be detected with other sources. Medium and large indications might be weakly detectable but the high risk of missing indications makes use of incandescent ultraviolet lamp bulbs unwise.

Measuring Ultraviolet Radiation in Fluorescent Liquid Penetrant Testing

The amount of ultraviolet radiation required to carry out a given test is often difficult to determine. A suitable intensity can be determined by simple trials on parts with known but very fine anomalies. Most rules applicable to inspection under white light apply to inspection under ultraviolet radiation. Because different amounts of ultraviolet radiation are necessary for different types of testing, some technique of evaluating and specifying illumination intensity is needed. Experience indicates that ultraviolet irradiation levels of 10 W·m^{-2} (1000 µW·cm^{-2}) at 380 mm (15 in.) distance from the source are generally adequate. A distance requirement has been treated as unnecessary in many European specifications. Instead the irradiation requirements are for the test surface.

Early Selenium Cell Measurements of Ultraviolet Radiation Intensity

As far back as 1942, selenium cell photoelectric meters were being used to measure ultraviolet radiation intensity. The most common, easily used footcandle meters were designed for use by illumination engineers. The footcandle was used as a unit of visible light as seen by the human eye under photopic conditions. There is no such thing as a footcandle of ultraviolet radiation. For convenience, ultraviolet radiation was incorrectly measured in footcandle for many years, with an unfiltered footcandle meter. Even though these readings did not make sense, they did give reproducible numbers. Further, no other meter capable of true measurements in the near ultraviolet wave length range was then available.

Modern Units for Measuring Ultraviolet Radiation Intensity

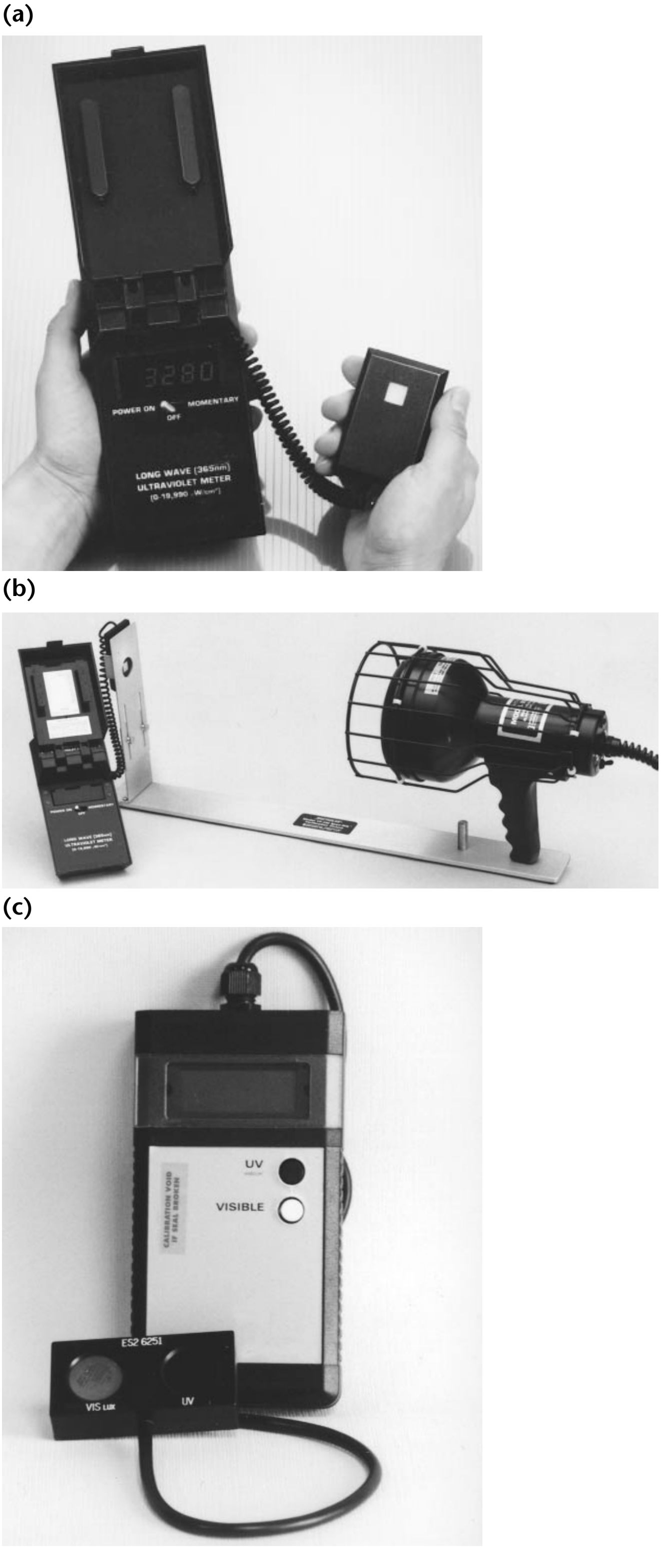
Obviously, it is important to have a unit of measurement for ultraviolet radiation intensity. As previously noted, ultraviolet radiation is electromagnetic radiation similar in nature to radio and infrared waves. These radiations are measured in units of energy per unit time, namely the unit of watt (W). Total ultraviolet radiation output can equally well be measured in watt. It should be noted, however, that although ultraviolet lamps are commonly rated by their wattage, the figures given are actually for electrical energy input rather than radiated output. The radiated output is much less than the input because of conversion losses.

Examples of Ultraviolet Radiation Measurement Instruments

Measurement of ultraviolet radiation intensity requires a special meter calibrated in watt per square meter or microwatt per square centimeter. An example is a commercially available, hand held digital radiometer or photometer (Fig. 35). The hand held instrument is shock resistant and water resistant and can be easily inserted in areas of limited accessibility. Through two interchangeable sensors, such portable radiometers provide long wave coverage from 0 to 199.99 $W \cdot m^{-2}$ (0 to 19999 $\mu W \cdot cm^{-2}$) and visible light coverage from 0 to 1999 lx (0 to 199.9 ftc).

Each sensor head contains an optical stack of specialty components to provide a cosine response, to define the spectral bandpass and to convert light radiation into electrical current.

Figure 35. Photoelectric instruments for measurement of ultraviolet radiation intensity: (a) hand held digital ultraviolet radiometer measures near ultraviolet radiation in 0 to 19 990 $\mu W \cdot cm^{-2}$ range; (b) radiation monitoring and verification fixture ensures accurate measurement of ultraviolet radiation at 300 mm (15 in.); (c) radiometer/photometer with dual sensor for measuring ultraviolet radiation and visible (white) light.



Some modern ultraviolet meters have an optical stack featuring interference filters that minimize the effects of other unwanted radiation, such as visible and infrared. Interference filters have a well defined bandpass with minimal transparency to other wavelengths. This optical stack uses a metal-and-quartz package ultraviolet photodiode for high linearity and signal-to-noise ratio response. The analog-to-digital converter uses a large scale integrated circuit and changes the direct current voltage into digital information. This digital information is decoded into seven segment information for the light emitting diode display.

To collect the maximum amount of light and render the most accurate irradiance readings possible, including applications with flooded and uncollimated sources, modern meters are designed to have an excellent lambertian or cosine response.

For maximum accuracy, calibration of these meters is done with an electrically calibrated pyroelectric radiometer (ECPR) traceable to the National Institute of Standards and Technology (NIST) and is correct to within five percent. Electrically, the meter's integrated circuitry features an accuracy of 0.5 percent in overall system performance.

Preferred ultraviolet radiation intensity meters measure only the ultraviolet radiation in reproducible radiation power units such as watt per square meter. ASTM E 1417 calls for a minimum ultraviolet radiation intensity of 10 $W \cdot m^{-2}$ (1000 $\mu W \cdot cm^{-2}$) at the test surface. Measurements at the test surface are required because of the variation in intensity with distance frm the source (Fig. 36).

ASTM E 1417 also requires a maximum visible light intensity in the viewing area (inspection booth) of 20 lx (2 ftc).[1] True measurement of the ambient visible light can be made with the same style digital radiometer as used for ultraviolet radiation. Several manufacturers offer digital readout units that will accept a visible light sensor. These sensors follow a standard curve of the International Commission on Illumination (CIE) and mimic the human response to visible light, peaking at a wavelength of 555 nm.

Selecting Ultraviolet Irradiation Levels for Fluorescent Liquid Penetrant Inspection

The amount of ultraviolet radiation necessary for any testing job depends on the particular application. It is preferable to establish specific limits by trial on each job, because it is only in this way that proper consideration can be given to all variables. Factors that have an effect on the ultraviolet radiation intensity necessary at the inspected surface include (1) the nature of the inspected surface, (2) extraneous white light entering the booth, (3) the amount and location of fluorescent materials near the inspector and (4) the speed with which testing is to be carried out.

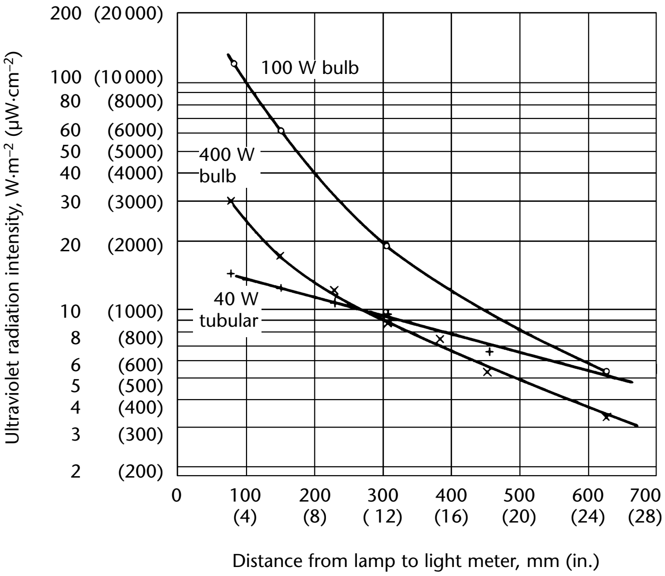
These factors are in addition to the obvious factors of size and type of indications sought, which depend on the service the part has to perform.

In the past, there have been two axioms used in selecting ultraviolet radiation intensities: (1) the greater the intensity of the ultraviolet radiation applied, the smaller the minimum detectable indications and (2) the lower the visible white light level, the better the contrast, hence the smaller the minimum detectable indication. These concepts are still true but it is possible to operate under less than optimum conditions with usable results.

Fluorescent Liquid Penetrant Testing in Subdued White Light

The improved liquid penetrant processing materials available now have made it possible to test in less than total darkness. This does not mean darkened inspection

FIGURE 36. Variations of ultraviolet radiation intensity with distance from face of ultraviolet sources, for 400 W bulb, 100 W bulb and 40 W tubular lamp.



booths are no longer necessary. It does mean that with bright liquid penetrant indications and adequate ultraviolet radiation intensity, medium and large indications can be detected under conditions of fairly high ambient white light. This has made some fluorescent liquid penetrant testing possible on aircraft outdoors on the flight line. However, ambient white light requirements must be met by using black cloth or other light shields.

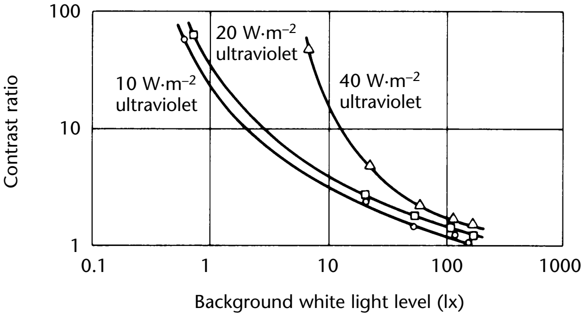
Extremely dark testing areas and high ultraviolet radiation levels are not always necessary. They are, however, always helpful and do ease the testing chore considerably. Further, in tests for the very smallest indications such as microcracks in jet turbine blades, they are necessary. In many instances, minute indications could only be detected by a dark adapted observer working in a booth with no more than 10 lx (1 ftc) of white light and then only by holding the part 50 or 75 mm (2 or 3 in.) from a 100 W mercury arc source, producing 150 to 180 $W{\cdot}m^{-2}$ intensities on the part.

The window lens of the visible radiation (white light) sensor must not fluoresce. Under near ultraviolet radiation of 35 $W{\cdot}m^{-2}$ (3500 $\mu W{\cdot}cm^{-2}$), visible radiation of 4.8 klx (440 ftc) has been reported instead of 13 lx (1.2 ftc) as measured with a photometer with a nonfluorescing sensor window.

The axiom that high ultraviolet radiation levels and low ambient light levels produce the best performance is still true. However, maximum performance is not always necessary, so tests can often be carried out under far from ideal conditions. Figure 37 shows how contrast ratio varies with ambient lighting. Nevertheless, those ideal test conditions will considerably ease the test and should be used if at all possible.

As an example, an ultraviolet radiation illumination level of about 8 to 10 $W{\cdot}m^{-2}$ (800 to 1000 $\mu W{\cdot}cm^{-2}$) is sufficient to reveal most anomaly indications. This will depend, of course, on the size of the indication and type of liquid penetrant system used. There will be applications where extremely high levels of ultraviolet radiation intensity will be required.

FIGURE 37. Contrast ratio of typical fluorescent liquid penetrant system at various levels of white light.



Care and Maintenance of Ultraviolet Lamps

Ultraviolet Lamp Warmup and Restart Times

When the current to an ultraviolet lamp bulb of the mercury arc type is first turned on, it takes 300 s or more for the bulb to warm up to its full output. No test should be started until this time has elapsed. If, for any reason, the arc is extinguished, as by interruption of the current, the bulbs will not respond immediately when the current is again turned on. Time must be allowed for the lamp to cool somewhat and then for the arc to reestablish itself. This may take about 600 s.

Once having established a level of illumination necessary for a particular job, it is important to observe precautions to ensure that this level is maintained. Various factors can affect the output of light from an ultraviolet lamp bulb but the meters described earlier can be used to maintain a check on performance. Experience and tests have shown that light output of an ultraviolet radiation source decreases gradually with age and hours of service. When intensities drop below usable levels, the situation should be corrected.

Proper Usage of Ultraviolet Radiation Sources for Liquid Penetrant Testing

Several things can cause reduction in light from a fixture. The bulb itself will lose output as it ages, because of discoloration of the cartridge or the outer container. As a bulb nears the end of its life, output may drop to as low as 25 percent of what it was when the bulb was new. The lives of these bulbs may vary widely. Nominal life expectancy is given by the manufacturer (1000 h for the 100 W spot) but the actual life of a bulb in testing service is less than this figure. The manufacturer's life tests are statistical estimates based on continuous, steady operation in a fixed and well ventilated position. Ultraviolet lamps used in testing are subject to numerous starts and shutoffs and to rough handling. In addition, because of the needs of filtering and portable housing, such lights may operate at higher temperatures than desirable. Fan cooled lamps are available to offset these problems.

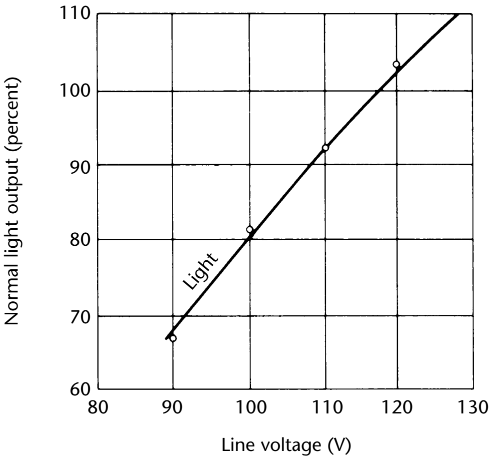
Accumulations of oil, of films or dust and of dirt on the bulb and filter seriously reduce the ultraviolet radiation output, sometimes by as much as 50 percent. This cause of variation can be avoided by keeping the filter clean but an output check with the meter is the only safe way to make sure that the cleaning has been effective.

Low voltage will extinguish the mercury arc and where line voltage is subject to wide fluctuations, with low points at 90 V or less, the lamp may go out (see Fig. 38). The lamp should be energized from a power source that maintains voltage as nearly constant as possible. The simplest way of overcoming this difficulty is, of course, to connect the lamp to a power line having extremely good voltage regulation. If such a line is not available, an alternative is to install a voltage regulating transformer between the line and the lamp. An additional advantage is obtained by using such a transformer. Where power lines are subject to sudden sharp drops in voltage when heavy machinery is started on the power system, the regulating transformer helps to eliminate the nuisance of having lamps extinguish themselves and waste operator time while the lamp cools off and reignites.

Extending Life of Ultraviolet Lamps

The user can contribute to lamp life in two ways. One of these is to avoid operating lamps above their rated voltage. Only slight increases in voltage will decrease lamp life tremendously. In some tests, increasing supply voltage to between 125 and 130 V resulted in burned out lamps in as little as 48 h. A second way to prolong life is to keep the number of starts as low as possible. Each time a lamp is started, a small amount of active material is removed from the electrodes. A single start is equivalent to several hours of continuous burning. It is generally more economical to leave lamps burning over rest periods and lunch hours than to turn them off and on again.

FIGURE 38. Variation in ultraviolet radiation output of 100 W mercury arc bulb varies with line voltage. Standard lamp power factor transformer, 117 V tap (see Fig. 31 for sketch of lamp structure).



Physiological Effects of Ultraviolet Lamps

Not directly in line with use or maintenance of ultraviolet lamps but of interest to hygiene directors and safety engineers are the effects of ultraviolet radiation on the operator. It has been demonstrated that moderate ultraviolet radiation in the wavelength range normally used for liquid penetrant testing is unlikely to cause permanent damage to persons exposed, so long as recommended filters are used on the ultraviolet lamps. The 365 nm wavelength is out of the range where most physiological effects take place. Such effects as damage to the eye, sunburn and destruction of tissue come into evidence at wavelengths under 320 nm. Here they become definitely injurious. Normal ultraviolet radiation as used for testing purposes is safe.[2]

Near ultraviolet radiation is a normal, nonionizing radiation that shares some effects of sun light. To inhibit the formation of cataracts, eyewear that blocks near ultraviolet radiation is recommended. Similarly, to inhibit the formation of carcinomas on the skin, it is recommended that inspectors wear caps, gloves when possible (depending for instance on dimensions of inspected parts) and long sleeved shirts. It should be noted that these recommendations are the same as for people working in sun light.

Consideration should be given to the disposition of lights within a booth and to the effect on an operator of placement of light sources. Although ultraviolet radiation will not damage the eye permanently, some of the layers of the eyeball exhibit strong tendencies to fluoresce. If the inspection light is placed so that its rays fall directly into or are reflected into the eyes of operators, this eyeball fluorescence can become extremely annoying and will impair inspector effectiveness to a marked degree.

More on safety aspects of liquid penetrant testing can be found elsewhere in this volume.

PART 4. Mechanized Scanning of Fluorescent Liquid Penetrant Indications

Advantages of Fluorescent Liquid Penetrant Test Systems

One of the most significant advances in nondestructive testing was the introduction of fluorescence in liquid penetrant testing. In this technique, the test object can be subjected to large quantities of excitation energy (generally near ultraviolet) with virtually no glare or highlights reflected from the part being inspected. Because of this, liquid penetrant indications containing very minute amounts of retained material may be readily seen and, therefore, very high sensitivity to small discontinuities is possible. Extraneous indications do develop from fluorescent material trapped in scale or on some rough spot etc. These are generally referred to as background. In many applications, the background level may limit the smallest size discontinuity that can be reliably detected.

Functions of Scanning Equipment for Liquid Penetrant Indications

The purpose of mechanized scanning of fluorescent liquid penetrant test indications is to automate the viewing and interpretation portions of the liquid penetrant test process. This is advantageous in obtaining reliable and reproducible results. The automatic scanning machine can theoretically be calibrated more accurately than the human, so simple *go/no-go* interpretations could be made more uniformly. Naturally, in addition to the above advantages, automated liquid penetrant testing potentially offers speed in inspecting large numbers of uniform parts that no human test operator can match.

Unfortunately, the potential has not been fulfilled. Scanning units in production applications have been too slow and less sensitive than a human operator and have had higher rates of false calls.

Ultraviolet Radiation Scanning Systems

Ultraviolet scanners consist essentially of (1) a source of ultraviolet radiation, (2) a photodetector sensitive to visible (converted) light but not to ultraviolet radiation and (3) the amplification and discrimination equipment necessary to interpret the signal produced. Generally, materials handling accessories will be required to move the parts to be inspected to and from the scanner, to index or move the parts under the scanner so that all desired areas are inspected uniformly and to mark or separate those parts rejected. Obviously, a system containing all the above functions would be very complex and may be expensive. It would also probably have to be specifically engineered for a particular part or group of similar parts, so it could be fairly inflexible. Two types of ultraviolet scanning equipment have been in comon usage in the late 1900's — the television scanner and the laser scanner. Each will be discussed separately here.

Television Scanner for Fluorescent Liquid Penetrant Test Indications

The television scanner illuminates the part with ordinary filtered ultraviolet radiation. A closed circuit television camera, equipped with a filter to remove the ultraviolet radiation, is used as the detector of the visible light test indications in this apparatus. The output video signal is then processed through a computer or other electronic equipment programmed to recognize the signals from rejectable anomalies. On receipt of a rejectable anomaly signal, the computer usually is programmed to initiate some rejection action such as marking the spot with paint for later disposal or sorting rejected parts into a rejection bin. Some pattern recognition and classification of anomalies are possible.

Laser Scanner for Fluorescent Liquid Penetrant Test Indications

The laser scanner uses a deep blue, violet or ultraviolet laser beam to illuminate the test parts. With this type of light source, a very narrow, very intense beam is produced. The scanning occurs as the beam passes over the part, illuminating only a very small area at any one time. The direction of the laser beam may be changed continuously by means of mirrors, the part may be moved under the beam or both may occur simultaneously. In any case, the level of fluorescence induced in the area covered by the beam is low unless the laser beam strikes a discontinuity indication, in which case a larger amount of fluorescent (visible) radiation is emitted. The fluorescence is detected by a simple phototube equipped with a filter to stop blue or ultraviolet radiation from the illumination source but permit the visible fluorescent light to pass. The signal takes the form of pulses that are then processed through a computer or other electronic equipment. A program to discriminate rejectable anomalies from background and initiate rejection action, is necessary. Pattern recognition and anomaly classification are possible.

Comparison of Laser and Television Scanning Systems

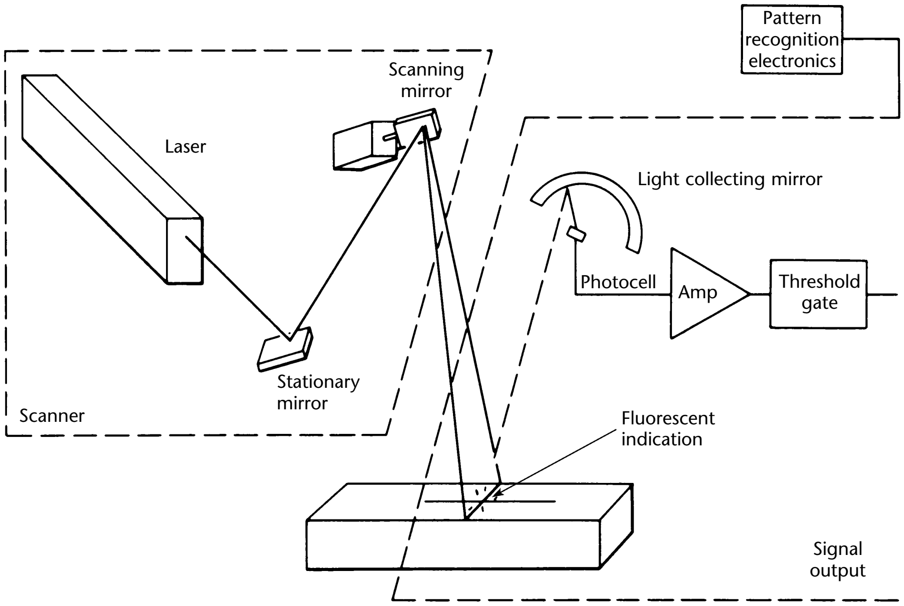
The laser scanner is the newer and better type of scanning system for the following reasons.

1. The laser beam provides much more intense excitation illumination in the area covered than an ordinary ultraviolet lamp, so the fluorescence excited is very bright and easily detected.
2. The detail discrimination is much better because a phototube can handle a larger contrast ratio than a television tube.
3. There are no depth of field problems because the fluorescent light is not imaged at any point. This makes part positioning much less critical than if an image must be formed.
4. The electronic circuitry required for the detector is much simpler and more troublefree than with a television system.

Flying Spot Laser Scanning of Fluorescent Liquid Penetrant Indications

A technique has been developed that uses a flying spot laser for detection of fluorescent liquid penetrant indications. As shown in Fig. 39, this system consists of three functional parts: a scanning laser, a photodetector and a data processor. The scanning laser causes a laser beam to move across the part to be inspected. When this exciting laser beam strikes fluorescent liquid penetrant materials retained in discontinuities open to the test object surface, a pulse of different wavelength light is generated. The photodetector converts this fluorescence pulse into an electrical signal. The data processor operates on these signals and

FIGURE 39. Functional components of flying spot laser scanning system for fluorescent liquid penetrant test indications.



determines if they represent discontinuities through pattern recognition techniques and signal intensity measurements.

The flying spot laser scanner with pattern recognition capabilities simulates a human operator for testing of fluorescent discontinuity indications in a large number of applications. The system has very large depth of field because system resolution is determined by the scanning beam cross section and not by large aperture optical imaging devices (as in the case of television devices). High density of excitation energy is available with a laser and extremely high sensitivity photodetectors will allow pickup of weak fluorescent liquid penetrant indications. The optical pattern recognition system simulates the human interpretation in that it recognizes shape and size for discontinuity determination and generally ignores background fluorescence effects.

Characteristics of Laser Beam

The scanner portion of the system contains a helium-cadmium (He-Cd) laser operating at a deep blue wavelength of 441.6 nm. The dyes and pigment used in fluorescent liquid penetrant testing materials will absorb blue as well as ultraviolet excitation and emit visible yellow light. Thus, a blue excitation source may be used rather than the familiar ultraviolet radiation. The blue has to be filtered out for visible interpretation, whereas ultraviolet is invisible. Photosensitive devices generally will detect both wavelengths so filters are required when either wavelength is used for automatic testing. The laser beam diameter is near 1 mm (0.04 in.) and the output power is nominally 15 mW. The laser beam divergence is very small, so generally no optical components are required. It is possible to use a lens or combination of lenses to reduce the beam diameter to a very small value and hence increase system resolution.

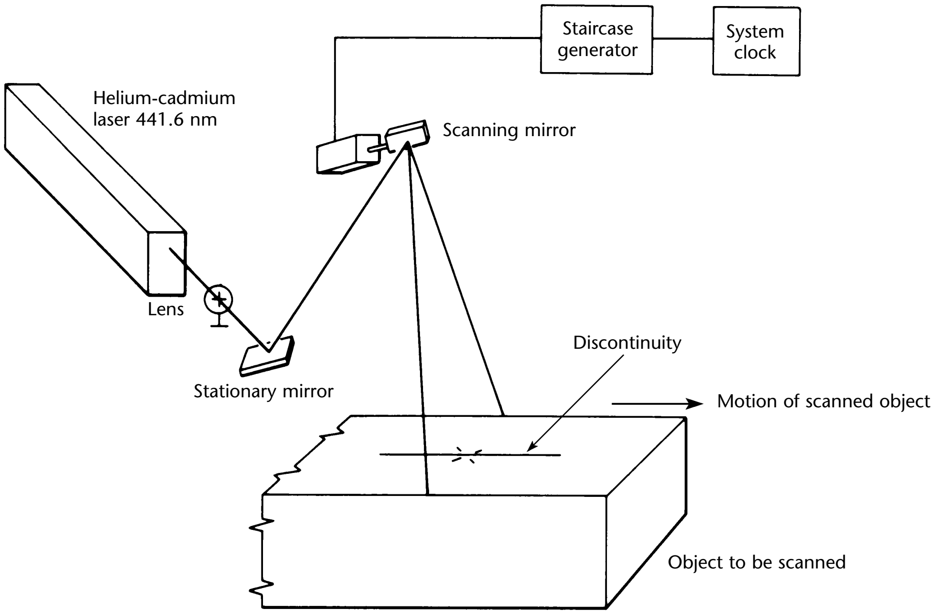
Laser Beam Scanning Motions

Figure 40 shows the arrangement of the components of the laser scanning system. The laser beam is directed to a scanning mirror that causes the beam to move back and forth across the test object and form, in effect, a line scan. The waveform used to drive the scanning mirror motor is a staircase function derived from the system clock. Thus, each position of the scanning mirror can be directly related to a given clock pulse. The scan waveform is adjusted as required. The scan motion is at right angles to the motion of the object being inspected so the entire surface is covered by the scanning beam.

Signal Detection and Analog Signal Processing

As the beam strikes the retained fluorescent material, it emits a pulse of yellow fluorescent light. Some of this light strikes the face of the photocell and is

FIGURE 40. Laser scanning arrangement for line scanning of test objects in motion.



converted into an electrical pulse signal. The amplitude of this pulse is directly related to the intensity of the pulse of yellow light. The phototube pulses are amplified and filtered and used to activate a threshold circuit. The threshold circuit output signal is a digital pulse used as input to the pattern recognition circuit.

These pulses may be used to generate a television image if desired, although this generally has no value in the automatic mode of operation. The beam position information plus the phototube analog output is all that is required for a television image. It is important to note that no optical lenses are used to generate this image. The image resolution depends on the beam cross section dimension. Therefore, the depth of field of the scanning system is very large because the laser beam has very small divergence.

Pattern Recognition of Fluorescent Liquid Penetrant Indications

Recognition of significant test indications is generally the most complex part of the automated scanning system. Pattern recognition is accomplished by one of three approaches: (1) an optical technique, (2) a hardwired digital process or (3) a microprocessor or digital computer.

Optical Pattern Recognition

In optical pattern recognition, a line shaped laser beam is oriented in the direction of the discontinuity (Fig. 41). This illustrates the formation of a line of light by use of anamorphic optics, that is, a cylinder lens that focuses the collimated light to a line parallel to the lens axis and maintains the beam's cross sectional width in the orthogonal direction because it does no focusing in that axis. A phototube detects and integrates the fluorescent flash that occurs when the exciting beam is coincided with the discontinuity. This is the simplest approach but it requires good parallel alignment of the beam and discontinuity and limits the system flexibility. A similar result can of course be obtained by laser beam scanning and electronically integrating the photocell output. This has the advantage of large depth of field but requires the more complex scanning arrangement. Figure 42 shows a laser scanning technique in which the line shaped laser beam illuminates the entire length of a parallel fluorescent indication of a linear discontinuity. Far less sensitivity would result if the beam and discontinuity were not parallel (Fig. 43). A

FIGURE 41. Optical pattern recognition of straight, linear fluorescent test indications.

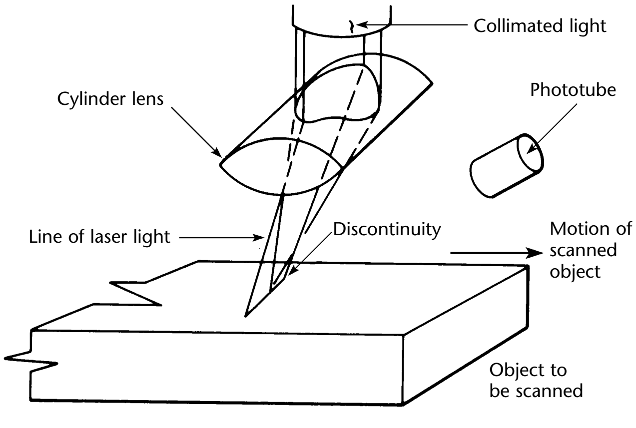


FIGURE 42. Example of test situation producing sharp electrical signal pulse from phototube detector: straight, linear fluorescent test indication is parallel to line focused scanning laser beam.

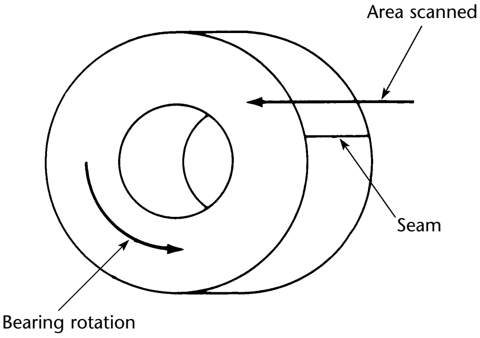
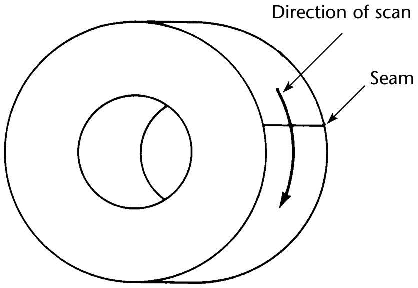


FIGURE 43. Example of test situation that produces reduced signal pulse levels from phototube detector when straight, linear test indication is perpendicular to line focused laser scanning beam.



parallel line of exciting radiation results in a form of optical integration of fluorescent light from the entire length of the indication. Similar slits of excitation illumination might conceivably permit optical pattern recognition for straight line fluorescent test indications in other orientations.

The background fluorescence usually consists mainly of the foggy yellow glow and a few isolated bright spots. In addition to this, indications that have many characteristics of discontinuities are frequently present. This includes indications caused by tool marks, scratches, thread crests and valleys, hole edges and others. A trained operator will ignore these and, if possible, so should the automatic system. This will increase the system complexity. In any case, most applications do require some sort of pattern recognition. This might range from the previous coincident light approach to a digital computer with pattern recognition algorithms programmed into its general operation.

Hardwired Digital Processor for Pattern Recognition

The hardwired digital processor for pattern recognition consists of multiple circuit boards, some consisting of several logic functions. The basic part of this portion is a large memory array; multiple bit elements are used. Each scan is adjusted for zone width. The input discontinuity signal is gated and fed into the array. The system clock pulses that were used to form the scanning waveform are also used as shift pulses and the discontinuity signals shift along in synchronism with the scanning beam. Auxiliary registers are arranged at the output of each array. These are grouped together to form a two-dimensional array.

Digital Computer Pattern Recognition

The digital computer signal pattern recognition technique is the most flexible because patterns can be changed by using different software programming. New programs are easy to input and output and may be continuously modified and improved as experience is gained. The software philosophy used is one of adjacent cell linking. If test indications (stored numbers in memory locations that are an analog of their location on the part) can be linked to adjacent indications, the probability is high that these are caused by discontinuities. The greater the number of links, the greater the discontinuity probability.

Flying Spot Fluorescent Liquid Penetrant Laser Scanning

The purpose of the flying spot laser system is to automate and speed detection of fluorescent indications and discontinuities. High volume testing of steel billets, roller bearings, welded pipe, automotive parts and the like is feasible. Inherently, the system minimizes the noise or confusion of surrounding indications and produces a discontinuity image that is more readily discernible.

The data processor operates on these signals and is programmed to determine through pattern recognition and intensities if a discontinuity has been detected. Automatic sorting and handling then takes over.

The advantages of human expertise in observation and interpretation are simulated through the system's attempts to recognize both shape and size in discontinuity determination while ignoring weaker signals from background indications. The computer can be programmed to recognize and act on different discontinuity patterns. The system has a large depth of field capability because resolution is determined by the scanning beam cross section and not by large aperture optical imaging devices, such as in television. In its broadest application, the system can be programmed to sort and assemble potentially discrepant indications and present them to the human operator for evaluation.

Although automated readout has been demonstrated to approach human capabilities in specific applications, the pattern recognition capability of the human operator exceeds that of automated readout systems. In addition, the false call rate of automated systems exceeds that of a human operator. Human intervention is necessary for critical applications.

References

1. ASTM E 1417, *Standard Practice for Liquid Penetrant Examination*. West Conshohocken, PA: American Society for Testing and Materials (1995).
2. Wald, G. "Alleged Effects of the Near Ultraviolet on Human Vision." *Journal of the Optical Society of America*. Vol. 42, No. 3. New York, NY: American Institute of Physics (March 1952): p 171-177.

8

CHAPTER

Comparators and Reference Panels

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PART 1. Cracked Metal Comparator Blocks

Simulating Cracks Found in Components

To conduct investigative programs on liquid penetrant tests, cracked test standards are needed. Panels containing networks of cracks of varying sizes are useful in establishing qualitatively the effect of liquid penetrant variables on general liquid penetrant effectiveness. A desirable characteristic of the cracks in cracked standards is that the size of the cracks be representative of cracks encountered in production parts or components. Of particular importance is the width of the cracks, because this dimension has an important effect on the ease with which a liquid penetrant enters the crack. During early experiments to artificially produce cracks simulating real process induced cracks, several production aircraft parts that had been rejected because of process induced cracks were examined to determine the width of the cracks. A summation of the crack widths in production aircraft parts is given in Table 1.

Various procedures have been tried to produce cracks that would be representative of process induced or service induced cracks. Some of those procedures applied to a variety of materials are described below.

Specimen with Low Cycle Fatigue Cracks

Concept of Fatigue Crack Specimens

To emulate small, tight fatigue cracks that might occur in gas turbine engine rotating parts, specimens have been manufactured with reduced fatigue cracks in each. High strength nickel and titanium alloys have been the materials of choice for these specimens because these are the materials used in the engines. The intent is not only to grow single cracks in each specimen but also to control the crack growth by using precise measurement techniques to gage the length of each crack after intervals of cyclically loading the specimen. Assuming a length-to-width aspect ratio of two to one leads to cracks with predictable depths. Thus, the performance of a liquid penetrant system can be precisely monitored.

One specialized application of this type of specimen has been the classification of liquid penetrant systems by the United States Air Force for inclusion in the qualified products list, QPL-AMS-2644.[1] For this application five specimens are used, each having a crack with a length in the range of 0.5 to 1.5 mm (0.02 to 0.06 in.). In this application, this type of specimen provides a source for a single unambiguous fluorescent liquid penetrant indication that could be analyzed. The set is processed according to standardized procedures specified in AMS 2644.[2] The luminance of each fluorescent indication is measured with a photometer. The sum of the measured luminances is then compared to similar sums from a set of reference liquid penetrant systems that produce a linearly increasing range of luminance values for the crack set. The reference system that produces the lowest sum produces no indication from the smallest crack.

It should be pointed out that even though indication luminance is used in this application to assign sensitivity classifications to liquid penetrant systems, luminance is not an absolute measure of system sensitivity. As discussed elsewhere in this volume, lack of control of the liquid penetrant processing variables, not the least of which is precleaning, can produce variations in brightness that do not correlate with the ability of a liquid penetrant system to indicate a small crack.

TABLE 1. Width of process induced cracks in production parts.

Material	Crack Origin	Crack Width µm	Crack Width (in.)
Titanium	forming cracks	7[a]	(0.0003)[a]
	unknown	17[b]	(0.0007)[b]
Aluminum	forging laps	2 to 50[a]	(0.0001 to 0.002)[a]
	unknown	20 to 90[b]	(0.0008 to 0.0035)[b]
Stainless Steel	welding defects	2[a]	(0.00008)[a]

a. Measured metallographically after cross sectioning.

b. Measured directly with electron microscope without cross sectioning.

Manufacturing of Low Cycle Fatigue Specimen[3-6]

The specimen material can be rolled or forged. In the former case, annealing is recommended to eliminate residual surface stresses. The approximate size of each specimen, 150 × 25 × 6 mm (6.0 × 1.0 × 0.25 in.), was chosen for convenience in manufacturing and liquid penetrant testing. However, the size of each specimen set should be uniform. One side of each specimen is arbitrarily chosen as the face in which a fatigue crack will be grown. The center section of this surface is smoothed by sanding followed by polishing with aluminum oxide powder with 3 µm (1.2×10^{-4} in.) particle diameter. The edges along the 150 mm (6.0 in.) dimension are slightly rounded to eliminate stress points that could result in undesired crack initiation during fatigue loading.

Various methods have been used to initiate fatigue cracks, including electrical discharge machined slots, mechanical notches in various forms and spot welds (thermal cracks). Spot welding has been used in some studies to produce a stress riser to initiate crack growth. Spot welds are easy to produce and almost always result in the initiation of a crack. However, extreme care must be taken to avoid multiple initiation or branching. Through experimentation, a heat and time setting for the welding equipment is found that will produce an area of damage about 2.5 mm (0.1 in.) in diameter. This damage consists of an area of recast metal and the surrounding heat affected zone. With this degree of damage, fatigue cracks have been found to initiate and grow in titanium (Ti-6Al-4V) to a detectable size after 20 000 to 50 000 cycles.

Typically these low cycle fatigue cracks are generated at room temperature using a load frame fitted with a three point bending fixture. A computer controlled servo hydraulic system is used to generate sine wave cyclic loading. In one setup a ratio $R = \sigma_{min}/\sigma_{max} = 0.1$ (where σ = stress) has been used with the maximum load set to produce a bending stress of approximately 80 percent of the material yield stress. For tight fatigue cracks, a stress level below 70 percent has been recommended.

During fatigue loading the crack starter defect is monitored with a microscope. Once a crack is detected, the length is carefully monitored in place or with a separate microscope. The measurements can be more accurate if they are made under bending stress to open the cracks. If the crack length falls within the target range, loading is discontinued and the cracked surface is machined to remove the crack initiation damage site. After final machining, the crack is stressed open again and measured to determine the final crack length. Additional machining can reduce the depth of the crack if desired. Final depth can be estimated from the originally assumed two-to-one length-to-depth ratio and the amount of material removed during machining. A light etch may be necessary after machining, even if the specimen has been stressed to open the crack for measurement. Etching is always recommended for panels to be used for liquid penetrant testing.

Occasionally two cracks will initiate. This may not be a problem if their included length is within the target range because they will eventually join to produce a long shallow crack with a length-to-depth ratio greater than two-to-one. Such cracks can facilitate the evaluation of certain characteristics of liquid penetrant systems. For example, a water washable liquid penetrant system may not detect such a crack as well as a postemulsifiable system.

Disadvantages of Low Cycle Fatigue Crack Specimens

These specimens are relatively expensive to manufacture. Because they are generated in fatigue, they are very tight and therefore difficult to clean between repeated processing. Ultrasonic cleaning in chlorinated solvents has been successful but chlorinated solvents have fallen into disuse because of effects on the ozone layer.

As of 1999, fatigue cracks were the only test specimens that could be used to satisfy fracture critical requirements of the National Aeronautics and Space Administration, and were used to classify the sensitivity of fluorescent liquid penetrant in accordance with SAE AMS 2644.[2]

Quench Cracked Aluminum Comparator Blocks

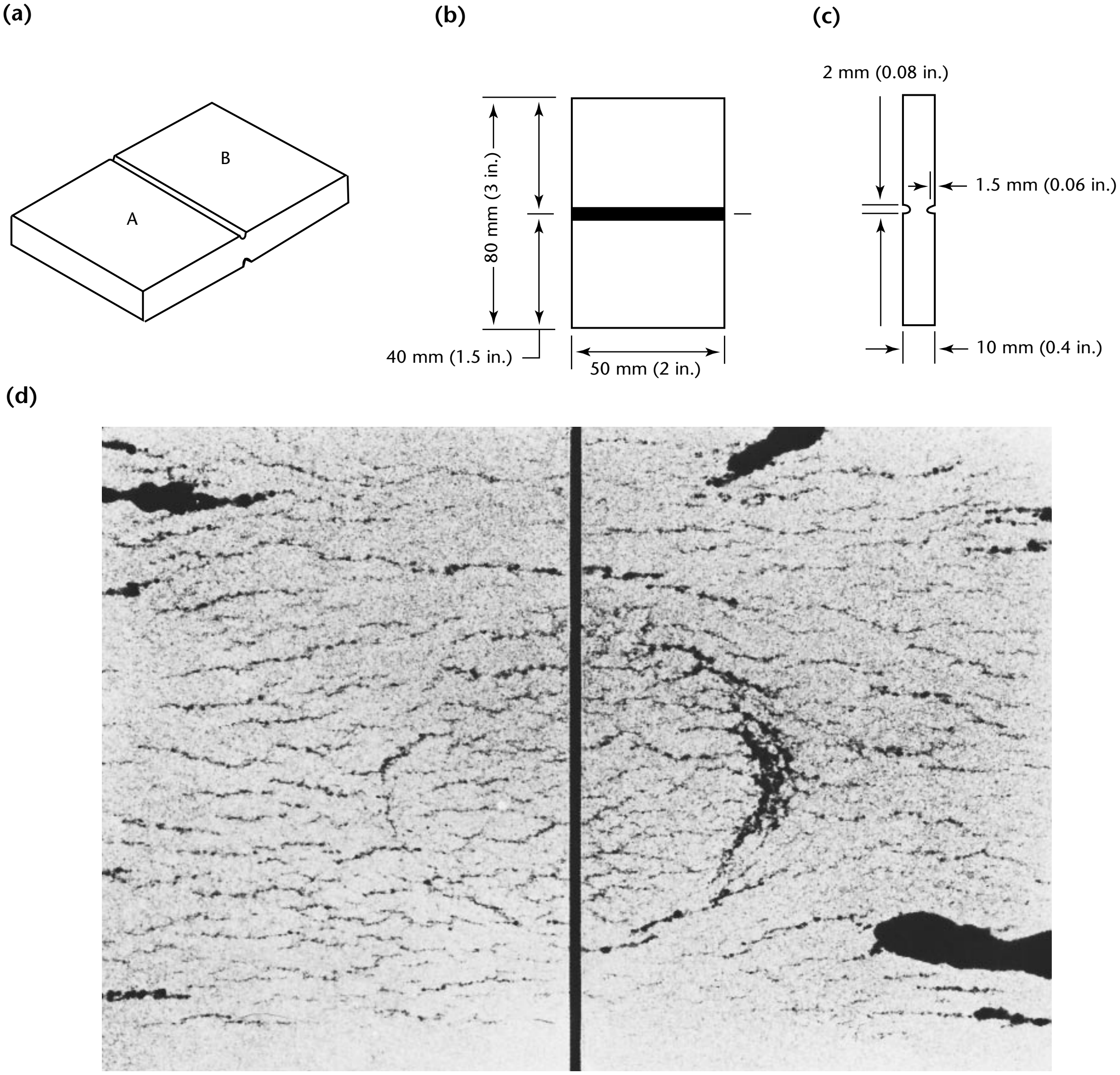
A tool that has been used to evaluate liquid penetrants and to judge the continued serviceability of a liquid penetrant testing system is the quench cracked aluminum comparator block. The cracked aluminum test block is described in both the *ASME Boiler and Pressure Vessel Code* (Part V, Article 6)[3] and in SAE AMS 2644.[2]

It is important to note that quench cracks rarely provide discrimination necessary for modern liquid penetrant materials and are not referenced in fracture control specifications. The following discussion of quench crack panels is included primarily for historical reference.

Preparation of Quench Cracked Aluminum Blocks

The liquid penetrant comparator panel (Fig. 1) is made from as-rolled 2024-T3 aluminum, as required in the applicable codes or specifications (for example, AMS 2644[2]), when smooth surfaces are desired. The grain direction of these panels is parallel to the largest dimension. To simulate surface roughness on test objects, a light surface machining operation may be used, if desired. Using a 510 °C (950 °F) temperature indicating material,[8] the panel is heated and then quenched in cold water. The temperature indicating material is applied in the exact center of the block in an area about 25 mm (1 in.) in diameter. A Bunsen burner flame is allowed to impinge on the underside. Quenching in cold water to induce cracking takes place immediately on full and complete color change of the temperature indicating material. Often, several repeat heating and quenching operations on the same block are needed to produce adequate crack patterns. A groove is then machined across the center

FIGURE 1. Cracked aluminum penetrant comparator block: (a) schematic; (b) planar view; (c) cross section; (d) photograph of liquid penetrant processed cracked aluminum block, sometimes referred to as liqiud penetrant comparator, used to compare performance of two different visible dye liquid penetrant processes. Dimensions are for guidance only and are not critical.



of each face of the panel, dividing it into two 50 × 40 mm (2.0 × 1.5 in.) sections (see Fig. 2).

A distinguishing identification mark should be inscribed on each section of the block to act as a reference for later determination of which material or technique was applied to different sections. A pencil mark is not satisfactory for this identification because it will usually be removed during processing. If it is a production practice to use acid or alkaline etching of parts before liquid penetrant testing to remove corrosion products, then cracked aluminum alloy blocks should be similarly etched for valid results.

Procedures for Cracked Aluminum Liquid Penetrant Comparator Block

In use, test liquid penetrant is placed on one section and standard liquid penetrant on the other section of the cracked aluminum block. The groove separates the two test sections. After liquid penetrant dwell, removal and developing, following established procedures, the two sections are usually compared for completeness of discontinuity patterns, sharpness of discontinuity delineation, color, general visibility and similar characteristics of interest. Either or both faces of the cracked aluminum panel may be used, as both top and bottom sides will have crack patterns. See elsewhere in this volume on the care and use of these panels.

Interference between Different Liquid Penetrants on Cracked Comparator Block

Two different liquid penetrants, coated on the separate sections of the cracked aluminum panel but still adjacent to each other, have an effect on each other even though the sections are separated by the groove. If the difference in surface tension of the liquid penetrant liquids is extreme, the liquid penetrant with higher surface tension is repelled from the center toward the outer edge of the panel. The other liquid penetrant with lower surface tension may cross the groove during the dwell period. Liquids that affect each other in this way should be compared on a panel cut into two separate sections, not merely divided with a groove. The sections should be well separated during the liquid penetrant dwell. Cutting the panel into sections facilitates the different processing techniques, such as different cleaning techniques or different developing agents. If high temperature or low temperature performance of a liquid penetrant is to be compared to performance of a standard liquid penetrant at ambient temperature, it is almost essential for the panel to be cut into two separate sections (see Figs. 2 to 4).

FIGURE 2. Aluminum block, cracked by heating and quenching, demonstrates performance of water washable fluorescent liquid penetrant without developer.

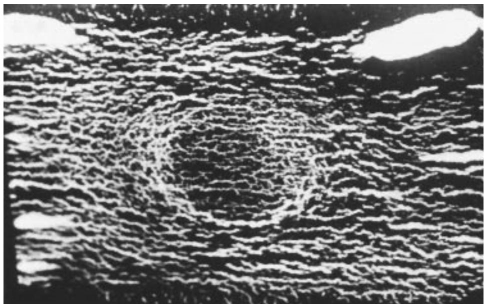


FIGURE 3. When comparing liquid penetrant performance at different temperatures, the liquid penetrant comparator is cut into equivalent sections for processing. This photograph illustrates two fluorescent liquid penetrant systems, one at 177 °C (350 °F), left, and the other at 27 °C (80 °F), right.

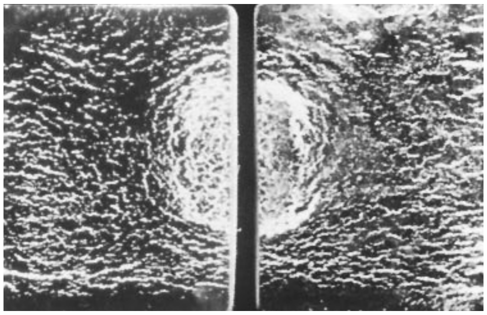
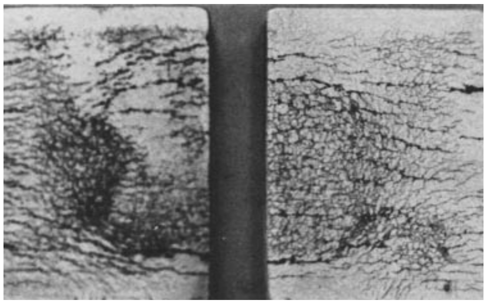


FIGURE 4. Liquid penetrant comparator divided into two separate equivalent sections to compare performance of same visible dye liquid penetrant and nonaqueous developer at 121 °C (250 °F), left, and 27 °C (80 °F), right.



Limitations of Cracked Aluminum Liquid Penetrant Comparator Blocks

The quench cracked aluminum block contains large and medium sized cracks that are easily detected by all but the lowest sensitivity materials. For this reason, little difference between medium and high performance liquid penetrant test materials is detected on these pieces. Any noticeable sensitivity difference becomes a gross difference in actual performance, so these quench cracked aluminum pieces are of limited usefulness.

The artificial cracks in the aluminum blocks are nonuniform by nature. It is impossible to make two blocks identical. Some are more effective than others in indicating differences in materials. It is important, therefore, to make a series of tests before reaching conclusions if results are critical.

Theoretically, discontinuity patterns of the two sections of a cracked aluminum block should be uniform or identical but although there should be similarity, the two sections will differ in crack patterns. In some cases, the difference is sufficient to make the panel of little value as a means of comparison. It is important to recognize a faulty cracked aluminum test panel as such and not misinterpret the poor reading as a faulty liquid penetrant. Only new panels should be considered to be valid comparators.

Adequate cleaning of cracked aluminum blocks to make them fully reusable is not possible. This is especially true when panels have been exposed to red visible dyes. Once used for visible dye liquid penetrants, panels should never be used for fluorescent dye liquid penetrants because traces of visible dye liquid penetrant seriously diminish the performance of fluorescent liquid penetrant. Techniques of cleaning include hot alkaline cleaners, ultrasonic cleaning with solvent, vapor degreasing and repeating the heat quench cycle. No cleaning technique is completely satisfactory. However, some basis for judging performance should be obtainable if a series of three or more used but cleaned panels are included in the evaluation. Cleaning and reuse of panels are discouraged and reuse of cracked aluminum test panels more than three times should be prohibited. Because aluminum surfaces oxidize in the atmosphere, comparison test results can vary considerably between a new block slightly etched and a similar block allowed to remain exposed to the atmosphere for 30 days, for example.

When supposedly identical liquid penetrant materials are being compared on these blocks, differences in crack indications may be quite subtle. Examination of the blocks and interpretation of results should be done by experienced personnel.

Quench crack panels rarely provide necessary discrimination for modern liquid penetrant materials and are not referenced in fracture control specifications.

Renewal of Quench Cracked Aluminum Blocks

Best results are always obtained when new test blocks are used. Some contaminating effect is likely to occur whenever tests are being made. Blocks should never be reused without renewing them according to one of the procedures outlined below. A comparison should not even be made on the reverse side without first renewing the entire block. In general, blocks renewed more than three times are no longer reliable. One renewal procedure uses solvents and heat in the following sequence.

1. Vapor phase degrease.
2. Scrub with a stiff brush, soap and water.
3. Soak in acetone, at least overnight.
4. Rinse with water.
5. Heat slowly with a gas burner to 425 °C (800 °F).

Use temperature indicating material and quench in cold water. Reheat moderately to drive off any water in cracks and allow to cool to room temperature.

A much less time consuming method of renewing cracked aluminum test blocks is ultrasonic cleaning in solvent. After ultrasonic cleaning, the cracked aluminum blocks are dried, are sprayed with nonaqueous developer and are inspected with illumination suitable for revealing any traces of residual liquid penetrant. Blocks are recleaned if any liquid penetrant is visible.

Alternate Procedure for Producing Cracked Aluminum Comparator Blocks

A second procedure used to produce 10 × 75 × 100 mm (0.4 × 3.0 × 4.0 in.) 2024-T3 aluminum panels involved heating in a furnace to 540 °C (1000 °F) for 30 min and quenching in ice water. These specimens were quenched individually and checked after each quench to obtain an acceptable crack pattern with a minimum number of severe cracks extending through the specimens. The specimens that did not show an adequate crack pattern after twelve cycles of heating and quenching were then heated with a torch and quenched in the same manner as the 50 × 75 mm (2 × 3 in.) specimens until an acceptable crack pattern was obtained. These panels, cut from bar stock, represented an end grain condition — specifically, the grain direction was parallel to the 10 mm (0.4 in.) thickness dimension.

Characteristics of Cracks Induced by Heating and Quenching 2024-T3 Aluminum Blocks

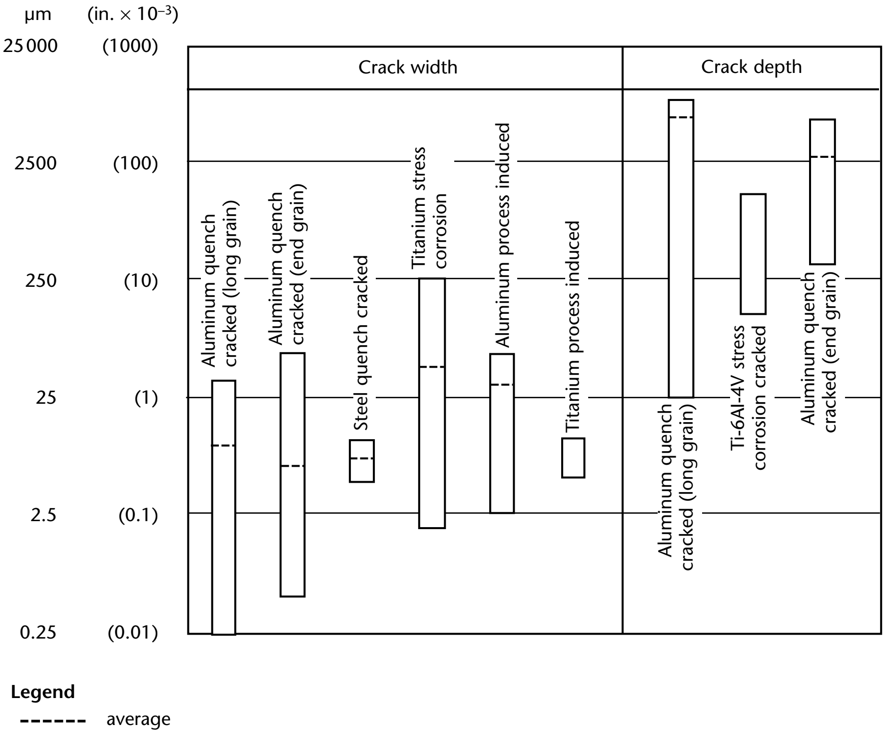
Crack patterns were produced using the two quench cracking procedures. Several cycles of heating and quenching were required to crack the specimens. Typical crack dimensions are shown in Fig. 5. The ranges of cracks widths were about the same for the two grain directions.

Also shown in Fig. 5 are the width dimensions of several naturally occurring process induced cracks in aluminum. These cracked parts were rejected from a production liquid penetrant testing facility. It can be seen that the widths of laboratory induced quench cracks were of the same general magnitude as some process induced cracks. Consequently, the laboratory quench cracked test standards contained a range of cracks that simulated naturally occurring cracks. When this is the case, test results obtained from the test standards in liquid penetrant programs apply directly to normal production inspection. However, the correlation between cracks generated in the laboratory and cracks generated in the manufacturing process must be verified for each situation — involving different material, part, configuration, manufacturing process etc.

Experimental Procedure for Producing Stress Corrosion Cracks in Titanium Comparator Blocks

Procedures were evaluated for producing 6.3 mm (0.25 in.) thick cracked Ti-6Al-4V titanium alloy liquid penetrant standards. The 50 × 125 mm (2 × 5 in.) specimens were initially ground to produce a surface finish of about 0.8 mm (0.03 in.) root mean square using a 60 mesh grit wheel 300 mm (12.0 in.) in diameter and 25 mm (1.0 in.) wide, 33 rotations per second (2000 rotations per minute) wheel speed, 0.05 to 0.07 mm (0.002 to 0.003 in.) down feed and about 2.5 mm (0.10 in.) cross feed per pass. The work piece was flooded with coolant during grinding.

FIGURE 5. Comparison of sizes of process induced and laboratory induced cracks in aluminum, titanium and steel.



(Note that the grinding of titanium or its alloys can result in oxidation and metallurgical damage at the roots of grinding grooves and can induce residual stress in surface layers.)

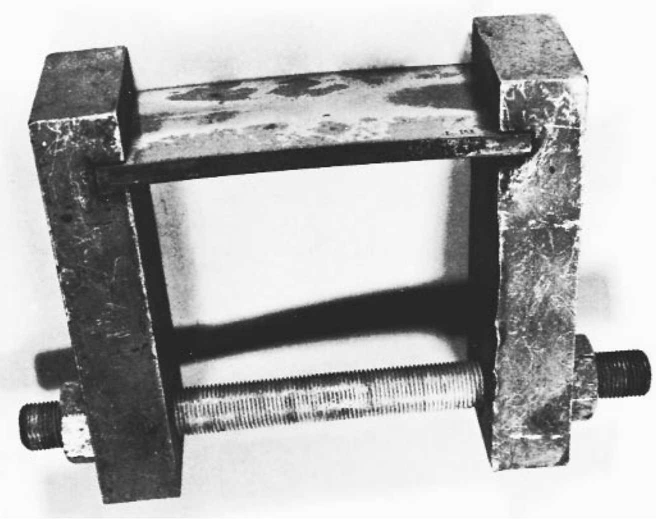
Next, the specimens were placed in the fixture shown in Fig. 6 and loaded to 20 to 35 percent of the yield stress. The loaded specimens were put into a solution of anhydrous (water free) methanol and table salt while still in the fixture. A satisfactory stress corrosion crack pattern developed in 6 to 24 h during exposure of methanol and salt.

Characteristics of Cracks Produced by Stress Corrosion of Titanium Alloy

The crack pattern produced by the methanol salt technique was satisfactory in that it consisted of a network of cracks of varying size. Similar crack patterns were produced in 31 specimens using this procedure to verify that the cracking procedure was reproducible. It is suspected that the residual stress pattern induced by harsh grinding is important to the cracking mechanism, although this aspect has not been investigated extensively.

It was found during the methanol salt test that, after initial cracking occurred, longer exposure or an increase in stress only resulted in fracturing the specimen. The original crack pattern was not beneficially altered by varying the exposure time or stress. As can be seen from Fig. 5, the stress corrosion cracks are of the same general magnitude in width as the cracks induced in manufacturing processes.

FIGURE 6. Fixture for stressing specimens.



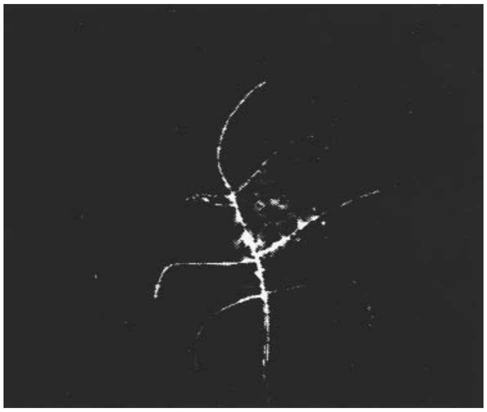
Experimental Procedure for Producing Quench Cracks in AISI 4340 Steel Comparator Blocks

Although ferromagnetic production parts are normally inspected using the magnetic particle test method, liquid penetrant testing is often used as a supplementary test method. Consequently, procedures were developed for producing cracked steel liquid penetrant comparator blocks. (Note that liquid penetrant tests should precede magnetic particle tests.)

The procedure for quench cracking 6.3 mm (0.25 in.) thick AISI 4340 steel was as follows. The 6.3 × 50 × 76 mm (0.25 × 2 × 3 in.) and 19 × 90 × 300 mm (0.75 × 3.5 × 12 in.) panels were austenitized at 800 to 840 °C (1475 to 1550 °F) in a furnace and quenched in cold water. The final hardness of the material was Rockwell C 51 to 53.

Cracked standards were also successfully produced from 19 mm (0.75 in.) thick 4340 steel by heating the material in a furnace to 800 to 840 °C (1475 to 1550 °F) followed by water quenching. Acceptable standards were produced from 6.3 mm (0.25 in.) thick 4340 steel by heating with a hydrogen torch. The material was heated nonuniformly to 980 °C (1800 °F) and then water quenched. To crack the 6.3 mm (0.25 in.) thick 4340 steel, it was necessary to heat to 980 °C (1800 °F) and quench several times. A photograph of typical cracks is shown in Fig. 7. The width of the cracks in the quench cracked 4340 steel panels varied from 5 to 15 µm (0.0002 to 0.0006 in.).

FIGURE 7. Typical quench cracks in 6.3 mm (0.25 in.) thick 4340 steel are revealed by high performance water washable liquid penetrant with nonaqueous wet developer.



Experimental Procedure for Producing Grinding Cracks in Steel Comparator Blocks

Grinding cracks are sometimes produced during fabrication. Several steels were hardened and then ground severely to produce this crack condition. The hardening procedures used were as follows.

1. A bar of 4340 modified (300M) steel (AMS 6419), 4.8 mm (0.19 in.) thick, was austenitized at 870 ± 14 °C (1600 ± 25 °F). Then it was quenched in oil at 24 to 60 °C (75 to 140 °F). The specimens were not tempered and the as-quenched hardness of the material was Rockwell C 58.
2. D6AC steel bar (MIL-S-8949), 22.4 mm (0.88 in.) thick, was austenitized at 900 ± 15 °C (1650 ± 25 °F) and oil quenched to 90 °C (200 °F). The specimens were not tempered and the as quenched hardness of the material was Rockwell C 55.
3. AISI 1018 and AISI 4310 steels were carburized in preparation for grinding.

Each AISI 1018, AISI 4130, AISI 300M and D6AC specimen was then ground severely to produce grinding cracks by the following techniques. An aluminum grinding wheel was used with a surface velocity grinding speed of 30 $m \cdot s^{-1}$ (6000 $ft \cdot min^{-1}$), with a commercial coolant.

The AISI 1018 and AISI 4130 steels were successfully cracked by carburization and grinding. Successful cracked liquid penetrant comparators could not be produced in 300M and D6AC steel by grinding.

PART 2. Surface Cracked Nickel-Chrome Liquid Penetrant Test Panels

Description of Panels

The cracked chrome plated panel was developed for the United States Air Force under contract study programs. This type of panel is made by burnishing a brass or copper panel to a mirror finish, then electroplating a thin layer of nickel followed by a layer of chrome on this polished surface. The chrome layer is brittle and cracks can be generated in it by bending the panel over a curved form. Crack depth is controlled by the thickness of the layer of chrome plating but there is no control over crack width. Crack depth may range from 1 or 2 µm (4×10^{-5} or 8×10^{-5} in.) to nearly 50 µm (0.002 in.). Crack width is determined by the degree of deformation of the panel during bending and straightening. The width varies from a fraction of a micrometer (less than 4×10^{-5} in.) for thin chrome layers) up to about 2 µm (8×10^{-5} in.) for chrome layers having a thickness in the range of 50 µm (0.002 in.). By following certain procedures, the cracked chrome plated panels can be manufactured to an excellent degree of reproducibility.

Crack Sizes in Nickel-Chrome Test Panels

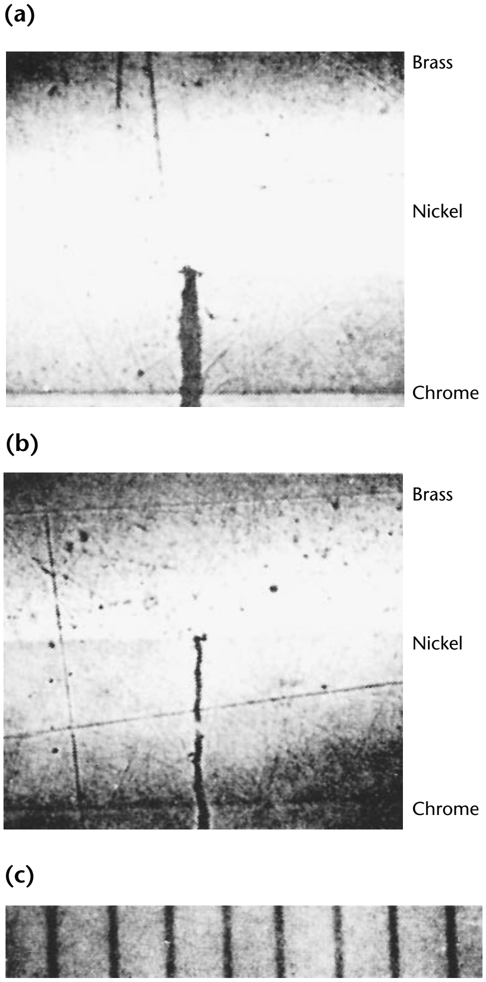
Variations in the composition of the plating baths and plating techniques determine the type and size of cracking in the nickel-chrome test panels: (1) coarse crack panel with cracks measuring about 10 µm (0.0004 in.) wide and 50 µm (0.002 in.) deep; (2) medium crack panel with cracks about 2 to 3 µm (8×10^{-5} to 1.2×10^{-4} in.) wide and 40 µm (0.0016 in.) deep; and fine crack panel with cracks about 0.5 µm (2×10^{-5} in.) in width.

Figure 8 shows a magnified cross section of the plated portion of a medium crack panel. The nickel-chrome sensitivity panels of Fig. 9 lend themselves to reuse with proper cleaning. The same panels were used throughout a test program; it was reported that, even after multiple use in tests, the panels showed no evidence of change in crack size.

Characteristics of Cracked Chromium Plated Test Panels

The cracked chromium plated reference panel provides a surface containing cracks of known dimensions and these discontinuities fall within a range of magnitudes close to the limit of the

FIGURE 8. Magnified cross section of medium crack nickel-chrome sensitivity panel: (a) crack width = 3.3 µm (1.3×10^{-4} in.); (b) crack width = 2.3 µm (9×10^{-5} in.); (c) stage microscopic gage with scale where 1 division = 10 µm (4×10^{-4} in.).



ability of test liquid penetrants to reveal them. The chromium plated test panels are useful for evaluation of a liquid penetrant system's discontinuity detection performance. They can provide useful results in qualitative side-by-side comparisons of liquid penetrant performance, as well as evaluation of developer performance (see Fig. 8).

Generally, tests made with cracked chromium plated test panels do not provide useful information on the background color or fluorescence caused by surface roughness of test parts or on the ability of a liquid penetrant to reveal microcracks in the presence of severe background porosity indications.

Application of Nickel Chrome Test Panels in Evaluating Liquid Penetrant Systems

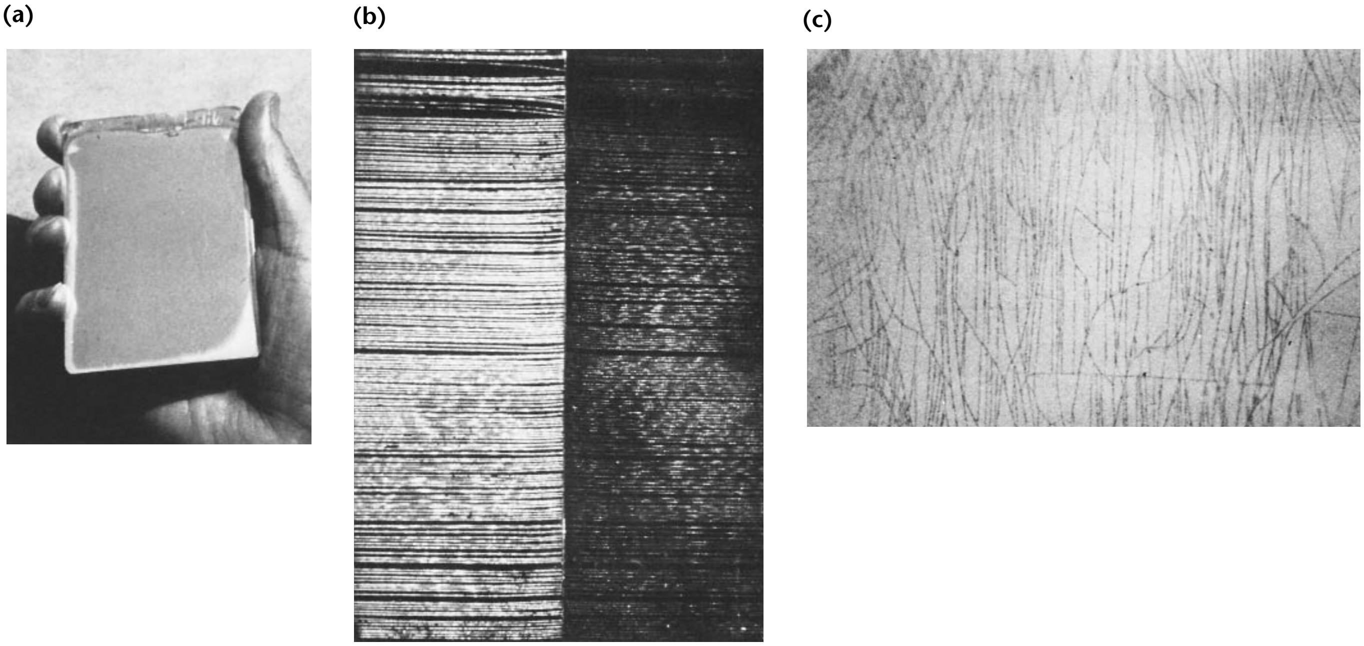
Because the nickel chrome sensitivity panel can be used over and over again, it is possible to compare one liquid penetrant system to another sequentially by first testing one system and accurately recording results and then, after cleaning and drying, testing the second system. Panels are selected as follows.

1. The coarse crack panel is primarily used for visible dye liquid penetrants and low sensitivity fluorescent liquid penetrants.
2. The medium crack panel is used for medium and high fluorescent liquid penetrants.
3. The fine crack panel is used for very high sensitivity fluorescent liquid penetrants.

A simultaneous comparison test of two different liquid penetrant systems can also be made by dividing the chrome panel into two equal sections by means of a longitudinal wax line or narrow vinyl tape. One liquid penetrant is applied to one half and a second on the other half of the panel. Using this technique, it is possible to obtain a side-by-side comparison of two liquid penetrants or process materials. However, evaluation of variations in processing times and techniques is not so feasible. Liquid penetrant systems should be compared not only as to the completeness of the discontinuity patterns but as to brightness and legibility of indications on the cracked chrome test panels.

Taper plated nickel-chrome panels are used throughout the world. They are not merely reproducible but provide a built-in metric for comparison as a function of crack depth.

FIGURE 9. Cracked nickel-chrome panels for testing crack sensitivity of liquid penetrant tests: (a) cracked chrome panel is made by plating brass panel with nickel and chromium, bending to create cracks and then straightening; (b) twin fine crack panels used to compare brightness enhancement capabilities of two different powder developers (same fluorescent liquid penetrant and processing procedures were used on both panels; (c) cracks in nickel-chrome panel run parallel to each other as shown in coarse crack panels used to evaluate red visible dye liquid penetrant system with nonaqueous developer system.



Removal of Excess Surface Liquid Penetrant from Nickel-Chrome Test Panels

As the cracks are relatively shallow, the removal procedure is critical with the nickel chrome test panels. A liquid penetrant that reveals the crack pattern with the wipeoff technique, using toweling dampened with solvent remover, may not do the job with toweling saturated with *remover.* Also, because of the shallow discontinuities a liquid penetrant that reveals the cracks with a 15 s emulsifier dwell may not perform with a 60 s emulsifier dwell. A water washable liquid penetrant that does not perform with a high pressure wash may reveal the cracks with a gentle wash, for example.

Nickel chrome panels can be used to indicate relative resistance to depletion of indications during water washing. If two or three water washable liquid penetrants of the same nominal sensitivity are applied side by side on the same panel and if that panel is washed for a specified period (for example, 30 s) and then is air dried and developed with the same developer, the relative differences in depletion rates are readily apparent.

Likewise, the relative activity of different emulsifiers can be evaluated by closely controlling the emulsifier dwell time or time of exposure while using the same liquid penetrant. The relative rates of depletion of emulsifiers can be evaluated similarly. However, production emulsification times should be determined on production parts. It is important, when using chrome plated crack specimens for these various types of comparative tests, that all parameters except the one being evaluated should be held constant.

Viewing Crack Indications on Nickel-Chromium Plated Test Panels

Because the chromium surface plating is highly reflective, the nickel chromium crack test panel should be held at such an angle that the ultraviolet radiation beam is not reflected directly into the observer's eyes. This reflective surface makes it difficult to read discontinuity indications produced without developer assistance. For this reason, evaluation of the self-developing characteristics of a liquid penetrant by means of nickel chromium reference panels is difficult.

Limitations of Cracked, Chrome Plated Reference Panels

The cracked nickel-chrome plated panels are not typical parts in that their surface finish is almost mirror smooth. This causes some liquid penetrants to dewet the surface in a way that seldom occurs in the field. This dewetting does not seem to degrade sensitivity but looks as if it would. A practical problem is that liquid penetrant is very easily removed from the smooth, chrome plated surface, so emulsification and washing proceed much faster than normal. In addition, the discontinuities are classed as open cracks because they are fairly shallow in relation to their width, so liquid penetrant washout occurs easily.

Furthermore, because the surfaces are highly reflective, the effectiveness of these panels is reduced as a tool for comparing liquid penetrant visibility without developer. Chrome crack samples are very useful if their peculiarities are taken into account. The results obtained cannot be considered equal to those on most industrial test parts subject to liquid penetrant testing. Furthermore, no two cracked specimens are identical, so these specimens must be used strictly for comparison of two systems on separate portions of the same crack specimen or on separate panels of a matched set obtained by shearing one large panel into two.

Care and Handling of Nickel-Chrome Test Panels

Use caution — do not bend the nickel chrome panels. Flexing or bending will increase the size of the existing cracks and may create new cracks. Postcleaning is important after each test. A suggested procedure for cleaning the panels between tests is as follows.

1. Scrub the panels with a soft cloth saturated with a mild liquid detergent solution. A typical hydrophilic emulsifier would be a suitable detergent. Then rinse the panels thoroughly with a water spray. This removes developer and some of the liquid penetrant.
2. Immerse the panels in acetone for several minutes with some agitation. This removes crack entrapped liquid penetrant. Replace the acetone at frequent intervals. Use caution — acetone is a hazardous and extremely flammable solvent.
3. Dry the panel. If cleaning does not seem complete, repeat these steps.

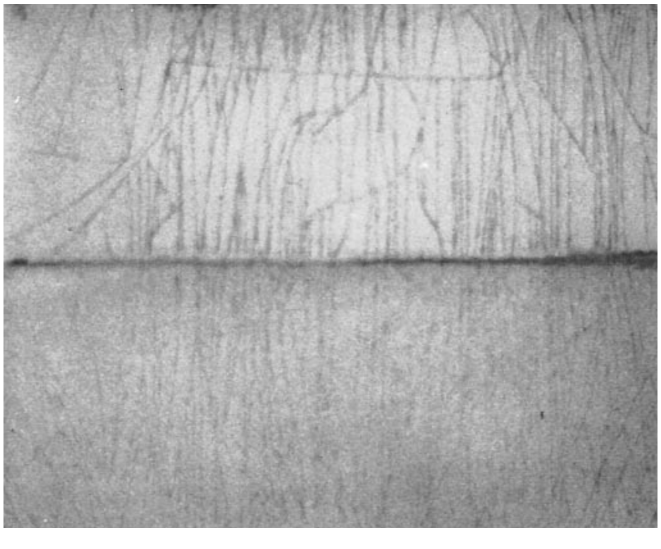
For more discussion on the use and care of these panels, see elsewhere in this volume.

Examples of Crack Indications on Nickel Chrome Test Panels

Figures 10 and 11 show typical liquid penetrant comparisons obtained with coarse crack nickel chrome reference panels. To prevent the opposing liquid penetrants from running together, the panel in Fig. 10 was divided into two equal sections by means of a longitudinal wax line. In photographing, the panel was framed to prevent the recording of liquid penetrant entrapments in the wax. Penetration time was 300 s for the postemulsifiable liquid penetrant and was 180 s for the water washable liquid penetrant. Comparisons were made for postemulsifiable and water washable liquid penetrants using dry powder and nonaqueous wet developers.

Several experiments were conducted to establish the dwell time for the emulsifier. No indications were obtainable on these shallow cracks when the emulsifier dwell time was long enough to remove surface liquid penetrant. Therefore, to remove the surface postemulsifiable liquid penetrant without displacing the discontinuity trapped liquid penetrant, a process of flowing on the emulsifier, allowing to stand 10 s, then rubbing lightly with the fingers for 5 s to mix the emulsifier and liquid penetrant, followed by washing with water, was established. The total emulsifier exposure time was no more than 15 to 20 s.

FIGURE 10. Two visible dye liquid penetrant systems compared on single coarse crack nickel-chrome sensitivity panel by dividing panel into equivalent sections with wax crayon line to prevent intermingling of liquid penetrant materials.



The exposure time for the water wash cycle for both the postemulsifiable and water washable systems was 30 s, a little longer than actually required and the pressure of the rinse was about 200 kPa (30 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$).

Liquid penetrants were applied by swabbing. The emulsifier was applied by pouring from a beaker and the wet and dry developers were applied by immersion. The nonaqueous developer was applied by spraying. The cleaning techniques used for the test specimens were those prescribed by the supplier of the test specimens.

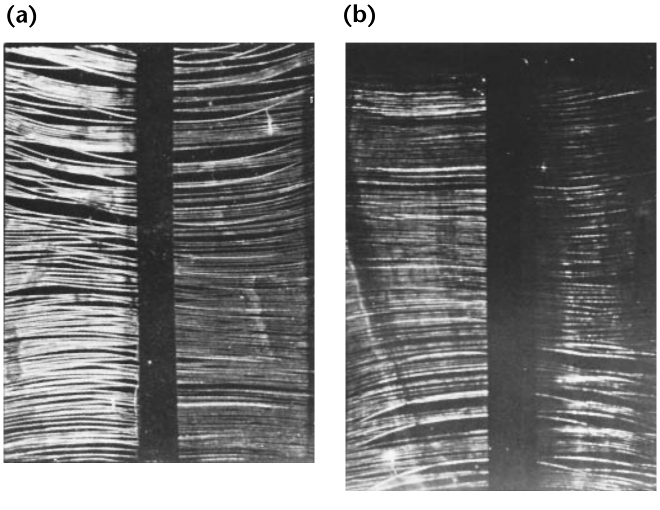
A course crack panel was used to compare a self-emulsifiable liquid penetrant to a postemulsifiable standard. The specimen had relatively large cracks characterized by their width-to-depth ratio of roughly 1 to 5, measuring about 10 µm (0.0004 in.) wide and 50 µm (0.002 in.) deep. This would be considered a wide *shallow crack*.

Developers with Opaque Crack Test Panels

In test panels and service parts that are opaque, liquid penetrant entrapments are for the most part below the surface of the part where they cannot be seen. In such cases, a developer must be used to draw the entrapments out to a point where they can be seen. Usually, a developer also augments the brightness of the entrapment.

The brightness increase that results from developer action involves at least two mechanisms and sometimes three.

FIGURE 11. Two different sets of liquid penetrants on pairs of coarse crack panels, water washable (left) and postemulsifiable (right) in each set: (a) with dry powder developer; (b) with aqueous developer.



1. The effective film thickness of an entrapment is increased as the entrapment is absorbed onto or into a layer of developer particles, thereby making the fluorescence brighter.
2. The developer particles are normally white and provide a reflective background, so that the brightness is further augmented.
3. In many cases, the developer contains a liquid ingredient and as the liquid penetrant entrapment diffuses into or is absorbed into the developer coating, an effect of dilution expansion augmentation of fluorescence response takes place.

