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# Study of the Factors Affecting the Sensitivity of Liquid Penetrant Inspections: Review of Literature Published from 1970 to 1998

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Final Report

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16. Abstract

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Over 40 factors have been identified that can affect the performance of a penetrant inspection. These factors include variables affected by (1) the formulation of the materials, (2) the inspection methods and techniques, (3) the process control procedures, (4) human factors, and (5) the sample and flaw characteristics. This information will be used by the Federal Aviation Administration to help guide future research efforts regarding LPI procedures.

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# EXECUTIVE SUMMARY

This report summarizes the factors that can have an effect on the sensitivity of a liquid penetrant inspection (LPI). The intent of this task was to identify and organize the body of work that has led to current LPI practices. The effort involved reviewing nearly 350 abstracts and more than 100 full articles and reports that were published between 1970 and 1998. In general, only reports in the public domain have been included. An effort was made to include only information that discussed accepted scientific principles, presented test data, or introduced strong arguments supporting theories and observations concerning the effectiveness of penetrant inspection systems. The report attempts to briefly summarize the main points of the published literature and to direct the reader to the references where they can obtain additional information.

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## 1. INTRODUCTION.

Liquid penetrant inspection (LPI) is one of the oldest and most widely used nondestructive testing methods. It is used to inspect parts ranging from common automobile spark plugs to critical aircraft engine components. Properly applied, it has excellent sensitivity with some users, reporting a high probability of detection of flaws as small as 0.0127 cm (0.005 inch) [1 and 2]. LPI is often referred to as one of the simplest nondestructive testing methods [3]. In general, it is simple to apply, and in most noncritical applications, will produce satisfactory results when a few basic instructions are followed. However, probably more factors can affect the sensitivity of a LPI system than other nondestructive testing (NDT) methods. LPI uses chemicals that can degrade or become contaminated. LPI requires multiple operations that must be closely controlled, and in most cases, the inspection relies heavily on the inspector's attention to details. In all cases, but particularly in critical applications, the factors that affect the sensitivity of the inspection need to be known and addressed. This report will review the factors that can affect the performance of LPI materials and the inspection process to reduce or enhance sensitivity by conducting a literature survey over the time period 1970 to 1998. The focus is on fluorescent penetrant inspection but much of the information will apply to visible inspection techniques as well.

The number of articles published over the years on penetrant inspection is very large and the topics diverse. In a literature search of the Nondestructive Testing Information Analysis Center (NTIAC) database, nearly 350 bibliographies with publish dates after 1970 were found using the key word "penetrants." Nearly one-third of these articles were judged from their titles and abstracts to be considered for review. Additional articles were located from the bibliographies of articles and through other literature database searches, such as the Iowa State University Library Scholar system. Literature published after 1970 was the main target of this review, but several relevant articles that predate 1970 are also included. In this report, an effort has been made to primarily focus on articles that discuss accepted scientific principles, present test data, or introduce strong arguments supporting theories and observations concerning the effectiveness of penetrant inspection systems and practices. Also, the focus of this effort is on standard LPI techniques, and does not address other less common and in some applications, possibly more sensitive techniques such as penetrant leak testing, krypton gas penetrant inspection, [4 and 5] ultrasonic- [6], magnetic- [7] or electrical field-assisted LPI, [8] or automated penetrant inspection [9 and 10].

## 2. FACTORS AFFECTING SENSITIVITY.

### 2.1 PROPERTIES OF PENETRANT MATERIALS.

#### 2.1.1 Penetrants.

The penetrant materials used today are much more sophisticated than the kerosene and whiting first used by railroad inspectors near the turn of the 20$^{th}$ century. Today's penetrants are carefully formulated to produce the level of sensitivity desired by the inspector. While visible dye penetrants still have many uses, fluorescent penetrants are used when a high level of sensitivity is required. Fluorescence occurs when a molecule absorbs a photon of radiant energy at a particular wavelength and then quickly re-emits the energy at the same or slightly longer

wavelength. The physical mechanisms that cause penetrants to fluoresce and must be considered when formulating penetrant materials are well explained by Graham, in a paper presented at the Fifth International Conference of Nondestructive Testing in 1967 [11]. Flaherty summarizes the development of modern penetrant materials in a 1986 article published in *Materials Evaluation* [12]. To perform well, a penetrant must possess a number of important characteristics. A penetrant must

- spread easily over the surface of the material being inspected to provide complete and even coverage.
- be drawn into surface breaking defects by capillary action or other mechanism.
- remain in the defect but remove easily from the surface of the part.
- remain fluid so it can be drawn back to the surface of the part through the drying and developing steps.
- be highly visible or fluoresce brightly to produce easy to see indications.
- not be harmful to the material being tested or to the inspector.

The physical properties of a penetrant that actually affect sensitivity have been the subject of some debate. The scientific principles thought to govern LPI are explained in a number of references, but supporting experimental data are lacking. For example, an explanation of the dynamic characteristics of liquid penetrants is provided in a 1967 *Materials Evaluation* article, [13] and this information was later incorporated into volume two of the Nondestructive Testing Handbook [14]. However, there is very little experimental test data presented to compare with the theory. Possibly the most detailed explanation of the theory involved in this inspection method can be found in a Russian manuscript titled "Introduction to Capillary Testing Theory" [15]. This book fastidiously explains the derivation of theoretical models and presents some experimental data to support the theory. The book also makes extensive use of references to support its various hypotheses. Unfortunately, most of the referenced articles are in Russian.

Only a couple of U.S. studies were found documented in the public collection of literature that focus specifically on correlating the sensitivity of penetrants to their physical properties. Two of these studies are documented in the early 1960s; unpublished U.S. Air Force reports that are discussed in reference 16 and the other is chronicled in a report published in 1969 [17]. By studying 10 commercially available penetrants, Lomerson showed that sensitivity was not directly tied to viscosity, specific gravity, flash point, water content, or pour point. The McCauley and Van Winkle studies, for the U.S. Air Force, concluded that penetrant sensitivity could not be linked to the static penetrability, the absorption coefficient, or the fluorescent efficiency of a penetrant. They also conducted their study using ten commercial penetrants, both water-washable and postemulsifiable. Tanner, Ustruck, and Packman [18] later revisited the McCauley and Van Winkle data and felt there was a correlation between the logarithm of the fluorescent absorption coefficient of a penetrant and its crack detection efficiency (CDE). Several data points that did not conform to the correlation represented water-washable penetrants that were thought to have too much detergent in their formulation, which resulted in over washing and reduction in the CDE.

A number of articles have been written to describe the various methods that have been developed to measure the sensitivity of the various penetrants available (or at least some indication characteristic such as brightness) [16, 17, 19, 20, 21, 22, 23, 24, and 25]. Alburger presents an excellent historical summary of the development of test specimens for the evaluation of the performance of penetrant materials [26]. However, there is no consensus as to which method best evaluates penetrant sensitivity and no simple, straightforward evaluation method currently exists. The major U.S. government and industry specifications currently rely on the U.S. Air Force Materials Laboratory at Wright-Patterson Air Force Base to classify penetrants into one of five sensitivity levels. This procedure uses titanium and Inconel specimens with small surface cracks produced in low-cycle fatigue bending to classify penetrant systems. The brightness of the indication produced is measured using a photometer. The sensitivity levels and the test procedure used can be found in Military Specification MIL-I-25135 and Aerospace Material Specification 2644, Penetrant Inspection Materials. Historically, MIL-I-25135 has been the controlling document for both military and civilian penetrant material uses. A recent change in military specification management has lead to the transition towards the use of industry specifications where possible. However, since history lies with the military specification, and the U.S. Air Force is primarily responsible for penetrant qualification testing, MIL-I-25135 is referred to throughout this document even though the discussion may also be applicable to AMS 2644.

The industry and military specification that control the penetrant materials and their use all stipulate certain physical properties of the penetrant materials that must be met. Some of these requirements address the safe use of the materials such as toxicity, flash point, and corrosiveness, and other requirements address storage and contamination issues. Still others delineate properties that are thought to be primarily responsible for the performance or sensitivity of the penetrants. The properties of penetrant materials that are controlled by MIL-I-25135E include surface wetting capability, viscosity, color, brightness, ultraviolet stability, thermal stability, water tolerance, and removability. These properties as well as others that have been shown to affect the performance of a penetrant will be discussed in the following sections.

2.1.1.1 Surface Energy (Surface Wetting Capability).

As previously mentioned, one of the important characteristics of a liquid penetrant material is its ability to freely wet the surface of the object being inspected. At the liquid-solid surface interface, if the molecules of the liquid have a stronger attraction to the molecules of the solid surface than to each other (the adhesive forces are stronger than the cohesive forces), then wetting of the surface occurs. Alternately, if the liquid molecules are more strongly attracted to each other and not the molecules of the solid surface (the cohesive forces are stronger than the adhesive forces), then the liquid beads up and does not wet the surface of the part.

One way to quantify a liquid's surface wetting characteristics is to measure the contact angle of a drop of liquid placed on the surface of the subject material. The contact angle is the angle formed by the solid-liquid interface and the liquid-vapor interface measured from the side of the liquid as shown in figure 1. Liquids wet surfaces when the contact angle is less than 90 degrees. For a penetrant material to be effective, the contact angle should be as small as possible. In fact, the contact angle for most liquid penetrants is very close to zero degrees [14].

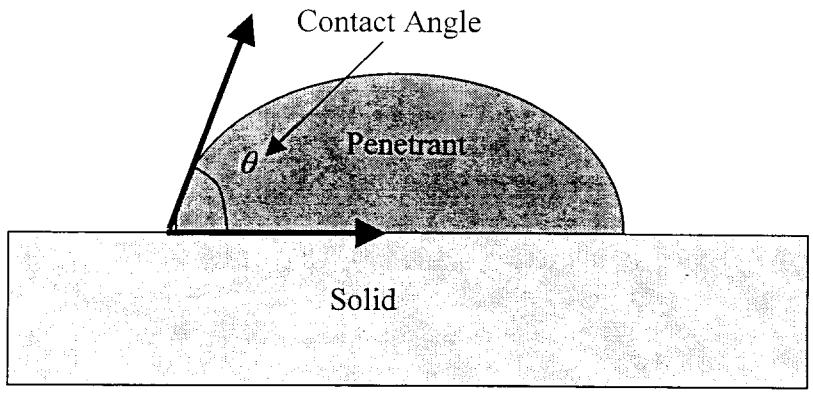


FIGURE 1. SKETCH SHOWING MEASUREMENT OF CONTACT ANGLE ($\theta$)

Wetting ability of a liquid is a function of the surface energies of the solid-gas interface, the liquid-gas interface, and the solid-liquid interface. The surface energy across an interface or the surface tension at the interface is a measure of the energy required to form a unit area of new surface at the interface. The intermolecular bonds or cohesive forces between the molecules of a liquid cause surface tension. When the liquid encounters another substance, there is usually an attraction between the two materials. The adhesive forces between the liquid and the second substance will compete against the cohesive forces of the liquid. Liquids with weak cohesive bonds and a strong attraction to another material (or the desire to create adhesive bonds) will tend to spread over the second material. Liquids with strong cohesive bonds and weaker adhesive forces will tend to bead up or form a droplet when in contact with the second material.

In liquid penetrant testing, there are usually three surface interfaces involved, the solid-gas interface, the liquid-gas interface, and the solid-liquid interface. For a liquid to spread over the surface of a part, two conditions must be met [14]. First, the surface energy of the solid-gas interface must be greater than the combined surface energies of the liquid-gas and the solid-liquid interfaces. Second, the surface energy of the solid-gas interface must exceed the surface energy of the solid-liquid interface.

A penetrant's wetting characteristics are largely responsible for its ability to fill a void. Penetrant materials are often pulled into surface breaking defects by capillary action. The capillary force driving the penetrant into the crack is a function of the surface tension of the liquid-gas interface, the contact angle, and the size of the defect opening. The driving force for the capillary action can be expressed as the following formula [27 and 28]:

$$Force = 2\pi r \sigma_{LG} \cos\theta$$

Where: $r$ = radius of the crack opening ($2r$ is the line of contact between the liquid and the solid tubular surface).

$\sigma_{LG}$ = liquid-gas surface tension.

$\theta$ = contact angle.

Since pressure is the force over a given area, the pressure developed, called the capillary pressure, is

$$Capillary\ Pressure = \frac{2\sigma_{LG}\cos\theta}{r}$$

The previous equations are for a cylindrical defect, but the relationships of the variables are the same for a flaw with a noncircular cross section. Reference 15 notes that capillary pressure equations only apply when there is simultaneous contact of the penetrant along the entire length of the crack opening and a liquid front develops that is an equidistant from the surface. A liquid penetrant surface could take on a complex shape as a consequence of the various deviations from flat parallel walls that an actual crack could have. In this case, the expression for pressure is

$$Capillary\ Pressure = 2(\sigma_{SG} - \sigma_{SL})/r = 2\Sigma/r$$

Where: $\sigma_{SG}$ = surface energy at the solid-gas interface.
$\sigma_{SL}$ = surface energy at the solid-liquid interface.
$r$ = radius of the opening.
$\Sigma$ = adhesion tension ($\sigma_{SG}$ - $\sigma_{SL}$).

Therefore, at times, it is the adhesion tension that is primarily responsible for a penetrant's movement into a flaw and not the surface energy of the liquid-gas interface. Adhesion tension is the force acting on a unit length of the wetting line from the direction of the solid. The wetting performance of the penetrant is degraded when adhesion tension is the primary driving force.

