Need for Clarity in Military Standards Pertaining to Levels of Optical Radiation in Penetrant and Magnetic Particle NDT Inspection Processes*

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Confusion and concern has arisen in the nondestructive testing (NDT) industry regarding the applicability of certain ultraviolet (UV)-producing lamps in the fluorescent liquid penetrant and magnetic particle inspection techniques described in MIL-STD-6866 and MIL-STD-1949. It appears that the confusion arises from certain ambiguities in the standards themselves relating to Types I and II penetrants and fluorescent magnetic particles and also from inadequacies of most of the visible-light–measuring equipment used in such measurements and of interpretation of the measurements. A solution is presented combining the use of suitably calibrated photometers, special eyewear, and clarification of the military standards that should eliminate all these problems as well as improve overall system sensitivity.

Introduction

The authors believe that there exists large-scale confusion in the I/II dye penetrant and fluorescent/nonfluorescent magnetic particle NDT inspection processes as to what optical radiation quantity should be measured, in what units, and what instrument should be used. (In MIL-STD-6866, all penetrant systems are classified into the following types: Type I, fluorescent dye; Type II, visible dye; and Type III, visible and fluorescent dye [dual mode].) This confusion presently exists owing to lack of clarity in terminology and definitions now cited in MIL standards dealing with these specific NDT issues. This lack of clarity will be discussed in this paper, and suggestions will be made as to how to remove these areas of confusion and improve quality control.

How should the UV user interpret existing requirements?

MIL-STD-6866, a standard establishing the minimum requirements for conducting liquid penetrant inspection of nonporous metal and nonmetal components, clearly states for Type I fluorescent dye penetrants:

- 4.5.2 "... the ambient white light background shall not exceed 2 ft.cd. (20 lux) and the black lights shall provide a minimum of 800 μW/sq.cm. when measured 15 in. (38 cm) from the front surface of the black light filter or bulb."
- 5.6.1 "... black lights shall provide a minimum of 1200 μW/sq.cm. at the component surface. ..."

MIL-STD-1949 (Mar. 1989), a standard establishing the minimum requirements for magnetic particle inspection used for detection of discontinuities at or immediately below the surface of ferromagnetic material, also states:

- 4.8.2 "... black light intensity at the examination surface shall be 1000 μW/sq.cm. or greater. ... Portable or hand held black lights shall produce an intensity greater than 1000 μW/sq.cm. when measured at 380 mm. (15 in.) from the black light source."
- 4.8.1 "... fluorescent magnetic particle inspection shall be performed in a darkened area with maximum visible light level of 20 lux (2 ft.cd.). ..."

(In these quoted paragraphs, the following abbreviations are used: ft. cd. = foot candle, a unit of illuminance, and μW/sq. cm. = microwatt per square centimeter, a unit of irradiance.)

On first observation, it would seem that the standards are very specific as to the requirements for levels of UV and visible radiations. Although they appear a little confusing in their UV-requirements (different values), it is well realized that visible light, regardless of its origin, will always obscure indications by reducing the contrast of the indication. However, part of the confusion arises when the standards and the preceding MIL-I-6866B and MIL-I-6868E are interpreted by some as referring only to the visible light (primarily blue and violet) emanating from the UV lamp, by others as being the ambient light level with the lamp not operating, and by still others as being a combination of the two. As a result of the increasing number of types of UV light sources being used in the industry nowadays—all with differing UV-light–to–visible-light ratios—these standards need clarification.

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Notice the language of the following two standards with reference to the above comments and the next section. MIL-STD-6866 states for Type II visible dye penetrants:

- 4.5.2 ". . . the lighting system shall provide at least 200 foot-candles (2000 lx/sq.m) of white light at the surface of the component being inspected."

and for nonfluorescent magnetic particles MIL-STD-1949 states:

- 4.8.1 ". . . The intensity of the visible light at the surface of the parts undergoing inspection shall be maintained at a minimum of 1000 lux (100 foot-candles). . . ."