Brightness augmentation by a developer can often exceed a full order of magnitude. For this reason, it is very difficult to obtain repeatability in developer action to a reasonable degree of accuracy. By using great care in the application of the developer, it is possible to make fairly accurate measurements of indication brightness, particularly where brightness ratios are sought in the determination of equivalent crack magnitudes. Also, side-by-side qualitative comparisons can be made successfully.

Side-by-Side Comparison Tests with Test Panels

Virtually any type of test panel may be used in side-by-side comparison tests and may yield some useful information. A necessary precept for this is that the panel shall contain a reasonably large number of cracks or discontinuities distributed over its surface, all of which fall in the same range of magnitude and configuration. Clearly, the crack distribution must be uniform; otherwise, different kinds and magnitudes of indications may be seen on different areas of the panel.

Side-by-side comparison tests are qualitative in nature but may be very useful as a check on liquid penetrant performance in comparison with a reference liquid penetrant or as a check in comparing the relative merits of two or more liquid penetrants with respect to a given performance characteristic.

Laboratory Procedure for Comparison Evaluation of Remover Systems

The following suggested laboratory testing technique is applicable to comparison evaluations of postemulsifier systems or solvent removal systems only. These artificial test conditions cannot be used in production liquid penetrant test processes where brushing and blotting are not acceptable techniques. If desired, two different material systems can be processed simultaneously on the same test panel, the technique being modified to accommodate the particular test being conducted.

The following outline is applicable to lipophilic postemulsifiable liquid penetrants.

1. Apply the liquid penetrant over the entire surface of the test panel. Blot up excess liquid penetrant with cleansing tissue and wipe the panel carefully.
2. For each emulsifier, use a small brush such as a solder flux acid brush or a small flat artist's brush about 6 mm (0.25 in.) wide to apply a streak of emulsifier on the panel. Use two brushes, one in each hand, to simultaneously apply emulsifier streaks side by side.
3. Let the streaks of emulsifier(s) stand for a precisely timed duration. In cases where a series of different emulsifier contact times are to be tested, apply several streaks side by side at timed intervals.
4. Stop the emulsifier action at the completion of the prescribed contact time by means of a strong spray of wash water. Use a sufficiently strong spray so that most of the surface liquid penetrant is dislodged and removed from the panel. This can be done with smooth panels, even though the liquid penetrant is insoluble in water.
5. Dry the panel with compressed air blast and inspect. Development is necessary in the case of opaque test panels and this step may be included in any event where it is desired to compare the behavior of two developers. Nonaqueous type developers may be applied to specific areas of the test panel by temporarily masking part of the panel. To avoid damage to developer coatings, bend the mask so that it touches the test panel only at its edges. Solvent removers may be compared by wiping respective halves of a panel with solvent dampened cloths. Wipe the same number of times with each solvent.

PART 3. Liquid Penetrant Comparators with Surface Indentations Simulating Discontinuities

The performance of a liquid penetrant system depends on processing material quality, including the precleaning chemicals, liquid penetrant, emulsifier and developer, plus the continued proper functioning of the several processing stages such as the liquid penetrant dwell, emulsifier dwell, wash, oven dry and developer dwell. A sudden, undetected deterioration of one of the processing chemicals or a malfunction in one of the stages may result in nondisclosure of a potentially dangerous discontinuity or in the acceptance of an anomalous, cracked part. The liquid penetrant operator must be alerted to the sudden change or deterioration in materials and in equipment as soon as possible and certainly before processing a substantial quantity of parts.

Liquid Penetrants System Monitor Panel

The liquid penetrant system monitor (PSM) panel was developed by Pratt & Whitney Aircraft Corporation and can be used to detect major changes both in fluorescent and visible color types of liquid penetrant systems and in water washable and postemulsifiable liquid penetrant systems. The liquid penetrant system monitor panel is normally processed at the beginning of each shift. It may be used more frequently, if the system has exhibited unreliable characteristics, in order to verify system performance. The liquid penetrant monitor panel is also processed whenever the liquid penetrant system is suspect.

Design of Test Panels for Monitoring Liquid Penetrant Systems

A liquid penetrant system monitor test panel is made from stainless steel 2.3 mm (0.090 in.) in thickness, in the form of a rectangle measuring about 100 by 150 mm (4 by 6 in.). A strip of chrome plating runs the length of one side of the panel. Five crack centers induced by means of indentation by a hardness testing apparatus with a variable load or by varying the backing are evenly spaced in the chrome plating, as sketched in Fig. 12a. Raised circular or starlike crack patterns are arranged in order of crack magnitude. The largest crack pattern is readily visible with low performance liquid penetrant materials and has considerable peripheral cracking, as shown in Fig. 12b. The smallest crack pattern is difficult to observe even with high performance liquid penetrant materials. On the same face of the panel and adjacent to the strip of chrome plating is an oxide grit blasted area of medium roughness. It is used to monitor background color or fluorescence (Fig. 12c).

Liquid Penetrant System Characteristics Affecting Monitor Panel Indications

Continued reliable performance of liquid penetrant systems is verified by detection of the required number of crack centers. The wash characteristics of the system are verified by the appearance of the grit blasted area after processing. Changes in any of the following aspects of a liquid penetrant system can adversely affect its performance: (1) liquid penetrant composition (or contamination); (2) emulsifier composition (or contamination); (3) developer strength; (4) liquid penetrant dwell time and mode; (5) emulsifier dwell time and mode; (6) wash water pressure, temperature and dwell; and (7) oven temperature and dwell. The liquid penetrant system monitor panel alerts the technician to major shifts, such as those listed above, that affect performance. The panel should be processed at frequent, regular intervals on a definite schedule. The processing of this liquid penetrant system monitor panel does not replace the usual chemical examination of the liquid penetrant materials, which is normally performed on a weekly or biweekly basis.

Interpretation of Liquid Penetrant System Performance with Monitor Panel

The effectiveness of the monitor panel of Fig. 12a is directly dependent on the skill of the technician using the panel. The technician must be able to discern a *difference* in the panel appearance from one test to another. The change might be an increase in background fluorescence or a marked decrease in discontinuity indication brightness (Figs. 12b and 12c). The skilled liquid penetrant technician uses the monitor panel to advantage in quality assurance programs.

The crack centers are examined for *how*, as well as *if*, they are shown. For example, if the developer system is not in operation, crack centers of a given magnitude may still be revealed but they will not be as bright as normal. The eye of the experienced technician is required to read the panel indications and to recognize that something is wrong.

Limitations of Liquid Penetrant System Monitor Test Panel

The liquid penetrant testing system monitor panel of Fig. 12 is not designed to replace periodic examination of liquid penetrant processing chemicals for brightness, water contamination or other deterioration. Neither does it replace periodic testing of pressure and temperature gages, nozzle apertures and other components of processing equipment. A gradual diminishment of brightness or other performance characteristics, in all probability, will not be noted by the liquid penetrant system monitor panel. The panel does permit test operators to detect sudden changes or major shifts in the characteristics of the chemical or in the performance of the apparatus.

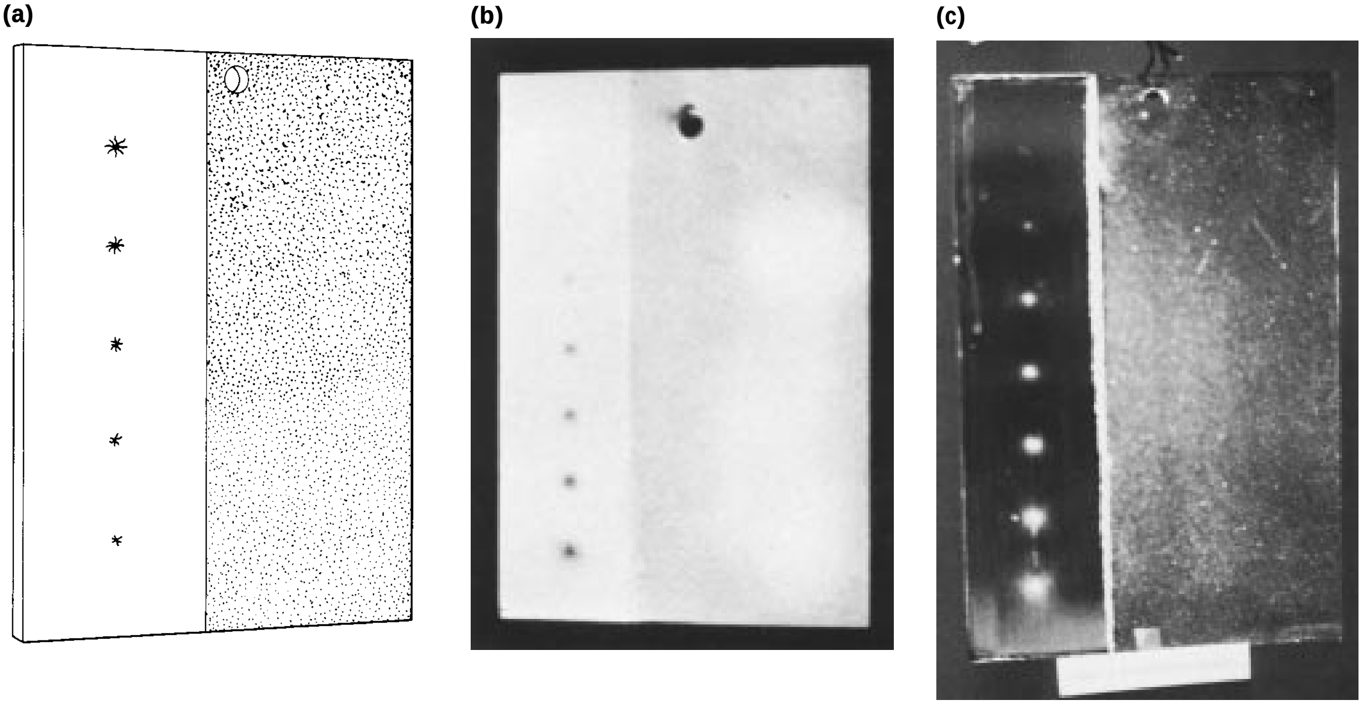
Maintenance and Storage of Liquid Penetrant System Monitor Panels

The monitor panel is fabricated from stainless steel to give long service but, like any instrument, it should be handled carefully. With improper maintenance, corrosion pits may develop in the chrome plating. The grit blasted section and the chrome plating are not immune to scratching. Constant wiping of the grit blasted section will diminish roughness.

The panel must be properly cleaned between tests. Crack centers must be free of residual liquid penetrant from previous tests for accurate result. Further, without proper cleaning between tests, the tighter crack centers will become clogged with oxidized liquid penetrant residue in a brief period of time. This may prevent liquid penetrant entry in subsequent tests, which might lead to a false rating of the liquid penetrant system.

It is suggested that, immediately following each test, the panel be washed with a mild soap and very soft brush, dried and cleaned with an ultrasonic cleaning unit charged with a solvent. If

FIGURE 12. Liquid penetrant system monitor panel includes five crack centers of different sizes for evaluating sensitivity and includes grit blasted section for judging wash characteristics of liquid penetrant system: (a) drawing; (b) under white light; (c) under ultraviolet radiation.



such equipment is not available, the chrome plated section can be scrubbed with a volatile solvent; the entire panel is then soaked in the solvent for 10 to 15 min. The panel is dried by blotting or with oven heat.

It is important to verify that liquid penetrant has been thoroughly removed from the cracks before storage. Application of a thin coat of nonaqueous developer should not produce fluorescent indication on a clean panel. If an indication is observed, the panel must be recleaned and reverified. The panel must also be recleaned to remove the developer even if no indication was produced. Unfortunately, failure to remove residual liquid penetrant can produce false confidence in the liquid penetrant testing process. Failure to remove residual liquid penetrants is a common error observed in liquid penetrant testing facilities.

Storage of Liquid Penetrant System Monitor Panels

Between tests, test panels should be stored completely immersed in a highly volatile solvent such as acetone or alcohol. Halogenated solvents are not recommended because they are corrosive and because, in the United States, production of certain chlorofluorocarbons and hydrochlorofluorocarbons has been banned to prevent ozone depletion. Before processing the panel through the system again, it is necessary to make certain that all solvents have completely evaporated from the crack centers as well as from the test panel surface. The panel should be removed from the volatile storing solvent in sufficient time to permit complete evaporation of the solvent before the panel is subjected to liquid penetrant application and processing.

Limitations of Reproducibility of Crack Patterns on Test Panels

Any type of crack or fracture, regardless of the production technique involved, will have an initiation point of infinitesimally small dimensions. This trouble zone of discontinuities with width (or length) less than 1 µm (4×10^{-5} in.) maintains a tremendous capillary force and is capable of entrapment and retention of all kinds of contamination. This fact along with an almost impossible task of cleaning this area is a major reason for nonreproducible results on liquid penetrant test panels. If the crack is produced on a laminated surface such as a plating or anodic coating, the nonreproducibility problem is compounded because of separation of the laminated layers. Rarely would a cracking or stressing technique be able to produce equal crack width separations. If the pattern of separation is not reproducible, then no single crack could be produced twice without some variations in dimension.

In many liquid penetrant test panels, the surface of a particular substrate is randomly cracked or perforated. This produces a massive bed of fine crack discontinuities. However, to use the data of liquid penetrant comparison tests for statistical comparison, it should be possible to count the individual indications, especially those indications with dimensions bordering the threshold of visibility. This task can only be accomplished if the position of each indication is well defined and there is ample contrast between the indication and the background.

Test Panel with Controlled Surface Cavities

A liquid penetrant test panel has been developed with small conical surface cavities. This panel permits simple comparisons of liquid penetrant systems and was designed to meet the following criteria for reproducibility.

1. The dimension of indications should be within the limits of visibility and resolution of a healthy, unassisted eye when the panels are processed in accordance with production line liquid penetrant testing procedure.
2. The dimension of discontinuities should be equal to the dimension of indications.
3. Individual discontinuities should be reproducible in every dimension.
4. Discontinuities should be produced in a single alloy metallic substrate, preferably of the same composition as the structural alloys used in aerospace industry.
5. Discontinuities should be of such dimension as to make their cleaning and reprocessing simple, fast and reproducible.
6. The distribution pattern and the number of discontinuities per area surface unit should be under exact control.
7. A high degree of contrast should be present between background and indication.

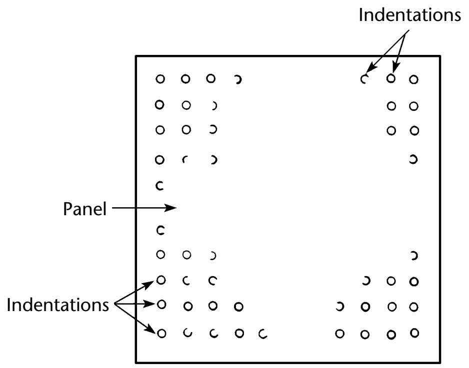
Practically all modern nondestructive testing liquid penetrants are capable of penetration into the finest cracks, down to a few micrometer (about 1×10^{-4} in.) wide. However, the human eye cannot differentiate a discontinuity indication of

2 µm (8 × 10^{-5} in.) width from a discontinuity of 4 µm (1.6 × 10^{-4} in.) width. It is only by means of the indications produced by the liquid penetrant entrapped within these discontinuities that the inspector can locate them. However, under normal inspection booth conditions, these indications are not visible to a healthy, unassisted eye until their surface area has expanded to several hundred square micrometer (a few square millionths of an inch).

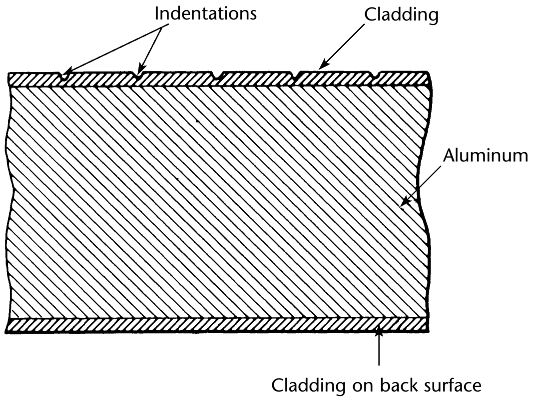
Many processing variables influence the final indication, from the liquid penetrant application stage to the inspection booth. If the size of the initial discontinuity were chosen to be equal to the size of the final liquid penetrant indication, then most of these variables would be eliminated.

FIGURE 13. Design of liquid penetrant test panel with discontinuities simulated by conical surface indentations: (a) planar view of test panel, showing locations of 100 surface indentations simulating discontinuities of various depths and diameters; (b) cross sectional view of test panel showing surface indentations in aluminum cladding.

(a)



(b)



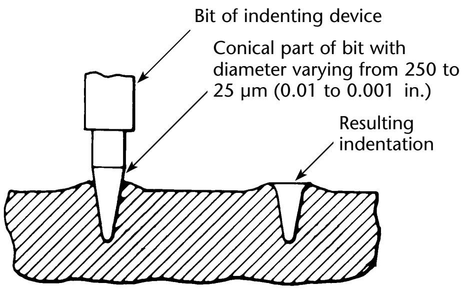
Examples of Test Panel with Conical Surface Indentations

Figure 13 shows a liquid penetrant test panel on a 75 × 75 mm (3 × 3 in.) clad aluminum block. On the polished, clad surface there are impressed 50 or 100 conical, discontinuity simulating cavities, as shown in Fig. 13. These cavities are produced individually and all dimensions can be reproduced to within 13 µm (0.0005 in.), as sketched in Fig. 14.[9] The diameter and depth of conical holes can be varied from 250 to 25 µm (0.01 to 0.001 in.) to produce surface discontinuities for evaluating liquid penetrants at various levels of sensitivity. The data obtained from actual count of the number of conical cavity discontinuity indications visible on the panels of Fig. 13 are quite reproducible and suitable for statistical analyses. The lower portion of these panels is sand blasted to provide a background for rinsing tests. The distribution of simulated surface discontinuities takes on different forms in three different types of conical indentation test panels, as described next.

The first type of panel contains two blocks, each with 50 discontinuities, separated by a central groove. All discontinuities have the same dimensions, in the range designed for the same liquid penetrant sensitivity level. This panel is best suited for side-by-side comparison of liquid penetrants or liquid penetrant systems, as well as for maintaining quality control between standard material and material in use.

The second type of test panel has a single face covered by 100 identical conical discontinuity indentations. The dimensions for these indentations can be selected for particular test applications. This panel can be used for comparing complete liquid penetrant systems, changes in individual processing steps or changes in liquid penetrants and

FIGURE 14. Technique for indenting cladding of test panel (after Tahbaz[9]).



processing materials. It can also be used for maintaining control over a liquid penetrant system's performance and for statistical studies of performance variations from time to time or between different liquid penetrant testing facilities.

The third type of test panel has conical indentations, whose dimensions vary in a continuous gradient of sizes. Five or ten rows of discontinuity indentations are arranged in order of decreasing discontinuity size on the face of the test panel. This gradient panel can be used to determine the relative sensitivity of a specific liquid penetrant used with various processing conditions or to indicate differences in performance levels of various liquid penetrant materials used under a single set of processing conditions. The data obtained from the actual counts of the number of discontinuities whose liquid penetrant indications are visible are quite reproducible and can be used easily for statistical analyses.

Liquid Penetrant Processing of Conical Cavity Test Panels

The test panels shown in Fig. 13 can be adapted for use in accordance with the user's liquid penetrant processing manual or they can be used as a fast and simple quality control gage. Normally, short and quick liquid penetrant processing such as follows will provide the necessary panel comparisons: (1) liquid penetrant application and dwell time of 60 s; (2) emulsification time of 30 to 60 s; (3) rinse time of 30 to 60 s at 150 to 200 kPa (20 to 30 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) jet spray pressure with water temperature of 15 to 20 °C (60 to 70 °F); and (4) forced air drying of 300 s in 65 °C (150 °F) oven.

Because all the liquid penetrant indications are the same size as the conical cavity discontinuity itself and all are within the visibility range, there is no need for any developer and the panels are ready for inspection. However, there is no objection to developer.

Cleaning of Liquid Penetrant Test Panels with Conical Surface Indentations

The cleaning of panels with conical indentations is normally achieved by a simple solvent rinse. The well defined surface of individual discontinuities allows the simplest cleaning procedure to be the most complete. However, if developer is used on these panels, a soft brush scrub with detergent and water is advisable. A solvent rinse should follow to ensure the removal of any residual liquid penetrant. Acetone is best suited for the solvent rinse because it is miscible with water and most liquid penetrants. One note of caution: ultrasonic cleaning is detrimental to the conical indentation test panels just described. Ultrasonic cleaning at high vibrational power levels, particularly if performed repeatedly, may erode the metal surrounding the indentations, thus reducing their dimensional accuracy and performance reproducibility.

Part 4. Test Panels for Measurement of Background Levels

Nature of Surface Roughness on Liquid Penetrant Background Comparators

Liquid penetrant comparators and reference panels designed to measure effects of surface roughness, porosity or cracks can be used to compare different means for removal of excess surface liquid penetrant or to complete background color or fluorescence levels. Any metallic, ceramic or glass surface that has been grit blasted to produce a rough surface will have microscopic tears and fracture cracks where material has been gouged out by the impact of grit particles. The larger the grit particles, the larger will be these tears and cracks. In the case of rough surfaces produced by metallized spray (such as the coating on jet engine turbine blades), many interstices are formed between grains of the metallized spray. These are equivalent to cracks. They form liquid penetrant entrapments in a manner similar to actual cracks. If surface roughness exists, microcracks also exist in most cases. If the magnitude of a significant crack approaches the magnitude of a background crack in a rough surface coating, the two cannot be differentiated by a liquid penetrant test. However, it is possible to design liquid penetrants to differentiate between background cracks and slightly larger significant cracks. Rough surface liquid penetrant comparator panels can be used to evaluate liquid penetrants for these capabilities.

Metallic Grit Blasted Panels

Description of Panels

These panels are typically made from a sheet of 16 gage Type 301 or 302 stainless steel. The panels may be any size, but a typical size is 38 × 51 mm (1.5 × 2 in.). Initially the sheet is cut into 100 × 150 mm (4 × 6 in.) sections. After being thoroughly cleaned, each section is grit blasted. Typically the grit blasting is done with 80 mesh aluminum oxide grit using 414 kPa (60 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) air pressure with the nozzle held normal to the surface of the metal about 450 mm (18 in.) away. The panels are then cut to their final size, cleaned and processed with a fluorescent liquid penetrant system. After the developer is applied and allowed to dwell, the panels are paired as closely as possible according to background fluorescence. It may take several attempts of blasting and processing before pairs of sufficiently identical backgrounds are achieved.

Side-by-Side Comparisons of Fluorescent Liquid Penetrant Backgrounds Using Two Panels

Evaluation of fluorescent liquid penetrant background is a comparative process conducted with standardized procedures. One way to use the panels is to process one panel of a matched pair with a reference set of liquid penetrant materials and the other panel with materials being evaluated. The respective steps of each process are timed identically, even run simultaneously when possible. Washing, the critical step, is usually done simultaneously with the panels mounted in a fixture with controlled water temperature, pressure, spray pattern and standoff distance. Both sides of the panels are sprayed simultaneously. Then follows drying of the panels and application of dry developer.

Visual comparison of backgrounds may be sufficient. For a more quantitative comparison an electrooptical device (that is, a photometer) may be used to measure the luminance of each panel. For example, each panel in turn is exposed to the same near ultraviolet radiation as an operator measures the background luminance within three 9 mm (0.38 in.) diameter fields of view located specified distances apart. The three readings on each panel are averaged and compared. Using a constant voltage transformer or voltage regulator for the electrical power inputs of both the ultraviolet lamp and the electrooptical measuring device will help minimize the systematic measurement errors.

Side-by-Side Comparisons of Fluorescent Liquid Penetrant Backgrounds by Using Single Panel

There are three important considerations that must be met in side-by-side comparisons of liquid penetrants. First, the test panel must be uniform in its crack distribution or surface features. Second, the panel must be absolutely clean, particularly in the case of anodized aluminum. Third, streaks of test liquid penetrant must be applied side by side in such a way that they do not run together. The following procedure is suggested for side-by-side comparisons of liquid penetrants.

1. Before starting the test, examine the panel under a near ultraviolet lamp in a dark work area. Make sure that there are no residual traces of fluorescence from previous tests. Where necessary, reclean the panel by soaking or rinsing in solvent and then drying.
2. Apply streaks of the test liquid penetrants, using a small, narrow brush applicator. Blot each streak with cleansing tissue before it has time to spread, then wipe the streak carefully to remove excess surface liquid penetrant.
3. If postemulsifiable liquid penetrants are being tested, follow an appropriate emulsification procedure.
4. Wash the prepared panel under controlled water temperature and spray conditions for a prescribed wash time.
5. Stop the wash action by blowing the surface water off with compressed air. Then dry the panel completely.
6. Inspect the panel, with or without developer, as needed.

Care of Grit Blasted Panels

Panels should be handled by their edges and should be wrapped in paper for protection against scratches and blemishes when not in use.

Panels should be cleaned immediately after each use and viewed under near ultraviolet radiation to check for any remnants of fluorescence, which if detected requires recleaning of the panel. One cleaning procedure is as follows.

1. Wash panels in soapy water with a soft brush or cloth to remove developer.
2. Dry panels by patting with a clean towel or cloth.
3. Dip panels into alcohol to remove traces of water remaining in the panel cracks and crevices.
4. Immerse panels in a volatile solvent and clean ultrasonically for ten minutes.
5. Remove panels from solvent and air dry.

Anodized Aluminum Test Panels with Transparent Surface Layers

An important category of liquid penetrant test panels is designed in the form of aluminum sheets anodized by the sulfuric acid process to produce a brittle anodic surface coating. The anodic layer thickness is accurately adjusted to a value of 20 µm (0.0008 in.). Various configurations of surface porosity (sealed or unsealed) and crack magnitudes are available in typical test panels of this series. Each type of panel is characterized by the transparency of the anodic layer that contains the cracks and porosity.

High Background Level, Crackfree Anodic Aluminum Test Panels

One type of anodic aluminum test panel has a smooth surface containing no cracks. These panels have surface connected porosity in the anodic coating layer. This type of panel is used for evaluating and comparing liquid penetrants and remover systems with respect to residual liquid penetrant adsorption or background noise (color or fluorescence). The high degree of porosity in the 20 µm (0.0008 in.) thickness of anodic coating can be further augmented by a chemical treatment that yields a surface with an extremely large liquid solid interfacial area. Contact of a liquid penetrant with this large surface area enhances any effects of adsorption that are present. This crack free porous surface panel has a strong adsorption effect that produces a bright fluorescent background when the panel is used with a high sensitivity liquid penetrant.

Low Background Level Aluminum Test Panels with Cracked Anodic Layer

Another type of surface condition is a glassy smooth surface that results when the anodic layer is sealed with a thin film of sodium silicate (water glass). This surface exhibits substantially no adsorption and results in minimal background fluorescence or color. Cracks can then be generated in the anodic layer either by bending the sheet over a curved form or by stretching the sheet in a stretching fixture. In either case, the craze cracks that form have a depth that is limited by the thickness of the anodic layer. These low background panels are cracked by stretching to an elongation of about 10 percent. This produces a pattern of cracks parallel to the long side of the panel. The cracks are 20 µm (0.0008 in.) in depth and vary in width up to 8 µm

(0.0003 in.), with an average crack width of 6 µm (0.0002 in.). Cracks appear at a spatial frequency of about 10 to 20 cracks per millimeter (250 to 500 cracks per inch). This low background craze cracked anodic aluminum test panel is used for measuring depletion of indications and effects of processing on the brightness of crack indications.

High Background Level Aluminum Test Panels with Cracked Anodic Layer

An unsealed anodic layer is used to provide a high background level in an anodic craze cracked test panel whose crack patterns are similar to those just described for sealed panels. The anodic surface between cracks has a fine porosity so that these panels can be used for measuring the signal to noise ratio (ratio of crack indication brightness to surface background brightness due to residual liquid penetrant). This type of reference panel permits measurements of both the width and depth of cracks that are present. This type of panel can be used to determine the relative ease with which the liquid penetrant and remover diffuses into each other, a property called *dispersibility.* The greater the dispersibility, the more rapid will be the remover action, the shorter will be the depletion time constant and the larger will be the depletion coefficient. The crack width to depth ratio is constant from one panel to the next, with a value near 0.33, with this type of test panel.

Low Background Reference Panels with Tight Cracks in Anodic Layer

A low background craze cracked anodic aluminum reference panel is similar to the cracked panel just described except that the cracks are tight instead of wide. This anodized panel is cracked by bending and restraightening so that the cracks tend to close tightly. In this panel, the average width of the tight cracks is about 0.3 to 0.5 µm (1.2×10^{-5} to 2×10^{-5} in.). This minimal crack width is determined by crack wall irregularities that prevent cracks from closing up to zero width. The cracks are too tight to permit crack width measurement by simple microscopic examination. The inside surfaces of the cracks will exhibit adsorption similar to that of the fine porosity in the unsealed anodized surfaces of the high background reference panels. However, in these low background, fine crack anodized panels, the anodic surface areas between the cracks are sealed to reduce background color or fluorescence to low levels.

Effects of Crack Geometry on Liquid Penetrant Indication Brightness

With regard to crack geometry, certain types of cracks have a constant width from top to bottom. This type of crack geometry is encountered in the cracked chrome plate and cracked anodic aluminum panels. When a crack pattern of this kind is filled with a liquid penetrant, wash removal of surface liquid penetrant may typically deplete the crack entrapment by only a few percentage points with respect to crack depth. Because the cracks have a uniform width, the depletion with respect to the entrapment volume will amount to the same number of percentage points.

The fractured glass panel has a crack geometry in which two features are significant. For one thing, the cracks in a given step on this panel vary considerably in their width. This means that some large wide cracks are present along with some smaller, tight cracks. In the second place, it is probable that many of the cracks have a tapered configuration, such that they are wide at the surface and taper down to very narrow (zero) widths at their bottom in the part interior. The behavior of this crack geometry with respect to washing is somewhat different than that of the constant width cracks. A few percentage points of depletion, with respect to effective crack depth, may result in a much larger percentage of depletion with respect to crack volume. This is because the initial few seconds of washing removes a sizable portion of the entrapments (in the wide region of the cracks).

Accordingly, it is important to standardize and accurately control the wash time, wash temperature and water pressure when making background comparisons. A suitable spray pattern is also essential. The washing can be stopped by blowing the water off the test panel with compressed air.

Fractured Glass Step Wedge Test Panels

To obtain quantitative comparative data for the detectability of a significant crack in the midst of fluorescent background, fractured glass step wedge panels have been used. Because these panels are transparent to near ultraviolet radiation, crack indications, whether because of significant cracks or merely surface roughness, can be related to flaw magnitudes because the entrapped liquid penetrant is visible.

Characteristics

Fractured glass test panels that have roughened surfaces containing fracture cracks and tears produced by grit blasting under conditions controlled by air pressure and mesh size of the grit. The 50 × 100 mm (2 × 4 in.) black glass plate has six graduated steps or areas of fractures whose discontinuity magnitudes increase from about 3.5 µm (1.4×10^{-4} in.) at step 1 to about 20 µm (8×10^{-4} in.) at step 6. The crack dimensions of each individual step depend almost entirely on the grit size, which ranges from about 1.0 mm (0.04 in.) for coarse cracks to about 44 µm (0.002 in.) for fine cracks — that is, from 16 to 325 mesh.

The ratio of crack magnitudes between successive steps is about 1.4 (the square root of 2). This permits the relative brightness values for successive steps to be measured and plotted on a logarithmic scale similar to that used for the well known Hurter and Driffield (H&D) film density characteristic curves used in photography and X-ray film radiography.

The *black* glass is not truly black and is transparent to ultraviolet radiation. However, the thick glass panel is sufficiently opaque to visible light so that internal reflections of light are eliminated. Entrapments of fluorescent liquid penetrant can be seen and measured as to their brightness without interference from light absorption or reflections.

Correlation of Fractured Glass Reference Panel and Porosity Conditions

Many porosity conditions that are found in production parts have effective magnitudes in the range of 5 to 10 µm (0.0002 to 0.0004 in.) or more. The fractured glass step wedge test panel is a reasonable representation of such surface porosities. However, it is apparent that there are significant differences in surface structure between the fractured glass test panel and surface porosity on service parts. Even through such differences exist, close correlation is possible between the test panel and real life porosity conditions, insofar as indication depletion rates are concerned.

Cleaning of Fractured Glass Step Wedge Panel for Reuse

If handled with care, the step wedge test panel can be used over and over and will yield accurately reproducible measurement results. However, it is necessary to remove completely all remaining entrapments of the previously used liquid penetrant before applying a new liquid penetrant to the fractured glass reference panel.

The preferred cleaning procedure is to soak the grit blasted plaques in a solvent for about 4 or 5 min, until all traces of fluorescent residues are removed from the coarse plaque.

Occasionally, scumlike residue will accumulate on the panel, forming spurious background indications. These may result from fingerprints or they may come from waxes that are deposited, adsorbed or precipitated from certain of the test liquid penetrants or emulsifiers. Residues of this kind can usually be removed by soaking the fractured glass panel in concentrated nitric acid. Place the panel face up in a dish or glass beaker and pour the nitric acid onto its surface. Let the acid treated panel stand for 5 or 10 min, then flush off the acid with tap water. Dry the panel with compressed air and rerinse several times, with drying in between, so as to obtain complete removal of acid residues. Never use any etchant mixtures that contain hydrofluoric acid. Use caution — acids are hazardous. Personnel protection and caution in handling acids are recommended.

Reference Brightness Conditions and Measurement Corrections

It is necessary to establish reference brightness conditions for discontinuity entrapments (in a given test panel, for example). Throughout this discussion, it should be remembered that the crack magnitudes (in the test panels) are small enough so that fluorescence response is in the range where film thickness controls brightness levels for the particular liquid penetrant being tested. Also, it should be remembered that for most liquid penetrants, the rate at which remover contact depletion occurs is so rapid that a substantial amount of depletion occurs within a few seconds of the initiation of remover contact (emulsifier or water rinse contact).

In measuring the depletion of indications, it is necessary to determine a starting point. This starting point is the initial brightness reading that would pertain if the cracks were completely filled with the test liquid penetrant. In view of the fact that wash removal of surface liquid penetrant also entails a partial removal of the entrapment, it is not possible to determine the initial brightness by direct measurement on the test liquid penetrant. It must be determined indirectly with a liquid penetrant that has a sufficiently large depletion time constant so that surface liquid penetrant may be removed (by the scrubbing action of the spray wash) without stripping the entrapment significantly. Some liquid penetrants satisfy this requirement but, even so, certain precautions must be taken. First, the effect of crack geometry must be considered. Second, it is necessary to consider the effect of relative values of intrinsic brightness.

The intrinsic brightness varies between different kinds of liquid penetrants and between different levels of performance. Although such variations may be only on the order of a few percent at most, an appropriate correction must be made in brightness readings. For this purpose, the intrinsic brightness of a given liquid penetrant is determined relative to a standard brightness plaque.

Calibration of Fractured Glass Test Panels

Before depletion measurements can be made on a test liquid penetrant, the test panel must be calibrated. This is accomplished with standard liquid penetrants. The panel is treated successively with liquid penetrants of each level of performance, with proper cleaning of the panel between measurements. A stable arrangement for brightness measurements similar to that described for metallic grit blasted panels can be used. Inasmuch as the crack magnitude is usually smaller than a few micrometer (about 1×10^{-4} in.), the brightness of a given crack indication will be less than the thick film (intrinsic) brightness. The measured brightness will be dependent on the crack magnitude, the frequency of the cracks (number of cracks per millimeter), the liquid penetrant film thickness and the level of liquid penetrant performance.

Use of standard reference liquid penetrants serves two purposes. First, the brightness ratio *R* between indications resulting from two brightness steps may be used conveniently to measure crack magnitude for the panel. Second, the brightness values for the particular performance level under test provides an index of the initial brightness of the test liquid penetrant, assuming of course that appropriate corrections are made as determined by relative values of intrinsic brightness. Table 2 shows the result of calibration of an experimental fractured glass test panel by determining the brightness ratio *R* for indications derived from standard liquid penetrants of different relative sensitivity levels. Note that the calibration results are similar, even when derived by different combinations of liquid penetrants.

Fluorescent Brightness Data Obtained with Fractured Glass Panels

Curves of Brightness Contrast Obtained with Grit Blasted Step Wedge

When the fractured glass panel is processed using a particular combination of fluorescent liquid penetrant and remover, the end result is a gray scale of brightness values where brightness increases as the fracture crack magnitude increases. When these brightness values are measured and plotted on log linear graph paper, curves are obtained that are similar to the photographic Hurter and Driffield (H&D) curve. They are also similar to the Beer's law curve of fluorescence response transition. A great deal can be learned from an examination and analysis of curves of this kind, including an understanding of the behavior of the test liquid penetrant with respect to intrinsic brightness, detectability (brightness) of large discontinuities, ability to see contrast for small discontinuities, suppression of background porosity indications, stability of crack indications, effects of developer action and resolving power of the process in the detection of microscopic discontinuities.

TABLE 2. Measured values of brightness, brightness ratio *R* and crack size for fractured glass test panel.

Panel Step	Relative Sensitivity Level	Brightness	*R*	Crack Size µm	Crack Size (10^{-6} in.)
Extra coarse	9 1	7.07 2.17	3.258	12.0	(450)
	11 3	7.31 3.61	2.025	11.0	(420)
Coarse	9 1	6.97 1.93	3.611	10.0	(400)
	11 3	7.21 3.09	2.333	8.6	(340)
Fine	9 3	5.33 1.13	4.717	3.0	(117)
	11 3	6.59 1.23	5.358	3.1	(123)
Extra fine	11 5	4.14 0.79	5.24	1.2	(46)
	11 3	4.14 0.39	10.615	1.2	(45)

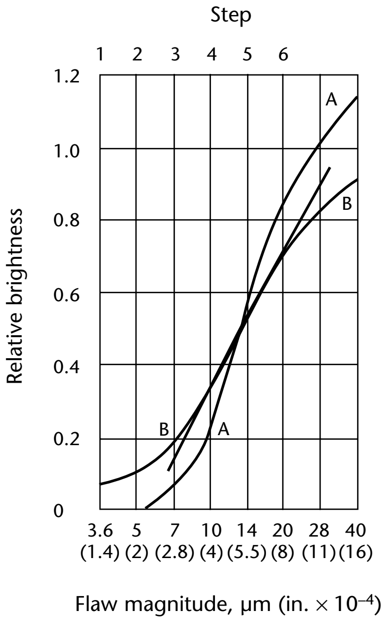
Figure 15 illustrates two typical brightness contrast curves, such as might be drawn from data derived from measurements on the fractured glass test panel. Curve A typifies the brightness contrast obtainable in a water washable liquid penetrant system; curve B represents the brightness contrast typical of a postemulsifier liquid penetrant system.

As the remover contact time (emulsifier contact or water wash time) is increased, the position of a curve on the chart is moved horizontally toward the right and the toe portion of the curve is depressed. The main features to note regarding these curves are the brightness values in the region of the fractured glass panel steps 2 and 3, the brightness value of step 6 and the brightness contrast (steepness or slope of the curves). Observe that curve B of Fig. 15 exhibits a high level of background indication brightness (in steps 1, 2, 3) whereas curve A shows a low level of background brightness. Also, curve A exhibits a much higher brightness contrast than curve B; this is indicated by the steeper slope (or *gamma*) of curve A.

Gamma Values for Brightness Curves

The preferred way to rate brightness contrast of a particular liquid penetrant process is to define it in terms of the slope of the response curve. In Fig. 15, a straight line has been drawn tangent to curve B at its inflection point. The slope of this curve may be expressed as the ratio of $\Delta I/\Delta t$, as indicated. Here Δt is the magnitude (crack size) differential corresponding to adjacent steps on the panel and ΔI is the differential of indication intensity or brightness. The values for slopes are known as gamma (γ) values and they correspond to the gamma values in photographic sensitometry. It should be noted that this procedure yields gamma values dependent on the brightness reference standard used. Gamma values are reproducible, as long as the same brightness reference standard is used.

Figure 15. Typical fluorescent brightness characteristic curves for fractured glass test panels: water washable liquid penetrant A and postemulsifiable liquid penetrant B.



Convergence of Seeability Contrast Curves

If a fractured glass panel with grit blasted steps were extended to a point where the effective liquid penetrant film thickness magnitudes become equal to 60 or 80 µm (0.002 or 0.003 in.) and if a liquid penetrant that has a reasonably high discontinuity entrapment efficiency is used, then one would expect that the measured brightness of the 80 µm (0.003 in.) step would remain nearly constant over a prolonged period of remover contact (emulsifier or wash time). This stability occurs because an equivalent discontinuity magnitude of 80 µm (0.003 in.) yields discontinuity entrapments equivalent to a liquid penetrant liquid film thickness of 80 µm (0.003 in.). This equivalency provides brightness values that are at or above the shoulder of the brightness curve, regardless of the dye concentration level.

At the same time, it could be expected that the brightness values in thin film steps 1, 2, 3 etc. of the fractured glass panel would diminish rapidly as remover contact time increases. This means that if a family of brightness response curves are plotted for various remover contact times, the curves will (or should) tend to converge at the shoulder region and diverge at the toe region of Fig. 15. Obviously, the curves converge at the extremes of both the toe and shoulder regions. However, the toe region of interest is where the relative brightness values are about 0.2 to 0.4.

Spread between Brightness Contrast Curves for Various Remover Times

Another feature that can be observed in families of brightness contrast curves is the extent to which the curves are separated on the graph paper. Different liquid penetrants perform differently in this regard. In cases where there is a wide spread between response curves, it means that the liquid penetrant is overly sensitive to variations in remover contact time. The ideal liquid penetrant system is one in which there is very little spread in a family of curves for remover contact times ranging from 30 to 240 s.

Extrapolation of Brightness Contrast Curves

The fractured glass test panel has six steps or grit blasted plaques and the fracture cracks have an equivalent magnitude of about 20 µm (0.0008 in.) in step 6. Cracks producing liquid penetrant film thickness indications larger than 20 µm (0.0008 in.) cannot be easily generated in the glass panel without danger of destroying the panel. It is possible to extrapolate curves plotted from measurements on the six step panel and the curves may be extended out to an equivalent magnitude of 40 µm (0.0016 in.) liquid penetrant film thickness or more, while retaining reasonable conformance to reality.

A given brightness contrast curve must reach a maximum level of brightness. This level may be determined with reasonable accuracy by measuring the brightness of fractured glass panel step 6 under conditions where the liquid penetrant is merely wiped from the rough surface, without washing. Also, each family of curves will tend to converge, so that the curves will meet at the *shoulder* point where the measured brightness reaches its maximum value. Finally, measurements on the six calibrated steps of the panel provide enough data to provide a clear indication as to the direction that must be taken in extrapolating a given curve.

Concept of Discontinuity Detection and Reliability Performance

In liquid penetrant testing, an essential step is the application of a remover to remove unwanted smears of liquid penetrant and background indications. If, during this step of remover application, severe variations in discontinuity indication brightness occur as the result of normal variations in remover contact time (*processing margin*), then the liquid penetrant process may be said to be unstable and unreliable. Where the family of response curves is in proximity, the liquid penetrant process may be said to be *forgiving* within the remover processing margin and relatively stable and consistent in performance.

Quantification of Discontinuity Detection Performance

With a properly calibrated fractured glass test panel, one can compare levels of discontinuity detection performance and assign numbers for gradation in performance. In Fig. 15, the inflection point of a brightness response curve is at about 50 percent level with respect to maximum brightness. This inflection point is also the point where maximum slope or gamma is obtained on the brightness characteristics curve. This half brightness point may be used as a measure of system performance.

Note that the half brightness value for a given liquid penetrant and processing condition is a mean value of performance transition. It may be possible to detect smaller discontinuities if care is taken in evaluating indications or to miss larger discontinuities if a low gamma brightness transition value is applicable.

Interpolation of Discontinuity Detection Sensitivity Values

The graphs of brightness transition, exemplified by Fig. 15, are plotted on linear graph paper. The scale of abscissas is one in which each major division (panel step) differs in magnitude from the adjacent step by the square root of 2 (1.41). A special chart paper, with an

TABLE 3. Extrapolated and interpolated half brightness values of film thickness corresponding to steps and fractions of steps on fractured glass step wedge test panels.

Step	µm	(10^{-3} in.)	Step	µm	(10^{-3} in.)	Step	µm	(10^{-3} in.)	Step	µm	(10^{-3} in.)
1.0	3.53	(0.14)	3.0	7.07	(0.28)	5.0	14.1	(0.56)	7.0	28.3	(1.11)
1.2	3.78	(0.15)	3.2	7.55	(0.30)	5.2	15.1	(0.59)	7.2	30.2	(1.19)
1.4	4.06	(0.16)	3.4	8.10	(0.32)	5.4	16.2	(0.64)	7.4	32.4	(1.28)
1.6	4.35	(0.17)	3.6	8.70	(0.34)	5.6	17.4	(0.69)	7.6	34.8	(1.37)
1.8	4.66	(0.18)	3.8	9.30	(0.37)	5.8	18.6	(0.73)	7.8	37.2	(1.46)
2.0	5.00	(0.20)	4.0	10.0	(0.39)	6.0	20.0	(0.79)	8.0	40.0	(1.57)
2.2	5.35	(0.21)	4.2	10.7	(0.42)	6.2	21.4	(0.84)	8.2	42.8	(1.69)
2.4	5.75	(0.23)	4.4	11.5	(0.45)	6.4	23.0	(0.91)	8.4	46.0	(1.81)
2.6	6.15	(0.24)	4.6	12.3	(0.48)	6.6	24.6	(0.97)	8.6	49.2	(1.94)
2.8	6.60	(0.26)	4.8	13.2	(0.52)	6.8	26.4	(1.04)	8.8	52.8	(2.08)

exponential scale of abscissas, could be made but it is simpler to use linear graph paper and interpolate values if necessary.

Table 3 lists half brightness values that correspond to the steps and fractions of steps on the fractured glass test panel. These values should be taken as theoretical because it is not possible to fabricate a fractured glass panel having crack magnitudes that conform exactly to the desired values that are indicated in Table 3 for steps 1, 2, 3 etc. In any event, this table may be used to approximate half brightness thicknesses of liquid penetrant films. For example, in curve A of Fig. 15, the midpoint (with a relative brightness of 0.6 on step 5.1) yields an interpolated half brightness film thickness value of about 15 µm (0.0006 in.).

Examples of Brightness (Luminance) Contrast Curves

Figure 16 shows several families of brightness contrast curves for various water washable liquid penetrants. In all of the tests that are illustrated, wash water temperature is 38 °C (100 °F). Also, each family of curves shown in Fig. 16 covers a wash time span varying from 30 to 240 s.

For a better understanding of the meaning of these curves, it should be noticed how steep the various curves are and how far they are separated from one another (in a given family). The slope or gamma (γ), of a given curve serves as a measure of brightness contrast. For the sake of establishing a reference point, the slope of the curve is taken at its inflection point, as indicated in Fig. 15. This slope may be used as a measure of brightness contrast. Thus, for liquid penetrant A of Fig. 16, seeability contrast γ for a wash time of 60 s is 2.1; for 120 s wash time, it is 2.6.

The distance by which the curves are separated provides an indication as to how tolerant the liquid penetrant process is to variable wash time. If the curves are widely separated, it means that the liquid penetrant process is somewhat intolerant of variations in wash time. In such cases, overwashing can readily take place and significant indications may be lost. Note, for example, in Fig. 16d, that the curves are quite widely separated.

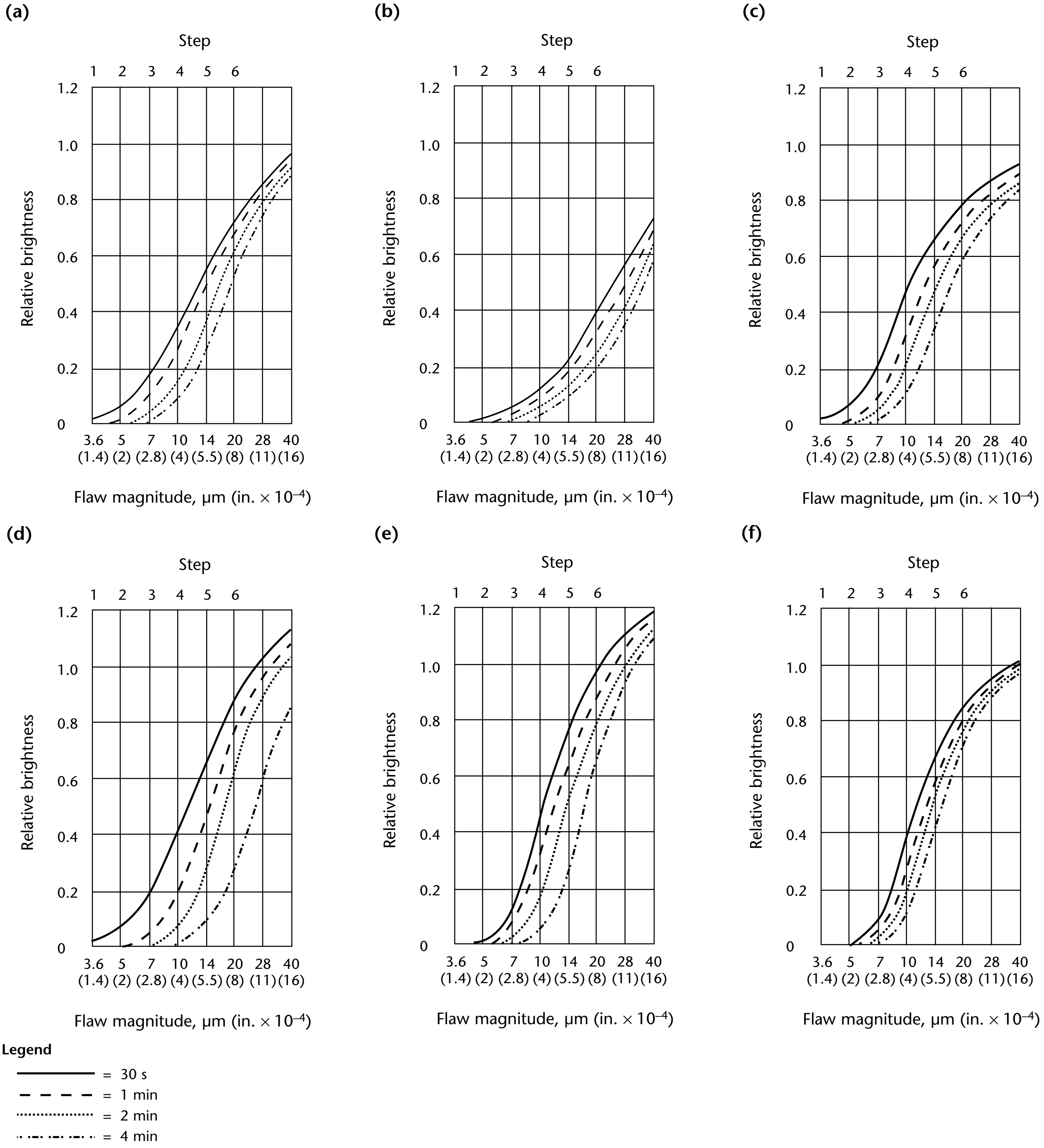
Discontinuity detection sensitivity may also be indicated by examination of these curves. For example, when seeking discontinuities having effective liquid penetrant film thickness values of 20 µm (0.0008 in.) corresponding to step 6, then it is necessary that the curve for a particular liquid penetrant and process yield a relatively high brightness at step 6, preferably greater than 0.5 or 0.6. With liquid penetrant in Fig. 16d, this objective may be achieved with a wash time of 120 s or less. If the wash time is increased to 240 s, a significant loss of brightness will be found in crack indications where the crack magnitudes are 20 µm (0.0008 in.) or less.

The family of curves in Fig. 16d is interesting, in that the curves are located down toward the bottom right of the chart. This results from the fact that this liquid penetrant is readily soluble in water, so entrapments tend to deplete rapidly. In the family of curves in Fig. 16e, it is seen that large cracks in the range of 20 µm (0.0008 in.) or more yield bright indications, even with wash times up to 240 s. However, background porosities in the range of 10 to 15 µm (0.0004 to 0.0006 in.) in magnitude show excessively bright indications at wash times less than 240 s.

The curves in Fig. 16f are closely spaced, indicating that the liquid penetrant is very *forgiving* to variations in wash time. Indications for 20 µm (0.0008 in.) film thicknesses are somewhat brighter (for a 240 s wash) than for the liquid penetrant in Fig. 16e product but brightness contrast for the liquid penetrant is less (3.1) than that for the liquid penetrant in Fig. 16e (3.4). In the group of liquid penetrants illustrated in Fig. 16, each with the exception of the one in Fig. 16b exhibits excessive background indications on surfaces with 10 µm (0.0004 in.) porosities.

Similar families of curves can be generated to compare the effects of using different postemulsification schemes.

FIGURE 16. Curves relating brightness contrast to liquid penetrant indication film thickness derived from fractured glass step wedge test panel brightness measurements, for various water washable liquid penetrants and processing conditions.



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CHAPTER

Liquid Penetrant Testing Crack Detection Capabilities and Reliability

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Introduction

Liquid penetrant testing is one of the most widely applied methods of nondestructive testing because of the low cost of application, the perceived simplicity of the process and its ability to be applied to complex shapes with little process adjustment. Liquid penetrant testing is not, however, absolute and is not capable of finding all cracks. The end-to-end liquid penetrant process is bounded by a lower limit for the detection of small cracks (detection threshold). In addition, the detection threshold is not a constant value but depends on multiple parameters inherent to the test object and liquid penetrant procedure applied or are a function of rigid process control in application. Although some confidence may be provided by the ability of a liquid penetrant procedure to reveal a known crack in a test coupon, the brightness or contrast intensity of the liquid penetrant indication may be such that it would not be detected under field conditions if its presence and location were not known. It is foolhardy to assume crack detection if the indication is small or dim or both. The inspection result of importance is *not the smallest discontinuity detected* but *the largest discontinuity missed* by application of a given liquid penetrant procedure.

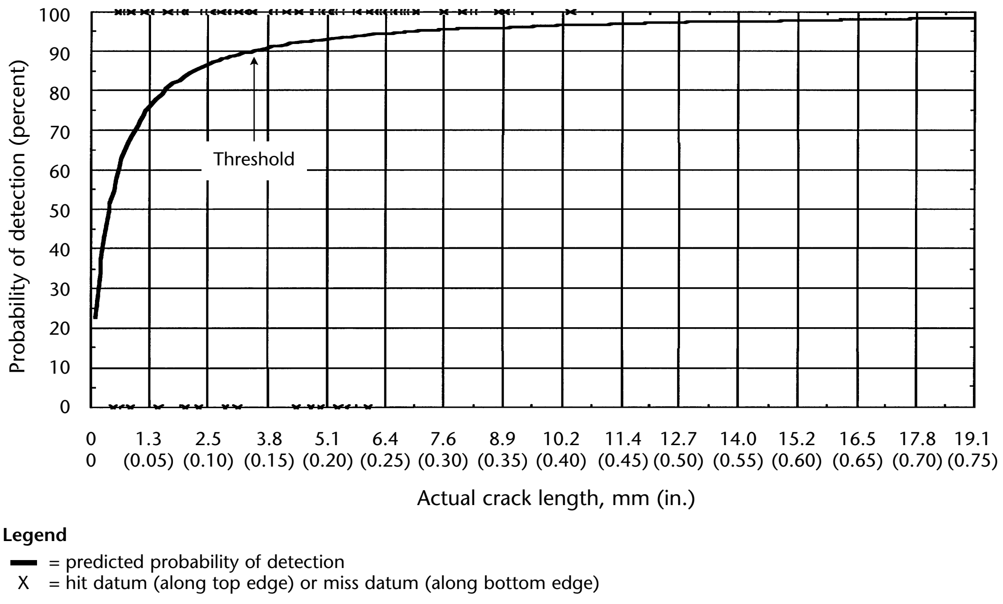
In many liquid penetrant testing applications where requirements are for the detection of large cracks, exceeding 25 mm (1 in.) long, demonstration of liquid penetrant detection capabilities may not be required. Inspections requiring detection of small cracks and critical inspection applications may require demonstration of detection capabilities and rigid process control that includes periodic revalidation of detection capabilities.

Probability of Detection (POD) As Measure of Liquid Penetrant Performance

The recognized metric for ascertaining the detection capability for a liquid penetrant procedure is the probability of detection (POD). A characteristic POD curve is generated by passing a large number of cracks of varying size through a liquid penetrant procedure and recording the cracks that are detected. A standardized data analysis procedure is then used to produce a plot of probability of detection as a function of crack size (typically crack length). Figure 1 is an example of a POD curve for a given liquid penetrant test procedure.

By convention, the threshold detection point is that point where the POD curve crosses the 90 percent threshold and is referred to as the *90/95 probability of detection value* (assuming the number and distribution of crack sizes meet the criteria for standardized analysis). In the example shown, the single valued detection capability is at the 3.5 mm (0.14 in.) crack

FIGURE 1. General form of probability of detection curve for liquid penetrant testing procedure. Accepted 90 percent threshold detection point is noted.



length. Although some cracks smaller than the 3.5 mm (0.14 in.) crack length were detected by the applied liquid penetrant procedure (Xs plotted at the 100 percent detection level) , the procedure did not reliably detect cracks smaller than the 3.5 mm (0.14 in.) crack size.

The *capability* of the procedure is stated as 3.5 mm (0.14 in.) crack length.

The *reliability* for detection of cracks at the 3.5 mm (0.14 in.) level is 90 percent and is a measure of the repeatability and reproducibility for finding a crack at that size.

The *confidence* level for detection at the 3.5 mm (0.14 in.) level is derived from the number and distribution of cracks used to determine the detection capability.

Multiparameter Process

Liquid penetrant testing is a multiparameter process. Changes in one or more of the process parameters can significantly change the liquid penetrant crack detection performance capability. Liquid penetrant process performance depends on the following: (1) test object, (2) discontinuity type, (3) discontinuity size, (4) discontinuity form and state, (5) test materials, (6) test equipment, (7) test process, (8) test environment, (9) test procedure applied and (10) human factors.

The *test object* material, shape (configuration), surface texture (porosity and surface finish), stress state, surface condition and object size are parameters that may affect liquid penetrant process capability. For example, titanium alloys wet differently than aluminum alloys used in aircraft.

The discontinuity type may be a significant factor; for example, a condition for detection is that the discontinuity must be open to the surface and must have an opening such that liquid penetrant can be retained using the applied liquid penetrant procedure. It is obvious that a crack that is covered by a paint layer or smeared metal from a machining or grinding process will not be consistently detectable.

The *discontinuity size* — i.e., length, depth and opening — greatly affect detectability. The brightness of a liquid penetrant indication for a small crack (less than 0.75 mm [0.030 in.]) will be significantly less than that for a larger crack because of the reservoir size. The ability of a human reader to discriminate small indications is typically greater than 0.75 mm (0.030 in.) in length. Because discontinuity size (length and depth) is a basic material parameter used in static design and life cycle analyses, it is the variable that is most often measured, reported or claimed.

The *discontinuity form and state* are more difficult to quantify but must be considered in each liquid penetrant application. It is obvious that a discontinuity must be clean and dry to support reliable liquid penetrant performance. Less obvious is the closure and stress state of a discontinuity (crack). It is known that the brightness of a liquid penetrant indication is decreased for a crack under compressive load, thus small cracks will not be detectable under some loading conditions. In addition, the past load history (in particular, a high overload) may change the configuration of a crack such that a liquid penetrant indication is segmented, with the crack ends visible and the connecting ligament producing a very dim indication.

The *test materials* (liquid penetrant materials) are known to affect the *sensitivity* of a liquid penetrant and liquid penetrant materials are classified by their ability to produce an indication under standardized test conditions. A variety of liquid penetrants of differing *sensitivity* are commercially available and are intended for use in different applications. For example, a high *sensitivity* liquid penetrant would not be suitable for the inspection of a porous material surface because of the background indications produced.

The *inspection equipment* introduces variables in the test process because of the inherent limits and variations for *process control*. For example, a temperature nonuniformity in a drying oven will add to the end-to-end process variance. Ultraviolet radiation intensity, white light background, tank contamination etc. are variables added by the type of equipment or equipment maintenance.

The *inspection process* may introduce major variance in end-to-end performance. For example, dry developer versus wet developer; hydrophilic emulsifier versus a lipophilic emulsifier; or inspection without a developer.

The *inspection environment* can produce wide variances in process performance. Consider variance between in-line processing in a factory environment during component overhaul versus field inspection in the arctic.

The *inspection procedure applied* may cause wide variance in process performance in the form of processing times. The most critical process parameter is the remover time or emulsification time but wash times, dwell times, drying time etc. can add significant performance variance.

Human factors variables are listed last because the human operator has little chance for discontinuity detection if other end-to-end parameters are not controlled. Human factors include the traditional health, attitude, skill level and attention to detail that are related to training, experience and recent experience with the same or similar parts, equipment and processes.

Process Control Is Critical to Liquid Penetrant Performance

The multivariate nature of a liquid penetrant process demands process control to effect repeatable and reproducible results. Indeed, liquid penetrant testing without attention to process control is often an exercise in parts washing. Process control aids and measurement tools such as ultraviolet radiation intensity measurement; artifact panels such as the testing and monitoring (TAM) panels; and periodic measurement of liquid penetrant material properties are essential to reliable liquid penetrant process performance. In addition, attention to detail in equipment and processing materials unique to a particular test object or process line is required for consistent performance.

Periodic proficiency demonstration and validation for human operators is also

Figure 2. Effect of ultraviolet radiation level for liquid penetrant testing procedure (water wash process without developer, on tightly closed fatigue cracks in cobalt alloy; with 55 to 107 lx [5 to 10 ftc] white light illumination): (a) 4 $W·m^{-2}$ (400 $\mu W·cm^{-2}$) ultraviolet radiation; (b) 12 $W·m^{-2}$ (1200 $\mu W·cm^{-2}$) ultraviolet radiation.[1]

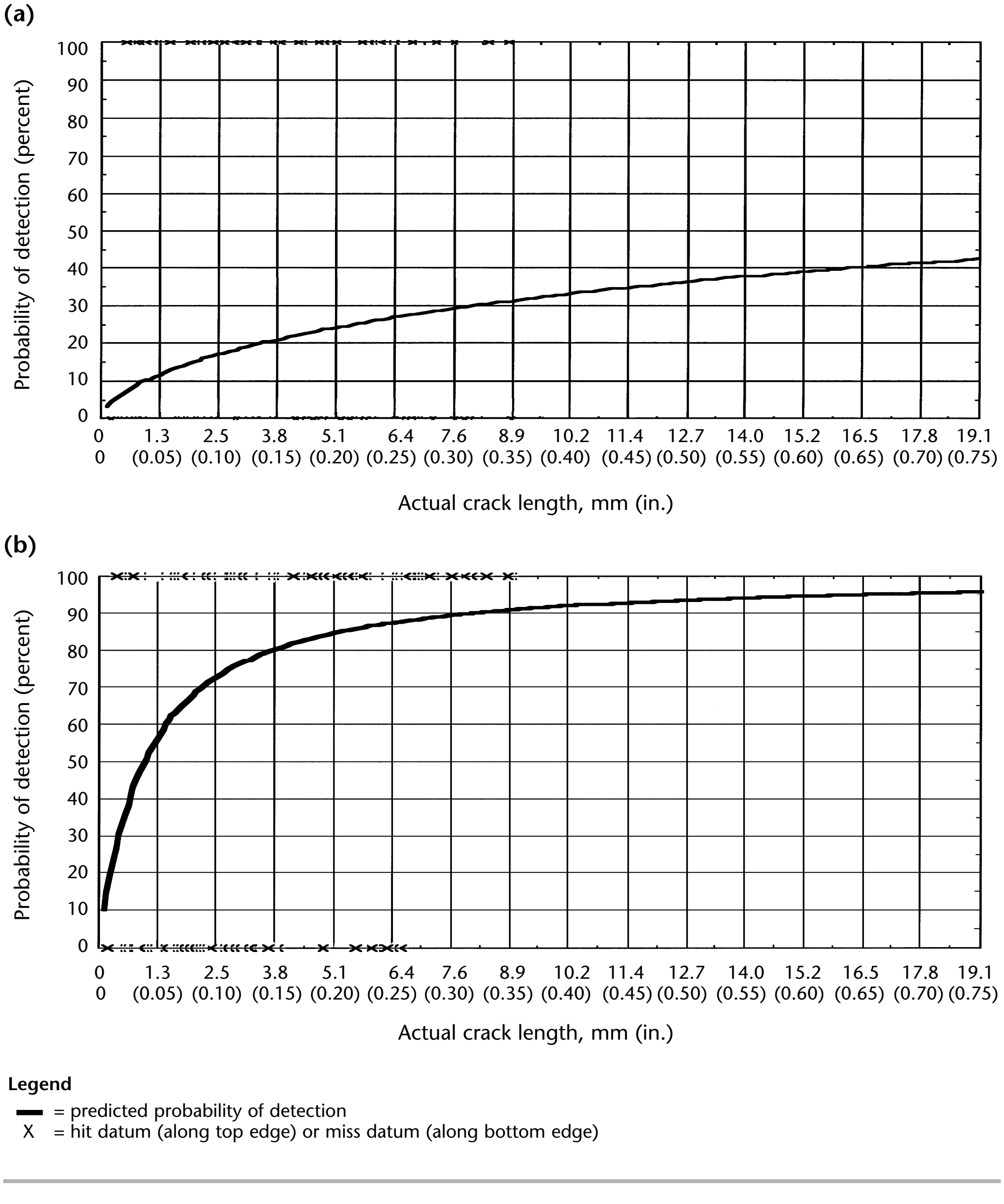
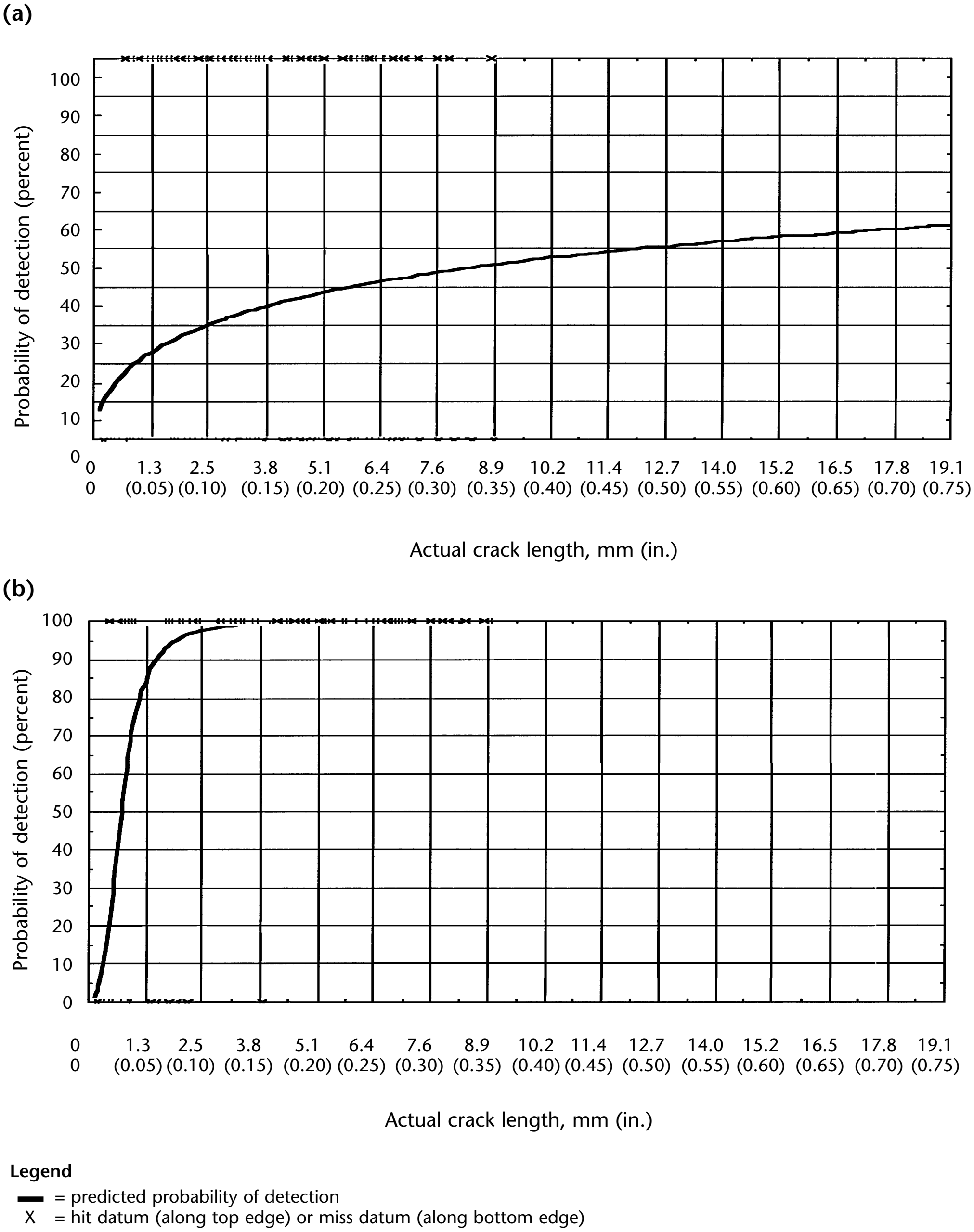


FIGURE 3. effect of developer for liquid penetrant testing procedure (water wash process on tightly closed fatigue cracks in cobalt alloy): (a) without developer, (b) with developer.[1]



essential to end-to-end process control. Additional training may be beneficial but additional training without proficiency demonstration is often a rerun of previous information and may have little benefit in maintaining skill levels.

Process Performance Assessment and Proficiency Demonstration

Variation in end-to-end liquid penetrant process performance is readily observed by comparison of probability of detection (POD) data as a function of varying liquid penetrant process parameters. Table 1 and Figs. 2 to 5 are examples of the assessment of liquid penetrant process parameters

FIGURE 4. Effects of etching and proof test for liquid penetrant testing procedure (solvent remover process; on tightly closed fatigue cracks in 6Al-4V titanium material): (a) as machined condition; (b) after etch; (c) after proof load.[1]

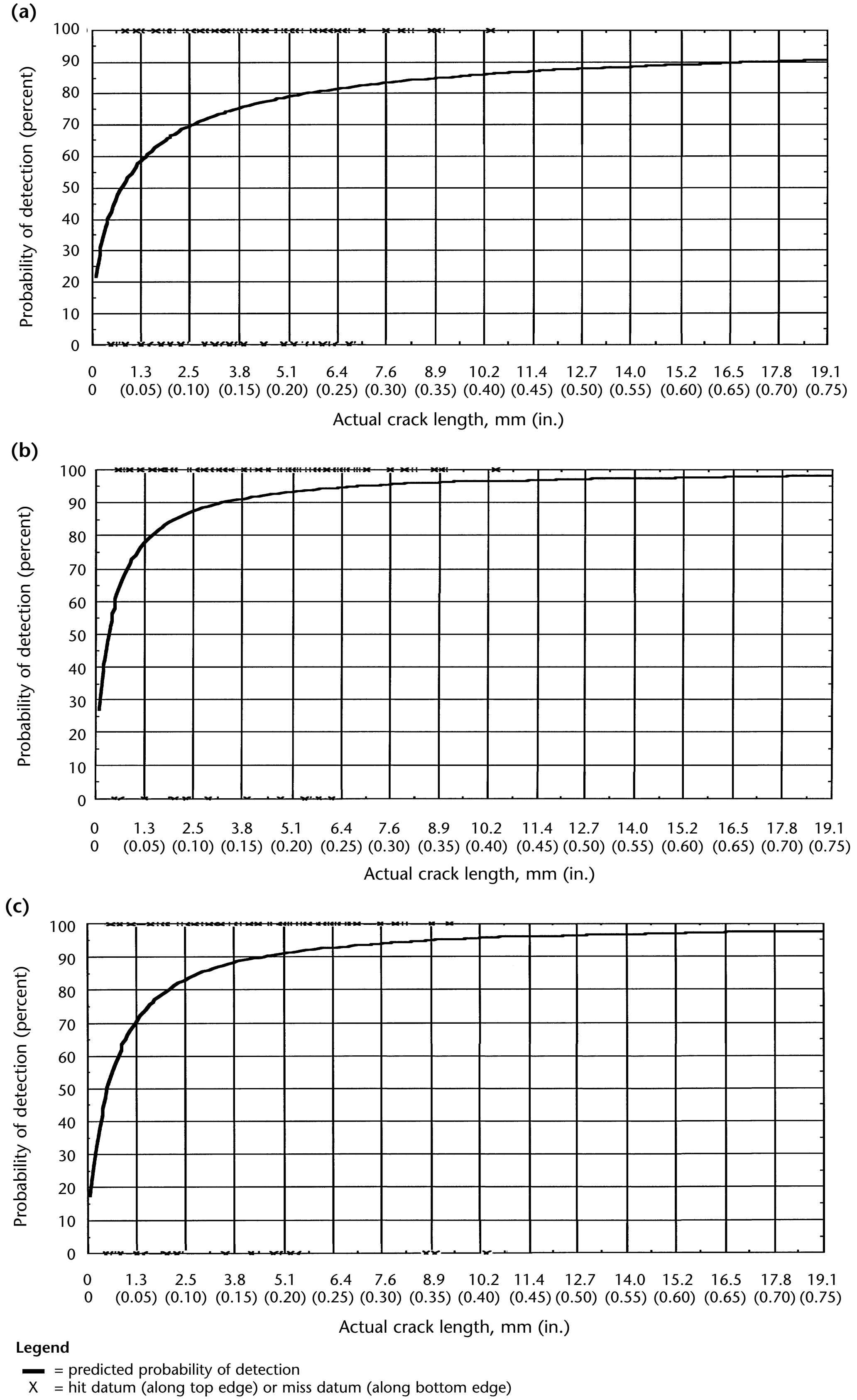
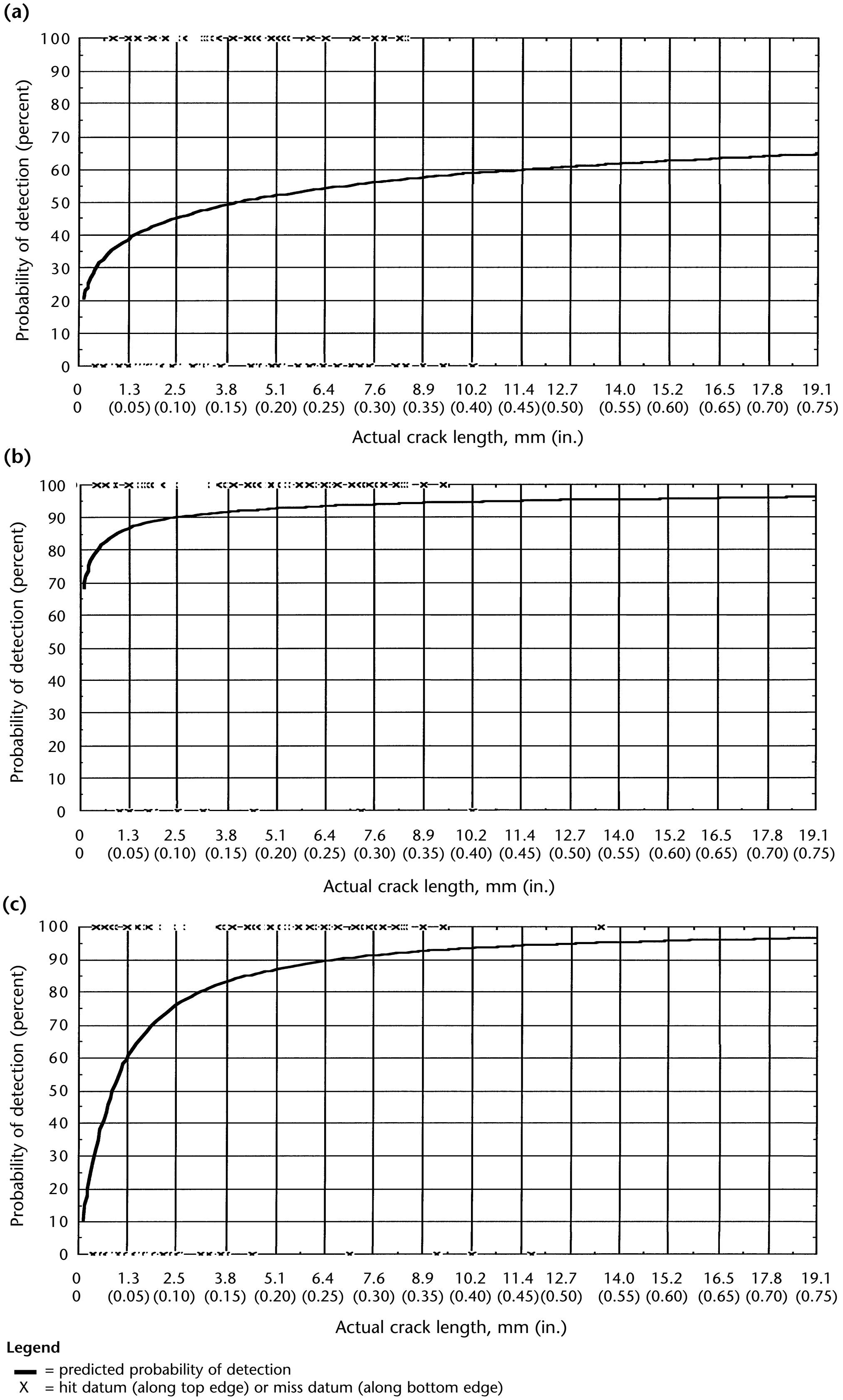


FIGURE 5. Effects of etching and proof test for liquid penetrant testing procedure (solvent remover process; on tightly closed fatigue cracks in AISI 4340 steel material): (a) as machined condition; (b) after etch; (c) after etch and proof load.[1]



using the POD metric. Figures 2 and 3 show results with a heat resistant cobalt alloy resembling SAE AMS 5608D.[2] Figure 2 shows the effect of ultraviolet radiation level on liquid penetrant performance. Figure 3 shows the benefit of using developer on liquid penetrant performance. Figures 4 and 5 show the effects of etching and proof loading on titanium and steel flat plate specimen. Human factors effects are reflected in all data presented. Variations in human factors were reduced by using the same operators for each test sequence presented.

The usefulness of the POD method of liquid penetrant performance assessment is self-evident for purposes of procedure development, procedure improvement and the qualification and validation of process and procedure. For critical applications, POD qualification and validation is often used as a requirement for both facility and personnel performance demonstration.

Human Performance in Liquid Penetrant Testing

The individual performance of the human operator is a significant element in end-to-end process performance capability and reliability. Inspection process parameters are readily measured and controlled by application of appropriate tools when applied by knowledgeable supervision. The readout or interpretation of liquid penetrant indications by human operators is more difficult and encompasses the multiple factors of the workplace environment and development of skill levels applicable to the procedure being performed.

Training and skill development are complimentary but not interchangeable. *Training* denotes transfer of knowledge whereas *skill development* denotes application of knowledge, procedure and experience in performing a specific task. When an operator views a liquid penetrant indication, interpretation is not a *yes/no* decision task as commonly viewed and desired in production application but is instead a problem in conditional probability. The operator is presented with a signal characterized primarily by brightness, size and pattern. The signal is superimposed on a background (nonrelevant indications inherent to the test object and liquid penetrant process — also termed *clutter*) characterized by the same parameters but of a lesser degree or level. For purposes of discussion, the signal characteristics will be termed *signal* and the background characteristics will be termed *noise*. The interpretation problem is to identify the signal in a field that consists of *signal* plus *noise*.

Varying cases of relative levels of signal and noise are shown in Fig. 6. Figure 6a is a case where the *signal* level is significantly greater than the *noise* and clear discrimination is possible. Figure 6b is a case where the *signal* level overlaps the *noise* and *noise* may be interpreted as *signal* (*false call*) or a *signal* may be

FIGURE 6. Three conditions of signal and noise, representing differing levels of defect detection: (a) clear signal-to-noise discrimination; (b) small overlap of signal and noise, some false calls and misses; (c) overlapping signal and noise, poor discrimination.

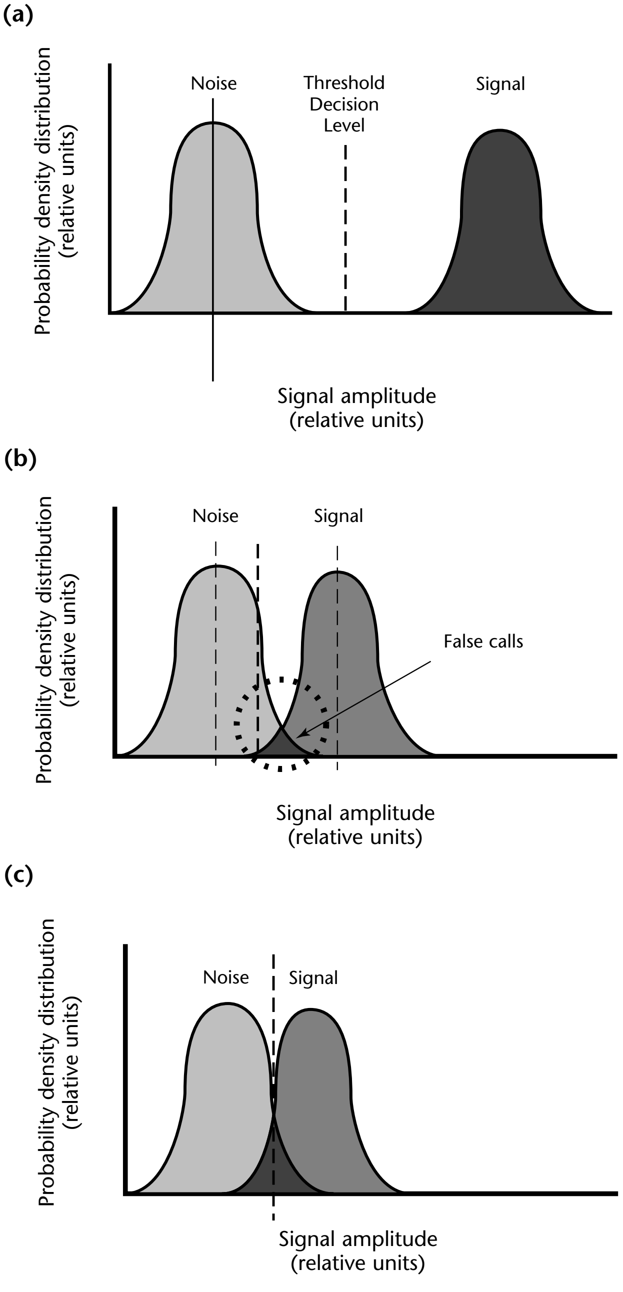


TABLE 1. Accept/reject decision process.

