

THIRD
EDITION

ASNT LEVEL III STUDY **GUIDE**

LIQUID PENETRANT TESTING



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The American Society for
Nondestructive Testing Inc.

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Full document details: ASNT 10110 2022

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third edition
first printing 2/22
ebook 2/22

Errata, if available for this printing, may be obtained from ASNT's website, asnt.org. Ebooks contain all corrections and updates, including the latest errata.

ISBN: 978-1-57117-549-6 (print)
ISBN: 978-1-57117-550-2 (ebook)

Printed in the United States of America

Published by:
The American Society for Nondestructive Testing Inc.
1711 Arlingate Lane
Columbus, OH 43228-0518
asnt.org

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ASNT Mission Statement:

ASNT exists to create a safer world by advancing scientific, engineering, and technical knowledge in the field of nondestructive testing.

ASNT Code of Ethics:

The ASNT Code of Ethics was developed to provide members of the Society with broad ethical statements to guide their professional lives. In spirit and in word, each ASNT member is responsible for knowing and adhering to the values and standards set forth in the Society's Code. More information, as well as the complete version of the Code of Ethics, can be found on ASNT's website, asnt.org.

FOREWORD

PURPOSE

This study guide is intended to aid individuals preparing to take the ASNT NDT Level III examination for liquid penetrant testing (PT). The material in this study guide addresses the body of knowledge included in ANSI/ASNT CP-105: *ASNT Standard Topical Outlines for Qualification of Nondestructive Testing Personnel*.

The ASNT NDT Level III certification program is a service offered by The American Society for Nondestructive Testing Inc. that gives nondestructive testing (NDT) personnel an opportunity to have their familiarity with the principles and practices of NDT assessed by an independent body. The program uses this independent body to review credentials and also uses comprehensive written examinations to identify those who meet the criteria for becoming an ASNT NDT Level III.

HOW TO USE THE STUDY GUIDE

This study guide is not intended to be the only source of preparation for the Level III examination. It provides a general overview of subject matter covered in the body of knowledge so that students can identify those areas in which further study is needed.

Readers should look through the text of the study guide, and if the discussion covers unfamiliar material, the references should also be studied. The review questions at the end of each chapter should be answered. Answering the questions successfully will help determine whether more concentrated study in particular areas is needed. Those familiar with some of the topics may wish to go directly to the review questions. If the questions can be answered confidently and correctly, additional study may be optional.

CHANGES TO THIS EDITION

This third edition builds on the first and second editions. The first edition was published in 1998 and written by Bernie Boisvert and Charles W. Eick. The second edition was updated and revised by William E. Mooz and was published in 2003. Changes to the third edition include:

- Material has been updated throughout to reflect the most current information on PT as outlined in CP-105. The book has been updated with new text and new figures.
- Many topics have been expanded or introduced, including materials and properties, wetting ability and contact angle, penetrant and developer application, continuity of inspection, dark adaptation and color blindness, postcleaning, lighting (including light intensity measurement), performance testing, standards and test panels, safety data sheets, and written procedures.
- All chapter review questions are multiple-choice, with four unique answers to more closely match the ASNT exam format.
- Because ASNT is an International System of Units (SI) publisher, throughout the text both SI and imperial units are used. Where SI units are not used in the original text of standards and codes, conversions to SI units are not made. Where SI units are used first, conversions to imperial units might not be added.

ADDITIONAL INFORMATION

In ASNT publications, the words *discontinuity* and *defect* have specific meanings. These words are used as follows:

- A *discontinuity* is an intentional (such as drilled holes) or unintentional interruption in the physical structure or configuration of a material or component. NDT techniques reveal *indications* of discontinuities. Discontinuities may exist without being detected.
- A *defect* is a discontinuity whose size, shape, orientation, or location make it detrimental to the useful service of the object, or exceed accept/reject criteria of an applicable specification. Some discontinuities do not exceed an accept/reject criterion and are therefore not defects.
- The process for determining rejectability is *interpretation* or *evaluation*. All defects are discontinuities, but not all discontinuities are defects.

In 2018 ASNT accepted the ASTM E1316 definitions of calibration and standardization for use in its publications. These words are used as follows:

- *Calibration* is the comparison (which may include adjustment) of a test instrument to a known reference that is normally traceable to some recognized authority (e.g., NIST). Calibration is typically performed by an organization considered qualified to do so (e.g., an accredited laboratory, or in some cases, the instrument manufacturer) at a determined, periodic interval. Calibration of electronic instrumentation typically involves verification of the linearity of the instrument's response over its usable range.
- *Standardization* is typically completed prior to performing an NDT test, and may also be performed at times during the performance of the test and at the completion of the test as a validation of proper instrument operation. It is the adjustment of an NDT instrument using a reference standard (that contains a known condition) to obtain or establish a known and reproducible response.

ACKNOWLEDGMENTS

The American Society for Nondestructive Testing Inc. is grateful for the volunteer contributions, technical expertise, knowledge, and dedication of the following individuals who have helped make this work possible.

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Figure used in Chapter 6, Review Question 4 provided by Magnaflux.
Cover photo: Shutterstock

FURTHER RESOURCES

ASNT, 2016, *Nondestructive Testing Handbook, Vol. 1: Liquid Penetrant Testing*, fourth edition, American Society for Nondestructive Testing, Columbus, OH.

ASNT, 2020, *Principles and Applications of Liquid Penetrant Testing: A Classroom Training Text*, second edition, American Society for Nondestructive Testing, Columbus, OH.

ASNT, 2019, *Personnel Training Publications: Liquid Penetrant Testing (PT), Classroom Training Book*, second edition, American Society for Nondestructive Testing, Columbus, OH.

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SAE, 2020, AMS2644H: *Inspection Material, Penetrant*, SAE International, Warrendale, PA.

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ASTM, 2018, ASTM E3022-18, *Standard Practice for Measurement of Emission Characteristics and Requirements for LED UV-A Lamps Used in Fluorescent Penetrant and Magnetic Particle Testing*, ASTM International, West Conshohocken, PA.

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CHAPTER 1

Introduction

OVERVIEW OF LIQUID PENETRANT TESTING

The liquid penetrant testing method (PT) is defined as a physical chemical nondestructive testing (NDT) procedure designed to detect and expose surface discontinuities in nonporous materials. The method also reveals void-type subsurface discontinuities that are open to the surface.