It can be seen from the equations in this section, that the surface wetting characteristics (defined by the surface energies) are important penetrant characteristics for filling the flaw. The liquid penetrant will continue to fill the void until an opposing force balances the capillary pressure. This force is usually the pressure of trapped gas in the void, as most flaws are open only at the surface of the part. Since the gas originally in the flaw volume cannot escape through the layer of penetrant, the gas is compressed near the closed end of the flaw. The Nondestructive Testing Handbook on penetrant testing [14] presents equations that use the pressure of the gas trapped inside the flaw to estimate the smallest flaw that can be infiltrated by a penetrant. The smallest flaw dimension is shown to be inversely proportional to the pressure of the trapped gas and directly proportional to the surface tension of the penetrant and the cosine of the contact angle.

Since the contact angle for penetrants is very close to zero, other methods have been devised to make relative comparisons of the wetting characteristics of these liquids [29]. One method is to measure the height that a liquid reaches in a capillary tube. However, the solid interface in this method is usually glass and may not accurately represent the surface that the penetrant inspection will be performed on. Another method of comparative evaluation is to measure after a set time has elapsed, the radius, diameter, or area of a spot formed when a drop of penetrant is placed on the test surface. However, using this method, other factors are also acting in the comparison. These methods include the density, viscosity, and volatility of the liquid, which do not enter into the capillarity equations but may have an effect on the inspection as discussed below.

2.1.1.2 Density or Specific Gravity.

The density or the specific gravity of a penetrant material probably has a slight to negligible effect on the performance of a penetrant. The gravitational force acting on the penetrant liquid can be working in cooperation with or against the capillary force depending on the orientation of the flaw during the dwell cycle. When the gravitational pull is working against the capillary rise, the strength of the force is given by the following equation [28]:

$$Force = \pi r^2 hpg$$

Where: $r$ = radius of the crack opening
$h$ = height of penetrant above its free surface
$p$ = density of the penetrant
$g$ = acceleration due to gravity

When the direction of capillary flow is in the same direction as the force of gravity, the added force driving the penetrant into the flaw is given by

$$Force = hAp$$

Where: $h$ = the height of the penetrant column
$A$ = cross-sectional area of the opening
$p$ = density of the penetrant

Gui [30] also found a relationship between the penetration speed of a penetrant and its specific gravity. Increasing the specific gravity by decreasing the volume percent of solvent in the solution will increase the penetration speed.

2.1.1.3 Viscosity.

A number of studies have found that the viscosity of a penetrant has an effect on speed at which the penetrant fills a defect. Deutsch [31] makes several calculations that relate the factors that control the fill time. The equations for fill time of cylindrical and elliptical voids are

Cylindrical Void

$$Fill\ Time = \frac{2l^2\mu}{r\cos\theta\sigma_{LG}}$$

Elliptical Void

$$Fill\ Time = \frac{2l^2\mu}{\sigma_{LG}\cos\theta} \cdot \frac{a^2 + b^2}{(a+b)ab}$$

Where: $l$ = defect depth
$\mu$ = viscosity
$r$ = defect width
$\sigma_{LG}$ = liquid-gas surface tension
$\theta$ = contact angle
$a$ = flaw width
$b$ = flaw length

These two equations do not take into account entrapped gas that can have a large effect in a closed end capillary. This will be discussed further in section 2.2.4.

The Russian textbook [15] also includes viscosity in the expressions for calculating the time necessary to fill a defect. The equations in reference 15 do take into account the pressure from the entrapped gas as well as atmospheric pressure and thus are more complex but similar to those of Deutsch. Gui [30] also notes a relationship between the performance and the viscosity of the penetrant material but no details are offered.

2.1.1.4 Color and Fluorescent Brightness.

The color of the penetrant material is of obvious importance in visual penetrant inspection, as the dye must give good contrast against the developer or part being inspected. When fluorescent materials are involved, the effect of color and fluorescence is not straightforward. LPI materials fluoresce because they contain one or more dyes that absorb electromagnetic radiation over a particular wavelength and the absorption of photons leads to changes in the electronic configuration of the molecules. Since the molecules are not stable at this higher energy state, they almost immediately re-emit the energy. There is some energy loss in the process causing the photons to be re-emitted at a slightly longer wavelength, which is in the visible range. Since the human eye is the most commonly used sensing device, most penetrants are designed to fluoresce as close as possible to the peak response of the human eye [11].

Alburger [32] and Gram [11] explain that two different fluorescent colors can be mixed to interact by a mechanism called cascading. The emission of visible light by this process involves one dye absorbing ultraviolet radiation to emit a band of radiation that makes a second dye glow. The radiation absorption and emission could take place a number of times until the desired color and brightness is achieved. Generally, the process employs one dye having a peak absorbency at 365 nm that fluoresces at a wavelength around 450 nm (and looks blue) and a second dye having a peak absorbency around 450 nm and a fluorescence peak around 530 to 550 nm. This produces optimal sensitivity since the peak of the visibility curve for the normal eye is around this wavelength under dim lighting conditions.

In his paper titled "Signal-to-Noise Ratio in the Inspection Penetrant Process" [33], Alburger states that fluorescent brightness was erroneously once thought to be the controlling factor with respect to flaw detection sensitivity. He points out that measurements have been made to evaluate the intrinsic brightness of virtually all commercially available penetrants and that they all have about the same brightness. Intrinsic brightness values are determined for thick liquid films, and the dimensional threshold of fluorescence (discussed in section 2.1.1.5) is a more important property.

The importance of fluorescent brightness in LPI and the process of measuring brightness were well explained by Alburger in a 1966 *Materials Evaluation* Article [34]. The process is now delineated in ASTM E-1135, "Standard Test Method for Comparing the Brightness of Fluorescent Penetrants." The specific equipment needed to make the brightness measurements is discussed in a number of papers [21, 23, 24, 35, and 36].

2.1.1.5 Dimensional Threshold of Fluorescence.

The dimensional threshold of fluorescence is a property that is not currently controlled by the specifications but largely determines the sensitivity of a fluorescent penetrant. A. L. Walters and R. C. McMaster conducted an early experiment that led to the understanding of this condition [26]. Two optically flat plates of glass were clamped tightly together, and a drop of fluorescent penetrant was placed at the interface of the plates. The penetrant could be seen migrating in between the plates, but when exposed to black light, no fluorescence was seen. The phenomenon was not fully understood until 1960 when Alburger introduced the concept of thin-film transition of fluorescent response.37.

Alburger [32] explains that the dimensional magnitudes of typical crack defects correspond to the dimensional thresholds of fluorescence response, which are characteristic of available penetrants. Alternately stated, the degree of fluorescence response, under a given intensity of ultraviolet radiation, is dependent on the absorption of ultraviolet radiation, which in turn depends on dye concentration and film thickness. Therefore, the ability of a penetrant to yield a visible indication depends primarily on its ability to fluoresce as a very thin film. It was also noted that the crack detectability could be improved by increasing the concentration of the fluorescent tracer dye in the penetrant. Alburger presents a modified Beer's Law equation that can be used to predict the performance of penetrants based on the physical constraints of the dyes. The instrument used for measuring the dimensional threshold of fluorescence is the Meniscus-Method apparatus.

Gram [11] also addresses the effect of dye concentration on the dimensional threshold of fluorescence. He, like Alburger, notes that a modified Beer's Law can be used to describe the performance of a fluorescent penetrant solution. When the dye concentration is increased, the brightness of a thin layer of penetrant generally increases. However, he also points out that the dye concentration can only be increased so much before it starts to have a negative effect of brightness. Gram presents data showing that for one particular dye (5Ga) in naphtha, the relative brightness of the solution began to decrease after the dye concentration reached 2 grams per liter.

2.1.1.6 Ultraviolet (UV) Stability.

Brittain [25] measured the intensity of fluorescent penetrant indications of a sample that was subjected to multiple UV exposure cycles. Each cycle consisted of 15 minutes of 800 microwatts/cm$^2$ UV light and 2.5 minutes of 1500 microwatts/cm$^2$ UV light. Two penetrants were tested in the study, water-washable, level 3 (Ardrox 970P25) and a postemulsifiable, level 4. The results from the study show that the indications from both penetrants faded with increased ultraviolet exposure. After eight exposure cycles the brightness of the indications was less than one-half their original values.

2.1.1.7 Thermal Stability.

The thermal stability of penetrants is discussed in a paper titled "Advances in Improving the Heat-Fade Resistance of Fluorescent Penetrants" by Muller and Fantozzi [38]. It is reported that at elevated temperatures, penetrants experience heat degradation or heat fade. The fading of indications takes place due to dye vaporization or sublimation. The tendency to volatize at high

temperatures is a function of the dye's melting point and chemical structure. The paper discusses ways of testing for heat degradation and a new formulation of a dye with a higher melting point that improves resistance to heat damage.

Sherwin and Holden teamed to publish a paper in *Materials Evaluation* titled "Heat Assisted Fluorescent Penetrant Inspection" [39]. In this paper, the authors discuss how the sensitivity of a fluorescent penetrant inspection (FPI) can be improved if a part is heated when a high boiling point penetrant material is used. However, when a high boiling point liquid is not used, heat generally reduces the sensitivity of the system. They point out that excessive heat (1) evaporates the more volatile constituents, which increases viscosity and adversely affects the rate of penetration; (2) alters wash characteristics; (3) boils off chemicals that prevent separation and gelling of water-soluble penetrants; and (4) kills the fluorescence of tracer dyes. A paper by James Borucki is referenced as saying, "The various types of fluorescent dyes commonly employed in today's penetrant materials begin decomposition at 71°C (160°F), and when the temperature approaches 94°C (200°F), there is almost total attenuation of fluorescent brightness of the total composition and sublimation of the fluorescent dyestuffs." Sherwin and Holden point out that by formulating penetrants with high boiling points, all the heat related problems are removed except this loss of fluorescent brightness. The authors go on to show that the loss of brightness takes place over a period of time while at elevated temperature. When one heat resistant formulation was tested, a 20 percent reduction was measured after the material was subjected to 163°C (325°F) for 273 hours.

Robertson conducted a set of experiments that also found the brightness of indications is reduced when the test specimens see temperatures above 65°C (149°F) [40]. He also found that when the dyes alone were heated in a petri dish there was no loss of brightness when the materials were heated for 30 minutes at 95°C (203°F). This led him to conclude that degradation of the dye materials, as suggested by Muller and Fantozzi, was not the reason for the reduced brightness.

Schmidt and Robinson [22] found that the heat stability of penetrant materials is a function of the airflow over the specimen, the temperature, and the time. Using D-20 cracked test panels and MX-2 penetrant, they developed the data shown in figure 2. At 54°C (130°F), and no airflow, 20 percent of the indication brightness is lost after 20 minutes and less than 30 percent of the brightness is lost after 50 minutes. If the temperature is raised to 71°C (160°F), a 20 percent loss is seen in about 8 minutes and nearly 50 percent of the brightness is lost after 50 minutes. At 93°C (200°F), 20 percent of the indication brightness is lost after 20 minutes. When the tests were run with 137 meters/minute (450 feet/minute) of airflow on the specimens, the loss in brightness occurred faster and was more severe.

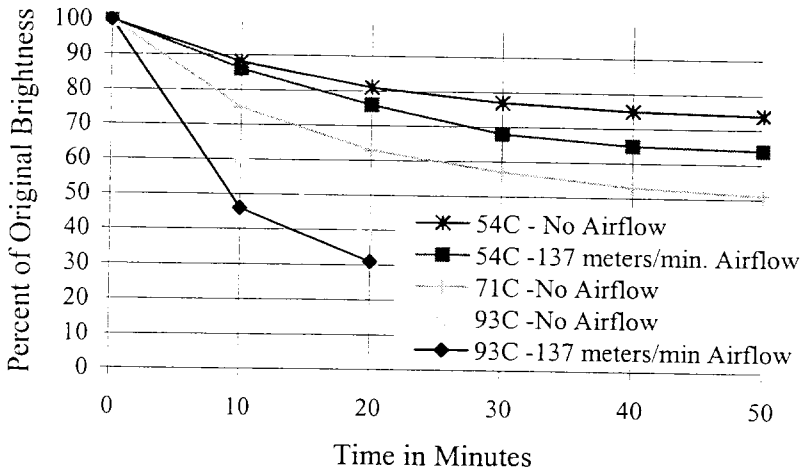


FIGURE 2. CHART SHOWING THE EFFECT OF TEMPERATURE, TIME, AND AIRFLOW ON MX-2 PENETRANT AS REPORTED BY SCHMIDT AND ROBINSON [22]

Lovejoy offers an explanation for heat fade in an article titled, "The Importance of the Physical Nature of Fluorescence in Penetrant Testing" 41. Lovejoy explains that the phenomenon of fluorescence involves electrons that are delocalized in a molecule. These electrons are not specifically associated with a given bond between two atoms. When a molecule takes up sufficient energy for the excitation source, the delocalized bonding electrons rise to a higher electronic state. After excitation, the electrons will normally lose energy and return to the lowest energy state. This loss of energy can involve a radiative process such as fluorescence or nonradiative processes. Nonradiative processes include relaxation by molecular collisions, thermal relaxation, and chemical reaction. Heat causes the number of molecular collisions to increase, which results in more collision relaxation and less fluorescence. This explanation is only valid when the part and the penetrant are at an elevated temperature. When the materials cool, the fluorescence will return. However, Lovejoy adds that while exposed to elevated temperatures, penetrant solutions dry faster. As the molecules become more closely packed in the dehydrated solution, collision relaxation increases and fluorescence decreases. Gram [11] calls this effect concentration quenching, and he presents data showing that as the dye concentration is increased, fluorescent brightness increases initially, but reaches a peak and then begins to decrease.