Call	Error Condition	Decision
True positive	none (discontinuity found when discontinuity is present)	reject (correct reject)
False positive	type II (discontinuity found when no discontinuity is present)	reject (false call)
False negative	type I (no discontinuity found when discontinuity is present)	accept (miss)
True negative	none (no discontinuity found when no discontinuity is present)	accept (correct accept)

interpreted as *noise* (*miss*). Figure 6c is a case where the *signal* and *noise* are superimposed and discrimination is not possible. The greater the separation of *signal* and *noise*, the greater the *margin* for correct interpretation. Because *signal* is a direct function of the size and brightness of a liquid penetrant indication, large and bright indications should be readily detectable and have a high probability of detection.

The varying cases of signal-to-noise discrimination are consistent with the POD results shown in Figs. 2 to 5. Larger and brighter liquid penetrant indications produce discrimination at a low level — i.e., developer versus no developer, higher ultraviolet radiation levels and removal of smeared surface material by etching.

As a result of this observation of the liquid penetrant indications, the decision of a human operator has four possible outcomes.

1. A discontinuity may be called when a discontinuity is present (correct call).
2. A discontinuity may be called when no discontinuity is present (Type II error).
3. A no discontinuity condition may be called when no discontinuity is present (correct call).
4. A no discontinuity condition may be called when a discontinuity is present (Type I error).

The conditional probability discrimination decision process is shown schematically in Fig. 7 and Table 1.

FIGURE 7. Four possible outcomes of accept/reject decision. (Probability P is discussed with the published POD data.[1])

Nondestructive evaluation signal (Response to discontinuity)	Stimuli (discontinuity presence) Positive (a)	Stimuli (discontinuity presence) Negative (n)
Positive (A)	$P(A,a)$ True positive (hit) No error	$P(A,n)$ False positive Type II error
Negative (N)	$P(N,a)$ False negative (miss) Type I error	$P(N,n)$ True negative No error

Liquid Penetrant Process Performance Demonstration

The structural integrity of modern engineering materials, components, structures and systems are increasingly dependent on the ability of nondestructive testing processes to find small discontinuities. Components requiring test capabilities below the general detection level are often termed *fracture critical.* Although well intentioned, the *assumed* capabilities for a given liquid penetrant test operation are generally incorrect and, in some cases, the criteria noted on engineering drawings are below the capabilities of the best performing test facilities. Qualification and validation of test facilities, procedures and personnel are therefore required for *fracture critical* components.

Two modes of qualification and validation are in general use; these are the full POD demonstration and the subset demonstration (widely known as the *29-out-of-29 method*). A full POD demonstration is always the most rigorous mode and is used when dealing with new materials, new fabrication processes or new liquid penetrant processing facilities. A full POD demonstration is desirable for qualification of less experienced inspectors. Although the full POD demonstration is desirable, the cost of test components and the time involved warrant consideration of alternative methods. A large amount of liquid penetrant process characterization data has been generated and is available.[1] When requirements are such that a significant *margin* is realized by the use of *standard*, generic liquid penetrant processing techniques, no demonstration may be necessary. When *standard,* generic process techniques are applied to the detection of small discontinuities within the envelope of previously demonstrated capabilities, a subset demonstration may be considered.

A subset demonstration is conducted by generating at least 29 *representative* discontinuities of nominally equal size (but within the previously demonstrated size envelope and using the same materials) and near or below the acceptance limit for the test component. The additional specimens are then considered to be a subset of those previously used for full POD demonstration. The 29 discontinuities are then subjected to the candidate test procedure (operator) and the inspection is completed. Success requires that all 29 of the discontinuities are detected. If a discontinuity is not detected, the detection failure must be resolved. If there is a legitimate cause for missing the discontinuity, the discontinuity may be replaced and the process repeated. Failure to resolve and rectify a missed discontinuity requires full demonstration by the POD method. When the subset method is used for operator skill demonstration and qualification, a failure to detect may be resolved by additional skill development (training alone is not sufficient) and retesting at the end of the defined skill development period. The subset, 29-out-of-29 method provides the required number of test opportunities for a 90 percent confidence level for a single discontinuity size and is consistent with a single point on a demonstrated full POD curve.

The rationale, complexity and analytical methods for full POD demonstration are beyond the scope of this publication. The reader is referred to MIL-STD-1823 for requirements and methodologies for a full POD demonstration.[3]

Summary

Liquid penetrant testing is an effective and economical method of discontinuity detection and is widely used in the process of ensuring the safety and structural integrity of engineering materials, components, structures and systems. Its wide use and superficially simple application result in a wide range of results that vary from consistent detection of critical discontinuities to parts washing exercises that do not add value to the parts. Fortunately, it costs no more to perform a valid inspection than it does to conduct a parts washing exercise. It is logical that a multiparameter testing process requires attention to detail and process control for successful application. The tools and techniques for materials and process control are readily available. The end to end process performance may also be quantified using the information and techniques discussed herein. If the principles and technique described are used, capable and reliable performance may be expected and demonstrated to ensure continuing excellence in liquid penetrant processing and continuing confidence in the safety and structural integrity of engineering systems.

The smallest discontinuity found is of academic interest. The largest discontinuity missed is of critical importance to reliable liquid penetrant testing.

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CHAPTER

Liquid Penetrant System Chemistry and Effluent Waste

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Part 1. Effects of Sulfur and Chlorine Impurities in Liquid Penetrant Materials

Influence of Sulfur and Halogens (Chlorides) in Liquid Penetrant Testing Materials

Considerable concern in the nondestructive testing field is directed toward the effects of sulfur and halogens, principally chlorides, present in small amounts in liquid penetrant testing materials. This is largely attributable to various high temperature and exotic alloys such as nickel base alloys, austenitic stainless steels and titanium in the aerospace and nuclear industries. Even though liquid penetrants and processing materials are removed following testing, residues may be retained in crevices, joints and blind holes or other inaccessible areas. With inadequate cleaning, such residues may react detrimentally with the alloy surface after the components are placed in service.

Sources of Sulfur and Halogen in Liquid Penetrant Testing Materials

There are several possible sources for the presence of sulfur and halogen in liquid penetrant products. Raw materials from which liquid penetrant products are formulated may contain either or both of these ingredients as constituents or as trace contaminants. Where extremely small amounts of these ingredients are of concern, contamination from a high sulfur or high halogen atmosphere may contribute trace amounts of sulfur or halides. There is considerable difference of opinion as to the allowable limits of these contaminants. Paradoxically, there are numerous sources of sulfur and halide contamination that far overshadow the amounts present in liquid penetrant products, as in the following examples.

1. In certain techniques, precleaning takes place before liquid penetrant testing. Conceivably, residues from these operations could contribute significant residues.
2. Other in-process sources of contamination include cutting fluids or drawing and stamping oils. These fluids may contain high percentages of sulfur and/or chlorides.
3. Industrial waters may contain relatively high contents of chloride. Therefore cooling water, rinse water, makeup water for alkaline cleaners and other types of chemical processes may contribute either chlorides or sulfur residues.
4. In the case of jet engine components, ingestion of sea air or air containing high sulfur through industrial pollution can contribute very significantly to the amount of chlorides or sulfur gaining access to high temperature alloy parts.
5. Another possible source for sulfur contamination in jet engine components would be the jet engine fuel itself. All petroleum derivatives tend toward trace amounts of sulfur and, because of the high rates of throughput of jet engine fuel, the aggregate amount could be substantial.

Specifications Restricting Halogen Content of Liquid Penetrant Testing Materials

The continued incidence of stress corrosion cracking in austenitic stainless steels has focused increased attention on the halogen and sulfur content in liquid penetrant materials used for nondestructive testing. Restrictions are placed on the halogen and sulfur concentrations allowed in liquid penetrant materials intended for use on austenitic stainless steels.

Influence of Sampling Procedures on Contamination Measurements

It is important to recognize that, because of the nature of certain liquid penetrant materials, the sampling procedures can often influence the results of a given way of measuring chloride concentration. When fluorocarbon propellants and halogenated hydrocarbon solvents (such as 1,1,1-trichloroethane) were being used, they affected the results of chloride analysis, whether the test was performed on the whole sample or on the residue after evaporation of solvent or propellant. Most specifications still require residue analysis that gives more consistent and meaningful results.

Significance of Postcleaning of Test Objects

The purpose of the final postcleaning step in a liquid penetrant examination is to remove, as thoroughly as possible, all liquid penetrant materials applied during the test process. Thus, simple knowledge of the halogen content in liquid penetrant materials provides little useful information relative to the amount of halogen remaining on the part after liquid penetrant testing. On the other hand, even if all traces of halogen or sulfur bearing liquid penetrant materials are removed from the smooth surfaces of the part, the possibility of retaining damaging quantities of these compounds in macro (mechanical) or micro (intergranular) crevices should not be ignored.

Stress Corrosion Testing of AISI 304 Austenitic Stainless Steel[1]

The potential for liquid penetrant induced stress corrosion cracking in American Iron and Steel Institute (AISI) 304 stainless steel was investigated by coating U-bend test specimens with various liquid penetrant materials and exposing them to a moist 90 °C (195 °F) atmosphere for about three months. Test specimens, representing three different metallurgical conditions, were used to evaluate 19 different liquid penetrant, developer, emulsifier and cleaner materials having different halogen content and representing several manufacturers.

Metallurgical Conditioning of AISI 304 Stainless Steel Specimens

Test specimens for each of the following metallurgical conditions were used in the evaluation: (1) solution annealed, (2) sensitized and (3) sensitized and etched. The solution annealed specimens were included because AISI 304 stainless steel in this metallurgical condition is much less susceptible to halogen induced stress corrosion cracking than material in the sensitized condition. Specimens that were both sensitized and etched were included to examine the effect of microcrevices, which can conceivably retain appreciable quantities of liquid penetrant materials in spite of normal postexamination cleaning procedures. On completion of the metallurgical conditioning processes, the specimens were stressed using a stainless steel nut and bolt. Figure 1 illustrates the specimen configurations after forming and after stressing.

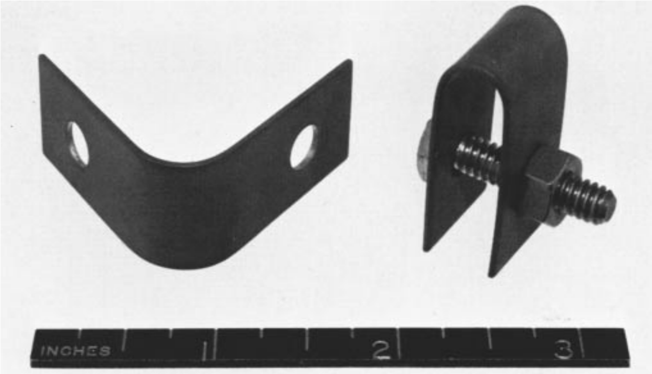
Application of Liquid Penetrant Testing Materials to Test Specimens

The final step in preparing the specimens for exposure testing was to apply the liquid penetrant materials. This was accomplished by immersing three stressed specimens from each of the three metallurgical groups in a given liquid penetrant material for about 6 h, after which the specimens were allowed to drain overnight in the open-end-down position.

Water Vapor Exposure Conditions for Test Specimens

Each specimen was hung, open end down, on a three layer rack formed from a single length of AISI 304 stainless steel tubing. The entire specimen and rack assembly was subjected to a warm, moist test atmosphere in an exposure chamber for a period of 80 days. A pool of distilled water was maintained in the bottom of the chamber and the temperature was maintained about constant at 90 °C (195 °F). Cold tap water was passed through the tubing rack to condense moisture on the specimen surfaces.

Figure 1. Stainless steel U-bend test specimens after forming (left) and after stressing (right).



Results of Stress Corrosion Exposure Tests of AISI 304 Stainless Steel

The effect of the moist exposure conditions on test specimen integrity was evaluated by metallographic examination. First, several of the control specimens were sectioned and examined at 100× magnification as a check on the validity of the test parameters. Specimens in the sensitized and etched conditions, each of which had been coated with one of the liquid penetrant materials, were similarly examined for evidence of stress corrosion cracking. Examples of the metallographic examination results are shown in Fig. 2 to 6. Figures 2a and 2b are typical of the control specimens in the sensitized and in the sensitized and etched conditions, respectively. These uncontaminated specimens were completely unaffected during the 80 day exposure test, as were most of the coated specimens.

Effects of Chlorine in Specific Liquid Penetrant Cleaner and Developer

Intergranular cracking to about midthickness is evident in the AISI 304 stainless steel specimen which is shown in Fig. 3 and which was sensitized and coated with developer containing 0.2 percent chlorides. Figure 4 is typical of the three specimens that were sensitized and etched before being coated with the same developer. Figures 5 and 6 illustrate the severe intergranular and transgranular cracking that occurred when sensitized test specimens were coated with a cleaner containing about 80 percent chlorides. The specimen shown in Fig. 5 was in the sensitized condition whereas the specimen in Fig. 6 had been sensitized and etched to a depth of about 130 µm (0.005 in.) before application of the cleaner.

Overall Results of Stress Corrosion Tests on AISI 304 Stainless Steel

The overall results of the moisture exposure tests on AISI 304 austenitic stainless steel specimens are summarized below.

1. Specimens coated with a cleaner that had a very high chloride content or a developer with low chloride content (see Figs. 3 to 6), consistently exhibited stress corrosion cracking after the 80 day exposure test when in the sensitized or sensitized and etched conditions.
2. None of the other liquid penetrant materials evaluated in this test caused detectable stress corrosion cracking.
3. Etching of the sensitized specimens did not appear to have reproducible effects on the severity of attack for the liquid penetrant materials that induced stress corrosion cracking.

FIGURE 2. Photomicrograph of sensitized AISI 304 stainless steel specimen (typical of five control specimens not coated with liquid penetrant test materials), after 80 day stress corrosion test in warm, moist atmosphere and after oxalic acid etch: (a) sensitized specimen; (b) etched specimen.

(a)

(b)

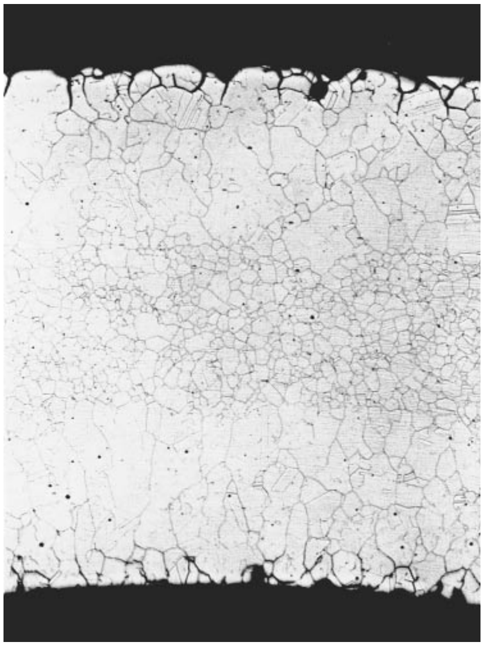


Figure 3. Photomicrograph of sensitized specimen after 80 day exposure test and oxalic acid etch is typical of three specimens coated with developer.

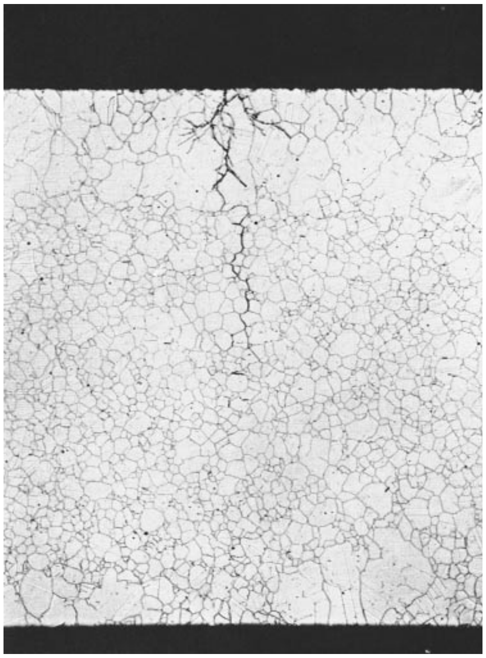


Figure 4. Photomicrograph of sensitized and etched specimen after 80 day exposure test and oxalic acid etch is typical of three specimens coated with developer.

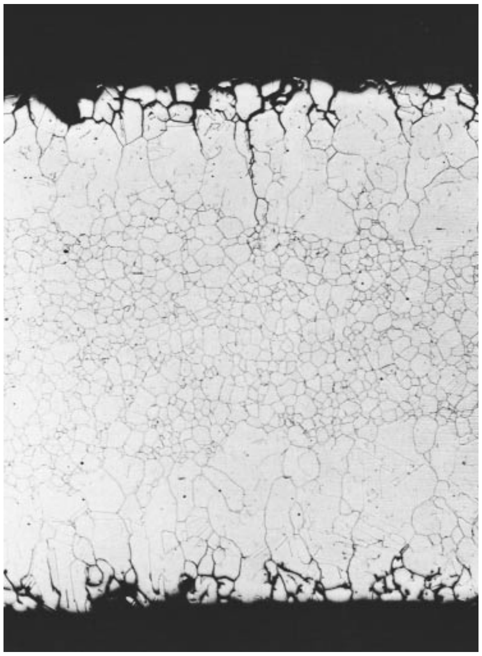


Figure 5. Photomicrograph of sensitized specimen after 80 day exposure test and oxalic acid etch is typical of three specimens coated with cleaner.

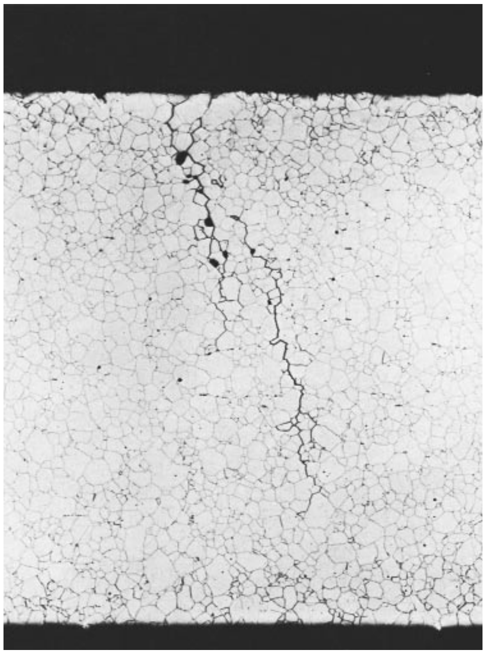
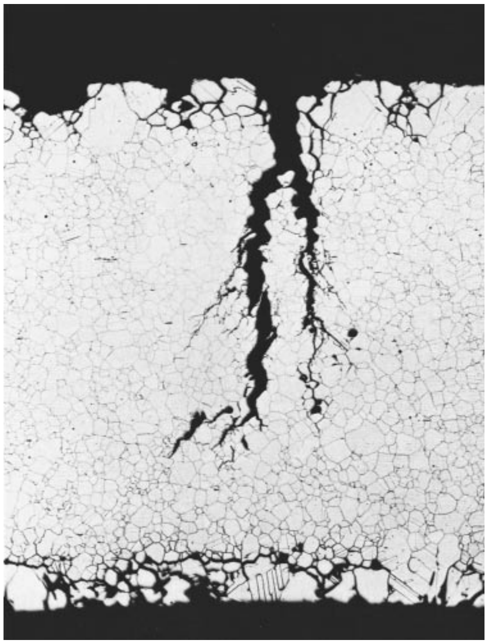


Figure 6. Photomicrograph of specimen sensitized and etched to depth of about 130 µm (0.005 in.) after 80 day exposure test and oxalic acid etch is typical of three specimens coated with cleaner.



4. Specimens in the solution annealed condition exhibited no evidence of stress corrosion attack.
5. Observations among triplicate specimens were fully reproducible.

The results obtained during this study support the following conclusions.

1. The reproducibility of the exposure test results provides convincing evidence that certain liquid penetrant materials can induce stress corrosion cracking under the moderate exposure conditions investigated.
2. The determination methods that were developed offer an economic and reliable means of measuring chloride concentration in whole samples of liquid penetrant materials over the range of 10 to 1000 $\mu g \cdot g^{-1}$.
3. Commercial liquid penetrant materials with total chloride concentrations below 1000 $\mu g \cdot g^{-1}$ are available.
4. Liquid penetrant materials from dichlorodifluoromethane (refrigerant-12) pressurized spray cans yield variable results when whole samples are analyzed, thus making it impossible to perform a reliable determination of chloride concentration.

Specifying Liquid Penetrant Materials to Avoid Induced Stress Corrosion Cracking[1]

It should be recognized that the cause of the stress corrosion cracking observed in the preceding tests is not actually known. These tests were designed only to examine the potential for liquid penetrant induced stress corrosion cracking under a specific set of exposure conditions and were not intended to isolate the cause of an attack that might be observed. Liquid penetrant materials that induced the observed stress corrosion cracking would qualify as acceptable materials in accordance with the halogen restrictions specified in applicable United States standards in effect from 1971 through 1981.

It thus appears that restrictions on contaminant concentrations might be more appropriately specified for whole samples (including volatiles) instead of only for the residue, as is the prevalent practice. It also seems significant that, although most specifications restrict *total halogens,* none of the methods normally used to verify compliance (including those discussed herein) respond to fluoride. Thus, in actual practice, the most reactive of the halogen elements was tacitly ignored until 1981.

Sources of Halogen Impurities in Liquid Penetrant Processing Materials

Except for the certain cleaners and carriers that use halogenated hydrocarbon compounds, liquid penetrant materials do not usually contain halogens as constituent elements. Rather, the halogens occur as impurities in the bulk chemicals used to formulate these liquid penetrant materials. Preceding tests also indicate that commercial liquid penetrant materials can exhibit a rather wide variation in chloride content. It is also apparent that liquid penetrant materials quite low in hydrolyzable and even in total chloride content are available. The same statement can probably be made about fluoride content.

Specification Restrictions on Sulfur Content of Liquid Penetrant and Leak Testing Materials

For years, most new standards have included an upper limit for total sulfur impurities in expendable materials such as liquid penetrants, cleaners and developers; leak test fluids; coatings; adhesives; lubricants; and ultrasonic couplants. In contrast to the effect of halogens, sulfur and its compounds were not found to be significantly corrosive nor otherwise damaging to austenitic stainless steels at ambient temperatures. However, stress cracking does take place on high yield strength ferritic and austenitic steels when sulfides exist in the aqueous phase and on nickel and its alloys when sulfides are present during elevated temperature processing.

Like halogens, sulfides have been related to the tendency toward hydrogen embrittlement. Investigators agree that minimizing residual amounts of sulfur in materials applied to iron base and nickel base alloys will reduce the likelihood of stress corrosion or sulfide stress cracking. Selection should be based on which product has the lowest sulfur content, as well as the lowest halogen content. The following information describes the action of sulfur compounds on different classes of structural materials.

Hydrogen Damage from Sulfur Compounds in Nonstainless Steels

When an acid solution attacks a carbon or alloy steel surface, hydrogen is generated and deposited on the metal surface as an adsorbed film of atomic hydrogen. Normally, the film builds up and bubbles off the surface as molecular hydrogen gas. However, in the presence of even a few parts per million of hydrogen sulfide in the solution environment, much of the atomic hydrogen enters high strength steel. The presence of a sulfide in the steel appears to catalyze the generation of hydrogen. The formation of molecular hydrogen internally in voids produces high pressure, creates blisters on the surface and reduces the ductility. Delayed failures then can occur at stress levels well below the yield strength. The minimum yield strength level for sulfide stress cracking is about 600 MPa (90 000 $lb_f \cdot in.^{-2}$). The tendency for cracking is reduced as the pH rises from 3 to 6 (solutions become less acid). Inorganic and aliphatic organic sulfur compounds are generally more reactive than aromatic organics. Sulfide corrosion of nonstainless steel is reduced by the presence of halides in the low temperature aqueous phase.

Corrosive Effects of Sulfur on Various Alloys

High Yield Strength Stainless Steels

The high yield strength AISI 635 stainless steel (17 percent chromium, 7 percent nickel) is very susceptible to cracking in a high sulfide environment (1000 $\mu g \cdot g^{-1}$ of hydrogen sulfide). Stainless steels with chromium contents less than 9 percent may corrode faster in a given sulfide concentration than carbon steel.

AISI 300 Austenitic Stainless Steels

Adequate protection against sulfide corrosion is provided by the lower strength standard AISI 300 series austenitic stainless steels with a basic alloy content of 18 percent chromium and 8 percent nickel.

Iron Base Alloy with 14 Percent Chromium and 14 Percent Nickel

The effect of sulfur as an impurity in a completely stable austenitic structure — a high purity 14 percent chromium, 14 percent nickel, iron base material — was evaluated in five such alloys with sulfur impurities: 80, 120, 240, 890 and 1700 $\mu g \cdot g^{-1}$. Nonstress corrosion rates appeared to be directly related to sulfur content. Corrosion was uniform rather than localized. The extent of attack was slight compared with that found for commercial purity 14 percent chromium, 14 percent nickel, 72 percent iron alloys and of commercial, high temperature steels such as AISI 304.

Stressed U-bend samples of 14 percent chromium, 14 percent nickel, iron base alloy representing the five levels of sulfur were exposed to 42 percent boiling magnesium chloride for 600 h. No evidence of cracking was observed. Similar alloys of commercial purity cracked after only 28 h exposure of the stressed samples to the strong chloride corrodent.

It was concluded that, to produce excellent corrosion resistance to aggressive media, all impurities, rather than just sulfur, must be excluded from austenitic stainless steels. Although increasing additions of sulfur increased the corrosion rate slightly in the high purity austenitic matrix, the corrosion rate of the 1700 $\mu g \cdot g^{-1}$ or 0.17 percent sulfur alloy was much below that of commercial purity materials. Residual sulfur accumulations from liquid penetrant materials would not pose a special corrosion or stress corrosion problem at temperatures below 100 °C (212 °F) for parts produced from austenitic stainless steels.

Nickel and Nickel Base Alloys

Materials in which nickel predominates are subject to intergranular attack when they are heated in the presence of sulfur and sulfur compounds. Grain boundary stress corrosion cracking and nickel has occurred in sulfide environments above 643 °C (1190 °F), the melting point of the nickel/nickel sulfide eutectic.

Fuels used in the heat treatment of nickel base alloy materials must have a low sulfur content. A marginal concentration of sulfur is stated to be 0.73 $g \cdot m^3$ of gases manufactured from coal and oil. Lubricants for deep drawing and spinning nickel alloys generally contain sulfur or lead and therefore must be removed before annealing.

Environmental Conditions Affecting Intergranular Attack

Intergranular attack by sulfur has been reported only for nickel base alloys subjected to elevated temperatures. However, it seems probable that austenitic stainless steels could also be adversely affected by exposure to sulfur or its compounds in its sensitizing temperature range of 590 to 650 °C (1100 to 1200 °F). At temperatures below 150 °C (300 °F), steels with a maximum yield strength of 520 MPa (75 000 $lb_f \cdot in.^{-2}$) should not be subject to sulfide stress cracking. The tendency for hydrogen absorption and embrittlement is reduced by raising the pH of the environment to 6 or greater. High yield strength austenitic such as 17 percent chromium, 7 percent nickel alloys should not be susceptible to cracking if the sulfide content of the environment is kept well below 1000 $\mu g \cdot g^{-1}$.

PART 2. Mechanisms of Stress Corrosion Cracking of Austenitic Stainless Steels

Restrictions on Halogens in Expendable Test Materials Used on Austenitic Stainless Steels

For years, it was common practice in the aerospace industry to use halogenated cleaners, acids and degreasers in the treatment of AISI 300 series stainless steels. However, pressure vessel codes and other standards in the United States prohibit expendable cleaners, liquid penetrants and processing materials containing more than one percent halogens. Investigations of cause and prevention of stress corrosion cracking of stainless steel have demonstrated that less than 50 $\mu g \cdot g^{-1}$ of certain hydrolyzable chlorides in combination with 1 to 200 $\mu g \cdot g^{-1}$ of oxygen can cause cracking under low stress and low temperature conditions. The likelihood of stress corrosion will diminish with decreases in concentration of halides and/or oxygen, with decreases in stress and with decreases in temperature. Laboratory specimens of stressed austenitic stainless steels failed when immersed in a 5 $\mu g \cdot g^{-1}$ chloride solution at 93 °C (200 °F) and in a 10 $\mu g \cdot g^{-1}$ chloride solution at 74 °C (165 °F).

Because chloride concentrations in normal environments and residual stresses from fabrication and heat treatment generally exceed these levels, one might wonder at the usual long life and high performance characteristics of most stainless parts. There may be a relationship between hydrogen embrittlement and stress corrosion cracking. A further restriction of hydrogen generation in the right form and location could limit the chance for stress corrosion cracking to occur.

The fact that many of the halogen compounds are volatile does not negate the potential danger. Cyclic evaporation and subsequent condensation is actually a means of concentrating the halogen in a restricted area such as a crack or crevice. Entrapment and contamination with surface adherent material can reduce the tendency of halogen compounds to become volatile.

Mechanisms of Stress Corrosion Cracking of Austenitic Stainless Steels

Austenitic stainless steels can fail by stress corrosion cracking, a brittle failure in ductile material which occurs as a result of the combined action of tensile stress and corrosion. Tensile stress may be externally applied or residual but it must be sustained or static. Where allowable, shot peening to alleviate surface tensile stresses will reduce the tendency for cracking. Although the minimum stress to initiate stress corrosion cracking will vary with the environment and with steel composition differences, stresses reportedly as low as 14 MPa (2000 $lb_f \cdot in.^{-2}$) have resulted in stress corrosion cracking of AISI 347 austenitic stainless steel. It would seem that significant stress concentrators would have to be operating to bring about such low stress failure in AISI 347 surrounded by vapors at 200 °C (400 °F) containing 50 $\mu g \cdot g^{-1}$ of chloride.

Other Mechanisms of Cracking of Austenitic Stainless Steels

Not all cracking occurring in fabrication or service is halide induced. Three other modes of failure exist that can take place at stress levels below the yield strength of austenitic stainless steel in a noncorrosive environment.

1. Fatigue failure may be induced thermally, mechanically or by vibration during operation.
2. Long time, elevated temperature stress rupture may occur.
3. Differences in coefficient of expansion and in thermal conductivity between cladding and base metal may lead to failure.

In boiling water reactors, non–stress corrosion cracks were found to be longitudinal in cold worked tube and circumferential in solution annealed tubing. Although all potential causes should be considered in a failure investigation, good design should minimize the likelihood of cracking from mechanisms other than stress corrosion.

Fracture Paths Resulting from Stress Corrosion

Both intergranular fracture and transgranular fracture may occur as a result of stress corrosion. Usually, cracking produced in stainless steel exposed to chlorides is transgranular. However, where there is a continuous grain boundary segregation, intergranular cracking will take place. There is a disposition toward a chemical concentration differential between grains and grain boundaries because impurities and alloy constituents tend to diffuse to the boundaries.

Segregated solute such as silicon or phosphorus can occur in the grain boundaries of properly solution annealed AISI 304. On the other hand, a continuous grain boundary part of second phase, alloy carbides is formed by a sensitizing treatment at 663 °C (1225 °F) for 2 h followed by slow cooking. The likelihood of forming continuous carbide at the grain boundaries is a function of grain size and carbon percent.

The tendency for grain boundary attack by a corrodent is independent of pH between 4.7 and 9.4. Surface pickling with boiling nitrate chromate can cause cracking only on sensitized material. Intergranular attack on an oxide free surface will only happen on stressed material or in crevices.

Causes of Crack Initiation

Plastic deformation may be a necessary condition for establishing a propensity for cracking. In austenitic stainless, even elastic strain is associated with a small amount of creep (plastic strain). Cracks can originate from elongated pits or from eroded grain boundaries. Reducing the temperature of the environment extends the life of the part before crack initiation but does not alter the minimum stress level requirements for cracking.

Stress corrosion cracking always produces corrosion products. Apparently, reaction of the chloride on bare metal exposed at breaks in the protective oxide film on the stainless steel produces local anodic areas. The latter set up galvanic action leading to pitting and thence to crack initiation when under tensile stress. The minimum stress to initiate stress corrosion cracking depends on (1) the nature of the corrodent medium, (2) temperature, (3) anion availability, (4) history of the material and (5) availability of minimum amounts of chloride and oxygen or minimum amounts of hydroxide.

The rate of corrosion is unaffected by varying the initial hydrogen ion concentration (pH) of the solution. The concentration effect of intermittent wetting and drying will shorten the time required for crack initiation. Under a constant stress level, cracking will occur most easily at 85 °C (185 °F), the maximum temperature for corrosion acceleration at a high enough level for crack initiation. The temperature limitation of 85 °C provides a minimum driving force for progressive corrosion such that cracking must occur within 48 h or the rate of passive film repair will exceed the rate of penetration.

Test for Susceptibility to Stress Corrosion

The establishment of a *standard* corrosion medium could serve as a tool for measuring the susceptibility of material or parts to stress corrosion cracking. Because 875 $\mu g \cdot g^{-1}$ of sodium chloride vapors at 200 °C (400 °F) will produce severe cracking in a short time, this might be used as such a standard corrosion medium.

Electrochemical Theory of Crack Propagation

The electrochemical theory of stress corrosion assumes crack advancement by anodic dissolution of stained metal at the crack tip. It has been postulated that nitrogen may be responsible for the corrosion attack on strained, crack sensitive areas. Based on work with low nitrogen, 18 percent chromium, 8 percent nickel and 20 percent nickel alloys, investigators suggest that nitrogen, under conditions of lattice strain, readily diffuses to lattice imperfection sites. Nitride precipitation then forms a cathodic area that stimulates corrosion of the adjoining alloy, thereby favoring crack propagation.

In nonsusceptible high nickel alloys, nickel apparently inhibits the formation of the cathodic precipitates. Electron microscopy has revealed what appear to be precipitated nitrides on slip planes. Slip increases the effective area of the cathodic nitride precipitates and thereby increases galvanic corrosion and aids crack propagation. Cracking may occur at anodic paths because of reaction of stainless steel with corrosion produced hydrogen. This hydrogen diffuses under an applied load to form stress oriented transgranular bands of hydrogen strained ferrite. Such transformed bands, highly anodic to the austenitic matrix, dissolve in a corrosive halide such as magnesium chloride to cause cracking. In nonsusceptible alloys, hydrogen precipitates as a hydride.

Some investigators suggest that cracking originates from a condition of reduced surface energy brought about by the adsorption of some ion species from the corrosive medium. Electrochemical processes might contribute to failure by removing existing films at localized areas that would otherwise prevent adsorption of the critical ion species or, at higher stress levels, might prevent healing of oxide films that become ruptured during loading.

Electrochemical/Mechanical Theory of Crack Propagation

The electrochemical/mechanical theory of stress corrosion presupposes a two stage repeating cycle consisting of a short period of chemical attack, which advances the crack very little but which triggers a sudden mechanical fracture over a longer distance and which is stopped apparently by a soft slip plane. Once a crack is initiated, it is not permanently arrested by contact with grain boundaries, twin planes, or inclusions, nor is its propagation influenced by changes in applied stress or by changes in the nature of the medium.

At a low stress level, cracking occurs only in the area of the highest stress. Studies indicate that cracks extend in short bursts at average rates up to 4 $mm{\cdot}h^{-1}$ in the condensing vapors above an 875 $\mu g{\cdot}g^{-1}$ sodium chloride solution at 204 °C (400 °F) or up to 10 $mm{\cdot}h^{-1}$, in a boiling magnesium chloride environment. Some investigators have recorded acoustic emission, suggesting association with crack extension. Other investigators were unable to detect acoustic emission during crack propagation.

These observations suggest that very little acoustic emission activity accompanies intergranular stress corrosion cracking whereas the opposite is indicated for transgranular stress corrosion cracking. Perhaps high *stacking fault energy,* indicating tangled dislocations and easy cross slips in an alloy, inhibits cracking. Rapid stress corrosion crack propagation occurs in alloys having highly oriented dislocations (low stacking fault energies) and restricted slip.

Effect of Wedging Action of Corrosion Products

Deposition of corrosion products within progressing cracks may provide a wedging action that causes brittle fracture beyond the tip of the crack. Pressures in excess of 50 MPa (7000 $lb_f{\cdot}in.^{-2}$) have been measured for the wedging action of the corrosion product. It has been proposed that the chemical aspects of cracking are due to preferential attack on small quantities of transformed austenite at the tip of the crack or as a network of strain bands within the austenite grains.

The trace of a crack on the surface does not necessarily indicate that the same propagation process fracture path has occurred in the bulk. The three dimensional path of a crack is determined mainly by the stress distribution near the advancing edge. This is not necessarily related to microstructural features (grain size and orientation) or crystallographic planes.

Effect of Hydrogen Embrittlement on Stress Corrosion Cracking

Hydrogen embrittlement must be assumed to have relation to stress corrosion cracking. It is known that protons (hydrogen nuclei) can move along with dislocations during plastic deformation because of the mobility of the proton. Hydrogen embrittlement can only occur when the proton diffusion rate is equal to or greater than the rate of movement of dislocations. Hydrogen collects preferentially in the tetrahedral lattice positions in the (112) planes, in the discontinuities associated with these planes and probably in the dislocations related to this crystallographic system. Movement of the most unstable dislocations can be accomplished in the presence of hydrogen by stresses well below the elastic limit, resulting in delayed failures.

Stress Corrosion Immunity, Susceptibility and Prevention

Six general rules postulated for susceptibility to stress corrosion are listed below.

1. A pure metal is immune to stress corrosion cracking.
2. Alloys made from pure metals may be susceptible.
3. Corroding conditions (media or environment) that produce cracking are specific to an alloy or alloy system.
4. Cathodic protection can prevent stress corrosion cracking or even stop crack propagation if applied while cracking is in process.
5. One or more minor impurity elements in a metal or alloy can affect its degree of immunity or susceptibility.
6. Changes in structure or homogeneity of an alloy by heat treatment can influence its immunity or degree of susceptibility.

Effect of Cathodic Protection on Stress Corrosion Cracking

A small amount of cathodic protection may inhibit stress corrosion cracking whereas a large amount may induce it. Arrangement of anodes in reactors, piping and heat exchangers for sufficient protection is frequently impossible and sacrificial anodes may be undesirable because of the corrosion products introduced into the coolant. Where the highly stressed component is the cathode, stress corrosion cracking may be stopped or restarted at will by applying an external potential.

Conditions Conductive to Stress Corrosion Cracking

Wherever combinations of high residual stress, crevices for entrapment of halides or hydroxides, heat transfer, evaporation and concentration occur, stress corrosion cracking is likely. Chlorides can also concentrate in aluminum corrosion products by an ion exchange mechanism. Thus, fabricated stainless steel parts that have been tested with liquid penetrants or cleaned by chlorinated solvents are prime targets for stress corrosion.

Conditions That Inhibit Stress Corrosion Cracking

Any approach to prevention or inhibition of stress corrosion cracking requires an understanding of the mechanism of cracking. A reduction of stress level will reduce the likelihood of rupture and will increase the life of the part. As previously stated, reducing the temperature will extend part life but will not alter the minimum stress level for cracking. Virtual elimination of either halides or oxygen from the environment (including liquid penetrant testing fluids) will prevent stress corrosion as long as the hydroxide concentration is under five percent. Cathodic protection will be an effective deterrent where it is practicable. Changes in design and operating conditions will be helpful if, for example, opportunities for fluid entrapment are reduced and operating temperatures and stress levels can be lowered. A substitution of less susceptible material such as carbon steel, nickel base alloys or corrosion resistant nickel-copper alloys for stainless steel is another preventive measure. Tensile stress relief by peening vibration or heat treatment can reduce the effect of a corrosive medium.

Table 1. Effects of chlorides on stainless steels.

Chlorides	General Attack	Stress Corrosion
Ammonium chloride	pitting	slow (long exposure)
Calcium chloride	nil	rapid
Chromium (III) chloride	heavy	nil
Iron (III) chloride	heavy	nil
Magnesium chloride	nil	rapid
Mercury (II) chloride	heavy	nil
Potassium chloride	pitting	slow (long exposure)
Sodium chloride	pitting	slow (long exposure)
Zinc chloride	nil	rapid

Corrosive Environments

The rate of corrosive attack on stressed stainless steel by various chlorides is essentially inversely proportional to their rate of attack on unstressed stainless. Information on the comparative effect of specific chlorides on stressed versus unstressed AISI 300 series stainless steels is given in Table 1.

It would appear that stress corrosion requires selective localized attack, which can only be provided by corrodents that do not affect the pure alloy.

Chloride Removal Following Liquid Penetrant Testing of Stainless Steels

Stainless steel components should be as free as possible of surface residual chlorides after cleaning or liquid penetrant testing, particularly before heat treatment, welding or long term storage. A quantitative chloride determination will be required to establish the accuracy of a given flushing procedure. Acid treatment should be avoided to ensure that no intergranular corrosion produces a site for liquid sodium attack in a breeder reactor or for stress concentration. Final flushing after liquid penetrant testing of AISI 304 stainless steel can be done with alcohol, acetone or an aromatic hydrocarbon solvent such as benzene or toluene. The latter should provide effective removal of adsorbed and entrapped chlorides. However, all are highly flammable.

Fluids for Cleaning of Stainless Steels

Several chlorinated solvents such as nonflammable, low toxicity trichlorotrifluoroethane (refrigerant-113) can be used to clean austenitic stainless steels regardless of heat sensitization and degree of stress. The accompanying low boiling point of 45.8 °C (114 °F) facilitates complete removal by evaporation.[2] However, these solvents are no longer available for cleaning. They were regulated because of their high potential for ozone depletion.

It has been reported that sulfamic acid, HSO_3NH_2, can be used for cleaning austenitic steel without causing stress corrosion cracking. A five percent solution of this acid at 70 °C (160 °F) can be applied for periods up to 24 h. No data have been reported to suggest that nonhydrolyzable halides such as fluorocarbons were associated with stress corrosion cracking.

Superior resistance to stress corrosion has been reported for a high alloy, columbium stabilized, iron base, nickel-chromium-molybdenum austenitic stainless steel. This has a nominal analysis of 30 percent chromium, 34 percent nickel, 2.5 percent molybdenum and 3.5 percent copper. The high nickel content is credited with supplying the improved resistance to stress corrosion cracking Laboratory tests in the most severe corrodent, boiling magnesium chloride, show more than a tenfold increase in life for the columbium stabilized nickel-chromium-molybdenum austenitic stainless steel over AISI 304; however, the cost of the high alloy material is about four times that of AISI 304 for tubular products.

Conclusions on Control of Stress Corrosion Cracking

As long as the *ASME Boiler and Pressure Vessel Code*[3] limits total halogens in liquid materials for nondestructive testing methods to one percent, materials for use on austenitic stainless steel components should be selected for minimum halide content consistent with effectiveness and cost. The lower the halide residual concentration in the environment, the lower the possibility of stress corrosion. Thorough cleaning for removal of halide containing materials after their use will effectively eliminate any potential for stress corrosion.

Stainless steels containing a nominal 8 percent nickel — such as AISI 304, AISI 316 and AISI 347 — have maximum sensitivity to chloride stress corrosion cracking. Attainment of minimum stress levels in stainless steel components is therefore desirable. Thermal, vibrational or peening stress relief can reduce residual stresses. Residual and/or applied tensile stresses as low as 14 MPa ($2000\ lb_f \cdot in.^{-2}$) in combination with 74 °C (165 °F) or higher fluid environments containing 1 to 50 $\mu g \cdot g^{-1}$ or less of certain chlorides and 1 to 200 $\mu g \cdot g^{-1}$ or less of oxygen can result in stress corrosion cracking.

Low concentrations of total halides (5 to 50 $\mu g \cdot g^{-1}$) cannot be accurately determined by current standard analytical procedures. Ion chromatography can analyze halide concentrations in this range (see ASTM E 165[4] for procedures).

Final cleaning is recommended before heat treatment, forming, fabrication, storage or shipment to remove water, dissolve grease and oil, float away insoluble particulate — without promoting stress corrosion cracking.

Part 3. Methods for Sulfur and Halogen Analysis of Liquid Penetrant Materials

Effects of Sulfur and Halogens on Liquid Penetrant Testing Materials

Liquid penetrant testing is used on most nonferrous metals, particularly aluminum, magnesium, titanium, stainless steel and high nickel alloys. Stainless steels and titanium have been found to be subject to corrosion and embrittlement because of contact with chloride ions. High nickel alloys have been found subject to corrosion and embrittlement by contact with sulfur in the form of sulfide ions at elevated temperatures.

Specifications Limiting Sulfur and Halogen in Liquid Penetrant Testing Materials

Because of these findings, limits have been placed on the amount of sulfur and halogen that may be present in liquid penetrant testing materials used on high nickel alloys, stainless steel and titanium, particularly in components of nuclear power plants. The specifications have usually been for total sulfur content and total halogen content. Here it was assumed that the worst possible case would be where the liquid penetrant testing materials are not cleaned off the part after inspection and the test part is heated to temperature that will decompose the test materials, releasing the elements present for reaction with the metal of the part.

Impurity Level Requirements for Liquid Penetrant Testing Materials

Impurity level requirements for liquid penetrant testing materials are restricted by the *ASME Boiler Code,* Section V, Article 6.[3] This code limits maximum residual to 1 percent total sulfur and 1 percent total halogens as determined by ASTM D 129[5] and ASTM D 808[6] analytical techniques either/or ion chromotography,[4] when liquid penetrant testing materials are applied to nickel base alloys, austenitic stainless steels and titanium. To accommodate requirements that are more restrictive than those specified in the *ASME Boiler Code,*[3] consideration has been given to lower limits on impurities in expendable materials that will contact such metal surfaces.

Contaminants levels are the result of impurities in the bulk chemical ingredients used to formulate liquid penetrant materials. Therefore, some variations may be observed between materials from different suppliers, between different types of materials from a single supplier and between samples of the same type of material purchased from a single supplier at different times.

Specifications for Analysis for Sulfur or Halogens

Analyses for sulfur or halogen impurities usually are conducted by the following methods although other methods are known to be equivalent or superior in accuracy, reproducibility and repeatability.

1. Analysis for water leachable chlorides is conducted according to ASTM D 2441[7] (modified by water reflux and potentiometric titration).
2. Analysis for halogenated compounds is conducted according to ASTM D 808.[6] Chloride compounds are absorbed in sodium carbonate (Na_2CO_3) solution. The chloride content is determined by potentiometric titration.
3. Analysis for sulfur is conducted according to ASTM D 129[5] or ASTM D 1552.[8]

Some specifications stipulate evaporation of sample (preceding sample decomposition) whereas other specifications call for an untreated (whole) sample. For example, Section V of the *ASME Boiler Code*[3] specifies ASTM D 129[5] and either ASTM D 808[6] or ion chromatography.[4]

Detrimental Sulfur and Halogen Content of Liquid Penetrant Testing Materials

There is some difference of opinion on how much sulfur or halogen content is really detrimental to any material. This is because the sulfur or halogen may be present in a number of forms and degrees of permanence and much is still unknown concerning the interactions of these elements with sensitive metals. Some specification writers feel that if the undesired elements are present in any form where they may be physically captured for analysis and in any amount over the slightest trace, the test material is unacceptable. These users require analysis of the as-received liquid penetrant testing material from its manufacturer.

Other specification writers note that liquid penetrant testing materials are often sprayed on the parts and, in any case, are present only in thin layers on the part, often for considerable amounts of time. Thus, during normal testing, considerable evaporation of volatiles may take place. The detrimental sulfur or halogen content then is considered to be that of the residue after normal evaporation has taken place. This evaporation can either increase or decrease the apparent sulfur or halogen content, depending on the form in which the contaminant is present. If the contaminant is present as part of a volatile vehicle, its apparent amount is decreased by evaporation. Any contaminant present in the nonvolatile residue will be concentrated.

Significance of Ionizable Compounds of Sulfur or Halogens

Still other specification writers feel that there is a difference between ionizable and nonionizable sulfur or halogen. Actually, no attack on or reaction with metal can occur unless the element can ionize. Then it can leave the compound in which it was originally bound and produce new bonds with the metal. Sulfur and the halogens are normally found in both inorganic and organic forms. The inorganic forms of sulfur and the halogens usually ionize fairly easily and so are readily available for reaction with the metal. The organic forms of sulfur and the halogens usually are very tightly bound. As long as the organic compounds containing sulfur and halogen are stable, these elements may be quite harmless to metal. For this reason, some specifications require tests of aqueous extractions of the test materials. Ionizable contaminants that could attack parts are then detected whereas nonionizable contaminants are ignored.

Analysis only for ionizable sulfur and halogen is probably adequate as long as the tested parts will not be subjected to conditions such as extreme heat that can break down the residual liquid penetrant testing material. The products of thermal or chemical breakdown are usually ionizable compounds that may cause attack.

Sulfur Analysis of Liquid Penetrant Testing Materials

The most common sulfur test specified is the ASTM D 129[5] method for total sulfur content. This sulfur analysis can be made on all organic materials. In this test, the sample is first decomposed by burning in a high pressure oxygen bomb. The sulfur present is thus converted to sulfur dioxide and sulfur trioxide. These are absorbed in a sodium carbonate solution, forming sodium sulfate. Barium chloride is added to convert the sulfur from soluble sodium sulfate to insoluble barium sulfate, which is filtered out and weighed. The amount of sulfur present is calculated from its molecular fraction in barium sulfate.

This method can reliably detect sulfur contents as low as 0.1 percent (1000 $\mu g \cdot g^{-1}$). It becomes very unreliable below this level because of weighing inaccuracies and losses of materials that pass through the filter used to collect the final yield. Further problems can arise with many liquid penetrant testing materials containing elements such as iron, aluminum, calcium, silicon or lead or substances such as silica, asbestos or mica. All these substances cause precipitates that may falsely be measured as the barium sulfate precipitate that indicates sulfur by this test.

Alternative Tests for Total Sulfur Content

Several sulfur tests can be used if preferred or where ASTM D 129[5] is not applicable. This ASTM D 1552[8] test method also measures total sulfur content. It operates by burning the sample in a stream of pure oxygen to form the sulfur dioxide and sulfur trioxide. A starch iodate solution normally blue in color is bleached clear by the absorption of sulfur oxides. The titrant is often added and the color measured photoelectrically by an automatic or semiautomatic titrator. This test can measure as little as 600 $\mu g \cdot g^{-1}$ sulfur in samples on which it is applicable.

Lamp Method for Total Sulfur Content

A third method that has been proposed is the ASTM D 1266[9] lamp method for total sulfur content. Here the liquid sample is burned in a wick type lamp. An absorbent wick collects the combustion products including the sulfur oxidized to sulfuric acid. Sulfur is then either determined acidimetrically by titration against standard sodium hydroxide or gravimetrically by precipitation as barium sulfate.

The lamp method is sensitive because large samples are used. It will easily find 20 $\mu g \cdot g^{-1}$. However, it is usable only on liquids that do not contain suspended solids. Therefore, it would not work on liquid penetrant testing developers. Further acid forming elements such as phosphorus or halogens if present in substantial quantity will interfere with acidometry. Phosphorus is often a constituent of penetrant materials.

Coulometric Measurement

Instrumentation is available that burns the sample in a stream of oxygen and inert gas (helium or argon). This converts the sulfur to sulfur dioxide, which flows into a titration cell where it reacts with an iodine solution. An electric current is run through the cell to regenerate the iodine and the current required is a measure of the sulfur content.

This test operates best with liquids but can be adapted to solids as well. The equipment for this test requires substantial investment.

Bomb Turbidemetric Sulfur Test

A fifth test that has been found very useful for the measurement of sulfur in materials that are completely combustible is bomb decomposition as in ASTM D 129[5] followed by turbidemetric sulfur determination as in ASTM D 516.[10]

For this test, samples are burned in an oxygen bomb as in ASTM D 129[5] except that sodium hydroxide is used as the absorber instead of sodium carbonate. The bomb washings are diluted to a known volume; glycerin, sodium chloride and barium chloride are added. Light transmission measured photometrically through the mixture is proportional to the amount of barium sulfate precipitate.

Ion Chromatography

Still another method for sulfur testing is ion chromatography. After the sample is prepared by bomb combustion, a filtered aliquot is injected into a stream of carbonate/bicarbonate eluant and passes through a series of ion exchangers. The anions of interest are separated on the basis of their affinities for a strongly basic anion exchanger. The separated anions are measured by conductivity. They are identified on the basis of retention time as compared to standards. Quantitation is a measurement of peak area or peak height. For details of technique, see Annex A4 of ASTM E 165.[4]

This method provides a single, instrumented technique for rapid, sequential measurement of common anions such as bromide, chloride, fluoride, phosphate etc. and must be considered an alternative technique for testing for those compounds as well as for sulfur. Ion chromatography is much easier and quicker to run than the standard ASTM D 129[5] and is much more sensitive with equivalent precision.

Halogen Analysis of Liquid Penetrant Testing Materials

Halogen is the family name for the group of elements including, from the lightest to the heaviest, fluorine, chlorine, bromine, iodine and astatine. Astatine is not stable and is not normally found in measurable or significant quantity in nature. For test purposes, it can be disregarded. Of the other four elements, fluorine is the most active and reacts differently from the remaining three. Therefore, it requires different methods of analysis than the others. In fact, fluorine is not measured as part of the *total halogen* analysis that is often reported. Although there is evidence that fluorine, in the form of fluoride ions, may attack some metals, only limited work has been done in this area. Limits on fluoride content are normally applied to test materials by only a few specifications, so fluoride analysis will be briefly detailed here. The reporting of total halogens (not including fluorine) is required by most specifications (including Section V of the *ASME Boiler Code*[3] and ANSI/ASME B 31.7[11]) and is recommended by ASTM E 165.[4]

Difficulties in Analysis of Chlorine Content

Chlorine is by far the most common and possibly the most troublesome halogen. Most of the analytical procedures used for the halogens are designated as chlorine tests although, in most cases, they are sensitive to bromine and iodine as well. Thus, if the analysis must be for chlorine only, it is necessary to use special procedures to remove the unwanted bromine and iodine before the chlorine analysis is performed. Furthermore, fluorine will probably not be reported because most of the tests applied in 1981 for chlorine will not respond to fluorine.

The chloride ion, when present in inorganic form, is very soluble in water and so is readily available for a variety of analytical methods. Refluxing the sample is necessary to leach out all the chloride for analysis. When chlorine is present in organic form, however, it binds very tightly to the rest of the molecule and cannot usually be obtained for analysis unless the molecule is destroyed. This destruction is usually accomplished by heat, often in the presence of oxygen. The effluent gases are then absorbed in some solution for analysis.

Bomb Decomposition Gravimetric Analysis of Chlorine

Probably the most common test for chlorine is the bomb decomposition gravimetric analysis method of ASTM D 808.[6] For this test, a weighed sample is burned with oxygen. The gaseous combustion products are absorbed into a sodium carbonate solution, which converts the chlorides to sodium chloride. Silver nitrate is added to precipitate the chloride as silver chloride, which is then filtered out and weighed.

The inadequacy of ASTM D 808[6] is generally recognized because this chlorine test is not sensitive below 0.1 percent (1000 $\mu g \cdot g^{-1}$) nor above 50 percent content. This test does break down and measure all organic chlorides as well as the inorganic chlorides. It measures not only chlorine but also bromine and iodine, because the silver salts of these elements are very similar to the silver chloride. The test will not measure any reportable quantity of fluorine, nor will it pick up all the bromine and iodine that may be present. Phosphorous causes interference with this test, leading to falsely high readings.

Metallic Sodium Method for Chlorine Analysis

Another method that was developed to measure chlorine content is the metallic sodium method. Here the sample is refluxed with metallic sodium in a mixture of butanol and toluene. The chlorides and other halogens are stripped out and form sodium salts. Methanol and acetone are added to the mixture and the chloride is titrated with silver nitrate. The end point is potentiometrically determined by using a glass electrode — silver billet electrode system.

This sodium refluxing method of chlorine analysis is quite sensitive, detecting as little as 3 $\mu g \cdot g^{-1}$ of chlorine. The procedure detects all the inorganic chlorine and most of the organic chlorine.

Bomb Decomposition Potentiometric Analysis for Chlorine

Another method for measuring chlorine is the bomb decomposition potentiometric titration method. This method decomposes the sample in an oxygen bomb as in ASTM D 808.[6] Analysis is done by potentiometric titration of the metallic sodium method described above.

This method is sensitive, detecting chlorine in samples down to 3 $\mu g \cdot g^{-1}$. The method, in common with many others, actually measures bromides and iodides along with the chlorides. This method is described in detail in Annex A2 of ASTM E 165.[4]

Characteristics of Various Methods of Analysis for Chlorine Content

All of the preceding methods can properly be used for the measurement of chloride ions, so long as each is used within its particular limitations. All actually measure total chloride, bromide and iodide. The bomb method of ASTM D 808[6] is less sensitive to bromide and iodide so these ions will not be fully detected. All may be subject to interference from other substances that may be present in liquid penetrant testing materials, so that test results may not always be accurate. The best way to check for accuracy is to add a known amount of chloride ion to the sample and remeasure. The percent of this known amount actually recovered will allow a good estimate of the accuracy of the analysis to be made.

Ion Chromatography for Chlorine Analysis

Another method for halogen testing is ion chromatography. After the sample is prepared by bomb combustion, a filtered aliquot is injected into a stream of carbonate/bicarbonate eluant and passes through a series of ion exchangers. The anions of interest are separated on the basis of their affinities for a strongly basic anion exchanger. The separated anions are measured by conductivity. They are identified on the basis of retention time as compared to standards. Quantitation is a measurement of peak area or peak height.

Fluorine Contamination of Liquid Penetrant Materials

Fluorine is the most active of the halogens, so it can cause all the problems ascribed to the other halogens plus some of its own. However, until 1981, most specifications did not test for or limit fluorine content, because adequate tests did not exist and sufficient work to determine valid limits was not done.

Fluorine can exist in either organic or inorganic compounds. Only the ionizable inorganics are likely to be reactive but the organics can be converted to inorganics by the application of heat, so the safest course is to test for total fluoride rather than just readily ionizable fluoride. For this reason, it is normally necessary to decompose the test material, thus liberating the fluorides to inorganic, ionizable form. This is best accomplished by oxygen bomb decomposition. (See Annex 3 and Annex 4 of ASTM E 165.[4])

Tests for Fluoride Content

A number of tests have been used with more or less success for the determination of fluoride content. In all cases, a general precaution is in order. Fluoride tests cannot use glass apparati because the fluoride ion reacts rapidly with silica, forming a nonreactive complex resistant to all methods of analysis. This effect also makes the analysis of silica containing developers for fluoride very difficult.

Possible Methods of Fluoride Analysis

The fluoride ion behaves quite differently from the other halogens, so special tests are necessary to obtain valid results. Fluoride is not detected along with the other halogens by standard tests, such as ASTM D 808.[6] A number of other analytical methods have been used with varying success, however. All of the described methods are assumed to be performed using the fully ionized product of a bomb decomposition. The earliest fluoride analyses used gravimetric techniques, which are low in sensitivity, tedious and subject to many interferences. They were seldom used after 1981.

Titrimetric Methods for Fluoride Analysis

Many titrimetric procedures have also been developed. One of these involves titration of the dissolved fluoride with a silver nitrate potassium thiocyanate reagent and a ferric alum indicator. Unfortunately, the method is subject to many interferences, including aluminum, beryllium, iron, potassium, sodium, ammonia, phosphate and sulfate.

Two other titrimetric methods operate on the basis of adding titrant and detecting the first excess of titrant, thus indicating that all fluoride has reacted. One of these titrations uses calcium nitrate titrant; the other is the lead nitrate–hydrochloric acid reaction. The calcium method, of course, would not work with developers that contain large amounts of calcium, and the lead nitrate method is subject to the same long list of interferences as ferric alum, noted above.

Probably the most promising of the titrimetric procedures is the thorium nitrate titration with sodium alizarin sulfonate indicator. This method is only partially applicable to liquid penetrant testing materials because of certain interferences. Even in small quantities, phosphate is a serious interference, causing a red color which hides the end point completely. Phosphorous is often a constituent of test materials. Another interference is any acid insoluble solid, e.g., many developer ingredients; these completely mask the end point.

Photometric Method for Fluoride Analysis

A third general procedure that has been used is the reaction of the dissolved fluorides with some color forming reagent to produce a solution capable of being measured photometrically. In these tests, the depth of color is proportional to the fluoride concentration. Probably the best known of these analyses is the method of ASTM D 1179,[12] which uses a compound of sodium, 2-(parasulfophenylazo), 1,8-dihydroxy and 3,6-naphthalene disulfonate (SPADNS). This material, dissolved in water and mixed with a zirconyl chloride hydrochloric acid mixture, is bleached by fluoride. The amount of bleaching is then measured photometrically.

The ASTM D 1179 method is subject to interference from aluminum, iron, phosphate and sulfate, all of which may be present in liquid penetrant materials.[12]

Fluoride Electrode Method for Fluoride Analysis

A device available in the 1980s eliminates most of the problems of the other methods and is now the preferred method for some fluoride measurements. This device is the fluoride specific ion electrode. When the electrode is immersed in a solution containing fluoride ions, an electrical potential is developed between the fluoride electrode and a reference electrode also placed in the solution. The potential decreases with increasing fluoride content. Further, the specific ion electrode responds only to fluoride ion and hydroxide ion if hydroxide is in greater concentration than fluoride. The proportion can be controlled easily by adjusting to a lower pH.

Fluoride ions can be lost through its complexing with cations such as aluminum (III) (Al^{3+}); ferric ion or iron (III) (Fe^{3+}); or silicon (IV) (Si^{4+}). This interference can be eliminated by the addition of an agent such as citrate, (cyclohexylenedinitrilo)acetic acid (CDTA) or ethylenediaminetetraacetate (EDTA). Another limitation to fluoride measurements with the specific ion electrode is that the response is not directly to concentration but to the ion activity. The activity of an ion in solution is modified by other ions in solution. If the fluoride present is ionized and the pH is properly controlled, there are essentially no interferences with this method.

Ion Chromatography for Fluoride Analysis

Another method for fluoride testing is ion chromatography. After the sample is prepared by bomb combustion, a filtered aliquot is injected into a stream of carbonate/bicarbonate eluant and passes through a series of ion exchangers. The anions of interest are separated on the basis of their affinities for a strongly basic anion exchanger. The separated anions are measured by conductivity. They are identified on the basis of retention time as compared to standards. Quantitation is a measurement of peak area or peak height.

PART 4. Techniques for Control of Pollution from Liquid Penetrant Waste

Liquid Penetrant Constituents Contributing to Waste Pollution

Liquid penetrants may contain a considerable variety of chemical compounds. Among those fairly widely used are petroleum products ranging from relatively low boiling range solvents to high boiling oils. Another generic group are nonionic surface active agents. Anionic surface active agents are less commonly used because their presence in liquid penetrants has disadvantages. These are generally considered to outweigh their excellent surface active properties and, what is perhaps more important in the present context, the comparative ease with which they are biologically degraded. Other constituents present in significant proportions may be alcohols, glycol ethers and esters, to name but a few. Finally, liquid penetrants contain dyes, both visible and fluorescent. These dyes are the most troublesome contaminants because they are visibly detectable at low concentration and can be readily traced back to the source of pollution.

Techniques for Reducing Liquid Penetrant Process Wastes

The following chemical engineering and/or liquid penetrant processing steps are suggested to reduce the amount of liquid penetrant product residues in the waste effluent from liquid penetrant testing processing systems.

1. Minimize the amount of liquid penetrant applied. Electrostatic spray or spray application is preferable.
2. Drain the liquid penetrant as long as possible to reduce carry over.
3. Rinse postemulsifiable liquid penetrant before applying emulsifier. This liquid penetrant will separate from the rinse water and may be skimmed off or otherwise separated. This step can allow the rinse water to be recycled.
4. Apply emulsifier sparingly and allow to dwell the required time. Spray techniques use less than dip techniques of emulsifier application.
5. Rinse the part with water immediately to stop emulsification.
6. Rinse water washable or emulsified postemulsifiable liquid penetrant residues in two stages: (a) the first rinse water may be recycled until contaminated beyond use and (b) second rinse water effluent can be added to the first rinse water as makeup.
7. Rinse waters can be treated to separate out the emulsifier and liquid penetrant by using special membrane filters. Activated charcoal can be used to remove the color, oil and most of the emulsifier (wetting agent).
8. Filtration of rinse water will remove developer residues, if any.

Specific recommendations for waste disposal treatment and the cost of such a system depend on numerous factors, such as (1) the type of liquid penetrant or emulsifier used, (2) whether application is by dip or spray, (3) the volume and type of work being processed, (4) the facilities and equipment in use and (5) the particular restrictions of applicable city, county, state or federal codes.

Treatment Processes Applicable to Liquid Penetrant Effluents

The actual effluent arising from a liquid penetrant process generally consists of a dilute emulsion formed by direct emulsification of the liquid penetrant with water, in the case of water washable liquid penetrants. Similar dilute emulsions can be formed by the action of an auxiliary emulsifier or liquid penetrant remover in the case of postemulsifiable liquid penetrants. The auxiliary emulsifying agents may contain constituents broadly similar to those of the liquid penetrants themselves and the surfactant system may be either lipophilic or hydrophilic in nature. The effluent emulsion generally contains less than one percent by weight of nonaqueous matter and is usually fairly stable. Conventional treatment can be designed to break the emulsion and thus separate nonaqueous matter. It involves collecting and treating the effluent successively with strong electrolytes and flocculating agents in a series of vats or tanks.

The coagulated contaminants are separated by filtration and finally incinerated, leaving water of acceptable purity for discharge or reuse. This is essentially a batch process, relying for its efficiency on accurate pH control. It also requires time and space: time for the various additives to become fully effective and space to accommodate the plant, the size of which is determined by the volume of effluent requiring treatment in a given period of time. Where liquid penetrant processes are used intensively and continuously, correspondingly large volumes of water are required for rinsing. More recently, membrane filtration has been used as a way of treating the effluent on a continuous basis and feeding back the purified water into the process and in effect creating a closed circuit system that is economical in the use of water.

Effects of Liquid Penetrant Waste Materials in Sewage and Streams

When an inspection liquid penetrant is rinsed from the test surface, it enters the rinse water as a fine, stable, oily emulsion. Typically, this emulsion is not considered to be toxic but does make the effluent turbid. It can leave an oil slick on the water's surface and even deplete some of the oxygen supply in the water. All these results lower the value of the water. Sewage regulations in some localities allow plant effluent water to contain as much as 600 $\mu g \cdot g^{-1}$ of such oils whereas other regulations allow none at all. The rinsings from liquid penetrant removal operations normally contain from 200 to 1000 $\mu g \cdot g^{-1}$ oil and are usually not an acceptable waste.

Measuring Concentration of Oily Contaminants in Waste Water

Oily contaminants can be detected either as hexane solubles or by the chemical oxygen demand (COD). Extraction of rinsings by hexane yields their total nonvolatile oil content. The chemical oxygen demand test measures the concentration of organic contaminants (oil, surfactants etc.) by the amount of oxygen used in oxidizing them completely by a dichromate reflux technique. The results are expressed in milligram of oxygen per liter of test solution or in parts per million. One gram of a typical oily liquid penetrant *may* consume about 2.5 to 3.0 g of oxygen in this manner. Thus, 1 L of rinsings containing 1 g of oily liquid penetrant may show a chemical oxygen demand of 2500 to 3000 $\mu g \cdot L^{-1}$. More dilute rinsing may show a lower chemical oxygen demand. The chemical oxygen demand technique of monitoring pollution concentration can be related empirically to the biological oxygen demand (BOD). The biological oxygen demand test measures the oxygen used during a specified incubation period for the biochemical degradation of organic material and the oxygen used to oxidize inorganic material such as sulfides and ferrous iron.

Avoidance of Environmental Water Contamination by Liquid Penetrants

Where local regulations allow some oil to be present in the plant effluent, the liquid penetrant rinsings, combined with other nonoily waste streams from within the plant, may happen to yield a total effluent within the acceptable range. In most cases, though, the situation is not this simple. Then something must be done with the liquid penetrant removal operation to lower the oil content of the effluent.

Worldwide, many attempts have been made to manage liquid penetrant removal without contaminating the environment. Some of these techniques use liquid penetrant compositions that meet prevailing pollution control regulations. Other control techniques alter the process so that the wastes never leave the test area. Still other techniques treat the rinsings to concentrate the oily contaminants for easy disposal.

Compositions of Liquid Penetrant Materials to Avoid Pollution

One approach to the pollution problem is to alter the liquid penetrant's composition so that the rinsings are less objectionable. For instance, formulating a liquid penetrant to be completely water soluble would avoid the formation of turbidity and oil slicks.[13] Such rinsings might pass all tests, even though the rinse water would still be contaminated. However, complete solubility makes effluent treatment more difficult. Liquid penetrants that are completely water soluble have been available since 1953.

Biodegradable Liquid Penetrants to Reduce Pollution

Another way to alter a liquid penetrant's composition is to make it biodegradable. Such a liquid penetrant need not be water soluble, yet it can have the same removal properties as oily liquid penetrants. The rinsings consist of the same sort of fine emulsion but with an important difference. Within a few days, the oily liquid penetrant is almost completely decomposed by organisms in the water. The liquid penetrant decomposition will use up a large amount of free oxygen from the stream that contains the oily wastes. This behavior limits the locations where such a liquid penetrant can be legally used.

It would be objectionable if liquid penetrant effluents were emptied directly into natural bodies of water where the oxygen depletion could harm the environment. Oily waste processed in a sewage treatment plant in the presence of ample oxygen and a large population of hungry microorganisms will disappear without harmful effects. This will increase the work load of the sewage treatment plant and perhaps might result in increased sewer charges. Biodegradable types of liquid penetrant testing materials are commercially available for use in situations where suitable treatment plants are available.

Recent Developments in Liquid Penetrant Waste Water Disposal

The increasing regulatory restrictions on water pollution brought greater scrutiny of liquid penetrant materials getting into waste water.[14] Tests were conducted to develop a better understanding of waste water characteristics resulting from liquid penetrant materials introduced around 1990.[15] The focus was on two distinct formulation approaches — compositions based on petroleum distillates and those based on *surface active agents* (*surfactants*), more commonly referred to as *biodegradable* liquid penetrant. The study investigated the treatability of waste water generated in the normal course of fluorescent liquid penetrant testing.

The popular theory at the time was that surfactant based liquid penetrants, because they were oilfree, were more biodegradable than the traditional oil based formulations.[16] Hence making them more drain disposable. However, the study came to the conclusion that the popular theory may not be true. This very limited study found that each of the studied factors important to a publicly owned treatment works (POTW) — treatment time, inhibition, respiration rate, percent biological oxygen demand (BOD) removal — is more favorable with an oil based liquid penetrant than with a surfactant based liquid penetrant. It further showed that even oil free liquid penetrants test positively for oil when tested in the laboratory.

Waste Water Disposal to Publicly Owned Treatment Works

The greatest challenge to liquid penetrant users is knowing whether waste water from liquid penetrant processes can be sent out to publicly owned treatment works through the sewer system.[17] The first step in finding the answer is to ask the operators of publicly owned treatment works if liquid penetrant waste water is acceptable for treatment at these facilities. *Waste water treatability* depends on how microorganisms in waste water treatment plants respond to the waste stream. Conducting tests on fluorescent dye liquid penetrants using a respirometer simulated the treatment of liquid penetrant materials in the activated sludge system. Activated sludge consists of microorganisms cultured in a controlled environment where waste water enters and clean water (effluent) exits. The microorganisms are fed oxygen, mixed, retained for a period of time, then settled. Most waste treatment plants use the activated sludge treatment system to reduce the soluble (dissolved) organic strength waste before the waste water is discharged to a river, stream or lake.

This reduction in organic strength is accomplished not only because the United States Environmental Protection Agency requires it but also because the waste water would quickly deplete the oxygen in the receiving stream. The publicly owned treatment works' objective is to remove organic and solid and soluble organic waste. Anything that threatens the achievement of this goal is a concern of the facility.

Drain Disposability

Drain disposability is a term loosely used to denote the environmental friendliness of a particular waste when it is put in a sewer system. In the case of activated sludge systems, drain disposability would mean that the waste water can be treated without hurting the microorganisms, within the capability of the air supply system (aeration) and within the treatment time (detention time). Drain disposability largely depends on the strength of the waste. Strength of waste is measured with the five day *biological oxygen demand* test, which measures the depletion of oxygen from primarily microbiological metabolism (respiration). The higher the biological oxygen demand, the larger the tank capacity and air requirements. Liquid penetrant materials that result in low biological oxygen demand values are more likely to be treated within the detention time allotted by publicly owned treatment works to treat waste water. In some tests, all oil based materials tested resulted in oxygen uptake rates below normal requirements whereas most surfactant based samples tested exceeded the maximum allowable range. In summary, all liquid penetrant products exerted certain amount of organic strength measured as biological oxygen demand and thus may require pretreatment before disposal to publicly owned treatment works.

Techniques of Posttreatment of Liquid Penetrant Rinsings for Pollution Control

Several liquid penetrant waste purification processes result in water pure enough to reuse in the rinsing step. Most of these processes rely on posttreatment of the rinsings. Posttreatment processes for liquid penetrant rinsings can be placed into four groups: (1) chemical destruction of the emulsion; (2) molecular filtration, such as reverse osmosis; (3) absorption of the emulsion onto a suitable substrate; and (4) a remover that forms an unstable emulsion that separates easily. Each of these techniques of pollution control is described in detail below.

Technique for Chemical Destruction of Water Liquid Penetrant

Surface active agents that allow liquid penetrant removal by water also stabilize the resulting emulsion. These surfactants can be destroyed by oxidizing agents. One of the most effective oxidizing agents is potassium permanganate. With the surface active agent destroyed, the fine emulsion can separate. The oily constituent is absorbed onto the manganese dioxide floc that forms and settles out when the permanganate reacts. This oxidation is a slow process. If permanganate is added to the collected rinsings in an amount equal to that of the liquid penetrant and the mixture is not heated, it takes about 2 h to break the emulsion. At this point, a small excess of ferrous chloride must be added to the collected rinsings to decompose any unreacted permanganate. The resulting ferric oxide floc helps absorb more liquid penetrant.

The liquid penetrant floc mixture can be easily separated by filtration or decantation but the technique is slow. Pound for pound, permanganate is more expensive than liquid penetrant. Finally, the chemical additions must be painstakingly balanced so that something more obnoxious than the original liquid penetrant does not go down the sewer unneutralized.

Reverse Osmosis Technique for Removal of Waste Liquid Penetrant

In reverse osmosis, the impure water is forced through an osmotic membrane under pressures up to 2.80 MPa (400 $\mathrm{lb_f \cdot in.^{-2}}$). In a single stage, from half to three fourths of the water passes through the membrane. The contaminants that cannot pass through the membrane are concentrated in the remaining waste water. Although such equipment is primarily used to separate pure water from mineral laden water, it also works well with water washable liquid penetrants that are surfactant based.

Figure 7 shows schematically how a membrane separator works and includes a simple flow diagram. This is a soluble oil waste treatment system in which the separation is nearly quantitative. Beginning with municipal water laden with 2000 $\mu g \cdot g^{-1}$ of emulsified liquid penetrant (chemical oxygen demand about 4000 $\mu g \cdot g^{-1}$), it is possible to salvage 65 percent of the water. This recovered water contains less than 10 $\mu g \cdot g^{-1}$ impurities, largely a water soluble emulsifying agent, and had a chemical oxygen demand of 60 $\mu g \cdot g^{-1}$. The waste water is about 35 percent of the total. This waste water contains over 90 percent of the mineral content of the original sample and all but a trace of the original liquid penetrant. Its chemical oxygen demand is around 18 000 $\mu g \cdot g^{-1}$. The reverse osmosis process concentrates the oily contaminant into 35 percent of the original waste water, which is still too bulky for disposal. However, this concentrated waste can be forced through another osmotic membrane to salvage more pure water and shrink the volume of the waste water.

Performance of Osmotic Liquid Penetrant Removal System

In one series of tests with the permeator of Fig. 7, liquid penetrant rinsings were subjected to three stages of purification.

Overall, about 94 percent of the rinsings was salvaged as pure water. The efficiency of the separation, as well as the rate of output, dropped as more concentrated water was fed to the permeator. The purified water from the first stage separation had a chemical oxygen demand of 60 μg·g^{-1}. By the third stage, enough impurities were passing to raise the chemical oxygen demand to 110 μg·g^{-1}. Table 2 shows the chemical oxygen demand values for the initial rinsings along with the values for reject and product water for each of the three successive stages.

TABLE 2. Effect of successive rinses on waste water purity.

	Chemical Oxygen Demand (μg·g^{-1})	
Stage	Waste	Product
Initial	4000	
1	18 000	50
2	32 000	75
3	66 000	110

This does not represent much contamination but there is another limit on the degree of waste concentration that can be obtained. The mineral content of the waste water also increases at each stage. Eventually it exceeds the solubility and precipitates out to form scale on the membrane, which stops further action. The scale can be removed but only by shutting down the permeator and flushing it out with scale dissolving chemicals.

The *permeator* can treat from 6 to 10 L (1.5 to 2.5 gal) of water per minute, depending on impurity level, pressure and separation ratio. Unfortunately, it is damaged by traces of chlorine and oil in water. In addition, it still requires disposal of a significant volume of waste materials.

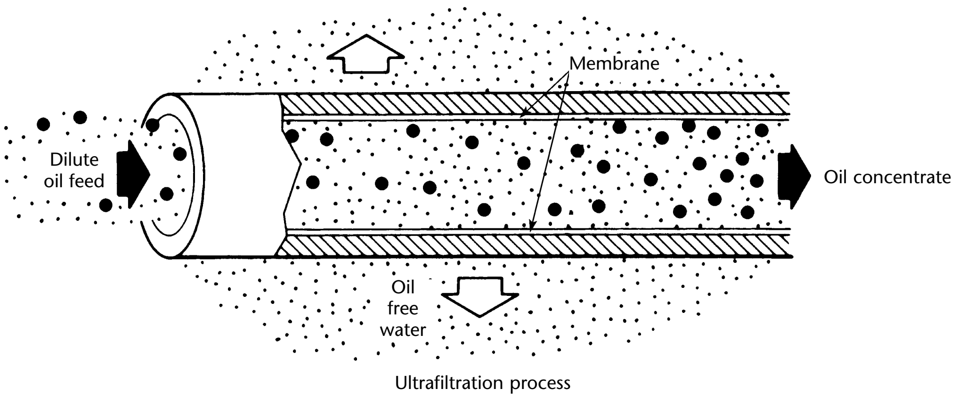
Filtration

There are a variety of membrane materials and configurations. Membranes are made from polymers, stainless steel and ceramics. Membrane selection is based on the size of the particles to be separated and the chemistry of the effluent stream as it relates to the chemistry of the membrane.

The standard membrane delivery system is a *dead end* filtration, so called because the feed fluid flow is directed at a right angle to the membrane without any attempt to control the thickness of the concentrate boundary layer at the filter's surface. Rapid buildup of retained solids to the membrane surface and continuous buildup of materials severely limit the flow and separation of the effluent. The most widely used dead end filters are the cartridge filters. Generally the cartridge filters are limited to feed streams of low viscosity and solid content. Once the filter flow rate has dropped off to an unaccepted level, the cartridge filter must be discarded.

To achieve relief from the accumulation of rejected effluent materials and the increasing pressure drop, filtration systems have been developed to flow the effluent stream parallel to the membrane's surface in *cross flow filtration,* or *tangential flow filtration.* In tangential flow filtration, the effluent feed is pumped at a high velocity in an attempt to shear away the concentration polarization layer and minimize its effect on the separation. Turbulent flow designs

FIGURE 7. Schematic cross section drawing of permeator showing membrane used to pass oil free water radially outward and retain oily contaminants in tubular enclosure.



operate at high shear rates and achieve higher filtration efficiencies.

Conventional tangential flow filtration configurations include plate and frame, spiral wound (stacks of membrane sheets with turbulent promoting screens between layers), hollow fibers (bundles of filament membranes) and tubular designs (membrane tubes). The spiral wound configuration is easily serviced and is the most energy efficient tangential flow filter design. It is used in the food, chemical and environmental industries for ultrafiltration and reverse osmosis applications.

Reuse of Separated Pure Water

The separated pure water can be drained into the sewer or it can be reused in the liquid penetrant removal process. The small amount of impurities that passed through the first stage did not increase after six cycles of liquid penetrant reuse and contamination. Table 3 shows the chemical oxygen demand values of the product water after six cycles of reuse (see chart). Different liquid penetrants should be checked for compatibility and processing characteristics.

Table 3. Purity of separated water after six cycles of reuse.

Cycle Number	Chemical Oxygen Depletion ($\mu g \cdot g^{-1}$)
1	60.8
2	57.6
3	57.2
4	64.0
5	48.0
6	64.0

Liquid Penetrant Removal by Adsorption

Studies have shown that the clarification of effluent containing liquid penetrant waste also can be accomplished by the adsorption technique. It is essentially based on the affinity of certain absorbent particles toward typical ingredients of liquid penetrants. In practice, the oil contaminant is extracted by stirring vigorously 7 kg (15 lb) of absorbent into 10 000 L (2600 gal) of waste water containing about 0.06 percent liquid penetrant. A solution of a flocculating agent is then added and the treated batch can be separated by any of the following techniques: (1) stratification, (2) filtration or (3) centrifugation.

Stratification for Recovery of Waste Water

Flocculated solid particles settle loosely at the bottom of the tank, allowing the purified water to be decanted off. The bottom layer (about 20 percent of the original volume) will then have to undergo further processing such as evaporation or filtration to reduce it to a more easily disposable, compact, wet solid waste.

Filtration for Recovery of Waste Water

The filtration of the treated effluent batch can be accomplished by using a precoated horizontal plate filter. The end products of this technique are purified water (oil content is about 25 $\mu g \cdot g^{-1}$) and a wet solid cake that has only slightly more bulk than the removed liquid penetrant itself.

Centrifugation for Recovery of Waste Water

A successful extraction of solid particles of clay from the treated batch of effluent was also achieved by means of a simple cream separator. However, a continuous separation would require special equipment that, although industrially available, is much more expensive than an ordinary centrifuge.

Water Immiscible Solvent Removers

Another approach to the effluent problem is the removal of non–water washable liquid penetrants by aqueous dispersions of volatile, water immiscible solvents. This results in an effluent whose typical composition is as follows: (1) 99 percent water, (2) 0.98 percent solvent and (3) 0.02 percent liquid penetrant.