The objective of PT is to locate cracks, porosity, laps, seams, and other surface discontinuities rapidly and economically.

PERSONNEL REQUIREMENTS

The success of PT is dependent primarily on the personnel who perform the various processing steps and those who interpret the cause and severity of indications produced. Qualification, skill, and excellence in performance are important for reliable PT.

The apparent simplicity of the process is deceptive. Very slight processing variations during penetrant application, removal of excess surface penetrant, application of developer, or examination of the part can produce varying results. Further complicating the process is that it is not always possible to determine the effectiveness of processing merely by examining the part in the inspection booth. The operator who is responsible for processing the parts must be trained, must have some experience in processing requirements, and must be aware of the detrimental effects of processing variations.

Individuals responsible for examining and evaluating indications must also be trained and experienced in the processing requirements. They should also be aware of the detrimental effects of processing variations. Individuals responsible for evaluating indications not only must have these

characteristics, but they must be capable of making decisions based on the interpretation of indications.

The penetrant process is highly dependent on the operator's skill, knowledge, vigilance, and integrity. Unlike the operator who produced the part, there is no tangible evidence (no permanent record) of the quality of the test. The reliability of and confidence in the testing is totally dependent on the operator.

For reliable PT, the personnel performing the processing and examination are required to be

- physically and mentally qualified to perform the required processing steps;
- trained and experienced as required in performing the actual processing steps;
- alert to consistent processing and resultant indications;
- motivated to perform with vigilance at the required detection and reliability level; and
- capable of consistent, independent, and unbiased decisions based on interpretation of resultant penetrant indications.

Recommended requirements for personnel training and experience are detailed in Recommended Practice No. SNT-TC-1A: *Personnel Qualification and Certification in Nondestructive Testing* (2020), available from ASNT.

HISTORY AND CLASSIFICATION OF PENETRANT MATERIALS

The earliest form of PT would be the oil and whiting process used by the railroad industry in the early 20th century. It grew from that usage to first the fluorescent method in the late 1930s, and then the visible dye methods in the mid 1940s. In 1955, the classification or designation of penetrant materials followed the military specification, MIL-I-25135. At that time, penetrant materials

were listed as six *family groups*. In 1964, a seventh group, Group VII, consisting of aerosol packaged Group VI penetrants, was added. In 1982, another change in designation occurred when Group VI was subdivided into Group VI A, high sensitivity, and Group VI B, ultrahigh sensitivity penetrant. Table 1 is a listing of the original groups.

By 1980, it became apparent that additional designations were necessary to include

- types of penetrant dye,
- methods of removal,
- penetrant sensitivities,
- forms of developers, and
- classes of solvent removers.

The MIL-I-25135D revision, released in June 1985, incorporated these designations. A subsequent revision, MIL-I-25135E, was released in June 1989. A consensus document (SAE-AMS 2644) superseded MIL-I-25135E in August 1996; however, the designations are identical. The revisions also eliminate the family group (penetrant, emulsifier, and developer) and substitute the *system concept* for postemulsifiable

penetrants. The system concept is based on the fact that manufacturers formulate their penetrants and emulsifiers/removers to be used together. The use of one manufacturer's penetrant with another manufacturer's lipophilic emulsifier or hydrophilic remover may not produce optimal results. Therefore, a manufacturer's penetrant and emulsifier/remover are considered to be a *system* and the components are not interchangeable from manufacturer to manufacturer. Developers and solvent removers are not part of the system and, therefore, any qualified material may be used. However, because each manufacturer has its own proprietary formula, the specification prohibits the mixing or combining of developers or solvent removers of different manufacturers. Table 2 is a listing of material designations and their descriptions. Note that from this point forward in this study guide, military specifications will not be used. Instead, the equivalent civilian document will be referenced. In addition, SAE International's Aerospace Material Specification AMS 2644, *Inspection Material, Penetrant*, will be address only as AMS 2644.

Table 1. MIL-I-25135E family group classifications

MIL-I-25135E Designation	Materials/Family Description		
	Penetrant	Remover	Developer
Group I	solvent-removable, visible dye	solvent	dry, wet, or nonaqueous (wet)
Group II	postemulsifiable, visible dye	emulsifier	dry, wet, or nonaqueous (wet)
Group III	water-washable, visible dye	none	dry, wet, or nonaqueous (wet)
Group IV	water-washable, fluorescent	none	dry, wet, or nonaqueous (wet)
Group V	medium sensitivity, postemulsifiable	emulsifier	dry, wet, or nonaqueous (wet)
Group VI	high sensitivity, postemulsifiable, fluorescent	emulsifier	dry, wet, or nonaqueous (wet)
Group VI A	high sensitivity, postemulsifiable, fluorescent	hydrophilic	dry, water-soluble, or nonaqueous (wet)
Group VI B	ultrahigh sensitivity, postemulsifiable	hydrophilic	dry, water-soluble, or nonaqueous (wet)
Group VII	high sensitivity, solvent-removable, fluorescent	solvent remover	nonaqueous (wet)

Table 2. Types and methods of liquid penetrant testing

Type	Method	Sensitivity	Developer	Solvent
Type I: fluorescent penetrant Type II: visible penetrant Type III: dual-mode penetrant	Method A: water-washable Method B: lipophilic postemulsifiable Method C: solvent-removable Method D: hydrophilic postemulsifiable	Level 1/2*: very low Level 1: low Level 2: medium Level 3: high Level 4: ultrahigh	Form a: dry powder Form b: water-soluble Form c: water-suspendable Form d: nonaqueous Type I (for fluorescent) Form e: nonaqueous Type II (for visible) Form f: special application	Class 1: halogenated Class 2: nonhalogenated Class 3: special application
*Sensitivity Level 1/2 applies to Type I, Method A penetrants only. There is no sensitivity level classification for Type II penetrant systems.				