2.1.1.8 Removability.

Removing the penetrant from the surface of the sample without removing it from the flaw is one of the most critical operations of the penetrant inspection process. Since the detectability of an indication is dependent on its brightness or contrast, relative to the background brightness, the penetrant must be removed from the sample surface as completely as possible to limit background fluorescence. In order for this to happen, the adhesive forces of the penetrant must not be so strong that they cannot be broken by the removal methods used. Ideally, the penetrant liquid and the cleaning solution should not commingle to dilute the penetrant.

Alburger discusses the critical parameter of cleaning the penetrant from the surface of a part without removing it from the defect. This paper titled, "Signal-to-Noise Ratio in the Inspection Penetrant Process" [33], provides a good history of the penetrant inspection method and the development of materials and testing procedures. Alburger briefly describes the various types of emulsifiers and explains self-emulsifying water-washable penetrants, which he refers to as "gel-forming" penetrants. These penetrants form relatively viscous gels upon contact with water and tend to resist rapid wash-removal due to the formation of gel-like plugs in the openings of flaws.

2.1.2 Emulsifiers.

Emulsifiers are designed to help control the excess penetrant removal process. As mentioned above, some penetrants include the emulsifier as and integral part of their formulation. These penetrants are commonly referred to as self-emulsifiable or water-washable penetrants since the excess penetrant can be rinsed from the surface without an intermediate emulsification step. However, when over washing of the sample is a particular concern, penetrants that require a separate emulsification step are recommended. There are two types of emulsification systems, lipophilic and hydrophilic. Lipophilic emulsifiers are oil based and diffuse into the penetrant film to render it emulsifiable in water. Hydrophilic emulsifiers are water based and work by displacing excess penetrant from the surface of the sample by detergent action. The type of emulsifier used is dictated by the penetrant used. The emulsifying agent used with postemulsifiable systems should blend with the penetrant on contact. However, it should diffuse through the penetrant at a rate slow enough to allow close control of the contact time.

2.1.3 Developers.

The role of the developer is to pull the trapped penetrant material out of defects and to spread the penetrant out on the surface of the part so an inspector can see it. The fine developer particles also reflect and refract the incident ultraviolet light, allowing more of it to interact with the penetrant, causing more efficient fluorescence. Additionally, the developer also allows more light to be emitted through the same mechanism. This is why indications are brighter than the penetrant itself under UV light [11 and 42]. It has been shown by Blackwell [43] that the visual perception of an object near its threshold intensity depends on the product of the brightness per unit area and the total area. In other words, the total light emitted from an indication determines whether it will be seen or not.

The kinetics of a developer are explained in a series of papers published in *Defektoskopiya – The Soviet Journal of Nondestructive Testing* [44, 45, 46, 47, 48, and 49]. These papers report that

- the penetrant indication that forms is a function of the volume of the defect and the extent that the cavity fills with penetrant;
- the coefficient of surface tension, viscosity, and microstructure coefficient (particle sizes) of the penetrant;
- the radius of the pores, the permeability and the porosity of the developer;
- the thickness of the layer of developer;

- the atmospheric pressure; and the contact wetting angle of the penetrant on the surface of the developer.

The following conclusions are drawn from the kinetic equations:

- The larger the defect volume, the larger the indication will be. The depth of the defect is highly important.
- The greater the fill factor of a void, the larger the indication will be.
- The larger the developer pore size, the longer it will take an indication to form.
- A thin layer of developer will produce an indication faster and improve sensitivity within limits. A developer thickness less than a few micrometers reduces sensitivity.

2.1.3.1 Permeability, Porosity, Dispersity, and Surface Energy.

Thomas [42] explains that the developer is composed of small particles that are nonabsorbent to the penetration. The penetrant coats the surface of the developer particles and fills some of the voids between the particles. Thomas presents an example calculation that shows that the penetrant does not fill all the interstices of the developer because there is not enough penetrant trapped in many defects. He theorizes that the penetrant is drawn out of the defect by the capillary forces of the interstices and then spreading forces move the penetrant around the surface of the developer particles.

The condition that is required for extraction of the penetrant from the defect cavity by a layer of powder developer is as follows [48]:

$$P_c + P_a < P_{cg} + P_{ex}$$

Where: $P_c$ = the capillary pressure
$P_a$ = the atmospheric pressure
$P_{cg}$ = the pressure of the gas trapped in the defect channel by the penetrant
$P_{ex}$ = the extraction pressure caused by the developer

The extraction force, $P_{ex}$, is a result of the absorption of the penetrant by the fine, porous layer of developer. The characteristics of a developer that affect its performance include its porosity, permeability, dispersity (the average pore size between particles), and surface energy [15]. The developer should be easily wet by the penetrant. It should be made of small, finely dispersed particles to produce a highly porous layer.

2.1.3.2 Particle Size.

As will be discussed in section 2.2.5, when the penetrant is removed from the surface of the sample, some of the penetrant trapped in the flaw will also be removed. The column of penetrant in the flaw then develops a concave upper surface. The liquid will likely reach the surface at the edges of the flaw but be depressed in the center. If the particle size of the developer exceeds the

width of the flaw, it is possible (depending on the amount of trapped penetrant lost) that the particle will contact only a very small amount of the penetrant surface or none at all. If the size of the particle is less than the width of the flaw, particles may penetrate in the crack cavity. The particles can advance to the point where they begin to jam in the narrowing portions of the channel, and this condition will reduce sensitivity [15].

In a paper titled "The Amplifying Action of Developer Powders" [50], Brittian showed that mixtures of various developer powders and a standard water-washable penetrant varied widely in the fluorescent light output. This variation was reported to be due to the nature and particle size of the powder. Brittian concluded that the developer particles must be transparent in the near-ultraviolet and visible spectra. He used pure hydrated alumina powders with fine, mean-particle sizes ranging from 7 to 17 microns (0.0003 to 0.0007 inch) to study the effect of the particle size of the developer. He found that as the particle size increased over this range, so did the fluorescent output. He also found that when the developer was mixed with penetrant to the point that all the interstitial voids in the developer were filled, the fluorescent output peaks at a value around three times the value of a thick film of the penetrant itself. The theory presented for this amplification effect is that the presence of the developer enables light that would normally be trapped inside the penetrant film and its containing surfaces (reflected between the surfaces of the penetrant layer and dissipated) to be released.

#### 2.1.3.3 Effects of Liquid Carrier.

In a paper presented at the 12th World Conference in Nondestructive Testing, researchers examined how a penetrant indication is affected by the interactions of the liquid phase of a developer [51]. They observed that two flow patterns are possible when a dead-end capillary tube is first loaded with one liquid and then immersed in a second liquid. One possible flow pattern is that both liquids are pulled deep in the capillary and stop. In other words, the developer could push the penetrant deeper into the flaw. The second possibility is that both liquids will initially be pulled into the capillary, stop, and the second liquid will begin to extract the first liquid from the tube. The researchers proposed that the extraction process occurs when the product of the surface energy and the cosine of the contact angle of the second liquid is less than that of the first liquid. This finding is of primary importance to penetrant material formulators but emphasizes the need for users to only use chemicals designed to work together.

#### 2.1.3.4 Whiteness.

In a Russian publication *Defektoskopiya – The Soviet Journal of Nondestructive Testing*, a paper addressed the result of an investigation to determine the whiteness of developers [52]. The report states "A high whiteness of the layer of developer determines satisfactory contrast on the indicating image of the defect on its background and facilitates rapid perception of the image by the eye of the examiner."

## 2.2 INSPECTION METHOD AND TECHNIQUE (VARIABLES CONTROLLED BY INSPECTOR).

While the formulation of the penetrant materials is very important in establishing the sensitivity of a penetrant inspection, many other variables can have an impact on the inspection results.

Some of these variables are controllable by the inspector and others are not. This section of the report reviews the factors that the inspector can control.

2.2.1 Preparation of the Part.

One of the most critical steps in the penetrant inspection process is cleaning of the part. A good cleaning procedure will remove all contamination from the part and not leave any residue that may interfere with the inspection process. It is also important that the cleaning process not produce metal smearing that can cover or close defects at the surface of the part. In many cases, chemical cleaning alone does not adequately prepare the surface of a part for inspection and mechanical cleaning methods must be employed. These mechanical cleaning methods such as grit, or other media blasting, sanding, and even steam cleaning have been shown to cause metal smearing in some alloys.

2.2.1.1 Metal Smear From Machining or Cleaning Operation.

It is well recognized that machining and peening operations cause a small amount of the material to smear on the surface of some materials. It is perhaps less recognized that some cleaning operations, such as steam cleaning, can also cause metal smearing in the softer materials. This metal smearing can have a very detrimental effect on an LPI, as defects that are normally open to the surface can partially or completely be covered over. Etching of the specimens was found to return the flaw to the premechanical processing level of detectability.

There are numerous studies concerning metal smearing of aluminum alloys documented in the literature. One of the earliest studies to publish results on the subject was published by McFaul [53] in 1965. McFaul reports on the efforts of researchers at Douglas Aircraft Company. They produced thermal fatigue-cracked blocks of 2024 aluminum alloy. The results are presented as a series of photographs, and show that sanding, milling, hand scraping, shot peening, grit blasting, vapor blasting, and tumble deburring all reduced the sensitivity of penetrant inspection. They also found that, with the exception of shot peening, a mild etch to remove 0.0076 mm (0.0003 inch) removed the metal smear and returned the penetrant indications. In a similar study [54], Cook, Lord, and Roehrs investigated the effect that sanding has on the LPI detectability of quench cracks in aluminum specimens. They found that the sanding process adversely affected the LPI procedure and that a minimum of 0.0051 mm (0.0002 inch) must be chemically removed from the surface in order to restore detectability of the quench cracks.

Perhaps the most quantitative data on this subject is presented by Rummel in his article on the use of probability of detection (PoD) data to evaluate process capabilities [55]. Two PoD curves are presented which show the effect that metal smear and etching can have on crack detectability. One curve shows the PoD of an as-machined, aluminum flat panel. A PoD of 90 percent is not attained until the crack length reaches 11 mm (0.435 inch). The second curve shows that when the sample is etched, a 90 percent PoD is possible with crack length around 2 mm (0.077 inch).

Volume 2, Liquid Penetrant Testing, of the ASNT Nondestructive Testing Handbook [14], shows the effects of a number of mechanical processes on the sensitivity of penetrant inspection. Side-by-side comparison photographs of mainly quench-cracked aluminum blocks show that penetrant indications are reduced or completely obscured when processes such as honing,

lapping, hand sanding, hand scraping, shot peening, grit blasting, vapor blasting, and tumble deburring are employed prior to inspection. This same reference also presents some information relative to materials other than aluminum alloys, namely ANSI 1018 and 4340 steel, 300M steel and Ti-6Al-4V.

Henkener and Salkowski [56] looked at the metal smear in 2024-T851 aluminum specimens with surface fatigue cracks. They studied end milling, fly cutting, grinding, polishing, and glass bead blasting. They concluded that with the exception of fly cutting, all the machining processes significantly degraded the penetrant inspection. Fly cutting slightly degraded about half of the indications and seem to improve the other half. Etching was reported to have invariably improved the dye penetrant inspections of both smeared and unsmeared cracks.

A study conducted in 1985, focused on the effect of blasting an aluminum alloy (with a hardness of 160 v.p.n.) with lignocellulose media [57]. Lignocellulose is a term used to describe wood-based blasting media, which can be derived from almond or walnut shells, or plum, peach, and apricot pits. The author reported that at a blast pressure of 172 $kN/m^2$ (25 pounds per square inch (psi)), some of the finer indications on the quench-cracked specimens either partially or totally disappeared. More serious indication losses were seen when the blast pressure was raised to 276 $kN/m^2$ (40 psi).

The effect of plastic medium blasting on the LPI detection of cracks in aluminum alloys was the subject of a study by Conrad and Caudill [58]. Plastic medium blasting is used to strip paint from aircraft to reduce the use of hazardous chemicals. Aluminum 2014-T61 and 7075-T7 specimens with both fatigue and stress corrosion cracks were used in the study. After subjecting the specimens to a worse case, plastic media blast, a reduction in crack detectability was observed in 24 of 33 samples. Microphotographs of the cracks showed the loss of detectability to be due to metal smearing and media entrapment. The researchers found that subsequent etching resulted in a gain in detectability that exceeded the baseline (prior to media blasting) values. Optical measurements were made to determine the lengths of the penetrant indications.

Burkle and Fraser conducted a study on the effect of metal smear on LPI using ASTM A-36 steel specimens. Copper-ferrite dilution cracking was induced in a V-groove butt weld. The study found that sandblasting to prepare a surface for painting or to remove paint, masked cracks so that penetrant inspection was not effective [59].

Pratt & Whitney Aircraft under contract by the US Air Force studied the effects of the cleaning processes used on Inconel 718, Ti-6Al-4V, and Ti-6Al-2Sn-4Zr-6Mo materials in engine overhaul facilities [60 and 61]. Using samples with low-cycle fatigue cracks, they found that grit blasting increased surface roughness and caused metal smear that reduced LPI sensitivity. Alternately, they found that a light vapor blast (689 $kN/m^2$ (100psi) at 406 to 457 mm (16 to 18 inches) for 30 seconds) did not degrade FPI sensitivity and actually enhanced crack indications by reducing background fluorescence and increasing the definition of the cracks. The authors cautioned that vapor blasting might cause metal smearing if applied too heavily. Chemically milling away between 0.0025 and 0.0038 mm (0.0001 and 0.00015 inch) was found to remove the smeared metal layer and restore flaw detectability.

It must be noted that under carefully controlled conditions, metal smear can be avoided. Researchers at Rockwell International produced a set of machining parameters and tool wear conditions that did not generate defect obscuring metal smearing in aluminum alloy 6061-T6. The report by Schaefer [62] does not detail the study results but instead presents general findings and references a number of internal Rocketdyne reports.