The mutual compatibility of the liquid penetrant and solvent remover and their combined immiscibility in water predetermines an easy separation of water by centrifugation or gravity stratification in a holding tank. Apart from exhibiting a slight bluish fluorescence, the recovered water is sufficiently uncontaminated (oil content less than 100 $\mu g \cdot g^{-1}$) to be disposed of as a regular aqueous waste. The density of the removing solvent must be either lighter than water or heavier than water in order for it to be separated by centrifugation or gravity. The considerably smaller volume of the remaining remover liquid penetrant mixture can then be distilled to recover the volatile solvent, leaving behind proportionally minute quantities of somewhat contaminated liquid penetrant. Or it can be skimmed off and collected for disposal as oily waste. The solvent fraction will have mostly liquid penetrant oils and traces of water and can be incinerated or used as a fuel blend.

It follows that the solvent removal of liquid penetrants represents a foundation for a closed circuit system that eliminates effluent entirely by reusing water and the remover and by collecting the liquid penetrant waste in concentrated form.

Technique for Liquid Penetrant Waste Purification with Activated Carbon

The technique of filtration through activated carbon and other filter media for decolorizing is a well known and established technique. It is usually carried out by making a slurry of carbon in the liquid from which the color is to be removed and by heating it if possible. After a suitable reaction time, which may vary from a few minutes to several hours depending on the nature of the coloring matter and its concentration, the carbon is separated by filtration. Where large amounts of color have to be removed, it is generally necessary to repeat the process several times. It is clearly a batch process suffering from limitations of time and space.

However, it has been found that it is possible to achieve the same end by allowing the effluent to flow through a bed of activated carbon and other filter media on a continuous basis. Two major factors determine the success of this technique. First, the type and particle size of carbon and filter medium is specific for a particular emulsion and apparently depends on its hydrophilic lipophilic balance (HLB). Secondly, the ratio of the rate of flow of effluent to the volume of carbon is highly critical in determining the rate at which color is removed. This in turn varies with the amount of contamination present in the carbon and filter medium, so that the rate of removal of color reduces as the degree of contamination of the filter media increases.

Mechanisms of Waste Purification by Carbon Filtration

Waste purification is not simply a matter of removing the organic dyes by a process of adsorption but rather a combination of this and filtration. This is confirmed by the fact that a combination of activated carbon and filter aid, such as for example, pearlite or diatomaceous earth, is more effective than either one of these on its own. If only carbon is used, the oily matter in the effluent quite soon forms an oily coating on the carbon particles that effectively prevents their functioning as adsorbents for the dye. If only pearlite or diatomaceous earth is used, only a filtration effect is attained, with little or no adsorption of dye taking place.

Experimental work has shown that a sandwich arrangement, whereby the effluent flows first through the filter aid and subsequently through the activated carbon, practically doubles filter life, that is, its capacity to function before reaching actual or apparent saturation.

Recycling of Purified Water after Carbon Filtration

Carbon filtration, with the correct grades of carbon and filter aid, will produce clean water that may be discharged to waste. The only contaminants that may still be present in the water are the strongly hydrophilic elements of the surfactant system of the liquid penetrant or emulsifier. If the water is to be discharged to waste, it is important that only surfactants that can be readily and substantially broken down by biological organisms like biodegradable detergents be used in the liquid penetrant or emulsifier formulation.

In the present state of knowledge, the choice of suitable nonionics that also meet the other required criteria is limited. However, a postemulsified liquid penetrant process in which a hydrophilic liquid penetrant remover is used presents a further problem if the rinse water is recirculated. Under such conditions the concentration of liquid penetrant remover in the rinse water gradually builds up to a level where it causes excessive foaming. This foam is deposited and dries on the parts being processed, staining them and thus hindering inspection.

Adsorption of Surfactants onto Carbon

Certain types of carbon are capable of removing surfactants. However, it was discovered that types of carbon that remove surfactants have no decolorizing properties with respect to the type of dye generally used in fluorescent liquid penetrants. Therefore, one has to adopt a sandwich arrangement of the two types of carbon, separated by a perforated plate, set up so that the effluent water passes first through the layer of decolorizing carbon and thereafter through the layer of carbon that removes the surfactants. It was also found that if the order of the two carbon types is reversed or if they are intimately mixed or blended, the desired effect is not produced. Reverting, therefore, to what has been said previously about filter aids, a three layered sandwich consisting of one layer of filter aid and two layers of carbon is required for some applications. Disposal of the saturated carbon is best carried out by incineration, which destroys the adsorbed organic matter. If the quantities justify it, regeneration of the carbon may be economically attractive.

Carbon Filters with Hydrophilic Emulsifiers

In view of the relatively high price of activated carbon, the cost of the carbon filter process is not insignificant and ways of improving the economics have therefore been sought. One technique that shows worthwhile savings uses a postemulsifiable hydrophobic liquid penetrant in conjunction with a hydrophilic liquid penetrant remover. In such a system, a preliminary water rinse is carried out before immersion in the liquid penetrant remover. This rinse removes the bulk of the excess liquid penetrant by mechanical action without forming an emulsion. Then, this liquid penetrant may be recovered from the water by a centrifuge or coalescer. Both achieve almost 100 percent separation, producing clean water for reuse or discharge and actually recovering usable liquid penetrant. In one particular installation, about 4 L (1 gal) of liquid penetrants (representing about 65 percent by volume of the total dragout) are recovered daily. This process, which may be carried out continuously, achieves a double effect. It economizes in expensive liquid penetrant and, by ensuring that far less liquid penetrant is carried over to the second rinse, reduces the amount of liquid penetrant to be removed by the carbon filter, thus increasing its service life and reducing the operating costs of the process.

PART 5. Recycling of Water Effluent and Postemulsifiable Liquid Penetrant

Hydrophilic Concept for Recovery of Liquid Penetrant

The *prewash* or *prerinse* concept, which uses a postemulsifiable liquid penetrant and a hydrophilic emulsifier, is known as the *hydrophilic postemulsification liquid penetrant process*. This process permits recycling of the wash water. The technique calls for removing the bulk of the postemulsifiable liquid penetrant from the surface with a plain water wash before treatment with an emulsifier. Properly formulated postemulsifiable liquid penetrant used in the *prewash* mode will yield nonemulsified effluent that separates by gravity when agitation ceases. The liquid penetrant should float for easy removal by skimming and for possible reuse if carefully collected. The water that remains on the bottom of the collection tank may also be reused in the prerinse step. Further processing may be required if separation is incomplete as evidenced by discoloration or organic contamination. The *prewash* concept can be used in closed loop liquid penetrant processes where waste water and unexpended liquid penetrants are recycled through the system rather than expelled into the environment.

Prewash Concept for Recovery of Liquid Penetrant

Another approach to control of liquid penetrant waste pollution uses a non–water washable liquid penetrant and gravity separation. This system permits recycling of the liquid penetrant as well as the rinse water. The technique calls for removing the bulk of the non–water washable liquid penetrant from the surface with a plain water wash before treatment with an emulsifier. Therefore, the principal effluent of this *prewash* technique is a nonemulsified mixture of liquid penetrant oil and water; the mixture quickly and completely separates by gravity. The liquid penetrant is skimmed off. The water is drawn from the holding tank and recirculated. The *prewash* concept can be useful in closed loop liquid penetrant processes where waste water and unexpended liquid penetrants are recycled through the system rather than expelled into the environment.

Development of Prewash Concept

In 1967, data were presented showing that higher liquid penetrant system performance and greater reliability were possible with the prewash approach.[18] Test data support the hypothesis that emulsifier contact time is not as critical in this system as in lipophilic postemulsification.

Potential Advantages of Prewash Techniques

The prewash system answers two contemporary exigencies: conservation of petroleum derived products and water pollution control. Its use results in lower material costs. Also, lower pollution abatement expenses will be experienced as the primary wash water is recycled without treatment and the second wash water is recycled with only minimal treatment. This is accomplished with a liquid penetrant system that (according to some authorities) has higher levels of performance and reliability than the existing water washable and postemulsifiable techniques.

Potential Advantages of the Hydrophilic Technique

The main advantage of the prewash technique from an environmental standpoint is control of water pollution. If recycling of the liquid penetrant is possible, the decrease in material costs is an added benefit. Pollution abatement expenses will decrease also as the primary wash water is recycled without treatment.

Example of Prewash Separation of Liquid Penetrant Oil and Water

Figure 8 compares the effluent generated by the prewash process to the effluents of the conventional water washable lipophilic and postemulsification processes. The prewash effluent shown in beaker 2 is in two layers: liquid penetrant oil and water. The liquid penetrant floats whereas the water is completely clean except for a few globules clinging to the sides of the beaker. Effluents in the other two beakers are stable, colored emulsions.

The first beaker contains the effluent of a water washable fluorescent liquid penetrant. The effluent in the third beaker is a mixture of a postemulsifiable fluorescent liquid penetrant and a lipophilic emulsifier. For photographic purposes, the effluents are 10 percent solutions, much higher than would result in practice. However, even though more concentrated than found under actual conditions, the results of stable, colored emulsions from the nonprewash processes and a floating liquid penetrant from the prewash process are accurately portrayed in the photograph.

FIGURE 8. Prewash liquid penetrant effluent floats (center beaker) whereas effluents from water washable (hydrophilic) liquid penetrant (left) and postemulsifiable (lipophilic) liquid penetrant (right) form emulsions.

Economic Feasibility of Liquid Penetrant Waste Water Clarification

In many localities, effluents from nonprewash liquid penetrant processes cannot go directly to the sewer. They require extensive treatment (1) to break the emulsion, (2) to separate the organics and (3) to clarify the water. Although water may be reclaimed after expensive processing, the separated liquid penetrant and emulsifier oils will be chemically altered and the economics of reclaiming these materials might be questioned. If the effluent is not an emulsion, then treatment costs are reduced. A nonemulsified effluent separates by gravity. Whether the pollutants float to the top of the tank or sink to the bottom depends on their specific gravity. In either case, separation takes place without expensive filtration or chemical addition. Therefore, a nonemulsified effluent can minimize water clarification cost.

Equipment for Prewash Separation of Liquid Penetrant and Water

The equipment required to capture and recycle liquid penetrant and rinse water from the prewash stage need not be elaborate. However, coalescers, precipitators, aerators, flocculators or similar devices are available to improve and hasten separation, especially if the water is going to be reused. In addition, there need be no chemical treatment of the effluent. The equipment needs only to use the gravity separation principle. Such equipment may involve holding tanks that allow the liquid penetrant to be skimmed from the surface of the tank or the water to be drained from the bottom.

Comparison of Hydrophilic with Lipophilic Liquid Penetrant Techniques

Using the hydrophilic technique is like using the lipophilic postemulsification technique inasmuch as a postemulsifiable liquid penetrant is used for both. Nevertheless, the two processes differ slightly. In the hydrophilic process, a plain water wash precedes application of an emulsifying agent. Also, instead of a full strength emulsifier solution, the hydrophilic system relies on a very dilute solution of hydrophilic emulsifier. The hydrophilic and lipophilic systems are distinguished elsewhere in this volume. Although an additional step is required to perform the hydrophilic process, this disadvantage may be more than offset by savings in the costs of material and reclaiming rinse water.

Principles of Operation of Hydrophilic Liquid Penetrant Systems

Prewashing with plain water physically removes from the surface all but a trace of the liquid penetrant. How completely the liquid penetrant is removed depends on factors such as (1) surface roughness, (2) water pressure and scrubbing action, (3) duration of the wash and (4) liquid penetrant characteristics such as viscosity and adhesive properties. On a typical turbine blade, for example, a non–water washable fluorescent liquid penetrant with balanced adhesive and cohesive properties and relatively low viscosity will be removed from the surface with a water wash so that the remaining liquid penetrant is only a microscopic film, as judged from its appearance under either white light or ultraviolet radiation.

Removal of Microscopic Surface Film of Liquid Penetrant after Plain Water Wash

After removing all but a trace of the surface liquid penetrant with water, the next step is to convert this remaining non–water washable liquid penetrant to a water miscible product, so it can be washed completely from the surface. This is accomplished by applying a hydrophilic emulsifier. Because the remaining liquid penetrant film is microscopically thin, the coating of hydrophilic emulsifier can also be microscopically thin. This contrasts with the conventional postemulsifiable process where a heavy layer of liquid penetrant requires a heavy layer of emulsifier. With the hydrophilic technique, only a thin coat of emulsifier is needed.

The final wash effluent is produced by the thin film of liquid penetrant and overlying film of hydrophilic emulsifier. Although it is an emulsion, it is highly diluted. If it were determined that this effluent required treatment, the cost of such treatment would be greatly reduced. A charcoal filter may provide a practical means of handling the final effluent.

Example of Hydrophilic Treatment of Jet Engine Turbine Blades

For demonstration purposes, the white light photograph of Fig. 9 shows the three stages of the hydrophilic process on a set of relatively smooth turbine blades. Blade 1 is coated with fluorescent liquid penetrant. Blade 2 has received a prewash. Blade 3 has gone through the complete processing cycle, including treatment in a 5 percent solution of emulsifier. The procedure for removing the residual liquid penetrant after the prewash is to immerse the blade in the weak hydrophilic emulsifier solution, remove it and allow it to drain for 60 to 120 s. Then the blade is flushed with water. Allowing the emulsifier solution to drain back to the tank conserves the solution and minimizes waste water contamination by reducing dragout. Also, because the water portion of the emulsifier solution substantially evaporates during the drain, the solution concentrates for maximum effectiveness.

Before using this procedure, allowing the emulsifier to sit on the part, a test should be run to determine that discontinuity detection is not degraded.

Evaluation of Hydrophilic Technique on Liquid Penetrant System Monitor Panel

Figure 10 is a composite ultraviolet radiation photograph that again illustrates the three stages of the process. The test piece is a *liquid penetrant system monitor* panel. This stainless steel panel has a chrome strip with five induced crack centers of varying magnitude whereas the balance of the panel has been sand blasted. The panel facilitates simultaneous sensitivity and washability evaluation. At

FIGURE 9. White light photograph shows three stages of prewash system: blade 1, liquid penetrant coated; blade 2, following plain water wash; and blade 3, after process completed.

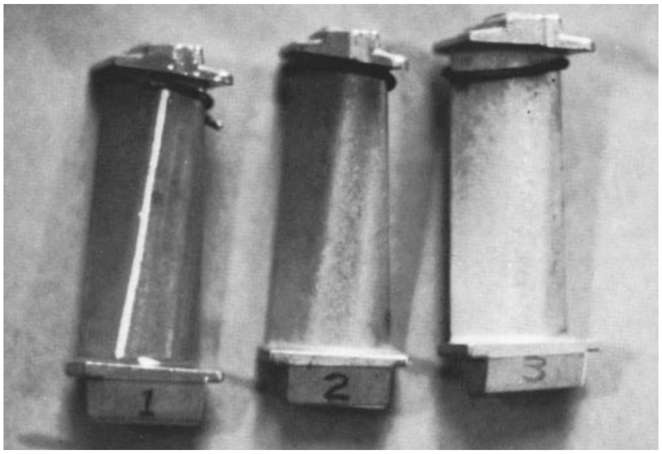
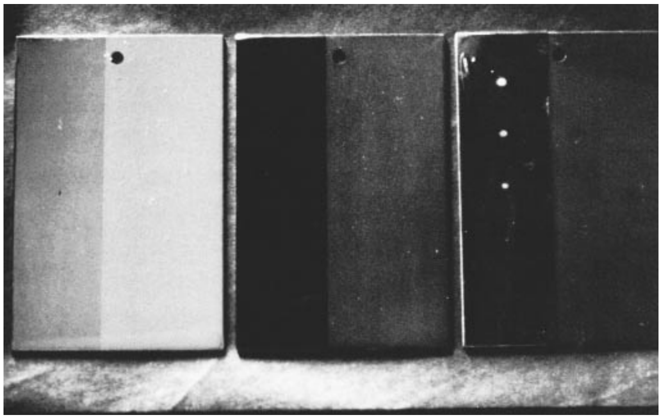


FIGURE 10. Ultraviolet fluorescent photograph shows three stages of prewash system on liquid penetrant system monitor panel: liquid penetrant coated panel (left), following plain water wash (center) and after process completed (right).



the left of the composite photograph, the panel is shown after being coated with fluorescent liquid penetrant. In the middle position, the panel has been washed, substantially removing the liquid penetrant from the smooth chrome plated strip. The quantity of liquid penetrant remaining on the blasted section may be considered objectionable. The right section shows the panel after full processing; four or five crack patterns are clearly delineated and the fluorescent background on the blasted section is at an acceptable level.

PART 6. Clarification and Distillation Recovery of Waste Water

Clarification of Waste Water Containing Liquid Penetrant and Emulsifier Contaminants

Modern inspection liquid penetrants are commonly made in the form of the *oil phase* system. This oil phase structure includes both postemulsifiable and water washable materials. The essential difference between the two types of materials is that, in the postemulsifier process, the emulsifier (detergent) is a separate process material whereas, in the water washable liquid penetrant process, the emulsifier is included as a constituent of the liquid penetrant.

The liquid penetrant process causes problems of water pollution generally produced by industrial and household detergents and by solubilized oils such as industrial cutting oils and inspection liquid penetrants. A suitable clarifier material acts to precipitate detergent materials out of solution and permits separation from water by means of a conventional settling tank clarifier (described below) or a continuous flow centrifugal separator. The clarifier material completely precipitates and adsorbs dissolved detergents along with complexed oils, solvent couplers and fluorescent dyes, leaving only a few parts per million of dissolved residue.

Function of Detergents in Oil Phase Liquid Penetrants

The function of the detergent ingredient in oil phase liquid penetrants is to render the oil constituent of the material emulsifiable in water. The detergent acts to combine with the oily liquid penetrant and when test parts coated with the liquid penetrant/detergent mixture are washed with water, the liquid penetrant oil is flushed from the test surfaces and is emulsified and partially solubilized.

The mechanics of oil emulsification imply that water added to an emulsifiable oil mixture forms molecular clusters known as *micelles*. These micelles become enlarged as water is added, until a point is reached where they become unstable and break apart into oil-detergent fragments that disperse in the water through dilution. Similar emulsification and solution mechanisms occur in virtually every soap and detergent composition. Hence, it is possible to group all soaps, emulsifiable oils and liquid penetrants together, insofar as their solution mechanism is concerned.

Detergents Producing True Solutions of Oil in Water

In some cases, where the detergent system in the emulsifier is designed for such purposes, the oil constituent of the liquid penetrant may be carried into true solution. According to the classic *micelle theory,* such materials remain as stable oil-water micelle clusters even with very large additions of water. Resulting mixtures often have the clarity of true solutions and behave in all respects like true solutions.

When industrial process materials that contain detergents are dispersed in wash water, an unusual form of pollution occurs. Many modern detergents of nonionic nature do not respond to chemical treatment, as do some ionic solutes. Also, the water mixtures are essentially free from solid matter, except for solid soil carried into suspension by detergent action. Hence, detergent containing water wastes possess a type of pollution or contamination that is difficult to extract from the water.

Pollution Resulting from Emulsifiers

In the postemulsifier liquid penetrant system, contamination of wash water effluent by oil carryover on parts may be minimized by removal of excess oil before the step of emulsification by using a high pressure spray of water. The water insoluble liquid penetrant floats to the surface of the water in a sump tank and may be recovered by means of a simple weir arrangement. Although this helps in the overall problem of water pollution, it still leaves the water contamination that results from the emulsifier used in the process. Lipophilic emulsifiers are themselves mixtures of oil and detergent materials.

Effects of Detergent Contamination of Lakes and Streams

Modern detergents, both industrial and household, have presented tremendous problems of water pollution. Several years ago, the detergent manufacturers were seeking commercially acceptable detergent products that were readily biodegradable. The idea was that all would be well if effluent waters containing such compounds would readily decompose or be eaten up by biological organisms.

Unfortunately, the idea of enhancing biodegradability of detergents did not solve the pollution problem. Some lakes and streams have such high concentration of detergent contaminants that thick layers of foam or suds remain and act to choke off oxygen from marine life. In certain cases of high biodegradability, algae proliferate to the point where the algae consume all the nutrients in the water. Then the algae die and create further damage by exhausting the water of dissolved oxygen through the process of decay and decomposition called *eutrophication.* It is becoming more and more evident that the only permanent solution to the problem of detergent pollution of water is to remove the detergent contaminants before the waste water is discharged into outfall sewers or into waterways.

Some detergents contain nonionic surfactants that are easily biodegradable. However, the issue of oxygen depletion by these surfactants has necessitated regulatory controls for waste water disposal.

Possible Techniques for Clarifiers to Precipitate Detergent Wastes

A possible useful approach to the extraction of detergent contaminants from water has been found in clarifier materials that have a unique property of causing the precipitation of the detergent substances out of a water solution. Although there may be some detergent materials that do not respond to the clarification action of a suitable clarifier, no such material has yet been found. The clarifier serves to completely precipitate all types of detergents, regardless of whether their chemistry has a linear or branched chain nature.

In physical form, the clarifier is a fine, white, inert powder that may be readily dispersed in water. If used in the dispersion mode, the clarifier is simply stirred into the waste water being treated and is allowed to settle, as in a settling tank clarifier. Another technique of usage is the filtration mode, in which the clarifier powder is included as part or all of the filter bed. Conventional nylon fabric grids in a spin filter configuration may be used to retain the clarifier powder. After use, the clarifier powder along with precipitated detergents may be recovered by conventional backwash and flushing techniques.

Chemical Behavior of Clarifier

In many respects, the clarifier behaves in accordance with normal chemical principles. The clarifier's adsorption and precipitating action is a predictable function of mole ratios of the clarifier and the detergent material in the waste water. However, the reaction of the clarifier goes beyond a simple precipitation reaction with detergents.

It has been found that the effect of oil solubilization in the presence of detergents is such that molecular clusters (or micelles) of oil, detergent and water occur as more or less firmly bound complexes. The result is that when the detergent substance becomes precipitated by reaction with a clarifier, it carries down with it the various other constituents that may be present in the micelle structure. This phenomenon extends even to fluorescent dyes and certain solvent couplers that may be present in an emulsifier or water washable liquid penetrant.

A typical water washable liquid penetrant consists of a mineral oil, an oil-water emulsifying detergent, a solvent coupler and one or more fluorescent dyes. When clarifier is added to the water, a precipitation of the detergent takes place. In addition, many of the related constituents are carried down out of the solution along with the detergent, leaving water with only a few parts per million of residual contamination.

Some pollutants in water take the form of colloidal dispersions or partial solutions of oil. Waste water of this kind may be purified in a two-step process, in which a detergent is first added to the waste water to initiate the formation of oil-detergent micelles, after which clarifier is added to the water. When the detergent is precipitated, it carries down with it the dispersed oil along with any other contaminants that can form micelle complexes with the detergent.

Determination of Reaction Ratios of Clarifier

If it is desired to provide an economically attractive process of water purification, it is necessary that the clarifier material be used at its highest possible efficiency. For rapid and complete precipitation, a slight excess of clarifier or some simple means must be used to determine when the clarifier is completely consumed.

The technique of mixing clarifier into waste water and subsequent removal of the precipitate by settling or centrifuging provides a highly efficient process. The clarifier particles normally remain suspended in the water for a sufficient time to permit the precipitation reaction to go to completion. On settling or centrifuging, the detergent and other complexed materials are separated from the water, leaving only a few parts per million of dissolved material. In this mode of usage, it is desirable to determine the percent of detergent contamination of the waste water in order to add the correct quantity of clarifier.

Technique of Filtering Waste Water through Clarifier

In the filter mode of usage, waste water containing dissolved detergents and complexed oils is pumped through a filter bed or clarifier. In this process, the waste water passes through the filter bed rapidly, so that the precipitation reaction may not go to completion in one pass through the filter. Recirculation of the water through the filter will serve to extract the dissolved detergents fully. In this mode of usage, it is desirable to know when the filter bed of clarifier becomes exhausted.

The detergency of the waste water may be determined by relatively simple techniques. One such technique involves the evaluation of surface tension of the water and comparison with samples having known detergency. Thus, it is not difficult to determine the detergent content of waste water, either before or after treatment with clarifier. Certain techniques of fluorescence analysis permit the quantitative measurement of residual contaminants by the degree of fluorescence response.

Clarifier Equipment for Separating Solid Precipitates from Water

Dissolved detergents are precipitated by a clarifier in the form of particulate solids. This solid material may be separated from the water by means of a settling tank clarifier or by means of a continuous flow centrifugal separator. The settling tank clarifier consists of a large circular tank with a shallow sloping bottom. Water containing suspended particles is pumped into the tank where particles settle to the bottom and clear water flows over a weir at the top. A rotating scraper moves the settled sludge in such a way that it passes out through an exit port in the bottom of the tank. This type of equipment requires a fairly large tank area and the movement of the water must be slow enough to permit settling of the fine particles of suspended matter.

Centrifugal separation may be accomplished with equipment considerably smaller and somewhat more efficient in operation than the settling tank clarifier. Here the water is injected into a vertical cylindrical tank rotating at high speed. Centrifugal force drives the heavy suspended particles toward the walls of the tank. A screw conveyor or spiral scraper blade moves the separated sludge toward the bottom of the tank and out through a conical orifice. The purified water flows over a weir lip at the top of the tank and is recovered.

Recovery of Clarifier Material for Reuse

The clarifier material is consumed while dissolved detergent is precipitated. However, the reaction is reversible in the same way that water softening reactions are reversible. Thus, the exhausted clarifier may be reclaimed, reconstituted and reused.

Onsite Clarification of Waste Water

Waste water that contains detergents and oil/detergent complexes and that is discharged into sewage lines may first be treated by the clarifier process. Systems for treating water by county sanitation departments or by municipalities must be properly designed and engineered with regard to appropriate projections of flow rates. In addition, accessory systems must be included for recovery and recycling of the clarifier material and the detergents and oils that are removed from the water. For such onsite clarification, small units may be constructed from currently available components. Various bag or grid filters are available, as are various sizes of centrifugal separators. Recovery and recycling of the clarifier material itself could be carried out in separate processing plants.

Closed Loop Liquid Penetrant Testing System

The closed loop concept evolved from the desire to implement an apparently simple and obvious expedient of recovering the liquid penetrant process materials for reuse. However, the implementation of this idea was not all that simple. First, it should be noted that complete recovery of the process materials will not be possible if any of the materials undergo a substantial physical chemical change during use.

One of the reasons for failure of water purification and chemical recovery systems in the case of emulsified oils is the fact that the liquid penetrant oil undergoes a substantial physical change by being emulsified in the wash water. The micelles or molecular clusters of oil and detergent become tightly bound to water molecules and then resist separation.

Slow Solubility Liquid Penetrants

Some water washable fluorescent liquid penetrants, referred to as *slow solubility liquid penetrants,* disperse in water without undergoing emulsification. Thus, the dissolved or dispersed liquid penetrant is not tightly bound to the water in the conventional micelle emulsion structure.

Another interesting feature of the slow solubility liquid penetrants is that they exhibit a high degree of discontinuity entrapment efficiency. Their entrapments in cracks are slow to dissolve and tend to remain in the cracks throughout a relatively prolonged washing period. Depletion time constants are controllable within broad limits, so the liquid penetrants can be designed to meet any desired condition of discontinuity entrapment efficiency. (Depletion time constants are described elsewhere.)

Another, very important feature of the slow solubility liquid penetrants is that they exhibit very little tendency to become adsorbed onto fine porosity surfaces. Conventional emulsion forming water washable liquid penetrants and even postemulsifiable liquid penetrants, are characterized by an effect of adsorption at the liquid solid interface on test parts. Where the solid surface has a large area, as in anodized surfaces for example, this feature of adsorption produces an excessive amount of *background* fluorescence, resulting in poor signal-to-noise ratio. Adsorption and unwanted background are minimized in the slow solubility liquid penetrants.

The first of the two new chemical categories is exemplified by liquid penetrants characterized by a relatively rapid rate of wash removal with a hot water spray wash at temperatures in the vicinity of 55 °C (130 °F). The second category liquid penetrants are chemically different and provide progressively larger indication depletion time constants.

Recycling Liquid Penetrant after Solvent Distillation

The new slow solubility liquid penetrants may be recycled in a closed loop operation through three stages. First, surface liquid penetrant is stripped from parts by means of a pressure spray of wash water. The liquid penetrant thus removed does not dissolve rapidly in the water; instead, it tends to float on the surface of the wash water and may be drawn off over a drainage weir and recovered.

Recycling of Wash Water

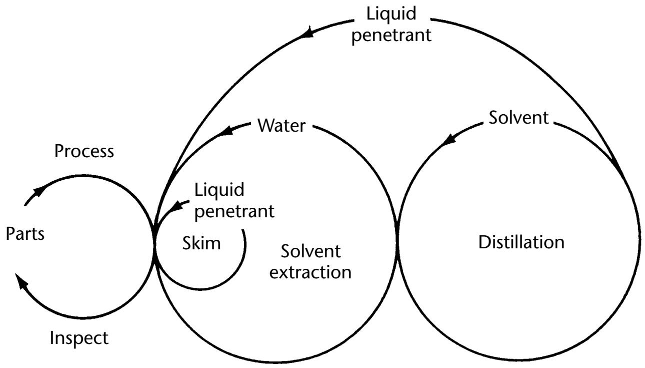
The wash water is circulated from a reservoir through wash nozzles and back to the reservoir. After considerable use, the wash water becomes saturated with dissolved liquid penetrant. It is necessary to extract the dissolved liquid penetrant continuously from the wash water to preserve its ability to dissolve liquid penetrant from test surfaces. This extraction is carried out as outlined above.

If it were required to purify the used prewash water enough to drink, liquid penetrant contamination would have to be reduced to a value of about 5 $\mu g \cdot g^{-1}$ or less. For purposes of prewash treatment in the closed loop process, it is not necessary for wash water to be so pure.

Process Diagrams for Closed Loop System

For reasons of economic feasability, the closed loop, water washable liquid penetrant testing technique has not been developed commercially, specified in standards or implemented by industry as of 1999. The process would consist essentially of five interlocking loops (Fig. 11).

FIGURE 11. Interlocking loops of closed loop system for water washable liquid penetrant testing process.



1. Test parts would be processed through the steps of (a) liquid penetrant application, (b) wash removal of surface liquid penetrant and (c) inspection for indications. Development, of course, would be included as part of the inspection step.
2. Part of the liquid penetrant would float and would be skimmed and retained for testing to determine its suitability for continued use.
3. Used wash water would be cycled through a solvent extraction stage and the purified water would be returned to the wash water reservoir.
4. The solvent that contains extracted dissolved liquid penetrant would be cycled through a distillation column and recovered solvent would be returned to the extraction column.
5. Liquid penetrant recovered by distillation of extraction solvent would be retained for testing to determine its suitability for continued use.

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11

CHAPTER

Filtered Particle Testing

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PART 1. Principles of Filtered Particle Testing[1]

Nondestructive Testing of Porous Materials

Visible and fluorescent liquid penetrant test techniques can be used on most solid materials. However, if the test materials are porous, the background *haze* or coloration of the entire surface by the penetrant reduces the contrast of indications. The surfaces of such porous materials trap so much test fluid that delineation of a discontinuity is no longer possible. For this sort of test condition, the filtered particle test technique is effective.

The procedure for locating discontinuities with filtered particles is to apply a liquid dispersion of properly sized and shaped particles to a porous material suspected of having discontinuities open to the surface. If a crack exists, a highly visible indication will appear almost at once.

This test is useful for testing of a wide range of porous materials. Generally speaking, the filtered particle technique operates on those materials whose particle size is 150 µm (0.006 in.) (100 mesh) or smaller. Thus the area of effectiveness of this technique is fairly well bracketed by the 150 µm (0.006 in.) limitation on one hand and the failure of liquid penetrants to work on the other. The filtered particle test was developed by Taber DeForest and Henry N. Staats in 1946.[2-4]

Principles of Operation of Filtered Particle Test Technique

The filtered particle test technique depends on selective motions of liquid and solid matter. The test fluid consists of a liquid vehicle (or tracer when it contains soluble dyes) that carries solid dyed particle tracers in suspension. This fluid, generally oil based, is sprayed on a porous material suspected of having a discontinuity or anomaly. At the site of a discontinuity, more liquid is absorbed than anywhere else, because of the extra liquid tracer absorption area in the discontinuity. The liquid enters the discontinuity opening while the suspended particles are filtered out and deposited on the part surface. The particles may be colored or fluorescent. Generally speaking in industry, fluorescent filtered particle tracers are used to the exclusion of all others. These fluid tracers may be of any base, although sharp boiling point hydrocarbons are preferred because of their economy and reasonable safety hazards.

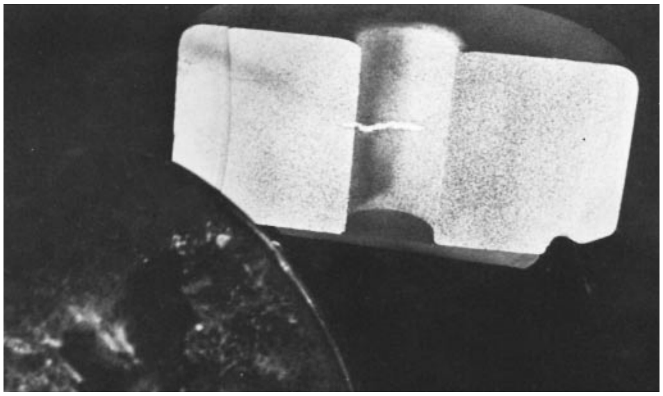
Forms of Filtered Particle Testing Media

Filtered particle test media commonly used in industry today are of two types: (1) a vehicle containing solid tracer particles only and (2) a liquid vehicle with soluble dye tracer and tracer particles.

The standard form of filtered particle testing medium consists of fluorescent particles and a base oil. When sprayed on a porous material such as clay, carbon, certain powdered metals and concrete, it will produce a highly visible indication, as shown in Fig. 1. The indication reveals the location of the discontinuity and the part may be rejected without further work. This material is used where salvage is not possible or worthwhile.

The soluble dye form of filtered particle test medium is commonly used in certain segments of the clayware industry where salvage is desirable. In this case, soluble dyes are included in the test liquid in addition to the particles. The filtered solid particles form the indication of the discontinuity on the surface.

FIGURE 1. Fluorescent filtered particle indication on unfired clay insulator.



Next the operator scrapes away or *chases* the discontinuity and reveals the soluble dye indication below the surface. The particles indicate the discontinuity at the surface, whereas the soluble dyes penetrate the piece and concentrate in the discontinuity. The discontinuity is chased until no traces of the dye material remain at the test site. This does not necessarily mean that the discontinuity has been completely removed.

Just as it is necessary to recheck in other techniques, it is essential in this case too. In continued salvage, water must be added to the surface of the material. This is known as prewetting and is always essential in salvage work. After the water has been absorbed, a fresh application of test medium can be used and a new surface particle indication developed. Salvage work can then continue.

The test medium fires off during the processing of clayware and leaves no residue. Filtered particle test media containing water have been developed and can be used on portland cement concrete.

Applications of Filtered Particle Tests

The most significant use of filtered particle testing is in the clayware industry.[5-8] This is particularly true of sanitary ware and high tension insulator manufacture.[9] Here, the objects under test usually are relatively expensive or involve a great deal of workmanship. The filtered particle technique is important in these two industries, because a crack in unfired clay always opens on firing. In the case of sanitary ware, if the crack opens wide enough to break open the glaze, the ware will have unsightly marks on it and cannot be sold. Opening of a crack during the firing process will provide a path for electrical breakdown on high tension insulators so that they cannot be used in service. Another application of filtered particle testing is for testing carbide inserts for cutting tools before final firing.

PART 2. Mechanisms of Operation of Filtered Particle Tests

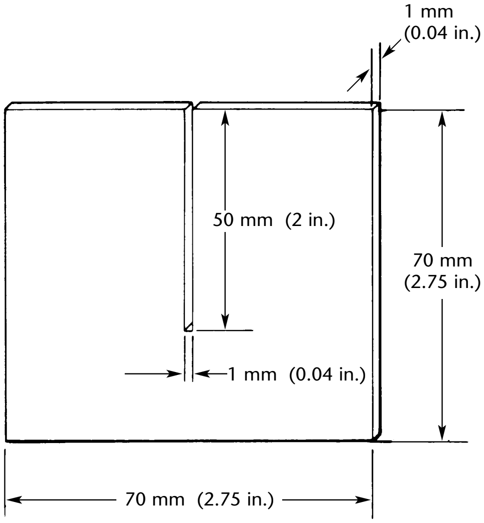
Selective Fluid Absorption in Porous Test Materials

Porous materials, in general, will absorb liquids in proportion to their surface area. More fluid is absorbed at a discontinuity in porous materials than anywhere else, because of the extra absorption area of the sidewalls in the discontinuity. The absorption is so pronounced that the suspended particles are drawn to the site of the discontinuity. Being wider than the dimensions of the top edges of the crack, they filter out and form a surface indication. Because a striking effect is produced readily, it seems reasonable to believe that very large differential absorption rates are involved.

Example of Crack Absorption of Liquid Tracer in Porous Material

Figure 2 shows a cross section of a porous material containing an idealized crack. The section is assumed to be 1 mm (0.04 in.) thick , 70 mm (2.75 in.) wide and 70 mm (2.75 in.) high. Assume that the crack is 50 mm (2.00 in.) deep and has a width at the opening of 1 mm (0.04 in.). The crack is schematically drawn in rectangular form although, in practice, cracks are nearly always wedge shaped.

FIGURE 2. Schematic cross section of porous material containing crack.

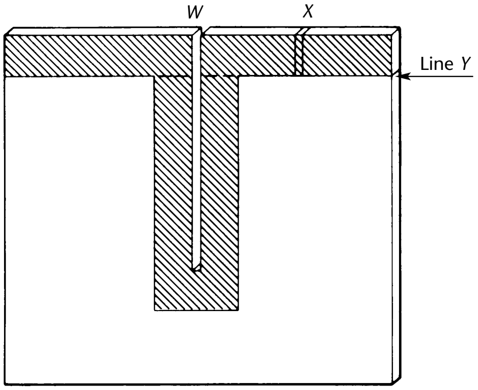


If 1700 mm^3 (0.11 in.^{3}) of a fluid are placed on the surface containing the discontinuity and a uniform entry of 10 mm (0.4 in.) is accomplished on all surfaces, the manner of penetration by diffusion and capillary action is substantially as shown in Fig. 3. If no crack were present the volume of liquid absorbed would be proportional to 700 mm^3 (0.04 in.^{3}), as indicated by the portion above line *Y* in Fig. 3. Because the specimen contains a crack, fluid will also be absorbed in the shaded zone below line *Y*. This crack region will contain about 1000 mm^3 (0.06 in.^{3}).

Suppose the width of the crack *W* to be 1 mm (0.04 in.). A slice *X* of unchecked porous material of similar dimension will possess a total volume of 10 mm^3 (6×10^{-4} in.^{3}). Comparing the absorption at point *W* and point *X*, it will be noted that 1000 mm^3 (0.06 in.^{3}) of liquid are absorbed at point *W* and 10 mm^3 (6×10^{-4} in.^{3}) at point *X*. Thus, there exists a differential absorption ratio of 1000 to 10 or 100 to 1. It is assumed that the volume of the imaginary crack is equal to the volume of contained liquid, which, of course, is never the case.

The dimensions and figures given are only illustrative for the purpose of showing the phenomenon of differential absorption. In practice, it has been noted that the ratio of crack width to depth is on the order of 1 to 300. Therefore, to be

FIGURE 3. Schematic cross section of porous material containing crack, showing penetration of liquid.



more exact, the crack width at point *W* may be considered to be 50/300 or about 0.15 mm (0.006 in.). Other dimensions remain the same. Thus, with point *W* at 0.15 mm (0.006 in.) and point *X* at 0.15 mm (0.006 in.) width, the differential absorption ratio would be 1000 mm^3 (0.06 $in.^3$) at point *W* and 1.5 mm^3 (9×10^{-5} $in.^3$) at point *X*, a ratio of 1000 to 1.5 or about 600 to 1.

From this simple example, it can be seen that high forces are involved in producing an indication on a porous material. The example given is idealized: a variety of factors may prevent such differential forces from ever being encountered in practice. Under certain conditions, it may be possible to increase or aid those forces by timely water barriers.

Characteristics of Differential Absorption

The phenomenon of differential absorption depends on a variety of factors, including (1) porosity characteristics of the test object, (2) substances in the pores of the test object and (3) characteristics of the test medium.

Effect of Size of Porosity of Test Object

If there is excessive porosity relative to the solid portion of the material to be tested, the porous body will absorb liquid too rapidly and the differential forces may be too low to produce an effective indication. If the size of the individual pores is relatively larger than the discontinuity width, the pores may be indicated more prominently than the discontinuity itself. In some cases, the amount of interconnection of the pores influences the absorption characteristics of the material considerably. Some types of ceramics have an extensive pore structure but each pore may be sealed off from its neighbors, thus preventing adequate penetration of the test fluids.

Effects of Characteristics of Filtered Particle Test Media

The size and shape of the solid tracer particles used in detecting cracks are quite critical. If the tracer particles are too small, they may enter the discontinuity rather than filter out. If the tracer particles are too large, they may lack mobility and drop out of suspension at random rather than filter out selectively over the discontinuity. The penetrating power of the suspending medium is also a critical factor in the ability of the filtered particle testing technique to locate discontinuities reliably. The abilities of various fluids to penetrate porous materials depend to a large extent on the type of material to be tested. Porous concrete can be readily tested with solid tracer particles suspended in water containing a wetting agent. The same water base medium used on clay will dissolve it. If the viscosity of the fluid vehicle is increased, the absorption rate may be retarded, thus preventing the differential forces from operating efficiently.

The concentration of solid tracer particles in the test fluid must be kept in certain limits. If the concentration is too high, excessive backgrounds may form, tending to reduce the visibility of the discontinuity indication. If the concentration is too low, the result may be a weak indication, lacking in brightness.

Effects of Substances Absorbed in Test Object Pores

Water or other substances that may be present in the pores of the material to be tested can influence the differential absorption forces in such a way as to aid or hinder the technique in its proper operation. For example, unfired or green hotel chinaware may not be porous enough for testing when the included water content exceeds 10 percent by weight. However laminar discontinuities can be located in green tile bodies with moisture contents ranging up to 12 percent.

Classification of Test Object Porosity

Porosity is relative and the best test for workability of the filtered particle test technique is an actual test on the material in question. Generally, porous materials may be divided into five groups, as described in subsequent paragraphs.

Very Porous Material

Very porous material can be illustrated by the porosity of a fired grinding wheel made from 250 µm (0.01 in.), or 60 mesh, particles or by the porosity in fired refractories where very large particles are bonded to still larger particles and the subtended spaces are left empty. The filtered particle technique rarely works on coarse material of this type. Attempts have been made, without success, to fill the voids temporarily to create an artificially good grain structure that will permit detection of discontinuities in this type of material.

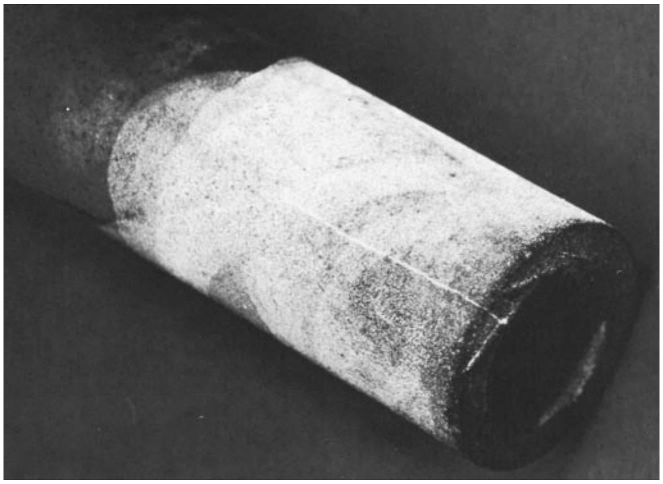
Moderately Porous Material

Examples of moderately porous materials are fired grinding wheels made from 100 µm (0.004 in.) or 150 mesh particles, some refractories and carbon materials whose range of particle size is smaller than in the first classification. Certain powdered metal compacts and some types of portland cement concrete belong in this category. The filtered particle test technique begins to operate on materials of this type. The indications may be slightly erratic because of cracks running through zones of large pores where differential absorption forces cannot operate effectively. Figure 4 shows a fired, porous, combustion tube containing a fluorescent indication of a crack. The background coloration indicates that the area that does not contain the crack is absorbing excessive amounts of fluid and that the differential absorption forces are much reduced.

Porous Materials for Filtered Particles Tests

Examples of medium porosity are many, for this group includes nearly all types of unfired dried clayware and certain fired porous ceramics. In this group also are certain refractories, both fired and unfired; semivitreous materials that are unglazed; unfired and fired cermets; and some fired compacts such as carbon and graphite. The filtered particle technique operates decisively and reliably on this group of materials. Figure 5 illustrates typical indications of laminar discontinuities in dried clay tile. Cracks of this type are usually caused by the entrapment of air at the time of pressing. The filtered particle technique will operate on materials of this type, providing differential absorption forces can operate. For instance, if there were water or wax present in the porous test material, the pores may be filled and the absorption forces cannot work as they would normally. However, it is frequently possible to remove the space filler before testing.

FIGURE 4. Fired, porous combustion tube with fluorescent indication of crack.



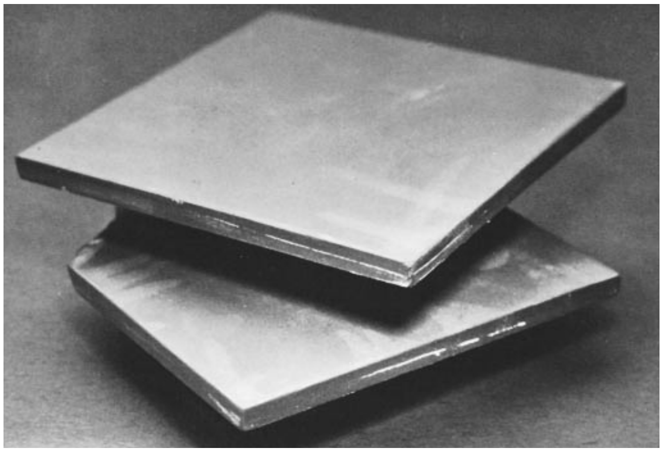
Slightly Porous Materials

More difficulty occurs with testing of slightly porous materials. A structure is present that may or may not have complete interconnection between bubble porosities. A void may or may not be present at the surface. Examples of this type of material are certain types of fired, partially vitrified, unglazed ceramic materials; some cermets; and certain types of carbon and graphite. In general, the technique will operate on materials of this sort, although very poor differential absorption forces are present and the sensitivity limit is in sight.

Filtered Particle Tests of Porous Glazed Materials

Examples of porous glazed materials are semivitreous wares that have a glazed surface. If there are cracks in the glazed surface that extend through to the porous underbody, the filtered particle test technique will operate efficiently.

FIGURE 5. Fluorescent indications of typical laminar cracks in dried clay tile.



PART 3. Design and Selection of Filtered Particle Test Media

Selection of Suspending Medium for Filtered Particles

The fluid vehicle used for filtered particle test medium of most porous materials in industry is a light petroleum distillate. This material is a compromise between cost, safety, odor and reasonably fast drying action. It has been highly satisfactory on all types of clayware, the solvent residues firing off in kilns with no complications. This solvent does not affect glaze slips applied over it.

In some cases where a ceramic glaze is fired at the same time as the body, as is the case with sanitary ware fired once, it is advisable to let the ware air dry for at least 15 min after testing before glaze is applied. Sometimes, if glaze slip is applied to freshly tested ware, the surface pores will be plugged with petroleum distillate and slip will not adhere tightly. This sometimes causes crawling of the glaze. This effect is the same as applying a glaze slip to a piece of clayware that had been freshly soaked with water.

For special applications, suspending media other than petroleum distillate may be used. Suspensions have been made successfully with water, glycols, heavy petroleum distillate and alcohol. In general, the suspending medium will be light petroleum distillate, now considered standard. Any suspending medium other than the standard distillate increases the cost of the basic material, because the solvents are inherently more expensive. The one exception is water itself. However, water tends to cause clay to dissociate and thus is not usable. Suspensions with fluid bases other than light petroleum distillate must be custom made for the specific application.

Solid Tracer Particles for Test Media

In all filtered particle test fluids, the solid tracer particles are selected for proper size and shape. The particles are extensively milled to produce a wide range of particle sizes with a predominance of particles of micrometer size. In all cases, these particles will fire off at temperatures of 200 to 315 °C (400 to 600 °F). Where glaze slips are applied onto clayware and other materials after testing, the suspending medium and particles fire off with no known effect on the glaze.

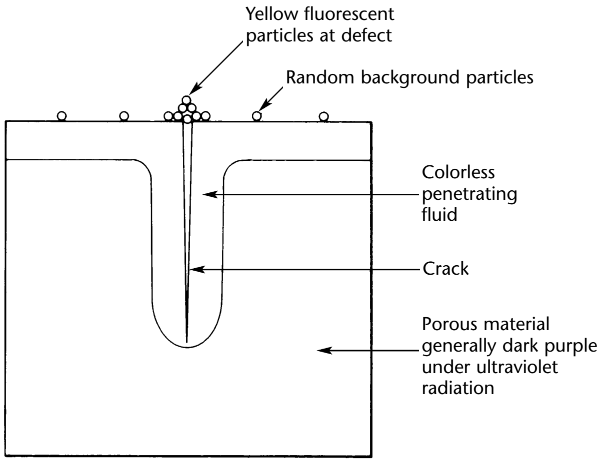
Types of Fluorescent Filtered Particle Test Media

In the manufacture of many clay products, the existence of a crack in unfired clayware is sufficient justification for scrapping the material. For instance, it is neither economical nor generally possible to repair cracks in dishes. The same thing is true in the testing of tile. On certain unfired porous products such as insulators and fired ceramic materials, the existence of a crack is cause for rejection. No repair techniques are generally feasible. On these materials, it is sufficient to provide a readily seen surface indication only.

Filtered Particle Test Media for Location of Surface Cracks Only

The fluorescent test medium recommended for surface indications only is a light petroleum distillate base in which are suspended vividly yellow fluorescent particles. The material is shipped ready to use. Figure 6 illustrates in schematic form a cross section of an idealized discontinuity in clay containing a surface indication only.

FIGURE 6. Schematic cross section of crack in clay with surface particle indication of defect.



Filtered Particle Media for Location of Repairable Cracks in Unfired Ware

On unfired sanitary ware, high tension insulators or other cast, assembled or machined green clay products, the surface indication of a discontinuity is not necessarily a reason for their rejection. With green clayware, it is usually possible to remove or *peg* the discontinuity or crack and salvage the piece. For example, if a crack appears in the body of an extremely large high tension insulator, it probably will be cause for rejection. However, if the crack appears in the petticoat or skirt of the insulator, it may be possible to *chase out* the discontinuities and thus salvage the piece, providing the shape change does not affect the electrical characteristics of the completed, fired insulator.

Where salvage of a porous object is desired, a test medium is used whose particles indicate the crack at the surface and whose staining dyes color the inside of the crack so that an inspector may *chase out* a discontinuity, that is, dig into the discontinuity, following it to the bottom. Figure 7 shows a typical fluorescent indication of a crack in the foot of a toilet bowl. Figure 8 illustrates how the inside of the crack is stained with fluorescent dyes, so that the discontinuity may be *chased out.*

Figure 9 illustrates in schematic form the cross section of a discontinuity where the surface as well as the subsurface portion is indicated by fluorescent materials. Here the dye tracer colors in order of viewing are as follows.

1. On the surface, yellow fluorescent particles are found with a fluorescent red yellow background.
2. About halfway down the crack, a red fluorescent indication with a fluorescent yellowish background will be found.
3. Below this zone, a yellowish blue fluorescent indication with a purple background will be found.

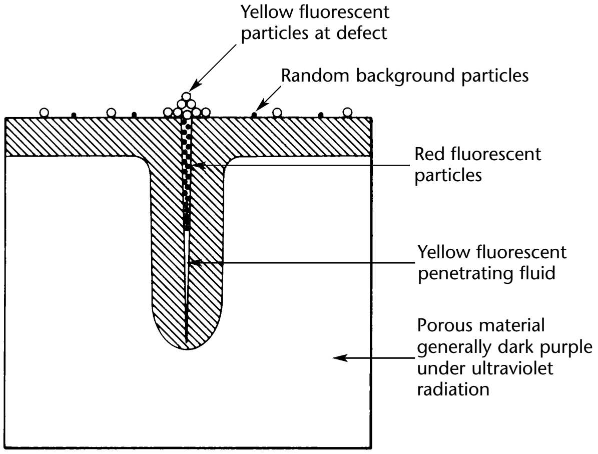
FIGURE 7. Fluorescent indication of crack in foot of toilet bowl.

FIGURE 8. Subsurface indication of crack after removal of surface material.

Nonfluorescent Filtered Particle Test Media

Colored but nonfluorescent test suspensions, although as sensitive in operating ability on porous materials, cannot be seen so readily as fluorescent materials on complex shapes such as insulators, sanitary ware or parts with hidden curves or recesses. Fluorescent material is recommended for such inspection problems. Generally, the nonfluorescent materials can be used on simple shapes such as bricks, carbon and concrete, although fluorescent materials may be simpler to use and more decisive.

FIGURE 9. Schematic cross section of defect containing subsurface as well as surface fluorescent indication.



PART 4. Filtered Particle Test Equipment

Light Sources for Filtered Particle Testing

For effective, rapid and reliable testing of fluorescent filtered particle indications, the near ultraviolet radiation output should be of high intensity. Ultraviolet radiation sources that meet this requirement generally consist of five items: a special bulb; a special filter; a fixture or shell, generally portable and with a handle; a transformer; and interconnecting wires. Generally, 120 V, 60 Hz alternating current is required. Figure 10 illustrates a typical portable ultraviolet lamp used widely in industry. After application of the fluorescent test materials, the test object is illuminated by the lamp held by the operator. Discontinuities indicated by flowing lines readily attract the operator's eye.

FIGURE 10. Portable ultraviolet lamp used in fluorescent inspection of high tension bushing.

Equipment for Applying Filtered Particle Suspensions

To get maximum benefits in the testing of porous products, it is essential that the test suspension be applied in such a way as to let the particles move about freely and penetrate discontinuities. In general, the correct amount of fluid to place on a piece to be tested is just enough to wet the surface or make it shiny. Any material in excess of this is generally wasted and anything less than this will not provide sufficient particle mobility.

Any equipment that disturbs the mobility of the particles is to be avoided. In the past, kerosene has been painted on clay objects to detect discontinuities. One should avoid the temptation to use a brush with a filtered particle medium, because the bristles of the brush tend to line up the particles in such a manner as to create false indications. These resemble true discontinuity indications and may confuse the observer.

Spray guns or similar equipment that apply the fluid by an exterior force should be used with caution, because it is possible to remove indications by applying the liquid with too great a force.

Pressure Gun for Spraying Filtered Particle Suspensions

A portable spray gun has been designed to spray a narrow, 60 degree spray pattern of test liquid onto porous objects without interfering with the formation of indications. This gun will hold about 0.5 L (0.1 gal) of liquid at an air pressure of 275 kPa (40 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$), which is placed on top of the liquid through a special valve. The air line can be disconnected and the gun carried about as a portable instrument. This feature is particularly valuable when the operator does not wish to be tied down by a hose connecting device. If desired, the air hose can be left connected and the gun filled to its capacity (1 L or 0.25 gal) and used at a fixed location.

Tank Pressure Equipment for Filtered Particle Tests

Tank equipment is the equivalent of a pressure gun, except that more than 4 L (1 gal) of test fluid is held in a tank that rests on a small dolly. Air can be pressurized and the hose removed to allow equipment to be moved about. The filtered particle test material is sprayed on the pieces through a 3 m (10 ft) hose by a gun with a nozzle similar to the pressure gun mentioned earlier. This equipment is small enough to be shaken occasionally to maintain the suspension in proper condition. Similar equipment is provided for the spraying of water.

Drum Agitator Equipment for Filtered Particle Tests

A larger type of equipment consists of a heavy duty pump and motor that can be mounted on a rack or a high table. A full drum of filtered particle suspension can be placed underneath and specially designed mixing hoses introduced into the drum. A long pair of hoses is attached directly to the pump and the liquid is continually recirculated in such a manner as to stir the contents of the drum and provide a constant concentration of particles in liquid to the operator. The fluid is applied with a gun similar to that used in the pressure tank equipment mentioned in the preceding paragraph. This equipment may be piped for supplying up to ten inspectors operating off the system.

Other Techniques for Application of Filtered Particle Test Media

Filtered particle test fluid can be applied by rather simple measures, depending on the object to be tested. For instance, some users have tested pole type electric power insulators that are about 600 mm (24 in.) long with a hole 50 mm (2 in.) in diameter running almost the entire length of the object. Cracks occasionally occur at the bottom on the inside. In this case, regular pressure type equipment may not be as useful as an ordinary eyedropper, tablespoon or an oil squirt gun. When using equipment of this type, it is essential that the test medium be poured or squirted as evenly as possible to avoid drain marks.

A simple pump spray applicator, such as is sold in supermarkets for household use with window cleaner etc., will also work well. These devices have adjustable nozzles, and the spray may be adjusted to suit the test. The operator must remember to shake these from time to time to ensure complete suspension of particles in the fluid.

PART 5. Prewetting and Associated Phenomena

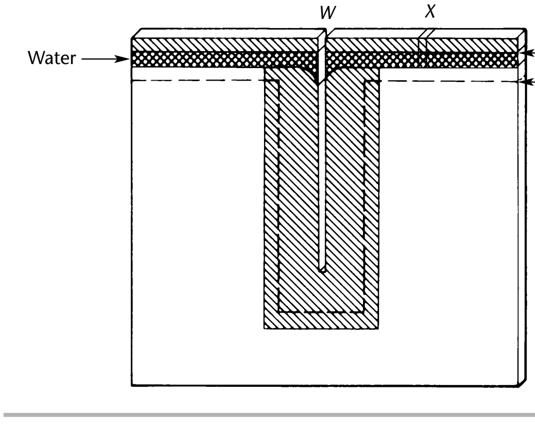
Effect of Water on Fluorescent Particle Indications

Many users of the filtered particle test technique have observed that water plays a very important role in the reproduction of an indication. As pointed out earlier, the forces involved in differential absorption are extremely large, running as high as 600 to 1. Water can increase this differential ratio. Figure 11 shows a cross section of a porous material containing a crack. The dimensions are similar to those shown in Fig. 2. If 200 mm^3 (0.012 in.^{3}) of water are placed on the surface containing the discontinuity and it penetrates uniformly, the manner of penetration is substantially as shown in Fig. 11. The water forms a band or layer, about 2 mm (0.08 in.) thick and about 2 mm (0.08 in.) below the surface. A limited amount of penetration will occur in the confines of the crack itself.

Penetration of Oil Based Fluid above Water Barrier

If 1700 mm^3 (0.11 in.^{3}) of an oil based fluid are placed on the surface containing the discontinuity, a uniform penetration will occur as shown in Fig. 11. Because the oil is not miscible in the water, it can only fill the vacant pores about line *Z*. The remainder must enter the discontinuity and penetrate where no water barrier is encountered. The dotted line *Y* shows the penetration of the fluid without benefit of water addition.

FIGURE 11. Schematic cross section of defect, illustrating penetration of oil based fluid with water.



Differential Absorption Ratios with Prewetting

If the absorption at point *W* is compared with that at point *X* in Fig. 11, it will be noted that about 1600 mm^3 (0.1 in.^{3}) of fluid are absorbed at point *W* and only 4 mm^3 (2.4×10^{-4} in.^{3}) at point *X*. By comparing amounts of fluid penetrant, it will be noted that the ratio is 1600 to 4 or 400 to 1.

Again, as indicated earlier, it has been noted that the ratio of crack width to depth is of the order of 300 to 1. Therefore, the crack width at point *W* is 0.15 mm (0.006 in.); all other dimensions remain the same. Thus, with point *W* at 0.15 mm (0.006 in.) and point *X* at 0.15 mm (0.006 in.) width, the differential absorption ratio would be 1600 mm^3 (0.1 in.^{3}) at point *W* and 0.6 mm^3 (3.7×10^{-5} in.^{3}) at point *X*. This is a ratio of 1600 to 0.6 or 2700 to 1.

Effects of Prewetting in Filtered Particle Testing

From this simple idealized example of the effect of water, it can be seen that the forces involved in producing a filtered particle indication where prewetting occurs are much higher than where no water is used at all. In practice, prewetting has the advantage of aiding in the production of sharp, clean cut crack indications with a substantially reduced background. Prewetting tends to slow the absorption rate; however, in most cases this has been no disadvantage. The value of prewetting may be nullified if the test operator allows too much time between the application of water and application of test fluid. Too much water applied to the porous surface of claylike objects may prevent indications from forming by clogging pores in cracks.

Indicating Contained Water in Green Clay Materials

The application of water to clay is usually discussed in terms of prewetting rather than of water already contained in the clay. If clay is not completely dried, the body may contain enough water to prevent the absorption of any externally applied fluid. Prewetting is only advantageous when used on dried clay materials.

In some instances, it is possible to use test fluids as a rough indicator of the amount of water contained in clay. For example, one filtered particle test medium contains, among other things, red fluorescent dye. Under certain conditions, this dye is a soluble in water as well as oil. In dry clay, the test medium will temporarily stain it a bright pink color. If the clay is damp, the red dye tends to dissolve into the water (contained in the clay) and will stain the surface of the clay object a very faint pink.

Applications of Prewetting Technique

The addition of water to clay plays a still more important role with test fluids for detecting discontinuities. In some instances, water is required. On clay surfaces that have been abraded with steel wool, turning tools, emery paper or the like, it is absolutely essential to prewet the ware before testing. If they are small enough, as are some electrical bushings, it is frequently easier to dip test objects very quickly into a tank of water and test in 5 min. On sanitary ware or other large objects, the water may be sprayed or sponged on just before testing. Generally, the amount of water required on the surface of the clay is just enough to change the color of the base material. If too much water is used, absorption of the test fluid is slowed, though not stopped. Practice will determine how much water is required.

Exceptions to Prewetting

In some cases, water need not be used before filtered particle testing. On as-cast clayware that is free of flash and abrasion, it is frequently possible to test the ware without the prewetting operation. However, a universal rule is always prewet when in doubt.

Reapplication of Filtered Particle Test Media

In all cases, regardless of the initial test technique, if it is desired to chase down the discontinuity and recheck with test fluid, it is absolutely essential that the chased area be prewet before a reapplication of test fluid. It is impossible to develop indications on reworked clay without prewetting.

Cracks Missed in Testing of Clayware

In certain instances in the past, there have been occasions when the filtered particle test technique seemingly missed cracks. In almost every case investigated, it was proved that the filtered particle technique missed cracks in unfired ware only because the cracks were not actually present at the time of the testing. It is thought that the cracks were produced after testing.

Cracks Produced by Glaze Application

This strange situation may be explained as follows: A crack in a porous product is an indication of a stress that was present at that site at one time. The existence of the crack is evidence that the stress relieved itself. It is entirely possible that other stresses locked in clay are not of sufficient magnitude to produce a crack unless encouraged to do so. Of all the things that seem to encourage the releasing of a locked in stress, water seems the most likely. In the case mentioned above, where cracks seemingly were missed, it has been fairly well established that the water applied at the time of the glaze application to clayware could have released some of the stresses and produced cracks that opened in firing. Thus, where clay products may have locked in stresses that have not produced cracks, it is possible to release them by applying water to the areas in question. This allows the cracks to open up and permits indication of discontinuities by filtered particle tests.

Detecting Locked In Stress

One way to determine whether locked in stresses are present is to use filtered particles to test the ware after drying, marking and locating any cracks and then indicating them on a sketch. The clay object is placed in a dryer or allowed to dry in air for 24 h and then is retested. If locked in stresses are present, more cracks will occur in the clay product the following day. In some cases it is possible to develop new cracks every additional day that the piece of ware is allowed to dry. Water tends to encourage the swelling and reshrinkage of clay. This tends to encourage the relief of stresses, with the resultant production of cracks that may be detected with the filtered particle test fluid.

PART 6. Interpretation of Filtered Particle Test Indications

Significance of Interpretation

The success of any technique of testing depends to a large extent on the interpretation of the indications of discontinuities. In addition, there is the problem of interpreting false or misleading markings that frequently resemble true discontinuity indications.

Discontinuities in Unfired Clayware

Many kinds of discontinuities occur in unfired clayware before firing. They may be contaminants such as iron, copper or plaster in clayware or they may be cracks and voids. No doubt there are many other types as well. One of the most irritating and persistent of all discontinuities appearing in unfired clayware is unquestionably the crack. It may have been caused by rough handling, mold sticking, improper forming and shaping techniques or incorrect drying and shrinkage. In most cases, the crack is open to the surface and generally invisible to the unaided eye. When examining wares after firing, inspectors sometimes confuse cracks that had been present before firing with cracks caused by the firing itself. Figure 12 shows comparable discontinuities in two hotel chinaware plates, one fired and one unfired.

FIGURE 12. Unfired (left) and fired (right) hotel chinaware containing similar defects.

Tightly Closed Cracks

There have been instances in which cracks, reliably established as present in unfired ware, did not appear to open up on firing. At one hotel chinaware plant, cracks were found in two types of plates before bisque firing. The cracks were S-shaped and occurred in the center of both dinner plates and saucers. On firing, the cracks in the dinner plates invariably opened widely and the cracks in the saucers did not. It was suspected that the crack indications on the unfired saucers had been false. When the fired saucers were examined closely under a microscope, cracks were found in the same locations as predicted. The cracks were so tightly closed that simple visual examination could not detect them without filtered particle tests.

Cracks in Fired Clayware

After several years of experimental work in potteries, a universal rule has been established: a crack in unfired ware always results in a crack in fired ware. Despite this, when a glaze is fired at the same time as the body, the results sometimes appear to be erratic. A crack in the unfired body will always result in an open crack after firing; however, its presence may be disguised by the covering glaze. Predicting which crack will break through the glaze after firing is possible only after becoming completely familiar with the type of discontinuities that cause trouble in a particular plant.

Stress Relief Cracking in Firing

Cracks may be considered as an indication of stress that has partially or completely relieved itself. Small cracks in unfired clayware frequently result in very much larger discontinuities in fired ware. This is a rough indication that at the time of firing, the crack, still being under stress, tends to relieve itself much in the manner of a run in a stocking. Very large cracks in unfired clayware nearly always maintain their size after firing.

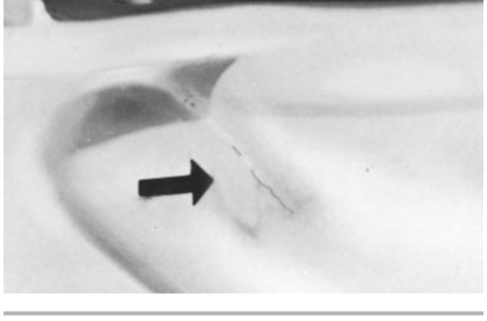
Chasing out Discontinuities in Green Clayware

When unfired ware is repaired by chasing or cutting out an anomalous area, it is considered good practice to recheck the repaired area by filtered particle testing to make sure that a new discontinuity has not been formed that might be more serious than the original one. It is also essential to determine the true length of a crack and to repair it accordingly. On sanitary ware, if a small discontinuity is chased out but the ends are not completely removed, these ends may act as stress raisers during firing and produce relatively large discontinuities after final firing. When discontinuities are patched, a rechecking of the area is in order. If the patching tool is used too roughly and the clay is too dry, a multitude of cracks will form that may open widely enough in firing to cause rejection.

Interpreting Crack Indications in Large Structural Ceramic Bodies

On large structured bodies, cracks due to the firing procedure may appear as if they had been unfired cracks. An easy way to tell the difference is to make a thorough check of the clayware before firing. Thus, fired ware that contains this type of discontinuity can be identified as such and not confused with true unfired cracks. However, if stresses have been locked in the unfired ware, as discussed earlier, the exact identification of a crack can only be made by the appearance of the internal faces of the fired discontinuity. Figure 13 illustrates the fired appearance of typical cracks that occurred in an unfired body.

FIGURE 13. Fired appearance of cracks in unfired ware.



Avoid Drain Marks in Filtered Particle Testing

The interpretation of fluorescent indications on porous materials is not particularly difficult, but some instances call for experience. In every instance when too much test fluid is placed in a restricted cavity or on a cuplike surface, an excess of fluid will develop in puddles that tend to drop out particles in a typical ringlike manner. Sometimes these drain marks appear to resemble cracks, particularly if they appear in the same direction as genuine discontinuities. Many times it is possible to prevent the formation of ring marks by continuous movement of the part while the test fluid is still mobile on the surface of the porous object. This technique, of course, can only be used on objects that are small enough to be manipulated.

Irrelevant Indications in Filtered Particle Tests

When test fluids are applied to porous surfaces repeatedly, an overlapping of the respective treatments tends to produce more marks and rings, which sometimes lead to confusion. Only experience can assist the viewer in identifying drain marks, overlaps, scratch marks and true crack indications. Frequently, horizontal scratches or grooves have a misleading appearance. True crack indications are totally different from those of purely mechanical markings. Crack indications generally look like cracks. In other words, they are slightly jagged and invariably occur in places where they might be expected to occur, such as sharp corners and joints.

If there is doubt concerning a particular mark or indication, it is possible to wipe away the existing indication and repeat the application of fluid. If a crack is present, it will repeat itself. Drain marks rarely show up in the same manner twice. When reproducing filtered particle indications, the initial application of fluid will have plugged many of the pores, thus reducing the sensitivity of the technique slightly. A short wait before reapplication of test fluid is always advisable.

PART 7. Filtered Particle Testing of Carbon Matrix Components

Carbon Matrix Material

Conventional liquid penetrant testing does not work well with porous materials. Conventional test methods such as radiographic or ultrasonic testing also frequently yield unsatisfactory results on these materials. It is in this situation that filtered particle testing can be used to great benefit. The method was developed for green or lightly fired ceramic components. Application of filtered particle testing to candidate turbine components should illustrate that the method is effective when conventional methods are not.

Carbon fiber reinforced carbon matrix composite materials have been considered for possible use in turbine blades and vanes. Components made of these composites have many advantages, including low density, high temperature strength and stiffness and high toughness or minimal sensitivity to cracklike discontinuities. However, these materials do have one significant disadvantage: they are combustible and therefore must be protected from the oxidation environment of the gas turbine engine. For this reason, these materials have only been considered for use in nonpiloted air vehicles or as nonstructural elements in piloted air vehicles.

Carbon fiber reinforced carbon matrix materials are often protected with a coating of silicon carbide (SiC). This is a stoichiometric carbide that is stable to very high temperatures and forms a protective, oxidation resistant silicon dioxide (SiO_2) film in the operating environment of a turbine engine. Because the composites are sensitive to oxidation, the integrity of this silicon carbide film is key to their use in high temperature, oxidizing environments. Any breach in this protective layer could be catastrophic, so the breaks in the silicon carbide film must be detected with a reliable test method. However, silicon carbide coated carbon matrix material is very porous. Conventional nondestructive testing cannot be used to detect discontinuities in this coating. This situation is perfect for filtered particle testing.

Case Study

A research program in the United States Air Force explored the concept of using carbon fiber reinforced carbon matrix composite materials in turbine blades and vanes.

Test Materials and Conditions

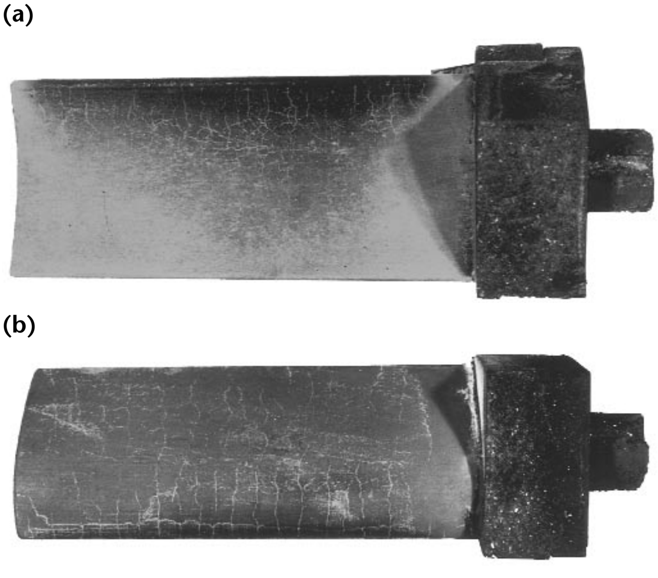
Filtered particle solutions were made by adding brightly colored daylight fluorescing pigment particles to an isopropanol carrier fluid. Daylight fluorescing pigments appear to emit more visible light than would be reflected from them. This occurs because the ultraviolet portion of the radiation illuminating the specimen is down converted to visible light by the pigment. Both yellow and red pigments were used because they produced the greatest contrast between the light gray background of the silicon carbide coatings and the discontinuity indications. No attempt was made to optimize the particulate concentration of the solutions or the wetting characteristics of the carrier.

Furthermore, prewetting was not used to enhance the sensitivity of the test described herein. Specimens were examined with standard white, fluorescent light sources. The only enhancement to this setup was to place the light sources on both sides of the specimen to illuminate it slightly off grazing incidence. This produced a useful visual crack enhancement. The fluorescing pigment emits light spherically, so the discontinuity indications do not have shadows. As a consequence of this, the crazing indications appear to be much larger than those produced in a normal filtered particle test.

Discontinuity Indications and Interpretation

The discontinuity indications produced from the examination of the silicon carbide coated carbon matrix specimens (Figs. 14 and 15) were very different from what might be expected from conventional test experience. Whereas one expects a single or at most a small number of indications, there are many crack indications on the candidate turbine vanes. On careful examination up to three different levels of crack indications may be discerned, each following the underlying weave pattern of the carbon matrix substrate. This seems reasonable when one considers the expansion characteristics of the carbon matrix substrate and the silicon carbide coating. Silicon carbide is a typical material with a positive, linear expansion coefficient. Carbon-to-carbon composite materials, on the other hand, have expansion coefficients that change from negative to positive above some temperature. The expansion coefficient of the carbon matrix used in the vanes shown in Figs. 14 and 15 is positive above about 550 °C (1020 °F) and negative below this temperature. The silicon carbide oxidation resistant coating is applied at a temperature well above 1000 °C (1800 °F) and then cooled to room temperature where it was inspected. At the fabrication temperature the coating and substrate are in mechanical equilibrium, but on cooling stresses build up in the two materials because the expansion coefficients are not equal. This stress buildup is fairly common in many manufacturing processes involving dissimilar materials. However, the stress buildup is aggravated if the substrate were to stop contracting or — worse — were to begin to expand on cooling as it does with carbon matrix. Therefore, one would expect the thin, polycrystalline silicon carbide coating to craze in a fairly regular pattern upon cooling and for this crazing to increase as the component cools below 550 °C (1020 °F). The extensive crazing of these components is evident in Figs. 14 and 15.

FIGURE 14. Filtered particle indications of crazing in oxidation resistant coating of carbon matrix composite compressor vane: (a) concave or pressure surface; (b) convex or suction surface. The vane has silicon dioxide coating from high temperature exposure in simulated jet engine test. Red filtered particles are daylight fluorescing pigment.

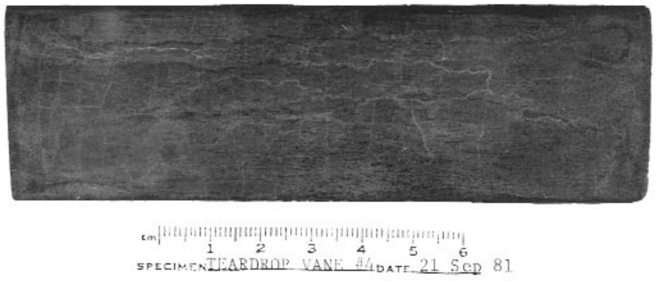


The nondestructive testing engineer must not only detect and quantify discontinuities but, to surmise their significance, should also be aware of how discontinuities might be generated during manufacture or service. In this study, the inspector might have expected to see a single crack in the silicon carbide coating as the dominant discontinuity permitting oxidation attack of the carbon matrix substrate. However, in this case, it is not the extensive crazing but rather absence of crazing that indicates the presence of a discontinuity. A regular pattern of cracks indicates that the tensile stresses that result from the expansion differences between the substrate and coating were relieved on cooling from fabrication temperatures. An area of the coating that does not contain a regular crazing pattern is one in which these thermal stresses were not relieved in a small area. The most probable cause of this appearance is the presence of a delamination between the coating and substrate. The size of the cracks at the boundary of a noncrazed plate would be several times larger than those in the uniform cracks associated with the craze pattern. The large crack would be the last to close on heating and would most likely permit atmospheric attack of the susceptible carbon matrix substrate. This was partially confirmed by sectioning and examining several vanes after simulated engine testing. There could well be other discontinuities associated with atmospheric attack of vanes that failed during other tests but an exhaustive study of coating failures was not pursued.

Conclusions

The results of this limited study indicate that filtered particle testing can be used to

FIGURE 15. Filtered particle indications of crazing in oxidation resistant coating of carbon matrix composite compressor vane. Vane is as fabricated, not mounted, for simulated jet engine testing. Yellow filtered particles are daylight fluorescing pigment.



detect discontinuities in porous materials and coatings when conventional methods fail. An exhaustive study of test indications and coating discontinuities was not attempted. However, the filtered particle test did show that the absence of a multiple discontinuity pattern can indicate the presence of a discontinuity. This situation would be different than one might expect from previous test experience.

Additionally, this test offered the opportunity for an enhancement of the filtered particle test method. The concept, in this case, would be to modify the composition of the particles to provide a surface treatment at the site of a crack in addition to providing a crack indication. Because only the surface of the particle is involved in the test, there is the opportunity to alter the chemical composition of its bulk for various beneficial treatments at a crack site. Thus if the materials engineer wished to apply a surface treatment at the site of a crack, the filtered particle test provides this opportunity in addition to a detection function.

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12

CHAPTER

Liquid Penetrant Testing in Primary Metals Production

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PART 1. Liquid Penetrant Testing in Foundries

Reasons for Liquid Penetrant Testing in Primary Metal Production

Liquid penetrant testing does *not* find extensive application in large scale production of primary metals, because many stages of production of metals and alloys represent intermediate products. Ingots, billets, bars, rod, slabs, sheet and strip are produced rapidly in great quantities at relatively low costs. Time delays and costs involved in liquid penetrant testing would be unacceptable where large tonnages of product are produced each day.

However, detailed surface testing may be desired on certain finished metal materials such as sheet and strip. Discontinuities in surface finish of sheet and strip will persist into final forms and such discontinuities may make final products unacceptable. Typically, in such cases, direct visual testing is used for most of the production lots and only small areas are subjected to sensitive tests to detect surface blemishes.

Liquid penetrant testing is generally not used for steels. Ferromagnetic materials are most frequently inspected by magnetic particles or flux leakage tests. For carbon steels, which are magnetic, magnetic particle testing offers the ability to detect discontinuities not open to the surface. Only where the metal is *not* ferromagnetic would liquid penetrant testing be the preferred test method.

However, liquid penetrant testing could be used. Surface anomalies on ingots, billets, bars and slabs, for example, are often extended and become unacceptable in the final finished sheet, strip or other shapes produced from these intermediate forms. In these cases, surface testing of the large metal pieces can often be justified before rolling or forming them into materials with much greater surface area that must be free from discontinuities. Examples of such testing are of light alloys such as aluminum, of magnesium and of nonferromagnetic steels.

If parts are tested with liquid penetrant, care must be taken when washing the liquid penetrant off the carbon steel casting surfaces because these surfaces are normally rough and coarse and improper washing may leave a masking film. The discontinuities may also be coarse and have a tendency to bleed profusely.

Of course, the greatest application of liquid penetrant testing occurs when the primary metals have been formed and machined into final forms and products whose serviceability and appearance requirements can be very severe. Other chapters in this volume describe uses of liquid penetrant testing in transportation and other industries where control of surface quality is vital to ensure adequate performance and freedom from premature failures.

Fluorescent Liquid Penetrant Testing of Precision Investment Castings

Because of the nature of investment casting operations and the critical applications of many precision investment castings such as jet engine blades and aerospace system components, quick and accurate systems for testing are imperative. Investment casting involves pouring liquid metal into cavities that have been left after wax patterns have been melted and burned out of the ceramic mold that surrounds them. The method is often used when the particular part is too complex in shape to be machined. Design engineers tool up a die from customer specifications, generally working with the customer's engineers to make sure the most efficient design results. For instance, it is often possible to redesign several parts originally fabricated by welding so that a one piece part can be cast by the investment process. If the die checks out with the prints, wax is injected into it and a series of patterns is formed and then gated together in clusters. The clusters are dipped into a slurry of fine grain investment material and then stuccoed, a process that involves pouring a coarser sand over the damp slurry.

The clusters are placed in metal flasks and the final investment material is poured into them. The flasks are baked and fired to melt out the wax and burn away most of the volatile material. Then the castings are poured and after cooling, the investment ceramic cores and shell molds are removed and the cast parts are trimmed of excess metal, including gates and risers. The precisely dimensioned cast parts are then typically inspected by radiographic testing (for internal cavities, cooling channels and discontinuities) and by magnetic particle testing (if ferromagnetic) or liquid penetrant testing (if nonmagnetic). Many investment castings are of either austenitic or martensitic stainless steels or of refractory high temperature alloys. A sensitive and precise test is needed for the final parts to ensure freedom from discontinuities and accuracy in dimensions. Tests are made for cracks and cuts, for ceramic inclusions or plugs in coolant passageways, porosity and shrinkage discontinuities. For the nonferromagnetic types of investment castings, fluorescent liquid penetrant testing is widely used for detection of surface discontinuities. Sensitive liquid penetrant systems described elsewhere in this volume have been developed for testing of turbine blades.

Liquid Penetrants in Primary Metals Production

Water Washable Liquid Penetrant

Water washable liquid penetrant can be either visible dye or fluorescent. This type of liquid penetrant contains an emulsifier in its composition and is removed from the surface of castings by a direct water wash. Even though visible red dye water washable liquid penetrant is frequently used on larger steel castings, the water washable fluorescent liquid penetrant is the mainstay of liquid penetrant testing in the aluminum foundry. This type of liquid penetrant is best suited for aluminum foundry work.

Solvent Removable Liquid Penetrant

Solvent removable liquid penetrant can be extremely sensitive. This liquid penetrant is dissolved and removed from the surface by the chemical action of the solvent. It is used on small parts or small areas such as those formed by welds. The solvent is applied with a lightly moistened cloth. It cannot be used in the manner of the water rinse because the action of the solvent is much more vigorous than that of water and can easily lead to overremoval. Solvent removable liquid penetrant is not recommended for large castings or large production runs. One reason is the additional cost and labor involved in wiping liquid penetrant from large areas or a large number of castings. Another is the danger that the solvent may start to dissolve the liquid penetrant in the discontinuities if left on the surface too long.