ADVANTAGES AND CAPABILITIES OF LIQUID PENETRANT TESTING

PT offers a number of advantages and capabilities when compared to other NDT methods. Some advantages are as follows:

- PT is capable of examining the entire exterior surface in one operation even though the object may have a complex shape.
- PT can detect very small discontinuities and the penetrant bleedout magnifies the size of indications, making them easier to see.
- Penetrant indications are formed directly over discontinuities on the surface of the part, providing information on location, orientation, and approximate length of the discontinuity.
- The process is relatively simple and rapid and can easily be automated where a large volume of parts is to be tested.
- PT can be used on a wide variety of materials, including ferrous and nonferrous metals, fired ceramics and cements, glass, and many types of plastics.
- The process sensitivity can be varied by selection of materials and processing procedures—a range of sensitivities are possible, allowing suppression of small, inconsequential discontinuities while indicating large discontinuities of concern.

LIMITATIONS OF LIQUID PENETRANT TESTING

There are a number of limitations associated with PT. Some include:

- PT will not reveal discontinuities that are not open to the surface—subsurface discontinuities cannot be detected by penetrant testing.
- The part surface and the interior of any discontinuities must be clean and free of contaminants, soils, and moisture—materials on the surface of the part, at the discontinuity edges, or inside the discontinuity can interfere with the penetrant entering and filling the discontinuity void.
- Porous materials, materials with interconnecting subsurface networks, or materials with seeped-in penetrant that is not removed during postcleaning, cannot be inspected by the PT process—the penetrant will enter the pores and migrate through the network, producing an overall fluorescence or color background that would mask any discontinuities.
- Penetrants usually contain petroleum-based liquids that can soften, craze, or attack some nonmetallic materials such as some plastic and rubber compounds.
- Penetrants, emulsifiers, and developers all contain chemicals that have good wetting and detergent properties; however, they can dissolve and remove the natural oils from human tissue if they come into contact with and remain on skin surfaces for any length of time. This causes drying and cracking, which are sources for secondary infections.

Review Questions

1. A certified PT Level II is performing a penetrant inspection and finds indications. The indications were documented and the component postcleaned. The following day a certified PT Level I performs the same inspection on the same component and finds additional indications. What is the most likely cause of these additional indications?
 - a. The postcleaning of the component thoroughly removed all traces of the previous penetrant inspection.
 - b. The Level II, based on experience, chose not to identify some of the indications found.
 - c. The Level I was more diligent and conscientious about finding all possible indications.
 - d. The postcleaning process allows penetrant in indications to remain in the surface openings.
2. How would a Type I, Method A, Sensitivity 3, Form d penetrant inspection be classified under the old penetrant classification system?
 - a. Group III
 - b. Group IV
 - c. Group VI
 - d. It cannot be correctly classified.
3. Can a Type II penetrant inspection be a more sensitive penetrant inspection than a Type I penetrant inspection?
 - a. No, since Type II penetrants are not assigned sensitivity levels.
 - b. No, since a Type I penetrant inspection is by classification a more sensitive inspection process.
 - c. Yes, if both processes are done correctly and with the same inspector.
 - d. Yes, if the Type I process is not correctly accomplished.

Answers

1c 2d 3d

CHAPTER 2

Materials and Properties

QUALIFIED PRODUCTS LISTING

AMS 2644 (formerly MIL-I-25135) establishes the classification, technical requirements, tests, and test procedures for the qualification, approval, and quality verification of all materials used in PT methods. Commercial products with well-documented properties are designated as reference standards. Many of the test requirements (sensitivity, fluorescent intensity, and removability) are comparative. The material to be qualified and the reference standard material are processed simultaneously under the same conditions and the results are compared. The material to be qualified must equal or exceed the reference standard material's performance. Materials found to be acceptable are listed on a qualified products list, QPL-AMS 2644.

The listing of a material on the qualified products list does not guarantee that subsequent batches of product of the same formulation will be acceptable. The listing only indicates that the original raw materials, formulation, and compounding practice can result in an acceptable product. There are many factors and conditions in compounding and manufacturing penetrant materials that can reduce their performance. Many users routinely verify the performance of each incoming batch of penetrant materials.

Penetrant Properties

Formulation of a liquid penetrant is a complex process because of the numerous and frequent conflicting requirements. High on the list of requirements is the ability to enter or penetrate and fill voids that contain tight or small surface openings. This conflicts with the need to be able to remove the excess surface penetrant. Another requirement of equal importance is the visibility or contrast between the penetrant indication and the surface background. Dye added to the penetrant solution helps to provide the necessary contrast between the indication and the surface background. To accept the dye into the penetrant solution, the

penetrant must have a high solvent ability. This tends to conflict with the requirement of a high flashpoint, 93 °C (200 °F), to permit its use in open tanks and a relatively low evaporation rate for longtime storage in open tanks.

Unfortunately, there is neither a fixed rule for formulating a liquid penetrant nor a set of criteria that will provide a satisfactory product. However, there are some fundamental prerequisites that are necessary for acceptable performance. The penetrant must

- be capable of smoothly and evenly distributing itself over the surface of the part to be tested—it must be able to wet the surfaces of the more common metals;
- be capable of entering and filling surface openings even though they may be very small;
- resist removal and remain in discontinuities during removal of excess penetrant on the surface of the part;
- be capable of exiting from the discontinuity after the excess surface penetrant has been removed;
- have high visibility or contrast in small quantities or thin films when viewed on the part surface;
- not etch, corrode, or otherwise degrade the part; and
- be nontoxic.

Hazardous Characteristics

Safety is a concern because of the possible hazardous characteristics of each material used in compounding penetrants, emulsifiers, and developers. Federal law requires the manufacturer to identify and define the hazardous characteristics of each material used in its formulation. This information must be listed in a safety data sheet (SDS) prepared in accordance with 29 CFR 1910.1200, section (g), *Safety Data Sheets*. Whenever a change in materials is made, the manufacturer must update the material's SDS. For more information, see Chapter 9, "Safety, Health, and Disposal."

Corrosive Properties

Penetrants, emulsifiers, and developers must not react with metals to cause pitting, etching, cracking, or tarnishing. Complicating this requirement is the fact that many of the parts tested by PT are subsequently subjected to varying temperatures. There may be no chemical attack at room temperature, but if traces of penetrant are left on the part and it is subjected to elevated temperatures, then pitting, intergranular corrosion, or stress corrosion may occur. All penetrant materials must be subjected to three corrosion tests: moderate-temperature corrosion, high-temperature stress corrosion, and high-temperature corrosion of nickel-based alloys. Another issue is that while the corrosive properties of the penetrant materials are tested, this does not mean that the use of them cannot create a corrosive environment on a component. For example, a penetrant test on an aluminum aircraft structure in which the developer is not completely removed can act as a catalyst for a corrosive environment by retain moisture.