2.2.1.2 Use of an Etchant to Remove Metal Smear.

In all the articles mentioned in the previous section, the authors agreed that etching prior to penetrant inspection improved flaw detectability. That is, if the etchant is properly removed from the part before applying penetrant. Kleint warns in a 1987 article [63] that acid entrapment from a prepenetrant etch can have disastrous effects on the penetrant inspection. The article states that the sodium hydroxide caustic often used to etch aluminum parts does not affect penetrants, but acids used to etch parts of other materials do. Experts in the penetrant field warn that caustics can in fact reduce penetrant brightness. Careful cleaning of both acid and caustic etches before penetrant inspection is highly recommended. A reversible developer is also recommended for verification of etchant removal.

There are several other risks to the parts being processed when an etchant is used. First, since the etching process is removing metal from the surface of the part, the minimum dimensional tolerances of the part must be considered. A second possible risk is that the etching process could have an effect on the material properties of the part. The chemical etchant used should uniformly remove material from the surface and should not etch microstructural features (such as grain boundaries) preferentially. Ideally, a study should be conducted to evaluate the effects of the etching process (or other chemical process) on the mechanical properties and performance of the component.

2.2.1.3 Plugging of Defect With Cleaning Media or Other Substance.

As mentioned previously, in their study on the effect of plastic medium blasting on the LPI detection of cracks in aluminum alloys [58], Conrad and Caudill found that media entrapment was partially responsible for loss of LPI indication strength. Microphotographs of the cracks after plastic media blasting showed media entrapment in addition to metal smearing.

2.2.1.4 Chemical Cleaning.

Sam Robinson of Sherwin Inc. discusses an important cleaning consideration in a paper titled "1,1,1-Trichloroethane Here Today, Gone Tomorrow! Replacing 1,1,1-Trichloroethane in the Penetrant Process" [64]. He cautions that some mild alkaline cleaners include sodium metasilicate as an ingredient. Sodium metasilicate, sodium silicate, and related compounds can adhere to the surface of parts and form a coating that prevents penetrant entry into cracks. In a recent paper by Ward Rummel [65], he states that based on his conversations with industry experts, "silicates in concentrations above 0.5 percent may be detrimental to subsequent penetrant inspection."

Klein showed that when a test specimen was contaminated with cutting oil, there was a reduction in sensitivity even when the specimen was vapor degreased before inspection [66]. The

specimens used for this study were quenched-cracked 2024 aluminum blocks. The reduction in sensitivity was believed to be the result of incomplete removal of the cutting oil from the defects.

Russian researchers have also found that the cleaning solution can have an effect on the inspection results [67]. They report that after parts have been washed with cleaning liquids containing a solution of domestic soap or oleic potash soap, some cracks are no longer detectable. They attribute this reduction in sensitivity to a clogging of the cavities and a reduction in wettability of the metal surface by the penetrant. Several photographs are offered that supports these claims.

In another article, the Russian researchers further investigated the effects of cleaning and rinsing components with aqueous solutions of commercial detergents (CDs) on the detectability of cracks [68]. They reported that some CD solutions improved crack detectability while others impaired detectability. Some of the cleaning solutions formed deposits in the cracks that were difficult to remove and could prevent the formation of penetrant indications. To ensure efficient capillary inspection of fatigue cracks in the vanes of gas turbine engines, they recommended that components be thoroughly rinsed in water with the aid of ultrasound and, if possible, dried at 350°-400°C (661°-751°F) for components made of creep-resistant nickel alloys, or at 140°-170°C (283°-337°F) for other alloys.

The U.S. Army Research Laboratory published the results of a recent study on penetrant precleaning [69]. Although this study does not make any direct measurements of the effect of cleaning on sensitivity, it does report on the performance of various cleaning chemicals in comparison to the 1,1,1 Trichloroethane (TCA). TCA is regarded as the industry's favorite cleaner for critical application, such as penetrant inspection precleaning. The use of TCA is rapidly being phased out since it is an ozone depleting substance. This study used a grease hydraulic fluid mix to contaminate the surface of titanium and Inconel specimens that contained low-cycle fatigue cracks ranging from 0.51 to 1.5 mm (0.020 to 0.060 inch) in length. One large crack, 9.5 mm (0.372 inch), was also included in the study to better evaluate the potential of a cleaner to wash the penetrant out of the defect. A variety of chemical cleaners were used to clean the specimens prior to penetrant inspection. Both solvent removal (method C) and hydrophilic postemulsifiable (method D) penetrant inspection methods were included in the study. A photometer was used to measure the brightness of indications produced. The brightness readings were compared to those obtained when TCA was used as a cleaner. The cleaners were determined to be acceptable or unacceptable as replacements for TCA and ranked by cleaning performance; the results are shown in table 1.

2.2.1.5 Ultrasonic Cleaning.

In the process of developing a method to measure the effectiveness of cleaning operations, researchers appraised several variables of an ultrasonic cleaning process [70]. The evaluation process consisted of recording an image of the flaw indication with a camera and analyzing the image with respect to the contrast between the indication and the background and the general brightness of the indication. The evaluation was conducted with samples contaminated with machine lubricating oil and magnetic particle inspection fluid. The source of the ultrasonic vibrations was a 22-kHz magnetostriction transducer in a bath of acetone. The two variables for

the study were the distance between the transducer and the test surface (1, 5, and 10 mm) and the length of cleaning time (1, 5, and 10 minutes). The results showed that the distance between the transducer and the test surface had a significant effect of the efficiency of the cleaning operation. A smaller distance between the transducer and surface resulted in better cleaning. Sample cleanliness (and indication detectability) increased with increasing time of exposure to the acoustic field.

TABLE 1. COMPARISON OF THE PERFORMANCE OF CHEMICAL CLEANING AGENTS AND EVALUATION AS A REPLACEMENT FOR 1,1,1 TRICHLOROETHANE

| | Solvent Removable | | Postemulsifiable | |
|---|---|---|---|---|
| Cleaner | Rank | Accept/Non-Accept | Rank | Accept/Non-Accept |
| Desoclean 45 | 1 | A | 3 | A |
| Dioact 113 | 2 | A | 10 | NA |
| DS-108 | 3 | A | 5 | A |
| TPC Solvent | 4 | A | 8 | A |
| Spotcheck SKC-HF | 5 | A | 4 | A |
| Electron NDT | 6 | A | 7 | A |
| TEKSOL EP | 7 | A | 1 | A |
| Citrex | 8 | A | 2 | A |
| Isopropyl Alcohol | 9 | A | 9 | NA |
| PD-680 | 10 | NA | 6 | A |
| Axarel 56 | 11 | NA | 11 | NA |

2.2.1.6 Effect of Oxides and Other Surface Coatings.

Surface coatings such as oxides, carbides, nitrides, and others that may form during heat treatment, welding, or corrosion of metals can reduce LPI sensitivity if they reduce or block the surface opening of the flaw. However, if they do not reduce the opening, the coatings can have a positive effect on sensitivity. Surface coating such as the ones mentioned here have higher room temperature surface energies then their parent material [14]. Because of the higher surface energies, the contact angle of the penetrant will be less and capillary forces will be greater, therefore, improving sensitivity.

Glazkov conducted a study to assess the effect of oxides on the turbine blades of gas turbine engines and evaluate a heat treatment procedure using a hydrogen atmosphere to remove the oxide [71]. He found that after oxidizing the blades by heating them in air to 850°-900°C (1562-1652°F) for 30 minutes and repeating several times, only 9 out of 33 fatigue cracks were found. After subjecting the parts to 860°C for 2.5 hours and then 950°C for 2 hours, 32 of the cracks were found.

2.2.1.7 Effect of Previous Penetrant Inspections.

In a report published in the December 1975 edition of *Materials Evaluation,* [72] researchers from the Canadian Armed Forces studied the effects of residual entrapped penetrants. The researchers concluded that repetitive inspections produce greatly reduced indications when pre- and postcleaning operations are not performed properly.

In his earlier article [66] (1958), R. E. Klein reported similar results. Klein concluded that the effectiveness of a penetrant was significantly reduced if the part had been previously inspected with a different penetrant although proper pre- and postcleaning (degreasing) operation had been performed. This was the case when the previous inspection was performed with a different fluorescent penetrant or a visible dye penetrant. When the same penetrant system was used for both inspections, there was no extensive loss in sensitivity when the specimens received the required pre- and postcleaning. Klein's study also showed that even the most careful postcleaning operations leave some penetrant in the defects.

Amos Sherwin revisits the issue in a 1990 "Back to Basics" article in *Materials Evaluation* [73]. The focus of this article is on the effect of a previous visible penetrant inspection on a fluorescent penetrant inspection. To illustrate the degrading effect of type II penetrant on type I penetrant, Sherwin suggests a simple experiment. He instructs to mix 1 percent visible and 99 percent fluorescent penetrant together and note the almost complete lack of fluorescence under black light. Apparently, the red dye acts as a UV filter and stops nearly all fluorescence. The article also notes that soaking the test piece in isopropanol for 10 minutes, between the two inspections, did provide some improvement, but did not result in acceptable performance.

Tanner, Ustruck, and Packman [18] developed a procedure to accurately measure the amount of penetrant absorbed into the cracks of a chrome-plated panel specimen. The procedure they used involved applying penetrant to the sample and letting it dwell for a set time. They then degreased the specimen using toluene in a closed flask and used a colorimeter to measure the fluorescence of the used toluene. Then by using a very accurate pipette, they added drops of penetrant to fresh toluene until the colorimeter value matched that of the toluene used to degrease the sample. With this very accurate method of measuring the amount of penetrant absorbed, they showed that a small amount of solvent, from the precleaning operation, if left trapped in a flaw can have a drastic affect on the performance of a penetrant.

As a side note, researchers in the Netherlands evaluated the length of time required to clean test specimens using an organic solvent bath with ultrasonic agitation [74]. Using specimens with fatigue cracks, five organic solvents were tested. When the specimens were evaluated 12 hours after the cleaning operation, the specimens were considered cleaned of the penetrant when no bleed-out was detected. The solvents tested were acetone, Freon, Chlorotene NU, Toluol, and MEK. For all solvents, at least 2 hours of processing were required to properly clean the specimens.

2.2.1.8 Dryness of Part and Defects Prior to Penetrant Application.

In a presentation made at the Engine Titanium Consortium Open Forum in May of 1996 [75], representatives from Rolls-Royce Aerospace Group presented data that showed that precleaner contamination could significantly reduce penetrant sensitivity. The experiment was carried out on a nickel-based alloy rig disc with a statistically valid population of fatigue cracks. An ultrahigh sensitivity penetrant process was used. The results were presented as a 90% PoD curve at the 95% and 50% confidence levels. At the 90/95 level, cracks contaminated with a nonhalogenated organic solvent needed to be 12 times larger than uncontaminated (dry) cracks to have the same PoD. Cracks contaminated with water needed to be 40 times larger to have the

same PoD as uncontaminated cracks. At the 50% confidence level, the factors were 3.5 and 5.6 times, respectively.

At the Air Transport Association NDT Forum in September 1997, Pratt & Whitney also presented some data on the effect of part dryness on sensitivity [76]. When wet parts were processed using a level 2, water-washable system or a level 3, postemulsifiable system, indications were dull and milky in appearance and some indications were undetectable. In comparison, when parts were air-dried, oven-dried, or flash-dried, all indications were sharp and detectable.

To ensure efficient capillary inspection of fatigue cracks in the vanes of gas turbine engines, Russian researchers recommended that components cleaned using commercial detergents be thoroughly rinsed in water with the aid of ultrasound and dried at elevated temperature. They recommended drying at 350°-400°C (661°-751°F) for components made of creep-resistant nickel alloys and at 140°-170°C (283°-337°F) for other alloys [68].

### 2.2.2 Selection of a Penetrant System.

The selection of a liquid penetrant system is not a straightforward task. Many factors must be considered when selecting the penetrant materials for a particular application. Factors such as initial equipment investment, materials cost, number of parts, the size of the area requiring inspection, and the portability all may need to be considered. When sensitivity is the primary consideration for choosing a penetrant system, the first decision that must be made is whether to use fluorescent dye penetrant, visible dye penetrant, or dual purpose. Fluorescent dye penetrants are generally more capable of producing a detectable indication from a small defect because the human eye is more sensitive to a light indication on a dark background. Thomas 42 presents a series of curves that show the contrast ratio required for an indication of a certain diameter to be seen. The curves show that for indications larger than 0.076 mm (0.003 inch) in diameter, fluorescent penetrant inspection only offers a slight advantage over visible penetrant inspection. However, when a dark indication on a light background is further reduced in size, it is no longer detectable even though contrast is increased. Furthermore, with a light indication on a dark background, indications down to 0.003 mm (0.0001 inch) were detectable when the contrast between the flaw and the background was high enough. Please note that this discussion concerns the indication size and not the actual size of the flaw.

Fluorescent penetrants are evaluated by the U.S. Air Force according to the requirements in MIL-I-25135, and each penetrant system is classified into one of five sensitivity levels. This procedure uses titanium and Inconel specimens with small surface cracks produced in low-cycle fatigue bending to classify penetrant systems. The brightness of the indications produced after processing a set of specimens with a particular penetrant system is measured using a photometer. A procedure for producing and evaluating the penetrant qualification specimens was reported by Moore and Larson at the 1997 ASNT Fall Conference [77]. Most commercially available penetrant materials are listed in the Qualified Products List of MIL-I-25135 according to their type, method, and sensitivity level.