How should the UV user interpret existing requirements? More importantly, which requirement is best for the task being performed and what are the ultimate quality control issues underlying these standards?

Radiometry

Radiometry is concerned with the measurement of radiation of all wavelengths and includes, as a special case, photometry (Figure 1). Radiometry has its own set of measurement quantities and units known as radiometric units. Photometry has an analogous, although different, set of units, which are applied only to measurements of visible light. Each photometric unit has a radiometric equivalent, but the units are not interconvertible without spectral information also being provided. In the visible spectrum, the conversion from radiometric to photometric units can be accomplished by multiplying the power radiated at each wavelength by the relative luminosity factor (a measure of the sensitivity of the eye) at that wavelength and summing the results. Conversely, by knowing the relative luminosity of the eye (at the particular light level) and the spectral distribution of the radiated power, the conversion from photometric to radiometric units may be accomplished. It is clear that if the eye has no sensitivity to the irradiated power (e.g., UV light), photometric units are meaningless and only radiometric units are valid.

Mathematically, for the conversion from radiometric to photometric units this can be expressed as

$$\text{(1a)} \quad \Phi_v = \sum_{400}^{760\ \text{nm}} K_m V(\lambda)\, \Phi_e$$

and, for continuous distributions, as

$$\text{(1b)} \quad \Phi_v = K_m \int_{400}^{760} V(\lambda)\, \Phi_e(\lambda) \cdot d\lambda,$$

where Φ_v is the total luminous power (expressed in lumens), K_m is the maximum value of the luminous conversion factor (or luminous efficacy), which for a photopic response is 680 lumens/watt, and $V(\lambda)$ is the relative luminosity function normalized to a maximum of unity; Φ_e is the radiant power at wavelength λ expressed in watts.

Photometry deals only with the measurement of visible light, which in the NDT industry is generally accepted as being that spectral region between the 400 and the 760 nm wavelengths. (These used to be known as 4000 and 7600 Å; the angstrom unit [Å] of wavelength measurement in the UV light and visible regions of the spectrum is no longer used and has been replaced almost completely by the SI unit, the nanometer.) It should be noted that both military standards define UV light as extending to 400 nm. An ideal photometric detector has a spectral response that matches that of a "standard eye" under high-level lighting conditions. Obviously, eyes have wide variations in spectral response and essentially depend upon the individual, so the concept in practice is somewhat abstract. Because the unambiguous quantitation of visible light is such an important measurement, many national standards laboratories have attempted to define photometric units in terms of a "standard eye response." This may be recorded subjectively by finding the energy required at each wavelength in the visible spectrum to produce a response of constant magnitude. That which is most commonly accepted nowadays is derived

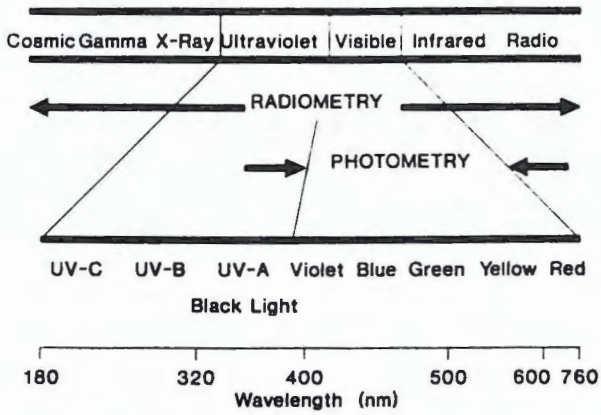

Figure 1—The electromagnetic spectrum.

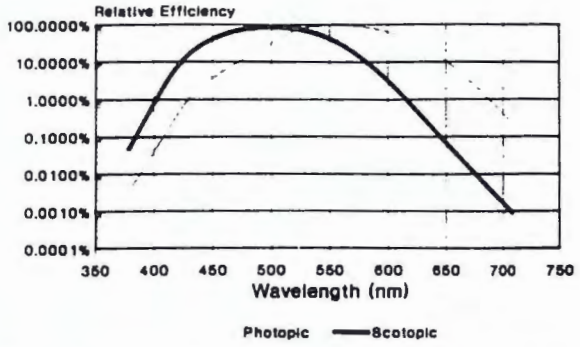

Figure 2—Spectral luminous efficiency of the human eye.