Corrosion testing of penetrant materials is detailed in AMS 2644. Penetrant materials listed in the QPL have been tested and passed the corrosive properties testing described in AMS 2644.

Color

The carrier or vehicle in liquid penetrant is practically colorless and transparent. This makes it very difficult to see when it is entrapped in small surface openings and voids. A dye or blend of dyes is dissolved in the vehicle to provide a high-contrast, readily visible indication. Two types of dyes are usually used: visible or fluorescent.

Visible Dyes

Visible dye penetrants, also called color contrast penetrants, are viewed under visible light and are available in red, orange, or purple. The most frequently used dyes are red because they provide high contrast with the developer and many metallic surfaces. They are inexpensive and readily dissolve in the penetrant oil. When used with emulsifiers or solvents to remove the excess surface penetrant, the small amount of penetrant trapped in the surface discontinuity is diluted when it spreads through the developer. To compensate for this, the deepest shade of red and the highest concentration of dye that can be dissolved in the oil without precipitation is used. The red dyes are visible in very thin films; however, fluorescent dyes are

visible in even thinner films. One of the basic reasons that a visible dye is considered to be less sensitive than a fluorescent dye is that fluorescent penetrants can locate an indication with a smaller, thinner volume of oil. The primary advantage of a visible penetrant is that it can be used with ordinary visible lighting at a level of at least 1076 lux (100 fc) and it can be applied from a small portable kit.

Fluorescent Dyes

Some minerals and chemical compounds have the ability to emit visible light when exposed to short wavelength energy (X-rays, ultraviolet [UV-A] light). This property of converting short wavelength energy to visible light is termed *fluorescence*; materials with this property are called *fluorescent*.

The mechanism of fluorescence involves the atomic structure of the fluorescent material and the energy level and quantity of the exciting radiation. A material will fluoresce only if it has a specific atomic structure. The energy holding the electrons in orbit in the outer shells must be low and there must be a vacant space in the outermost ring. When a photon of short wavelength radiation impacts a fluorescent material, some of the photon's energy is transferred to an electron in the outer ring, displacing it from its normal shell to the next higher ring. This is an abnormal or unbalanced condition; the displaced electron quickly returns to its normal shell. In returning to equilibrium, the electron releases the excess energy as electromagnetic radiation.

Fluorescent penetrant dyes are designed to fluoresce when exposed to 365 nm wavelength UV-A light. The released energy always has a longer wavelength than the exciting radiation. The released energy in fluorescent materials has a wavelength of 400 to 700 nm, which is in the visible light range. The wavelength of released energy depends on the type of dye used. Fluorescent penetrant dyes usually release energy in the range of 475 to 575 nm, which is in the visible spectrum of green to yellow.

Viscosity

Viscosity is a measure of a liquid's resistance to a change in physical shape. Viscosity varies widely with temperature, decreasing when temperatures are raised and increasing when temperatures are lowered. Viscosity is an important factor in the application process of both penetrant and lipophilic emulsifiers. Viscosity has no effect on penetrating ability; some very viscous fluids, such as molasses,

have very good penetrating ability, while some low-viscosity fluids, such as pure water, have very poor penetrating ability.

From an application viewpoint, the viscosity of penetrant materials affects the rate of penetration and higher viscosity fluids require a longer penetration time. Viscosity also determines how much penetrant or emulsifier remains on the part surface at the end of the dwell time. High-viscosity penetrants cling to the part surface and require increased effort in removal, which increases tank drag out losses in stationary equipment. Very thin (low-viscosity) penetrants may drain from the part so quickly that insufficient penetrant remains on the part surface to fill any discontinuities. High-viscosity emulsifiers are slow to diffuse into penetrant and require an increased emulsifier dwell time. Viscosity is measured in accordance with ASTM D445, at $37.8 \pm 2^\circ\text{C}$ ($100 \pm 5^\circ\text{F}$). There is no set value required for viscosity. The manufacturer must state the nominal viscosity of each penetrant and lipophilic emulsifier. This viscosity, $\pm 10\%$, is required on each batch or lot of material delivered by the manufacture per AMS 2644.

Flashpoint

Flashpoint is the temperature at which a liquid gives off enough flammable vapor that it could ignite in the presence of a flame. The flashpoint does not affect the performance of a penetrant, but it is important as a safety precaution. The Occupational Safety and Health Administration (OSHA) establishes a minimum flashpoint of 93°C (200°F) for flammable liquids used in open tanks without special precautions and equipment. Flashpoint is measured in accordance with standard practice ASTM D93. Penetrant materials packaged in aerosol containers are not affected but must be labeled in accordance with CFR 173.115.

Specific Gravity

Specific gravity is a ratio between the density of a substance and distilled water. The performance of a penetrant in seeping into a surface opening and bleeding back out is not affected by the penetrant's specific gravity. However, specific gravity does come into play when contamination of a penetrant tank in a stationary system is considered. For non-water-washable penetrants, any water introduced into the stationary penetrant tank will sink to the bottom. Normally, this is not a problem unless large amounts of water accumulate. However, if the tank is made of a material that is not corrosion

resistant, this situation could lead to the tank bottom developing corrosion.

Storage Stability

Penetrant and developer materials can deteriorate over time. For example, aqueous developer powders are prone to deterioration in storage. Penetrant and developer materials are required to meet all specification requirements after a one-year period of storage in fully closed containers stored at temperatures between 16 and 38°C (60 and 100°F). This is confirmed by testing samples submitted for qualification to the specification requirements.

Temperature Stability

Temperature stability is a requirement of the newer specification and should not be confused with thermal stability. *Temperature stability* refers to the resistance to separation of penetrants and emulsifiers when exposed to temperatures, both low and high, outside of the recommended processing range. Details of the stability test appear in AMS 2644. Thermal stability refers to the effect temperature has on a penetrant's fluorescent intensity.