Visible dye and dual-purpose penetrants are not classified into sensitivity levels as fluorescent penetrants are. The sensitivity of a visible dye penetrant is regarded as level 1 and largely dependent on obtaining good contrast between the indication and the background. One major advantage that a fluorescent penetrant has over a visible dye penetrant is that the eye is naturally drawn to a fluorescent indication. When a visible penetrant is used, the inspector must be much more diligent in seeking out indications. Data presented in reference 74 supports this statement. "Identical" fatigue-cracked specimens were inspected using a red dye penetrant and a fluorescent dye penetrant. The fluorescent penetrant found 60 defects while the visible dye was only able to find 39 of the defects. No specific details were offered about the penetrant materials tested. However, under certain conditions, the visible penetrant may be a better choice. In a series of articles on a round-robin study involving 30 companies in Denmark, Finland, Norway, and Sweden [78, 79, 80, and 81] researchers found that when surface roughness is high or when flaws are located in areas such as weldments, visible penetrants give better results.

Another consideration in the selection of a penetrant system, is whether water washable, postemulsifiable, or solvent removable penetrants will be used. Postemulsifiable systems are designed to reduce the possibility of over washing which is one of the factors known to reduce sensitivity. Solvent removable penetrants, when properly used, can have the highest sensitivity, but are usually not practical for large-area inspection or in high-volume production settings.

### 2.2.3 Penetrant Application Technique and Drain-Dwell Method.

In a study reported on by Sherwin [82] the effects of penetrant dwell modes on sensitivity are discussed. The two dwell modes discussed are immersion-dwell and drain-dwell. Prior to this study, the immersion-dwell mode was generally considered to be more sensitive but recognized to be less economical because more penetrant was washed away and emulsifiers were contaminated more rapidly. The reasoning for thinking this method was more sensitive, was that the penetrant was more migratory and more likely to fill flaws when kept completely fluid and not allowed to loose volatile constituents by evaporation. However, Sherwin showed that if the specimens are allowed to drain-dwell, the sensitivity is higher because the evaporation increases the dyestuff concentration of the penetrant on the specimen. As pointed out by Alburger in reference 32, sensitivity increases as the dyestuff concentration increases. Sherwin also cautions that the samples being inspected should be placed outside the penetrant tank wall so that vapors do not accumulate and dilute the dyestuff concentration of the penetrant on the specimen.

Researchers in France [83] found that the method of application on the penetrant can have an effect on the sensitivity of the inspection. Using an UV laser beam and sensor to scan a TESCO panel, the effect of penetrant immersion time was studied. Tests were made with immersion times of 1, 30, and 60 seconds and compared to results obtained using a 10-minute immersion time. The total contact or dwell time was 20 minutes in all cases, i.e., a 1-second immersion time had a 19-minute 59-second dwell time while the 10-minute immersion time test had a 10-minute dwell time. Samples having crack depths of 10, 20, 30, and 50 microns (0.0004, 0.0008, 0.0012, and 0.0020 inch) were used. The results show that compared to the 10-minute immersion time, shorter immersion times can decrease sensitivity. For the 50-micron (0.0020-inch)-deep crack, only the 1-second immersion time decreased sensitivity. For the other three crack depths, all three of the shorter immersion times showed a loss in sensitivity with the 30-micron (0.0012-inch)-deep crack showing the largest change. The amount of sensitivity loss was

inversely proportional to immersion time with the greatest relative loss being 16 percent. Industry experts have called the results of this study into question. Two problems with the study have been cited. First, the panels used have open channels and are not representative of cracks. Second, the panels were only processed once and only scanned once so the data does not account for normal processing variations.

Rolls-Royce Aerospace Group also studied the effect of applying the Penetrant, using an electrostatic spray [83]. Three different spray application procedures were used and the results compared to the 10-minute immersion and 10-minute dwell process. A modest gain in sensitivity was reported for all three of the spray application procedures. Over the range of crack depths, a 3.3-percent increase was reported when two spray applications were used with an interval of 10 minutes between sprays. A 2.3 percent increase was seen when the interval between sprays was 5 minutes. A 0.7 percent increase was seen when a single electrostatic spray was used to apply the penetrant. The improvements in sensitivity seemed to be limited to the samples with crack depths of 20 and 30 microns (0.0008 and 0.0012 inch). For the 50-micron (0.0020-inch) specimen, all four procedures were equal. The single spray procedure was slightly less sensitive for very shallow (10-micron or 0.0004-inch) cracks.

### 2.2.4 Penetrant Dwell Time.

Penetrant dwell time is the total time that the penetrant is in contact with the part surface. The dwell time is important because it allows the penetrant the time necessary to be drawn or to seep into a defect. Dwell times are usually recommended by the penetrant producers or required by the specification being followed. The times vary depending on the application, penetrant materials used, the material, form of material being inspected, and type of defect being inspected for. Minimum dwell times typically range from 5 to 60 minutes. Generally, there is no harm in using a longer penetrant dwell time as long as the penetrant is not allowed to dry. The ideal dwell time is often determined by experimentation and is often very specific to a particular application. However, it seems that very little actual data is available in the literature to support the recommended or required dwell times in the specifications.

In the book titled "Penetrant Testing, A Practical Guide" [84], Lovejoy questions the theory that capillary action is primarily responsible for penetrant entering a defect. His observation is that the equation presented suggests that the tighter the defect, the greater the capillary pressure will be and the faster the penetrant should enter the defect. Lovejoy feels that experience shows that tighter cracks require longer dwell times and, therefore, capillary action is not the driving force. Lovejoy offers a concept that considers only the surface energy between the penetrant and the metal and ignores the surface energies across the air-solid and air-liquid interface.

Lovejoy's observation that tighter defects are more difficult to detect is a valid observation and does support that capillary action alone is not completely responsible for the penetrants performance. The Russian book previously mentioned [15] supports Lovejoy's observation and presents a complex formula that shows that the fill time of a flaw is a function of the following parameters:

- Surface tension of the penetrant.
- Contact angle of the penetrant.

- Dynamic shear viscosity of the penetrant, which can vary with the diameter of the capillary. The viscosity of a penetrant in microcapillary flaws is higher than its viscosity in bulk, which slows the infiltration of the tight flaws.
- Atmospheric pressure at the flaw opening.
- Capillary pressure at the flaw opening.
- Pressure of the gas trapped in the flaw by the penetrant.
- Radius of the flaw or the distance between the flaw walls.
- Density or specific gravity of the penetrant.
- Microstructural properties of the penetrant.

By furthering his calculations using the equations presented in section 2.1.1.3, Deutsch [31] also shows that entrapped gas can have a large effect on the penetrant process. Another interesting point that Deutsch makes about dwell time is that if the elliptical flaw has a length-to-width ratio of 100, it will take the penetrant nearly ten times longer to fill than a cylindrical flaw with the same volume.

A statement contrary to the fill-time observation above is made in the Nondestructive Testing Handbook [14]. Here, it states that the penetrant is immediately drawn into the void by the strong forces of capillary action and that even relatively tight cracks become filled with penetrant within a few seconds. The reference goes on to say that any gain in sensitivity due to a prolonged drain-dwell time is due to evaporation of the carrier liquid of the penetrant, which leads to an increase in the dye concentration of the penetrant producing the indication.

Lord and Holloway looked for the optimum penetrant dwell time required for detecting several types of defects in titanium [85]. Both a level 2 postemulsifiable fluorescent penetrant (Magnaflux ZL-2A penetrant and ZE-3 emulsifier) and a level 2 water-washable penetrant (Tracer-Tech P-133A penetrant) were included in the study. The effect of the developer was a variable in the study and nonaqueous wet, aqueous wet, and dry developers were included. Specimens were also processed using no developer. The specimen defects included stress corrosion cracks, fatigue cracks, and porosity. As expected, the researchers found that the optimal dwell time varied with the type of defect and developer used. Table 2 summarizes some of the findings.

Researchers at Pratt & Whitney evaluated the effect of dwell time of one Mil-I-25135 group VI penetrant system (ZL-35, ZR-10, ZP-13A) [60 and 61]. Ten specimens with low cycle fatigue cracks were inspected using dwell times of 5, 15, 30, and 45 minutes. Each specimen had one indication and the visual brightness of each indication was noted. The 30-minute dwell time was reported to have provided the best sensitivity without any potential of penetrant removal problems. The data seem to suggest that the indications were better at 45 minutes and the report does not clearly account for why the longer dwell time was not deemed best.

TABLE 2. MINIMUM PENETRANT DWELL TIMES FOR DEFECTS IN TITANIUM AS DETERMINED BY LORD AND HOLLOWAY

| | Postemulsifiable Penetrant | | | Water-Washable Penetrant | | |
|---|---|---|---|---|---|---|
| Developer | Fatigue Crack | Porosity | Stress Corrosion Crack | Fatigue Crack | Porosity | Stress Corrosion Crack |
| None | 20 | 20 | 20 | 5 | 10 | 20 |
| Nonaqueous Wet | 10 | 20 | 20 | 5 | 10 | 5 |
| Dry | 5 | 20 | 20 | 5 | 10 | 5 |
| Aqueous Wet | 5 | 10 | 20 | 5 | 20 | * |

* Few indications were produced

2.2.5 Penetrant Removal Procedure.

The penetrant removal procedure must effectively remove the penetrant from the surface of the part without removing an appreciable amount of entrapped penetrant from the defect. If the removal process extracts penetrant from the flaw, the flaw indication will be reduced by a proportional amount. If the penetrant is not effectively removed from the part surface, the contrast between the indication and the background will be reduced. The visibility of the indication increases as the contrast increases, and this will be discussed in more detail later in this report.

When penetrant loss from the defect due to over-washing of the part is a concern, a postemulsifiable penetrant system can be used. The emulsifier is allowed sufficient time to react with the penetrant on the surface of the part but not given time to make its way into defects to react with the trapped penetrant. The penetrant that has reacted with the emulsifier is easily cleaned away. Controlling the reaction time is of essential importance when using a postemulsifiable system.

2.2.5.1 Rinse Time and Method of Water-Washable Penetrants.

Vaerman [83] evaluated the effect that rinse time had on a high sensitivity water-washable penetrant and two postemulsifiable penetrants (one medium and one high sensitivity). The evaluation was conducted using TESCO panels containing numerous cracks ranging in depth from 5 to 100 microns deep. A 38 percent decrease in sensitivity for the water-washable penetrant was seen when the rinse time was increased from 25 to 60 seconds. When the rinse times of two postemulsifiable penetrants were increased from 20 to 60 seconds, a loss in sensitivity was seen in both cases but it was much reduced from the loss seen with the water-washable system. The relative sensitivity loss over the range of crack depths was 13 percent for the penetrant with medium sensitivity and roughly 4 percent for the high sensitivity penetrant.

In a 1972 paper by N.H. Hyam [86], the effects of the rinse time on the sensitivity of two level 4, water-washable penetrants are examined. It was reported that sensitivity decreased as spray-rinse time increased and that one of the penetrants was more affected by rinse time than the others. Alburger [87], points-out that some conventional fluorescent dyes are slightly soluble in water and can be leached out during the washing processes.

Brittian [25] evaluated the effect of wash time on a water-washable, level 4 penetrant (Ardrox 970P25) and found that indication brightness decreases rapidly in the first minute of wash and then slowed. The brightness value dropped from a relative value of 1100 to approximately 500 in the first minute and then continued to decrease nearly linearly to a value of 200 after 5 minutes of wash. Brittian concluded that wash time for water-washable systems should be kept to a minimum.

Robinson and Schmidt used a Turner fluorometer to evaluate the variability that some of the processing steps can produce in the brightness of indications. To find out how much effect the wash procedure had on sensitivity, TESCO panels were processed a number of times using the same materials but three different wash methods. The washing methods included spraying the specimens with a hand-held nozzle; holding the specimens under a running tap; and using a washing machine that controlled the water pressure, temperature, spray pattern, and wash time. The variation in indication brightness readings between five trials was reported. The variation was 16 percent for the running tap water, 14 percent for the hand-held spray nozzle, and 4.5 percent for the machine wash.

2.2.5.2 Hand Wiping of Solvent Removable Penetrants.

When a solvent removable penetrant is used, care must also be taken to carefully remove the penetrant from the part surface while removing as little as possible from the flaw. James Hill [88] offers a cleaning procedure to maximize the inspection sensitivity for a visible dye penetrant but notes that the procedure is good for fluorescent inspections as well. The first step in this cleaning procedure is to dry wipe the surface of the part in one direction using a white lint free cotton rag. One dry pass in one direction is all that should be used to remove as much penetrant as possible. Next, the surface should be wiped with one pass in one direction with a cleaner-moistened rag. One dry pass followed by one damp pass is all that is recommended. Instructions for a simple experiment, which show that sensitivity is reduced with every additional wipe, are offered in the article.

Japanese collaborators manufactured a test specimen out of acrylic plates to view the movement of the penetrant in a narrow cavity [89]. The sample consisted of two pieces of acrylic with two thin sheets of vinyl clamped between as spacers. The plates were clamped in the corners and all but one of the edges sealed. The unsealed edge acted as the flaw. The clearance between the plates varied from 15 microns (0.059 inch) at the clamping points to 30 microns (0.118 inch) at the midpoint between the clamps. The distance between the clamping points is believed to be 30 mm (1.18 inch). Although the size of the flaw represented by this specimen is large, an interesting observation was made. They found that when the surface of the specimen was wiped with a dry cloth, penetrant was blotted and removed from the flaw at the corner areas were the clearance between the plates was least. When the penetrant at the side areas was removed, penetrant moved horizontally from the center area to the ends of the simulated crack were

capillary forces are stronger. Therefore, across the crack length, the penetrant surface has a parabola-like shape where the liquid is at the surface in the corners but depressed in the center. This shows that each time the cleaning cloth touches the edge of a crack, penetrant is lost from the defect. This also explains why the bleed-out of an indication is often largest at the corners of cracks.