Postemulsifiable Liquid Penetrant

The postemulsifiable liquid penetrants are difficult to handle on the relatively coarse as-cast surfaces. This also applies to castings, mainly aluminum ones, that have very intricate configurations. On such castings, the liquid penetrant film is of uneven thickness and is trapped in the hollows of the rough surface and in the pockets between intersecting structural members. If the emulsification time is too short, the trapped thick layer of liquid penetrant will not be sufficiently affected; if the emulsification time is too long, the liquid penetrant in existing discontinuities may be completely emulsified and subsequently removed by washing.

Control of Liquid Penetrant Materials and Processes

The liquid penetrant process is used in many nondestructive testing departments and is tightly controlled. Control of liquid penetrant materials and control of the processing system in which they are used are vital for optimum results.

The physical and chemical characteristics of liquid penetrant materials are certified by the manufacturers to comply with the requirements of relevant specifications. Certificates of compliance are issued by the manufacturers for each specific batch number. Numerical values for typical characteristics such as fluorescent brightness, flash point, water tolerance etc. are listed on this certificate.

The control of the liquid penetrant system consists of daily, weekly and monthly checks to assure the inspector that the characteristics of the liquid penetrant being used have not deteriorated to values lower than the minimum permitted by the appropriate specification. These checks also determine if the other components of the system — such as water pressure, water temperature, ultraviolet radiation intensity — are within the limits of the procedure.

These controls and checks, especially in the aerospace industry, are rigidly enforced. Materials and process specifications are continually updated to ensure the latest technology is applied to provide the optimum liquid penetrant test.

Liquid Penetrant Process

A liquid penetrant system can be assembled in a number of ways. For example, it can be designed to provide maximum sensitivity, to perform well on rough surfaces or to satisfy particular demands of a specification. Nevertheless, all systems will follow this fundamental sequence of steps with some modifications. The steps outlined below are treated more thoroughly elsewhere in this volume.

Precleaning

Any substances on the surface of the casting that may block the openings of discontinuities must be removed. This operation is essential. Methods of precleaning include spraying with beads, which removes scale; brushing or scraping, which removes paint; and solvent cleaning and vapor degreasing, which remove grease and dirt. Acid etching is another means of precleaning that is often used on aircraft castings. One or more of these techniques may be involved in the preparation of a casting for liquid penetrant testing. Any form of cleaning that may close or smear over the discontinuities must be followed by an appropriate etch.

Acid Etching

Some aerospace and military specifications require castings to be etched or pickled before a liquid penetrant test. Etching is an acid bath that reacts with the surface of the casting to remove dirt and some of the metal. Because of this last characteristic, etching is also known as chemical milling. Depending on its strength, etching acid can strip 0.03 to 0.01 mm (0.001 to 0.0004 in.) of metal per minute. Bright etch or triacid etch (nitric, chromic, hydrofluoric) is commonly used on castings. Aluminum, which is perhaps etched more often than other metals, turns silvery white in the triacid bath — hence the name bright etch.

Another etching solution is sodium hydroxide or caustic soda. Unlike the triacid etch, sodium hydroxide attacks the metal preferentially, meaning that it does not react with all surface conditions in the same manner. In aluminum, for example, it will make the surface look blotchy. It will discolor areas of cutoff gates. It reacts differently with cast areas as opposed to ground areas. Both sodium hydroxide and triacid etches will strongly tint all welds. Sodium hydroxide is sometimes regarded as too damaging for regular etching jobs.

The strength of etching solutions and the length of the application must be controlled. Overetching may create problems by enlarging discontinuities and occasionally combining them into linear patterns. Etching acids are dangerous and must be used in properly ventilated rooms and by operators wearing protective equipment.

Application of Liquid Penetrant

The liquid penetrant may be applied to the surface of the casting by spraying, dipping or brushing. It will remain on the surface for the length of time prescribed by experience or by specification. The dwell time (the time the liquid penetrant remains on the surface of the casting) must be long enough to let enough liquid penetrant seep into the discontinuities. If the testing is done by dipping the casting in a line of tanks, the casting is immersed in the liquid and placed on a shelf above the liquid penetrant to reclaim some of the liquid by allowing it to drip back into the tank. When large castings are tested on the floor of the foundry, the excess liquid penetrant runs into a drain. Recovery depends on provisions of the plant drainage system.

Washing

Washing is a simple yet critical operation. The dangers of overwashing and underwashing are always present. In the case of extreme overwashing, the liquid penetrant is completely removed from the relevant discontinuities and no indication can be formed. To prevent this, water washable liquid penetrants are removed by a water spray under controlled angle, pressure, temperature and time; solvent removable liquid penetrants are wiped off with rags moistened by the solvent. Fluorescent water washable liquid penetrants are rinsed under ultraviolet radiation. The rinsing stops when the surface of the casting is free from visible dye or fluorescent background. The underwashing of the red dye liquid penetrant leaves enough of the liquid on the surface to tint the developer. Underwashing fluorescent liquid penetrant will give the developer a fluorescent glow. In both cases, the visibility of indications can be seriously reduced.

Drying

Solvent liquid penetrant removers evaporate and do not require drying in an oven. Small aluminum or steel castings that are washed by water are put into an oven and left there for a predetermined length of time at a set temperature. Larger castings are left to dry in still air or are exposed to a flow of air from a fan.

Development

The function of the developer is to reverse the capillary and provide a contrasting background. The liquid penetrant that entered the discontinuities open to the surface of the casting is now drawn from them by the blotting action of the developer. The relatively minute amount of liquid penetrant extracted from the discontinuities spreads out in the developer and clearly indicates the location of the discontinuities. The developers can be applied as dry powder or suspended in liquid that evaporates, leaving a dry powder film. Wet developers are sprayed onto the surface of the casting and require drying time unless they are suspended in a solvent. Dry developers are either sprayed on or applied inside tanks where fans disperse them into a fine cloud.

Viewing and Interpretation

Movie. Rejectable discontinuity.

The viewing of liquid penetrant indications is most effective when the formation and progress of the bleedouts is observed from the very beginning. This can be done best by spraying a solvent suspended, fast drying developer over small areas of a casting. The characteristics of the discontinuities can be judged and evaluated by observing the developing bleedouts.

On larger areas and on castings that were processed in developer tanks, the indications or bleedouts are inspected after some time has elapsed. They are by then in an advanced, enlarged and possibly deformed state. The wipe-and-watch technique is frequently used to clarify the connection between the shape of the bleedout and the shape of the discontinuity that caused it. In this technique, the bleedout is gently removed with a solvent and the new reappearing bleedout is observed and evaluated. In the early stages of developing, the bleedout closely resembles the shape of the discontinuity. Even though this technique is recommended, it is time consuming and, on large production runs, economically prohibitive. It is generally reserved for suspected cracks and tears.

Because liquid penetrant indications grow and change with time, the interpreter must always remember that the size of the bleedout may not be a dependable indicator as to the size or depth of the discontinuity and that the shape of the bleedout alone is not a dependable indicator of the shape of the discontinuity. After a while, a bleedout from a crack may look like a bleedout from a gas hole.

It is a common practice with fluorescent liquid penetrants to locate the bleedouts under ultraviolet radiation and to investigate their cause under ordinary white light. Omitting the developer eliminates one step in the liquid penetrant process and a condition that tends to promote a misjudgment as to the size of the discontinuity. The bleedout can be magnified by the developer when the fluorescent flow becomes concentrated in the domelike buildup over the discontinuity. This is particularly noticeable on large castings where the amount of applied developer may be relatively large.

Components of Liquid Penetrant Testing System

Liquid penetrant testing can be conducted using conventional liquid penetrant equipment or automatic systems.

Conventional Liquid Penetrant Equipment

Of all the nondestructive testing equipment currently in use, conventional liquid penetrant equipment is the simplest to use. It is not, however, without controls, gages and thermometers that regulate its operation.

Conventional liquid penetrant equipment can be divided into portable equipment such as aerosol cans or larger pressurized tanks and stationary lines of processing tanks. The type of equipment to be used will be determined by the size of the castings and the sensitivity requirements of the specification.

The aerosol cans serve as a general purpose liquid penetrant for quick local applications. All types of liquid penetrants and sensitivity levels can be obtained in the aerosol systems. Apart from spot application, they are not economical. Furthermore, they cannot always be used under the controlled conditions (pressure, temperature etc.) required by many specifications.

Aerosol liquid penetrants, especially the visible dye liquid penetrants, have a sensitivity advantage on small areas because an indication can be observed as it develops. Portable pressurized tanks are used on larger castings. This type of equipment, along with electrostatic spraying units, can be applied efficiently and economically when testing large castings. Liquid penetrant sprayed from portable tanks is generally not recovered, which adds to the cost of testing. The waste of liquid penetrant in electrostatic spraying is substantially less. (Electrostatic spraying works best on flat surfaces; on castings with curved surfaces or recesses, the charged liquid droplets may be attracted by the nearer surface.)

In steel and aluminum foundries that cast small parts, the most frequently used liquid penetrant setup is the line of tanks. These lines usually include a liquid penetrant dipping tank, dwell stack, wash tank, drier oven and developer tank. The sizes of the tanks will depend on the sizes and volumes of castings processed. If fluorescent liquid penetrant is used, the line will be enclosed in a darkened area. Ultraviolet lamps will be included over the wash tank and the examination table.

Foundries making castings for the aerospace industry will often perform special precleaning operations such as degreasing or etching. Etching and degreasing require their own location, safety equipment and calibration procedures.

Automatic Liquid Penetrant Systems

Automatic liquid penetrant systems of the carousel type are often installed when large quantities of small parts are processed. The parts are sent through all the stages of the liquid penetrant operation by means of rotating (or straight) conveyors. Operations such as spraying, drying and timing are done automatically. Viewing and acceptance/rejection functions are performed by human inspectors.

Computerized robotic systems manipulate parts for application of liquid penetrants and developers and for final viewing and evaluation. Optoelectronics may be used for viewing with a computer program to establish the boundary conditions of acceptance. In some types of foundry operations, these advanced systems have an economic advantage. Computer programs for evaluation of discontinuities are still in the development stage.

Control of Liquid Penetrant Process

Regardless of what product is being tested, liquid penetrant testing is rigidly checked and controlled in accordance with many specifications. Because the effectiveness of liquid penetrants depends on their ability to enter discontinuities open to the surface and remain there after all processing has been completed, the factors that affect that ability such as wetability, water contamination, temperature and pressure of the rinse are checked periodically.

In liquid penetrant testing, there is no way to check or prove that the liquid penetrant has entered all the discontinuities open to the surface. In magnetic particle testing, the existence of a field can be checked and it can be assumed that a crack cutting across it will develop an indication; in ultrasonic testing, the inspector knows that the beam has entered the part because it is reflected from the back wall. In liquid penetrant testing, there is no way to know what is happening after application; there is no feedback. Because of this, strong process control of all factors affecting the liquid penetrant's application, removal and development are crucial.

The two most dangerous conditions that can arise during liquid penetrant testing are underwashing and overwashing. Some specifications, such as ASTM E 1417,[1] reflect this concern. Both underwashing and overwashing are of special interest on castings with rough surfaces (e.g., sand castings) or very complex configurations. Such castings are difficult to wash properly because underwashing will leave a masking background and overwashing will remove liquid penetrant from discontinuities.

Process control and periodic checks of a liquid penetrant system may be accomplished by physical and chemical tests of the liquid penetrant materials and calibration of thermometers, pressure gages and ultraviolet lamps.

Many of the physical and chemical tests, usually performed monthly, require laboratory equipment and trained technicians. Many foundries use outside sources to perform these tests. Other checks, usually performed weekly and daily, are done in house. Gages and thermometers are normally calibrated and certified annually by outside service laboratories.

Typical checks include daily checks on sensitivity and fluorescent background, water temperature and pressure, dryer temperature and developer contamination; weekly checks on ultraviolet radiation intensity; a weekly comparison check of used versus unused liquid penetrant; and monthly checks on dryer uniformity, developer brightness, precipitation, liquid penetrant brightness, water content, water washability, sensitivity and ambient white light.

Typical liquid penetrant system materials and process specifications are ASTM E 1417,[1] ASTM E 165,[2] SAE AMS 2644[3] and *ASME Boiler Code,* Section V, Article 24.[4] Control of the liquid penetrant testing process is covered in more detail elsewhere in this volume.

Drawbacks to Liquid Penetrant Testing of Castings

It has already been stated that liquid penetrant testing is an extremely sensitive method. This sensitivity is based on the ability of liquid penetrants to enter even the smallest and shallowest discontinuities and surface depressions and the natural tendency of liquid penetrants to resist being rinsed out of such discontinuities and depressions.

This kind of sensitivity is desired in liquid penetrants; however, on many cast surfaces, this property is also a drawback. On some raw cast surfaces and even on the fine surfaces of precision cast parts with complex configurations, the number of bleedouts can be very large. Most but not all of these bleedouts or indications will be evaluated as irrelevant. The iron rule of nondestructive testing is that no indication is irrelevant until proven so. Practical resolution of such problems may take considerable time and an inspector with considerable foundry experience.

Another problem sometimes emerges when the irrelevant indications have been eliminated and the relevant ones have to be evaluated. In liquid penetrant testing, reference standards may consist of black and white photographs that are difficult to evaluate because liquid penetrant testing is always in color. The written descriptions with these standards may describe parameters such as the maximum size of permitted indications, their distances from one another and their number per unit of area. Such references are difficult to use because their in-process applications are lengthy and their practical value questionable. Bleedouts are often very small (in the range of 0.8 to 1.6 mm or 0.03 to 0.06 in.) and measurements are cumbersome and inaccurate.

One source of confusion during the measurement of relevant indications is whether the discontinuity or the bleedout is to be measured. If possible, the actual discontinuity should be measured. Bleedouts are not usually measured because their size grows during the early stages of development and often misrepresents the size of the discontinuity they indicate. The measurement of discontinuities is not always easy, particularly when the discontinuities are very small. One result of these difficulties is that questionable areas are often inspected by another nondestructive testing method. Radiography is often used to find and measure subsurface discontinuities that are large relative to their surface opening. Sometimes the inspectors refer to a totally different field of investigation, such as metallurgical analysis, for an answer. The lack of a good liquid penetrant reference standard is, unfortunately, a shortcoming inherent to the method.

Even though bleedouts are not always an accurate guide as to the size of an indication, their size can be used to locate linear indications. A linear indication is defined as an indication with a length that is at least three times larger than its width. On castings, a literal application of this definition can lead to considerable problems and indecision. On a raw casting, there will always be a number of bleedouts that will fit this definition.

The Future

In the 1990s, the liquid penetrant method has not been integrated into the world of image intensification, computerized analysis and automation to the extent that radiography has been, nor have liquid penetrant test processing parameters been stored in an electronic box as ultrasonic and eddy current test parameters have been.

Like other nondestructive testing methods, liquid penetrant testing indicates discontinuities and announces their presence. The tests of liquid penetrant chemistry, the checks of the system and the calibration of the equipment are intimately related to that indicating aspect, because it is paramount for the liquid penetrant to get into the discontinuities and stay there so it can eventually be developed and seen. Because there is no feedback on the formation of an indication to provide a basis for adjusting the test process, the operator has only one chance to correctly control the processing parameters to produce a discontinuity indication.

There will continue to be further improvements in the performance of liquid penetrants and further tightening of system calibration and process control. For small castings, automatic processing systems will most likely become more sophisticated. Such systems may be able to segregate parts with indications from parts without them.

PART 2. Liquid Penetrant Testing of Ferrous Metals

Low Carbon Alloy Steels

Low carbon alloy steels have a better castability than high carbon steels. Their fluidity is better and their resistance to cracking is higher. There is, however, a little difference in the response to nondestructive testing between low alloy and carbon steels.

Because low carbon alloy steels are magnetic, liquid penetrant testing is not used. If liquid penetrant testing has to be used, its sensitivity should not be too high. Low or medium sensitivity as specified by SAE AMS 2644[3]or equivalent is best suited for cast surfaces of steel or aluminum.

On large areas that require time for testing, fluorescent liquid penetrants are often substituted for red dye liquid penetrants.

High Carbon Alloy Steels

Ferromagnetic products of the steel industry are typically subjected to eddy current and flux leakage magnetic field tests in large scale automated test systems. Some stainless steels with martensitic structure (e.g., the AISI 400 series) lend themselves to testing by magnetic techniques. Liquid penetrant testing on large area steel products is often not feasible because of surface conditions, speed of travel and high temperatures of steel on processing lines. The fact that austenitic grades of stainless steels (including the AISI 300 series) are not ferromagnetic rules out magnetic particle and flux leakage tests. For this reason, there has been more liquid penetrant testing on stainless steel than on the carbon and alloy steel grades. Where surface finish is required in many stainless steel products, there has been a heavy emphasis on visual testing supplemented by liquid penetrant testing.

Austenitic Steel

Because the 300 series austenitic steels are nonmagnetic, liquid penetrant testing becomes the primary method for detection of surface discontinuities. Austenitic steels can be tested dependably by liquid penetrants for external discontinuities and by radiography for internal ones.

Cast Irons

Cast iron tends to be microscopically *porous* and liquid penetrant testing may be difficult because the porous surface bleeds and forms a film that masks indications.

Stainless Steel

There may be times when the visual inspection process needs help to find hard-to-see surface discontinuities. When this happens on magnetic steel products, a magnetic particle test is often used. However, when the same problem arises with a nonmagnetic steel product, liquid penetrant testing is used to reveal the presence of minute surface imperfections not apparent with normal visual testing of surface conditioned slabs of stainless steel. This procedure has been used to predict hot band surface quality accurately on certain critical products.

Most stainless steels have excellent castability, particularly the 300 series. The main problems are not cracking and shrinkage but inclusions and porosity. Normally, liquid penetrant testing is not used on martensitic steels.

Work Rolls in Steel Rolling Mills

In steel manufacturing operations, work rolls of the tandem mill are subjected to severe stresses when cold working sheet steel. Four stands of work rolls and one stand of skin pass rolls, each with two pairs of rolls, must be removed for surface grinding and shot peening after 6 h of use. Occasionally a strip will break or a piece of slag will mark the roll before completion of 6 h of use. These events can cause cracks in work roll surfaces, so rolls are removed from service and inspected with liquid penetrant testing. Markings on the steel from a tandem mill may indicate fatigue cracks in a roll surface. This condition also requires an early removal of rolls from service for liquid penetrant testing.

Visible dye liquid penetrant techniques of testing are applied to the working zone of these large work rolls. Their working zone is about 0.54 m (21 in.) in diameter and 1.65 m (65 in.) long. All liquid penetrant testing materials are applied from aerosol cans. Tiny indications will usually be remedied when grinding the surface of the roll. However, large indications will mean that the roll must be scrapped to avoid a costly roll failure in service. Experienced liquid penetrant inspectors can make this judgment. After indications have been found and the roll is surface ground to remove cracks, each roll is again tested with liquid penetrant before being returned to service. In one large mill, production interruptions due to roll failure were a monthly occurrence before introduction of liquid penetrant testing; after introduction of liquid penetrant testing, it was many years since the last work roll failure in service.

Fluorescent Liquid Penetrant Testing Used in Malleable and Gray Iron Foundries

Malleable and gray iron castings are widely used in heavy machinery and transportation industries producing diesel engines, tractors and earthmoving equipment, for example. Foundry testing of pilot castings and sampling testing of production runs by fluorescent liquid penetrants allows the foundrymen to see immediately whenever one of the many variables in casting is out of control. This dictates changes in gating procedures, pouring temperatures, metal composition, molding sand etc., to permit pouring of good castings and to avoid the expense of scrap castings.

In many facilities, experience with liquid penetrant testing began on a small scale with hand processing and visual testing of critical castings, both in the foundry and in the customer's receiving test departments. As needs increased, automatic conveyorized liquid penetrant processing equipment was installed in larger plants. Fluorescent indications are viewed with overhead ultraviolet lamps in test booths or with portable ultraviolet lamps. Inspectors evaluate the seriousness of casting discontinuities and set aside rejectable anomalous castings for disposal. Effective control of malleable and gray iron is claimed by liquid penetrant testing. Some castings are spot checked; more critical parts are often given 100 percent testing. A reject during spot checking results in 100 percent checking of the entire lot of castings. Experience shows that although control of castings is thorough with liquid penetrant testing, an actual decrease in numbers of rejects is often realized. Intelligent use of information on discontinuities located improves foundry practice and reduces the number of anomalous parts cast.

PART 3. Liquid Penetrant Testing in Light Alloy Foundries

Metallurgical Aspects of Cast Aluminum Alloys

Apart from special applications, pure aluminum is rarely used for castings; however, aluminum alloys are used frequently. Just as in steel, the alloying elements change the properties of aluminum.

Common aluminum alloying elements include magnesium, copper, nickel and silicon. Magnesium strengthens aluminum and silicon improves corrosion resistance and the fluidity of the molten metal — a property much desired by the foundry worker. Most modern aluminum alloys, however, derive their properties from more than one alloying element. Alloys such as 355, 356, 357 and 712, which are regarded as the most suitable for investment castings, belong to this category.

Reasons for Nondestructive Testing of Light Alloy Castings

Testing of aluminum and magnesium alloy castings in a foundry has one primary objective — to make sure that parts being processed actually meet all required specifications established by the buyer. If nondestructive testing is performed in close cooperation with the foundry's quality control department by keeping the department advised of any and all deviations in procedure, the quality control department can then make the necessary adjustments in foundry practice to ensure high quality castings.

To prevent the production of excessive scrap castings, it is necessary for the nondestructive testing department to catch a faulty casting as soon as possible. In this way, the faulty casting can be isolated so no further labor or time will be wasted on it and secondly, the quality control department can make corrections before too many castings are poured.

Discontinuities Sought by Liquid Penetrant Testing of Light Alloy Castings

The casting discontinuities for which the inspector looks during fluorescent liquid penetrant testing include cold shuts, cracks, blows, shrinkage and dross. Also found are small surface pits and metal flow lines. The latter are usually ground off the surface to improve the appearance of the castings. Otherwise, many customers may misinterpret these minor discontinuities, mistaking them for porosity, dross or cold shuts and may often reject the castings.

This ease of misinterpretation of liquid penetrant indications is one of the objectionable characteristics of the fluorescent liquid penetrant testing process. It makes discontinuities look larger than they actually are and therefore exaggerates their importance. Fluorescent liquid penetrant testing is excellent for finding sharp discontinuities such as cracks, cold shuts and heavy shrinkage that extend to the surface but all other discontinuity indications require further nondestructive tests before castings are rejected. One foundry reported that about 95 percent of all parts returned by customers as fluorescent liquid penetrant rejections were salvaged. Only a minor amount of grinding was required to remove the objectionable indications noted. The number of castings rejected for fluorescent liquid penetrant discontinuity indications is often greatly reduced as the customer's test department becomes more familiar with this method. Foundries have also become more adept in determining what types of surface indications should be removed to prevent misinterpretation during liquid penetrant testing.

Discontinuities Common to Aluminum

Aluminum and its alloys have a number of casting characteristics that can cause problems when using nondestructive testing. Generally, radiography and liquid penetrant testing are the most effective nondestructive testing methods used to detect discontinuities in aluminum castings.

When using liquid penetrant testing, it should be mentioned that there are types of aluminum alloys (e.g., 21 percent silicon) that are very difficult to test. They are porous, absorb liquid penetrant and retain a very strong fluorescent or visible dye background masking indications after washing.

It is advisable to test for surface discontinuities in aluminum castings after the T4 heat treatment. The high temperature of this treatment will open any existing tight discontinuities as well as discontinuities hiding just under the surface. Furthermore, the rapid quenching from the high temperature may induce stresses and distortions that may result in cracking.

Porosity

MOVIE. Porosity in casting.

Porosity is a common discontinuity in aluminum castings. It usually appears on a radiographic film as distinct, globular, gas voids. Porosity can also be detected by liquid penetrant testing if the gas voids are on the surface of the casting. Porosity is formed at elevated temperatures when aluminum absorbs hydrogen. As the temperature of the aluminum rises, hydrogen separates from moisture in contact with the molten metal. When the metal cools near to the point of solidification, its capacity to hold hydrogen in solution drops drastically. The hydrogen then comes out of solution and is embedded in the casting as porosity.

Eutectic Melting

Eutectic melting is a rare metallurgical deformation caused by exceeding the melting point of the eutectic component in the casting during heat treatment. Radiography rarely detects eutectic melting because the cavities left by it are too small to appear on the film. Liquid penetrant testing will reveal eutectic melting if the indications form as a mass of minute discontinuities on the surface.

Limitations in Detecting Shrinkage

Because light alloys are less prone to tearing and cracking than steel is, spongy shrinkage and porosity are the discontinuities encountered most often. Fluorescent liquid penetrant testing can be used to find sharp discontinuities such as cracks, cold shuts and heavy shrinkage that extend to the surface of castings. All other discontinuity indications require further testing before castings are rejected.

MOVIE. Fluorescent bleedout reveals shrinkage.

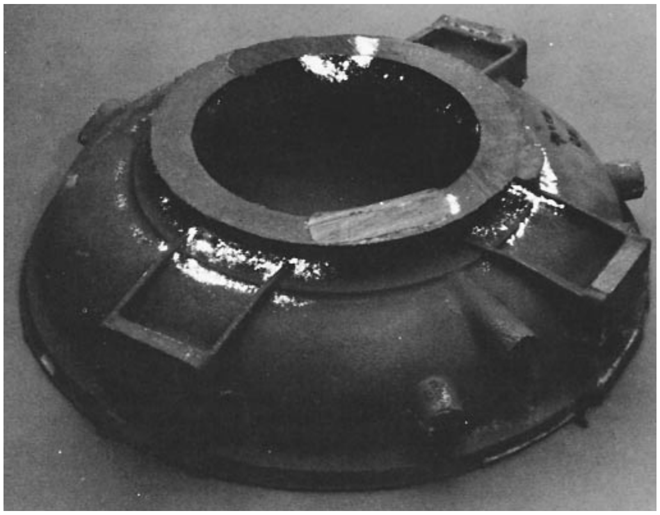
Unless the shrinkage extends to the surface of the castings, it will not be revealed. If shrinkage does extend to the surface of castings, the discontinuity is clearly visible with liquid penetrant (Fig. 1). Foundry control castings that under ultraviolet radiation would appear to have liquid penetrant indications of serious shrinkage have been shown by X-ray to be well within acceptance standards. Conversely, foundry control castings that looked perfect under ultraviolet radiation have been shown to be below acceptance standards by radiography. This is logical, of course, because a liquid penetrant can only show discontinuities that are on or are connected to the casting surface. However, most shrinkage is completely internal and radiography is ideal for detection of internal discontinuities.

Multiple Method Testing

Most castings are tested by more than one method. Problems may arise if the sequence of tests and the discontinuity evaluation process are not clearly established. Assume that a casting has to be examined by liquid penetrant testing and radiography. It should be understood that, for example, if radiography is performed before any removal of discontinuities, including excavations and the subsequent repairs, the results of these procedures must be verified by radiography. Liquid penetrant testing will be used also to verify the discontinuity excavations and the repairs. However, if an attempt is made to check a radiographically tested excavation by liquid penetrant, some difficulties may be encountered. What is acceptable radiographically may not be accepted by liquid penetrant.

There is one exception to this rule. Because liquid penetrant lacks clearly defined acceptance reference standards, radiography is sometimes used on thin walled aluminum castings to check whether the discontinuities detected by liquid penetrant are within the acceptable range. This exception is only valid when

FIGURE 1. Photograph of aluminum housing shows typical fluorescent liquid penetrant indications of shrinkage under ultraviolet radiation.



the acceptance grade is the same for liquid penetrant testing and radiography.

Checking Internal Quality of Light Alloy Castings by Radiography

The internal quality of light alloy castings is typically controlled as follows. Before any job goes into production, the gating technique is checked by sample castings made for examination both by fluorescent liquid penetrant and by radiography. Production is not started until these initial castings have been approved by the quality control department. However, quality control approval is never given until the sample castings show that the parts to be produced will be well above the minimum required standards, even if four or five samples must be made to attain this result. Thereafter, no changes are made in the gating system without the approval or permission of the quality control department and such changes are usually followed by a new radiographic control. By following this type of procedure, some foundries have been able to keep radiographic rejection rates lower than 0.1 percent. Using radiographic control in combination with fluorescent liquid penetrant testing permits light alloy foundries to turn out better quality castings.

Liquid Penetrant Testing

Liquid penetrant testing is the standard method for detection of surface discontinuities. Porosity in aluminum is often open to the surface and readily revealed by the liquid penetrant method. On thin parts, liquid penetrant may be washed out of discontinuities that go through the section. Aluminum castings quenched in polyalkaline glycol and not washed properly carry a gelatinous film that interferes with liquid penetrant testing.

Procedure for Overall Foundry Inspection of Light Alloy Castings

A brief outline of a typical foundry's procedure for production testing of light alloy castings includes the following:

1. hot testing of castings at the time of shakeout;
2. rough testing for dimension and quality after removal of cores, gates and risers;
3. fluorescent liquid penetrant testing for surface connected discontinuities;
4. dimensional checking after trimming operations and before heat treatment of castings; and
5. final testing after heat treatment, picking and straightening. Because most of the testing is concentrated in the early stages of production, fluorescent liquid penetrant testing is one of the rough test methods.

As soon as a casting is shaken out of the sand, it is tested visually for gross discontinuities. New or troublesome castings are rushed to fluorescent liquid penetrant testing before any further operation is performed. Castings often reach the fluorescent liquid penetrant while still warm from the shakeout operation, with the gates and risers still in place. Troublesome castings may be tested three or more times before being shipped.

When the gates and risers are removed, the castings are lightly sand blasted with sharp grit sand. Then visual testing for large discontinuities is carried out in conjunction with the rough grinding. Following this, regular fluorescent liquid penetrant testing is carried out. Final tooling and a cleanup are also accomplished at this stage.

Advantages of Prompt Testing of First Castings in Each Run

An average molder with an average squeezer pattern will produce several sand molds per hour. The pouring, cooling and shakeout will require about 30 min. By the time the first casting reaches the initial or hot test, there are probably several molds already made. If this initial casting in the run contains a discontinuity not seen by the inspector, it may be several hours before the trouble is found later in testing. By that time, a considerable number of castings will have been made that probably contain the same discontinuities. Therefore, it is vitally important that foundry test departments be given every facility needed to locate trouble as soon as possible.

The water washable fluorescent liquid penetrant testing process has many advantages that fit test needs at light alloy foundries. The cost of liquid penetrants and processing materials used to test a casting is low and the liquid penetrant process is fast enough to keep up with production and give quick and accurate answers on casting quality. Additionally, there is no objectionable residue left on tested castings that could interfere with subsequent machining or finishing operations.

Procedure for Fluorescent Liquid Penetrant Testing in the Foundry

Foundry nondestructive testing with water washable fluorescent liquid penetrants is completed in seven steps, as follows.

1. Each casting is cleaned of sand and any other adhering foreign material.
2. A thin film of fluorescent liquid penetrant is applied over the casting by immersion, spraying or pouring and adequate dwell time is allowed for the capillary action of the liquid penetrant to take place, causing it to flow into any surface discontinuities. This liquid penetrant dwell time is accomplished while castings are on the drain rack. Excess liquid penetrant returns to the tanks.
3. Each casting is subjected to a thorough water spray wash under ultraviolet radiation, to remove excess surface liquid penetrant.
4. Wet soluble aqueous developer is used at a concentration specified by the manufacturer. This consistency is closely maintained to ensure uniformity in the inspection.
5. The castings are dried in a recirculating, thermostatically controlled hot air dryer.
6. Before visual inspection for liquid penetrant indications, the castings are allowed to cool (after removal from the dryer) for about 10 min. This gives the developer ample time to complete the developing action. It acts like a blotter, bringing the liquid penetrant trapped within discontinuities back to the developer surface.
7. The castings are then visually inspected for fluorescent indications of discontinuities under ultraviolet radiation. Castings containing discontinuities are sent to the rework department. During the grinding operation (when removing surface discontinuities), dry or nonaqueous developer is used to bring back liquid penetrant indications of remaining discontinuities. The grinder operator applies the developer and rechecks the casting under ultraviolet radiation. When all signs of the discontinuity have been removed, the casting is sand blasted and sent back to the fluorescent liquid penetrant testing area for a final test.

Preparation of Aluminum Product Surfaces for Liquid Penetrant Testing

For each of the following examples of liquid penetrant testing in the aluminum industry, proper preparation of the test surface is critical to the ability of the inspector to discern and to characterize certain discontinuities. Using liquid penetrants on unprepared aluminum surfaces will usually disclose gross porosity and large cracks. However, for the most part, it is essential to use machining, caustic etching, acid pickling or a combination of these surface treatments before application of liquid penetrants, to permit the inspectors to distinguish fine porosity and cracking from other superficial anomalies on the surfaces of aluminum and its alloys. This preparation is also required after any grinding, excavating or sand blasting.

Aluminum, however, poses some problems in the process of cleaning and preparing the surfaces for liquid penetrants. In some cases and particularly with aluminum ingot and heavy plate sections, preferential etching of constituents in the alloys can create superfluous liquid penetrant indications. In these instances, acid pickling is recommended in preference to caustic etching.

Acid Pickling of Aluminum before Liquid Penetrant Testing

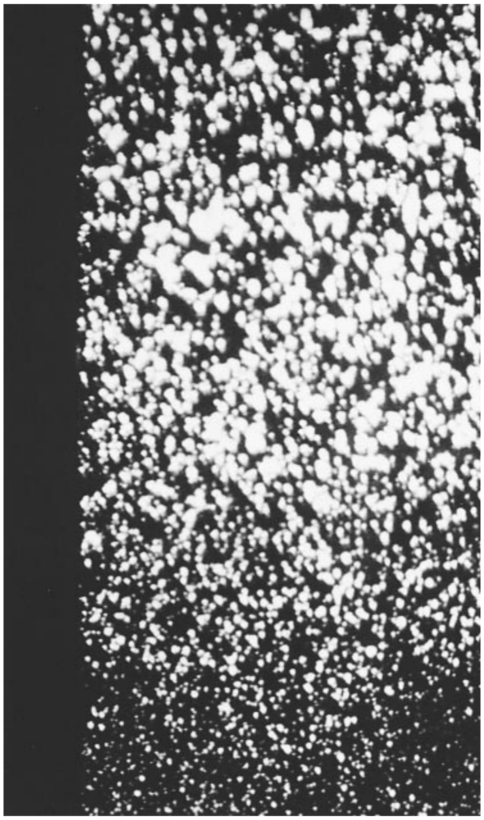
If substantial metal removal is required, longer pickling times will cause an increase in the level of background liquid penetrant indications due to pitting. This should be taken into consideration when making the final test.

Interpretation of Liquid Penetrant Indications

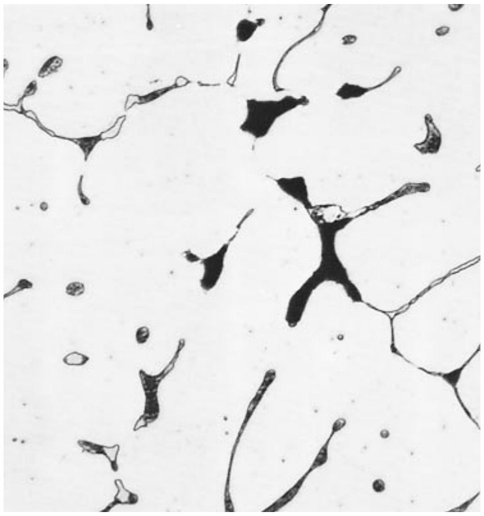
Interpretation of liquid penetrant indications of aluminum can be accomplished on both the macroscopic and microscopic scales. Macroscopic examination of the surface under testing, using either incidental or direct lighting will sometimes alleviate confusion as to characterization of discontinuities. With fluorescent liquid penetrants, ultraviolet irradiation in a darkened room can be used with macroscopic testing while the liquid penetrant indications are still shown by their fluorescence. This practice enables the inspector to distinguish readily between actual discontinuities and surface anomalies such as etch pits, machining discontinuities and other extraneous discontinuities causing background indications in materials in primary aluminum production facilities.

Figure 2. Porosity in aluminum ingot:
(a) hydrogen content of 2.50 $mm^3 \cdot g^{-1}$ = 2.5 $mm^3 \cdot (0.37\ cm^3)^{-1}$ = 6.75 $mm^3 \cdot cm^{-3}$ = 0.675 or about 0.7 percent;
(b) photomicrograph of pore corresponding to liquid penetrant indication.

(a)



(b)



Metallography to Aid Interpretation of Liquid Penetrant Tests

Metallographic examination remains a most important aspect of determining cause and microscopic features of discontinuities found in aluminum and its alloys by liquid penetrant testing. When using this technique to determine the cause of liquid penetrant indications more accurately, however, care should be taken in the preparation of metallographic samples. Metal must not be allowed to flow and fill the surface openings of the discontinuities during polishing of metallographic test specimens. This is necessary so that microscopic details of the discontinuities remain intact. Unfortunately, it is often not possible to achieve exact correlation of liquid penetrant indications to microscopic discontinuities. In these cases, quantitative metallographic procedures are used to reinforce interpretations based on liquid penetrant test indications.

Fluorescent Penetrant Testing in Aluminum Industry

Through refinements of test techniques and the addition of macroscopic visual examination, both the locating and the characterization of smaller discontinuities in aluminum and its alloys have come within the realm of liquid penetrant testing. In the primary aluminum production industry, liquid penetrant testing has expanded from a single *go/no-go* testing to its use in actual process quality control.

Liquid Penetrant Testing of Aluminum Ingots

Cross sections of all sizes of aluminum ingots are inspected for cracks and porosity before and after macroetching. Most cracks and gross porosity can be detected readily on the machined surface of the ingot slice. However, macroetching is usually required to permit the inspector to distinguish fine porosity (see Fig. 2). Testing of this type can be used as a routine check on degassing and casting practices in primary production of aluminum.

Porosity is reported as a ratio of volume to volume and can be expressed as a percentage. For the case in Fig. 2, hydrogen content in aluminum was measured as 2.5 $mm^3 \cdot g^{-1}$. This calculates to 2.50 $mm^3 \cdot (0.37\ cm^3)^{-1}$ = 6.75 $mm^3 \cdot cm^{-3}$ = 0.675 or about 0.7 percent. Therefore the hydrogen content should be reported as 6.75 $mm^3 \cdot cm^{-3}$ in volume for a porosity of 0.7 percent.

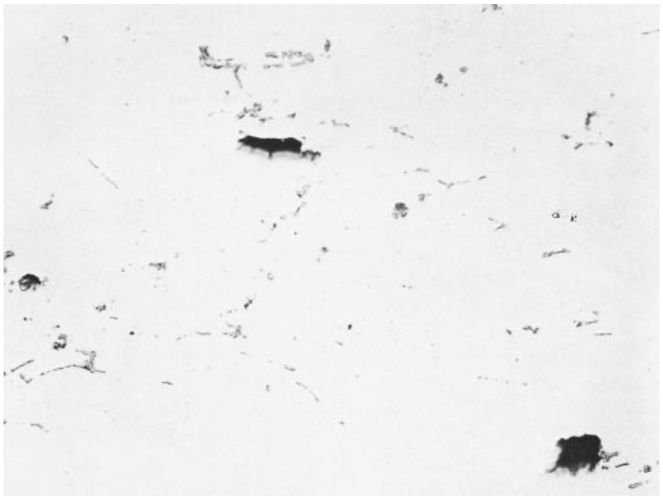
Heavy Rolled Aluminum Plate

Although ultrasonic testing is widely used as a test method for heavy gage rolled aluminum alloy plate, liquid penetrant testing can be used to locate fine hydrogen related porosity of a size smaller than that which can be detected through ultrasonics (see Fig. 3). Again, the cross sectioned surface of the aluminum plate is machined and prepared either by macroetching or by acid pickling. The aircraft industry also commonly uses the methods of liquid penetrant testing for examination of components machined from heavy gage aluminum alloy plate.

Aluminum Alloy Forgings

The objective of liquid penetrant testing of machined or macroprepared aluminum forgings is detection of incipient cracking, delamination and forging lap folds with associated included oxides. Proper preparation of test surfaces for liquid penetrant testing of aluminum alloy forgings is critical as this type of working tends to close up openings and disguise discontinuities. Only those discontinuities that are open to the surface and that can entrap liquid penetrant will be detected in liquid penetrant testing. Longer liquid penetrant dwell time on test surfaces can also help to define those discontinuities that are partially closed during mechanical working.

FIGURE 3. Porosity in heavy aluminum plate. Photomicrograph of pores corresponding to liquid penetrant indication near center of plate.



General Inspection of Aluminum Parts — Cast, Fabricated, Welded or in Service

The profound ability of liquid penetrant testing to detect quench cracks, fatigue cracks and the fine cracks resulting from stress corrosion has often prevented catastrophic failure of a part or possible installation of a anomalous part. The aircraft industry commonly uses liquid penetrant testing as the final assurance of quality of aluminum components before installation in aircraft. Automobile manufacturers use liquid penetrant testing on aluminum automotive pistons, valves, steering and suspension components and aluminum alloy wheels.

Liquid penetrant testing is also an important nondestructive test used to ensure quality in welding of aluminum and its alloys. In the field, where radiographic test equipment is not available, liquid penetrants are used in the weld area to detect weld cracks and base metal cracks open to the surface. Liquid penetrants are often also used in conjunction with radiographic testing of aluminum welds to discern those cracks not oriented perpendicular to the part surface (that cannot always be detected by radiographic testing). Thus, liquid penetrant testing has become a useful tool for both aluminum fabricators and users. If proper liquid penetrant processing and test procedures are used, discontinuities cannot only be located; they can also be characterized as to their form and size.

Aerospace Applications

Early Aerospace Manufacturing Experience in Testing of Light Alloy Castings

Typical of the requirements established by the customers for light alloy foundries are those developed by early airframe manufacturers during inspection. These manufacturers found a high rate of rejection on nonferrous castings because of porosity, gas pockets, warps, dimensional error, shrink, core shift and cracked parts. These rejections were taking place somewhere along the production line, during machining or on completion of the parts. It was then decided to set up a receiving inspection and precision dimensional checking of castings received from foundries. Precision mechanical gaging inspectors were assigned to set up and precision check incoming castings and forgings. Castings not built to blueprint dimensions were returned to the vendors. This dimensional testing took care of the part of the problem involving dimensional errors due to print change, warp, shrinkage or core shift.

X-Ray Fluoroscopic and Liquid Penetrant Incoming Testing by Customers

Aerospace manufacturers then set up fluorescent liquid penetrant and X-ray fluoroscopic testing of light alloy castings and forgings to detect those that should be rejected because of cracks, porosity, gas pockets and shrinkage. These tests found failures due to stress raisers set up by shrinkage, failures due to porosity and failures because of gas pockets in critical areas. It was also determined that fluorescent liquid penetrant and fluoroscopic testing should precede precision dimensional testing because only a fraction of the time required for precision gaging would be required for liquid penetrant or fluoroscopic testing. These lower cost, high speed nondestructive tests permitted immediate rejection of parts on which precision test time would otherwise be wasted.

It was found that two operators could provide fluorescent liquid penetrant testing of about 2500 average size castings per day. The equipment in use was composed of a liquid penetrant dip tank and drain station; a water spray rinse station for use with water washable liquid penetrants, with overhead ultraviolet lamps; a wet developer tank; a drying oven; and two separate ultraviolet radiation inspection booths. The additional booth was used as a review booth for engineering salvage of castings in which discontinuities had been found. This salvage operation involved decision by qualified engineers as to which parts would be serviceable in spite of the discontinuities. Such rejected but salvageable parts were sometimes salvaged by grinding out the discontinuities or by welding.

Customer Cooperation with Foundries in Correction of Unacceptable Castings

In early aerospace industry experience, during a 60 day period, some 21 000 parts were tested with fluorescent liquid penetrants, of which 1413 were returned to the vendor as not acceptable. To assist the vendors in handling of parts returned because of discontinuities, every possible effort was made to test the castings as soon as possible after receiving them. Some vendors were able to make changes in foundry technique by the addition of gates and risers, slight changes in fillet sections and by analyzing the discontinuities found. Many orders of like parts rejected by fluorescent liquid penetrant testing were found to contain casting discontinuities in the same area.

The early experience of aerospace manufacturers established the policies that generally apply today in procurement of light alloy castings. Castings purchased for aerospace systems should meet the dimensional requirement of the drawings, taking care of warp, core shifts and other causes of dimensional discrepancies. Other factors such as cracks, excessive porosity and gas pockets are not desirable in castings and represent a problem that the foundries are forced to face if they intend to meet competition. Until foundries set up a control on these factors, there remains a problem of cooperation between customers and foundries to assist the foundries in supplying the best material possible.

References

1. ASTM E 1417*, Standard Practice for Liquid Penetrant Examination*. West Conshohocken, PA: American Society for Testing and Materials (1995).
2. ASTM E 165*, Standard Test Method for Liquid Penetrant Examination*. West Conshohocken, PA: American Society for Testing and Materials (1995).
3. SAE AMS 2644, *Inspection Materials, Penetrant*. Warrendale, PA: Society of Automotive Engineers (1996).
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CHAPTER

Electric Power Applications of Liquid Penetrant Testing

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PART 1. Applications of Liquid Penetrant Testing in Electric Power Plants

Electricity is created when the rotors of electrical generators are forced to spin within a static magnetic field. The rotational forces are derived usually from steam turbines and in some cases from hydroelectric turbines. Steam used to drive the turbines can come from the burning of fossil fuels (coal, gas, oil) in large boilers or by the use of steam generators (special pressure vessels) that derive their thermal drive from heated water that has passed through a nuclear reactor. Thus we speak of fossil power plants and nuclear power plants.

Liquid penetrant testing is used to detect discontinuities and time based degradation processes within the moving parts of the electrical generation system as well as the pressure containing complex of pressure vessels and associated piping subassemblies of nuclear power plants. It also finds application in support of the general integrity of structures found within the balance of plant facilities. However, because fossil plants are constructed primarily from ferromagnetic materials, magnetic particle inspection tends to be the preferred mode of surface sensitive nondestructive testing. As is the case of other complex engineering systems, the use of liquid penetrant testing varies somewhat from one situation to the next but the fundamental principles of its application remain the same as for other field related inspections.

Liquid penetrant testing is used as part of the quality assurance programs associated with new equipment manufacture and installation, with ongoing inservice maintenance inspections and technical support of investigations, research and development projects as well as occasional procedure, process or personnel qualification activities.

New Manufacture

Liquid penetrant testing is used to inspect original equipment integrity *before* components are put into service (including both fabrication and installation).

A typical example is the checking of raw materials (forgings, castings, pipe, fittings, and attachments) made of aluminum, brass, copper, steel and nickel before welded installation. These inspections ensure that contaminants entrapped within the base materials do not induce weaknesses in the final weld. Joint preparations are inspected by liquid penetrant testing before welding to avoid conditions such as escape of fluids entrained in laminations or porosity. Such conditions tend to interfere with the welding process. Welding of stainless steel components and cladding deposited within carbon-steel pressure vessels in nuclear power plants is another common use of liquid penetrant testing.

Another example is the testing of hard surfacing on the seats of valve bodies. Cracks in these seats tend to lead to premature failure of a valve, usually resulting in excessive leaking. When an in-process repair must be made during the manufacture of components, especially if it involves the repair of questionable welding in stainless steel components, the repair welds are inspected using liquid penetrant testing to ensure absence of questionable surface connected discontinuities.

Inservice Inspection

Liquid penetrant testing is used to verify equipment condition on a continuing, periodic basis *after* components have been put into service.

Operating components suffer degradation from both variable mechanical stresses and extreme temperatures. Because power plant components are exposed to wide temperature extremes, mechanical stresses are induced because of thermal expansion cycles. Welds often retain residual stresses that can lead to stress cracking in some environments. Vibrations and differential loading also tend to initiate stress relieving cracking. In exceptionally high temperature areas, metal creep can occur in pressurized piping systems. Turbine blades are exposed to high frequency oscillations that induce fatigue cracking in the protective cobalt based alloy on their leading edges. Aluminum fan blades on electrical generators are inspected using liquid penetrant testing as are other nonferromagnetic blades found on gas turbines.

Routine inspections, including those done using liquid penetrant testing, are used to detect the presence of such potential failure modes before they can cause a serious operational problem. These inspections are conducted during routine maintenance outages and as part of an overall program of plant assessments conducted on a partial plant, rotating schedule.

Support of Other Operations

Liquid penetrant testing is performed for purposes other than assessing the integrity of items for their acceptance for future use.

A third general and equally important function of liquid penetrant testing is its use in assisting in determining: (1) the extent of cracking associated with component failure investigations, (2) the demonstrated performance of unusual liquid penetrant testing applications as part of research and development activities, and (3) support for procedure, process and personnel qualification. This last class of liquid penetrant testing applications is very popular in that it accommodates the need to get a spot check on the severity of surface connected discontinuities, often identified at the specific location of a failure or other area of special interest. It represents an intermediate step between general visual examination and the detailed sectioning and microscopic analysis of test pieces.

For example, liquid penetrant tests of copper-nickel steam condenser tubes, subjected to adverse chemical environmental conditions, assisted in demonstrating the adverse effects of different test conditions. Experimental evaluation of automatic welding equipment for nickel clad tube sheet used liquid penetrant testing to validate welds made during remote operations in nuclear facilities. Liquid penetrant testing was used to confirm the through-wall nature of cracks found in the base welds of male slip joints used in steel transmission line poles. When radiography determined the presence of galvanizing coating materials within the cracks, an investigation found that the base welds had been repaired earlier to remove some root cracking. The repairs had been finished off with a regalvanizing touchup. It was evident that the hot ticking method of regalvanizing was the root cause of the recurring base weld cracking.

PART 2. Liquid Penetrant Testing of Pressure Components of Nuclear Power Plants

Standards for Liquid Penetrant Testing in Nuclear Power Plants

Inspection of the most critical parts and systems of nuclear power plants in the United States is governed by the *ASME Boiler and Pressure Vessel Code,* Section III, *Nuclear Power Plant Components,* and Section XI, *Rules for Inservice Inspection of Nuclear Power Plant Components*. Section V, *Nondestructive Examination,* contains the requirements and methods for nondestructive examination.[1]

The *ASME Boiler Code,* Section V, Article 1, "General Requirements," describes the purpose and scope of the nondestructive testing methods, the manufacturer's examination responsibility, the duties of the authorized inspector and required written test procedures and qualifications required of nondestructive examination personnel. Article 1 also defines the special distinction established in the various *ASME Boiler Code* sections between *inspection* and *examination* and the personnel performing them. The term *inspection* applies to the functions performed by the *authorized inspector* but the term *examination* applies to those quality control functions performed by personnel employed by the manufacturer. It also states that the terms *inspection, testing* and *examination* used in documents of the American Society for Testing and Materials (ASTM) do not describe duties of the authorized code inspector but rather denote the things to be done by the manufacturer's examination personnel.

ASME Boiler Code, Section XI, covers the *Rules of Inservice Inspection of Nuclear Power Plant Components*. Article 6 of *ASME Boiler Code,* Section V, "Liquid Penetrant Examination," describes the liquid penetrant method, procedures and tests and the qualification of liquid penetrant procedures for nonstandard temperatures. It also limits liquid penetrant and processing material contaminants to not exceed one percent by weight of sulfur when using liquid penetrant testing for nickel base alloys or one percent by weight of total residual halogen content when examining austenitic stainless steels or titanium.

The *ASME Boiler Code,* Section V, Article 24, "Liquid Penetrant Standards," contains ASTM E 165[2] and lists other ASTM nondestructive testing standards accepted by the American Society of Mechanical Engineers (ASME).

ASME Boiler Code Definitions of Visual, Surface and Volumetric Examinations

ASME Boiler Code, Section XI, Article IWA-2000, "Examination and Inspection," defines the term *examination* to denote the performance of all visual observation and nondestructive testing such as radiography, ultrasonic, liquid penetrant and magnetic particle methods. It further defines the term *flaw indication* as denoting the evidence or signal obtained by application of a nondestructive test that may reveal the presence of a discontinuity. These discontinuity indications may be caused by cracks, slag inclusions or segregates, aligned or clustered porosity, lack of weld penetration, lack of weld fusion, laminations or combinations of these conditions. Methods, techniques and procedures for the inservice inspections are titled *visual, surface* and *volumetric.* Each of these terms denotes a general method and permits a selection of different techniques or procedures restricted to that method to accommodate varying degrees of accessibility and radiation levels and the automation of nondestructive testing equipment.

ASME Boiler Code Description of Visual Examination and Lighting

A visual test is used to provide a report of the general condition of the part, component or surface to be examined in a nuclear power plant application. Examples of conditions to be observed and reported include scratches, wear, cracks, corrosion or erosion of the surfaces; misalignment or movement of the part or component; or evidence of leakage. Access, lighting and angles of vision are important considerations in performing visual testing either directly or remotely, depending on existing conditions.

Direct visual testing may usually be made when access is sufficient to permit the examiner's eye to be placed within 0.6 m (24 in.) of the surface to be examined and at an angle no less than 30 degrees to the plane of the surface to be inspected. Mirrors may be used to improve the angle of vision and aids such as a magnifying lens may be used to assist tests. Lighting, natural or artificial, sufficient to illuminate the area to be examined, is required. In the area to be examined, the lighting shall be a minimum of 540 lx (50 ftc). Visual testing personnel shall have an annual vision acuity examination to ensure natural or corrected near distance vision acuity such that they can read standard J-1 letters on standard Jaeger test type charts for near vision or demonstrate equivalent vision acuity by other means of evaluation.

Because of recognized variations in Jaeger vision test charts, Section XI of the *ASME Boiler Code* specifies near distance acuity of 20/25 or greater Snellen fraction and provides maximum test chart character heights, depending on near vision test acuity test distance (refer to IWA-2322 in Section XI).

For inservice nondestructive testing of nuclear power plant systems or components according to Section XI of the *ASME Boiler Code,* remote visual testing may have to be substituted for direct visual testing. Remote visual testing may use visual aids such as mirrors, telescopes, borescopes, fiber optics, cameras, television or other suitable instruments. Such systems shall have a resolution capability at least equivalent to that obtainable by direct visual observation.

The *ASME Boiler Code* specifies that lighting for examination of visible dye liquid penetrants must be adequate to ensure that no loss of sensitivity occurs in the liquid penetrant test. Some situations may require levels of lighting or visual aids comparable to those described here for visual testing to achieve the optimum level of vision acuity in observing liquid penetrant indications.

ASME Boiler Code Description of Surface Examination and Discontinuity Indications

A surface test is specified to delineate or verify the presence of surface or near surface cracks or discontinuities. It may be conducted by either magnetic particle testing or liquid penetrant testing where the surface condition, material and accessibility permit such a test. In surface inspection, a continuous indication shall be considered as a surface planar discontinuity if the detected area of the indication is oriented primarily in any single plane, other than parallel to the surface of a component, and if any portion of the indication penetrates a surface of the component. Linear indications are defined as those in which the length is more than three times the width. No linear indications are acceptable in welds or in bolts, studs etc. (unless such indications are axially oriented). In forgings, bar, plates, tubular products and castings, only indications over 1.6 mm (0.06 in.) in length are considered relevant. Acceptance criteria for rounded (nonlinear) indications are identical for welds and for nuclear power piping. In all cases, however, the applicable or specified version of the *ASME Boiler Code* should be consulted to determine the applicable acceptance criteria.

ASME Boiler Code Description of Volumetric Examination

A volumetric test has the purpose of indicating the presence of subsurface discontinuities with a technique that can examine the entire volume of material beneath the surface to be examined. Obviously, liquid penetrant testing is not volumetric. Radiographic testing and ultrasonic testing are typically used for volumetric inspection of nuclear power plant components and systems.

Surface Examinations — Liquid Penetrant versus Magnetic Particle

Liquid penetrant testing is used on nuclear power plant piping, welds, pressure vessels, valves and fittings. Fittings may be castings or forgings. Liquid penetrant testing is used for surface inspection of magnetic as well as nonmagnetic materials. Magnetic particle testing may sometimes not be feasible because of inaccessibility for applying magnetizing current prods to root welds or small fittings such as elbows. Visibility in areas requiring surface inspection may be so limited that measurement of particle accumulations is difficult. Visible dye liquid penetrant testing avoids both of these problems. Where only a small area of material requires inspection, such as with a repair weld, liquid penetrant tests are frequently used to avoid moving magnetic particle power supplies and test equipment for such a small job.

Liquid Penetrant Testing of Nuclear Power Plant Components

Liquid penetrant tests are used throughout the construction and life cycle of nuclear power plants on components ranging from the smallest valves to the largest and most critical pressure vessels. The discontinuities sought during liquid penetrant testing are those common to pressurized systems in conventional nonnuclear power plants and pressure vessels and components throughout industry. Common discontinuities are caused by cracks, porosity, laminations, weld discontinuities and other discontinuities open to exposed surfaces. Discontinuities may be judged as acceptable or be rejected, depending on the specified acceptance criteria.

Many of the tests performed are required by regulatory agencies in conformance with applicable provisions of the *ASME Boiler and Pressure Vessel Code.*[1] However, many other tests are performed by manufacturers and erectors as an economic consideration, as inprocess steps before expensive fabrication or testing operations.

Materials and Fasteners

Nuclear power plant materials in *ASME Boiler Code* Class 1 (the most critical of the *ASME Boiler Code* Section III code classes) require surface testing: (1) pressure retaining materials with outlet sizes greater than 50 mm (2 in.); (2) forgings and bars; (3) tubular products welded with filler metal; (4) castings, all surfaces; and (5) bolts, studs and nuts greater than 25 mm (1 in.) bolt size. Classes 2 and 3 of *ASME Boiler Code* materials are tested in accordance with the requirements of the applicable material specification contained in the *ASME Boiler Code,* Section II.

Welds and Seals

Class 1 welds of specially designed seals and Class 1 and 2 welds of the following listing require surface testing: (1) pipe welds; (2) vessel welds; (3) corner welds; (4) fillet and socket welds; (5) welded branch and piping connections; (6) butt welded nozzles; (7) deposited metal used as reinforcement of openings for nozzles, branch and piping connections; and (8) structural attachments.

For fabrication, all hard surfacing (except on valves with inlet connections less than 100 mm (4 in.) nominal pipe size), tube-to-tube sheet welds and weld metal cladding require liquid penetrant testing. Vessels require liquid penetrant testing only before pneumatic pressure testing.

Tubular Products

Nuclear power tubular products, both seamless and welded without filler metal, require performance of one of the following types of tests: (1) liquid penetrant testing, (2) magnetic particle testing, (3) ultrasonic testing, (4) radiographic testing or (5) eddy current testing. Class 3 components require liquid penetrant testing or magnetic particle testing on piping or tubular products over 100 mm (4.0 in.) pipe size.

Magnetic particle testing is used for much of the surface testing of carbon steel piping in boiling water reactors. However, in both boiling water reactors and pressurized water reactors where austenitic stainless piping is used, low halogen liquid penetrant materials are specified for nondestructive testing of welds and piping. This requires low halogen liquid penetrant testing materials consisting of the cleaner, liquid penetrant, removers and developers.

Onsite Liquid Penetrant Examination of Nuclear Power Plant Systems

ASME Boiler Code requirements for critical Class 1 nuclear components permit fluorescent or visible dye liquid penetrant systems designated as either solvent removable or postemulsifiable. However, liquid penetrant testing at the construction site is almost without exception accomplished with solvent removable visible dye liquid penetrant materials packaged in spray cans. These materials are readily portable in kit form and do not require special processing facilities or wash water, hot air dryers or dark room examination facilities. Spray cans of liquid penetrant, cleaner and wet developer suspensions are stamped with the identification number and material batch analysis taken before packaging into spray cans. This makes possible both traceability and validation of material type and quality. Spray cans prevent contamination of the materials during or between use periods.

Operating Conditions in Onsite Liquid Penetrant Examinations

Onsite liquid penetrant testing of nuclear power plant systems is often accomplished under difficult conditions. Testing may be done in the swamps of tropical areas where the worst process interference comes from operator perspiration or in cold climates where one of the major problems is spraying liquid penetrants or developers while wearing mittens. The examiner may be testing many small welds while crammed into a hole where the biggest problem is to provide illumination required by code. Or the examiner may be examining a seam weld while suspended in a crane cage at the top of a nuclear reactor containment structure where the major problem is to avoid looking downward. Many other examples of operator discomfort, distraction or hazard could be listed.

Temperature Conditions in Onsite Liquid Penetrant Examinations

Inspectors working at nuclear power plant construction sites commonly use liquid penetrant systems qualified to operate at temperatures from 2 to 130 °C (36 to 270 °F). Some manufacturers of liquid penetrant materials have systems qualified to operate at temperatures as low as –12 °C (10 °F). High temperature liquid penetrants have proven to be very useful in nuclear power plant inspection, especially for multipass welds. High temperature liquid penetrant test materials save time by eliminating part of the waiting period required for welds to cool before inspection. Liquid penetrant manufacturers offer specialized liquid penetrant testing materials for use on surfaces at 175 °C (350 °F), a typical weld preheat temperature.

Use caution — irritating vapors are generated more rapidly when volatile materials such as solvent type cleaners, removers or developers are applied to high temperature surfaces. Care should be taken to provide adequate ventilation. The *ASME Boiler Code* (Section V, Article 6) specifies a procedure for qualification of liquid penetrant procedures for use at nonstandard temperatures, using cracked aluminum reference blocks. When it is not practical to make a liquid penetrant test within the standard temperature range of 10 to 52 °C (50 to 125 °F), the nondestructive test at the proposed nonstandard temperature requires qualification.

Surface Preparation for Liquid Penetrant Testing of Nuclear Components

Preparation of material surfaces for liquid penetrant testing may be unnecessary for some raw or semifinished materials having good surface finishes. All types of welding, except inert gas tungsten arc welding (GTAW), generally require preparation of test surfaces either by grinding or by manual wire brushing (with the brush wire material matching the material to be examined). When unacceptable liquid penetrant indications are found, the discontinuities they reveal are removed by grinding or thermal techniques. To be sure that the discontinuity has been removed completely or reduced to an acceptable size, the entire original liquid penetrant test procedure is applied again. (Etching is not used to determine that the discontinuity has been fully removed. Spot etching, however, is sometimes required to confirm removal of smeared metal.) If repair welding is needed to restore dimensions, the repair surface is prepared as described above and is again examined, using the full liquid penetrant test procedure. Pipes that have been bent in the field are frequently examined with liquid penetrant to make sure that the strains and stresses developed during bending did not initiate cracking. If necessary, their surfaces should also be prepared by grinding or wire brushing as described above. (High speed wire brushing may necessitate spot etching to remove smeared metal.)

Timing of Steps in Onsite Liquid Penetrant Tests

In the case of many fillet welds on nuclear power plant structures, liquid penetrant testing may be the only type of nondestructive testing applied. (Critical butt welds are often examined by radiographic or ultrasonic testing.)

Proper sequencing of liquid penetrant tests and care on the part of each test operator is needed. For example, if several areas or parts are to be examined simultaneously by liquid penetrant testing, the operator should perform each step of the test by using the same sequence of parts. If this is not done, confusing variations may arise. A part that has had the longest penetration time or the longest developing time can have indications that appear to be quite different from those on parts that receive minimum penetration or developing times, especially when the extremes of time variations allowed by the test procedures are approached. If an operator tries to apply liquid penetrant test materials simultaneously to too great a length of weld or to too many small welds in a system and runs into trouble completing processing steps within their allotted time, it creates an obvious cause of discrepancies in examination and evaluation of discontinuity indications.

Avoiding Interference among Multiple Operators

During onsite liquid penetrant tests of nuclear power plant systems, two or more test operators working in the same area may interfere with each other's test processes in ways that might not be noticed. For example, if liquid penetrant tests are being performed in too close proximity, one operator might inadvertently spray developer on the other operator's test surface area, possibly just before the other operator's visual examination and interpretation of indications. The second application of developer could cover an existing indication and, if the second operator performs the interpretation before the liquid penetrant has had a chance to bleed through the new covering of developer, a discontinuity could be missed. However, the operator who applies developer last can use care to see if there is developer on an adjacent test area and avoid this type of interference with another test.

Another situation of interference between adjacent liquid penetrant test operators is more difficult to recognize. Suppose that, in a confined area, one operator develops the test area first but inadvertently applied developer to another adjacent clean area of weld that has no visual indication under test. However, if the second operator had just applied cleaner/remover to that weld area and it had not completely evaporated, the premature coating of developer could absorb the cleaner, leaving a layer of relatively inactive developer on that section of the weld. If the second operator now sprays developer on that section of the weld, waits the prescribed time and examines this surface for indications, it is possible that the cleaner or remover in the underlying developer layer will interfere with proper development of indications.

This type of coincidence is most likely when the two operators are working on opposite sides of a welded barrier and have to reach around the edges of this barrier to apply processing materials and must use an inspection mirror to see the resultant indications. In this case, one operator may not be fully aware that the second operator is working on the adjacent area and could be unaware of the interfering operations that have occurred. Neither may notice the developer inadvertently sprayed onto the back side of the weld and indications might be missed.

Limitations of Liquid Penetrant Testing for Nuclear Power Plant Inspection

Although many indications have been detected and analyzed correctly for nuclear power systems, both preservice and inservice, it cannot be positively stated that all existing discontinuities have been detected by liquid penetrant testing or other nondestructive testing methods. An example is a reactor pressure vessel where cracking of weld deposited cladding was suspected. This cracking was confirmed before service through liquid penetrant testing but most of the cracks were not apparent during subsequent inservice inspection. The problem was that the corrosion product (scale) developed in service had completely covered the crack. Therefore, because of interference from the scale, liquid penetrant testing could not detect cracks in the underlying metallic cladding. Only after the scale was removed by grinding was liquid penetrant testing able to reveal liquid penetrant indications of the cracks. This problem has been observed on other reactor systems.

Despite the fact that nondestructive testing cannot always detect a significant discontinuity in a nuclear piping system, there are other additional safeguards against disastrous failures.

1. The moisture detection system will detect small leaks.
2. The material used in construction of the critical piping system are resistant to fast fracture.
3. The containment vessel is designed to protect the public against radiation release due to a break in the largest pipe housed in the containment vessel.

There have been no recorded instances of failure to detect significant discontinuities in the reactor pressure vessel; in fact, very small discontinuities have been detected and correctly analyzed. Even though these safeguards exist, research has sought to increase the reliability of nondestructive testing methods for nuclear power systems.

PART 3. Examples of Liquid Penetrant Indications of Discontinuities in Reactor Piping

Liquid Penetrant Indications of Cracking in Reactor Cooling Systems

Ultrasonic testing, occasionally supported by radiographic testing, was used to identify questionable welds at several nuclear power plants. Liquid penetrants were often used to try to confirm the presence of inservice cracking in welds once they had been removed from service and split longitudinally to permit access to their inside diameter surfaces. Typical examples included core spray lines as well as valve bypass lines.

In this case, ultrasonic tests had indicated several sections of 250 mm (10 in.) American Iron and Steel Institute (AISI) type 304 stainless steel piping suspected of containing stress corrosion cracks.

These intergranular cracks are caused by residual stresses within the welds used to join pipe sections and attachments to fittings such as elbows, tees, pumps and valves. Residual stresses are often compounded by the presence of applied stresses found in piping systems attached to rigid structures such as pressure vessels. The presence of trace amounts of contaminants in the circulating water as well as grinding marks on the inside diameter of the pipes near the weldments are all considered to be factors contributing to the onset of the stress cracking.

Four typical examples of the weld conditions and the types of indications found are shown in the photographs of Figs. 1 to 4. The liquid penetrant indications were obtained after the pipe segments were halved so that access to the inside diameter surface was available. In each case, the inside surface of the pipes had to be descaled to lower the excessive radiation levels and to remove sites for the entrapment of liquid penetrants, a potential source of excessive background indications.

The investigations showed the presence not only of intergranular stress corrosion cracking but also of internal material inclusions and incomplete fusion of backing materials into the pipe materials during original working.

Indication of Lack of Fusion at Weld Root in Pipe

Figure 1 shows the type of liquid penetrant indications observed when detecting and identifying the extent of lack of fusion between a weld root insert (Grinnel insert) and pipe base metal. Figure 1a shows a white light photograph of the partially sectioned pipe segment. The relatively rough contours in the vicinity of the root can be seen, as well as a ground out area in the center of the picture between the 6 and 8 in. marks. Figure 1c shows a close up of the cut surface, near the right side of Fig. 1b. The slight indication near the root of the weld tends to follow the contour of what would be the remnants of the unfused Grinnel insert. Figure 1d shows a close up of the same area after metallurgical sectioning and preparation. The indication is along the line between the coarse and fine grained insert base metals. More detailed sectioning and examination of this region showed oxide inclusions in unfused regions.

Liquid Penetrant Indications in Base Metal near Nuclear Pipe Weld

Figure 2 shows examples of liquid penetrant indications observed in a boiling water reactor (BWR) stainless steel pipe material. The discontinuity lies near a girth weld and is oriented circumferentially. Indications near welds are often expected to have been caused by the welding process.

The pipe segment is shown in the white light photograph of Fig. 2a. Note that the root area near the weld has been ground to a fairly rough surface finish and a large change in wall thickness occurs between the pipe segment (bottom) and the elbow fitting to which the pipe is attached (top). This highly irregular contour and the as-welded condition of the outside surface made this type of joint very difficult to test ultrasonically.

Figure 2b shows a close up fluorescent liquid penetrant indication in the vicinity of the weld. Note how the indications appear to be in a straight yet broken line with the leftmost indications somewhat rounded. These indications are caused by

FIGURE 1. Lack of fusion between weld root insert and pipe base metal in nuclear power plant piping: (a) white light photograph of partially sectioned pipe segments, showing partially ground area between 6 and 8 in. marks; (b) fluorescent liquid penetrant indication at weld root insert edge; (c) closeup macroscopic photograph of weld root with fluorescent liquid penetrant indication of weld root notch at bottom; (d) photograph of cut surface, after metallurgical sectioning and preparation, with dark diagonal line indicating lack of fusion.

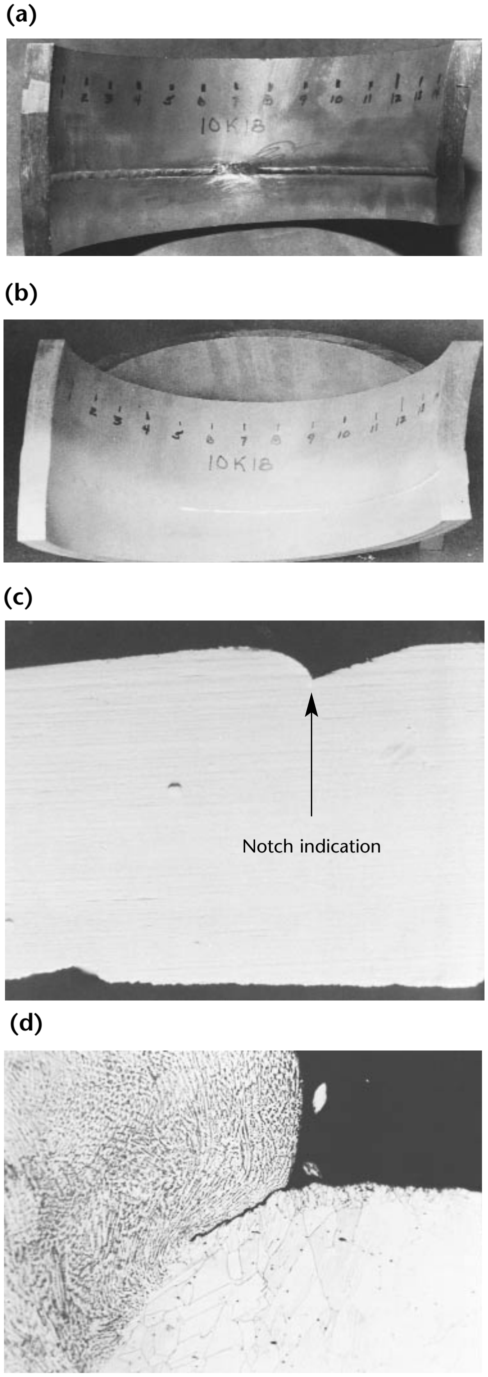


FIGURE 2. Surface defects in base metal near circumferential weld in nuclear power plant piping: (a) white light photograph of inside surface, showing weld location and contour of weld root area (note wall thickness change at weld); (b) fluorescent liquid penetrant indications in base metal, paralleling weld root area between 13 and 18 inch marks; (c) microscopic photograph of cross section through pipe wall showing nonmetallic sliver in base metal.

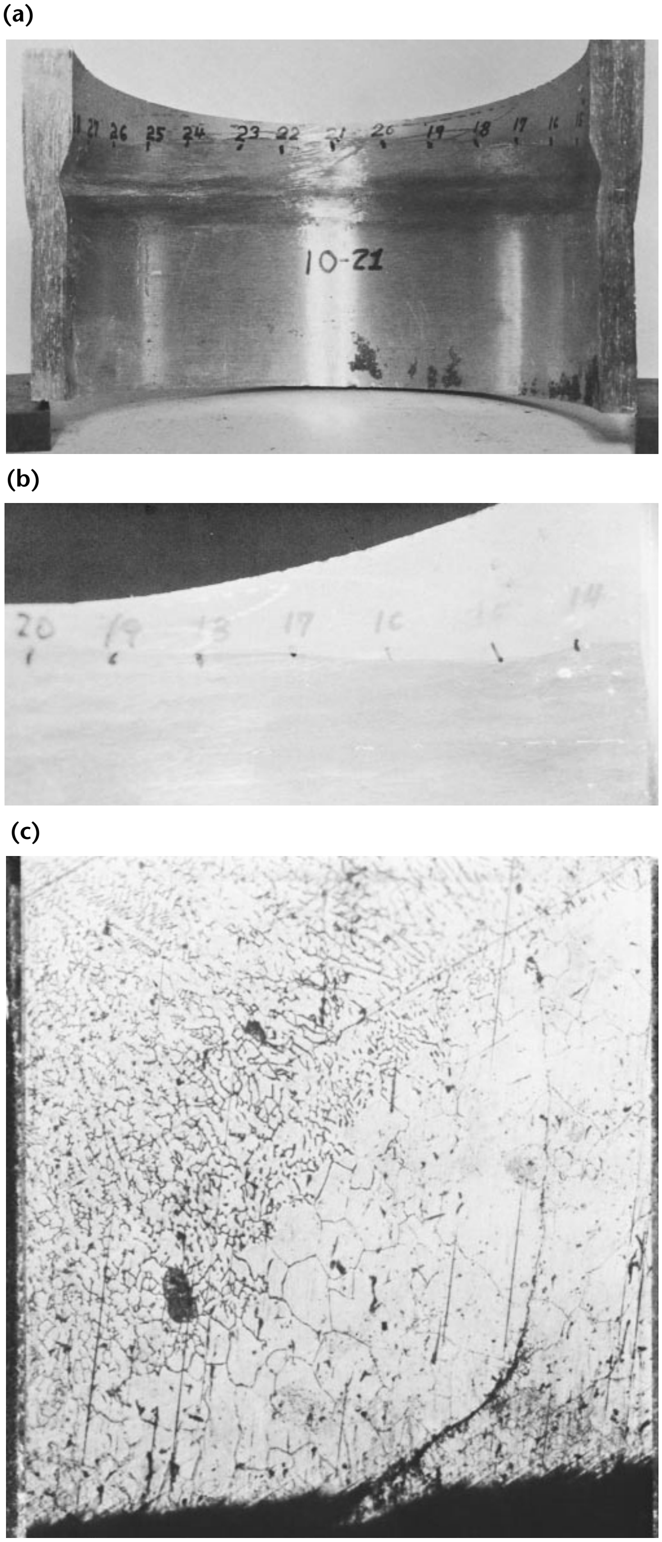
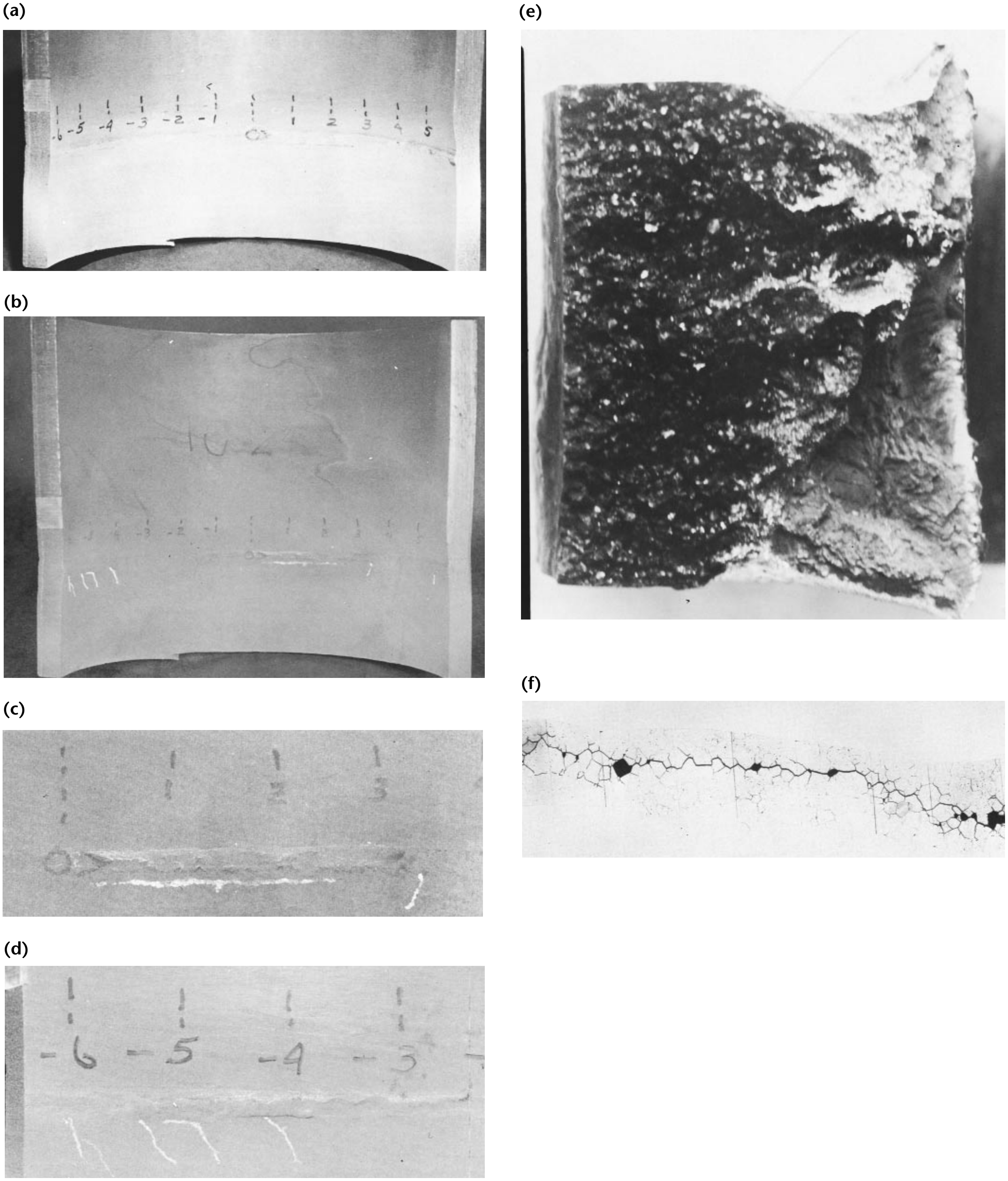


FIGURE 3. Stress corrosion cracking in nuclear grade type 304 stainless steel piping: (a) white light photograph of typical pipe to pipe weld segment; (b) fluorescent liquid penetrant indications of cracks angled to and parallel to weld center line; (c) closeup photograph of long, parallel fluorescent crack indication in Fig. 3b; (d) closeup photograph of short, angled crack indications in Fig. 3b; (e) photograph of sample, broken through stress corrosion crack; (f) cross section of typical stress corrosion crack in pipe wall.



nonmetallic slivers embedded in the base material that have emerged during the grinding operations.

Figure 2c shows a micrograph taken through one of the slivers. Note that the discontinuity existed only in the pipe base material, adjacent to the weld zone and was not induced in service; it was a manufacturing discontinuity that was not large enough to be readily detected during fabrication and processing testing.

Examples of Liquid Penetrant Indications of Stress Corrosion Cracking

Figure 3 shows an example of the types of liquid penetrant indications observed when detecting the presence of stress corrosion cracking near the heat affected zones of circumferential welds in nuclear grade type 304 stainless steel piping. Figure 3a shows a photograph of a typical pipe-to-pipe weld segment. The root area is slightly rough and some hint of counterbore preparation can be seen just adjacent to the weld root. The as-welded condition on the outside diameter is quite acceptable for most nondestructive testing applications.

However, Fig. 3b shows the presence of several severe cracks when viewed under ultraviolet radiation and when fluorescent liquid penetrants are used for detection purposes. The 60 mm (2.5 in.) long crack in the center of the pipe is aligned in a circumferential direction (as would be expected from the stress distribution in such piping assemblies). The angled cracks at the left are neither parallel nor perpendicular to the weld center line and were not detected when using generally accepted inservice ultrasonic test procedures. The indications from the large crack appear to be very diffuse because the liquid penetrant was running out of the crack while the photograph was being taken. The tighter, angled cracks did not have this problem because the photographs were taken only seconds into the development period.

Figure 3c and 3d show close ups of the long and angled cracks, respectively. The long crack was broken open and found to extend more than halfway through the pipe wall. A 10× photographic enlargement of the broken sample is shown in Fig. 3e. The granular type of surface morphology can be seen in the upper part of the photograph; the normal ductile fracture of stainless steel can be seen in the lower portion. Figure 3f shows the typical crack morphology when sectioned in the transverse direction.

FIGURE 4. Cracking in heat affected zone of weld base metal, paralleling weld center line: (a) fluorescent liquid penetrant indication of base metal cracking; (b) transverse section through crack in base metal, with liquid penetrant indication; (c) microscopic photograph on left, showing initiation site for corrosion cracking, and macroscopic photograph on right, showing initiation site for corrosion cracking.