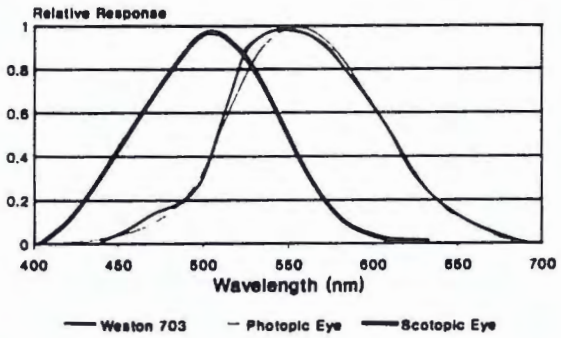

Figure 3—Typical photographic light meter and photopic and scotopic eye responses.

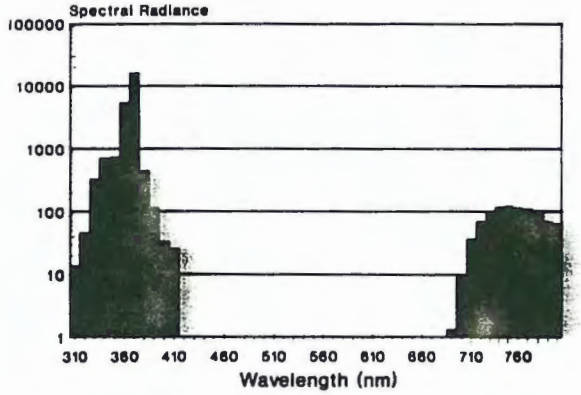

Figure 4—1100 W PAR 38 with Kopp #41 filter.

from the Commission Internationale de l'Eclairage (CIE) of Paris, France; these data were based upon young women's eyes in the early 1900s. This was augmented by data from several US investigators and has proved to be an acceptable criterion in high-level, photopic-response type situations since the 1930s. This standardized CIE photopic response is shown in Figure 2.

Unfortunately, an additional complication in photometry is the existence of two standard eye responses: at luminance levels above about 3 cd/m^2, the eye's spectral response is determined primarily by the cone-shaped cells in the retina, which exhibit a *photopic response*,[1] whereas at levels much below this level (i.e., 0.03 mcd/m^2) the eye's rod-shaped cells take over and the eye becomes very much more sensitive in the blue end of the spectrum.[2] These effects occur because of a spectral sensitivity shift and also because the rods are more sensitive than the cones to light (*scotopic response*). The scotopic response curve was standardized by the CIE in 1951 and is also shown in Figure 2.

For the cones, the observations have to be made under photopic conditions, or by using the foveal area of the retina, whereas the rod sensitivity is obtained at near-threshold illumination conditions by using the extra-foveal areas. The spectral sensitivity curves are then determined by plotting the inverse of the required energy to elicit a constant response against the wavelength. Because scotopic vision is inherently colorless, the determination of the scotopic curve presents no difficulty in principle, but with the photopic, or cone, curve, the observer has a more difficult task because of the intrusion of color. Because the fovea centralis of the eye is composed entirely of tightly packed cones and the peripheral areas of the retina are composed of both cones and rods, with the cone-to-rod ratio decreasing with increasing distance from the fovea, faint indications are seen better with the dark-adapted eye when viewed indirectly, especially at the extremities of the visual range. The fovea becomes a "blind spot" when observing low luminances, and maximum sensitivity occurs some 10 degrees from the center of the fovea, which itself has an angular diameter of 1 to 2 degrees in the visual field.