2.2.5.3 Emulsifier Concentration, Prewash Time, and Contact Time.

The optimal emulsifier contact time is dependent on a number of variables that include the emulsifier used, the emulsifier concentration, the surface roughness of the part being inspected, and other factors. Usually some experimentation is required to select the proper emulsifier contact time. The emulsifier used must be matched to the penetrant material. For hydrophilic postemulsifiable (Method D) penetrant systems, the concentration of the emulsifier should not exceed the percentage specified by the supplier and if working to a specification should not exceed the concentration specified. Since the emulsifier is mixed with water, which is prone to evaporation, it is recommended that the starting concentration be less than that recommended by the supplier. One penetrant manufacturer recommends the following starting concentrations: 20 percent if the maximum concentration is 30 percent, 13 percent if the maximum is 20 percent, and 6.5 percent if the maximum is 10 percent [90].

Vaerman [83] reported on the effect of emulsifier concentration on sensitivity. He varied the contact time of a lipophilic emulsifier and compared the results to those from a 5 percent concentrate hydrophilic emulsifier with a 3-minute contact time. For a normal contact time of 45 seconds, the lipophilic emulsifier was found to average nearly 18 percent less sensitive over the range of crack depths (10 to 50 microns (0.0004 to 0.0020 inch)). The loss of sensitivity increased rapidly as the lipophilic contact time was increased in steps to 5 minutes. Also, as expected, the decrease in sensitivity increased with increasing crack size.

Vaerman also looked at the effect of hydrophilic emulsifier concentration. It was found that increasing the concentration from 5 percent by volume to 33 percent, decreased sensitivity by 15 percent when a 3-minute contact time was used. When a contact time of 1 minute was used, the decrease in sensitivity was just over 9 percent.

In reference 86, Hyam also reports on the effect of the emulsifier concentration and contact time. Both hydrophilic and lipophilic removers were tested. The results showed that as the concentration of the emulsifier was increased from 2.5 to 20 percent, sensitivity decreased. The contact time was shown to have little effect on the hydrophilic system tested (up to 20 minutes) but to have a significant effect on the lipophilic system with sensitivity decreasing as contact time was increased from 2 to 10 minutes. Industry experts feel that this study was flawed because the defects were not representative of cracks and that the contact time of hydrophilic systems is more important than indicated. Several other studies have found that the concentration and contact time of hydrophilic emulsifier are important.

The Magnaflux Corporation conducted a study of the variable involved in the hydrophilic emulsification process [91]. Unlike the previous study, this study found that the emulsifier contact time had a significant effect on indication brightness. Using chrome-plated test panels with 20-micron-deep cracks, fluorescent brightness measurements of the indications were made

with a fluorometer. The effect of emulsifier concentration, contact time, and prewash time were reported. The study found that a 5 percent emulsifier concentration gave the brightest indications in comparison to 20 and 33 1/3 percent mixes. On the average, indication brightness decreased by 17.5 percent when the emulsifier concentration was increased to 20 percent and decreased by 26 percent when the concentration was increased to 33 1/3 percent. However, the report cautioned that longer contact and prewash times might be required to reduce background fluorescence to an acceptable level, and these variables can have a much larger impact on indication brightness. The data shows that the brightness can be reduced by 60 to 70 percent when the emulsifier contact time is increased from 30 to 180 seconds or when the prewash time is increased from 30 to 180 seconds.

Two researchers from Japan evaluated the effect of hydrophilic emulsifier concentration and contact time on the sensitivity and water washability of normal and ultrahigh sensitivity penetrant materials [92]. Test panels with a tapered thickness of chromium plating that was cracked to give a variety of crack depths were used to evaluate sensitivity. Sensitivity was determined by evaluating how shallow of a crack was detectable. PSM-5 chromium plated and grit-blasted panels were used to evaluate washability. The level of background fluorescence was measured with a light meter. For both of the penetrants tested, the study concluded that sensitivity decreased with increasing emulsifier concentration and with increasing contact time. The decrease in sensitivity as contact time increased became more pronounced as the emulsifier concentration increased. As expected, background fluorescence also decreased, increasing emulsifier concentration and contact time.

Pratt & Whitney [60 and 61] evaluated the effect of emulsification concentration and time of one Mil-I-25135C group VI system (ZL-35, ZR-10, and ZP-13A) using Inconel and titanium specimens. For their particular application, they concluded that for 33 percent emulsifier concentration, 1 1/2 minutes of contact time gave optimum inspection results for both materials.

In the study conducted by Brittain, [25] a level 4, postemulsifiable penetrant (Ardrox 985P14 penetrant and 9PR12 emulsifier) was tested. A 5-minute prewash and a 1-minute postwash were used. The results show that indication brightness decreases linearly with remover contact time. The study also showed that the remover temperature could have an effect on sensitivity. The sample was processed with the remover at various temperatures between 11° and 35°C (51° and 94°F). The brightness of the indications fell almost linearly with increasing remover temperature.

Emulsification time was also part of the study by Lord and Holloway [85]. The study was conducted using Magnaflux ZL-2A, level 2 postemulsifiable penetrant with ZE-3 emulsifier and three different developers, ZPX-437 nonaqueous, ZP-4 dry, and ZP-13 aqueous wet. Samples were also processed without a developer. A penetrant dwell time of 20 minutes was used. Emulsification times of 1, 3, and 10 minutes were evaluated. The bleed-out time was set at 15 minutes. The study determined the optimal emulsification contact times for detectability of several types of defects and these values are shown in table 3.

TABLE 3. EFFECTIVE EMULSIFICATION CONTACT TIME TO PRODUCE OPTIMAL INDICATIONS FOR THE DEFECTS AND SPECIFIC CONDITIONS EVALUATED IN REFERENCE 85

| Developer Used | Large Fatigue Cracks | Porosity | Small Stress Corrosion Cracks |
|---|---|---|---|
| None | 1 to 10 min. | 1 to < 3 min. | 1 to < 3 min. |
| Nonaqueous Wet | 1 to 10 min. | 1 to < 3 min. | 1 to 3 min. |
| Dry | 1 to 10 min | 1 to 3 min. | 1 to < 3 min. |
| Aqueous Wet | 1 to 10 min | 1 to 3 min. | 1 to < 3 min. |

2.2.6 Developer.

The developer is an important part of the penetrant inspection process. The developer extracts entrapped penetrant from the flaw and spreads the penetrant on the surface of the sample to increase the apparent size for the defect. The developer works to increase the thickness of the penetrant bleed-out to a level that exceeds the threshold of visibility. The developer also increases the contrast between the flaw indication and the background and helps to reduce light reflection from the sample surface. The use of a developer is almost always recommended but in special situations may not be necessary or desirable. Developers are available in a variety of forms that all have advantages and disadvantages.

2.2.6.1 Use of a Developer.

Brittain [50] reported that the thick film output from a fluorescent penetrant could be multiplied by up to seven times when a suitable powder developer was used. This study concluded that the developer should be transparent to visible and UV light, have a low refractory index, and have a particle size above 1 micron (0.0004 inch). The author noted that the extent of spread of a penetrant material through a powder developer likely depends on both the penetrant and the developer used. To obtain optimum sensitivity, developers may need to be selected to suit particular penetrants.

Rummel [55] shows that the use of developer can have a dramatic effect on the PoD of an inspection. When a Haynes Alloy 188, flat panel specimen with a low-cycle fatigue crack was inspected without a developer, a 90 percent PoD was never reached with crack lengths as long as 19 mm (0.75 inch). The operator detected only 86 of 284 cracks and had 70 false calls. When a developer was used, a 90-percent PoD was reached at 2 mm (0.077 inch), with the inspector identifying 277 of 311 cracks with no false calls.

It is pointed out in a paper titled "Evaluation of High-Sensitivity Water-Washable Fluorescent Penetrants" [93], that in special situations the use of a developer may actually reduce sensitivity. The specific example used in this report was the inspection of jet engine turbine blades for leading-edge cracks. The blades had a crazed coating and some surface porosity that entrapped the penetrant resulting in numerous nonrelevant indications.

In a round-robin experiment organized by McDonnell Douglas [94], it was concluded that a developer might not always be necessary. Ten aluminum specimens were used in the study.

Two of the specimens were said to be production parts with manufacturing defects. The other eight specimens were produced by placing electrical discharge machined notches in a machined surface groove, compressing the grooves closed with a load frame, and then machining the surface smooth. The ten specimens contained 22 defects total. The size of the defects was not reported. The specimens were processed by inspectors at ten companies using a fluorescent penetrant with a sensitivity level of 2 or 3. It is reported that 216 indications were recorded for the 220 find opportunities. It was also noted that in all cases, flaws detected with the application of a dry developer were also detected without a developer. It is not clear whether the author meant that the technique with no developer used was equivalent to the technique employing the dry developer. The author did caution that this study was aimed at certain manufacturing defects and the results should not be extended to parts with possible fatigue cracks.

Gram [11] reported that indications could be produced in the absence of a developer if the defect is large such that the penetrant seepage from it forms a fairly thick layer. He reports that cracks 0.025 mm (0.001 inch) in width were detectable without a developer but only a few microns wide were not detectable because the indication thickness was below the dimensional threshold of fluorescence. Therefore, developers must be used for highly sensitive inspection involving fine cracks.

2.2.6.2 Type of Developer Used and Method of Application.

In Military Specification Mil-I-25135E, there are five forms of developers listed: dry powder, water-soluble, water-suspendible, nonaqueous, and those for special applications. Several different application techniques can be employed to coat the part with the developer. The Nondestructive Testing Handbook explains that nonaqueous developers are generally recognized as the most sensitive when properly applied. There is less agreement on the performance of dry and aqueous wet developers, but the aqueous developers are usually considered more sensitive. Aqueous wet developers form a finer matrix of particles that is more in contact with the part surface. However, if the thickness of the coating becomes too great, defects can be masked. Also, aqueous wet developers can cause leaching and blurring of indications when used with water-washable penetrants. The Handbook rates the relative sensitivities of developers and application techniques as shown in table 4.

In a PoD study reported on by Martin Marietta Aerospace and NASA [95], researchers produced a set of Inconel 718 specimens with a total of 281 fatigue cracks ranging in length from 0.254 to 6.350 mm (0.010 to 0.250 inch). They found that flaw detectability for a sensitivity level II, inspection improved from 69 percent detection to 75.1 percent when the dry powder developer was replaced with a nonaqueous wet developer.

In addition, in reference 86, the influence of developers on sensitivity was studied using two postemulsifiable penetrants and the twofold congruence test. It was shown that the type of developer used has a considerable influence on the sensitivity attained. It was reported that a wet suspension and a dry powder developer produced a nearly equal improvement in sensitivity over no developer and that solvent suspension produced significantly better results than the other developers.

TABLE 4. SENSITIVITY RANKING OF DEVELOPERS PER THE NONDESTRUCTIVE TESTING HANDBOOK

| Sensitivity Ranking | Developer Form | Application Technique |
|---|---|---|
| 1 (highest) | Nonaqueous Wet | Solvent Spray |
| 2 | Plastic Film* | Spray |
| 3 | Water Soluble | Spray |
| 4 | Water Suspendible | Spray |
| 5 | Water Soluble | Immersion |
| 6 | Water Suspendible | Immersion |
| 7 | Dry | Dust Cloud (Electrostatic) |
| 8 | Dry | Fluidized Bed |
| 9 | Dry | Dust Cloud (Air Agitation) |
| 10 (lowest) | Dry | Immersion (Dip) |

* No longer used or available.

As part of a study to develop an improved FPI process for detecting small flaws in aircraft turbine blades [60 and 61], Pratt & Whitney reported that a water-soluble developer (ZP-13A) provided higher sensitivity and less background fluorescence when compared to a dry developer (ZP-4B). The water-soluble developer was reported to produce brighter indications, which is not a critical factor in detectability for relatively large cracks. However, for small cracks, a slightly brighter indication may mean that an otherwise missed indication will be seen.

In a paper presented by Mooz at the 12th World Conference for Non-Destructive Testing [96], the selection of the proper developer is reviewed. The paper primarily discusses how different developer types function and when they should be used or not used. The paper ranks the relative sensitivities of the various types as follows from low to high: dry developer, soluble developer, suspendible developer, and nonaqueous developer. Dry developers are least sensitive because they depend on a certain amount of penetrant to be present at the flaw opening for the developer to stick and they provide no contrasting background. Soluble developers form a very thin continuous coating over the part to absorb the penetrant but are opaque and provide little in the way of a contrasting background. Suspendible developers produce a relatively thick coating that provides good blotting action and a good contrasting background. Nonaqueous developers wet the surface with a solvent that carries the powder particles. The solvent enters the flaw and dilutes the penetrant so it is less viscous and can quickly be blotted up by the developer particles. Once the solvent evaporates, a full strength penetrant indication is left on the surface. The advantages and disadvantages of each developer type are summarized in table 5.

MacCracken [97] points out several other potential problems that could affect penetrant sensitivity when using wet soluble developers. These problems could also occur when a wet suspendible developer is used. When components with complex shapes are being inspected, it is sometimes difficult to get an even coating when a wet soluble or suspendible developer is used. Pooling can take place if excess solution is not removed properly. The parts must also be handled very carefully before drying as fingerprints, water drops, or other marks can hide

defects. Finally, lint and other particles can be trapped in the coating and can result as a false call.