Sensitivity

When used to describe a penetrant performance characteristic, *sensitivity* is defined as the ability to produce a visible indication from very small, tight surface openings. It involves both penetrating ability and contrast with surface background. The penetrant must enter and exit the discontinuity with enough dye to produce a noticeable indication.

Fluorescent penetrant systems (Type I) are classified into five sensitivity levels:

- Sensitivity level 1/2 – ultralow
- Sensitivity level 1 – low
- Sensitivity level 2 – normal
- Sensitivity level 3 – high
- Sensitivity level 4 – ultrahigh

The test for sensitivity level involves the use of the selected reference standard material. The test panels of titanium and nickel alloy containing very small, laboratory-generated fatigue cracks are first processed using the applicable reference standard penetrant system. The luminance of the resulting indications is measured using a digital ultraviolet radiometer with a spectral sensitivity from 320 to 400 nm. The panels are then cleaned and reprocessed using the penetrant system to be evaluated. The resulting luminance numbers must equal or exceed those of the reference standard material.

There is only one set of *qualification* test panels. The US Air Force is the qualifying agency and maintains the test panels. It is not possible to duplicate fatigue cracks with identical penetrant system performance characteristics. Therefore, *nonqualification* comparison tests are performed using a variety of test panels, such as cracked nickel-chromium plates, alternate fatigue-cracked panels, and actual service-cracked parts.

While visible dye (Type II) penetrants are not classified by sensitivity level, they do have to meet certain minimum requirements. The test depends on the visual comparison of indications on thermal cracked aluminum blocks. Half of the block is processed with the reference standard penetrant system and the other half is processed with the material that is being evaluated. After processing, the two halves are visually compared. The penetrant under evaluation must produce indications equal to or greater than the standard. Figure 1 is a photograph of the indications from two visible dye penetrants.

Selection of the sensitivity level to be used depends on potential discontinuity size, width and volume of the discontinuity, part size, shape, surface finish, residual stress, and intended function of the part. The general rule is to use the lowest sensitivity that will reveal the possible discontinuities. Difficulties can arise if the sensitivity is either too low or too high. Low-sensitivity levels may not reveal potentially harmful discontinuities, while a sensitivity level that is too high can result in a residual background that could obscure any discontinuity indications.

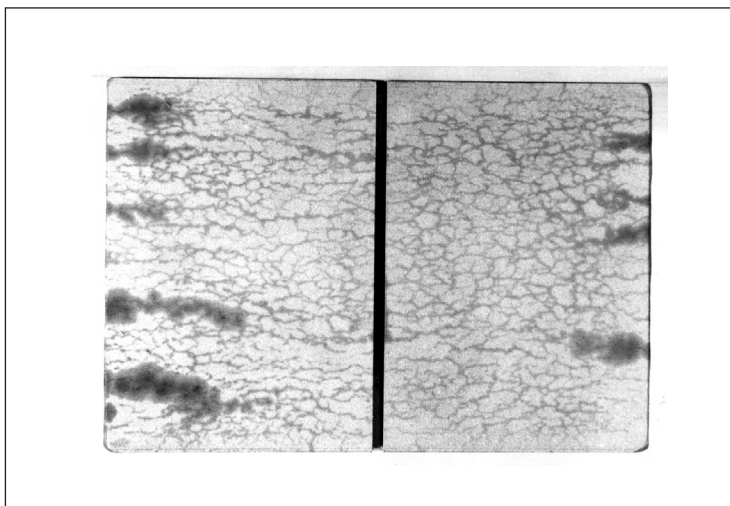


Figure 1. Comparison of two visible dye (Type II) penetrants on a cracked 2024-T3 alloy aluminum block.

Fluorescent Intensity

Fluorescent intensity is the amount of visible light given off when fluorescent dye is exposed to UV-A light. There are a number of variables that influence fluorescent intensity. Some of these are

- the thickness of the penetrant film,
- the intensity of the UV-A light impinging on the surface,
- the amount or concentration of fluorescent dye in the penetrant,
- the capability of the dye to absorb UV-A light (absorptivity), and
- the efficiency of the dye in converting the released electrons to visible light (quantum yield).

Variables that can be controlled by the operator are the intensity of the ultraviolet light impinging on the surface and the thickness of the penetrant film (emulsifying, washing, and developing). The other variables are controlled by the penetrant manufacturer. Increasing the amount of dye in solution proportionally increases the fluorescent intensity. The absorptivity and quantum yield are characteristics of the dye system. These are controlled by the dye blends, because most penetrant systems contain a blended dye. An activator dye, which has an optimum absorptivity in the 365 nm wavelength region, may have a high quantum yield but not in the 475 to 575 nm range (yellow-green). A second dye can be selected that has a good absorptivity where the activator dye has its peak emission. The second dye, called a *colorforming dye*, will emit in the 475 to 575 nm range. This interaction of different dye types is called *cascading*.

Measurement of fluorescent intensity is performed in accordance with ASTM E1135, *Standard Test Method for Comparing the Brightness of Fluorescent Penetrants*. Reference standard sensitivity level 4 penetrant is used as a baseline. A thin film is achieved by accurately diluting both the standard and material to be tested. Four small squares of filter paper are dipped into the diluted reference standard and four squares are dipped into the diluted test material. The samples are then dried. This produces a thin, uniform film of penetrant on the filter paper squares. The fluorescent intensity on both the reference standard and test material are measured using a fluorometer. For sensitivity level 4 penetrant, the fluorescent intensity of the test material must be at least 95% of the intensity of the reference standard. Sensitivity levels 1/2, 1, 2, and 3 penetrants are also

compared against sensitivity level 4 reference standard penetrant. Sensitivity level 1/2 must be at least 50%, sensitivity level 1 must be 65%, sensitivity level 2 must be 80%, and sensitivity level 3 must be at least 90% of the intensity of the reference standard penetrant.