Between the levels at which the eye exhibits photopic and scotopic responses, the spectral response of the eye is continuously variable. This condition is known as the *mesopic* state, the luminous efficacy-spectral curve of the eye shifting progressively from that of photopic vision to that of scotopic vision and K_m increasing from 680 lm/W to 1746 lm/W (see Equation 1 and Figure 2). It is under mesopic conditions that most work is performed for fluorescent magnetic particle and penetrant inspection work, and under photopic conditions for visible dye penetrant and nonfluorescent magnetic particle inspection work. Unfortunately, no "mesopically" calibrated light meter exists, so that what one has to ask is what range of light levels would be used. Both scotopically and photometrically calibrated light meters remain only an approximation of the magnitude of the eye's stimulus under low-light–level conditions and are thus unsatisfactory for the measurement of low light levels. Photometers satisfac-

tory for the purpose of measuring the high light levels prevalent in Type II visible-dye penetrants and nonfluorescent magnetic particles are readily available.[3]

Light Meters and the Eye's Detectivity

Traditionally, in the NDT industry, for both Types I and II penetrants, light measurements have been made with photographic, general-purpose light meters (Weston 703 and others. Figure 3) which more or less closely resemble the CIE photopic response over much of the visible spectrum.

A "good" detector may be specified as being "within two percent of the CIE photopic response." This generally means that the area under the detector's response curve approximates the area under the idealized CIE response curve within two percent. This can be misleading because mismatches at specific wavelengths may deviate considerably more than two percent and can cause large errors, especially if the wavelength being measured is located at the lower-wavelength sensitivity region of the meter. As a result, general-purpose photometers, even under photopic conditions, are inadequate when the measured radiation is predominantly in the blue or red regions of the response; such photometers generally indicate less than they should (Figure 3). They may be perfectly adequate when the light is distributed such that a lot of the radiation is in the middle of the visible spectrum (as is usually the case in Type II inspections) or even if it is uniformly distributed throughout the response such that the insufficient response in the lower sensitivity regions is overwhelmed by correct response over much of the spectrum. However, this is not the case in NDT because of both the lamp's spectral output and the luminance level (Figure 4).

For the mesopic conditions prevalent in fluorescent magnetic particle and penetrant inspection work, it is clear that blue light will be underestimated if calibration of the photometer is performed using the usual standard broadband light sources or monochromatic radiation in the center of the visible spectrum (Figure 3). This is the source of the problems now being experienced in the NDT industry with photometers calibrated conventionally as outlined above and those calibrated for the normal blue/violet light experienced in the inspection booth. The prevailing ambiguities presented by existing industry and military standards, based upon "photographic" light meters, also do nothing to help. The spectral irradiance curve of a lamp based upon the American National Standards Institute's Specification H44GS-R100 (for a bulb obtainable from several manufacturers: a 100 W, mercury-vapor bulb in the PAR 38 configuration) and the Kopp® 1041UV filter is shown in Figure 5. Other newer lamps based upon the same bulb and the Kopp® 1071UV filter, and those based on the Philips® HPW 125W bulb and others, will differ but in general will have more or less visible in the blue/violet part of the spectrum and more or less of other radiations. (Kopp 1041UV and Kopp 1071W are registered trademarks of Kopp Glass Inc., Pittsburgh, PA, and Philips HPW 125W is a registered trademark of Philips Lighting Co., Somerset, NJ.)

Such blue/violet calibrated meters will not necessarily read the same as, and will generally read higher in most applications than, light meters such as the Weston 703 or equivalent, calibrated with broadband light sources (even with exactly the same relative spectral response) because of the predominance of blue/violet light in commonly used NDT inspection lamps and the way in which they are calibrated. Inspections that appear to be in conformance with standards when a Weston 703 is used may not appear to be in conformance when a photometer calibrated for the blue/violet ambient light of fluorescent magnetic particle and penetrant inspections is used. The latter meters, however, should never be used for high-level, wide-spectrum visible light inspection of parts (Type II penetrants and nonfluorescent magnetic particles) because they would yield excessive values, possibly leading to an erroneous belief that the minimum industry and military visible levels demanded of such inspection have been met.