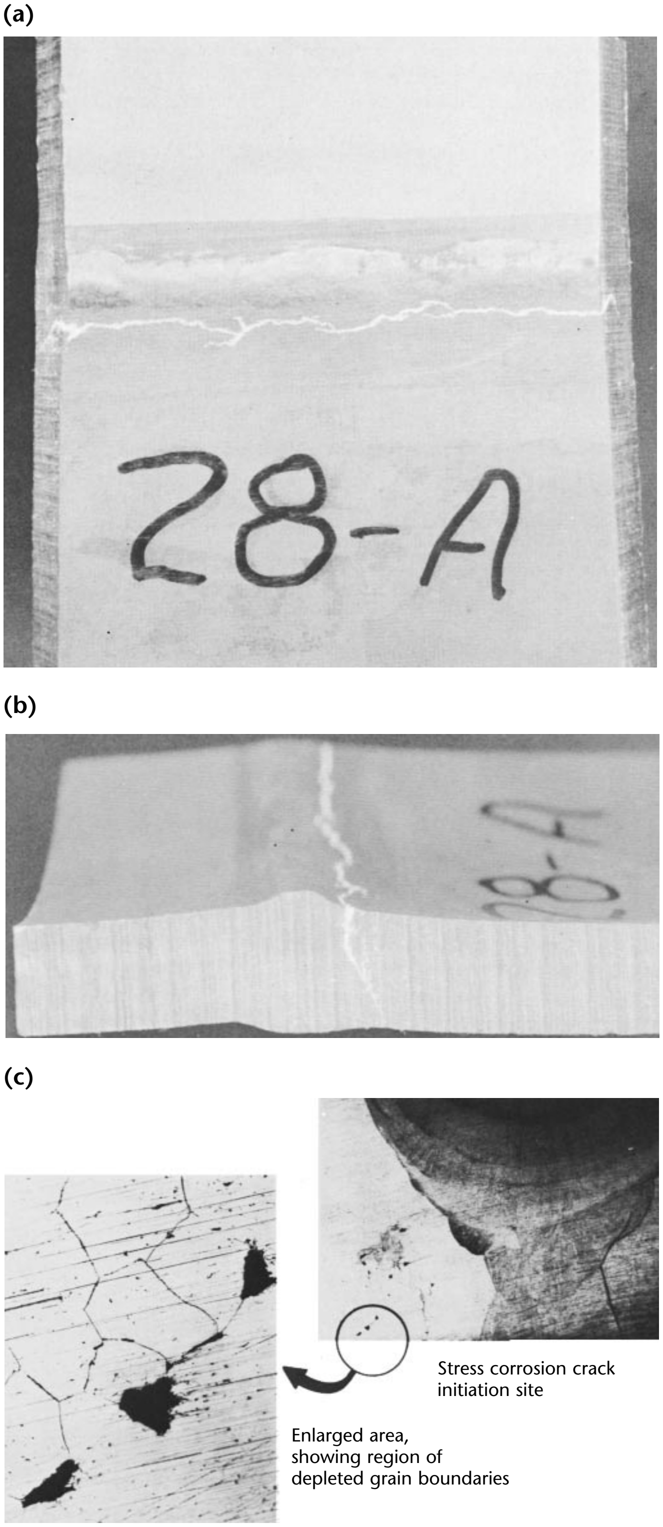
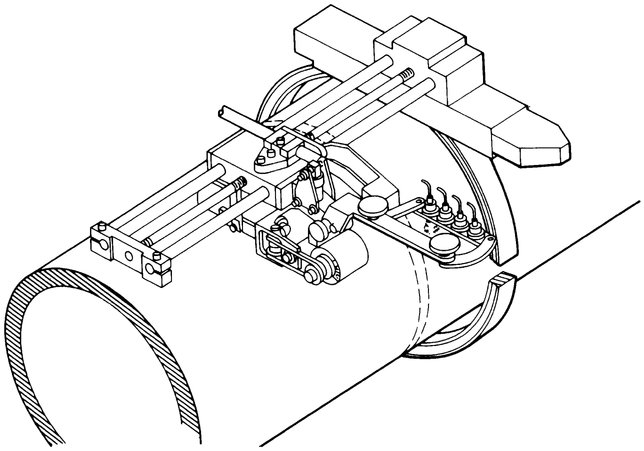
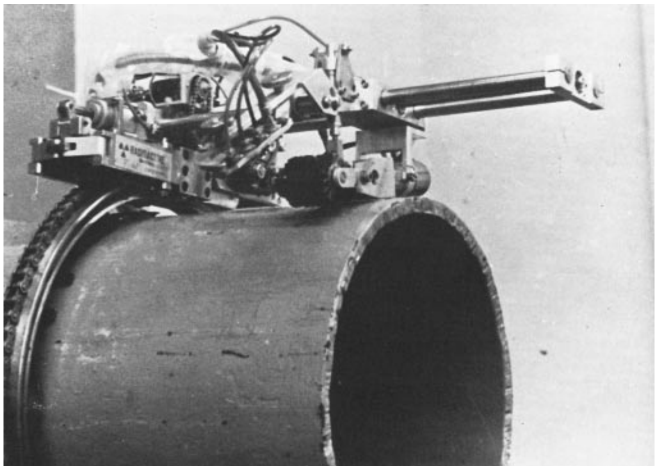


FIGURE 5. Remotely controlled mechanized scanning system for liquid penetrant testing of outside surface of nuclear piping welds: (a) schematic drawing; (b) system in laboratory; (c) inspection of nuclear pipe weld in nuclear plant. Liquid penetrant indications are displayed on remote color monitor and are video taped.

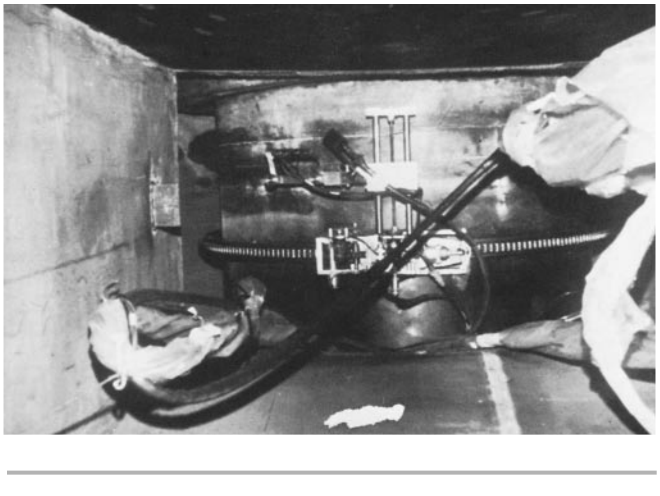
(a)



(b)



(c)



Cracking Parallel to Weld Center Line and in Heat Affected Zone

Figure 4 shows weld cracking parallel to the weld center line exclusively in the predicted direction. The crack travel tends to follow in the grinding marks found on the inside diameter surface of the pipe. As the photographs show, the cracking is just adjacent to the welds and usually found in the heat affected regions of the base material.

Example of Mechanized Remote Liquid Penetrant Pipe Weld Testing Device

Two basic problems involved in liquid penetrant testing of nuclear power systems are (1) lack of adequate access for human test operators and observers and (2) presence of high radiation fields in areas to be inspected. Figure 5 shows a device developed specifically for remote liquid penetrant testing of piping welds from the outside surface. This device cleans the surface, applies liquid penetrant, removes excess liquid penetrant, applies developer and presents images of the liquid penetrant indications by means of fiber optics and a remote color television monitor. Visual and position data are recorded in real time by means of a video recorder. Test identification data may be recorded directly on the record tape by using the keyboard printer and special effects generator.

PART 4. Personnel Performing Liquid Penetrant Testing in Power Plants

Ensuring Test Quality through Independent Inspections and Audits

An essential part of a quality program, the structure of which will be discussed later, is the assurance of consistent quality and independence of its inspections and tests. The best way quality can be ensured is by the performance of periodic surveillance. There are standard provisions for periodic audits of operations but these are designed more as a check on the completeness and accuracy of documentation, proper systems interfacing and the functioning of management controls. These audits can be helpful in determining whether nondestructive tests are performed properly, particularly in radiography. A system of slightly less formal surveillance is invaluable in evaluating the performance of liquid penetrant test personnel and equipment. In summary, surveillance of liquid penetrant testing operations is used to evaluate the test operator's (1) procedure knowledge and conformance, (2) technique of application and (3) judgment and motivation.

Motivation of Inspectors Doing Repetitive Work

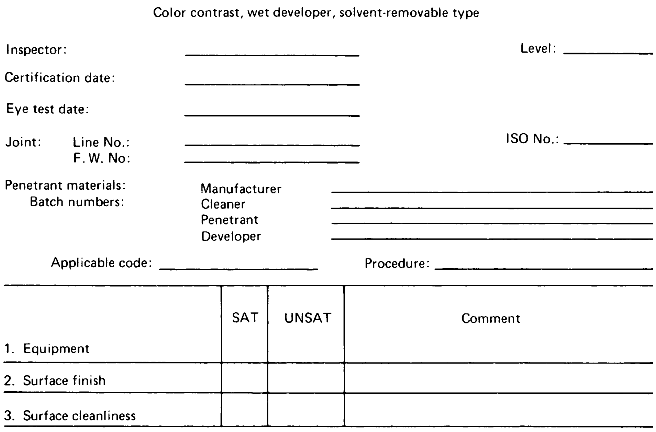
A major problem in repetitive tests on large structures is boredom. Because the operations are largely rote, there are no tangible results of the labor and it is hoped that, discontinuities occur very rarely. The inspector tends to have a feeling of not contributing to the total job. Surveillance counteracts this in two ways. It shows the inspector that management feels that the work is important by their monitoring and it gives the staff an opportunity to discuss the importance of the work with the inspector as that inspector performs tests. When liquid penetrant testing is the only inspection required, it assumes as much importance as the most sophisticated ultrasonic or radiographic tests performed in other instances. Figure 6 shows a portion of a *liquid penetrant inspector evaluation sheet,* which allows the observer to record a variety of information on the performance of the liquid penetrant test inspector.

Psychology of Field Test Surveillance Operations

Essential to the success of surveillance is the conversation during the waiting periods required in liquid penetrant testing. The operator must be put at ease to perform as nearly normally as possible. If this cannot be done, the type and amount of nervousness must be evaluated and used to interpret any errors made. Mistakes made under surveillance are normally on the conservative side, that is, to reject more than normal or necessary. When mistakes tend in the other direction, it indicates that the operator feels justified doing so. This should be investigated and then judged accordingly.

The time during the waiting periods can be put to other uses too. This is an opportunity to encourage the operator to talk about problems — either technical problems with the testing procedures or equipment or scheduling and access problems that can give information about the total program. It is essential that the surveillance be carried out by qualified and knowledgeable nondestructive testing personnel. A rote audit by an uninformed administrator with a checklist negates the benefits and can negate motivation.

FIGURE 6. Liquid penetrant inspector evaluation checklist.



Color contrast, wet developer, solvent-removable type

Inspector: ____________________ Level: __________

Certification date: ____________________

Eye test date: ____________________

Joint: Line No.: ____________________ ISO No.: __________

F. W. No: ____________________

Penetrant materials: Batch numbers:

Manufacturer ____________________

Cleaner ____________________

Penetrant ____________________

Developer ____________________

Applicable code: ____________________ Procedure: ____________________

	SAT	UNSAT	Comment
1. Equipment			
2. Surface finish			
3. Surface cleanliness			

Retraining Test Operators for Recertification

Periodic retraining of test operators for recertification is a necessary part of a good liquid penetrant testing program. This is necessary for familiarization with changes in codes, standards and procedures. This is also a time to warn about errors of familiarization, mistakes made because an operator is too experienced. These take the form of engineering judgments made by nondestructive testing personnel. For example, the operator may decide not to retest an indication that proved to be a surface irregularity coupled with inadequate removal of excess surface liquid penetrant. But the instance in which the operator decides not to retest may be the case in which a combination of inadequate cleaning and slightly too much developer blurs the darker center line and masks a relevant indication. This external vigilance is not inbred; it is promoted by certification, continual monitoring and retraining.

Retraining is the time for the examiner to emphasize the reasoning behind the waiting times, the sequence of operations and all those other things the examiner wants to tell a liquid penetrant test operator, now that the examiner is not afraid of confusing the operator and making the operator forget to wait at least 7 min before interpretation. This should provide another opportunity to elicit feedback to the original training program or to the test procedure writers.

Organization of Power System Quality Assurance Department

Organization for a quality assurance program is shown in Fig. 7a. The functions of a quality assurance department are as follows.

1. Identify quality requirements.
2. Determine how and when to measure quality.
3. Keep records of the above functions.
4. For quality control, document all materials, fabrication processes and fabrication quality.

The structure of a typical quality control department is shown in Fig. 7b. Liquid penetrant testing is performed by the nondestructive testing group in the field. Records are filled out there and fitted into system packages by the documentation section. In the manufacturer's plants, liquid penetrant testing is witnessed by a qualified inspector who performs duties parallel to the field sites' documentation section. The quality control phase of all nondestructive testing is overseen by the headquarters' nondestructive testing division by means of surveillance, technical assistance and procedure writing for field activities and review and approval of vendor nondestructive testing procedures.

One of the main duties of a nondestructive testing function is to promote high quality of all nondestructive testing — essential to the quality of materials and workmanship in a power plant.

Training of Personnel for Power Plant Inspections

The problems associated with inservice inspection include the scarcity of personnel trained and qualified for reactor system examination; the variability in procedures and data recording among inspection agencies in the United States and worldwide; and the increasing problem of radiation exposure of test personnel in nuclear plants.

The scarcity in the general labor force of qualified, trained and experienced personnel whose standards or certifications can be compared among inspection agencies is a major problem. Each inspection agency trains its own personnel, because it is practically impossible to obtain personnel with the necessary training and experience to be immediately used in performance of inservice inspection unless they are hired from another inservice inspection agency. The unique requirements of materials, component geometry and standards of inspection require that personnel require extensive training before they perform independent tests. Owing to economic necessity, the training program of each inspection agency must be adequate to maintain the labor force required. The principal problem arises during peak reactor outage periods or is due to a generic problem that requires inspection of a large number of systems in a short period of time.

Nondestructive Testing Personnel Certification

Pressure Vessels and Piping

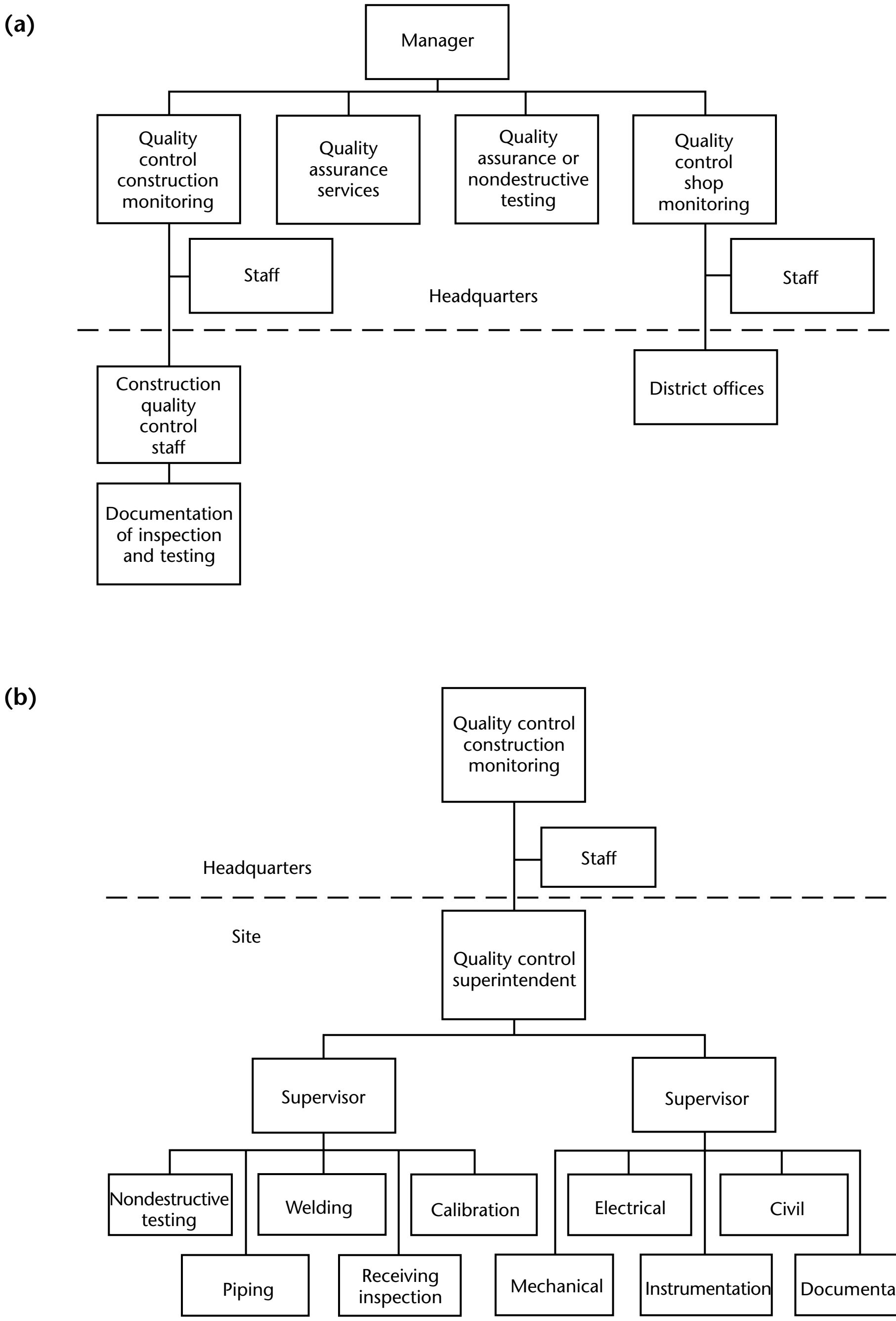
Power plants, contractors and agencies concerned with the qualification and certification of nondestructive testing personnel must begin by referring to the standards that govern the operation of their facilities. In the United States and many other nations, the standard is the *ASME Boiler and Pressure Vessel Code,* published by the American Society of Mechanical Engineers.[1]

Fossil power plants must be concerned with vessels and connections for fuel. The American Petroleum Institute publishes ANSI/API 510 (for pressure vessels) and API 570 (for piping) for organizations that employ or have access to technically qualified engineering and inspection personnel.[3,4]

ASNT Recommended Practice No. SNT-TC-1A

Personnel certification and standards of certification of nondestructive testing personnel are described by the American Society for Nondestructive Testing (ASNT) in its *ASNT Recommended Practice No. SNT-TC-1A: Personnel Qualification and Certification in Nondestructive Testing.*[5] This

FIGURE 7. Typical quality assurance department of nuclear power system: (a) organizational chart; (b) personnel structure.



document has been adopted by the American Society of Mechanical Engineers for use in sections of the *ASME Boiler and Pressure Vessel Code*.[1]

ASNT NDT Level III

The competence of Level III personnel before 1977 had tended to vary widely between different inspection agencies. Because the Level III personnel prepare the tests and provide training for working technicians at Levels I and II, the qualifications of these test operators also tended to vary widely. However, in 1977, the American Society for Nondestructive Testing established the ASNT NDT Level III examination service for Level III nondestructive testing personnel. If stipulated by the producer and consumer, the ASNT NDT Level III examination can be used to show compliance with the basic and method parts of the Level III recommended practices. Specific Level III examination areas are devoted to each of several basic nondestructive testing methods.

ANSI/ASNT CP-189

ANSI/ASNT CP-189, *ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel,*[6] provides minimum requirements for certification that are more stringent than the recommendations of *ASNT Recommended Practice No SNT-TC-1A*. CP-189 requires central certification plus employer certification of Level III personnel and employer certification of Levels I and II. In the United States, *central certification* entails personnel examination through the ASNT NDT Level III program. CP-189 is little used by electric utilities, however, because its requirements are redundant with other applicable standards and programs, such as the ACCP, described below.

International Standards

ISO 9712, *Non-Destructive Testing — Qualification and Certification of Personnel,*[7] is used in many nations and in different parts of the world. Developed by the International Organization for Standardization, the standard requires central certification of nondestructive testing personnel. A similar document for Europe is EN 473, *Qualification and Certification of NDT Personnel — General Principles*.[8]

ISO 9712 and EN 473 stipulate central certification without providing it. Just as individuals cannot be certified to SNT-TC-1A but rather only to an employer based *written practice* as recommended by *ASNT Recommended Practice No. SNT-TC-1A,* so too individuals may only be certified to a document based on ISO 9712 and not to ISO 9712 itself.

ACCP

The present ISO 9712 document stipulates that the organization that represents a country in the International Organization for Standardization (ISO), which organization for the United States is the American National Standards Institute (ANSI), is supposed to recognize the *national certifying body* (NCB) for central certification of nondestructive testing personnel; however, the American National Standards Institute has not had any mechanism to recognize a national certifying body, so no ISO 9712 compliant program existed for industry recognition in the United States in the early 1990s.

Accordingly, the American Society for Nondestructive Testing chose to develop and implement a central certification program that has not only provided for compliance but in many ways has exceeded the minimum requirements of ISO 9712 while addressing inspection personnel performance.

The American Society for Nondestructive Testing Central Certification Program (ACCP) was developed because there was a need in the United States for independent, third party qualification and certification of nondestructive testing personnel. The recognition of this need evolved gradually. The American Society for Nondestructive Testing had been developing parallel portions of such a program since 1988, including centralized qualification and certification for nondestructive testing Level II personnel and a program for NDT Level III personnel that was more comprehensive than the ASNT NDT Level III program of the mid-1990s.

The choice between an employer based certification or an ACCP certification is a function of the relationship between employees, employers, and customers. These certification alternatives are only meaningful in the context of the choice resulting from the particular needs and expectations of the employee, employer and customer. The employer and customer have expectations and need to determine the program of nondestructive testing personnel qualification and certification that is best for them.

Rationally, no single product, service, or program can best meet the expectations and needs for all. For this reason, the American Society for Nondestructive Testing offers SNT-TC-1A, ANSI/ASNT CP-189 and the ACCP.

References

1. *ASME Boiler and Pressure Vessel Code.* New York, NY: American Society of Mechanical Engineers (1998).
2. ASTM E 165, *Standard Test Method for Liquid Penetrant Examination.* West Conshohocken, PA: American Society for Testing and Materials (1995).
3. ANSI/API 510, *Pressure Vessel Inspection Code: Maintenance Inspection, Rating, Repair, and Alteration,* eighth edition. Washington, DC: American Petroleum Institute (June 1997).
4. API 570, *Piping Inspection Code: Inspection, Repair, Alteration, and Rerating of In-Service Piping Systems,* second edition. Washington, DC: American Petroleum Institute (October 1998).
5. *ASNT Recommended Practice No. SNT-TC-1A.* Columbus, OH: American Society for Nondestructive Testing.
6. ANSI/ASNT CP-189, *Standard for Qualification and Certification of Nondestructive Testing Personnel.* Columbus, OH: American Society for Nondestructive Testing.
7. ISO 9712, *Nondestructive Testing — Qualification and Certification of Personnel.* Geneva, Switzerland: International Organization for Standardization.
8. EN 473, *Qualification and Certification of NDT Personnel — General Principles.* Brussels, Belgium: European Committee for Standardization.
9. *ASNT Central Certification Program (ACCP),* Revision 2. Columbus, OH: American Society for Nondestructive Testing (September 1998).

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CHAPTER

Aerospace Applications of Liquid Penetrant Testing

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PART 1. Liquid Penetrant Testing Process Specifications in Aerospace Manufacturing

Aerospace Industry Requirements for Liquid Penetrant Process Specifications

To establish a liquid penetrant testing procedure, a number of engineering requirements must be generated. Among these are (1) requirements and procedures for application of the liquid penetrant method, (2) product acceptance classes and (3) requirements and procedures for the qualification and control of the equipment and personnel. Once the engineering requirements are decided on, a way is needed to implement those requirements and to ensure their proper application both in prime manufacturer's facilities in house and at subcontractor facilities. The common means of implementing liquid penetrant testing in the aerospace industry is the process specification.

Arrangement of Liquid Penetrant Process Specification

An aerospace liquid penetrant process specification is typically divided into several sections. A section might list all documents and related process specifications applicable to the liquid penetrant testing specification. Such listed documents should include related military specifications, consensus standards and other company process specifications (such as cleaning process specifications). Other sections of the liquid penetrant process specification might describe the materials used in the liquid penetrant testing process. Requirements for the various steps in performing the liquid penetrant test include cleaning the parts before liquid penetrant testing, the liquid penetrant dwell time and the conditions under which the part must be inspected.

Example of Materials Information in Aerospace Process Specification

A typical aerospace industry process specification for liquid penetrant testing would contain a section providing information on the expendable test materials and families of materials, together with the controlling specifications. The specifications would be accompanied by a statement of requirements for materials used in liquid penetrant testing, such as the following excerpt.

Materials. All materials used for liquid penetrant testing shall conform to and be qualified per SAE AMS 2644 and appear on its qualified products list except as noted in the table.[1]

Example of Equipment Information in Aerospace Process Specification

Test equipment such as that necessary for applying the liquid penetrant materials and for drying the parts to be inspected may be described in an equipment section of an aerospace industry process specification. An excerpt from an equipment section is as follows.

Drying Equipment. The drying equipment for drying after cleaning shall consist of heated dryers with temperature controls to maintain dryer operating temperatures. The drying equipment for drying after removal of excess liquid penetrant shall consist of circulating hot air ovens with temperature controls to maintain dryer operating temperature or hot air blast heaters with controls such that the hot air temperature at the part surface does not exceed the maximum allowed.

Process Control Information in Aerospace Process Specification

A process control section might detail the requirements for periodically checking the liquid penetrant materials and the equipment used during inspection.

The following properties are commonly checked or calibrated periodically: (1) water content of the liquid penetrant (water washable liquid penetrant); (2) liquid penetrant sensitivity; (3) liquid penetrant fluorescent brightness; (4) liquid penetrant removability; (5) emulsifier concentration (hydrophilic); (6) water content of lipophilic emulsifier; (7) emulsifier removability; (8) water and air pressure gages; (9) temperature gages; (10) white light and ultraviolet radiation meters; (11) ambient white light in the inspection booth; and (12) radiation intensity of ultraviolet lamps.

The following items are commonly checked daily: (1) system performance; (2) contamination of liquid penetrant; (3) contamination of developer (aqueous — soluble and suspendable); (4) developer condition (dry powder); (5) pressure and temperature gages; (6) ultraviolet radiation intensity; (7) ultraviolet filters on white light inspection lamps; and (8) cleanliness of inspection areas.

Example of Process Control Specification for Water Content of Liquid Penetrant Process Materials

An example of an aerospace manufacturer's process control specification covering water content control of water washable liquid penetrants or lipophilic emulsifiers used in dip tanks is given below.

Water Content. When tanks are used for applying water washable liquid penetrant or when lipophilic emulsifier is used, the water content of any of the materials that have any water solubility shall be checked at minimum intervals of 30 days. Water content tests shall be performed according to ASTM D 95.[2] Test results shall be recorded.

Examples of Process Control Specification for Developers

The following excerpt is an example of an aerospace manufacturer's process specification for control of developers used in liquid penetrant testing.

Developer Characteristics. The specific gravity of aqueous wet developer shall be checked initially and at least weekly with an accurate hydrometer. The specific gravity recommended by the supplier shall be maintained. Both wet and dry developers shall be checked for fluorescence daily with an ultraviolet lamp. Any developer fluorescence is unacceptable and requires replacement with fresh developer. Before use, aqueous developers shall be checked for discoloration or agglomerated solids, scum on the surface or inability to completely wet the surface being inspected. Any of the foregoing shall be cause for rejection and subsequent replacement. Test results shall be recorded.

Example of Process Control Specification on Selection of Liquid Penetrant Materials

The requirements related to the choice of liquid penetrant testing materials should be clearly detailed in the liquid penetrant testing process specification or in a quality assurance document or on an engineering drawing. A different liquid penetrant type might be required depending on the application. For example, a low sensitivity liquid penetrant might be acceptable for use on a raw forging whereas an ultrahigh sensitivity (SAE AMS 2644[1] Level 4) liquid penetrant might be required for a major rotating component. Or a particular developer type might be required for inspection of certain components. A sample of requirements for liquid penetrant materials is quoted in the paragraphs below.

Liquid Penetrant Materials. Liquid penetrant testing shall be performed with high sensitivity, water washable fluorescent liquid penetrant (SAE AMS 2644[1] Level 3, Method A, Type 1) or medium sensitivity postemulsifiable fluorescent liquid penetrant (SAE AMS 2644[1] Level 2, Method B, Type 1) unless indicated otherwise by drawing note.

Developer. A nonaqueous wet developer shall be used when it is specified on the applicable engineering drawing, process specification, material specification or purchase orders.

Example of Aerospace Specification Requirement for Personnel Qualification

Liquid penetrant testing, in most cases, depends on human judgment for interpretation of results. In certain instances, where large numbers of simple symmetrically shaped parts are to be inspected, the parts can be accepted or rejected by automated means. But by and large, the inspections are conducted and the results interpreted by people. Therefore, the skill competence and knowledge of the person performing the inspection are highly important.

An important specification requirement, then, for an aerospace liquid penetrant testing performed either in house or by outside subcontractors is that of personnel qualification. Such a requirement is as follows.

Personnel Qualification. Personnel performing nondestructive tests described herein shall be qualified in accordance with *ASNT Recommended Practice No.*

SNT-TC-1A[4] and NAS 410.[5] The practical portion of the qualification shall emphasize applicable procedures on components representative of the products to be inspected. Personnel who read and interpret indications for this testing process shall be qualified to Level II of *ASNT Recommended Practice No. SNT-TC-1A*.[4]

As cited above, one method of personnel qualification used in the aerospace industry is based on *ASNT Recommended Practice No. SNT-TC-1A*. SNT-TC-1A was compiled by the American Society for Nondestructive Testing and is recognized in the aerospace industry as a recommended practice for qualification and certification of nondestructive test personnel. An individual is required to obtain necessary classroom training, on-the-job experience and passing grades in selected specific and general inspections for qualification. In addition to vision acuity and color perception, it may be required that all qualified personnel meet or exceed the requirements of AIA NAS 410.[5] The liquid penetrant process specification also may require that the records of certification for personnel conducting the liquid penetrant testing be available at the inspection facility.

Written Procedures Required by Aerospace Specifications

A subcontractor working to an aerospace prime contractor's specification must make decisions on how the particular liquid penetrant testing is to be carried out. The liquid penetrant process specification provides the basic information on how to conduct the liquid penetrant test but it is the responsibility of the subcontractor to decide, based on the general specification requirements, what are the detail requirements of the particular test. The specific liquid penetrant procedure will be affected by such factors as (1) the material from which the part is fabricated, (2) the stage in the fabrication process in which the test is performed and (3) the liquid penetrant system normally used by the subcontractor. To more effectively control the liquid penetrant testing system used by a subcontractor, some aerospace companies require, in their liquid penetrant process specification, that the subcontractor submit a written procedure for approval. If the procedure is judged acceptable by the prime contractor, the subcontractor is given permission to inspect parts to that procedure.

Example of Written Procedure from Aerospace Subcontractors

An example of the written procedure requirement that might be included in a liquid penetrant testing process specification is as follows.

Procedure Requirement. A detailed written procedure shall be prepared by the inspection group for the liquid penetrant testing performed on parts and materials under this specification. Before performing any inspections according to this specification, unless otherwise specified, this procedure and revision shall be approved by quality assurance qualified/certified personnel. The written procedure shall contain the date, a procedure identification number and the latest revision or process bulletin to which the procedure applies. The written procedure shall comply with the general requirements contained in this process specification and shall include at least the following information:

1. brand names and specific types (number or letter designation if available) of test materials used in liquid penetrant testing system;
2. details of the technique of preinspection cleaning and drying, including cleaning materials used and time allowed for drying;
3. details of the technique of liquid penetrant application, the length of time that the liquid penetrant remains on the surface and the temperature of the surface and liquid penetrant during the inspection;
4. details of the technique of removing excess liquid penetrant from the surface and of drying the surface before applying the developer. For water spray rinsing, indicate the water pressure, air pressure and water temperature;
5. details of the technique of applying the developer and length of developing time before inspection (for aqueous wet developer, indicate drying temperature to be used);
6. details of inspection procedure including maximum white light intensity in the inspection booth, ultraviolet light intensity used, dark adaptation time and the acceptance requirement or standard to be used;
7. technique of postinspection cleaning;
8. statement to the effect that this procedure complies with all manufacturer's specification requirements that are not specifically mentioned in this procedure.

Reapproval is required (1) when any previous processing that may affect the liquid testing is changed (included here are processes that may close the surface openings of discontinuities or leave interfering deposits); (2) when a change or substitution is made in the type of cleaning materials or methods; or (3) when a change or substitution is made in the type of liquid penetrant materials (including developer etc.) or in the processing technique.

Aerospace Process Specification for Cleaning of Parts before Testing

Having made provisions for the choice of liquid penetrant materials and personnel qualification, the process specification should control each step in the inspection as it is to be performed by the test personnel. First, the parts must be properly cleaned to remove all grease, oil or other contaminants that could prevent entrance of the liquid penetrant into existing discontinuities. The exact cleaning procedure to be used can be specified or, if the cleaning procedures are detailed in other process specifications, they might be referenced instead. The following is an example of the latter.

Cleaning. Clean all parts to be liquid penetrant inspected in accordance with applicable process specifications. Cleaning methods, including etching, selected for a particular component shall be consistent with the contaminants to be removed and shall not be detrimental to the component or its intended function.

Example of Aerospace Process Specifications for Liquid Penetrant Application

After the parts have been properly prepared for inspection, they are ready for the application of the liquid penetrant. The manner in which the liquid penetrant is applied to the parts and the length of time that the liquid penetrant is to remain in contact with the parts (dwell time) are generally controlled by the process specification. The minimum and maximum liquid penetrant dwell time is usually based on consensus standards or manufacturer's specification requirements. An example of a process specification callout for liquid penetrant application is shown below.

Application of Liquid Penetrant. Unless otherwise specified, the entire surface of the part shall be covered with liquid penetrant. Liquid penetrant shall be applied by spraying, dipping, brushing or other technique to provide coverage as required. The part and liquid penetrant shall both be in the range from 4 to 49 °C (40 to 120 °F) for fluorescent (Type 1) liquid penetrants unless otherwise specified. The liquid penetrant dwell time, unless otherwise specified, shall be a minimum of 10 min. Rotate or otherwise move components, if required, during dwell time to prevent pooling of the liquid penetrant in holes and pockets. For dwell times greater than 2 h, the liquid penetrant shall be reapplied to prevent drying. If the dip (immersion) application technique is used, the component shall be immersed for no longer than half the total dwell time.

Example of Aerospace Process Specification for Removal of Excess Liquid Penetrant

After the liquid penetrant has been on the part for the required dwell time, the excess liquid penetrant must be removed. Both water washable and postemulsifiable fluorescent liquid penetrants are widely used in the aerospace industry and, of course, the removal requirements depend on the type of system used. Typical requirements for removal of water washable liquid penetrant are as follows.[3]

Method A Process. Water washable liquid penetrants shall be removed with a manual water spray, automated water spray, a manual wipe or an air agitated immersion wash.

Manual Spray. Water pressure adequate to remove the liquid penetrant shall be used but shall not exceed 275 kPa (40 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$). Water temperature shall be between 10 to 38 °C (50 to 100 °F). When hydro air nozzles are used the air pressure shall not exceed 172 kPa (25 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$). A coarse spray shall be used with a minimum distance of 300 mm (12 in.), when possible between the spray nozzle and the part. Washing shall be conducted under appropriate illumination. Caution shall be exercised to ensure that overwashing does not occur. Overwashed components shall be thoroughly dried and reprocessed. After rinsing, drain water from the component and use repositioning, suction, blotting with clean absorbent materials or filtered shop air at less than 172 kPa (25 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) to prevent pooling in cavities, recesses and pockets.

Caution. Overremoval of the surface liquid penetrant shall require that the component be cleaned and reprocessed. A good indicator of overwash or overremoval of the surface liquid penetrant is evidenced by the total lack of residue that may occur on all or a specific area of the part (see ASTM E 165[6]).

Automated Spray. For automated spray systems, the wash parameters shall be such that the requirements of this practice are met. Water temperature shall be maintained at 10 to 38 °C (50 to 100 °F).

Manual Wipe. Excess liquid penetrant shall be removed with a clean, dry, lintfree cloth or absorbent toweling. The remainder of the surface liquid penetrant shall then be removed with a water dampened cloth or towel. The surface shall not be flushed with water and the cloth or towel shall not be saturated with water. The component shall be inspected under appropriate illumination to ensure adequate removal of the surface liquid penetrant. The surface shall be dried by blotting with a clean, dry towel or cloth or by evaporation.

Immersion. Immersion wash may be used if the water is air agitated and good circulation is maintained throughout the wash operation. Water temperature shall be maintained at 10 to 38 °C (50 to 100 °F).

As can be seen, restrictions are put on the rinse water pressure and temperature because, if these are too high, overwashing can occur. The temperature of the drying air is controlled because, if the temperature is too high, the fluorescence of the liquid penetrant can be adversely affected.

Example of Aerospace Process Specification for Drying

After the removal of excess liquid penetrant, the part is ready to be dried unless an aqueous developer is to be used. A sample specification requirement for drying parts is as follows.

Drying. The parts shall be dried before application of dry developer, before nonaqueous developer or before inspection without developer. The parts should be drained of excess water but not dried before application of aqueous developers. Parts shall be air dried at room temperature or in a drying oven. Oven temperatures shall not exceed 70 °C (160 °F). Drying time shall only be that necessary to dry the part. Be sure parts are not put in the oven with pooled water, pooled aqueous solutions or pooled aqueous suspensions.

Example of Aerospace Process Specification for Application of Developer

After washing and drying, the parts are ready for developer application, if required. A specification callout controlling the application of nonaqueous wet developer is as follows.[3]

Developing. Unless otherwise specified, developers shall be used for liquid testing. Fluorescent (Type 1) liquid penetrants qualified to SAE AMS 2644[1] may be used without developer under either one of the following conditions: manufacturing inspection of castings (except machined surfaces) classified by MIL-STD-2175[7] as Class 3 or 4, or with the express approval of the contracting agency. Minimum and maximum liquid penetrant bleedout times without developer shall be 10 min and 2 h respectively. In all cases, components that are not inspected before the maximum bleedout time shall be cleaned and reprocessed.

Dry Developers. Components shall be dry before the developer is applied. Dry developer shall be applied in such a manner as to contact all surfaces to be inspected. Excess dry developer may be removed after the development time by light tapping or light air blowoff with air pressure not exceeding 35 Pa (5 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$). Minimum and maximum developer dwell times shall be 10 min and 4 h respectively. Dry developers shall not be used with Type 2 liquid penetrants.

Nonaqueous Developers. Components or areas requiring inspection shall be dry before application of the developer. Nonaqueous developer shall be applied by spraying. For fluorescent (Type 1) liquid penetrants, the developer shall be applied as a uniform thin coating over the entire surface to be inspected. For visible dye (Type 2) liquid penetrants, the developer shall be applied over the entire surface to form a uniform, white coating to provide suitable color contrast for the liquid penetrant indications. The uniformity and thickness of the developer coating is important for both types of liquid penetrant systems. If the developer coating is too thick for fluorescent (Type 1) systems such that the metallic surface is completely masked, the component shall be cleaned and reprocessed. Unless otherwise specified, the minimum and maximum development times for nonaqueous developers are 10 and 60 min respectively. For nonaqueous suspendable developer, the developer container shall be frequently agitated during application.

Aqueous Developer. Aqueous soluble developers shall not be used with visible dye (Type 2) liquid penetrants or fluorescent (Type 1), Method A liquid penetrants. Aqueous suspendable developers can be used with both fluorescent (Type 1) and visible dye (Type 2) liquid penetrants. Aqueous developers may be applied to the component after rinsing. Developers shall be applied by spray, flowing or immersion. The applied developer shall not be allowed to puddle and shall completely cover all surfaces to be inspected. Components shall be air dried or oven dried. Minimum and maximum development times, after the part is dry, are 10 min and 2 h respectively. Aqueous suspendable developers must be either constantly agitated to keep the particles from settling out of suspension or they must be thoroughly agitated before use to ensure that particles are in suspension.

Example of Aerospace Process Specification for Inspection of Liquid Penetrant Indications

After the required development time, the parts are ready for inspection. As previously mentioned, fluorescent liquid penetrant systems are widely used in the aerospace industry and special circumstances are required for proper inspection when using these liquid penetrants. The darkness of the inspection booth and the intensity of the ultraviolet radiation are two important parameters for inspecting with fluorescent liquid penetrants. A specification callout for inspection of parts is cited below:

Inspection. Inspect parts or material after the required developer dwell time. When ultraviolet radiation is used during inspection, allow the bulb to warm up for a minimum of 5 min before its use in inspection. Allow a minimum of 1 min for dark adaptation of the eyes when inspecting with fluorescent liquid penetrant.

Inspect in a darkened booth where the ambient white light intensity is less than 20 lx (2 ftc). During testing with fluorescent liquid penetrants, position the ultraviolet lamp at a distance from the test part surface such that the ultraviolet radiation intensity is a minimum of 10 $W \cdot m^{-2}$ (1000 $\mu W \cdot cm^{-2}$) at the test part surface. Measure the ultraviolet radiation intensity of the lamp with a calibrated ultraviolet radiation meter.

Example of Aerospace Liquid Penetrant Testing of Parts — Acceptance Criteria

For the parts to be properly dispositioned after testing (accept, reject or rework), acceptance criteria must be defined. The chosen acceptance criteria are usually established by structural and design engineering personnel. All types of liquid penetrant indications should be included in the acceptance criteria. An example of acceptance criteria is cited below.

Acceptance Criteria

Penetrant indications shall be dispositioned according to the following acceptance criteria.

Linear Indications. Linear indications are unacceptable. Linear indications are those indications in which the length is more than three times the width. All linear indications shall be marked on the part.

Rounded Indications. Acceptance classes in applicable standards and specifications govern the acceptability of rounded liquid penetrant indications.

1. The maximum permissible numbers of rounded indications noted earlier relate to those contained in any surface area of 40 cm^2 (6 $in.^2$) with the major dimension of this area not to exceed 150 mm (6 in.) and with the area located to contain the maximum number of indications being evaluated.
2. Each indication must be separated from another indication by a distance of at least four times the diameter of the largest adjacent indication (edge to edge) except as noted elsewhere in this specification document.
3. Linearly disposed indications are acceptable except when there are four or more such rounded indications linearly disposed and each is separated from the adjacent indication by less than four times the diameter of the largest adjacent indication (edge to edge).
4. Reject all parts containing rounded indications in excess of those permitted by the applicable acceptance standard.
5. If the indications will be removed in subsequent machining or are removable within engineering dimensional requirements, accept the indications.

PART 2. Liquid Penetrant Performance without Developer[8]

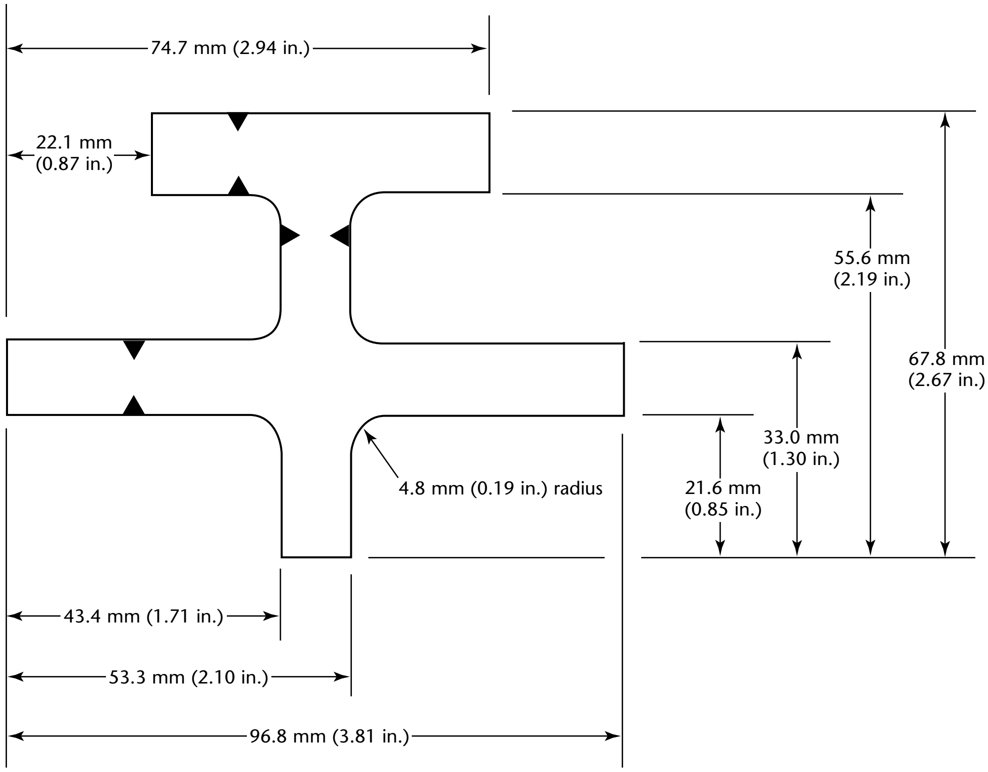
Background

Before development of the high sensitivity water washable liquid penetrants, postemulsified liquid penetrants were used for final testing of aerospace parts. As aircraft grew in size it became difficult to emulsify the large parts within the required dwell time, which affected the sensitivity of the liquid penetrant. To remedy this problem, Douglas Aircraft approached the liquid penetrant manufacturers for a solution. The answer was to reformulate the low sensitivity water washable liquid penetrants to perform at an equivalent sensitivity to the postemulsified liquid penetrants. The newly developed water washable liquid penetrants were capable of producing the equivalent sensitivity on aluminum parts without developer.

As the approach to classifying the sensitivity of fluorescent liquid penetrants for the United States Department of Defense changed to using the brightness of developer enhanced indications of small low cycle fatigue cracks as the metric, all water washable liquid penetrants then in use failed the sensitivity test without developer.

A study was initiated to evaluate the capability of currently qualified water washable liquid penetrants to detect manufacturing discontinuities in aluminum parts without developer (excluding fracture critical parts and parts that have been subjected to fatigue). Members of the Nondestructive Testing Committee of the Aerospace Industries Association of America (AIA) and the Materials Directorate of the Air Force Research Laboratory at Wright-Patterson Air Force Base participated in the round robin study.

FIGURE 1. Cross section of extrusion blank with typical groove locations.



Description of Test Specimens

Ten aluminum test specimens were selected for the liquid penetrant performance study. Two of the specimens were production parts with manufacturing discontinuities. The remaining eight specimens had been used as part of a nondestructive testing comparison sensitivity evaluation.[9] These eight specimens were made from 2024 aluminum extrusion blanks. To simulate cracks, vee grooves were machined in the blanks and electric discharged machined (EDM) notches of various lengths were fabricated in the bottom of the grooves. (See Fig. 1 for groove locations.) The extrusion blanks were then positioned in a tensile machine and the notches were compressed. Following compression, the blanks were milled to remove the grooves to establish a smoothly machined surface.

Photomicrographs of sections through two compressed notch discontinuities in the extruded aluminum specimens are shown in Fig. 2. One section was obtained with the groove retained and the other was made from a specimen with the groove machined away. These discontinuity widths are of the order of 5 µm (0.0002 in.) wide although the discontinuity opening at the surface of the specimen from which the groove has been machined away has a constriction that reduced the width to 2.5 µm (0.0001 in.) or less. This is perhaps evidence of a surface smearing tendency associated with machining of aluminum alloys and that sometimes leads to a requirement of an etch cleaning before liquid penetrant testing.

Figure 3 presents fractographs of the compressed electric discharge machined notches in the aluminum cruciform extrusion specimens revealing the contour of the electric discharge machined electrode having a 90 degree included angle and a 0.25 mm (0.010 in.) tip radius.

The notches were randomly located in the flanges of the extrusions and ranged in length from 2.5 to 10 mm (0.10 to 0.40 in.). A serial number was vibration etched on the end of each extrusion specimen and the flanges were marked for identification. This identifying system was used to document the discontinuities when photographing the liquid penetrant findings.

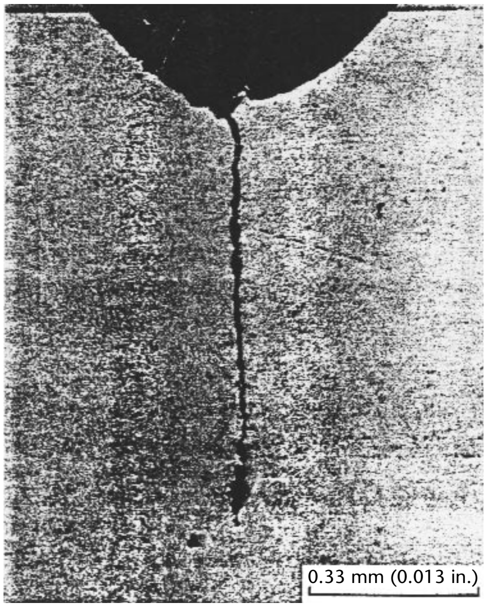
One forging and one joggle formed extrusion were representative of the two production parts. The manufacturing discontinuities were a forging lap and a 0.090 forming crack in the radius of the extrusion (see Fig. 4).

Liquid Penetrant Performance Test Procedure

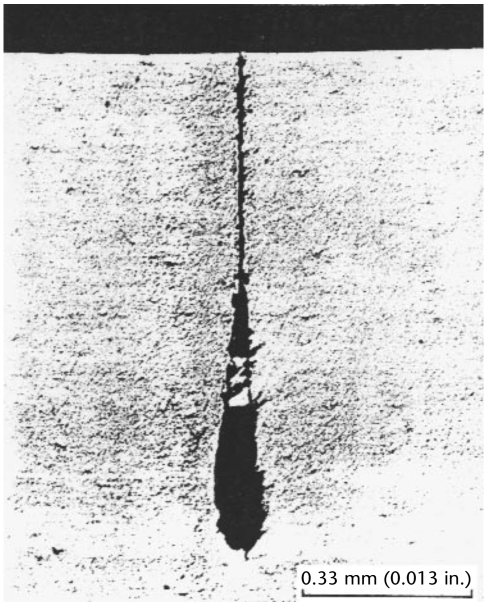
The test procedure was written in accordance with requirements equivalent to those in ASTM E 1417.[3] It was then reviewed and commented on by ten round robin participants.

Figure 2. Metallographic sections through two compressed notch discontinuities: (a) groove retained; (b) groove machined away.

(a)



(b)



Specimen Preparation

All of the test specimens were visually inspected with a 3× magnifying glass for minor surface imperfections that could cause false indications. Scratches and gouges were evident on the eight extrusion test specimens from previous testing. Corrosion was also evident on the extrusion test specimens, so after all of the imperfections had been blended, the eight specimens were cleaned in a triacid aluminum etch before the first liquid penetrant evaluation. The remaining two production parts were solvent cleaned. An evaluation test kit was assembled to protect the parts during shipping to the participants.

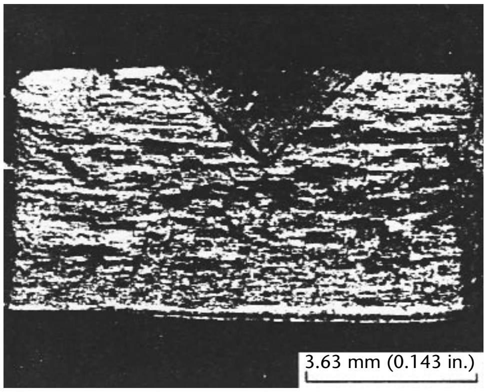
Liquid Penetrant Processing and Evaluation Procedure

The test was performed by personnel certified to either Level II or Level III in the test method and application. Each participant completed an equipment and process data sheet as part of the evaluation procedure. The following test procedure was used to evaluate the ten test specimens with and without developer.

1. **Precleaning.** Solvents shall be used to clean the parts before liquid penetrant testing. To facilitate the removal of liquid penetrant entrapped in discontinuities from previous tests, the specimens should be immersed in a solvent such as acetone, methyl-ethyl-ketone or trichloroethylene and ultrasonically cleaned for 20 to 30 min. Examine the parts under ultraviolet radiation before processing, to ensure that all residual liquid penetrant has been removed.
2. **Penetrant Application.** Immerse parts in a Type 1, Level 2 or 3 water washable liquid penetrant (Level 2

FIGURE 3. Two representative fractographs of compressed notch discontinuities in extruded aluminum specimens.

(a)



(b)

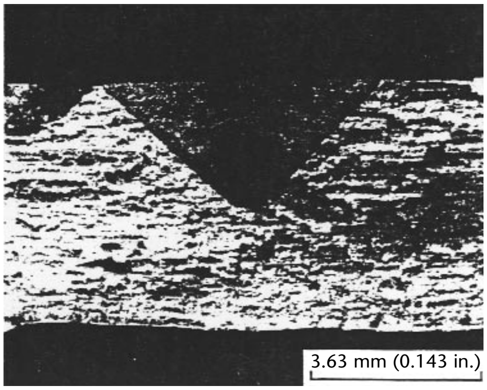
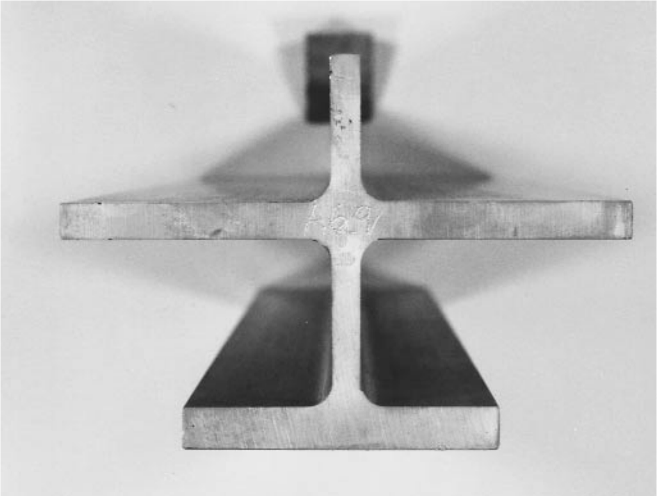


FIGURE 4. Test specimens: (a) specially made extrusion; (b) production parts.

(a)



(b)

preferred). Remove and let parts dwell for 10 min.

3. **Penetrant Removal.** Rinse parts using a coarse spray with a maximum 275 Pa (40 $lb_f \cdot in.^{-2}$) pressure and a temperature range of 10 to 38 °C (50 to 100 °F). Parts shall be observed under adequate ultraviolet radiation during rinsing. Caution shall be exercised to ensure overwashing does not occur. After rinsing, rotate parts to remove water from cavities and recesses to prevent pooling of water.
4. **Drying Parameters.** Place parts in a recirculating air oven. The temperature of the oven shall be a maximum of 70 °C (160 °F). Drying time shall not exceed 30 min.
5. **Inspection without Developer.** Allow parts to bleedout for 10 min and then examine parts under ultraviolet radiation with minimum intensity of 10 $W \cdot m^{-2}$ (1000 $\mu W \cdot cm^{-2}$) at the part surface. When a discontinuity is discovered it shall be photographed as prescribed in the photographic documentation procedure.
6. **Inspection with Developer.** Immediately following step 5, dust all part surfaces with dry developer (supplied with parts). Allow 5 min developing before reinspection. Photograph discontinuities as previously.
7. **Postcleaning and Preservation.** Remove the dry developer by wiping the surfaces with a clean dry cloth. The liquid penetrant shall remain in the discontinuities until the next liquid penetrant evaluation. This will inhibit corrosion of the discontinuity interfaces. Corrosion inhibiting oils shall be avoided to prevent contamination of the discontinuities and subsequent cleaning difficulties. Test parts shall be replaced in their protective packaging for shipping.

Photographic Documentation Procedure

The following equipment is used: 100 × 125 mm (4 × 5 in.) positive printing camera, back mounted camera or enlarger with stand; macro lens or enlarger lens (2× magnification); light yellow filter; maximum f-stop 16 aperture setting; exposure times (see Table 1); 100 × 125 mm (4.0 × 5.0 in.) instant, positive printing, black-and-white film; mercury vapor ultraviolet lamps and indirect white light; 150 mm (6.0 in.) scale graduated in tenths and hundredths; background material or manila folder paper or equivalent.

In a room darkened to about 30 lx (3 ftc) ambient light, position a 100 W ultraviolet lamp on each side of the test part at a 45 degree angle as shown in Fig. 5. The ultraviolet radiation intensity at the part surface should be about 30 $W \cdot m^{-2}$ (3000 $\mu W \cdot cm^{-2}$). Position and focus the camera to provide a 2× magnification. Use a 150 mm (6.0 in.) scale to aid in setting up the camera. Before the actual test parts are photographed, set up another part with a fluorescent indication to establish a correct exposure.

A white light exposure (see Table 1) shall be added to the ultraviolet radiation exposure to increase the definition of the part and separate it from the background. The white light should be 100 lx (10 ftc) at the part surface and positioned so that it does not illuminate the indication areas either directly or by highlight. Prepare as much of the photographic setup in advance as possible. This will enable the development cycle of the liquid penetrant

FIGURE 5. Setup for ultraviolet radiation photography.

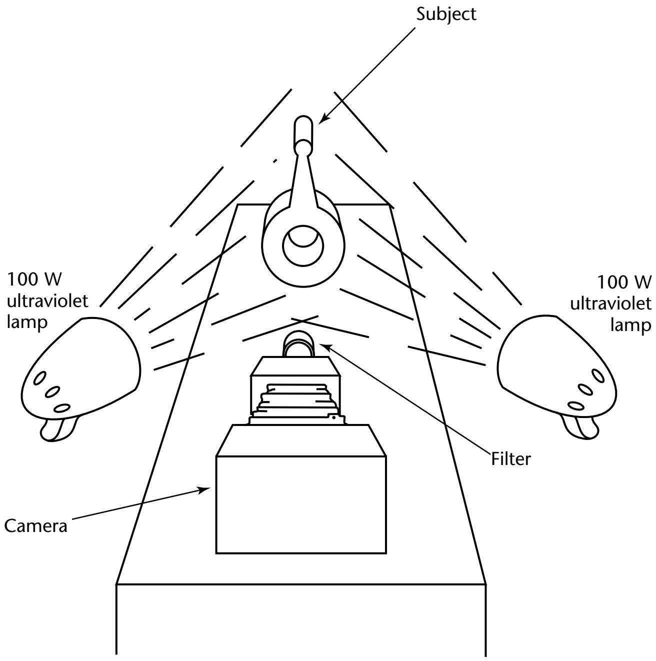


TABLE 1. Photographic exposure data (filter over lens during all exposures).

		Exposure Times	
Positive Print, Instant Film	Aperture Setting	Ultraviolet Radiation	White Light
ISO 400	f16	20 s	2 s
Type 53 ISO 800	f16	10 s	1 s

testing procedure to be consistent. All photographs shall include a 150 mm (6.0 in.) scale and identify with the serial number of the test part.

Test Results

The results of the liquid penetrant performance study are as follows.

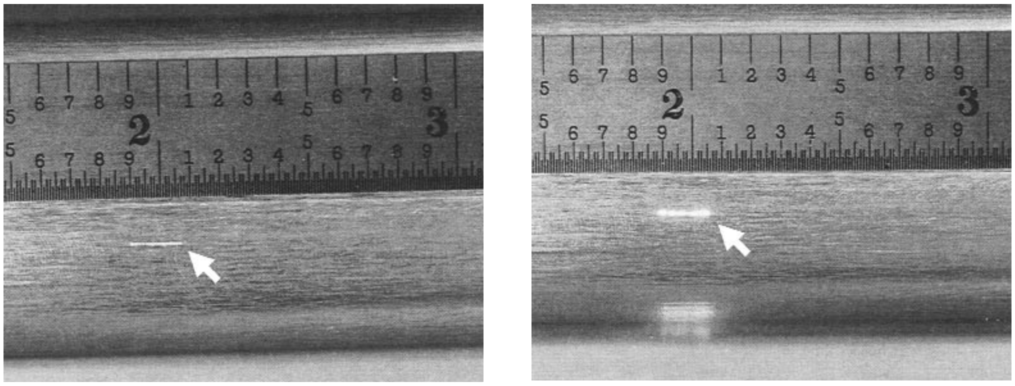
1. Ten different participating companies processed the ten aluminum test specimens using a Type 1, Level 2 or 3, water washable liquid penetrant with and without developer as a comparison of sensitivity.
2. All of the evaluations were processed in accordance with a consensus test procedure, which complied with ASTM E 1417.[3]

FIGURE 6. Ultraviolet radiation images of fatigue cracks in extruded aluminum specimens, without and with developer: (a) 4.6 mm (0.18 in.) long; (b) 2.3 mm (0.09 in.) long; (c) 2.5 mm (0.098 in.) long.

(a)

Without developer

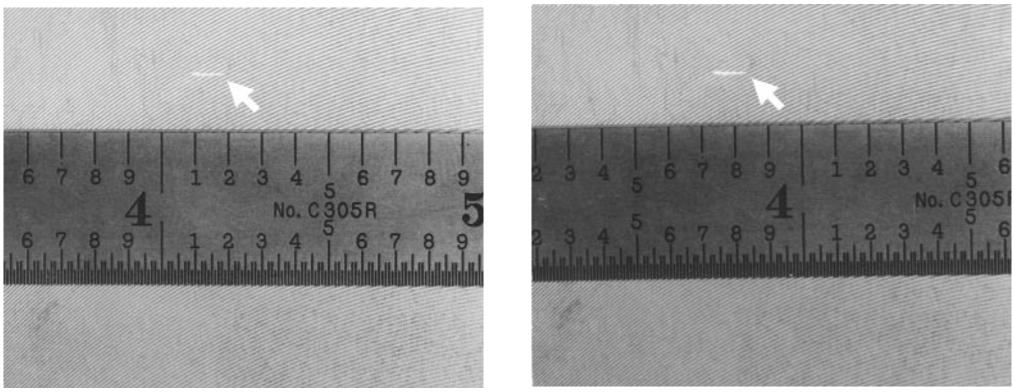
With developer



(b)

Without developer

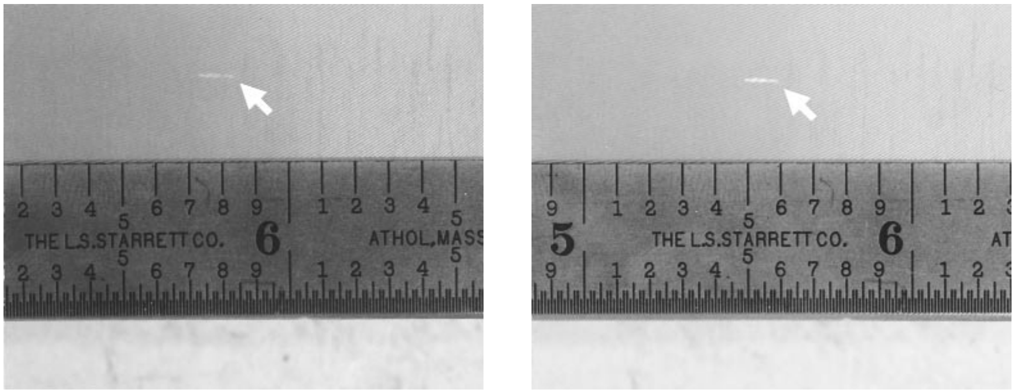
With developer



(c)

Without developer

With developer



3. Table 2 shows the test results of the 10 evaluations. There were 10 test parts with 22 discontinuities (representing manufacturing discontinuities), which equates to 220 possible finds. Of the 220 possible finds 216 were found and documented, resulting in a 98 percent efficiency.
4. In all cases, discontinuities detected with the application of dry developer were also detected without developer. For examples see Fig. 6.
5. On the basis of the test results, increased ultraviolet radiation intensity at the part surface of 30 W·m^{-2} (3000 $\mu\text{W·cm}^{-2}$) during inspection was recommended.
6. With proper approval, it might be appropriate to perform liquid penetrant testing to detect manufacturing discontinuities in non–fracture critical aluminum parts. Demonstration of the efficacy of such a test on specific parts is recommended.

TABLE 2. Liquid penetrant test results with and without developer. Discontinuity lengths were measured from undeveloped indications during first inspection.

Discontinuity Length, mm (in.)	Discontinuity Indication With and without Developer	Detected[a] only with Developer	Faint without Developer	False Negative[b]
2.54 (0.100)	9	0	0	1
3.30 (0.130)	10	0	0	0
3.56 (0.140)	8	0	1	1
3.81 (0.150)	10	0	0	0
3.81 (0.150)	9	0	1	0
4.06 (0.160)	10	0	0	0
4.06 (0.160)	10	0	0	0
4.32 (0.170)	9	0	1	0
4.32 (0.170)	10	0	0	0
4.32 (0.170)	10	0	0	0
4.57 (0.180)	10	0	0	0
5.08 (0.200)	9	0	0	1
5.08 (0.200)	10	0	0	0
5.59 (0.220)	10	0	0	0
5.59 (0.220)	10	0	0	0
5.84 (0.230)	10	0	0	0
6.10 (0.240)	5	0	4	1
6.35 (0.250)	10	0	0	0
7.62 (0.300)	10	0	0	0
10.16 (0.400)	10	0	0	0
uncertain	10	0	0	0
2.29 (0.090)	10	0	0	0

a. Discontinuity present and indication detected.
b. Discontinuity present but indication not detected.

Discussion

As previously mentioned in the report, the eight cruciform extrusions were etched before the first evaluation to remove corrosion and oxidation from the test surface, with all subsequent cleaning done with solvents. Even though the test specimens were protected between evaluations, the eight month period needed to complete the study became a factor with evidence of some degradation of the indications because of oxidation. This demonstrates the fact that proper cleaning before liquid penetrant testing is a key factor in detection of surface discontinuities.

To further compare the sensitivity of crack detectability using fluorescent water washable liquid penetrant with and without developer, two aluminum fatigue crack blocks were picked from another set of blocks. The test blocks were processed with the same test procedure except the liquid penetrant dwell time was increased to 15 min instead of 10 min. The liquid penetrant sensitivity was classified as Level 2.

Again the cracks were found with and without developer. Although the photographs in Fig. 6 do show an improvement in the appearance of the cracks after application of the developer, these cracks were seen when viewed under ultraviolet radiation intensity of 30 W·m^{-2} (3000 $\mu\text{W·cm}^{-2}$) at the test part surface. This test was conducted, not to promote liquid penetrant testing without developer on parts subjected to fatigue, but rather to evaluate the qualitative difference in fluorescent brilliance from fatigue cracks as compared with manufacturing discontinuities. The comparison proves that fatigue cracks, being tighter and usually having a smaller reservoir, will not trap as much liquid penetrant as a manufacturing discontinuity. Therefore developer is usually required to enhance the indication by drawing the entrapped liquid penetrant to the surface.

Disclaimer

The tests made in these studies are applicable to the narrowly defined cracks tested and in the materials tested. Nonuse of developer may require a waiver of specification requirements and may have to be supported by a test program on the actual parts to be tested.

PART 3. Applications of Liquid Penetrant Testing to Liquid Oxygen Systems

Reactivity and Hazards of Liquid Oxygen

Certain parts used in space vehicles, such as valves, pipelines, tanks and even structural members, may be in contact with liquid oxygen during normal use. Any residues of oxygen reactive materials that remain on the surfaces of such parts or in porosities or cracks or between faying surfaces are potential sources of trouble due to the vigorous reactions that can take place with liquid oxygen.

Liquid oxygen not only has an extremely high degree of chemical reactivity but, under conditions of impact, shock or vibration, exhibits this reactivity in the form of potentially catastrophic detonations. It therefore becomes an important consideration to ensure that any liquid penetrant process materials that are allowed to come into contact with liquid oxygen usage parts shall either be completely removed or else shall be compatible with liquid oxygen.

In the 1970s, liquid penetrant tests of liquid oxygen systems used chlorinated hydrocarbons as emulsifiers. Environmental regulations prevented use of such emulsifiers in the 1990s. Removal of liquid penetrant residue remains a challenge for liquid penetrant testing of oxygen systems.

Requirements for Liquid Oxygen Compatible Liquid Penetrant Testing

In brief, a liquid penetrant system for inspection of liquid oxygen system parts must be compatible with liquid oxygen. This must be combined with an appropriate level of discontinuity detection sensitivity. This means that the liquid penetrant system must have a properly designed capability for detecting surface discontinuities while being safe from the standpoint of liquid oxygen usage.

Two approaches to the design of liquid oxygen usage liquid penetrant materials are given here. One approach involves the design of liquid penetrant process materials, all elements of which are completely volatile, so that they dissipate from test parts by evaporation (see Fig. 7).

The second and preferred approach is to use a system that lends itself to complete removal of residues during postcleaning. Water soluble materials, especially those that can be thinned with water to nearly infinite dilution, are preferred where liquid oxygen compatibility is of concern. Not only do water soluble liquid penetrant materials dissolve in water base cleaning agents but, once dissolved, the contaminated cleaning agent itself can be flushed away with water.

Water Base Liquid Penetrants for Testing of Liquid Oxygen Related Apparatus

Because of ease of postcleaning, water base liquid penetrants, both visible and fluorescent, that use water instead of a hydrocarbon as the thinner have been accepted for inspection of liquid oxygen related apparatus. (Water base liquid penetrants, if their water content is sufficiently high, are found to be liquid oxygen insensitive when subjected to the impact test. However, as the water evaporates, such liquid penetrants lose their inherent liquid oxygen compatibility characteristics and residues would not be classified as liquid oxygen insensitive.) Success with water base liquid penetrants under liquid oxygen usage conditions is attributed to the ease of removal of residues, both on the surface and entrapped in discontinuities. This residue will be primarily a water soluble, surface active agent, detergent in itself, which facilitates postcleaning (the most critical step in the process when liquid oxygen usage is involved).

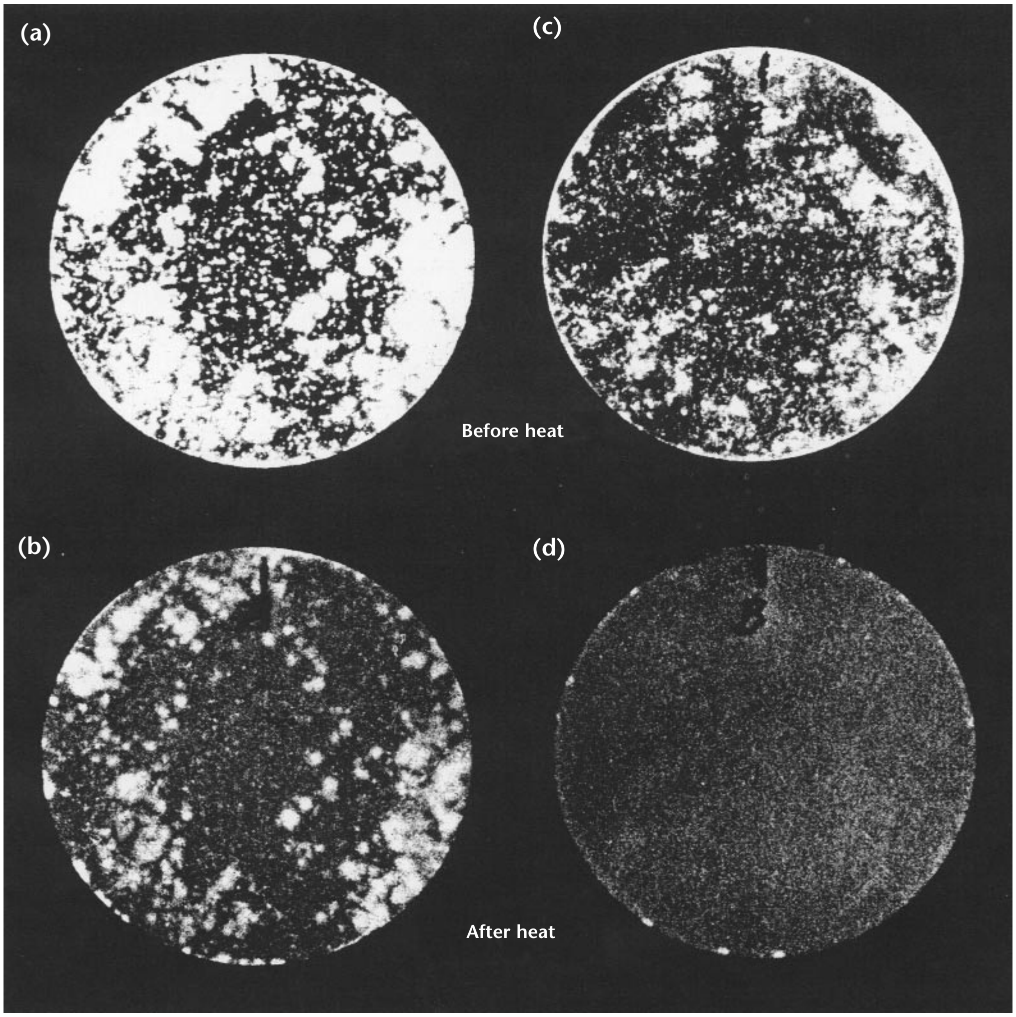
Self-Developing Water Base Fluorescent Liquid Penetrant for Liquid Oxygen Apparatus

Postcleaning is simplified if the water base liquid penetrant is of the self-developing fluorescent type. Because there is no remover (other than water) and no developer, the postcleaning operation involves only liquid penetrant residue and can be tailored for the single residue. Usually, the residue of the water soluble liquid penetrant dissolves more rapidly when the water base cleaner includes an additive such as a volatile glycol ether or light alcohol to lower the residue's viscosity.

Test to Determine Liquid Oxygen Nonreactive Characteristics

Agencies and contractors concerned with the manufacture of liquid oxygen equipment and apparatus usually require testing of each individual bath of liquid penetrant material (as well as greases, oils and various coating) for liquid oxygen compatibility. The test material is placed in a liquid oxygen environment and impacted by dropping a weight on it. A typical aerospace specification[10] calls for dropping a plummet weighing 9 kg (20 lb_m) through a distance of 1.0 m (40 in.) onto a striker pin that in turn impacts a cup containing the test substance. This will transmit an impact energy of about 90 J (70 ft-lb_f) to the test sample. The material is tested 20 times. Cause for rejection is (1) an audible explosion, (2) a visible flash in a darkened room, (3) discolorations and (4) charring or other evidence of burning.

FIGURE 7. Dissipation of volatile tracer with heat: (a) oil phase liquid penetrant, before heat; (b) oil phase liquid penetrant, after heat; (c) self-destruct liquid penetrant, before heat; (d) self-destruct liquid penetrant, after heat. After heating test blocks in oven for 15 min at 93 °C (200 °F), indications of oil phase liquid penetrant are blurred but still present, while indications of self-destruct liquid penetrant are completely dissipated.



Procedures Used to Avoid Liquid Oxygen Reactions with Liquid Penetrant Test Materials

There are two obvious ways to avoid liquid oxygen reactions.

1. Remove reactive and potentially reactive residues completely.
2. Use only those process materials that are chemically inert.

These two ways may be obvious but they are not exactly simple. For example, the process of solvent cleaning of residues from a surface may progress nicely as long as the residues are entirely on the surface. However, entrapments of residues in microscopic pinholes or porosities in the surface or even in regions where the surface is somewhat rough can be removed only through a mechanism of molecular diffusion. Removal of entrapments by molecular diffusion in the liquid phase can be very slow. The liquid viscosity is a controlling factor. If a process of gaseous diffusion is possible, where the entrapped residues are allowed to evaporate, then the removal process becomes relatively rapid. Evaporative removal of residues would, therefore, appear to be a desirable technique for cleaning liquid oxygen usage parts.

Selection of Materials for Volatile Liquid Penetrants

For a self-destruct or self-dissipating liquid penetrant system, it is desirable to select ingredients all of which are volatile to a sufficient degree that they will dissipate by evaporation within some reasonable time interval, either at room temperature or at some nominal elevated temperature. Of course, elevated temperatures may be impractical for large test objects and must be avoided if test objects are susceptible to heat damage. Many kinds of volatile liquids may thus be selected that will evaporate completely from test parts with in a few minutes or hours, as may be desired. Such volatile materials should be of sufficient purity as to contain negligible nonvolatiles and leave no residues.

Selection of Dye Indicators for Liquid Oxygen Usage Liquid Penetrants

In the course of devising a workable self-destruct inspection liquid penetrant system, a problem presents itself with regard to the selection of an indicator dye for the liquid penetrant. A dye indicator, usually a fluorescent dye, must be used to display the presence of surface discontinuities. Residues of the dye remaining after the liquid penetrant carrier evaporates will result in a liquid oxygen-reactive situation.

Dyestuffs of the coumarin class or chemical group are particularly advantageous with respect to their ability to apparently sublime at room temperature or up to temperatures in the range of 50 to 65 °C (120 to 150 °F). Other specially prepared nondye fluorescent compounds have been developed that are capable of yielding brilliant fluorescence and that will dissipate entirely from relatively deep surface cracks after about 24 h at room temperature. When the temperature of the test part is raised to about 90 °C (194 °F), the question to be answered must be, Will it redeposit in an area that will be subjected to liquid oxygen? Also, before acceptance of this theory, determination of 100 percent dissipation merely by disappearance of indication does not mean a residue free crack or surface. Application of heat will thin the liquid to a point where attenuation of thin film fluorescence is significant and, of course, application of heat can cause molecular change or chemical breakdown so that the substance is no longer fluorescent.

Selection of Removers and Developers for Liquid Oxygen Applications

In a volatile, self-destruct liquid penetrant system, the liquid penetrant is the critical component, because it is the only component that contains a dye. The other components, these being the solvent remover and developer, may be formulated using pure volatile liquids. With respect to the remover or surface cleaner component in a liquid penetrant system, it should be noted that conventional emulsifiers or high viscosity liquids are not liquid oxygen compatible because of their nonvolatile character. Low viscosity, volatile solvent removers, when used in the conventional manner, tend to strip liquid penetrant entrapments out of shallow surface discontinuities. Hence, if a high degree of discontinuity entrapment efficiency is wanted, it may be necessary to limit the contact time of the test part with the volatile solvent remover to an extremely short interval, such as a few seconds.

Spray Removers with Diluted Solvents

A technique has been developed for applying solvent remover liquids to test surfaces, whereby discontinuity entrapment efficiencies close to 100 percent may be achieved. This technique adapts the spray scrubber technique that has been successfully used with postemulsifiable liquid penetrants.

A volatile solvent material such as alcohol may be diluted with water to depress its solvent characteristics (its ability to dissolve the indicator dye or surface liquid penetrant). Under this condition of dilution, residues of dry dye on the surface of a test part may be washed away by the mechanical scrubbing impact of spray droplets of the diluted solvent. By virtue of the depressed solvent activity of the wash liquids, entrapments of the liquid penetrant down inside a crack in the test part will not become dissolved. This minimizes stripping out of liquid penetrant from discontinuity entrapments and permits development of brighter or finer liquid penetrant indications.

Volatile Developer for Liquid Oxygen Usage Applications

After wash removal of surface liquid penetrant, development of indications may be carried out by applying a fine spray of a suitable solvent liquid of medium volatility onto the test surface. The function of this liquid is twofold. First, it dissolves the dry dye within the discontinuity entrapments, then enhances the brightness of liquid penetrant indications by expanding the film thicknesses. Under proper conditions of use, intensely brilliant fluorescent indications of microdiscontinuities may be obtained. The ability of a liquid penetrant system to reveal the presence of surface discontinuities can be readily demonstrated with a ceramic test block. The ceramic test block has a porous surface that is glasslike and sufficiently transparent so that entrapments of dye or dyed liquid penetrant inside surface cracks can easily be seen (see Fig. 7).

After inspection is completed, the test part may be placed in an oven and warmed for an appropriate interval of time so as to dissipate all of the volatile residues. The liquid penetrant uses a special nonfluorescent indicator that yields bright bluish white fluorescent indications. After use, all residues will dissipate within about 24 h at room temperature. The dissipation of the dye residues from surface discontinuities can be readily demonstrated with the ceramic test block of Fig. 7.

Controlling Performance Level of Liquid Oxygen Compatible Liquid Penetrants

Dimensional sensitivity in a fluorescent liquid penetrant is defined as the threshold thickness of a film of liquid penetrant liquid below which the fluorescence response law that produces this extinction of fluorescence only applies in liquid solutions of fluorescent materials.

The operation of a self-destruct type of liquid oxygen usage liquid penetrant depends on the evaporation of the liquid carrier, leaving the fluorescent dye in a concentrated form. In this case, the performance level of the liquid penetrant is a function of the amount of indicator dye that accumulates in a crack and its visibility when properly drawn out of the discontinuity by a suitable developer liquid. It is possible to evaluate liquid penetrant performance by side-by-side comparison tests on cracked nickel-chrome panels or cracked aluminum blocks.

Characteristics of Liquid Oxygen Usage Dual Sensitivity Liquid Penetrant System

Liquid oxygen usage liquid penetrant must consist of ingredients that are essentially nonreactive with liquid oxygen. Inasmuch as all organic dyes are inherently reactive with liquid oxygen, the reactivity of a dye indicator in a liquid penetrant must be depressed or inhibited by means of some suitable nonreactive and nonvolatile ingredient that will retain the dye in solution. Furthermore, the dye or dyes must exhibit color and/or fluorescence, as the case may be, when dissolved in this nonreactive ingredient. Similar requirements are found for liquid oxygen usage developers for liquid penetrants.

The combination of conditions that must be met to provide a workable liquid oxygen usage liquid penetrant and developer system is quite difficult to satisfy.

PART 4. Fluorescent Liquid Penetrants with Depth Sensing Capabilities

Testing for Water Entry Potential

One of the most difficult procedures performed during maintenance of aircraft structures is the test for water entry and corrosion in structures containing honeycomb core (see Fig. 8). It is difficult to detect corrosion byproducts and it is particularly difficult to determine those discontinuities that permit water entry into the structure. X-radiography is often used to detect water present at the time of inspection or to detect separation of honeycomb nodal bonds as a result of corrosion. The technique outlined here is a simple modification of the fluorescent liquid penetrant technique to indicate which discontinuities — e.g., pores, cracks etc. — could permit water entry into a honeycomb structure. It also may be used to detect which discontinuities in a nonmetallic coating penetrate to a metallic substrate, for example, the penetration of paint or other protective coating on metal.

Liquid Penetrants That Detect Metals

A liquid penetrant capable of detecting depth can be formulated by adding a small amount of a chelating agent to a low surface tension carrier. Organic chelating agents possess a chemical affinity for metallic ions and are frequently used in chemical analysis to detect their presence. They accomplish this by binding to the metal ion to form a chemical complex that fluoresces in the visible spectrum under ultraviolet light. The fluorescence spectra of this complex shifts from the ultraviolet, of the original organic molecule, to longer wavelengths of the visible spectrum. Therefore, the liquid penetrant is colorless until it comes in contact with a metal at which time it fluoresces an easily detected color. This distinctive action allows this liquid penetrant to differentiate between discontinuities that penetrate to a metal substrate and those that do not. Chelating compounds can be quite specific in that they will bind with certain metal ions and not to others. These materials are often used in the qualitative and quantitative analyses of metals, including aluminum, bismuth, cadmium, copper, iron, magnesium, nickel, zinc etc.