Ultraviolet Stability

The efficiency of fluorescent dyes in converting UV-A light to visible light is reduced by prolonged exposure to UV-A light. The test for ultraviolet stability is performed in a manner similar to the test for fluorescent intensity (ASTM E1135) with the following changes. No reference standard specimens are necessary. Ten filter paper specimens are dipped into the diluted material to be tested. Five of the dried specimens are then placed in a darkened area such as a desk drawer. The remaining five specimens are exposed to $800 \mu\text{W}/\text{cm}^2 \pm 50 \mu\text{W}/\text{cm}^2$ UV-A light for 1 h. After the exposure period, the fluorescence of the specimens is measured in the fluorometer in accordance with ASTM E1135, alternating between exposed and unexposed specimens. The minimum accepted averaged values are as follows:

- sensitivity levels 4 and 3: 70% of unexposed brightness
- sensitivity levels 2, 1, and 1/2: 50% of the unexposed specimens

Thermal Stability

Elevated temperatures can reduce the fluorescence of penetrant. The test for thermal stability is similar to the fluorescent intensity tests and the ultraviolet stability tests previously described. Ten filter paper specimens are dipped into diluted penetrant to be tested. Five of the test specimens are placed in a location away from strong light, heat, and air current. The remaining five specimens are placed on a clean metal plate and held in a dead air oven at $116 \pm 3^\circ\text{C}$ ($240 \pm 5^\circ\text{F}$) for 1 h. After exposure, the fluorescent intensity is measured according to ASTM E1135. Alternating between exposed and unexposed samples is recommended. Average intensity of the exposed samples shall not be less than 60% for sensitivity levels 1/2, 1, and 2, and 80% for sensitivity levels 3 and 4 compared to the average for the unexposed samples.

Tank Life

It is possible that problems can occur when compounding penetrants and lipophilic emulsifiers. These problems usually result in separation,

precipitation, or scum forming on the surface of the material after it has been in the tank. When problems occur, they result in degraded performance. The test for tank life involves placing a 50 mL sample in an uncovered 150 mm (5.9 in.) nominal diameter petri dish that is in turn placed in a convection oven and maintained at a temperature of $50 \pm 3^\circ\text{C}$ ($122 \pm 5^\circ\text{F}$) for 7 h. At the end of the period, the material is removed from the oven, allowed to cool, and then examined visually. Any evidence of separation, precipitation, or scum formation is cause for rejection.

Water Tolerance

Water-washable penetrants (Method A) are controlled mixtures of penetrant and emulsifier. Water contamination from adjacent wash stations can cause gelling, separation, or coagulation. Therefore, limiting water contamination is necessary. Method A penetrants should show no gelling, separating, or coagulating at water concentrations up to 5%.

Removability

Removability, commonly referred to as *washability*, is a common property applicable to water-washable (Method A) and postemulsified penetrants (Methods B and D). The manufacturers carefully formulate the emulsifiers depending on the penetrant to be used. Therefore, penetrants and emulsifiers are tested as a system, and emulsifier from one manufacturer may not perform adequately on a different manufacturer's penetrant. This matching of the same manufactures penetrant and emulsifier is often referred to as "the family concept;" however, this is technically incorrect as AMS 2644 in 1996 eliminated the family group concept and substituted the system concept. The surface roughness of the test item has an effect on the test. Smooth machined parts are easily emulsified, while rough surface parts require a more active emulsifier. Overremoval is tested during the sensitivity test because removal of entrapped penetrant will decrease sensitivity on the relatively smooth panels. Underremoval, which causes excessive background, can obscure potential discontinuities and is tested as a separate item.

Special stainless steel test panels are produced by grit blasting under carefully controlled conditions. Procedures for producing and testing the panels and the type of washing apparatus to be used are detailed in AMS 2644. Four of the panels are processed in the applicable reference standard

system and four are processed in the system to be tested. Procedures for immersing and draining water-washable (Method A), postemulsified lipophilic (Method B), and postemulsified hydrophilic (Method D) penetrants are the same. They consist of dipping the test samples and allowing them to drain for approximately 10 min while at a 60° angle.

Procedures for washing, drying, emulsifying, and applying developer vary slightly, depending on the system being tested. After processing, the fluorescent background on the samples is measured using an electro-optical meter that is corrected for photopic response to visible light with negligible response to ultraviolet light. Three measurements are made on each panel. The measurements are totaled and compared to the sum of the measurements of the appropriate reference standard. Penetrant systems should leave no more residual penetrant than the same sensitivity level reference standard.

Emulsifier/Remover Properties

Petroleum-based penetrants are not soluble in water; however, there are chemicals that will combine with the penetrants to form a mixture that can be removed with a water spray. These chemicals are called *emulsifiers*. Emulsifier/removers are a complex mixture of chemicals. Ideally, during removal of surface penetrant, all excess surface penetrant should be removed from all surface areas (including fillets, corners, and recesses) without removing penetrant entrapped in discontinuities. Formulating the ideal emulsifier mixture is a delicate balancing act. A mixture that is too aggressive will leave a clean surface but will also remove entrapped penetrant, while a low aggressive mixture will leave an excessive background. Each manufacturer has its own formulation for penetrants and the emulsifiers must be formulated for that specific penetrant (except for solvent removers). Emulsifiers from one manufacturer may not perform satisfactorily on a different manufacturer's penetrant. Generally, emulsifiers are tested for sensitivity and removability during the penetrant tests.

Water-washable or self-emulsifiable penetrants (Method A) contain emulsifier as an integral part of their formulation. Adding a lipophilic emulsifier to a postemulsifiable penetrant will not produce a satisfactory water-washable penetrant. Because water-washable penetrants already contain an

emulsifier, they are susceptible to water contamination. A specification requirement is that water-washable penetrants tolerate at least 5% water addition without gelling, separating, or coagulating. They must also meet the requirement for tank life without separation of emulsifier from the penetrant.

Lipophilic emulsifier (Method B) is a type of liquid soap that will diffuse into the penetrant, producing a mixture that can be removed with a water spray. These emulsifiers are required to be a distinctly different color from the penetrant.