In the NDT application, it is necessary to analyze what is being observed and the various influences that may cause the indication to go unobserved. Total darkness is never achieved, and may not be desirable from purely safety considerations, but it can be closely approached. What one has is a fluorescent indication, generated by a UV source, which is observed against a background of predominantly blue/violet light from the same lamp reflected and scattered back into the eyes, fluorescence of the ocular media generated by reflected UV, and a general ambient background that may or may not be blue/violet, depending upon the environment and how well the area is darkened. The inspector's clothes may produce fluorescence, and there may be other sources of fluorescence in the booth.

The sensitivity of the detection under the prevailing conditions depends on the sensitivity of the observer's visual system (including protective eyewear), the spectral distribution of the back-

ground radiation (including both reflected and other ambient) and the indication's size, larger indications obviously being easier to see.

The Blue and Violet Light

For many Type I penetrants, the blue and violet even cause additional fluorescence of the penetrant. It is not at all clear whether this "visible light" is all bad: there may be a net gain in having a certain amount of this type of visible light. Measurements by Moss (private communication) on 14 common penetrants showed that a 10 to 50 percent improvement in the fluorescent output could be achieved using 410 instead of 365 nm as the excitation wavelength. Certainly, if the recommendations of Holden, Rhoads-Roberts, and Moss[4] are heeded and the appropriate blue/violet (and UV) absorbing eyewear is used, then the contrast can be further enhanced together with the elimination of UV-induced, lenticular, and vitreous-humor fluorescence, a reduction of ocular chromatic aberrations because of the reduced spectral bandwidth, and an increase in inspector comfort and safety. Further, the "wide band" visible light leaking into the so-called "darkness booths" and causing a 2 ftc (21 lx) illuminance on the subject may be, by far, more destructive to the inspector's perception of the indication than 2 ftc (21 lx) of blue or violet light, especially when appropriate blue-absorbing eyewear is worn. It seems only reasonable then, that to get a measure of detectability with currently available instrumentation, two measurements of visible light should be taken: (a) one of basically "white" light leaking into the darkness booth and from fluorescent materials (clothing etc.) and (b) one of essentially blue and violet visible light at 436 and 405 nm emanating from the lamp or lamps of adjacent inspectors under normal operating conditions.

Obviously, if blue-absorbing eyewear is being worn, higher levels of blue and violet light on the part can be tolerated without adversely affecting and possibly enhancing the contrast of the indication because of additional excitation of fluorescence. The detectability would be a function of the ratio of (b) to (a). However, if a photometer responsive in the region that the blue-absorbing eyewear transmitted existed, then a good measure of signal-to-noise could be estimated by taking readings with and without the presence of the operator's UV light lamp.

Luminance of the Indication

Another concept that it is important to understand is that the reader of this page, for example, and of course the inspector of the part are more concerned that the luminance be high enough rather than that the illuminance of the page (i.e., the power consumption of the lamp producing the illumination) be high. The illuminance may be very high, yet, if the reflectivity is very low then it may be no more distracting to see fine fluorescent detail on the part than if the illuminance were very low and the reflectivity high. This is another source of confusion in the industry and military specifications, which have frequently measured illuminance at the inspected parts and could have led to variable detectivity of flaws, depending upon the surface finish and material of the parts being inspected.[4]

In practice, there is a possible reduction in the light reaching the retina (as a function of the inspector's age) such that an older inspector would tend to need a higher fluorescent output (and therefore higher UV-irradiance at the part) than a younger person using the same penetrant. This is both because of the decreasing size of the pupil with age when observing the same luminous surface and because of the inevitable physiological changes within the eye that lead to reduced luminous flux at the retina and changed indication detection capabilities, apart from any contrast con-