TABLE 5. ADVANTAGES AND DISADVANTAGES OF THE VARIOUS DEVELOPER TYPES

| Developer | Advantages | Disadvantages |
|---|---|---|
| Dry | Indications tend to remain brighter and more distinct over time.<br>Easily cleaned from the surface after inspection. | Does not form contrast background so cannot be used with visible systems.<br>Difficult to assure entire part surface has been coated. |
| Soluble | Ease of coating entire part.<br>Easily cleaned from the surface after inspection. | Coating is translucent and provides poor contrast (not recommended for visual systems). Indications for water-washable systems are dim and blurred. |
| Suspendible | Ease of coating entire part.<br>Indications are bright and sharp.<br>White coating for good contrast can be produced which works well for both visible and fluorescent systems. | Indications weaken and become diffused after time. |
| Nonaqueous | Very portable.<br>Easy to apply to readily accessible surfaces.<br>Provides highest sensitivity.<br>Indications show up rapidly and are well defined. | Difficult to apply evenly to all surfaces.<br>More difficult to clean part after inspection. |

Lord and Holloway [85] rated the relative effectiveness of various developers at producing indications for several common defects in titanium. Both a level 2 postemulsifiable fluorescent penetrant (Magnaflux ZL-2A penetrant and ZE-3 emulsifier) and a level 2 water-washable penetrant (Tracer-Tech P-133A penetrant) were included in the study. Nonaqueous wet, aqueous wet, and dry developers were studied. Specimens were also processed using no developer. The specimen defects included stress corrosion cracks, fatigue cracks, and porosity. The study was qualitative with conclusions from side-by-side caparisons of the indications. Table 6 summarizes their findings.

TABLE 6. RANKING OF DEVELOPER EFFECTIVENESS FOR THREE DIFFERENT DEFECTS

| | Postemulsifiable Penetrant | Water-Washable Penetrant |
|---|---|---|
| Large Fatigue Cracks | (1) All developers equally effective.<br>(2) No developer | (1) All developers equally effective<br>(2) No developer |
| Porosity | (1) Dry<br>(2) Nonaqueous wet<br>(3) No developer<br>(4) Aqueous | (1) All equally effective |
| Small Stress Corrosion Cracks | (1) Nonaqueous wet and dry – equally effective<br>(2) No developer<br>(3) Aqueous | (1) Nonaqueous wet and dry – equally effective<br>(2) No developer<br>(3) Aqueous |

## 2.3 QUALITY CONTROL.

### 2.3.1 Quality Control of Materials.

#### 2.3.1.1 Freshness of Penetrant Materials.

In a paper by James Alburger [98], it was reported that virtually all organic dyes deteriorate over time resulting in a loss of color or fluorescent response. Eight different mechanisms were identified which can contribute to fading. These mechanisms are photochemical fading, color deterioration, contamination fading, oxidation fading, dye sublimation, concentration quenching, thin-film depletion of fluorescence, and apparent fading. The paper discusses each of these mechanisms and offers precautions to avoid problems.

#### 2.3.1.2 Contamination of Penetrant.

Contamination of a penetrant by another liquid will change the surface tension and contact angle of the solution. For a water-washable penetrant, Antinoff's rule can be applied [14]. This rule states that the surface tension of the mixture is equal to the sum of the surface tensions of the two parts. If water is the contaminant, the surface tension and contact angle of the mixture will increase since water has a higher surface tension than most oil-base penetrants. In self-emulsifiable penetrants, water contamination can produce a gel break or emulsion inversion when the water concentration becomes high enough. The formation is an important feature during the wash process but must be avoided until then. Data presented in the form of a gel formation chart indicates that water contamination must be significant (greater than 10%) for gel formation to occur.

In the paper titled "Environmental Controls for Penetrant Inspection" [99], it is mentioned that acids and chromates have the ability to destroy fluorescence. Alkalis are also detrimental and care should be taken to keep all cleaning materials out of the penetrant baths.

Lovejoy, Balinski, and Maya from Magnaflux Ltd., presented a paper titled "The Effects of Common Chemical Cleaning Agents on the Fluorescent Brilliance of Penetrants" [100]. In this study, six penetrants were contaminated with varying amounts (from 2 to 10 percent by volume) of 12 common cleaning chemicals. The cleaning chemicals included an organic solvent, aqueous solutions of acids, alkali, oxidizing agents, acid oxidizing agents, and alkaline oxidizing agents. A spectrophotometer was used to study the relative loss of brilliance of each penetrant. The paper presents the results in tabular and graphical form. The conclusions of the study are that any contamination will reduce the brilliance of the penetrants and the more contamination, the greater the reduction. The amount of brilliance reduction depended on the penetrant and the contaminant, but some contaminants, even in concentrations of 2 percent, had a catastrophic effect on all penetrants.

2.3.1.3 Emulsifier Bath Concentration.

The importance of the emulsifier bath concentration was previously discussed in section 2.2.5.3. Amos Sherwin directly discusses the control issue involved with using hydrophilic emulsifiers [101]. This paper discusses the effects of improper concentration, contamination, extended dwell times, and over removal. Photographs show the effects that failing to dilute hydrophilic emulsifiers or to replace water due to evaporation can have on results.

2.3.1.4 Emulsifier Bath Contamination.

Emulsifier solution can tolerate some penetrant contamination. However, as little as 1 percent by volume of penetrant contamination can seriously affect the performance of an emulsifier. Sherwin [90] states that 1 to 1.5 percent penetrant contamination will affect solution of a 10 percent concentration of emulsifier. As the emulsifier concentration increases in the solution, the penetrant contamination tolerance also increases and a solution with a 30 percent emulsifier concentration can tolerate from 5 to 8.5 percent penetrant contamination.

The Nondestructive Evaluation Handbook [14] discusses an emulsifier's tolerance for contamination by an oily penetrant. The percentage of added penetrant required to destroy washability of the emulsifier is easily measured. An oil tolerance index is commonly used to compare the tolerance of different emulsifiers to contamination by penetrants.

In a paper by Fricker [93], testing showed that penetrant dragout was dependent on the type of material being processed. The data showed that on both polished and grit-blasted surfaces, aluminum and stainless steel parts had a greater dragout than titanium parts.

2.3.2 Quality Control of the Procedure.

Dan Marks summarized the process control variables that must be monitored in compliance with various government and industry specifications in a 1994 article [102]. The following variables are addressed: penetrant and part temperature when applying penetrant, light (both white and black) intensity during examination, black light warmup time, developer dwell time, and wash parameters and procedures. Marks notes that the various specifications contradict each other in several places. While no test data are presented in this article, it does provide a good overview/summary of some of the process control requirements.

2.3.2.1 Temperature of Penetrant Materials and the Part.

The temperature of the penetrant materials and the part being inspected can have an effect on the inspection. Since the surface tension of most materials decreases as the temperature increases, raising the temperature of the penetrant should increase the wetting of the surface and capillary forces. Of course, the converse is also true and lowering the temperature will have a negative effect on the flow characteristics. Temperatures between 27° to 49°C (80° to 120°F) are reported by one source to produce optimal results [102]. Temperatures lower then 4.8°C (40°F) are said to produce unsatisfactory results. Raising the temperature will also raise the speed of evaporation of penetrants, which could have a positive or a negative impact on sensitivity. The impact would be positive if the evaporation served to increase the dye concentration of the penetrant trapped in a flaw up to the concentration quenching point and not beyond (see section 1.1.4). Evaporation would have a negative effect if the dye concentration was caused to exceed the concentration quenching point or the flow characteristics were changed to the point were the penetrant did not flow or dried in the flaw.

2.3.2.2 Wash Temperature and Pressure.

The wash temperature and pressure are two parameters that are typically controlled in penetrant inspection process specification. A coarse spray or an immersion wash tank with air agitation is often used. When the spray method is used, the water pressure is usually limited to 276 $kN/m^2$ (40 psi). The temperature range of the water is usually specified as a wide range (e.g., 10° to 38°C (50° to 100°F) in AMS 2647A.) No literature was found that discussed the wash temperature and pressure requirements, but the reasons for the control on these variables seems straightforward. A low-pressure, coarse water spray will force less water into flaws to dilute and/or remove trapped penetrant and weaken the indication. The temperature will have an effect on the surface tension of the water and warmer water will have more wetting action than cold water. Warmer water temperatures may also make emulsifiers and detergent more effective.

2.3.2.3 Thickness of the Developer Layer.

One of the functions of the developer is to pull the penetrant from the flaw and spread it over the surface of the part to a width that is detectable by the eye. A thin layer of developer can spread more of the available penetrant horizontally since there is less distance for vertical spread. In their study of the kinetics of the penetrant process, Migun and Prokhorenko [45] developed several equations to describe the interaction of the penetrant and the developer. From these equations, they concluded that a thin layer of developer would produce an indication faster and improve sensitivity within limits. A reduction in the developer layer thickness to less than a few microns will actually reduce sensitivity because it will not absorb enough penetrant. In addition, if the developer layer is not thick enough, it will not provide good contrast, which is another important function of the developer.

Reference 15 presents a number of equations to estimate the size of the indication likely produced as a function of various flaw sizes and penetrant fill conditions. From the analysis it is clear that the narrower the defect, the thinner the developer layer must be for an indication to be detectable. Some experimental data is also presented that supports the mathematical formulas developed.

2.3.2.4 Light Intensity and Wavelength Range.

Proper lighting is of great importance when visually inspecting a surface for a penetrant indication. When using a visible penetrant, the intensity of the white light is of principal importance. When a fluorescent penetrant is being employed, the ultraviolet illumination and the visible light inside the inspection booth from various sources including the ultraviolet light source is important. The intensity of both visible light and ultraviolet light are controlled by the inspection specification. For both visual and fluorescent inspections, the light source must be positioned so as not to create glare and to be of adequate strength to reveal the penetrant indication.

The source of ultraviolet light (UV) is often a mercury arc lamp with a filter. The lamp produces high intensity electromagnetic energy in the 365 nm or near violet range. It also produces a significant amount of energy in the visible range that must be filtered out using a dense red-purple filter. The filter also removes harmful short wave energy in the ultraviolet range [42].

Lovejoy [103] points out that the ultraviolet lamp itself can be a source of visible light. The lamps emit many wavelengths and a filter is used to remove all but the UV and a small amount of visible light between 310 and 410 nm. Visible light of wavelengths above 410 nm interferes with contrast, and UV emissions below 310 nm include some hazardous wavelengths. Penetrant dyes are excited by the UV of 365-nm wavelength and emit visible light somewhere in the green-yellow range between 520 and 580 nm.

Since fluorescent brightness is linear with respect to ultraviolet excitation [32], a change in the distance of the light source from the surface being inspected and a change in the intensity of the light (from age or damage) will have a direct impact on the inspection. Stadthaus [104] presents data that shows that the luminance of an indication increases linearly with increasing UVA intensity. This linear increase in luminance continued up to a UVA intensity of 80 $W/m^2$, which was the maximum value included in the study. Stadthaus also showed that contrast between the indication and two background conditions, a clean surface and one covered with fluorescent magnetic particles, increases with increasing UVA intensity. The indication visibility increases as contrast increases.

Clarke presents a variety of useful information about the operation, use, and care of black lights in a paper [105]. This report also presents the findings of an informal study on the light intensities required to produce indications. Thirty people with a range of knowledge about LPI were asked to inspect nine specimens for crack indications. The subjects were told to lower the light towards the sample until they first saw the indication and a light intensity reading was recorded. The results showed that 90 foot-candles was sufficient in nearly all instances to find grinding cracks and other very fine defects. Fatigue cracks, heat treatment cracks, laps, and seams were located with 70 foot-candles.

Rummel [55] shows the effect that ultraviolet light intensity can have on an inspection using PoD curves. Haynes Alloy 188 flat panel specimens with low-cycle fatigue cracks, were inspected using UV light intensities of 400 mW and 1200 mW. At the 400 mW light intensity, the inspector detected 50 of 284 flaws and 95 false calls. The PoD was only around 40 percent for cracks 19 mm long. When the inspections were performed using an UV light with 1200 mW

intensity, 4.6 mm (0.182 inch) cracks were found with a 90 percent PoD. With the stronger light, the inspector found 210 out of 284 flaws with 20 false calls.

Measuring the strength of the light intensity is not completely straightforward and has been discussed several times in the literature. First, it should be noted that when measuring the strength of the light, it is important to make the measurement with the lamp at the maximum distance away from the inspection surface that it will be used. Holden [106] points out that ultraviolet and visible light follow the inverse square law, as does all other electromagnetic radiation. Therefore, a small change in the distance of the light source from the sample will reflect a much larger decrease in the light intensity.

An article published in the March 1990 edition of *Material Evaluation* [107] discusses confusion in interpreting the light requirements of standard inspection procedures and the measurement of the wavelength and intensity of visible and ultraviolet light. Much of the confusion discussed involves the measurement of visible light when performing a UV inspection. Visible light is said to always obscure indications by reducing contrast of the indication, but there are several interpretations as to how to measure the amount of visible light. Some believe the specification requirements are addressing only the visible light (primarily blue and violet) emanating from the UV inspection lamp. Another interpretation is that ambient light level in the inspection booth with the UV lamp not operating should be measured. A third interpretation is that a combination of the ambient light and visible light produced by the UV lamp should be measured. Since optimum sensitivity occurs when all visible light is absent from the inspection booth except that produced from the fluorescence of the indication, it seems that the third interpretation would be correct. The article points out that there are a number of possible sources of visible light in the inspection booth including the fluorescence of the inspector's clothes.