The three properties of lipophilic emulsifiers that control the washing characteristics are activity, viscosity, and water tolerance. These properties are factored against the characteristics of the oil-based penetrant. If a penetrant is highly resistant to water, an emulsifier with a high activity is needed. The rate of diffusion of the emulsifier into the penetrant depends on the viscosity of the emulsifier. High-viscosity emulsifiers diffuse more slowly than low-viscosity emulsifiers. A highly active emulsifier with a low viscosity can be adjusted by blending it with a more viscous emulsifier to provide the desired washing characteristics. Emulsifier stations are generally located next to the wash/rinse stations and water contamination from overspray or splashing can occur. As water is added to the emulsifier, the emulsifier gels, separates, or coagulates. A specification requirement is that the emulsifier tolerate 5% water by weight without gelling, separating, or coagulating and still be capable of passing the penetrant removability test. As parts are processed through the emulsifier, some of the surface penetrant dissolves in the emulsifier. Because Method B emulsifiers are 100% soluble in penetrant, a gradual buildup of penetrant slows the emulsification rate. With continued buildup, the emulsifier begins to function as a penetrant. Method B emulsifiers must tolerate at least one part penetrant to four parts emulsifier and still pass the removability test. Method B emulsifiers are supplied in the ready-to-use form and do not require further mixing.

Hydrophilic emulsifiers are often called *removers* to differentiate them from lipophilic emulsifiers. They consist of a mixture of chemicals called *surfactants*. Surfactants are supplied as concentrated liquids and are mixed with water either before or during the removal process. They remove excess surface penetrant by preferentially wetting the test surface and peeling the penetrant

away and by dispersing or dissolving droplets. This action occurs during final rinse as well as during immersion, whether assisted by gentle agitation or not. The concentrate is required to contain a maximum of 5% water.

It is important to understand the difference between lipophilic and hydrophilic emulsifiers. As stated above, an attempt to differentiate them is by referring to hydrophilic emulsifiers as removers, a term which is, in a way, descriptive of the difference. Lipophilic emulsifiers work primarily by diffusion and solubility into the postemulsifiable penetrant, whereas hydrophilic emulsifiers (removers) work by use of detergent and scraping or scrubbing actions.

Developer Properties

Developers assist in the withdrawal of entrapped penetrant from discontinuities and provide contrast between an indication and the part background. They must provide a smooth, even coating covering the entire surface to be tested. Their sensitivity and removability are tested using reference standard materials and are compared only to the developer action of the material being tested. Dry powder (Form a) and nonaqueous developers (Forms d and e) are supplied in the ready-to-use form. Water-soluble (Form b) and water-suspended (Form c) developers are supplied as concentrates to be mixed with water according to the manufacturer's instructions. No form of developers shall contain compounds of hexavalent chromium. Developers for Type I penetrants (fluorescent) must not exhibit any green, yellow, or orange fluorescence, and fluorescence of other colors shall not be greater than that of the reference standard developer. Developers for Type II penetrants (visible dye) shall provide good contrast with the penetrant to be used. Solvent developers shall not contain any Class I ozone layer depleting substances. Water-suspended developer must also be capable of redispersing after settling for a specified time.

SPECIAL PURPOSE MATERIALS

There are a number of penetrant materials that are different from those previously described. These materials are formulated for special applications and purposes. Because of their limited usage, they are not covered by AMS 2644. Some of these special purpose materials are described in the following paragraphs.

Oxygen-Compatible Penetrants

Liquid oxygen and gaseous oxygen are extremely chemically reactive. They can react explosively when they come into contact with a combustible material or when subjected to shock, impact, or vibration. There is not too much of a testing problem for simple disassembled parts from which all traces of penetrant testing residue are removed. Difficulties are encountered with assemblies and complex-shaped parts that contain crevices, recessed areas, or faying surfaces where testing residues become entrapped and are not removed by cleaning.

The test for liquid oxygen-compatible materials involves dropping a weight on the material while in contact with an oxygen environment. If the material is not liquid oxygen-compatible, it will cause an audible explosion or a visible flash in a darkened room, discolor the anvil, or leave evidence of charring.

Low-Sulfur and Low-Chlorine Penetrant Systems

When small quantities of sulfur and chlorine are ionized and come into contact with austenitic stainless steels, high-nickel alloys, cobalt alloys, and titanium alloys, corrosion may result. This corrosiveness is accelerated when the alloys are used at elevated temperatures and/or under residual stress resulting in intergranular corrosion, hydrogen embrittlement, and stress corrosion. Sulfur and chlorine are not essential to penetrant systems, but they do exist in trace amounts in the raw materials. The military and consensus specifications do not set limits on chlorides or sulfur content, but they do rely on corrosion tests. Materials listed on the qualified products list must meet several tests for susceptibility to corrosion at moderate temperature, high temperature, and ultrahigh temperature of cast nickel alloy under sustained stress. Most airframe and jet engine manufacturers have agreed to accept these tests rather than formulate specific limits on chlorides and sulfur.

There is a considerable difference of opinion concerning the allowable limits for chlorides and sulfur. Nuclear and boiler codes specify from 0.5% to 1% by weight as the maximums. Many of the existing commercial materials will meet at least the upper limit. Penetrant manufacturers, on special order, can provide materials meeting most of the power generation specifications.

High-Temperature Penetrant Materials

The recommended upper limit for standard penetrant systems is 52 °C (125 °F). There are fluorescent and visible dyes that resist heat degradation at temperatures higher than this. In formulating a high-temperature penetrant, the vehicles and solvents are selected to remain liquid and resist evaporation at the desired operating temperature. The upper limit for high-temperature penetrants is in the range of 177 °C (350 °F). The nonaqueous developer must be modified because standard developers will peel or curl at these temperatures. Applications for high-temperature penetrants include live steam lines and intermediate weld beads.

Dye Precipitation Penetrant Systems

Dye precipitation penetrants are commonly referred to as *high-resolution penetrants* because they are extremely sensitive to small, tight discontinuities. These penetrants contain a high concentration of either fluorescent or visible dyestuffs dissolved in a highly penetrating volatile solvent. The penetrant is applied to small areas by brushing and enters any surface discontinuities. During the penetrant dwell, the volatile solvent evaporates, precipitating the dye as a solid or gel in the discontinuity. After removal of the excess surface penetrant, a two-step developer is used. The first developer is a solvent that redissolves the penetrant, expands its volume, and extracts it from the discontinuity. The indication can be increased by applying additional layers of the solvent developer. When the indication reaches the desired size, a plastic developer is applied as a topcoat. This freezes the indication and allows it to be removed or stripped from the part surface for a permanent record.