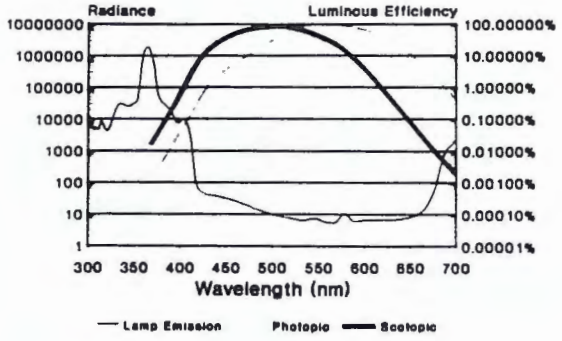

Figure 5—UV lamp and the luminous efficiency of the eye.

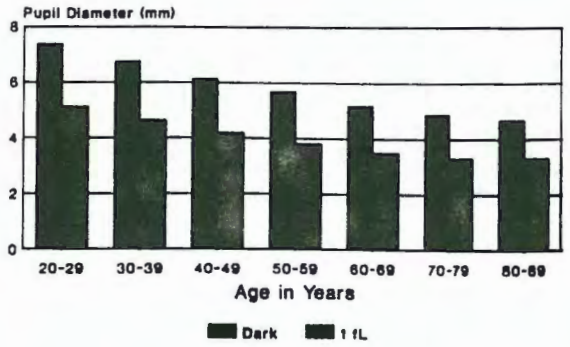

Figure 6—The change in pupil diameter with age and lighting conditions.

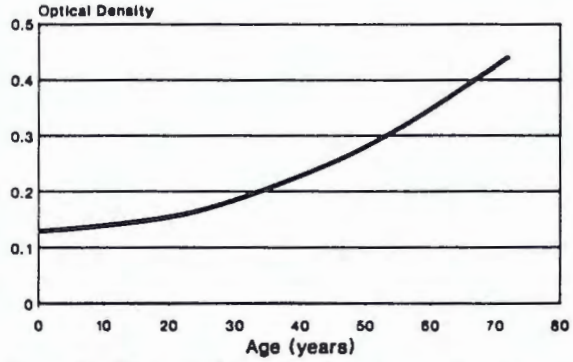

Figure 7—The optical density of the human lens as a

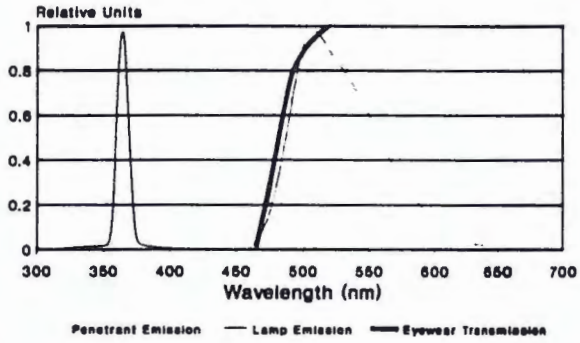

Figure 8—Penetrant fluorescence and lamp spectral output.

siderations. Figures 6 and 7, which are modified from the *IES Lighting Handbook*,[3] clearly demonstrate the effect. Additionally, less than perfect preparation conditions may exist; complete removal of the penetrant from the surface of the part may not have taken place and good contrast of the indication may not be possible, inevitably leading to reduced inspector performance. There is also a great variation in fluorescence efficiency of commonly used penetrants (a variation documented by Holden et al.[4]), although this can be expected because the penetrants are often used under different conditions. All this is not to say that an inspection was inadequate and the task was unaccomplished, but that perfectly legitimate questions may be posed as to the meaning of the specifications and their practical compliance. Such a possible source of misinterpretation or confusion is certainly not the way to guard against substandard inspections unless this is considered in the initial generation of specifications and a sufficient safety factor is included.

If eyewear is used that absorbs any part of visible light, then a completely different contrast problem arises and the possibility of fluorescence indication enhancement exists. One example of such enhancement has been documented in the literature[4] and has been partially reproduced here by way of example (see Figure 8) to demonstrate the different contrast situations.