The above article also discusses spectral luminous efficiency of the human eye as determined by the Commission Internationale de l'Eclairage of Paris, France. It is also shown how the response to light of a typical light meter compares to the response of the human eye. The article concludes that most photometers do not accurately measure low levels of any color visible light and especially do not have correct blue/violet responses. However, this may not be a major concern especially if blue-absorbing eyewear is worn. If blue-absorbing eyewear is worn, higher levels of blue and violet light on the test part can be tolerated since it will be filtered out before it reaches the eye and the indication may even be enhanced. The article reports that Moss performed measurements on 14 common penetrants and found that a 10 to 50 percent improvement in fluorescent output could be achieved using an excitation wavelength of 410 nm, which is in the visible violet range, instead of 365 nm, which is in the UV range. The violet visible light from the black light causes additional fluorescence of the penetrant.

2.3.2.5 Drying Oven Temperature.

As discussed in section 2.1.1.7, penetrant materials will fade at high temperatures due to dye vaporization or sublimation. Most specifications require that the operating temperature of the drying oven be kept below 60°C (140°F). Brittian [25] studied the effect of drying temperatures between 20° and 90°C (67° and 193°F) on one level 4, postemulsifiable penetrant (Ardrox 985-P14) with a powder developer (Ardrox 9D4A). The brightness of the indications was found to

increase approximately 50 percent and peak at 40°C (103°F) and then decreases linearly with further increasing temperature. At 60°C (140°F), the indication brightness had fallen to a value approximately equal to the value at 20°C (67°F).

Vaerman [24] also showed that drying temperature could affect sensitivity. Using the UV laser scanning system, mentioned previously, and the TESCO panels with cracks of four different depths, two drying temperatures were evaluated, 70° and 82°C (157° and 179°F). The results showed that for cracks less than 50 microns (0.0020 inch) deep, raising the drying temperature lowered the probability of detection. Changing the drying temperature had no effect on the detectability of the 50-microns (0.0020-inch) -deep cracks.

## 2.4 INSPECTION VARIABLES (FACTORS NOT COMMONLY CONTROLLED BY THE INSPECTOR).

### 2.4.1 Human Factors of Inspectors.

The inspection is usually performed visually and, therefore, all the factors that affect visual inspection will affect liquid penetrant inspection.

#### 2.4.1.1 Inspector's Vision.

In a German paper presented at the Eighth World Conference on Nondestructive Testing [108], the importance of the inspectors' vision is discussed. The paper introduces various eye conditions including visual acuity, accommodation, astigmatism, dark adaptation, and dazzling effects; and explains how these conditions affect an inspector's performance. The paper points out that most conditions can be corrected with lenses, but many inspectors and employers are unaware that a condition exists. At the age of 45, eyesight becomes a growing concern, and at the age of 55, changes in the eye can hardly be corrected to the extent required for a person to hold a visual inspection position.

In a later article by Stadhaus [104], it is explained that visual acuity (the ability to recognize a certain object) depends on five parameters. These parameters include the contrast of the luminance between the object and its surroundings, the adaptation luminance or the ability to which the eye adapts its sensitivity to changing lighting conditions, the objects dimensions, the presentation time of the object, and the recognition probability of the object. Visibility increases as each of these five parameters increase.

In references 107 and 109, it is pointed out that as an inspector ages, there is a possible reduction in the light reaching the retina. This statement is drawn from data in the IES Lighting Handbook110 that shows the size of the pupil, when observing a luminous surface, decreases with age and other physiological changes within the eye that lead to a reduced luminous flux at the retina. Reference 109 also points out that as a person ages, there is a reduction in the amount of short-wavelength energy transmitted by the eye lens which is attributed to the yellowing of the lens from cumulative exposure to ultraviolet radiation.

Experiments have also shown that threshold of light perception of a particular inspector can regularly fluctuate [43]. It was further shown that the threshold perception level could be

influenced by a number of factors including the size of the defect, the orientation of the defect, and the inspector's knowledge and history of the part and its potential defects.

2.4.1.2 Color Vision.

In a 1985 *Materials Evaluation* article [111], Bailey addresses the various medical conditions that can affect color vision and the need for color vision testing for inspection. He offers that statistically eight percent of males have color vision deficiencies (the female population was not discussed) that are the result of either hereditary or acquired defects. Bailey notes that some color deficiencies may be treated to alleviate or minimize the condition. Bailey adds that since the visual spectrum is made up of colors of varying wavelengths and the black and white colors consist of various combinations of colors, deficiencies in any part of the color spectrum could have an impact on inspections. Bailey recommends that all inspection personnel have color and visual acuity tests annually. The Farnsworth D-15 testing method should be used in conjunction with the Ishihara test, as pseudo-isochromatic plates alone do not sufficiently screen industrial inspectors.

Color vision of an inspector is also important because the color of a crack indication can provide information about the size of the crack. In reference 72, it is noted that in many instances the penetrant indications of extremely fine cracks fluoresce a light blue instead of yellow-green.

2.4.1.3 Inspector's Eyewear.

In a 1996 article, the need for proper eye protection from UV light is discussed 112]. Ultraviolet protective eyewear is important to protect the inspector from possible UV and foreign object damage to the eye. However, the article goes on to say that proper eyewear can also reduce eye fatigue and nearly eliminate the distraction from "blue haze" in the eye that is caused by UV-induced lenticular and vitreous humor fluorescence. In references, 107, 109, and 113, it is mentioned that eyewear which filters black light and most violet and blue light, but lets yellow-green fluorescent light pass, can enhance the sensitivity of fluorescent penetrant inspection. Eyewear that reduces the bandwidth of the light reaching the eye increases the acuity of the eye.

2.4.1.4 Training and Knowledge of Anticipated Defects.

As mentioned in section 4.1.1, one of the parameters that affects visual acuity (the ability to recognize a certain object) is the recognition probability of the object. If an inspector is trained to recognize a particular defect, the probability of detecting that defect will likely be higher. The probability of false calls is also likely to decrease.

In the December 1978 publication of *Materials Evaluation*, a paper titled "NDT Reliability and Human Factors" [114] was published. In this paper, three studies were reported on; one study dealt with magnetic particle inspection, one with ultrasonic inspection, and the third with penetrant inspection. One of the stated objectives of the penetrant study was to demonstrate that 2.54 mm (0.10 inch) defects in aluminum parts could be detected with a 90 percent probability of detection at a 95 percent confidence level in a production inspection environment. One of the observations noted was that one of the four inspectors participating in this study had a much higher incident of false calls. This particular inspector had recently been recalled to the

penetrant inspection area, and his lack of "practice" affected his performance. The study also noted that the inspector's performance improved as each trial test was completed indicating that the inspector was learning on the job.

The result from a round-robin experiment involving 30 Scandinavian companies [78] indicated that training did have a small but noticeable effect on the probability of detection of defects. A sample set comprised of 33 aluminum specimens and 33 stainless steel specimens with 151 and 190 total defects, respectively, were inspected to produce over 1000 data points. Details on the specifics of the inspection or the penetrants used were not provided.

2.4.1.5 Inspection Environment and Inspector's Attitude and Motivation.

Another point made in reference 78 was that one inspector was not clear on the type of defect he was inspecting for and this had a negative effect on his performance. Although not specifically linked to the penetrant study, other human factor issues that the report mentioned were the inspection environment and the inspector's attitude and motivation. The inspection environment is important since inspectors will fatigue and lose concentration when working in uncomfortable settings. The attitude and motivation of the inspector is important because an inspector will not consistently perform well if he feels the job is not important or that the inspection criterion is unrealistic.

2.4.2 Surface Roughness and Condition of the Subject Part.

The surface roughness of the part primarily affects the removability of a penetrant. Rough surfaces tend to trap more penetrant in the various tool marks, scratches, and pits that makeup the surface. Removing the penetrant from the surface of the part is more difficult and a higher level of background fluorescence or over washing may occur.

2.4.3 Nature of the Defect.

Although not really a variable of the inspection process, the effect of the defect itself on sensitivity deserves mention. Sensitivity is defined in this report as the smallest defect that can be detected with a high degree of reliability. Typically, the crack length at the sample surface is used to define size of the defect. A survey of any probability-of-detection curve for penetrant inspection, such as those published in reference 115, will quickly lead one to the conclusion that crack length has a definite effect on sensitivity. However, the crack length alone does not determine whether a flaw will be seen or go undetected. The volume of the defect is likely the more important feature. As pointed out by Alburger [32], the flaw must be of sufficient volume so that enough penetrant will bleed back out to satisfy the dimensional thresholds of fluorescence.

It was noted in section 2.1.1.3 that the width to length ratio has an effect on the amount of time it takes for penetrant to fill a flaw. Deutsch points out that an elliptical flaw with length to width ratio of 100 will take the penetrant nearly 10 times longer to fill than a cylindrical flaw with the same volume.

The Scandinavian round-robin study [78] confirms that penetrant inspections are more effective at finding small round defects than small linear defects. The researchers also report that PoD increases as the depth of the defect increases. The defect depths were measured with eddy-current and potential-drop techniques.

Vaerman, from France, published a curve that plotted crack depth versus PoD [24]. In his experiment, Vaerman used TESCO panels with cracks that ran from one side of the panel to the other (35 mm (1.38 inch)). The depth and width of the cracks were varied by controlling the thickness of nickel and chromium plating on the surface of the specimens. When the specimens were bent, the plating fractured, but the crack did not continue into the base metal. Specimens with four crack depths were produced—50, 30, 20, and 10 microns (0.0020, 0.0012, 0.0008, and 0.0004 inch). Crack widths respective to the crack depths were 2.5, 1.5, 1, and 0.5 microns (0.00010, 0.00006, 0.00004, and 0.00002 inch). Using an automated method of inspection involving a laser and photodetector, the samples were scanned and a PoD curve produced. The PoD curve showed that PoD decreased as crack depth and width decreased.

The surface roughness of the flaw faces may also be a factor in the speed at which a penetrant enters a defect. Thomas discussed the spread of a penetrant as a function of surface roughness in a 1963 article [42]. He reported that, in general, the penetrant spreads faster over a surface as the surface roughness increases. He also reports that a particular penetrant may spread slower than others on a smooth surface but faster than the rest on a rougher surface.

In a 1987 study at University College London [116], the effect of crack closure on detectability was evaluated. Researchers used a four-point bend fixture to place tension and compression loads on specimens that were fabricated to contain fatigue cracks. All cracks were detected with no load and with tensile loads placed on the parts. However, as compressive loads were placed on the parts, the crack length steadily decreased as the load increased until a load was reached where the crack was no longer detectable.

## 3. SUMMARY.

Although liquid penetrant inspection (LPI) can be a relatively simple process to apply, many factors can affect the inspection results. Clearly, the formulations of today's penetrants are complex and several (if not many) characteristics of the formulation affect their performance. Inspection sensitivity seems to be affected most by surface tension, dye content, and the dimensional threshold of fluorescence. The properties of the emulsifier, if required, and the developer have also been shown to have an effect on sensitivity. The inspector is usually not involved with the formulation of the penetrant materials, but understanding the characteristics of a penetrant helps to understand the need to control process variables and not to mix chemicals between penetrant systems. Process variables, such as temperature, are known to have an effect on the surface tension, viscosity, and volatility of a penetrant that will have a somewhat obscure effect on sensitivity. Processing parameters, such as the preparation of the part and the penetrant removal process, have a much more straightforward impact. Finally, there are factors beyond the control of the inspector that can affect the inspection result. These factors include the inspector's eyesight, the training and knowledge of the inspector, and the nature of the defect to be detected.

Obviously, not every factor that can affect LPI sensitivity has been addressed in this report. However, it is believed that the most common factors have been at least broached. As mentioned in the introduction, not every LPI inspection requires that attention be given to the entire set of identified variables. However, a general awareness of the forty-plus factors that can affect the results will likely focus attention on the more important details of an inspection. A summary of the factors identified as having the ability to affect the sensitivity of a liquid penetrant inspection is presented in table 7.

TABLE 7. SUMMARY OF FACTORS THAT CAN AFFECT THE SENSITIVITY OF A LIQUID PENETRANT INSPECTION

| | | |
|---|---|---|
| Materials | Penetrants | Surface Wetting<br>Viscosity<br>Specific gravity<br>Color and fluorescence brightness<br>Dimensional threshold of fluorescence<br>Ultraviolet stability<br>Thermal stability |
| | Emulsifiers | Removability<br>Emulsifier contact time and wash time |
| | Developers | Permeability, porosity, and dispersivity<br>Surface energy<br>Liquid carrier<br>Whiteness |
| Inspection Method/Technique | Preparation of the part | Part cleanliness<br>Metal smear from machining or cleaning<br>Use of etchant<br>Plugging of defects with cleaning media<br>Chemical cleaning process<br>Dryness of part and defects<br>Previous penetrant inspection |
| | Selection of penetrant method/technique | Penetrant type<br>Sensitivity level<br>Application method<br>Dwell time |
| | Penetrant removal procedure | Emulsifier concentration<br>Emulsifier contact time<br>Rinse method and time |
| | Developer | Use of a developer<br>Type of developer used<br>Application method |

TABLE 7. SUMMARY OF FACTORS THAT CAN AFFECT THE SENSITIVITY OF A LIQUID PENETRANT INSPECTION (Continued)

| | | |
|---|---|---|
| Process/Quality Control | Control of materials | Freshness of materials/tank life<br>Penetrant contamination<br>Emulsifier bath concentration<br>Emulsifier contamination<br>Developer contamination<br>Storage temperature |
| | Control of the procedure | Temperature of the materials<br>Wash temperature and pressure<br>Drying temperature<br>Thickness of developer layer<br>Inspection lighting |
| Inspection Variables | Human factors of inspectors | Visual acuity<br>Color vision<br>Eyewear<br>Training and knowledge of defects<br>Inspectors attitude and motivation<br>Inspection environment |
| | Nature of part and defect | Surface condition of part<br>Complexity of part<br>Defect type<br>Defect dimensions<br>Loading condition of part (closure) |

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