Reversed Fluorescence Method

The reversed fluorescence method is similar to that of a photographic negative of the standard fluorescent penetrant. The penetrant, similar to standard visible dye penetrant, is applied to the surface of the part. After a dwell period, the excess surface penetrant is removed in the standard

manner. Under UV-A light, a special developer powder containing a low-intensity fluorescing dye is applied by spraying. The entire part surface will fluoresce except where an entrapment is present. The penetrant will quench the developer fluorescence and the indication appears as a dark line where the penetrant bleedout occurs.

Thixotropic Penetrant

A thixotropic material is one that changes form or structure as a function of time or shear stress. A thixotropic penetrant is applied as a solid or gel that changes to a liquid after application. One example is a high-temperature penetrant in the form of a crayon or stick that is used to test welds before they are cooled.

Dilution Expansion Developers

Dilution expansion developers do not use the conventional blotter adsorption/absorption action. Powder or pigment particles are not required in dilution expansion developers and may even interfere with the action. In dilution expansion developers, the small film of penetrant that exudes from an entrapment is diluted and its volume is expanded into the liquid developer layer. Because no pigment particles are used, the resolution of the resulting indication is improved.

Plastic Film Developers

Plastic film developers are either one-part or two-part developer systems. One-part plastic film developers consist of a variety of organic or resin polymers dispersed or dissolved in a volatile solvent. In some cases, a powder is added to scatter the light and add contrast to the indication. Because adsorption/absorption is not involved, the indication does not spread and the resolution is high. In two-part developers, the first part consists of, or is similar to, a solvent-suspended developer or a dilution expansion developer that forms the indication. The second part is then sprayed on, stopping the developer action, freezing the indication, and forming a clear plastic layer that can be peeled from the part surface to form a permanent record of the indication.

Review Questions

1. The storage stability of penetrant materials is important because:
 - a. very low temperatures can cause fluorescent penetrant materials to lose fluorescent properties.
 - b. very high temperatures can cause fluorescent penetrant materials to lose fluorescent properties.
 - c. extreme temperature variations can cause penetrant materials to separate.
 - d. properties of penetrants and developers can deteriorate over time.
2. A visible dye penetrant is not as sensitive as most fluorescent dye penetrants because:
 - a. fluorescent dye reflects light, making it less sensitive.
 - b. a visible dye emits light to attract the eye.
 - c. a thin developer coat to provide a grey background can mask an indication.
 - d. a red visible dye requires a thicker volume of oil.
3. Which property of a penetrant controls the rate of penetration of penetrant and has a direct correlation to temperature?
 - a. Viscosity of the penetrant.
 - b. Surface tension of the penetrant.
 - c. Volatility of the penetrant.
 - d. Wetting action of the penetrant.
4. A penetrant has a density less than water, which results in water contamination sinking to the bottom of a stationary tank. Which property of the penetrant allows this to occur?
 - a. Viscosity.
 - b. Surface tension.
 - c. Volatility.
 - d. Specific gravity.
5. Evaporation of volatile constituents of liquid penetrant processing materials will result in:
 - a. decreased viscosity.
 - b. changes in fluorescence.
 - c. lower developer concentration.
 - d. dry penetrant.
6. An ultraviolet stability test is performed on 10 samples of a Type II penetrant. The test exposes five samples of the penetrant to $800 \mu\text{W}/\text{cm}^2$ for 60 min. The other five samples are maintained in a dark container. The fluorescence of all specimens is then measured in accordance with ASTM E1135. The samples are alternated between exposed and unexposed specimens during the measuring. Is this a valid ultraviolet stability test to measure the fluorescence of this penetrant?
 - a. Yes, since all the requirements and steps were followed.
 - b. No, since the percentage of sensitivity level 3 penetrant must be 70% of the unexposed brightness.
 - c. No, since the percentage of sensitivity level 4 penetrant must be at least 50% of the unexposed samples.
 - d. No, since it is not on a fluorescent dye penetrant.

7. A primary consideration in the formulation of liquid penetrants is the ability of the penetrant to enter and fill a discontinuity open to the surface. Does this consideration conflict with the primary objective of PT?
 - a. No, since the primary objective is to enter a surface opening through capillary action.
 - b. No, since the component under test must be covered in penetrant for a specified length of time.
 - c. No, since all components of the penetrant process work together at the same time during the dwell time.
 - d. Yes, since the overall objective is to be able to remove the surface penetrant and find surface openings through the bleed out of the penetrant in openings.
8. Can modern penetrant materials approved in the qualified products list (QPL) cause corrosion on components?
 - a. No, since all penetrant materials are tested per AMS 2644 for corrosive properties.
 - b. No, but when these materials leave residues and the components are subjected to very low temperatures, corrosion can develop.
 - c. Yes, if the penetrant materials used are not properly postcleaned; otherwise, no.
 - d. Yes, due to the low amounts of sulfur and chlorine products allowed to be in the penetrant materials.
9. How do hydrophilic emulsifiers remove penetrant during the wash cycle compared to lipophilic emulsifiers?
 - a. Hydrophilic emulsifiers attack the penetrant molecules by diffusing into them and rendering the molecules water-washable.
 - b. Hydrophilic emulsifiers are absorbed by the penetrant oils and make the penetrant molecules denser, thus rendering them water-washable.
 - c. Hydrophilic emulsifiers attach to the penetrant molecules and with a detergent action render them water-washable.
 - d. Hydrophilic emulsifiers work like lipophilic emulsifiers with the exception that the hydrophilic are more resistant to water molecules.
10. Penetrant from XYZ manufacture is to be used with an emulsifier from ABC manufacture since the work center performing penetrant testing has a shortage of XYZ's emulsifier. Both the penetrant and emulsifier are for Method B, are the same sensitivity, and are listed in the QPL. Is this acceptable, and why or why not?
 - a. Yes, since both materials are in the QPL and are the same method and sensitivity.
 - b. Yes, since the ABC manufacture's emulsifier is lipophilic.
 - c. No, since the ABC manufacture's emulsifier acts by detergent action.
 - d. No, because the products are approved in the QPL by matching the same manufacture's products as a system concept.

Answers

1d 2d 3a 4d 5b 6d 7d 8c 9c 10d