Detection of Corrosion Initiations

To demonstrate this concept, small amounts, from 0.1 to 20 mg·g^{-1} (0.01 to

FIGURE 8. Schematic representation of typical aircraft structural component composed of aluminum honeycomb core and graphite epoxy skin.

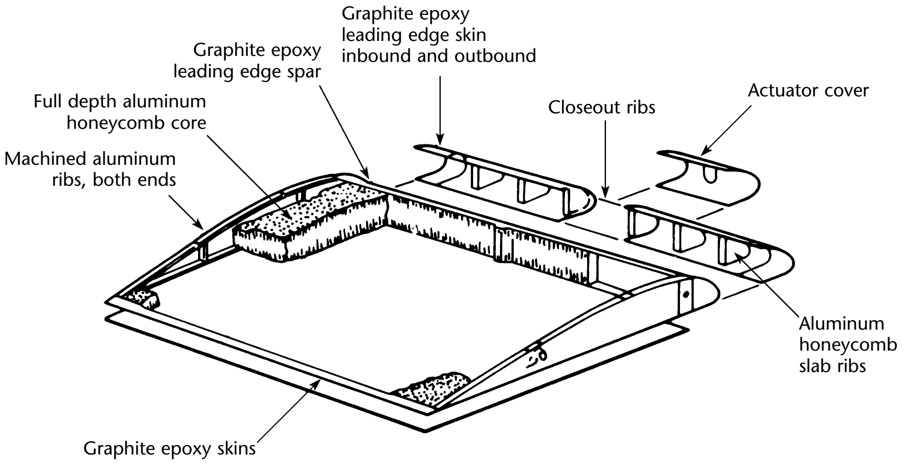


TABLE 3. Colors of fluorescent compounds after chelating with aluminum.

Compound	Fluorescence Color
2,2′-Dihydroxyazobenzene	yellow
8-Hydroxyquinoline	yellow
2,2′-Dihydroxy–1,1′-azonaphthalene, 4-sulfonic acid, sodium salt	red
2,2′-Dihydroxy–1,1′-naphthalene, azobenzene–5-sulfonic acid, sodium salt	orange
2,4,2′-Trihydroxyazobenzene–5′-sulfonic acid, sodium salt	yellow
Salicylidence–O–amino–phenol	green
2′,3,4′,5,7-Pentahydroxyflavone	blue
2-Hydroxy–3-naphthoic acid	blue

2.0 percent by weight), of the chelating agent 8-hydroxyquinoline were dissolved in isopropyl alcohol, which served as the carrier. Using standard liquid penetrant techniques, this solution was applied to the surface of an organic matrix composite aircraft component with an aluminum honeycomb core. Some cracks and indentations were quickly outlined by a fluorescent halo when the part was viewed under near ultraviolet light. Because the dry fluorescence of the chelate complex is frequently brighter than wet fluorescence, it is advisable to permit the solution to dry before an inspection is performed. A developer could also be applied to the component to absorb the chelated solution and thus enhance the indication. In this inspection those discontinuities that penetrated the composite skin to the aluminum honeycomb core were easily detected. While many surface discontinuities could be seen, only those that would have permitted water to penetrate to the aluminum core and thus cause corrosion were detected.

Advantages of Chelate Liquid Penetrant System

If chelating compounds specific to a particular metal are used, then different metals can be detected by the color of their fluorescence. In this way the depth of the discontinuity can often be determined. This liquid penetrant technique can also be used to detect through-thickness discontinuities in the corrosion protective coatings on metal holding tanks. Three important features of the chelating liquid penetrant system should be noted. First, the low surface tension isopropyl alcohol carrier appears to penetrate into very small cracks faster than water or oil base liquid penetrants. Second, this system is inexpensive because the raw materials cost little and its use requires only minor changes to existing liquid penetrant techniques. Third, this system avoids oil contamination that can make repair of a composite structure difficult.

Alternative Chelating Agents for Liquid Penetrant Systems

It is possible to use any one of many chelating agents to make a workable liquid penetrant system. A compound might, for example, be chosen because it detects a specific metal to the exclusion of others. Several chelating compounds are listed in Table 3 along with their fluorescence color after chelation with aluminum. It should be noted that some of these compounds may have toxic properties. Even those thought to be safe should be used with caution particularly when long exposures are involved.

PART 5. Low Viscosity Liquid Penetrant Testing of Braze Bond Open Face Honeycomb Seals

Liquid Penetrant Testing of Open Face Honeycomb Gas Turbine Seals

Various nondestructive testing techniques and methods have been developed to determine the braze quality of honeycomb structures for aerospace applications. Generally, honeycomb test methods are designed for inspecting honeycomb structures with two facing sheets. The following discussion applies to open face honeycomb ring seals in which the honeycomb is open at the inner diameter and brazed to a ring at the outer diameter. Seals of this type are in general use in hot gas turbines where the turbine blades cut a gastight seal in the open honeycomb face. Seals of this nature provide for a slight variation in dimensional tolerances and concentricity between mating components. A low viscosity liquid penetrant testing technique is described and compared with other nondestructive test methods such as radiographic, ultrasonic, thermographic and conventional liquid penetrant testing. A number of honeycomb seals were used to establish comparisons of the several nondestructive test methods for determining the braze quality of the honeycomb-to-ring bond; these methods are illustrated in Fig. 9 and 10.

Technique with Low Viscosity Liquids

Liquids with low specific gravity have been used for open face honeycomb inspection. In one investigation, trichlorotrifluoroethane (CCl_2FCClF_2) was chosen as the test solution for evaluation. The rings were placed in a clear trichlorotrifluoroethane solution, about 150 mm (6 in.) at a time, and allowed to dwell until air bubbles were out of the cells (see Fig. 9e). The ring was then removed from the solution and rotated about 30 degrees circumferentially. As the honeycomb drained for about 30 s, the area was inspected under visible white light for anomalous braze joints. If the cells were of good quality, a meniscus formed across the top of the cell. If the braze quality was poor, the level of the solution lowered, forming a shadow area within the cell. Figure 10e shows the darkened cells caused by poor quality braze joints. The trichlorotrifluoroethane vaporizes quickly and the parts do not need to be cleaned after inspection. Inspection was performed under a forced air vent hood to limit inspector exposure to the vapors.

Technique with Low Viscosity Fluorescent Tracer Additives

A mixture of 1 mL of supersensitive fluorescent liquid penetrant was added to 1200 mL of trichlorotrifluoroethane to enhance the contrast of the test results. The resultant solution then was used as shown in Fig. 9f. The part was inspected under an ultraviolet (360 nm) lamp. This technique clearly defined the disbonded and leaking cells in relation to bonded ones. Figure 10f does not illustrate the various colors that can be seen under the inspection lamp. The brazed cells are somewhat blue whereas the unbrazed cells are dark and are outlined by a greenish tint. The parts were ultrasonically cleaned after testing.

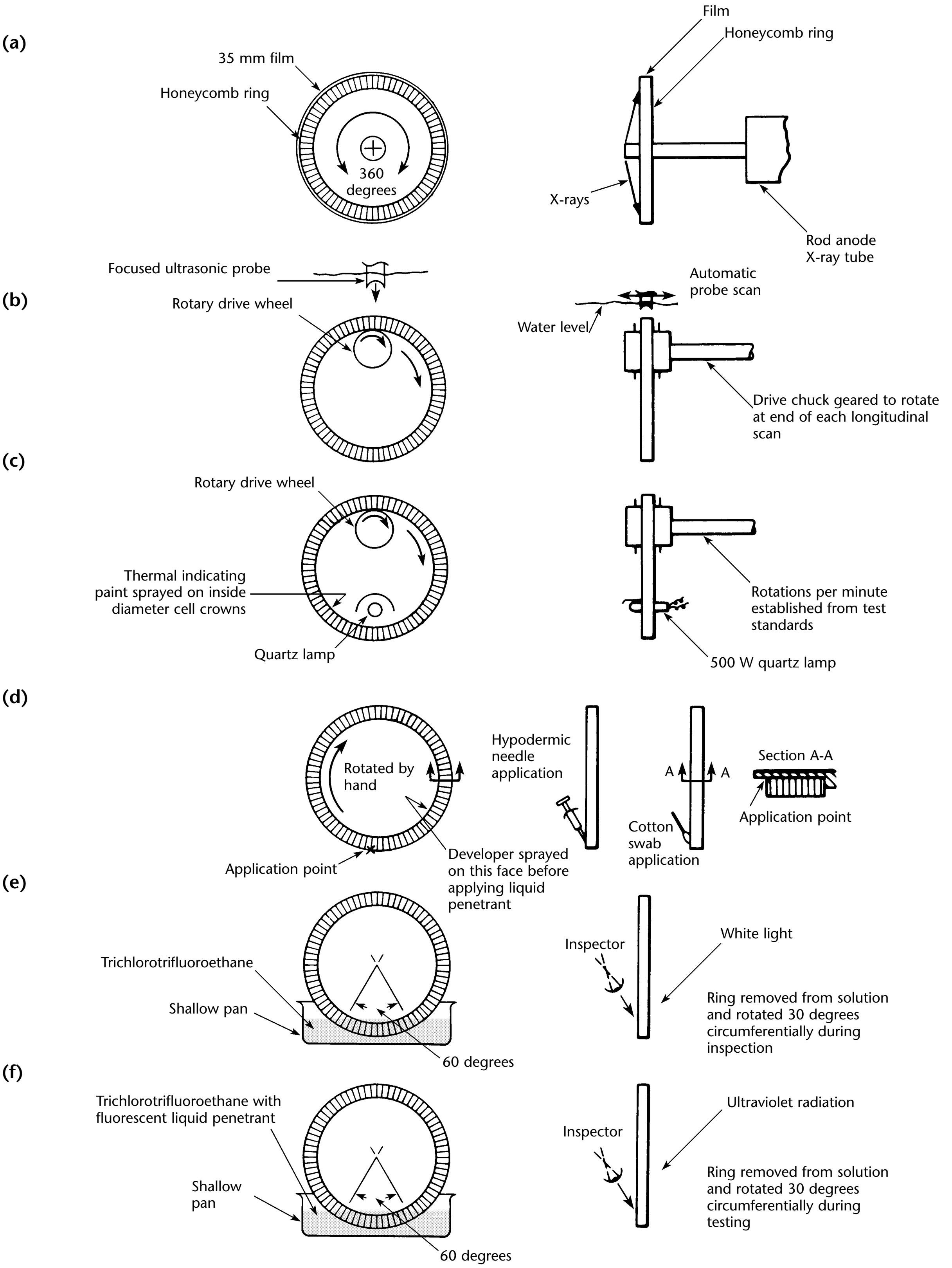
Discussion of Mechanisms of Penetration Action

The open face honeycomb core was nonperforated, resistance welded type, per AMS 5850.[11] The foil material was made from a nickel-chromium alloy with good oxidation resistance at high temperatures and resistance to chloride ion stress corrosion cracking, to corrosion by high purity water and to caustic corrosion; the foil was 0.05 mm (0.002 in.) thick, with a cell size of 1.6 mm (0.063 in.). Because of the variety of materials encountered in the braze ring and the difference in surface tension between test media and the ring, calculation of the forces involved is difficult. However, the mechanism involved is described in Fig. 11 and Eqs. 1 to 3:

$$(1) \quad \sum Fx = \gamma_{LV} \sin\theta - A = 0$$

$$(2) \quad \sum Fy = \gamma_{SV} - \gamma_{SL} - \gamma_{LV} \cos\theta = 0$$

FIGURE 9. Nondestructive test methods for inspecting open face honeycomb seal rings: (a) X-radiography; (b) ultrasonic scan facsimile recording method; (c) thermography; (d) visible dye liquid penetrant testing; (e) trichlorotrifluoroethane (refrigerant-113) method using white light; (f) trichlorotrifluoroethane (refrigerant-113) method using ultraviolet radiation.



$$\gamma_{SV} - \gamma_{SL} = \gamma_{LV} \cos\theta \tag{3}$$

where adhesive force $A = \gamma_{LV} \sin\theta$, total hydrostatic pressure $F = 0.5\ WLH^2$, pressure head H = height to free liquid surface, L = length of cell wall segment, W = weight per unit volume of fluid, γ_{LV} = surface tension of liquid-to-vapor film, γ_{SL} = surface tension of solid-to-liquid film, γ_{SV} = surface tension of solid-to-vapor film and θ = contact angle.

The low viscosity liquid testing medium readily runs out through the openings when disbonded cells are open to the edge of the ring. However, when these cells are not open to the edge, the test still reveals the voids. As the ring is rotated through an angle of 30 to 45 degrees, the force and pressure are increased as a result of the change in potential energy caused by the change in height of the medium. If the cell is not brazed, the liquid flows downhill into the adjacent good cells. The surface tension forces are so great that the medium does not flow out of good quality cells even when the ring is rotated 90 degrees.

Limitations of Liquid Penetrant Testing of Open Face Honeycomb

One problem to be considered in tests of open face honeycomb is that the liquid also will flow out if a poor resistance weld exists in the cell material. However, this problem was not encountered, possibly because a poorly welded ribbon is sealed by the alloy during brazing. A second consideration that has not been completely evaluated is the ability of the fluid to flow out of disbonded cells, surrounded by good cells, when the height to width increases to a ratio above 3:1 (which has been the upper limit studied). It appears that for ratios above 3:1, the surface tension and capillary forces may prevent the fluid from flowing. This is not true for disbonds open to the edge.

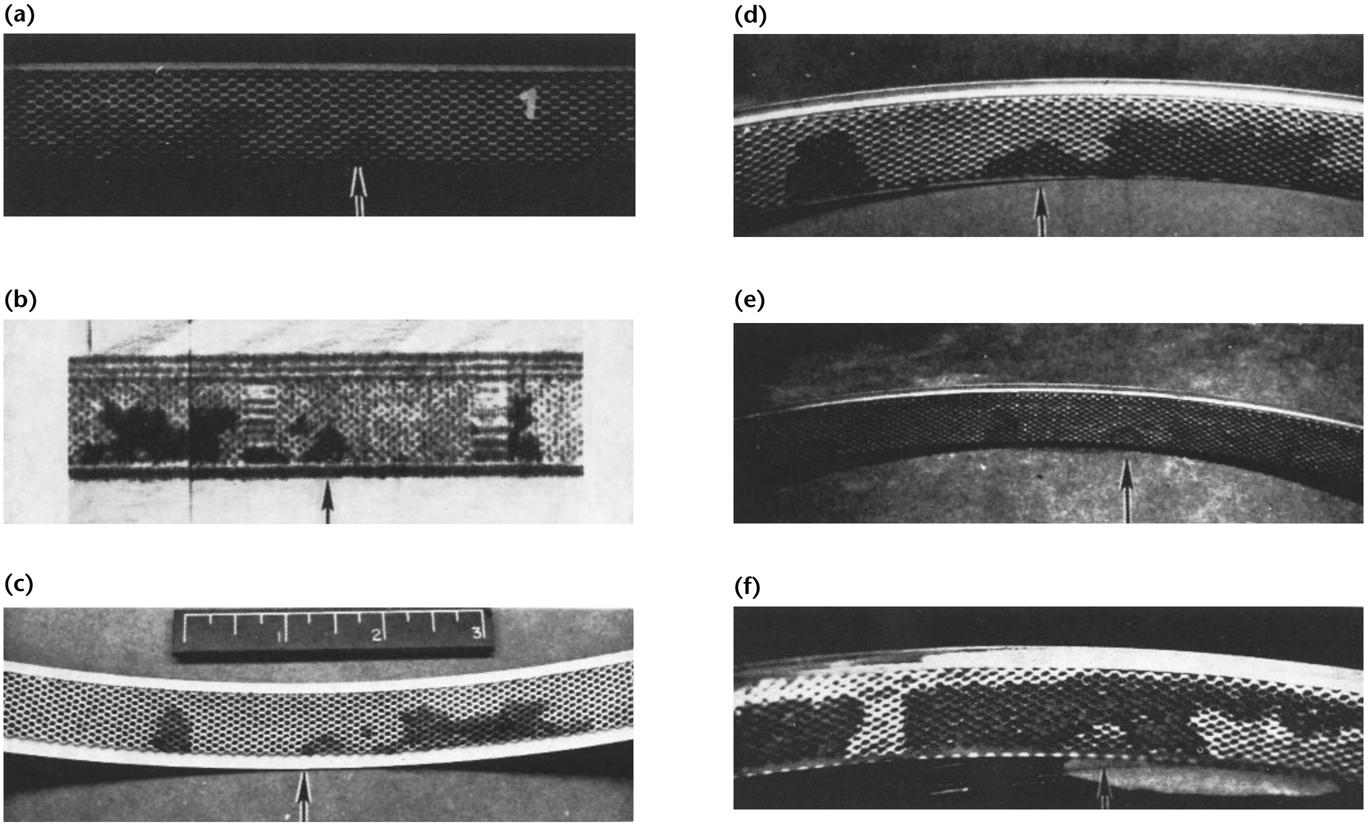


Figure 10. Nondestructive test results from inspection of brazed open face honeycomb ring seals. Arrows denote same defective area during each test method: (a) radiography; (b) reverse ultrasonic C-scan facsimile recording; (c) thermographic temperature indicating paint; (d) liquid penetrant testing with water base visible dye placed along edges of honeycomb; (e) test method with normal white light background using trichlorotrifluoroethane; (f) test method using trichlorotrifluoroethane and fluorescent liquid penetrant photographed under ultraviolet radiation.

Liquid Penetrant Testing of Brazed Ring Seals

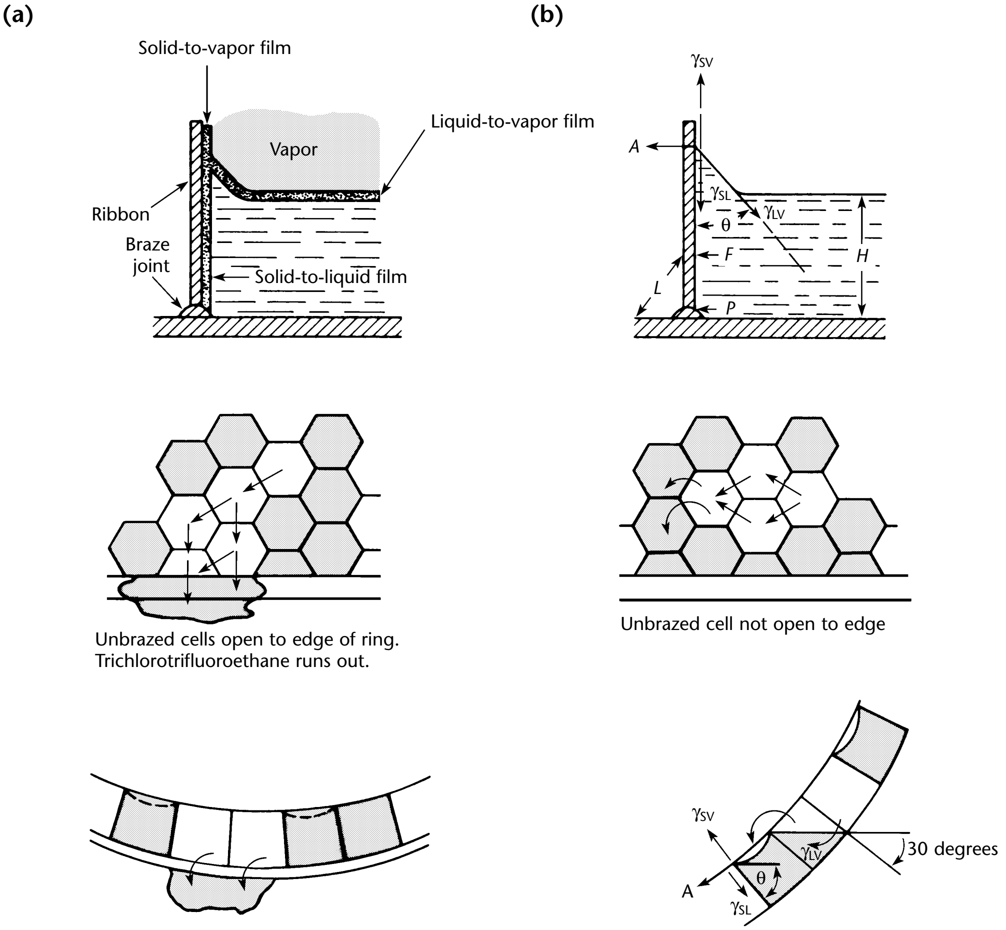
Visible Dye Technique

For visible dye liquid penetrant tests, the inside diameter cells were first sprayed with a light coating of developer. Liquid penetrant was applied to the edge of the ring-to-ribbon braze joint with a small hypodermic syringe or a cotton swab applicator; the ring was slowly rotated as the liquid penetrant was applied. When a disbond is open to the edge, the liquid penetrant is drawn very rapidly by capillary action into the opening. The results are shown in Fig. 10d. The dye liquid penetrant technique was only successful on rings having edge disbonds.

Fluorescent Technique

For inspecting the braze quality in open face honeycomb seal rings, the low viscosity ($<1 \times 10^{-6}$ m^2·s^{-1} [<1 centistokes]), liquid penetrant test technique is low in cost, fast and reliable for detecting disbonds. The addition of fluorescent additives to the liquid enhances the sensitivity of the test. Proof of the ability of these test methods to reveal braze bond quality was provided by metallurgical evaluation.

FIGURE 11. Surface tension forces acting on honeycomb cells using low viscosity liquids: (a) unbrazed cells open to edge; (b) unbrazed cells not open to edge.



Unbrazed cells open to edge of ring.
Trichlorotrifluoroethane runs out.

Unbrazed cell not open to edge

Legend

A = adhesive force, N (lb$_f$)
F = total hydrostatic force, N (lb$_f$)
H = pressure head, m (in.)
L = length of cell wall segment, m (in.)
P = hydrostatic pressure, Pa (lb$_f$·in.$^{-2}$)
γ_{LV} = surface tension of liquid-to-vapor film, N (lb$_f$)
γ_{SL} = surface tension of solid-to-liquid film, N (lb$_f$)
γ_{SV} = surface tension of solid-to-vapor film, N (lb$_f$)
θ = contact angle between liquid and solid (degree)

PART 6. Ultrasonic Enhancement of Liquid Penetrant Indications of Cracks in Aerospace Structural Weldments

Detecting Cracking in Precision Aerospace Weldments

The combination of supersensitive liquid penetrants capable of fluorescence at very thin film levels with ultrasonic fluid excitation during precleaning and during liquid penetrant application provides a means of reliably demonstrating the presence of extremely tight fatigue cracks in small precision weldments. A similar problem is that of microscopic intergranular cracking in small, precision investment castings required to function in a high temperature environment where thermal cycling accelerates crack propagation and early failure. Another typical example is inspection of an investment cast bearing housing welded to a high temperature strength sheet material (nickel-chromium-iron-molybdenum alloy resistant to oxidation and stress corrosion cracking). Extremely tight microshrinkage existed in this casting before welding but was frequently missed both by radiography and conventional fluorescent liquid penetrant testing. Unfortunately, after welding, a final fluorescent liquid penetrant testing revealed, with embarrassing clarity, typical and unacceptable shrinkage and chicken wire crack complexes.

Difficulty of Detecting Microcracks with Conventional Liquid Penetrant Process

It is desirable to identify the maverick pieces before welding, when the ingredients of the problem are present but latent, before the welding operation. Many pieces, subjected to liquid penetrant testing and then destroyed, provided abundant evidence that the liquid penetrant had entered the minute cracks. It had not, however, exuded at a rate capable of overcoming the thin film fluorescence threshold. Thus, on inspection with ultraviolet radiation, no indications were evident at the surface.

On parts removed from service for routine inspection, the presence of acids, chromates and combustion byproducts in tight discontinuities further hampers the mechanics of the static liquid penetrant process. No amount of precleaning by conventional techniques adequately cleansed the discontinuity interfaces. The remaining contaminants were observed to actually repel the liquid penetrant material and in some cases to negate fluorescence.

Ultrasonic Pumping to Enhance Liquid Penetrant Performance

In an attempt to overcome the limitations of static processing, ultrasound at an optimized frequency can be used as a means of pumping the fluorescent liquid penetrant into places it would not otherwise enter or where it would enter but perhaps not in sufficient quantity to bleed back at a useful rate. The ultrasonic energy transmitted through a liquid penetrant medium acts (1) to shake loose trapped adherents (2) to flush entrapped contaminants from the discontinuity interfaces and (3) to deposit the discontinuity indicating fluid rapidly and minimize the required liquid penetrant dwell time.

Ultrasonically Enhanced Liquid Penetrant Testing of Small Weldments

With ultrasonic liquid penetrant testing equipment embodying all the steps of the liquid penetrant process, including the spray rinse and the various associated timing devices, the time from beginning of the procedure to the dry and ready-to-inspect stage is 5 min or less. The procedure lends itself well to automation. Thus, it permits inspecting a continuous flow of moderately sized precision weldments. Tests indicate that more liquid penetrant is deposited more positively and at greater speed with ultrasonic excitation than would otherwise be the case. The sequence and timetable shown in Table 4 is used with ultrasonic enhancement and postemulsifiable liquid penetrants.

The precleaning is optional, because the liquid penetrants themselves are excellent cleaners and inhibitors. Ultrasonic cleaning is a well known industrial means for obtaining maximum cleaning action yet is rapid and gentle enough to cleanse parts otherwise too

Table 4. Ultrasonic enhancement process.

Step	Time (s)
1. Immerse in precleaning solvent in ultrasonic tank at room temperature	30
2. Dry (infrared)	60
3. Immerse in liquid penetrant, ultrasonic tank	30
4. Emulsify, static tank	30
5. Controlled temperature, spray rinse	30
6. Dry	120
7. Develop	60
8. Inspect	

fragile to be processed. step 4 may be eliminated if gel forming, water washable liquid penetrant materials are used in place of the postemulsifiable types.

Selecting Frequency of Ultrasonic Excitation of Liquid Penetrants

Choice of ultrasonic frequency will depend on the size of the test parts and their fragility. Lower frequencies produce greater penetrating power (more suitable for massive parts and penetrating deep into interstices). Below 20 kHz, the noise is bordering on the audible and fragile parts, as well as ears, have been superficially damaged at that level. The unique feature of ultrasonic cavitation is that it can be generated anywhere that a sound wave of sufficient intensity can penetrate, so that cleaning action might occur deep within the interstices of a part or assembly and may be effective in some parts with complicated geometric configurations.

PART 7. Applications of Liquid Penetrant Testing in Aircraft Fleet Maintenance

Preventive and Corrective Maintenance of Commercial Aircraft

Top quality maintenance is the key to successful operation of any airline. Because reliable day-after-day service depends on thorough maintenance, all efforts of an airline maintenance base are directed toward achieving the utmost in safety and continuous serviceability while offering the public an economical, attractive, modern and comfortable means of transportation.

While corrective maintenance is sometimes necessary to overcome malfunctioning of aircraft components, far greater emphasis is placed on preventive maintenance. It is extremely important, from the standpoint of cost as well as of safety, that discontinuities be discovered in their incipient state rather than after they have developed to such a degree that they impair airworthiness.

Phases of Airline Maintenance

Essentially, there are three phases of airline maintenance that blend together to activate the overall program. Each phase uses various inspection techniques.

1. Preflight check includes walk-around visual testing of such items as the airframe and control surfaces as well as operational check of engines and flight controls.
2. Line servicing encompasses detailed repetitive inspection of prescribed components and structures. It is performed at specific operating intervals, usually every 100 to 125 h.
3. Base overhaul encompasses planned replacement and overhaul of removable components, meticulous inspection and repair of the airframe structure and modification of airframe and components for improved serviceability. Overhaul is performed progressively by most airlines at specific operating intervals ranging from 2000 to 5000 h. It is mainly in the base overhaul phase of airline maintenance that nondestructive testing is most important.

Forms of Nondestructive Testing in Aircraft Maintenance

Many forms of nondestructive testing are used in airline maintenance, ranging from the simple visual check given the control surface before flight to the highly scientific inspection of hidden structures during overhaul. Radiography, of course, has become one of the most valuable tools in airline maintenance. Also used extensively are fluorescent liquid penetrants, magnetic and ultrasonic tests and various electronic test instruments. Together these forms of nondestructive testing trigger a significant amount of the total maintenance work that is done on any aircraft in airline service.

Fatigue Cracks in Aircraft Structures

Although corrosion is replacing fatigue life as the limiting factor for continued flight of aging aircraft, detecting fatigue cracks is still a major concern. Fatigue cracks are normally quite small and in many locations are extremely difficult to detect. They have been known to develop undisclosed under rivet heads, for example. If they are not detected in their very early stages, they can endanger the structural integrity of the aircraft and eventually result in the necessity for major and possibly emergency repairs. Early discovery, on the other hand, permits the operator to schedule repairs without disruption to services and at a fraction of major repair cost.

Aircraft Structural Integrity Program

Experience gained in past years with large pressurized airliners has emphasized the importance of maintaining a high level of structural integrity, particularly through vigilance against fatigue deterioration. This, in turn, has emphasized the importance of inspection programs under which aircraft may attain long, safe service lives. Such programs must cover the primary structure and structural joints systematically and must give attention to hidden areas and members subject to repetitive cyclic loads.

Specifications for Aircraft Structural Integrity Programs

An assessment of structural integrity is based on thorough review of the airplane structure, with particular attention to service experience, vital joints, critical members and points, stress levels, shape and associated factors. A structural integrity program specifies structural areas and items to be inspected and frequency of inspection. The combination of inspection intervals and levels for each area or structural item is selected to provide for continuously adequate knowledge of the condition of that structure as related to the individual airplane and/or a fleet of airplanes and for detection of fatigue cracks or other deterioration at an early stage.

Organization of Inspection of Inservice Aircraft

The entire aircraft structure is given a routine visual testing at each visit to the airline overhaul base. These tests are supplemented by a standard and a special level of inspection of certain primary structural elements. These are accomplished repetitively on all fleet airplanes at appropriate frequencies and scheduled to provide for effective continuous monitoring of the fleet. Further, fleetwide sampling inspections are provided for the more significant structural items and are required on a fixed percentage of the fleet annually. Finally, numerous special programs are set up to provide for extraordinary maintenance of certain removable components, for removal of certain other components to permit inspection of hidden areas and for other preventive measure such as replacement of certain structural fasteners.

Action Resulting from Inspection of Inservice Aircraft

From these tests, the experiences of other airline operators and studies by the airframe industry, patterns of incipient structural discontinuities come to light from time to time. When this occurs, the findings are evaluated (usually in conjunction with the aircraft manufacturer) and appropriate action is taken to safeguard airworthiness.

This action may consist of one or more of the following procedures: (1) accelerated fleet sampling; (2) one time fleet campaign testing; (3) interim repetitive inspection, pending final evaluation and corrective action; (4) corrective action to maintain or improve the integrity of the structure; and (5) adjustment of the scope and frequency of inspections of the structural inspection program or an addition of new tests.

Fail Safe Aircraft Design

All modern airliners built in the United States are constructed so that each can continue to land safely even though some structural member has failed (cracked, stretched, warped, fractured, sheared or snapped). This design concept is called *fail safe* and is applied particularly to the wing and fuselage structure. By incorporating design features such as multiple structure and multiple load paths, each airframe is engineered to accommodate some unpredictable loads, stress concentrations or deterioration by fatigue and corrosion without significant effect on the overall structural integrity. Thus, it is readily apparent that structural integrity programs are aimed at preserving the inherent soundness of the fail safe design throughout the service life of the aircraft.

Problems of Sealants on Aircraft Structures

One of the major problems confronting airline inspectors is the presence of sealing materials at joints in aircraft structures. Sealant is used either to confine fuel in tank compartments or to maintain air pressure within the aircraft cabin. Sealants have a density comparable to the density of aluminum. Even a thin film of sealing compound can seriously affect the performance of liquid penetrant tests. Sealants may prevent entry of liquid penetrant into surface discontinuities. Also, cracks or voids in sealants may possibly be interpreted as cracks in the metallic aircraft structure. Undoubtedly there are cases where sealant has obscured minor discontinuities in the structure.

Fluorescent Liquid Penetrant Testing of Aircraft Components

Fluorescent liquid penetrant testing is used in inspecting many aircraft parts, especially those that are nonmagnetic. While this type of nondestructive test is quite commonplace, certain precautions must be taken to ensure detection of extremely small, tight discontinuities. Cleanliness is most critical. Rubber, carbon, grease and other foreign materials may contaminate cracks, clogging the openings so that the liquid penetrant cannot enter.

Although many types of cleaners may remove surface dirt from magnesium, aluminum and stainless steel parts, it is most important to determine first whether these cleaners will affect the fluorescent properties of the liquid penetrant. With some cleaners, the degree of fluorescence is markedly reduced; in other instances all trace of fluorescence disappears.

Skills and Training of Aircraft Inspectors

Many forms of nondestructive testing have become so common that some industries tend to assume that the average worker can operate specialized equipment. Although most test machines are relatively simple to use, optimum results can be obtained only by skilled, highly trained personnel. In airline applications, the nondestructive test operator should have a thorough knowledge of test equipment, aircraft structure and manufacturing and repair techniques. In addition, the operator should possess inherent curiosity and a high level of interest, permitting accurate interpretations and prompting the operator to verify questionable indications. And finally, the operator should have a well developed ability to weigh facts and render sound decisions. A skilled operator can reap a fine harvest of savings for the employer whereas a poorly trained or careless operator is apt to plow under the potential benefits and possibly generate false confidence in the performance capability of the aircraft components and structures.

Field Liquid Penetrant Testing of Military Aircraft

All types of military aircraft require rework for updating and extending the service of the aircraft and also repairing damaged aircraft. Damages range from minor to crash damage. Much repair work is done by field teams at outlying bases. All aircraft receive thorough inspection of their structures both before and during rework or repair. Liquid penetrants are instrumental in conducting these inspections.

When aircraft are returned to rework or repair, there are considerable variations in the surface conditions of their structures. These variations are caused by many factors such as age, operating environment and past maintenance. These and other factors also affect the selection of the liquid penetrants and processing materials required to conduct an inspection and still maintain a high quality and airworthy product. With components and small parts, the liquid penetrant testing process presents no problem because these parts are all inspected in shops designed for this type of inspection. However, on the aircraft many problems exist, such as whether the airplane is in the field or hangar, whether access is possible to the area to be inspected and whether test equipment is available. All of these factors must be taken into consideration when selecting a liquid penetrant that will highlight the type of discontinuity sought. This problem becomes a prime consideration for line and field teams who must literally work out of a tool box with minimum support equipment.

Limitations of Fluorescent Liquid Penetrants in Field

This process presents problems of having to mask or shield each area of inspection from white light to conduct an inspection. The hooding or masking is cumbersome and time consuming, as each area requires its own makeshift cover. These hoods can also present a hazard to the inspector, who at times is required to inspect wings etc. from stands and platforms. These facts are especially true for inspectors on the line and in the field. A lesser problem is encountered in the inspection of rough castings such as the transmission housings on helicopters. When the residual liquid penetrant has to be removed by hard wiping, it is sometimes difficult to obtain a low fluorescent background without risking an overwash and removal of the liquid penetrant indications.

Limitations of Using Both Visible and Fluorescent Liquid Penetrants

If visible dye liquid penetrant is allowed, there may be the problem of resolving questionable indications encountered with visible liquid penetrants. Even after recleaning the questionable area for reinspection with fluorescent liquid penetrant, there could be no assurance that all of the visible dye had been removed from the suspected discontinuities. Because the dye of visible liquid penetrants will quench the fluorescence of fluorescent liquid penetrants, a reinspection by this technique would not provide conclusive results.

PART 8. Liquid Penetrant Testing of Radioisotope Heat Source Capsules for Deep Space Missions

Liquid Penetrant Testing of Fragile Radioisotope Capsule Parts

Fabrication and inspection of exotic alloy parts of large radioisotope heat source capsules used for long life deep space missions require careful handling and processing to prevent damage and contamination of these fragile and critical components. Capsules in service can experience temperatures as high as 1100 °C (2000 °F) with internal pressures up to 14 MPa (2000 $\text{lb}_\text{f}\cdot\text{in.}^{-2}$) for periods of five years. Close dimensional control of capsule parts must be obtained and maintained to ensure easy assembly after fueling because assembly must be performed remotely with thermally hot parts fitted with cold parts. Cleanliness is essential to avoid material degradation from small quantities of contaminants under severe service conditions.

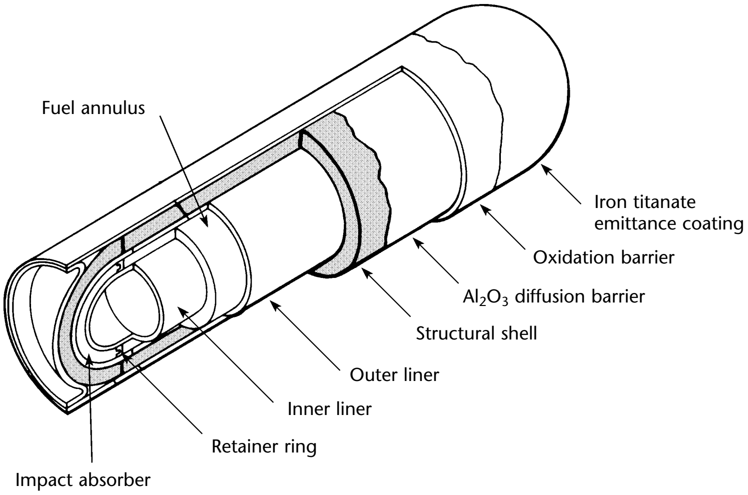
Figure 12 depicts a typical radioisotope capsule configuration with an exterior 140 mm (5.5 in.) long by 63 mm (2.5 in.) diameter. The wall thicknesses are 0.76 mm (0.03 in.) to 2.3 mm (0.09 in.) for the tantalum alloy shells and 0.5 mm (0.02 in.) for the platinum alloy shells. Maximum permissible deviation from form (sphericity and cylindricity) is ±50 µm (±0.002 in.). Maintaining such tolerances requires careful handling and a minimum number of handling operations. Inspection operations are not exempted from this handling criterion. Liquid penetrant testing was one of the principal nondestructive tests used to determine the integrity of the deep drawn capsule parts. A way to perform this test that minimized handling was required. It was particularly desirable to use a readily removable developer, because normal developers can be difficult to remove from reentrant cavities, posing handling damage and contamination problems.

Self-Developing Liquid Penetrant System

It should be noted that special applications such as vehicles for deep space missions require specially developed liquid penetrant process specifications rather than conventional standards.

To reduce handling and cleaning of the nuclear heat source capsules, a fluorescent, water washable liquid penetrant system not requiring a developer was used. This eliminated the operations of applying a developer and of postcleaning to remove the developer. This final cleaning operation was

FIGURE 12. Typical large radioisotope heat source capsule design. Capsule outside diameter is 63 mm (2.5 in.), with an overall length of 140 mm (5.5 in.).



considered to have the greatest potential for damage to parts as a result of liquid penetrant testing.

Control of parts contamination was less troublesome, because the degree of removal of the water washable liquid penetrant from the inspected parts could be established simply by inspecting the postcleaned parts under an ultraviolet radiation source. The time required to process a group of parts was reduced, because a 2 min penetration time followed by a 2 min self-developing time was feasible without reduction in the reliability of discontinuity detection.

Sensitivity Control

The proprietary water washable, self-developing fluorescent liquid penetrant system used to inspect the radioisotope capsules permits liquid penetrant sensitivity control by mixing ultrahigh and moderate sensitivity components to achieve a liquid penetrant with an intermediate sensitivity. Caution — mixing of conventional liquid penetrants is unacceptable because most liquid penetrant systems are incompatible. Table 5 below shows relative sensitivities of the family of compatible liquid penetrants used in this research. The listed SAE AMS 2644[1] sensitivity levels are valid only when developer is used.

Figure 13 shows a graph relating the sensitivity of the liquid penetrant mixture to the proportions of two members of the family of compatible fluorescent liquid penetrants. The sensitivity numbers shown on the ordinate scale of Fig. 13 are inversely proportional to the liquid penetrant sensitivity levels. The ultrahigh sensitivity level is identified as P-1 whereas the lower liquid penetrant sensitivity level is identified as P-3. For liquid penetrant testing of the radioisotope capsule parts, a mixture of sensitivity 2.5 was found to be optimum. This mixture provided a maximum sensitivity level compatible with the metal forming processes and the finish characteristics of the capsule alloy that did not yield excessive numbers of nonrelevant liquid penetrant indications.

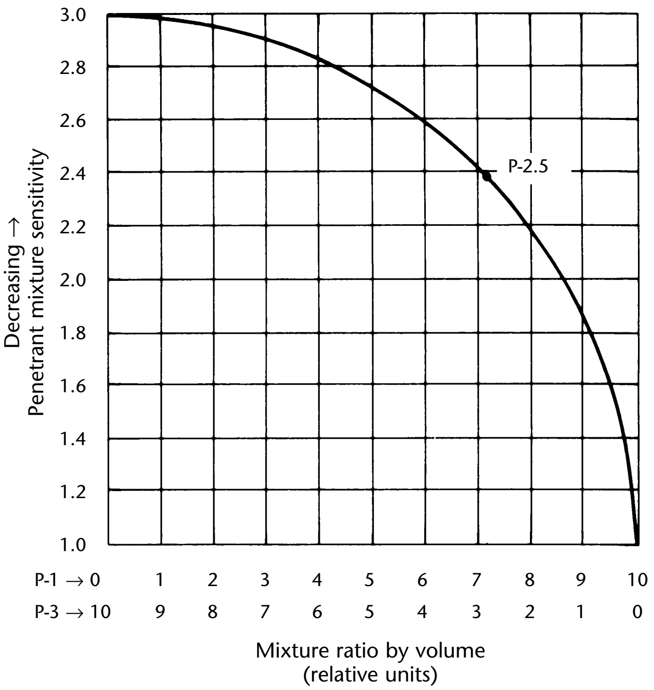
The test procedure used a self-developing fluorescent liquid penetrant of appropriate sensitivity.

1. Cleaned parts were received after passing a water break test in accordance with ASTM F 22-65, *Hydrophobic Surface Films by the Water Break Test*.[12]
2. Parts were dipped in the liquid penetrant at temperatures of 15 to 50 °C (60 to 120 °F), were removed and drained for at least 2 min.
3. Excess liquid penetrant was removed by flooding with tap water followed by a distilled water rinse. Rinsing was performed under an ultraviolet light to prevent overwashing, discontinuing rinsing as soon as the liquid penetrant background glow disappeared.
4. Parts were inspected for fluorescent indications immediately after drying, using standard fluorescent liquid penetrant ultraviolet lighting of 365 nm wavelength and 30 $W\cdot m^{-2}$ (3000 $\mu W\cdot cm^{-2}$) minimum illumination.

TABLE 5. Relative sensitivities of compatible liquid penetrants for inspection of radioisotope capsules.

Penetrant Sensitivity Number	Relative Sensitivity
1.0	Ultrahigh sensitivity — useful principally for investigations such as displaying very small discontinuities on specimens prepared for metallographic studies
2.0	Very high sensitivity — equivalent to SAE AMS 2644, Level 4,[1] useful where high discontinuity detection reliability is mandatory as required for fracture critical aircraft structures
2.5	High sensitivity — equivalent to sensitivity of liquid penetrants of SAE AMS 2644, Level 3[1]
3.0	Medium sensitivity — equivalent to sensitivity of liquid penetrants of SAE AMS 2644, Level 2[1]

FIGURE 13. Developerless fluorescent penetrant system variable sensitivity mixture ratios.

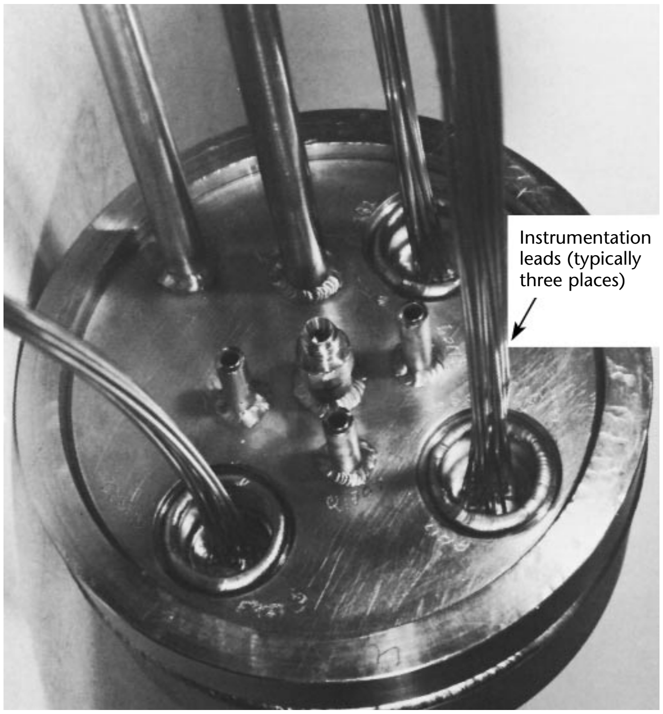


The developerless water washable fluorescent liquid penetrant was found to be effective for surface testing of the critical radioisotope capsule parts whereas risk of handling damage and contamination was substantially reduced. Additionally, the short penetration and development times could yield substantial cost savings for large scale production quantities of parts.

High Sensitivity Fluorescent Liquid Penetrant Examination of Welds in Fuel Module Assemblies

Spray applied, nonaqueous wet developers are used extensively with color contrast liquid penetrants for inspection of welds on nuclear power plant components. This technique, however, was determined to be unsatisfactory for testing of an experimental fuel assembly because spraying of the developer contaminated areas between instrumentation leads. Figure 14 shows a loss of fuel test (LOFT) fuel module assembly with welds that are liquid penetrant tested. The tubing is stainless steel; the base material is a corrosion resistant nickel-chromium alloy. This loss-of-fuel-test reactor is at a test facility of the Idaho National Engineering Laboratory whose fuel elements are heavily instrumented.

FIGURE 14. Fuel module assembly. Insulated bushings for instrument leads are typically welded into three locations. Liquid penetrant testing is used to reveal any weld cracks. Tests are made remotely.



High sensitivity fluorescent liquid penetrants without developer have been permitted with customer approval in certain applications in the aerospace industry. In the absence of special procedures developed and approved for special applications, those performing liquid penetrant tests must follow applicable standards and use materials on the corresponding qualified products lists in the same manner in which they were qualified.

Procedure for Liquid Penetrant Testing of Module Assembly for Loss of Fuel Test

A special procedure using a high sensitivity fluorescent liquid penetrant without developer was established for the LOFT fuel module assembly welds. The liquid penetrant is applied to the localized area of the welds using cotton swabs. After a liquid penetrant dwell time of 10 to 20 min, the excess liquid penetrant is removed using dry cotton swabs followed by cotton swabs dampened with solvent remover. The welds are then inspected under ultraviolet radiation. A minimum intensity of 30 $W \cdot m^{-2}$ (3000 $\mu W \cdot cm^{-2}$) is used. If developer were used, the minimum specified ultraviolet radiation intensity would be 10 $W \cdot m^{-2}$ (1000 $\mu W \cdot cm^{-2}$). The higher intensity of 30 $W \cdot m^{-2}$ (3000 $\mu W \cdot cm^{-2}$) helps to compensate for not using developer. The special procedure using the high sensitivity fluorescent liquid penetrant without developer solved the cleaning problem and provided increased discontinuity detection capabilities over the color contrast, solvent removable technique used with nonaqueous wet developer.

Liquid Penetrant Examination of Automatic Machine Welding of Irradiated Fuel Rods

Remote assembly of irradiated fuel rods for the power burst test facility required weld certification of two hot cell technicians for the remote automatic welding of the end cap to cladding and fill tube seal welds. Testing of the welds consists of a remote liquid penetrant test followed by a metallographic inspection. For the liquid penetrant test, the welds were to be inspected for all surface indications, particularly cracks, at 4× magnification using a stereo periscope mounted for viewing through the cell wall.

The liquid penetrant initially specified for the test was solvent removable dye. However, it was very difficult to remove the excess liquid penetrant using remote handling methods. A considerable amount of liquid penetrant remained on the surface, enough to mask relevant indications. It was decided to try a water washable dye liquid penetrant to efficiently remove the excess liquid penetrant. A spray developer was then used for interpretation. This technique proved to be successful. All test welds and fabrication welds are liquid penetrant tested in this manner.

End Fittings and Welds on Advanced Test Reactor Fuel Elements

Each end fitting for the advanced test reactor (ATR) fuel element is inspected for surface discontinuities by liquid penetrant to the requirements described in United States Department of Energy Standard RDT F3-6T.[13]

The liquid penetrant used is a visible, solvent removable liquid penetrant. The penetration time is 20 min minimum and the developing time is 10 min minimum. All surfaces inspected must be free of linear discontinuities (cracks, laps, fissures etc.) and of four or more rounded discontinuities separated by 1.6 mm (0.06 in.) or less distance from edge to edge.

Inspection of End-Fitting-to-Side-Plate Welds on Advanced Test Reactor Fuel Elements

The following liquid penetrant procedure is applicable to advanced test reactor fuel element end-fitting-to-side plate welds using visible solvent removable liquid penetrant on the outside only with the following materials: (1) bleached cheesecloth or (2) acetone reagent grade. The liquid penetrant system consists of (1) visible dye liquid penetrant, (2) solvent remover and (3) nonaqueous developer. Components of approved liquid penetrant systems may not be intermixed.

Cleaning before Inspection of Fuel Elements

The surface of all materials and parts to be inspected shall be free of oil, grease, dirt, scale, weld flux and other matter that might interfere with proper application or distribution of the liquid penetrant. The test surface and any adjacent area within at least 25 mm (1 in.) of it shall be free of grease, oil, paint, loose scale or other conditions that might obscure the surface openings or interfere with accurate interpretation of indications. Drying of the cleaned surface shall be by normal evaporation for a minimum of 5 min. The surface must be completely dry before application of liquid penetrant.

Restrictions on Surface Treatments of Fuel Elements

The following surface treatments will bridge over discontinuities and shall not be used before liquid testing: (1) plating, (2) anodizing, (3) painting and (4) dye or layout paint. The following cleaning methods tend to limit the effectiveness of liquid penetrant testing and shall not be used before liquid penetrant testing without specific written approval: shot blasting, sand blasting, vapor blasting, buffing, burnishing or any other surface treatment that will have a smearing or peening action on the surface.

Procedure for Applying Liquid Penetrant to Fuel Elements

A film of the liquid penetrant shall cover all surfaces to be inspected and may be applied by brushing. Caution — liquid penetrant must be kept out of fuel-plate-to-side-plate swage joint. Both the surface to be inspected and the liquid penetrant shall be at a temperature not less than 15 °C (60 °F) nor more than 50 °C (120 °F) throughout the inspection period. Penetration time shall not be less than 10 min or more than 20 min. If liquid penetrant materials are allowed to dry, repeat test including cleaning of test surfaces.

Removing Excess Liquid Penetrant from Fuel Elements

The surface film of liquid penetrant shall be thoroughly cleaned from the part after the penetration time has elapsed. This cleaning must be complete so that the only liquid penetrant remaining will be within the discontinuities of the parts. With solvent removable liquid penetrant, excess liquid penetrant, insofar as possible, shall be removed by using clean, dry cloths or absorbent paper. The operation should be repeated until most traces of liquid penetrant have been removed. A clean, dry cloth or absorbent paper shall then be dampened with solvent and the surface shall be wiped lightly until all remaining traces of excess liquid penetrant have been removed. Care shall be used not to use an excess of the solvent, to avoid removing liquid penetrant from discontinuities. Flushing the surface with solvent following the application of the liquid penetrant and before developing is prohibited. Special care shall be exercised to remove all liquid penetrant from holes and corners. All parts shall be dried thoroughly by normal evaporation for a minimum of 5 min before application of developer.

Applying Developer to Fuel Elements

The developer shall be applied to advanced test reactor fuel elements by spraying as soon as possible after the liquid penetrant removal step and shall not exceed a time interval of 15 min. Caution — developer must be kept out of the swage joint joining the fuel plates to the side plate. Nonaqueous developer shall be thoroughly agitated by shaking or stirring before and during the time of application. For best results and greatest sensitivity, the developer shall be applied by spraying a light, even coat, avoiding laps, runs and heavy deposits.

Examination of Indications on Fuel Elements

Sufficient time shall be allowed between the application of developer and the inspection of parts for the indications to appear. Final interpretation shall be made after allowing the liquid penetrant to bleed out for a minimum of seven minutes to a maximum of thirty minutes. If the surface is sufficiently large to preclude complete inspection within the prescribed time, the surface shall be inspected in suitable increments.

Rejection Criteria for Advanced Test Reactor Fuel Elements

For all welds, the following relevant indications are unacceptable: (1) any cracks; (2) any linear indications; (3) rounded indications with major dimensions greater than 0.40 mm (0.016 in.) or with dimensions exceeding ten percent of the nominal weld thickness or 3 mm (0.13 in.), whichever is smaller (rounded indications separated by 1.6 mm (0.06 in.) or less from edge to edge shall be evaluated as single indications); (4) four or more rounded indications in a line separated by 1.6 mm (0.06 in.) or less from edge to edge; (5) six or more indications in any 40 cm^2 (6 $in.^2$) of weld surface with the major dimension of this area not to exceed 150 mm (6 in.), with the area taken in the most unfavorable location relative to the indications being evaluated; (6) aligned indications in which the average of the distance from center to center between any one indication and the two adjacent indications in a straight line is less than 5 mm (0.2 in.). Only those indications with major dimensions greater than 0.4 mm (0.06 in.) are considered relevant for item 6.

Confirmation of Nonrelevant Indications on Fuel Elements

Any indication that is believed to be nonrelevant shall be regarded as a discontinuity and shall be reinspected to verify whether or not actual discontinuities are present. Surface conditioning may precede the reinspection. Nonrelevant indications and broad areas of pigmentation that would mask indications of discontinuities are unacceptable.

Cleaning of Fuel Elements after Inspection

After completing inspection, all liquid penetrant and developer materials shall be removed using clean cheesecloth with solvent remover or acetone. Components shall be cleaned to the extent that no contamination of any surface is visible to a person with normal vision acuity, natural or corrected. Lighting in inspection areas shall provide an illumination level of at least 1 klx (100 ftc) on surfaces being inspected.

Quality and Examination Requirements

Personnel performing liquid testing to the procedure shall be qualified and certified in accordance with the requirements of *ASNT Recommended Practice No. SNT-TC-1A*[4] or *ANSI/ASNT-CP-189*.[14] Personnel qualified and certified as Level I may perform liquid testing processes if under the supervision of a Level II but shall not have responsibility for technique selection.

Record of Examination of Advanced Test Reactor Fuel Elements

Liquid testing reports shall be filled out and signed by certified personnel and shall document the following information: (1) examiner's name; (2) procedure used (number and latest revision); (3) ASNT certification level; (4) date of inspection; (5) part inspected; (6) area inspected; (7) governing documents; (8) liquid penetrant, developer and cleaner batch numbers, type and manufacturer; (9) disposition of part; and (10) reinspection information (if any).

Identification of Liquid Penetrant Testing Materials

Each acceptable batch of liquid penetrant, developer and cleaning materials will be identified by a quality assurance tag containing the following information: (1) manufacturer, (2) purchase order number, (3) batch number of product, (4) certification that contents meet RDT F3-6T[13] requirements per ASTM D 808[15] and ASTM D 129,[16] (5) quality assurance laboratory report number, (6) date of report and (7) acceptance stamp.

Certification of Advanced Test Reactor Fuel Element Inspections

Inspections conducted using this procedure are certified as being in accordance with the requirements of the following standards and specifications: *ASME Boiler and Pressure Vessel Code,* Section V, *Nondestructive Examination;*[17] RDT F3-6T;[13] ANC IN-F-9-ATR;[18] RDT F6-2T;[19] *ASNT Recommended Practice No. SNT-TC-1A*;[4] and *ANSI/ASNT-CP-189*.[14]

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CHAPTER

Various Applications of Liquid Penetrant Testing

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PART 1. Liquid Penetrant Testing of Metal Cutting Tools

Need for Nondestructive Testing of Machine Tool Bits

Metal cutting tools, ranging from small bits and drills to costly milling cutters, are replacement items that influence costs in manufacturing industries, particularly if some tools are anomalous or dysfunctional. Even excellent tools can be misapplied or used improperly and perfectly good tools can be used to produce either quality products or scrap, depending on how they are assigned and used. Reasonable standards of tool quality can be agreed on by both manufacturer and user to achieve economy in tool use. Standards on limits, tolerances and test methods for tools and on the ability of the tool to produce results, can be based on nondestructive tests and manufacturing experience.

Various types of discontinuities in cutting tools can cause problems for their manufacturers and users. High speed steel cutting tools may contain voids or inclusions in the metal, cracks produced by heat treatment, variations in stress relief or grinding checks. Carbide tools have potentials for brazing, grinding and lapping discontinuities. Hard, cobalt based alloy tools may be subject to difficulties related to welding, porosity or grinding.

Advantages of Liquid Penetrant Testing of Cutting Tools

Sensitive liquid penetrant testing reveals many types of relevant discontinuity conditions and permits anomalous or dysfunctional tools to be eliminated from those to be sold or used in production. It also assists the tool manufacturer in early detection and correction of faulty methods of processing tools during their manufacture. Anomalous materials can be weeded out of incoming stock before costly processing has been wasted on them. Magnetic particle testing can be used only on ferromagnetic materials such as high speed tool steels. Fluorescent liquid penetrant testing is recommended for carbide tools, which do not lend themselves to magnetic particle testing and for hard, cobalt based alloy tools, which are nonmagnetic. It is also applicable to testing of carbide tipped tools, both for cracks and discontinuities in the tip material and for poor braze bonds between tip material and support materials. Fluorescent liquid penetrant testing permits inspection of the complete tool surface and provides adequate test sensitivity that can be controlled for specific testing needs. In small plants, liquid penetrant testing is used by shop personnel to detect problems in heat treating, brazing and grinding processes. Shop personnel can acquire the needed skills readily, with proper instruction and experience.

Equipment and Techniques for Liquid Penetrant Testing of Cutting Tools

General purpose stationary liquid penetrant testing equipment used for testing of small parts finds wide use in testing of cutting tools. It includes liquid penetrant dip and drain station, wash station, recirculating hot air dryer and developing and inspection stations. Penetration times may vary, depending on the type of tool material and the tightness of discontinuities to be detected.

Interpreting Liquid Penetrant Indications on Cutting Tools

Liquid penetrant indications produced by tool discontinuities will vary in brilliance, depending on the depth, width and length of the discontinuities and on the particular liquid penetrant systems used. Porosity in braze bonds will show up as brilliant fluorescent specks along the bond line. If there is depth or an extended subsurface area of porosity, the indication will grow in size and brilliance with time after application of developer.

Under certain processing conditions, *shims* and *sandwich braze,* used to eliminate brazing strain and other problems, may result in porosity. When questionable porosity occurs in braze bonds, its position and the service conditions in which the tool will be used should be deciding factors in evaluating the acceptability of the tool. The desirable factors of good thermal conductivity of the braze metal and its cushioning effect should be compared (in light of the job the tool must do) with the fact that the braze bond may be soft and consequently may not provide sufficient rigidity and support for the cutting tip in service.

Evaluating Liquid Penetrant Indications of Cracks in Cutting Tools

Liquid penetrant indications of minute checks and larger cracks can be identified on tools. Because scratches are relatively wide and shallow, as compared with cracks that are narrow and deep, they will not show at all with conventional water washable liquid penetrant systems because washing removes liquid penetrant from scratches.

Discontinuities such as cracks are probably due to combined brazing strain and improper grinding. Although these are rejected because of their directions and locations, it is conceivable that tools with cracks in certain locations and generally parallel to the principal stress, would give satisfactory service. The value of the tool relative to the value of the work in process and the danger involved would probably be deciding factors but the problem should receive much consideration.

Evaluating Liquid Penetrant Indications of Cracks and Checks in Thread Gages

Indications of extensive cracks and minute indications extending over one thread only were found on a hard, cobalt based alloy thread gage. Slight cracks in the rough stage after welding grew during the following grinding and thread cutting operations. The minute indications correspond to grinding checks that originated in the final grinding. The indications are similar to those of *pickling cracks* and, in this case, were caused by acid attacking areas of high residual stress during macroetching.

Correlating Liquid Penetrant Test Results with Tool Service Life

For control of quality, in many cases, it may be desirable to keep records of quality or of the life expectancy of typical tools. The manufacturer may plot the percentage of anomalous tools on a day-to-day or lot-to-lot basis to illustrate quality averages graphically. Any trend toward excess scrap can be noticed and corrective measures taken. Similar procedures can demonstrate the efficiency of an individual machine or process.

When such records are properly used, the specialized job knowledge of the practical person is coordinated with that of test personnel and should result in reduced scrap loss. The tool user must have the right tools available for repeat usage. Otherwise quick decisions are often necessary to select the optimum tool for the job from the types of tools that happen to be available. It would be desirable to keep shop records showing the length of service between grindings as well as the ultimate life of certain types of tools as used for various processes. Similar records of tool regrinding for individual machines could assist the selection of proper tool grinding wheels, speeds and feeds.

Inspection of Carbide Tipped Milling Cutters

Carbide tipped milling cutters each normally contain between 8 and 24 cutting blades, yet if only one tip shatters and drops out of its blade during the machining cycle and the operator does not immediately back off on the controls, then the entire cutter and possibly the workpiece could be ruined. Machine downtime also would result, which is quite costly for some of the larger milling machines.

Causes of Failure of Carbide Cutting Tips

The most frequent cause of carbide tip fracture is tiny, hairlike cracks that form in the carbide section during heat treating, brazing and grinding operations. Manufacturers of milling cutters try to prevent such cracks throughout tool fabrication, grinding, shipping and handling. Combinations of standard and metallurgical tests and nondestructive testing methods are used. Large scale users of milling cutters who resharpen their own cutters can benefit by using these procedures.

The carbide tips are brazed into a variety of blade materials in various ways, depending on their ultimate use. For example, a tip would be brazed into the tool body with copper brazing if a high amount of heat is expected to be generated during cutting. Some tips are brazed in with silver solder where less heat is generated. During the brazing, uneven material stresses could cause tiny cracks to form in the carbide.

Liquid Penetrant Processing of Carbide Tipped Milling Cutters

Once the tips are brazed into the cutting tool bodies, they are sent in baskets to the blade inspection area. Here, they are first put through a postemulsification fluorescent liquid penetrant testing station to seek the almost invisible cracks that might be present. This equipment will reveal the tiny cracks under ultraviolet radiation after they have been processed.

One man handles the entire operation. It takes about 25 min for a part to go through this test — from liquid penetrant application through ultraviolet radiation inspection. However, the operator has many different parts in various stages of preparation on the roller conveyor.

Fluorescent Inspection of Carbide Tips and Blades

Each blade tip is then viewed under ultraviolet radiation. At this point in the test, the tiniest cracks in the carbide tips will show up as thin, brightly flowing lines. Cracked blades discovered at the test station are not necessarily scrapped. If economical, they are sent back to production to have anomalous inserts removed and new ones brazed in. The reinserted blades must then go through the entire liquid penetrant procedure again.

When the blades pass the liquid penetrant test, they go through to the identification station. Here, numbers and letters are etched into the blades with an acid pad and stencil. The blades then undergo a Rockwell hardness test if a special blade shank hardness is read. If a 10 percent random sample of the batch passes this test, the entire batch is allowed to pass.

Then the blades go to the size test. At this station, the inspector compresses the size of the production blade with a master blade in a tabletop comparator. At this 100 percent go or no-go testing, the blades that do not pass are scrapped. Replacement blades that pass are ready for shipment. Others go to the assembly area where they are inserted in milling cutter bodies and given a final grinding operation.

Final Inspection of Cutter Assemblies after Finish Grinding

Because final grinding could cause tiny checks in the carbide tips, the entire cutter assembly goes to the liquid penetrant station for final testing. This time, the body and blades are processed overall and the entire assembly is inspected for cracks in critical areas.

Liquid penetrant test kits are available for small lot postproduction test needs. To inspect parts with this kit, the operator sprays them with a cleaner, wipes them dry and sprays on a red dye liquid penetrant. After this is wiped from the surface, the operator sprays on a white developer. Any crack that is present will then show up as a red line on the white background. The cleaner is also used elsewhere for general parts cleaning.

PART 2. Liquid Penetrant Testing of Oil Field Down Hole Tubular Parts

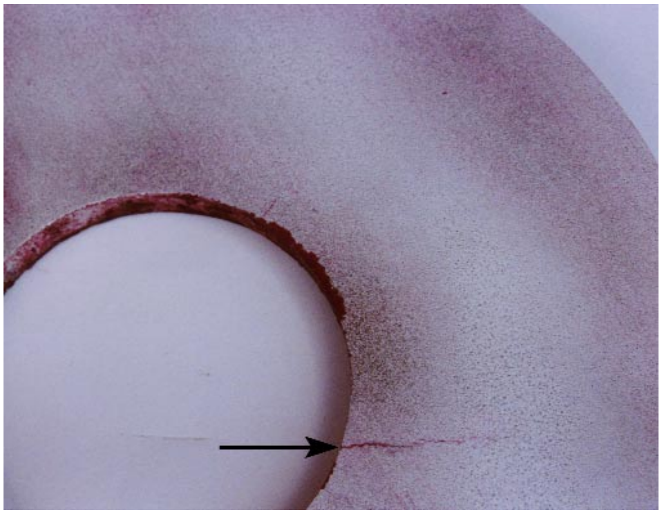
Range of Applications

Most of the products used in drilling an oil well are made of ferrous steels and therefore inspected with magnetic particle and electromagnetic methods. Some products used down hole are made of austenitic stainless steels or beryllium copper. These parts are normally used for directional survey or other application where a magnetic field would interfere with the results that would be obtained with ferromagnetic materials.

These tubulars normally fall into the category of *bottom hole assembly* (BHA) components. The bottom hole assembly is used to put weight on the bit so that it will break up the formation as it rotates. The tubulars have large outside diameters and minimal inside diameters to maximize weight on the bit and stability. The cross section of the nonmagnetic tubular shown in Fig. 1, is 200 mm (7.75 in.) outside diameter and 70 mm (2.8 in.) inside diameter.

During use, the nonmagnetic bottom hole assembly components develop cracks because of fatigue and stress corrosion. Fatigue cracks originate in the thread roots because this is the weak point for cyclic stress. The cyclic stress is caused by the rotation of the bottom hole assembly while it is bent from compression or in a dogleg. Stress corrosion cracking originates from the bore of the nonmagnetic bottom hole assembly (Fig. 1). Stress corrosion cracking is caused by a combination of stress and corrosion. These cracks can be either longitudinal or transverse.

FIGURE 1. Cross section of nonmagnetic tubular from bottom hole assembly.



Cleaning

Steam cleaning is the method of choice for cleaning bottom hole assembly components. The heat both opens the cracks and makes the thread lubricant less viscous. For this system to work the cleaning must be done for sufficient time to warm up both the bottom hole assembly material and any thread lubricant.

If steam cleaning is not available solvent is the next choice. Solvent can also be used after steam cleaning, to remove the detergent residue. The final cleaning solvent should be one that the liquid penetrant manufacturer has deemed compatible. Residues from cleaning agents, strong alkalies, picking solutions and chromate may adversely react with the liquid penetrant and reduce sensitivity and performance.

Liquid Penetrant Testing Technique Selection

Visible dye liquid penetrants are used to inspect nonmagnetic bottom hole assembly materials. Visible dyes provide the required sensitivity for the type and size of cracks found in nonmagnetic bottom hole assemblies. Further, because nonmagnetic bottom hole assembly connections are inspected many times in their life and it is not advisable to use fluorescent liquid penetrant after visible dye liquid penetrant, the use of fluorescent is avoided.

Liquid penetrant used to inspect the threaded area is normally removed by the solvent wipe technique. Because of the restricted access to the box threads and the difficulty in removing excess water, water washable liquid penetrant is not appropriate.

Because of the small inside diameters, water washable liquid penetrant is the most appropriate for the bore. Either postemulsifiable or water washable liquid penetrant is used for the outside diameter surface.

Test Process

Temperature

Surface temperature is normally the biggest problem in testing of oil field equipment. The acceptable range of temperatures for liquid penetrant testing is 10 to 52 °C (50 to 125 °F), it is important that the temperature remain within this range throughout the testing process. Because most of these tests are done in the field, the inspector has little control over the environment. If steam cleaning is done, the bottom hole assembly must be allowed to cool to an appropriate temperature. In the winter while doing the testing outdoors, the bottom hole assembly may be too cold to do a reliable test. In this case the bottom hole assembly must be moved inside and allowed to warm up before testing. It is important that the surface temperature remain within the proper range during the entire test time.

The bottom hole assembly temperature is the main consideration for dwell time. As the temperature approaches the minimum temperature of 10 °C (50 °F) the dwell time should be extended to 30 min. Longer dwell times do not affect the sensitivity of the test as long as the liquid penetrant is not allowed to dry, so if in doubt extend the dwell time.

Removing Excessive Liquid Penetrant

Standard liquid penetrant removal procedures are used for the removal of both the postemulsifiable and water washable liquid penetrants. When liquid penetrant is removed with a solvent wipe, a technique for both the dry wipe and damp wipe should be developed so that the minimum number of passes over the surface are required to thoroughly clean the surface. Ideally, if all the excessive liquid penetrant could be removed with one pass of the dry cloth and one with the dampened cloth the optimum result for the test would be achieved.

Drying

The surfaces of the bottom hole assembly to be inspected must be completely dry before the application of the developer. With the solvent remover system, this is not normally a problem, because the solvent dries quickly.

Developer Application

Solvent based (nonaqueous wet developer) spray-on developer is normally used in the testing of bottom hole assembly threaded areas. This of course is difficult in rotary shouldered connections, particularly the box, because you cannot spray directly on the thread roots because of the restricted diameter. Emphasis for an even thin coating should be focused on the thread roots because that is the location of cracks.

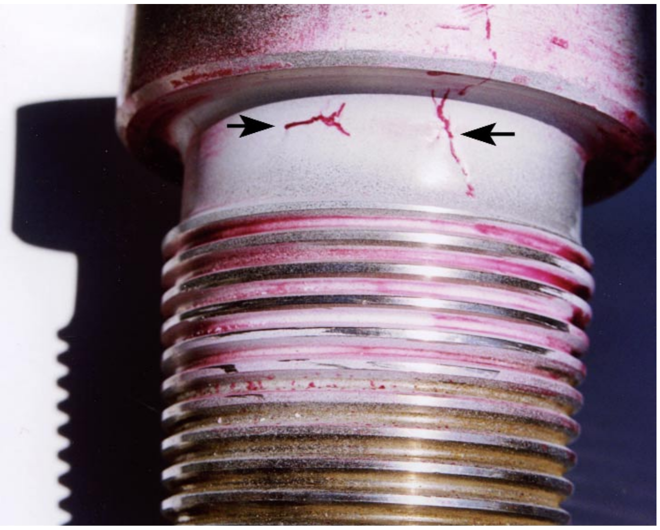
For the inside and outside diameter surfaces dry powder developer is also used.

Evaluation

The area to be inspected should be observed periodically during the development time. In the evaluation process, the observations concerning indication development will be helpful. The test should be done with at least 500 lx (50 ftc) light intensity at the surface to be inspected. The final examination is only done after the full development time has elapsed. Figure 2 shows crack indications on the connection outside diameter after the development time.

Cracks regardless of size render the bottom hole assembly unfit for further service and the part is rejected. Other indications are classified according to the appropriate testing standard.

Figure 2. Crack indications on connection outside diameter after development time.



PART 3. Marine Applications of Liquid Penetrant Testing

Liquid Penetrant Testing in Shipbuilding, Maintenance, Overhaul and Repair Yards

Liquid penetrant testing has been used in shipyards since the first half of the twentieth century.[1] The method's applications in shipyards are varied. The uses range from checking many sizes of ship propellers to inspecting welded or brazed joints in small diameter stainless steel tubing used for instrumentation on turbines and boilers. Generally an all inclusive procedure specification (typically ASTM E 165[2]) covering the different liquid penetrant techniques is the basis for testing. The United States Coast Guard, American Bureau of Shipping, United States Navy, Lloyd's Registry, Det Norske Veritas etc. each have specific areas for which they require liquid penetrant nondestructive testing and in some cases they have established acceptance criteria.

Liquid Penetrant Testing in New Ship Construction

Typical applications of liquid penetrant testing that may be required include the following: (1) testing of welded or brazed joints in austenitic piping, (2) checking nickel copper, stainless and other nonferrous alloy cladding or buttering of steel components, (3) inspecting welded joints in reactor piping systems using nonmagnetic materials, (4) testing of ship propellers where both hub and blades are visually inspected with the aid of visible dye liquid penetrants and (5) checking joints and nozzles in stainless steel pressure vessels and steam accumulator tanks.

Good marine workmanship requires liquid penetrant testing to check many other welded joints in nonmagnetic materials.

Liquid Penetrant Testing in Ship Repair and Maintenance

Applications of liquid penetrant testing in ship repair are generally the same as those in shipbuilding. However, it is also used in the overhaul of turbines, reduction gears, pumps and other ship machinery components. Many different applications occur in the cargo handling equipment and piping systems of specialized ships such as liquid sulfur tankers, refrigerated ships and liquid natural gas carriers.

Liquid penetrant nondestructive testing is also used in recreational boating. Many skippers in the highly competitive sailing races have titanium or stainless fitting in the rigging checked before races. In power boat racing, the stainless steel fittings in control systems are checked by many operators and owners.

Components Typically Inspected by Liquid Penetrants in Ship Repair Yards

The following are typical applications of liquid penetrant testing in ship repair facilities:

1. checking for cracks and discontinuities in bronze and stainless steel propeller blades and hubs;
2. checking for cracks in castings with as-cast surfaces (for example, checks for cracks can be made in valve bodies where surfaces are too rough for dry powder magnetic particle testing);
3. checking for cracks in bronze pump castings and impellers;
4. checking highly polished tail shaft and rudder stock tapers (often it is more convenient to use visible dye liquid penetrants because there is no need then to bring magnetic particle test equipment or electric power leads into shaft alleys);
5. checking for through-wall cracks in bulkhead welds by application of liquid penetrant on one side and developer on the other;
6. checking welds on copper or brass pipe used on salt water service lines;
7. checking crank pins and crank webs on diesel engine crankshafts, cylinder liners and connecting rods; and
8. checking hydraulic pump and motor parts (pistons, plungers, rods, cranks and ported heads).

The above components are usually checked with a standard visible dye liquid penetrant. Testing with fluorescent liquid penetrants is seldom used in shipyards because it is difficult to isolate test parts in a darkened area after installation.

Table 1. Typical United States Navy standards and specifications on liquid penetrant testing of ship hulls and nonnuclear machinery.

Item	Fabrication or Inspection Document	Acceptance Standard
Welding of pipe, pressure vessels, machinery[a]	NAVSEA Technical Publication T9074-AR-GIB-010/278[3]	MIL-STD-2035[4]
Structural welds, ships' hulls[b]	MIL-STD-1689[5]	———
Structural welds, HY-80 submarine hulls	NAVSEA Technical Publication T9074-AD-GIB-010/1688[3]	———
Castings of pressure vessels	NAVSEA Technical Publication T9074-AR-GIB-010/278[3]	———
Machinery-bronze propeller blades	NAVSEA Technical Publication T9074-AR-GIB-010/278[3]	———
Hull castings other than HY-80	MIL-STD-1689[5]	MIL-STD-1689[5]
HY-80 hull castings	NAVSEA Technical Publication T9074-AD-GIB-010/1688[3]	NAVSEA Technical Publication T9074-AD-GIB-010/1688[3]

a. Technique requirements (how to do inspection) are covered in NAVSEA Technical Publication T9074-AS-GIB-010/271.[3]

b. Other than HY-80 submarine hulls.

Liquid Penetrant Testing Specifications in Marine Industries

Liquid penetrant testing requirements in the marine construction industry are as varied as the applications. Marine specifications fall into two broad classifications: (1) United States Navy new construction and overhaul/repair requirements and (2) maritime (commercial) new construction and repair/overhaul. Table 1 lists typical nonnuclear United States Navy specifications controlling liquid penetrant testing.[3-5]

Specifications for Liquid Penetrant Testing of United States Navy Vessels

For construction of new United States Navy vessels, each ship (or ship class) has a set of detail specifications that invoke basic fabrication and test requirements (see Table 2). These basic fabrication and testing documents specify (1) what to inspect, (2) where to inspect, (3) acceptance criteria and (4) test methods. The acceptance criteria requirements of these fabrication/inspection documents generally invoke an acceptance standard, such as MIL-STD-2035.[4] This acceptance standard requires a certain class or severity level to be used for the various components or areas to be inspected. In some cases, the fabrication/inspection documents specify that particular materials be used for a component and the material must be inspected in accordance with specification. A typical situation of this type would be that of machinery studs fabricated to specification.

The test method requirements given in the fabrication and inspection documents generally invoke NAVSEA Technical Publication T9074-AS-GIB-010/271.[3] However, many times this standard is invoked with limitations and modifications. It should also be noted that ship detail specifications may also limit or modify the basic fabrication documents, acceptance criteria or method specification.

Table 2. Maximum permissible rounded indication sizes. Total indication area is 0.50 percent of weld surface area.

Nominal Weld Thickness		Maximum Permissable Rounded Indication	
mm	(in.)	mm	(in.)
≤ 3.2	(≤ 0.125)	2.0	(0.08)
3.2 to 4.8	(0.125 to 0.19)	2.0	(0.08)
4.8 to 6.4	(0.19 to 0.25)	2.4	(0.09)
6.4 to 9.5	(0.25 to 0.375)	2.4	(0.09)
9.5 to 12.7	(0.375 to 0.50)	3.2	(0.125)
12.7 to 19.0	(0.5 to 0.75)	3.2	(0.125)
≥ 19.0 mm	(≥ 0.75 in.)	3.2	(0.125)

Specifications Covering Liquid Penetrant Testing in Nuclear Navy Ship Systems

United States Navy nuclear fabrication/inspection requirements are generally contained in NAVSHIPS 250-1500-1[6] as invoked by the ship's specifications. For some applications, the test methods are specified in accordance with MIL-STD-2132.[7]

Specifications Covering Liquid Penetrant Testing in Navy Ship Repair and Overhaul

Repair and overhaul requirements are given in the overhaul work package (OWP) or the repair contract and invoke the *Naval Ships' Technical Manual* (NSTM).[8] The NSTM is published in chapters as a NAVSEA document. Typical of these is Chapter 556 on hydraulic equipment (NAVSEA 0901-LP-556-000).[9] These documents specify (a) what to inspect, (b) where to inspect, (c) how to inspect and (d) the acceptance criteria for each component.

Specification for Liquid Penetrant Testing of New Commercial Ship Construction

New construction of commercial (maritime) ships starts in accordance with the ship's specifications issued by the owners. This document gives the ship engineering and naval architect requirements for the ship's machinery and hull structure. These design requirements also state that these components and structure shall "be in accordance with the requirements of the regulatory agencies." This means that the requirements of the United States Coast Guard (USCG) and the American Bureau of Shipping (ABS) are invoked.

United States Coast Guard Requirements for Maritime (Commercial) Ship Construction

The United States Coast Guard requirements for new commercial ship construction are contained in Title 46 of the Code of Federal Regulations (CFR), Subchapter F-Marine Engineering.[10] For test methods, this subchapter invokes the *ASME Boiler and Pressure Vessel Code*.[11] Section V of the *ASME Code* is used as the basis of the liquid penetrant testing procedure. However, because the liquid penetrant procedure of the *ASME Code,* Section V, is based on ASTM E 165, *Standard Recommended Practice for Liquid Penetrant Testing Method,*[2] the United States Coast Guard will accept this ASTM procedure. Part 56 of subchapter F of Title 46 of the CFR specifies (a) what to inspect, (b) where to inspect and (c) the acceptance criteria for liquid penetrant testing during commercial (maritime) ship construction in the United States.

American Bureau of Shipping Requirements for Maritime Ship Construction

The American Bureau of Shipping requirements for liquid penetrant testing in maritime (commercial) ship construction are given in the *Rules for Building and Classing Steel Vessels*.[12] Sections invoking requirements are 30, 32, 43 and 44 of these American Bureau of Shipping rules. American Bureau of Shipping surveyors (inspectors) will generally accept procedures satisfactory to United States Coast Guard requirements because American Bureau of Shipping rules in some areas are not definitive as to test methods and acceptance criteria. Both the American Bureau of Shipping and the United States Coast Guard regulatory agencies rely on *ASME Boiler and Pressure Vessel Code*[11] Requirements and ASTM standards for basic inspection specifications.

Confirmation of Liquid Penetrant Indications in Ship Structures

All indications at the toe of weld and in weld craters shall be considered relevant and shall be evaluated in accordance with the applicable acceptance standards. If indications are believed to be nonrelevant or false, the area in question shall be investigated by the following means:

1. liquid penetrant retesting after complete cleaning of the area;
2. 5× magnification visual testing; and
3. exploration of at least 10 percent of the area in question by removing the surface condition believed to have caused the indications.

The absence of indications during retesting by liquid penetrant testing after elimination of conditions believed to have caused the indications shall be considered to prove that the indications were nonrelevant or false with respect to actual discontinuities. If reinspection reveals any indication(s), these indications and all of the original indications shall be considered to be relevant and shall be evaluated in accordance with the applicable acceptance standards. A description and the location of all liquid penetrant indications dispositioned as nonrelevant and the means of confirmation shall be recorded in the inspection report.

Acceptance and Rejection Criteria for Welds in United States Surface Ship and Submarine Structure

Linear Indications

All welds and at least 13 mm (0.5 in.) of adjacent base metal on each side shall be free of linear indications greater than 1.6 mm (0.06 in.) long, except for acceptable undercut and base metal indications that meet the base metal specification requirements. Indications 1.6 mm (0.06 in.) and less shall be considered nonlinear.

Nonlinear Indications

Nonlinear indications meeting the standards of Table 2 are acceptable.

Nonrelevant indications

Rounded indications with diameter of 0.4 mm (0.016 in.) and less shall be disregarded for material with thickness of 4.8 mm (0.19 in.) and less.

Rounded indications with diameter of 0.8 mm (0.03 in.) and less shall be disregarded for material with thickness greater than 4.8 mm (0.19 in.).

Linearly Aligned Indications

Linearly aligned indications shall be cause for rejection if one or more of the aligned indications is 1.6 mm (0.06 in.) or greater.

Precautions in Liquid Penetrant Testing of Ship Structures

Operator Safety

Operators should avoid skin contact with liquid penetrant materials. The inhalation of oils and possibly certain other components of liquid penetrant materials in moist form can cause lipoid pneumonia. To protect against this hazard, use a half mask respirator with organic vapor cartridges while spraying. At other times, avoid prolonged breathing of vapors or volatile components. If natural ventilation is poor, use exhaust ventilation to prevent a high atmospheric droplets from the air. Keep respirator on if mist is visible in the air.