When such goggles are worn, the only visible light that will interfere with the "indication" are those visible wavelengths (essentially room background) in the region from 480 to about 600 nm, a well-defined and relatively easily measurable part of the spectrum in terms of the CIE response. To arrive at a realistic yet relatively easy-to-measure "signal-to-noise ratio," all that would be needed would be to measure the "indication" with and without the irradiating UV because the lamp produces essentially nothing in this spectral region (Figure 5). This, of course, would require a completely new set of calibration concerns for the industry but has the attraction that it is unitless, is a real measure of "seeability," and the temptation to use improper instrumentation is much reduced, reserving the general-purpose photometers for visible penetrant inspection, an appropriate application.

Conclusion

Unfortunately, most photometers are badly matched to the challenge of measuring low levels of any color visible light and even more so for low-level blue/violet light. This is because of the eye's spectral response shift and increased sensitivity at low light levels and also because light meters in general do not have correct blue/violet response, even at high levels. However, for the Type II nonfluorescent penetrants and magnetic particles, conventional "general-purpose" light meters are sufficient at present, provided that they have adequate illuminance range, MIL-STD-6866 and MIL-STD-1949 currently requiring a minimum of 200 ftc (2150 lx) and 100 ftc (1070 lx), respectively, for visible dye inspection and nonfluorescent magnetic particle methods.

Once meaningful measurements as suggested above can be made, it is probably in everybody's interests that the relevant sections of MIL-STD-6866 and MIL-STD-1949 be re-examined to provide an unambiguous statement of the requirements to perform the task. This could take the form of possibly using the signal-to-noise ratio criterion sug-

gested above, or, in our opinion less satisfactorily, adjusting the permissible light levels to reflect true values in view of the new measurements. The use of visual-indication–enhancing eyewear should also be admitted because of both its enhancing properties and inspector safety, including splash protection. Clearly, such procedures will have to be incorporated in the teaching/training programs to supersede previous practice.

The units of lx/m^2, a meaningless expression, in paragraph 4.5.2 of MIL-STD-6866 should in any case be changed to lm/cm^2 or just lux (lx), the SI unit of illuminance.

References

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2. Crawford, B. H., *Proceedings of the Physical Society, B*, 1949, Vol. 62, p 321.
3. *IES Lighting Handbook*, 1981. Illuminating Engineering Society, New York, NY.
4. Holden, W. O., J. L. Rhoads-Roberts, and C. E. Moss, "Radiation Safety and Visual Enhancements in the Fluorescent Dye Penetrant Processes," *Materials Evaluation*, Vol. 44, No. 12, Nov. 1986, pp 1435–1442.

Penetrant Handbook Update

An errata review has been completed for *Nondestructive Testing Handbook* on *Liquid Penetrant Tests*, Vol. 2 of the second edition. Designed to fit conveniently inside the volume's jacket, the errata booklet contains technical corrections and critical additions to the *Handbook*'s text and illustrations.

The eight-page errata booklet is available at *no charge* from ASNT to *NDT Handbook* owners. Phone orders cannot be accepted. Write to ASNT, Dept. Z, PO Box 28518, Columbus, OH 43228-0518, and ask for ASNT catalog #126E.

Historical Photos Needed

Historical photographs of nondestructive testing and of American Society for Nondestructive Testing (ASNT) activities are needed for publication in the 50-year ASNT history to be published in 1991 for the Society's semicentennial celebration. Both black-and-white and color photographs will be usable; all will be returned to the owner following publication of the commemorative issue, which will be provided to all ASNT members. Persons with photographs they are willing to loan to ASNT should contact Publications Manager Jody Van Cooney, American Society for Nondestructive Testing, Inc., 1711 Arlingate Lane, PO Box 28518, Columbus, OH 43228-0518; (614) 274-6003, 800-222-ASNT, or (in Ohio) 800-NDT-OHIO; telex 245347; fax (614) 274-6899.