Fire Prevention

During liquid penetrant testing of ships, dispose of all wiping cloths and papers by depositing in a closed metal container. Do not dispose of wiping materials or liquids in open containers. Do not subject liquid penetrant materials to heat. Do not smoke in a space where liquid penetrants are being or have just been, used. Do not use liquid penetrants or process materials near open flames. Make certain that welding on a common bulkhead is not being performed in the adjacent space when using liquid penetrants aboard ships. Flammable liquids should be dispersed only from approved safety cans. Only explosion proof portable lights should be used in flammable atmospheres.

PART 4. Liquid Penetrant Testing of Automotive Parts

Liquid Penetrant Testing of Automotive Engine Blocks

The automotive industry uses liquid penetrant testing primarily during the development of parts design and a little in maintenance of production equipment. When an engine manufacturing plant found visible cracks in the bottom of cylinder bores of certain engine cylinder blocks after machining, all cylinder blocks of this type were subjected to visible dye liquid penetrant testing until the cause was remedied. Magnetic particle testing was not used because cracks were in an inaccessible area for prods and because the area was finish machined. Procedural steps included the following: (1) clean parts thoroughly; (2) apply liquid penetrant to parts and allow 10 min to penetrate; (3) remove surface liquid penetrant from parts, using a clean cloth dampened with cleaner; (4) apply developer powder to parts and allow 5 min for powder to dry and indication to form; (5) inspect parts under white light; and (6) clean parts, using a cloth dampened with cleaner.

Liquid Penetrant Testing of Aluminum Alloy Automotive Parts

Visible dye liquid penetrant testing has been used to inspect experimental aluminum automotive power train components in service, including (1) aluminum cases of automatic transmissions, (2) aluminum wheels, (3) aluminum rocker arm supports and (4) aluminum rocker arm covers.

Procedural steps include the following: (1) clean parts thoroughly; (2) apply liquid penetrant to part and allow 10 to 15 min to penetrate; (3) remove surface liquid penetrant from parts, using a clean cloth dampened with cleaner; (4) apply developer powder to parts and allow 5 to 15 min for powder to dry and indication to form; (5) inspect parts under white light: (6) clean parts, using a cloth dampened with cleaner.

Fluorescent Liquid Penetrant Testing of Aluminum Automobile Engine Components

Fluorescent water washable liquid penetrant testing is also used on experimental aluminum automotive engine components, new and used, such as (1) aluminum pistons, (2) aluminum connecting rods, (3) aluminum manifolds and (4) radiators.

Procedural steps are as follows: (1) clean parts by vapor degreasing; (2) dip parts into tank of fluorescent liquid penetrant for 5 s; (3) drain parts held by wire hanger for 10 min; (4) rinse parts with water spray at 45 degree angle for about 15 s (rinse is performed in a darkened booth with a 100 W ultraviolet lamp to ensure uniform removal of background indications); (5) dry parts for 4 min, using forced air at 71 °C (160 °F); (6) dip parts into dry developer powder for 3 min; (7) inspect parts within 0.4 m (15 in.) of a 100 W ultraviolet spot lamp; and (8) clean parts in industrial washer.

Fluorescent Liquid Penetrant Testing of Automotive Engine Piston

Figure 3 is a photograph of sectioned hemi head engine piston used in maximum performance (racing) applications. In the pristine condition, no fluorescent liquid penetrant indications are allowed in these forged aluminum alloy parts. Frequently, some polishing is required to remove surface folds etc. The most severe discontinuity is any detectable discontinuity in the three o'clock to nine o'clock orientation about the 28 mm piston pin hole. This disqualifies the part for use.

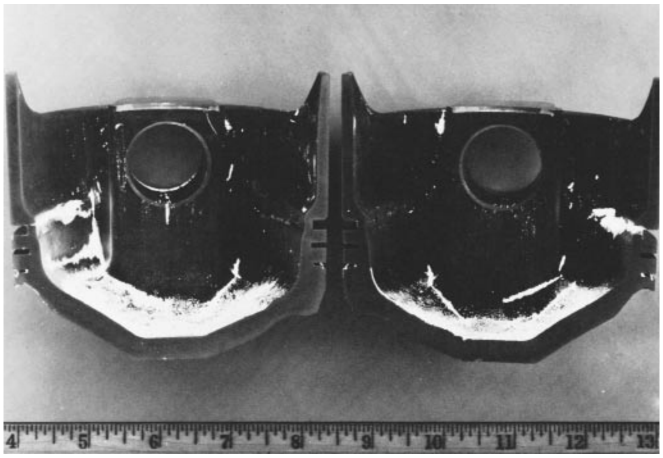
Figure 3a shows a used piston with several indications. First, the head area shows indications in all four head-to-skirt reinforcing rib sections. These are through cracks and are probably caused by the extreme stresses from engine operation. This racing engine had more hours of run on it than would be encountered in service. Secondly, in Fig. 3b an indication of a through crack in the upper ring groove area (compression ring) is present for about 20 mm on the photo. Finally, there is an indication of a through crack in the bottom ring groove (oil ring) almost halfway around the piston and through the plane of the sectioning. The postemulsifiable liquid penetrant testing procedure used for these pistons included the following steps.

1. Vapor degrease at 80 °C (180 °F) and allow to cool to room temperature.
2. Dip part in liquid penetrant, remove and drain for 15 min.
3. Dip part in emulsifier, remove and drain for 60 s, dip part again in emulsifier, remove and drain for 60 s.
4. Wash part to remove emulsifier using warm water, at about 27 °C (80 °F) under moderate pressure.
5. Place part in forced heated air drying oven at 65 °C (150 °F) until dry.
6. Remove part from oven and apply dry developer.
7. Inspect parts under ultraviolet light for discontinuities.

Fluorescent Liquid Penetrant Testing of Cars in Service

Liquid penetrant testing can be used by the automotive service technician to save and reuse sound parts and to detect and discard anomalous ones. Modern automotive design features thinner sections of material, in line with higher strength-to-weight ratios and more precise fits, stemming from increased complexity in parts and systems. Increasing popularity of nonmagnetic materials — aluminum, magnesium, cements, plastics and fiber glass — adds to the shop problem in determining the condition of key parts. Under ultraviolet radiation, the developed liquid penetrant highlights fatigue, grinding, heat treating or casting cracks, forging laps, porosity areas or other imperfections, in brilliant color.

Figure 3. Fluorescent liquid penetrant indications on sectioned hemi head forged aluminum alloy engine piston: (left) through cracks in head-to-skirt reinforcing rib section; (right) through crack in compression (upper) ring groove and in oil (bottom) ring groove. Scale is in inches (1.0 in. = 25.4 mm).



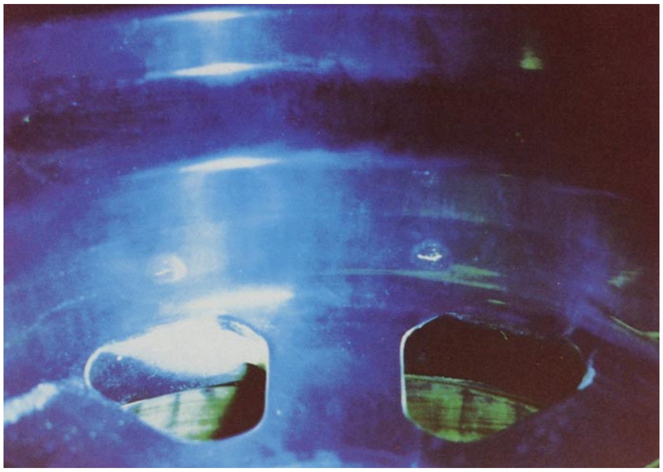
Fluorescent Leak Testing

A firm specializing in rebuilding automatic transmissions has always found it difficult to locate the source of leaks that could be either in the engine or the transmission and to make certain that there were no leaks in rebuilt engines. A wrong guess could mean taking a transmission apart in a vain effort to find

Figure 4. Fluorescent liquid penetrant testing of racing wheel: (a) test station; (b) indication under ultraviolet radiation.

(a)

(b)



a leak, which would later turn up in the engine. Leaking rebuilt units mean lost time and extra cost. The high intensity ultraviolet radiation beam is used to examine the underside of cars to determine the source of any leak. The appearance of oil under ultraviolet radiation gives the answer: transmission oil appears purple and engine oil brown. Fluorescent liquid penetrant additives that can be added to the oil in the automotive crankcase or transmission are also available. These additives produce a bright fluorescent indication at the point of the leak exit when inspected with ultraviolet radiation. Parts that go into rebuilt transmissions are sprayed with fluorescent liquid penetrant on one side, then inspected on the other side under ultraviolet radiation. Liquid penetrant soaks through the leaks and reveals them by brilliant fluorescent indications.

Maintenance Inspection of Open Wheel Racing Cars[13]

In 1965, the Nondestructive Testing Committee of the United States Auto Club (USAC) was formed for the inspection of cars participating in the Indianapolis 500 formula race. The committee has written specifications for formula racers and the United States Auto Club has mandated that all a car's critical components — transmission, steering, suspension, wheels — be inspected before the car is permitted on the track. In maintenance of formula racing cars, liquid penetrant testing is used to inspect aluminum and magnesium brackets, aluminum and magnesium gear box housings, magnesium wheels and aluminum pistons. Figure 4 shows the application of liquid penetrant testing to a racing wheel.

Nondestructive Testing of Magnesium Wheels of Open Wheel Racing Cars[14]

The following procedure shall apply to the inspection of magnesium wheels (Fig. 5) as required by the competition rules of the United States Auto Club.

Linear Indications

All surfaces shall be free of linear indications and free of linearly disposed rounded indications where there are four or more rounded indications in a line and each is separated from the adjacent indications by less than 1.6 mm (0.063 in.). Rounded indications are any indications that are circular or elliptical with the long axis less than three times that of the other axis. Linear indications are lines, continuous or broken, and may be caused by cracks or other serious discontinuities such as cold shuts or misruns in castings and such as laps or bursts in forgings.

Cluster Porosity and Microshrinkage

Cluster porosity or microshrinkage shall not exceed 13 mm (0.5 in.) square and the frequency of the indications in the affected area must be less than 50 percent of the area. Cluster indications on the opposite side must not exceed 6 mm (0.25 in.) square in area and the frequency of indications must not exceed 50 percent of the area. These cluster porosity or microshrinkage indications are acceptable when they are not within 13 mm (0.5 in.) of a bolt hole, rim edge or spokes or of any radius on the wheel configuration.

Porosity

Scattered indications of porosity up to 1.6 mm (0.063 in.) maximum in diameter and individual (isolated) indications of porosity up to 4.8 mm (0.19 in.) maximum in diameter are acceptable. Parts with discontinuities that can be removed by a suitable blending procedure while still maintaining minimum wall thickness in the affected area will be accepted after retest.

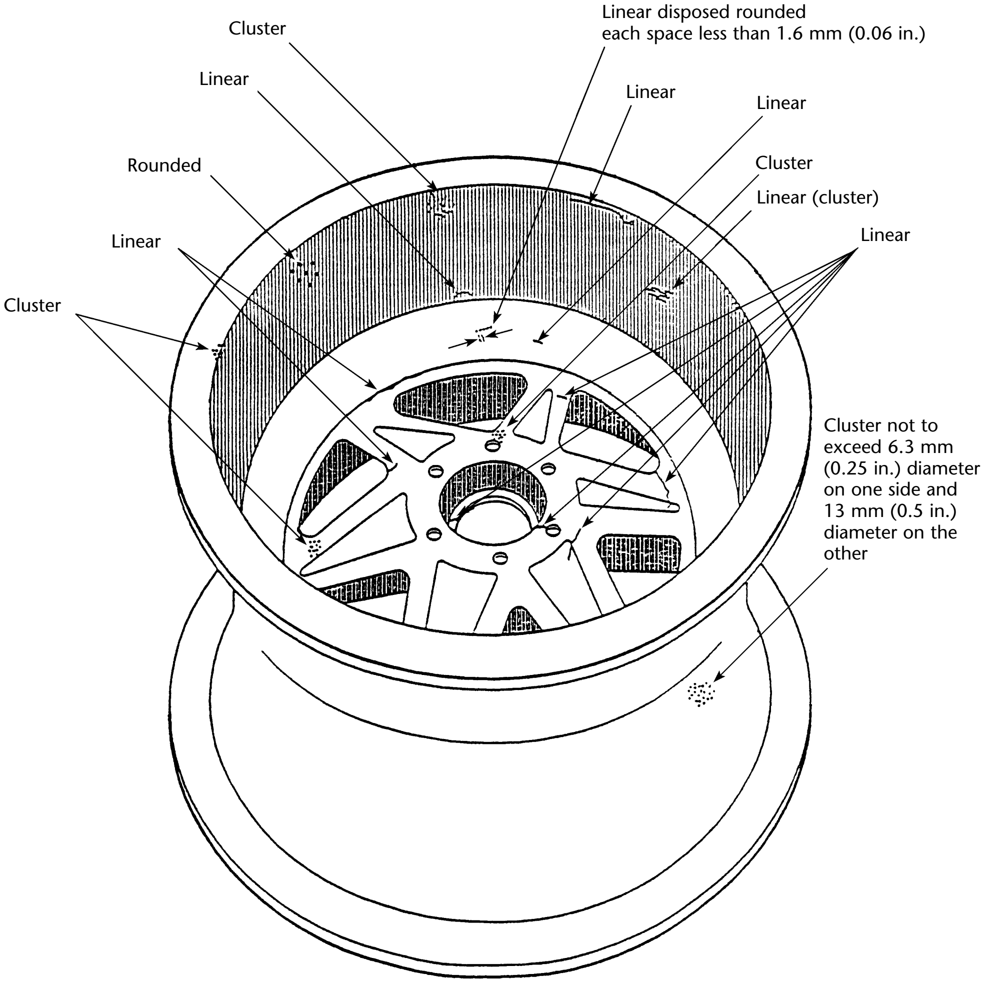
Indication Evaluation

Rounded indications that exceed the specified class level when invoked for the specific component shall be cause for rejection. Linear indications that exceed the specified class level when invoked for the specific component shall be cause for rejection.

If allowed by the specific procedure, indications may be evaluated by wiping the indication with a solvent dampened swab, allowing the area to dry, and by redeveloping. Redevelopment time shall be as long as the original development time. If no indication reappears, the original indication is considered false. This procedure may be performed twice for any given original indication.

When allowed by the specific examination procedure, discontinuities may be removed by an approved procedure such as sanding, either powered or manual, or grinding to determine the depth and extent of the discontinuities. After the mechanical operation, the area shall be cleaned, etched (if permitted) and reinspected. The process used for reinspection shall be at least as sensitive as the original process.

FIGURE 5. Fluorescent liquid penetrant indications in magnesium wheel of open wheel racing car.



Caution

Wheels must be free of surface contamination (especially in the bead seat area) that would prevent liquid penetrant from entering any discontinuities. Special attention should be given to areas of highest stress such as the pin drive holes in the hub and the junction of the spokes to the web, with both the hub and the rim. The attached sketch is an example of the inner wheel area only. The entire wheel is to be inspected using the same accept/reject criteria.

Marking of parts shall be per specifications.

This procedure is not intended to limit the type or amount of testing performed. It is recommended that, whenever practical, further testing be conducted to reveal any potentially harmful internal discontinuities and surface anomalies.

PART 5. Liquid Penetrant Testing of Plastic Materials

Causes of Cracks in Plastic Products

Cracks in molded organic resins or plastics can result from stresses set up in the molding process or in cooling, handling or assembly operations, as well as from chemical environments. Inservice cracking of plastics can also result from mechanical shock and electrical and thermal loads. These discontinuities in a broad spectrum of plastic components can easily be detected by liquid penetrant testing. This method has been applied to the design and processing of such plastic products as electronic insulators, business machine housings, plastic pipe, small gears and bearings, tetrafluoroethylene sheet, phenolic resin parts and switch housings for high altitude aircraft and missiles.

Reasons for Testing of Plastics

Nondestructive testing has become a tool of increasing value for industries that produce plastic products. Tests are used with three different philosophies, each having a different principal objective.

One approach is for quality assurance, testing for discontinuities to ensure that the final product is as free as possible from discontinuities that would interfere with its satisfactory performance. This objective alone justifies a large effort and expenditure for inspection and testing equipment. But, if applied only to this end, much of what can be realized from testing is lost.

The second philosophy includes quality assurance but adds to it this important concept. By applying nondestructive tests on new materials and at various strategic times during processing, an actual dollar profit will result and at the same time, the original objective will still be reached. The basic principle is to use nondestructive testing at such times that the tests locate anomalous material as soon as it becomes anomalous and then remove this material from further processing before additional work has been performed. Thus, production personnel time is devoted to producing usable products and not to producing a product already anomalous, which would be rejected as scrap on final testing. Liquid penetrant testing, along with other nondestructive tests, is used for this objective in most industries.

The third philosophy, which results in substantial returns, simply uses systematically the information developed under the first two. By tabulating and analyzing the nature and times of occurrence of the various discontinuities, found during manufacture, raw materials may be better selected, designs improved and processes corrected to the end that the incidence of discontinuities is reduced or eliminated, production costs lowered and the service life of the product extended.

When liquid penetrants are used to find cracks that develop in service, the prime purpose is to avoid failures during operation, with their resultant losses. By intelligent use of data on location and character of discontinuities, permanent improvement in materials and designs can be made if the information is fed back to the proper places.

Selection of Liquid Penetrants for Tests of Plastics

Water washable liquid penetrants, postemulsifiable liquid penetrants and water base liquid penetrants, both fluorescent and visible dye, are the basic types used in nondestructive testing of plastic materials. In addition, filtered particle testing is used on porous materials, including some reinforced plastics. No special techniques are required in most plastics applications, except that care must be taken that the plastic in question is not attacked by the liquids used in the particular liquid penetrant system being considered. In those cases where standard liquid penetrants and plastics are incompatible, several special formulations have been made to handle the testing problem.

Fluorescent Water Washable Liquid Penetrants

Molded phenolic resin parts for electrical components such as distributor caps and switch housings are examined for cracks using the standard water wash liquid penetrant formula, because this type of plastic is unaffected by most liquids. Indications are in the form of minute molding cracks. An interesting type of molded product is made by precision molding a mixture of mica and glass (glass bonded mica) into complex parts, many of which are used for electrical insulating purposes such as tube sockets and coil forms. Liquid penetrant testing has shown indications of cracks in glass bonded mica insulators.

Another application of water wash fluorescent testing is the plastic switch housings used in high altitude aircraft and missiles. Switching components housed in a plastic case are of pure silver and gold, so that they can be stored for long periods of time without problems of damage and corrosion. Because moisture entering the housing will affect the switching components, no cracks can be tolerated. Another application of water wash liquid penetrants is in checking the bond in printed circuit boards.

Visible Dye Liquid Penetrants

Color contrast liquid penetrants are also used successfully in many plastic testing applications. Cracks that occur in plastics are usually clean and easy to find with liquid penetrants. Color contrast liquid penetrants are used to test sheets of tetrafluoroethylene resin for surface characteristics such as degree of porosity. Lack of bond between inserts or reinforcements in molded plastics is another use in this field; an example is the testing of the edges of thick canvas phenolic resin sheets for lack of bond between resin and reinforcements.

Interpretation of Glass Bonded Mica and Ceramoplastics

Glass bonded mica products are formed by pressure blending powdered glass and mica into electrical insulators. The resultant mixture becomes a workable material called glass bonded mica that combines the advantages of low loss factor and high dielectric strength while eliminating the major deficiencies of the brittleness of glass and the weak structural homogeneity of mica.

Glass bonded mica and ceramoplastics, a blend of powdered glass with synthetic mica, are used in making many types of insulated electronic devices. Depending on the type, the material can be precision molded to size, compression molded in sheets for fabrication or machined in the plant. The precision molding operation is extremely critical, because small variations in temperatures or pressure can cause the parts to crack. It is difficult to predict the exact requirements for a given job.

Fluorescent liquid penetrant testing detects the cracked parts. With previous test techniques, the parts were molded and annealed. Only at the end of an 8 h annealing was the first check on product quality obtained. Until they had been put through annealing, there was no way of knowing to what extent the pieces would be free of failure because of knit lines and cracks.

The liquid penetrant process is used to determine in advance whether or not the pieces will be good after they have come through the annealer. The molding cycle can be modified until the desired results are obtained. No time is wasted on further processing of anomalous parts. This control process gives a high percentage of good parts, whereas the old process might produce a total loss for the 8 h run.

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CHAPTER

Liquid Penetrant Testing Glossary

Introduction

Most of the definitions in this glossary are adapted from the text of published volumes of the *Nondestructive Testing Handbook*.[1-10] The definitions in this glossary have been modified to satisfy peer review and editorial style. For this reason, references given in this glossary should be considered not attributions but rather acknowledgments and suggestions for further reading.

The definitions in this *Nondestructive Testing Handbook* volume should not be referenced for inspections performed according to standards or specifications or in fulfillment of contracts. Standards writing bodies take great pains to ensure that their documents are definitive in wording and technical accuracy. People working to written contracts or procedures should consult definitions referenced in real standards when appropriate.

This glossary is provided for instructional purposes. No other use is intended.

Glossary Entries

A

absolute temperature: Temperature measured from absolute zero temperature, expressed in kelvin (K) in SI.[1,10]

acceptable quality level (AQL): Maximum percent defective (or the maximum number of units with rejectable anomalies per hundred units) that, for purposes of sampling tests, can be considered satisfactory as process average.[8,10]

acceptance criteria: Standard against which test results are to be compared to establish functional acceptability of part or system being examined.[10]

acceptance standard: Specimen similar to the test object containing natural or artificial discontinuities that are well defined and similar in size or extent to the maximum acceptable in the product. See *reference standard* and *standard*.[4,6,7,10]

accommodation: Of the eye, adjustment of the lens' focusing power by changing the thickness and curvature of lens by tiny muscles attached to lens.[8,10]

accuracy: Degree of conformity of measurement to a standard or true value.[1,10]

adaptive thresholding: Threshold value varying with inconstant background gray level.[8,10]

age hardening: Process of aging that increases hardness and strength but that ordinarily decreases ductility. Also known as *precipitation hardening*.[3,10]

agency: Organization selected by an authority to perform nondestructive testing, as required by a specification or purchase order.[2,10]

ambient light: Light in environment as opposed to illumination provided by the testing system.[8,10]

ambient or **atmospheric temperature:** Temperature of surrounding atmosphere. Also called dry bulb temperature.[10]

angle: See *field angle*.[10]

Angstrom unit (Å): Disused unit to express electromagnetic radiation wavelength. 1Å = 0.1 nm.

annealing: Process of heating and cooling a material, usually to reduce residual stresses or to make it softer.[2,3,8,10]

anomaly: Variation from normal material or product quality.[4,10]

AOQ: Average outgoing quality.[10]

AOQL: Average outgoing quality limit.[10]

AQL: See *acceptable quality level*.[10]

arc strikes: Localized burn damage to object from arc caused by breaking an energized electric circuit. Also called arc burns.[6,10,11]

arc welding: See *electric arc welding*.[10]

artifact: In nondestructive testing, an indication that may be misinterpreted as a discontinuity.[2,10]

ASNT: American Society for Nondestructive Testing.[10]

***ASNT Recommended Practice No. SNT-TC-1A*:** Set of guidelines for employers to establish and conduct nondestructive testing personnel qualification and certification programs. *SNT-TC-1A* was first issued in 1968 by the Society for Nondestructive Testing (SNT, now ASNT) and has been revised every few years since.[8,10]

atmosphere: See *standard atmospheric conditions*.[10]

automated system: Acting mechanism that performs required tasks at a determined time and in a fixed sequence in response to certain conditions.[8,10]

B

background: Surface of object on which indication is viewed in surface methods such as liquid penetrant and magnetic particle testing. It may be the natural surface of the object or the developer coating on the object surface. This background may contain irrelevant information that can interfere with indication visibility.[2,6,10,11]

background fluorescence: Fluorescent residue observed over the part surface or in localized areas caused by surface contamination or surface finish, which interferes with liquid penetrant removal or is due to improper technique for liquid penetrant process removal.

black light: Disfavored term for electromagnetic radiation or light energy in the *near ultraviolet* range (UV-A) with wavelengths from 320 to 400 nm, just below the wavelengths of visible light. Also a term for ultraviolet radiation source used in fluorescent nondestructive testing. Near ultraviolet sources often have a predominant wavelength of 365 nm. See the preferred term, *ultraviolet radiation*.[2,6,8,10,11]

black light filter: Filter that transmits ultraviolet radiation between 320 and 400 nm wavelengths while absorbing or suppressing the transmission of the visible radiation and hard ultraviolet radiation with wavelengths less than 320 nm.[6,10,11]

blacklight: See *black light*.[10]

bleedback: Ability of liquid penetrant to bleed out of a discontinuity subsequent to removal of the indication without reapplying the liquid penetrant.[2,10]

bleedout: Action by which a liquid penetrant exudes from discontinuities onto the surface of a material. Action of the entrapped liquid penetrant in spreading out from surface discontinuities to form an indication.[2,10]

blind spot: Portion of the retina where the optic nerve enters, without rods and cones and hence insensitive to light.[8,10]

blister: Discontinuity in metal, on or near the surface, resulting from the expansion of gas in a subsurface zone. Very small blisters are called pinheads or pepper blisters.[2,10]

blotch: (1) Irregularly spaced area of color change on a surface. (2) Nonuniform condition of surface characterized by such blotches.[8,10]

blotting: Action of developer in soaking up liquid penetrant from surface of a discontinuity so as to cause maximum bleedout of liquid penetrant for increased contrast and sensitivity.[2,10]

blowhole: Hole in casting or weld caused by gas entrapped during solidification.[2,3,10]

blue hazard: Exposure to high frequency visible light at intensities and durations that may damage the retina, particularly with overheating.[8,10]

borescope: Industrial endoscope; periscope or telescope using mirrors, prisms, lenses, optic fibers or television wiring to transmit images from inaccessible interiors for visual testing. Originally used in machined apertures such as gun bores. There are both flexible and rigid, fiber optic and geometric light borescopes.[8,10]

borescope, fiber optic: Borescope that uses fiber optic materials (such as glass or quartz) in optical path and for transmission of light to and from test surface.[8,10]

borescope, ultraviolet: Borescope equipped with ultraviolet lamps, filters and special transformers to transmit radiation of ultraviolet wavelengths.[8,10]

brinell hardness: Measure of metal hardness. Determined by pressing hard steel ball into smooth surface under standard conditions.[10]

brinelling: Stripe indentations made by spherical object. *False brinelling* refers to type of surface wear.[8,10]

brittle crack propagation: Very sudden propagation of crack with absorption of no energy except that stored elastically in body. Microscopic examination may reveal some deformation even though it is not visible to unaided eye.[2,10] See *ductile crack propagation*.

brittleness: Quality of material that leads to crack propagation without appreciable plastic deformation.[2,10]

buckle: Indentation in casting, resulting from expansion of molding sand.[3,10]

burnt-in sand: Discontinuity consisting of mixture of sand and metal cohering to surface of casting.[3,10]

burr: Raised or turned over edge occurring on a machined part and resulting from cutting, punching or grinding.[8,10,12]

burst: In metal, external or internal rupture caused by improper forming.[8,10]

butt weld or **butt joint:** Weld joining two metal pieces in the same plane.[8,10]

C

caked: Of dry developer, having a semisolid condition caused by moisture or other liquid contaminants.

candela: Base unit of measure in SI for measuring luminous intensity. Luminous intensity in a given direction of a source that emits monochromatic radiation of frequency 5.4×10^{14} Hz and that has a radiant intensity in that direction of $1.464\ \mathrm{mW{\cdot}sr^{-1}}$. Symbolized *cd*. Formerly known as *candle*.[8,10]

candle: Former name for *candela*.[8,10]

capillary action: Tendency of liquids to penetrate or migrate into small openings, such as cracks, pits or fissures. The positive force that causes movement of certain liquids along narrow or tight passages.[2,10]

carrier fluid: (1) Fluid that acts as a carrier for the active materials. (2) Fluid in which fluorescent and visible dyes are dissolved or suspended, in liquid penetrants or leak tracers.[2]

case crushing: Mechanism producing fracture of the case, like subcase fatigue but attributable to static overloading rather than to fatigue alone. In many instances the movement of the subcase causes the case to crack or spall.[8,10]

cast weld assembly: Assembly formed by welding one casting to another.[3,10]

casting: Object of shape obtained by solidification of a substance in a mold.[10]

certification: Process of providing written testimony that an individual is qualified. See also *certified*.[8,10]

certified: Having written testimony of qualification. See also *certification*.[8,10]

chalk test: Past method of locating cracks by applying penetrating liquid to an object and then removing excess from surface. After the surface is coated with whiting or chalk, liquid penetrant seeps out of the cracks into whiting, causing an appreciable difference in whiteness. Also known as *oil and whiting* method.[2,10]

chatter: (1) In machining or grinding, vibration of tool, wheel or workpiece producing a wavy surface on the work. (2) Finish produced by such vibration.[2,10]

checks: Numerous, very small cracks in metal or other material caused in processing. Minute cracks as in a die impression, usually at a corner, caused by forging strains. Also called *grinding checks* and *check marks*.[2,10]

clean: Free from interfering solid or liquid contamination on the test surface and within voids or discontinuities.[2,10]

cleaner: Volatile solvent used to clean a surface before liquid penetrant application or to remove excess liquid penetrant.

cocoa: Debris (usually oxides of the contacting metals) of fretting wear, retained at or near the site of its formation — a condition especially helpful during visual tests. With ferrous metals, the debris is brown, red or black, depending on type of iron oxide formed. For this reason, ferrous debris is called *cocoa* or, when mixed with oil or grease, *red mud*.[8,10]

code: Standard enacted or enforced as a law.[8,10]

cold cracks: Discontinuities appearing as straight lines usually continuous throughout their length and generally existing singly. Cold cracks start at the surface and result from cold working or stressing of metallic materials.[2,10]

cold light: Obsolete word for *fluorescence*.[8,10]

cold shut: (1) Casting discontinuity caused by two streams of semimolten metal coming together inside a mold but failing to fuse. Cold shuts are sometimes called misruns but the latter term correctly describes incomplete filling of the mold.[3] (2) Discontinuity that appears on surface of test metal as result of two streams of liquid meeting and failing to unite. A cracklike discontinuity caused by forging, where two surfaces of metal fold against each other to produce discontinuity at the point of folding. This is usually at some angle to the surface. It may also be a separate piece of metal forged into the main component. See *lap*. (3) Portion of the surface of forging that is separated in part from main body of metal by oxide.[2,3,10]

color: Visual sensation by means of which humans distinguish light of differing hue (predominant wavelengths), saturation (degree to which those radiations predominate over others) and lightness.[10]

color blindness: Deficiency in ability to perceive or distinguish hues.[8,10]

color contrast dye: Dye that can be used in liquid penetrant to impart sufficient color intensity to give good color contrast indications against background on a test surface when viewed under visible light.[2,10]

color contrast liquid penetrant: Liquid penetrant incorporating dye, usually nonfluorescent, sufficiently intense to give good visibility to discontinuity indications under visible light.[2,10]

color discrimination: Perception of differences between two or more hues.[8,10]

comparator, penetrant: Test block or reference panel with artificial cracks or special surface conditions, typically having two separate but adjacent areas for application of different liquid penetrants or processing materials or operations so that direct visual comparison can be made between different liquid penetrant processes or materials.[2,10]

complete testing: Testing of entire production lot in prescribed manner. Sometimes complete testing entails inspection of only critical regions of part. One hundred percent testing requires inspection of the entire part by prescribed methods. Compare *sampling, partial*.[8,10]

confidence level: Level of assurance for detecting a specified discontinuity size with a specified probability.

contact time: See *dwell time*.

contaminant: Any foreign substance present on the surface of a part, in the cracks or in the inspection materials that will adversely affect the performance of liquid penetrant materials.

continuous casting: Casting technique in which an ingot, billet, tube or other shape is continuously solidified while being poured so that its length is not determined by mold dimensions.[3,10]

contrast: Difference in visibility (brightness or coloration) between an indication and the surrounding surface.[13]

control: See *in control, process control* and *quality control*.[10]

cooling stresses: Residual stresses resulting from nonuniform distribution of temperature during cooling.[2,3,10]

corrosion: Deterioration of a metal by chemical or electrochemical reaction with its environment. Removal of material by chemical attack, such as the rusting of automobile components.[2,10]

corrosion, crevice: Type of galvanic corrosion caused by differences in metal ion concentrations in neighboring portions of the corrodent.[8,10]

corrosion embrittlement: Severe loss of ductility of a metal, resulting from corrosive attack, usually intergranular and often not visually apparent.[2,10]

corrosion fatigue: Fatigue cracking caused by repeated load applications on metal in a corrosive environment.[2,10]

corrosion, fretting: Corrosion facilitated by fretting, particularly where a protective surface has been chafed in a corrosive environment.[8,10]

corrosion, poultice: Corrosion occurring under a layer of foreign material (e.g. under mud in automobile rocker panels).[8,10]

corrosion-erosion: Simultaneous occurrence of erosion and corrosion.[8,10]

coupon: Piece of metal from which a test object is prepared, often an extra piece, as on a casting or forging.[3,10]

crack: (1) Break, fissure or rupture, usually V shaped and with a relatively high depth-to-width aspect ratio. A discontinuity that has a relatively large cross section in one direction and a small or negligible cross section when viewed in a direction perpendicular to the first.[2,10]
(2) Propagating discontinuity caused by stresses such as heat treating or grinding. Difficult to detect unaided because of fineness of line and pattern (cracks together may have a radial or latticed appearance).[6,10]

crack contaminant: Material that fills a crack and that may prevent liquid penetrants from entering or from forming indications.[2,10]

crack, base metal: Cracks existing in base metal before a manufacturing or welding operation or occurring in base metal during the operation.[2,10]

crack, cold: Cracks that occur in a casting after solidification, due to excessive stress generally resulting from nonuniform cooling.[2,10]

crack, cooling: Cracks in bars of alloy or tool steels resulting from uneven cooling after heating or hot rolling. They are usually deep and lie in a longitudinal direction, but are usually not straight.[2,10]

crack, crater: Multisegment crack in a weld crater. Segments radiate from a common point, often called star cracks.[10]

crack, fatigue: Progressive cracks that develop in the surface and are caused by the repeated loading and unloading of the object.[2,10]

crack, forging: Crack developed in the forging operation because of forging at too low a temperature, resulting in rupturing of the steel.[2,10]

crack, grinding: Thermal crack caused by local overheating of surface being ground.[2,10]

crack, hot: Crack that develops before casting has completely cooled, as contrasted with cold cracks, which develop after solidification.[2,10]

crack, longitudinal: Crack parallel to length of the test object.[2,10]

crack, machining: Crack caused by too heavy a cut, a dull tool or chatter. Typically called *machining tear*.[2,10]

crack, pickling: Crack caused by immersing objects with high internal stresses in an acid solution.[2,10]

crack, plating: Crack similar to pickling cracks, but occurring during plating when the object is immersed in a strong electrolyte.[2,10]

crack, quenching: Rupture produced during quenching of hot metal because of more rapid cooling and contraction of one portion of test object than occurs in adjacent portions.[2,10]

crack, transverse: Crack at right angles to the length of the test object.[2,10]

crack, weld: Crack in weld fusion zones or adjacent base metal. Usually a result of thermal expansion or contraction stresses related to temperature changes during welding.[2,10]

crater: (1) In machining, depression in cutting tool face eroded by chip contact. (2) In arc or gas fusion welding, cavity in the weld bead surface, typically occurring when heat source is removed and insufficient filler metal is available to fill the cavity.[2,10]

creep: Gradual and permanent change of shape in a metal under constant load, usually at elevated temperature. Occurs in three stages: primary creep, secondary creep and tertiary creep. See also *deformation.*[8,10]

crevice corrosion: See *corrosion, crevice.*[10]

crush: Casting discontinuity caused by a partial destruction of the mold before the metal was poured.[3,10]

D

dark adaptation: Adjustment of the eye over time to reduced illumination, including increased retinal sensitivity, dilation of the pupil and other reflex physical changes.[2,6,10,11]

dark adapted vision: See *scotopic vision.*[10]

deburring: Removing burrs, sharp edges or fins from metal objects by filing, grinding or rolling the work in a barrel with abrasives suspended in a suitable liquid medium. Sometimes called *burring.*[2,3,10]

deep etching: Severe etching of a metallic surface for examination at a magnification of ten diameters or less to reveal gross features such as segregation, cracks, porosity or grain flow.[2,10]

defect: Discontinuity whose size, shape, orientation or location make it detrimental to the useful service of its host object or which exceeds the accept/reject criteria of an applicable specification. Note that some discontinuities may not affect serviceability and are therefore not defects. Compare *discontinuity, flaw* and *indication.*[2,6,8,10,12]

deformation: Change of shape under load. See also *creep.*[8,10]

degreasing fluid: Solvents or cleaners employed to remove oil and grease from test surfaces before the liquid penetrant is applied.[2,10]

delamination: Laminar discontinuity, occurring where two layers of differing materials are bonded together

depth of field: In photography, the range of distance over which an imaging system gives satisfactory definition when its lens is in the best focus for a specific distance.[8,10]

descaling: Removing the thick layer of oxides formed on some metals at elevated temperatures.[2,10]

detergent remover: Liquid penetrant remover that is a solution of a detergent in water.[2,10]

developer: In liquid penetrant testing, a material that is applied to the surface after excess liquid penetrant has been removed and that is designed to enhance the liquid penetrant bleedout to form indications. May be a fine dry powder, a solution that dries to form a dry powder or a suspension (in solvent or water) that dries leaving an absorptive film on the test surface.[2,10]

developer, dry: Dry, fine powder applied to the surface after excess liquid penetrant is removed and the surface dried in order to increase the bleedout by means of capillary action.[2,10]

developer, nonaqueous: Sometimes called *nonaqueous wet developer* or *solvent developer.* Fine particles suspended in a volatile solvent. The volatile solvent helps to dissolve the liquid penetrant out of the discontinuity and brings it to the surface. It then dries, fixing the indication.[2,10]

developer, soluble: Fine particles completely soluble in its carrier (not a suspension of powder in a liquid) that dries to form an adsorptive coating.[2,10]

developer, solvent: See *developer, nonaqueous.*[2,10]

developer, suspendible: Developer that consists of fine particles suspended in water and that dries to an absorptive coating. Applied to the part after removal of excess liquid penetrant and before drying.

developer, wet: Liquid penetrant developer that is wet when applied to a surface. See developer, soluble; developer, solvent; developer, suspendible.

developing time: Elapsed time necessary for the applied developer to absorb and show indications from penetrant entrapments.[2,10]

dewetting: Flow and retraction of liquid on a surface, caused by contaminated surfaces or dissolved surface coatings.[8,10]

diffuse indications: Indications not clearly defined — for example, indications from surface contamination.[2,10]

dip rinse: Means of removing excess surface liquid penetrant in which the test objects are dipped into a tank of agitated water or remover.[2,10]

direct viewing: Viewing of test object in the viewer's immediate presence. The term *direct viewing* is used in the fields of robotics and surveillance to distinguish conventional from remote viewing.[8,10]

directional lighting: Lighting provided on the work plane or object predominantly from a preferred direction.[8,10,14]

discernible image: Image capable of being recognized by sight without the aid of magnification.[2,10]

discontinuity: Intentional or unintentional interruption in the physical structure or configuration of a part. After nondestructive testing, an unintentional discontinuity interpreted as detrimental in the host object may be called a *flaw* or *defect.* Compare *defect, flaw* and *indication*.[6,8,10,11]

discontinuity, artificial: Reference discontinuities such as holes, indentations, cracks, grooves or notches that are introduced into a reference standard to provide accurately reproducible indications for determining sensitivity levels.[2,10]

discontinuity, inherent: Material anomaly originating from solidification of cast metal or weld material. Pipe and nonmetallic inclusions are the most common and can lead to other types of discontinuities in fabrication.[8,10,12]

discontinuity, primary processing: Material anomaly produced from the hot or cold working of an ingot into forgings, rod and bar.[8,10,12]

discontinuity, secondary processing: Material anomaly produced during machining, grinding, heat treating, plating or other finishing operations.[8,10,12]

discontinuity, service induced: Material anomaly caused by the intended use of the part.[8,10]

distal: In manipulative or interrogating system, of or pertaining to the end opposite from the eyepiece and farthest from the person using the system. Objective; tip.[8,10]

dragout: Carryout or loss of liquid penetrant materials as a result of their adherence to objects dipped into the materials.

drain time: Portion of dwell time during which the excess liquid penetrant, emulsifier, detergent remover or developer drains off an object.[2,10]

drop: Discontinuity in a casting due to a portion of the sand dropping from the cope or overhanging section of the mold.[3,10]

dross: Scum that forms on the surface of molten metals largely because of oxidation but sometimes because of the rising of impurities to the surface.[3,10]

dry bulb temperature: Alternate term for ambient or atmospheric temperature.[1,10]

drying oven: Oven used for increasing the evaporation rate of rinse water or of an aqueous developer vehicle from parts.

drying time: Time allotted for an object to dry in a drying oven.

dual response penetrant: Liquid penetrant that produces discontinuity indications that can be seen under either ultraviolet radiation or visible light.[2,10]

ductile crack propagation: Slow crack propagation that is accompanied by noticeable plastic deformation and requires energy to be supplied from outside the body.[2,10] See *brittle crack propagation*.

dwell time: Total time that the liquid penetrant or emulsifier is in contact with the test surface, including the time required for application and the drain time.[2,10]

E

electric arc welding: Joining of metals by heating with electric arc. Also called *arc welding*.[8,10]

electrostatic spraying: Technique of spraying a uniform surface coating, wherein the material being sprayed is given a high electrical charge (potential) while the test piece is grounded.[2,10]

emulsification time: In liquid penetrant testing, the period of time that an emulsifier is permitted to combine with liquid penetrant before removal. Also called *emulsifier dwell time*.[2,10]

emulsifier: Liquid that mixes with an oily liquid penetrant such that the mixture can then be washed from the surface with water.

emulsifier, contact: Emulsifier that begins emulsifying liquid penetrant upon simple contact with the liquid penetrant. Usually oil based (lipophilic).[13]

emulsifier, hydrophilic: Water based liquid that interacts with the liquid penetrant oil in the manner of a detergent, allowing the liquid penetrant to be washed from the surface with water.

emulsifier, lipophilic: Oil based liquid that mixes with liquid penetrant oil to form an emulsion that can be removed from the surface with water.

emulsion: Dispersion of fine droplets of one liquid in another that can be stabilized by the addition of an emulsifier.[2,10]

endoscope: Device for viewing the interior of objects. From the Greek words for *inside view,* the term *endoscope* is used mainly for medical instruments. Nearly every medical endoscope has an integral light source; many incorporate surgical tweezers or other devices. Compare *borescope*.[8,10]

equivalent 20/20 near vision acuity: Vision acuity with remote viewing or other nondirect viewing that approximates 20/20 direct viewing closely enough to be considered the same for visual testing purposes.[8,10]

equivalent sphere illumination: Level of perfectly diffuse (spherical) illuminance that makes the visual task as photometrically visible within a comparison test sphere as it is in the real lighting environment.[8,10]

erosion-corrosion: Simultaneous occurrence of erosion and corrosion.[8,10]

etch crack: Shallow crack in hardened steel containing high residual surface stresses produced by etching in an acid.[2,8,10,12]

etching: Cleaning process for the controlled removal of surface material by chemical agents before liquid penetrant application. Subjecting the surface of a metal to preferential chemical or electrolytic attack in order to reveal structural details.[2,10]

evaluation: Process of determining the magnitude and significance of a discontinuity after the indication has been interpreted as relevant. Evaluation determines if the test object should be rejected, repaired or accepted. See *indication* and *interpretation*.[2,6,7,10]

examination: Study of test object indications to determine if the test object meets specified acceptance criteria.[6,10]

exfoliation: Corrosion that progresses approximately parallel to the outer surface of the metal, causing layers of the metal to be elevated by the formation of corrosion product.[2,10]

external discontinuities: Discontinuities on the outside or exposed surface of a test object.[2,10]

eye sensitivity curve: Graphic expression of vision sensitivity characteristics of the human eye. In the case of a physical photometer, the curve should be equivalent to the standard observer. The required match is typically achieved by adding filters between the sensitive elements of the meter and the light source.[8,10]

F

false indication: Test indication that could be interpreted as originating from a discontinuity but which actually originates where no discontinuity exists. Distinct from nonrelevant indication. Compare *defect*.[2,7,8,10]

family: Obsolete term, formerly denoting a complete series of materials from one manufacturer necessary to perform a specific process of liquid penetrant testing.[2,10]

farsightedness: Vision acuity functionally adequate for viewing objects at a distance, generally beyond arm's length. Also called *hyperopia*. Compare *nearsightedness*.[8,10]

fatigue fracture: Progressive fracture of a material that begins at a discontinuity and increases under repeated cycles of stress. The phenomenon leading to fracture under repeated or fluctuating stresses having a maximum value less than the tensile strength of the material.[2,10]

filled crack: Cracklike discontinuity, open to the surface, but filled with some foreign material, such as oxide, grease, etc. that tends to prevent liquid penetrants from entering.[2,10]

fillet weld: Weld at the corner of two metal pieces.[8,10]

fine crack: Discontinuity in a solid material with a very fine opening to the surface, but possessing length and depth greater than the width of this opening. Usually the depth is many times the width.[2,10]

flakes: Short discontinuous internal fissures in ferrous metals attributed to stresses produced by localized transformation and/or decreased solubility of hydrogen during cooling usually after hot working. On a fractured surface, flakes appear as bright silvery areas; on an etched surface they appear as short, discontinuous cracks.[8,12] Also called *shatter cracks* and *snowflakes*.[2,10]

flash point: Lowest temperature at which vapors of a substance ignite in air when exposed to flame.[6,10,11]

flaw: Anomaly or unintentional discontinuity. Compare *defect* and *discontinuity*.[2,10]

fluorescence: Emission of visible light from a material in response to ultraviolet or X-radiation. Formerly called *cold light*.[8,10]

fluorescent contamination: Unintentional presence of fluorescent liquid penetrant on parts, in emulsifier, in developer or in the examination area.

fluorescent liquid penetrant: Highly penetrating liquid used in the performance of liquid penetrant testing and characterized by its ability to fluoresce under ultraviolet radiation.[2,10]

fluorescent liquid penetrant testing: Technique of liquid penetrant testing that uses fluorescent liquid penetrant.[10]

focus: Position of a viewed object and a lens system relative to one another to offer a distinct image of the object as seen through the lens system. See *accommodation* and *depth of field*.[8,10]

footcandle: Former unit of measure for illumination, equivalent to one lumen evenly distributed over a square foot or to a surface illumination at a distance of one foot from a point of one candela. Abbreviated *ftc* or *fc*. See also *lux*.[8,10]

footlambert: Former unit of luminance. Measured in the SI system by candela per square meter.[8,10]

forging crack: Discontinuity formed during mechanical shaping of metal.[8,10]

FPI: Fluorescent penetrant inspection. See *fluorescent penetrant testing*.

fracture: Break, rupture or crack large enough to cause a full or partial partition of a casting or other part.[2,3,10]

fretting: Action that results in surface damage, especially in a corrosive environment, when there is low amplitude motion between solid surfaces in contact under pressure. Also called *fretting corrosion*.[2,10]

fretting corrosion: See *corrosion, fretting*.[10]

G

galling: Type of adhesive wear more gross than fretting.[8,10]

gas tungsten arc welding (GTAW): Inert gas shielded arc welding using a tungsten electrode. Also called *tungsten inert gas (TIG) welding*.[8,10]

general examination: Test or examination of a person's knowledge, typically (in the case of nondestructive testing personnel qualification) a written test on the basic principles of a nondestructive testing method and general knowledge of basic equipment used in the method. (According to ASNT's guidelines, the general examination should not address knowledge of specific equipment, codes, standards and procedures pertaining to a particular application.) Compare *practical examination* and *specific examination*.[8,10]

glare: Excessive brightness (or brightness varying by more than 10:1 within the field of view) which interferes with *clear vision*, *critical observation* and *judgment*.[8,10]

gouge: Surface indentation caused by forceful abrasion or impact or flame cutting. Also called *nick*. Compare *tool mark*.[8,10]

grain boundary: Interface that forms between grains of solidifying metal as the random oriented crystal lattices meet.[8,10]

grain size: Size of the crystals in metal. When compared with a standard, usually referred to as being fine, medium or coarse.[2,10]

grinding cracks: Shallow cracks formed in the surface of relatively hard materials because of excessive grinding heat or the high sensitivity of the material. Grinding cracks typically are 90 degrees to the direction of grinding.[2,8,10,12]

H

halide: Compound of two or more elements, one of which is a halogen.[1,10]

hardness: Resistance of metal to plastic deformation, usually by indentation. However, the term may also refer to stiffness or temper or to resistance to scratching, abrasion or cutting.[2,10]

heat affected zone (HAZ): Base metal not melted during brazing, cutting or welding, but whose microstructure and physical properties were altered by the heat.[2,10]

heat checking: Surface cracking caused when metal rapidly heated (or cooled and heated repeatedly) is prevented from expanding freely by colder metal below the surface. Friction may produce the heat. Sometimes called *thermal fatigue*.[8,10]

heat treatment: Heating and cooling a metal or alloy in such a way as to obtain desired conditions or properties. Heating for the sole purpose of working is excluded from the meaning of this definition.[2,3,10]

high temperature penetrant: Liquid penetrant material specifically designed for use on high temperature surfaces where conventional liquid penetrant would be unsatisfactory.[2,10]

hot cracks: Ragged dark lines of variable width and numerous branches. They have no definite line of continuity and may exist in groups. They may originate internally or at the surface. Cracks occurring in hot solid metals, caused by stresses of thermal expansion or contraction and originating either internally or at the surface.[2,3,10]

hot tear: Fracture formed in a metal during solidification because of hindered contraction. Surface cracks on castings produced by contraction of the metal during cooling. Hot tears often occur where areas of different thickness adjoin.[2,3,8,10]

hot working: Deforming metal plastically at temperature and rate such that strain hardening does not occur. Low temperature limit is recrystallization temperature.[2,10]

hundred percent testing: See *one hundred percent testing.*[10]

hydrophilic emulsifier or **remover:** See *emulsifier hydrophilic*.

I

icicles: Coalescence of metal protruding beyond the root of the weld. Sometimes called *burn through.*[2,10]

illuminance: Density of luminous flux on a surface. Measured in the SI system by lux.[8,10]

illuminate: Shed light on.[8,10]

illumination: Act of illuminating or state of being illuminated. See also *illuminate*. Compare *illuminance.*[8,10,14]

image: Visual representation of a test object or scene.[8,10]

image guide: Fiber bundle that carries the picture formed by the objective lens at the distal end of a fiber optic borescope back to the eyepiece.[8,10]

image segmentation: Process in which the image is partitioned into regions, each homogeneous.[8,10]

impurity: Element or compound whose presence in a material is unintentional or unwanted.[2,3,10]

in control: Within prescribed limits of process control.[8,10]

incandescence: Emission of visible radiation due to thermal excitation.[8,10]

incomplete fusion: Fusion less than complete. Failure of weld metal to fuse completely with and bond to the base metal or preceding bead.[2,10]

incomplete penetration: In welding, root penetration less than complete, or failure of a root pass and a backing pass to fuse with each other. Also called *lack of fusion.*[2,10]

indication: Nondestructive testing response that requires interpretation to determine its relevance. Compare *defect, discontinuity* and *false indication.*[8,10]

indication, discontinuity: Visible evidence of a material discontinuity. Subsequent interpretation is required to determine the significance of an indication.[2,10]

indication, false: Indication produced by something other than a discontinuity. Can arise from improper test procedures.[6,10]

indication, nonrelevant: Indication due to misapplied or improper testing. May also be an indication caused by an actual discontinuity that does not affect the usability of the object (a tool mark, for instance).[2,10]

indication, relevant: Indication from a discontinuity (as opposed to a nonrelevant indication) requiring evaluation by a qualified inspector, typically with reference to an acceptance standard, by virtue of the discontinuity's size or location.[8,10,11]

inert gas shielded arc welding: Joining of metals by heating them with an electric arc between the electrode(s) and the work piece, using an inert gas to shield the electrode(s). See also *gas tungsten arc welding.*[8,10]

inherent discontinuity: Discontinuity produced in the material at the time it is formed (for example, during solidification from the molten state).[2,10]

inherent fluorescence: Fluorescence that is an intrinsic characteristic of a material.[6,10,11]

inspection: See *examination* and *inspection, nondestructive*. Sometimes *inspection* denotes that part of the liquid penetrant testing process involving visual examination of a part for test indications after completion of the liquid penetrant processing steps.

intensity, radiant: Luminous flux per steradian emanating from a visible source, measured in $\text{lm}\cdot\text{sr}^{-1}$. Also, from a nonvisible source, the radiant flux per steradian emanating from that source and measured in $\text{W}\cdot\text{sr}^{-1}$.[10]

intergranular corrosion: Corrosion occurring preferentially at grain boundaries.[2,10]

interpretation: Determination of the significance of test indications from the standpoint of their relevance or irrelevance. The determination of the cause of an indication or the evaluation of the significance of discontinuities from the standpoint of whether they are detrimental or inconsequential.[2,10]

iris: Ring of variable area around the pupil and in front of the lens of the eye. The surface area of the iris adjusts spontaneously to change the amount of light entering the eye.[8,10]

irradiance: Power of electromagnetic radiant energy incident on the surface of a given unit area. Compare *radiance*.[8,10]

J

Jaeger eye chart: Eye chart used for near vision acuity examinations.[8,10]

joint penetration: Distance that weld metal and fusion extend into a joint.[2,10]

K

known discontinuity test standard: Part containing known discontinuities and used to perform system performance checks and to classify liquid penetrants.

L

lack of fusion: Discontinuity due to lack of union between weld metal and parent metal or between successive weld beads. Also called *incomplete penetration*.[2,10]

lamination: Discontinuity in plate, sheet or strip caused by pipe, inclusions or blowholes in the original ingot or by rollover during rolling mill operations. After rolling, laminations are usually flat and parallel to the outside surface.[6,10]

lap: Surface discontinuity, usually parallel to the surface, appearing as a fold or tangential seam in a wrought product and caused by folding over of a hot metal fin or sharp corner in a thin plate, then rolling or forging it into the surface but not welding it. See also *cold shut*.[2,6,10]

leaker penetrant: Liquid penetrant especially designed for leak testing.[2,10]

level, acceptance: Test level above or below which, depending on the test parameter, test objects are acceptable. See *level, rejection*.[2,10]

level, rejection: Value established for a test signal above or below which, depending on the test parameter, test objects are rejectable or otherwise distinguished from the remaining objects.[2] See *level, acceptance*.[10]

light: Radiant energy that can excite the retina and produce a visual sensation. Visible portion of the electromagnetic spectrum, from about 380 to 770 nm.[8,10,14]

limited certification: Individuals certified only for specific operations are usually called *limited Level* (I, II *or* III) or designated as having *limited certification* because they are not qualified to perform the full range of activities expected of personnel at that level of qualification.[8,10]

lipophilic emulsifier or **remover:** See *emulsifier, lipophilic*.

liquid penetrant: Liquid that can enter discontinuities open to the test surface and that is adapted to the liquid penetrant test process by being made highly visible in small traces. Fluorescent liquid penetrants fluoresce brightly under ultraviolet radiation and visible liquid penetrants are intensely colored to be readily visible on developer backgrounds when illuminated with visible light.[2,10]

liquid penetrant comparator: See *comparator, penetrant*.[10]

liquid penetrant leak testing: Technique of liquid penetrant testing in which the liquid penetrant is applied to one surface of a test material while the opposite surface is tested for indications that would identify a through leak or void passing through the material thickness.[2,10]

liquid penetrant system: In certain specifications for liquid penetrant materials, the designation given to a water washable liquid penetrant, or to a postemulsifiable liquid penetrant and emulsifier combination, that meets the technical requirements of the specification.

liquid penetrant testing (PT): Nondestructive testing method using liquid penetrant.[10]

liquid penetrant, fluorescent: Liquid penetrant characterized by its ability to fluoresce when excited by near ultraviolet radiation.[2,10]

liquid penetrant, postemulsifiable: Liquid penetrant that requires the application of a separate emulsifier to render the excess surface liquid penetrant water washable.[2,10]

liquid penetrant, visible: Liquid penetrant characterized by an intense visible color dye that allows it to give contrasting indications on a white liquid penetrant system developer background.[2,10]

liquid penetrant, water washable: Liquid penetrant with built in emulsifier that makes it directly water washable.[2,10]

longitudinal direction: Principal direction of flow in a worked metal.[2,10]

LOX-safe penetrant: Liquid penetrant material or system specifically designed to be compatible with or nonreactive in presence of liquid oxygen.[2,10]

lumen: Luminous flux per steradian from source whose luminous intensity is 1 candela. Symbolized *lm*.[8,10]

luminance: Ratio of surface's luminous intensity in a given direction to a unit of projected area. Measured in candela per square meter.[8,10]

luminosity: Luminous efficiency of radiant energy.[8,10]

luminous efficacy: Ratio of total luminous flux of a light source to total radiant flux or to power input. Sometimes called *luminous efficiency*.[8,10]

luminous efficiency: See *luminous efficacy*.[10]

luminous flux: Radiant energy's time rate of flow. Measured in lumen.[8,10]

luminous intensity: Luminous flux on a surface normal to the direction from its light source, divided by the solid angle the surface subtends at the source. Measured in candela. Also known as *candlepower*.[8,10]

lux: Unit of measure for illuminance in SI. Equivalent to lumen per square meter and symbolized *lx*. Formerly known as *meter-candle*.[8,10]

M

macrostructure: Structure of metals as revealed by examination of the etched surface of a polished object at a magnification not exceeding ten diameters.[2,10]

malleable cast iron: Cast iron made by prolonged anneal of white cast iron in which decarburization or graphitization or both, take place to eliminate some or all of the cementite. The graphite is in the form of temper carbon.[3,10]

material safety data sheet: Document that contains information relative to safety and health in handling and disposal of chemicals. Manufacturers of liquid penetrant materials are required to provide material safety data sheets to users in accordance with the *OSHA Hazard Communication Standard*.[14]

mechanical properties: Properties of a material that reveal its elastic and inelastic behavior where force is applied, thereby indicating its suitability for mechanical applications (for example, modulus of elasticity, tensile strength, elongation, hardness and fatigue limit).[2,10]

mesopic vision: Vision adapted to light level between photopic at 3.4×10^{-2} cd·m^{-2} (3.2×10^{-3} cd·ft^{-2}) and scotopic at 3×10^{-5} cd·m^{-2} (2.7×10^{-6} cd·ft^{-2}).[8,10]

metallic discontinuity: Break in the continuity of metal of an object. May be located on the surface (e.g., a crack) or deep in the interior of the object (e.g., gas pocket).[2,10]

micro: Prefix that divides a basic unit of measure by one million (1×10^6).[2,10]

microfissure: Crack of microscopic proportions.[2,10]

micrograph: Graphic reproduction of the surface of a prepared object, usually etched, at a magnification greater than ten diameters. If produced by photographic means it is called a photomicrograph (not a microphotograph).[2,10]

microporosity: Porosity visible only with aid of a microscope.[2,10]

microscope: Instrument that provides enlarged images of very small objects.[8,10]

microscope, compound: Conventional microscope, using geometrical optics for magnification.[8,10]

microscope, interference: Magnifier using the wavelength of light as a unit of measure for surface contour and other characteristics.[8,10]

microsegregations: (1) Segregation within a grain, crystal or small particle. Also called *coring*. (2) Extremely narrow cracks, usually long and straight, on the surfaces of highly finished wrought metals. Often very shallow, their identity must be established to ensure that indications are not from detrimental cracks, deep laps or long inclusion stringers.[2,6,10]

microstructure: Structure of polished and etched metal as revealed by a microscope at a magnification greater than ten diameters.[2,10]

monochromatic light: Light from a very narrow portion of the visible spectrum.[8,10]

multiaxial stresses: Any stress state in which two or three principal stresses are not zero.[2,10]

multiparameter: Of or pertaining to the many parameters of a test system. These parameters often affect test response and can often be distinguished with a multifrequency technique.[4,10]

N

NDC: Nondestructive characterization.[10]

NDE: (1) Nondestructive evaluation. (2) Nondestructive examination.[8,10]

NDI: Nondestructive inspection.[8,10]

NDT: Nondestructive testing.[8,10]

near ultraviolet radiation: Ultraviolet radiation with wavelengths ranging from about 320 to about 400 nm (UV-A). Sometimes called *black light.*[8,10]

near vision: Vision of objects nearby, generally within arm's length. Compare *far vision.*[8,10]

nearsightedness: Vision acuity functionally adequate for viewing objects nearby, generally within arm's length but not at greater distances. Also called *myopia.* Compare *farsightedness.*[8,10]

nick: Surface indentation caused by forceful abrasion or impact. Also called *gouge.* Compare *tool mark.*[8,10]

nit: Former unit for measuring luminance, equivalent to one candela per square meter. Abbreviated *nt.*[8,10]

nodular cast iron: Cast iron that has been treated while molten with a master alloy containing an element such as magnesium or cerium to give primary graphite in the spherultic form.[3,10]

nonaqueous developer: See *developer, nonaqueous.*

nondestructive characterization (NDC): Branch of nondestructive testing concerned with the description and prediction of material properties and behaviors of components and systems.[10]

nondestructive evaluation (NDE): Another term for *nondestructive testing.* In research and academic communities, the word *evaluation* is often preferred because it emphasizes interpretation by knowledgeable personnel.[8,10]

nondestructive examination (NDE): Another term for *nondestructive testing.* In the utilities and nuclear industry, *examination* is sometimes preferred because *testing* can imply performance trials of pressure containment or power generation systems.[8,10]

nondestructive inspection (NDI): Another term for *nondestructive testing.* In some industries (utilities, aviation), the word *inspection* often implies maintenance for a component that has been in service.[8,10]

nondestructive testing (NDT): Determination of the physical condition of an object without affecting that object's ability to fulfill its intended function. Nondestructive testing techniques typically use a probing energy form to determine material properties or to indicate the presence of material discontinuities (surface, internal or concealed). See also *nondestructive evaluation, nondestructive examination* and *nondestructive inspection.*[8,10]

nonrelevant indication: See *indication, nonrelevant.*[10]

O

objective: In discussion of a lens system (camera, borescope, microscope, telescope), of or pertaining to the end or lens closest to the object of examination — at the end opposite from the eyepiece. Distal; tip.[8,10]

oil and whiting: See *chalk test.*

one hundred percent testing: Testing of all parts of an entire production lot in a prescribed manner. Sometimes, *complete testing* entails the testing of only the critical portions of the part. Compare *sampling, partial.*[8,10]

organoleptic: Relying on or using sense organs, such as the human eye.[8,10]

overemulsification: Excessive emulsifier dwell time that results in removal of liquid penetrants from some discontinuities.

overwashing: Too long or too vigorous washing or both, which results in removal of liquid penetrant from some discontinuities.

P

parts per million (ppm): Concentration of a substance in a mixture. For example, the amount of solvent vapor in a working environment that is a health and safety hazard. The ratio of parts per million is expressed in units — for example, $\mu g \cdot g^{-1}$.

penetrability: Condition of being penetrable so that liquid can enter into very fine openings such as cracks. Often erroneously used to describe the property of a liquid penetrant that causes it to find its way into very fine openings.[2,10]

penetrant: See *liquid penetrant.*

penetration time: *Dwell time* allowed, after liquid penetrant has been applied to a surface, for the liquid penetrant to enter discontinuities that may be present.

photometric brightness: Luminance of a light source.[8,10]

photometry: Science and practice of the measurement of light or photon-emitting electromagnetic radiation. See also *relative photometry.*[8,10]

photon: Particle of light.[8,10]

photopic vision: Vision adapted to daylight and mediated mainly by the cones. Vision is wholly photopic when the luminance of the test surface is above 0.034 $cd \cdot m^{-2}$ (0.0032 $cd \cdot ft^{-2}$). Also known as *foveal vision* and *light adapted vision.* Compare *mesopic vision* and *scotopic vision.*[8,10,14]

pitting: Discontinuity consisting of surface cavities. See also *cavitation fatigue* and *pitting fatigue*.[8,10]

pitting fatigue: Discontinuity consisting of surface cavities typically due to fatigue and abrasion of contacting surfaces undergoing compressive loading. See also *cavitation fatigue* and *pitting*.[8,10]

pooling: Collection of excessive amounts of liquid penetrant, emulsifier, water or developer in an incompletely drained area of a part.

pores: (1) Small voids within a metal. (2) Minute cavities, sometimes intentional, in a powder metallurgy compact. (3) Minute perforations in an electroplated coating.[2,10]

porosity: Discontinuity in metal resulting from the creation or coalescence of gas. Very small pores are called pinholes.[8,10,12]

postcleaning: Removal of liquid penetrant testing residues from the test piece at the end of a liquid penetrant test.

postemulsification: Liquid penetrant removal technique using a separate emulsifier applied over the surface liquid penetrant to make it removable with water spray.[2,10]

practical examination: In certification of nondestructive testing personnel, a hands-on examination using test equipment and sample test objects. Compare *general examination* and *specific examination*.[8,10]

precleaning: Removal of surface contamination from the test piece so that it cannot interfere with the liquid penetrant testing process.[2,10]

prewash technique: Liquid penetrant removal technique in which major portion of a nonwater washable liquid penetrant is mechanically removed with a water spray prior to application of emulsifier. Formerly called *prerinsing*.

process: Repeatable sequence of actions to bring about a desired result.[8,10]

process control: Application of quality control principles to the management of a repeated process.[8,10]

process testing: Initial product testing to establish correct manufacturing procedures and then by periodic tests to ensure that the process continues to operate correctly.[2,10]

pseudoisochromatic plates: Color plates used for color vision examinations. Each plate bears an image which may be difficult for the examinee to see if his or her color vision is impaired.[8,10]

psychophysics: Interaction between vision performance and physical or psychological factors. One example is the so-called vigilance decrement, the degradation of reliability based on performing visual and/or repetitive activities over a period of time.[8,10]

PT: Liquid penetrant testing.[10]

pupil: Aperture in the center of an eye's iris, through which light focused by the lens passes.[8,10]

Q

qualification: (1) Process of demonstrating that an individual has the required amount and the required type of training, experience, knowledge and capabilities. See also *qualified*.[8,10] (2) Process of demonstrating that a liquid penetrant testing material meets the property and performance requirements of a governing material specification.

qualified: (1) Having demonstrated the required amount and the required type of training, experience, knowledge and abilities.[8,10] (2) Having passed the required property and performance tests. See also *qualification*.

quality: The ability of a process or product to meet specifications or to meet the expectations of its users in terms of efficiency, appearance, longevity and ergonomics.[8,10]

quality assurance: Administrative actions that specify, enforce and verify a quality program.[8,10]

quality control: Physical and administrative actions required to ensure compliance with the quality assurance program. May include nondestructive testing in the manufacturing cycle.[8,10]

quality of lighting: Level of distribution of luminance in a visual task or environment.[8,10]

quenching of fluorescence: Extinction of fluorescence by causes other than removal of the ultraviolet radiation (the exciting radiation).[2,10]

R

radiance: Radiant flux per unit solid angle and per unit projected area of the source. Measured in watt per square meter steradian. Compare *irradiance*.[8,10]

radiant energy: Energy transmitted through a medium by electromagnetic waves. Also known as *radiation*.[8,10]

radiant flux: Radiant energy's rate of flow, measured in watt.[8,10]

radiant intensity: Electromagnetic energy emitted per unit time per unit solid angle. Measured in watt per steradian.[8,10]

radiant power: Total radiant energy emitted per unit time.[8,10]

radiometer: Instrument for measuring radiant power of specified frequencies. Different radiometers exist for different frequencies.[8,10]

radiometric photometer: Radiometer for measuring radiant power over a variety of wavelengths.[8,10]

recommended practice: Set of guidelines or recommendations.[8,10]

Recommended Practice SNT-TC-1A: See *ASNT Recommended Practice No. SNT-TC-1A*.[10]

reference standard: Typical test object with known artificial or natural discontinuities of various specific sizes, used as a basis for test comparisons, equipment calibration or determining the efficiency of the discontinuity detection process. Also called *reference* or *test panel, reference* or *test block* and *reference* or *test piece*.[2] See also acceptance standard.[10]

refractometer: Device that measures the refractive index of a liquid. This value increases in proportion to the dissolved solids in the liquid and hence has been used to measure hydrophilic remover concentration.

reinforcement of weld: (1) In a butt joint, weld metal on the face of the weld that extends out beyond a surface plane common to the members being welded. (2) In a fillet weld, weld metal that contributes to convexity. (3) In a flash, upset or gas pressure weld, weld metal exceeding base metal diameter or thickness.[2,10]

relative photometry: (1) Evaluation of desired photometric characteristic based on assumed lumen output of test lamp. (2) Measurement of one uncalibrated light source relative to another uncalibrated light source.[8,10]

repeatability: Ability to reproduce a detectable indication in separate processings and tests from a constant source.[1,2,10]

reserve vision acuity: The ability of an individual to maintain vision acuity under poor viewing conditions. A visual system with 20/20 near vision acuity under degraded viewing conditions has considerable reserve vision acuity compared to that of an individual with 20/70 near vision acuity.[8,10]

retina: In the eye, the tissue that senses light.[8,10]

rinse: Process of removing liquid penetrant testing materials from the surface of a test object by means of washing or flooding with another liquid, usually water. Also called *wash*.[2,10]

robotic system: Automated system programmed to perform purposeful movements in variable sequences.[8,10]

root crack: Crack in either the weld or heat affected zone at the root of a weld.[2,10]

root penetration: Depth to which weld metal extends into the root of a joint.[2,10]

S

sampling, partial: Testing of less than one hundred percent of a production lot. See *one hundred percent testing*.[8,10]

sampling, random partial: Partial sampling that is fully random.[8,10]

sampling, specified partial: Partial sampling in which a particular frequency or sequence of sample selection is prescribed. An example of specified partial sampling is the testing of every fifth unit.[8,10]

scale: Oxide formed on metal by chemical action of the surface metal with oxygen from the air.[2,10]

scale pit: Shallow surface depression in metal, caused by scale.[2,10]

scaling: (1) Forming a layer of oxidation product on metals, usually at high temperatures. (2) Deposition of insoluble constituents on a metal surface, as in cooling tubes and water boilers.[8,10,12]

scoring: (1) Marring or scratching of any formed part by metal pickup on a punch, die or guide. (2) Reducing the thickness of a part along a line to weaken it purposely at a specific location.[8,10,12]

scotopic vision: Dark adapted vision, using only the rods in the retina, where differences in brightness can be detected but differences in hue cannot. Vision is wholly scotopic when the luminance of the test surface is below 3×10^{-5} cd·m^{-2} (2.7×10^{-6} cd·ft^{-2}). Also known as *parafoveal vision*. Compare *mesopic vision* and *photopic vision*.[8,10]

seam: (1) On the surface of metal, an unwelded fold or lap that appears as a crack, usually resulting from a discontinuity obtained in casting or working. (2) Mechanical or welded joints.[3] (3) Longitudinal surface discontinuity on metal originating from a surface crack or blowhole near the surface of the ingot, that is drawn out during rolling and follows the rolling direction. Also due to overfill while rolling. After forging, seams generally follow the direction of flow lines.[2,10]

seeability: Characteristic of an indication and/or liquid penetrant that enables an observer to see it against the adverse conditions of background, outside light etc.[2,10]

self emulsifiable: Of or pertaining to liquid penetrant able spontaneously to form an emulsion with water, a property that lets it be rinsed off with water, with more control than if it actually dissolved in the rinse water. Also called *water washable.* See *penetrant, water washable.*[2,10]

sensitivity: (1) Performance characteristic of a liquid penetrant system, of a developer or of an entire liquid penetrant process that provides a relative measure of the ability to detect discontinuities. (2) Enumerated level of performance of a liquid penetrant system determined by applying standardized processing procedures on reference standards with known defects.

shallow discontinuity: Discontinuity open to the surface of a solid object that possesses little depth in proportion to the width of this opening. A scratch or nick may be a shallow discontinuity in this sense.[2,10]

shear break: Open break in metal at the periphery of a bolt, nut, rod or member at approximately a 45 degree angle to the applied stress. Occurs most often with flanged products. Also called *shear crack.*[8,10,12]

shear crack: See *shear break.*[10]

shot peening: Cold working the surface of a metal by metal shot impingement.[3,10]

shoulder: Cylindrical metal component surface, machined to receive threading indentations but in fact not threaded, where the thread stops on the outside surface.[8,10]

shrink: Internal rupture occurring in castings due to contraction during cooling, usually caused by variations in solidification rates in the mold. Includes shrinkage sponge, small voids (stringers or bunches) or a fingerprint pattern of semifused seams. Also applied to surface shrinkage cracks.[2,6,10]

shrinkage: See *macroshrinkage* and *microshrinkage.*[2,3,10]

shrinkage cavities: Cavities in castings caused by lack of sufficient molten metal as the casting cools.[2,3,10]

shrinkage cracks: Hot tears associated with shrinkage cavities.[2,3,10]

shrinkage porosity or sponge: Porous metal often with a network of fine cracks formed during solidification of molten metal. At a surface, may form a localized, lacy or honeycombed liquid penetrant indication.[2,10]

SI: The International System of units of measurement. An international system of measurement based on seven base units: meter (m), kilogram (kg), second (s), kelvin (K), ampere (A), candela (cd) and mole (mol).[10]

SNT-TC-1A: See *ASNT Recommended Practice No. SNT-TC-1A.*[10]

soak time: Period of time when the emulsifier remains in contact with the liquid penetrant on the surface of the test object. Soak time ceases when the liquid penetrant emulsifier is quenched with water or completely removed by water rinsing. Also called *emulsification time.*[2,10]

solvent action: Ability of a liquid to dissolve another material.[2,10]

solvent developer: See *developer, nonaqueous.*

solvent removal: Process of removing excess liquid penetrant from the surface of a test object by hand wiping with a solvent dampened cloth.[2,10]

solvent remover: Volatile liquid that can dissolve liquid penetrant and that is used to remove excess surface liquid penetrant from object surfaces by appropriate hand wiping techniques.[2,10]

spalling: Cracking or flaking of small particles of metal, usually in thin layers, from the surface of an object.[2,10]

special application: Of a remover or developer, qualified for use only with a specific liquid penetrant.

specific examination: In certification of nondestructive testing personnel, a written examination that addresses the specifications and products pertinent to the application. Compare *general examination* and *practical examination.*[8,10]

specific gravity: Ratio of the density of a substance (usually aqueous developer) to the density of water, usually measured at 15.6 °C (60 °F).

specification: Set of instructions or standards invoked by a specific customer to govern the results or performance of a specific set of tasks or products.[8,10]

specular: Pertaining to a mirror-like reflective finish, as of a metal. Compare *lambertian.*[8,10]

spot check tests: Testing a number of objects from a lot to determine the lot's quality, the sample size being chosen arbitrarily, such as five or ten percent. This does not provide accurate assurance of the lot's quality.[2,10]

spot examination: Local examination of welds or castings.[2,10]

spray scrubber: Technique of pressure washing nonwater soluble liquid penetrant from the surface by introducing a hydrophilic emulsifier or detergent into the water wash.[2,10]

standard: (1) A physical object with known material characteristics used as a basis for comparison or calibration.[10]
(2) A concept established by authority, custom or agreement to serve as a model or rule in the measurement of quantity or the establishment of a practice or procedure.[7,10]
(3) Document to control and govern practices in an industry or application, applied on a national or international basis and usually produced by consensus. See also *acceptance standard, working standard* and *reference standard.*[4,8,10,11]

steel: Iron alloy, usually with less than two percent carbon.[8,10]

stress: (1) In physics, the force in a material that resists external forces such as tension and compression.
(2) Force per unit area.[8,10]

stress corrosion cracking: Failure by cracking under combined action of corrosion and stress, either applied or residual. Cracking may be either intergranular or transgranular, depending on the metal and corrosive medium.[2,10]

stress raiser: Contour or property change that causes local concentration of stress.[8,10]

stress riser: See *stress raiser.*[10]

stringer: In wrought materials, an elongated configuration of microconstituents or foreign material aligned in the direction of working. Commonly, the term is associated with elongated oxide or sulfide inclusions in steel.[2,10]

substrate: Layer of metal underlying a coating, regardless of whether the layer is base metal.[2,10]

subsurface discontinuity: Any discontinuity that does not extend through the surface of the object in which it exists.[2,10]

system: With respect to liquid penetrant testing materials, a combination of liquid penetrant and emulsifier that are furnished by the same manufacturer and are qualified together. For water washable and solvent removable liquid penetrants, a system consists of liquid penetrants only.

T

temperature: Measure of intensity of particle motion in degrees Celsius (°C) or degrees Fahrenheit (°F) or, in the absolute scale, kelvin (K) or degrees Rankine (°R), where $1\ \text{K} = 1\ ^\circ\text{C} = 1.8\ ^\circ\text{R} = 1.8\ ^\circ\text{F}$.

temperature envelope: Temperature range over which a particular liquid penetrant testing technique will operate.[2,10]

test: See *examination.*[10]

test object: Part subjected to testing.[10]

test surface: Exposed surface of test object.[2,7,10]

U

ultraviolet borescope: See *borescope, ultraviolet.*[10]

ultraviolet radiation: (1) Electromagnetic radiation with wavelengths ranging from about 4 to about 400 nm, between visible light and X-rays. Compare *near ultraviolet radiation.*[8]
(2) The range of wavelengths used for fluorescent nondestructive testing is typically between 320 and 400 nm (UV-A). Shorter wavelengths are very hazardous. Compare *black light.*[6,10]

ultraviolet radiometer: Meter, usually calibrated at 365 nm, used in fluorescent liquid penetrant and magnetic particle testing to measure the viewing conditions under near ultraviolet irradiation.

UV: Ultraviolet.

UV-A radiation: Near ultraviolet radiation.

V

vigilance decrement: Degradation of reliability during performance of visual activities over a period of time. See also *psychophysics.*[8,10]

viscosity: State or degree of being viscous. The resistance of a fluid to the motion of its particles.[13]

visibility: Quality or state of being perceivable by the eye. In many outdoor applications, visibility is defined in terms of the distance at which an object can be just perceived by the eye. In indoor applications it usually is defined in terms of the contrast or size of a standard test object, observed under standardized viewing conditions, having the same threshold as the given object.[8,10,14]

visible dye penetrant: Liquid penetrant characterized by its intense visible color, usually red. Also called *color contrast* or *nonfluorescent penetrant*.[13]

visible light: Radiant energy generated in the 400 to 700 nm wavelength range.[6,10,11]

vision: Perception by eyesight. See *mesopic vision, near vision, photopic vision, scotopic vision*.[8,10]

vision acuity: Ability to distinguish fine details visually. Quantitatively, it is the reciprocal of the minimum angular separation in minutes of two lines of width subtending one minute of arc when the lines are just resolvable as separate.[8,10,14]

visual acuity: See *vision acuity*.[10]

visual efficiency: Reliability of a visual system. The term *visual efficiency* uses 20/20 near vision acuity as a baseline in the United States for 100 percent visual efficiency.[8,10]

visual field: Locus of objects or points in space that can be perceived when head and eyes are kept fixed. The field may be monocular or binocular.[8,10,14]

visual perception: Interpretation of impressions transmitted from the retina to the brain in terms of information about a physical world displayed before the eye. Visual perception involves any one or more of the following: recognition of the presence of something (object, aperture or medium); identifying it; locating it in space; noting its relation to other things; identifying its movement, color, brightness or form.[8,10,14]

visual performance: Quantitative assessment of the performance of a visual test, taking into consideration speed and accuracy.[8,10,14]

visual task: Appearance and immediate background of those details and objects that must be seen for the performance of a given activity. The term *visual task* is a misnomer because it refers to the visual display itself and not the task of extracting information from it.[8,10,14]

visual testing: Method of nondestructive testing using electromagnetic radiation at visible frequencies.[8,10]

voids: Hollow spots, depressions or cavities. See also *discontinuity*.[8,10]

W

water break free: Rinse water, having the ability to cover an entire surface in an unbroken film.[2,10]

water content: Proportion of water contamination of a sample of water washable liquid penetrant or lipophilic emulsifier taken from process tank.

water suspendable particle developer: Developer in which the developer particles are mixed with water to form a suspension.[13]

water tolerance: Amount of water that a liquid penetrant or emulsifier or wet developer can absorb before its effectiveness is impaired.[2,10,13]

water wash: Liquid penetrant removal technique wherein excess liquid penetrant is washed or flushed from the test surface with water.[13]

water washable penetrant: Liquid penetrant that contains its own emulsifier, making it water washable.[13]

weld crack: Crack in weld metal.[2,10]

wet developer: Developer in which developing powder is applied as suspension or solution in a liquid, usually water or solvent.[2,10]

wetting action: Action of liquid in spontaneously spreading over and adhering to solid surfaces.[2,10]

white light: Light combining all frequencies in the visible spectrum and in equal proportions.[8,10]

working standard: Work piece or energy source calibrated and used in place of expensive reference standards. In calibrating of photometers, the standard would be a light source.[8,10]

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CHAPTER

Liquid Penetrant Testing Bibliography

Introduction

This bibliography lists published works cited in the references at the end of each chapter, as well as other works not cited elsewhere in this volume. A listing in this bibliography is not be construed as any sort of endorsement or recommendation of a technique, a service or equipment described.

The bibliography is divided into sections, and a published work is generally cited only once. The reader is therefore urged to look in more than one section of the bibliography. A publication on fluorescent indication enhancement, for example, may be found under *Specific Techniques* or under *Evaluation of Liquid Penetrant Materials and Systems* or under *Lighting and Indication Visibility* but not under more than one of those headings.

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Movie. Porosity in casting — American Society for Nondestructive Testing, Columbus, OH.
Movie. Process control can mask discontinuities — American Society for Nondestructive Testing, Columbus, OH.
Movie. False indications — Hellier Associates, Incorporated, Niantic, CT.
Movie. Nonrelevant indications can mask relevant ones — American Society for Nondestructive Testing, Columbus, OH.
Movie. Nonrelevant indication from part geometry — American Society for Nondestructive Testing, Columbus, OH.

Chapter 6

Movie. Postcleaning — American Society for Nondestructive Testing, Columbus, OH.

Chapter 12

Movie. Rejectable discontinuity — Hellier Associates, Incorporated, Niantic, CT.
Movie. Porosity in casting — American Society for Nondestructive Testing, Columbus, OH.
Movie. Fluorescent bleedout reveals shrinkage — ASM International, Materials Park, OH.