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Standard Guide for Computed Radiology (Photostimulable Luminescence (PSL) Method)[1]

This standard is issued under the fixed designation E 2007; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ϵ) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide covers practices and image quality measuring systems for the detection, display, and recording of CR data files. These data files, used in materials examination, are generated by penetrating radiation passing through the subject material and producing an image via a storage phosphor imaging plate. Although the described radiation sources are specifically X-ray and gamma-ray, the general concepts can be used for other radiation sources such as neutrons. The image detection and display techniques are nonfilm, but the use of a hard copy as a means for permanent recording of the image is not precluded.

1.2 This guide is for tutorial purposes only. It outlines the general principles of computed radiology (CR) imaging in which ~~photostimulable~~ luminescence is emitted by ~~the penetrating radiation detector,~~ a storage phosphor imaging plate, by means of photo stimulation after the detector has been penetrated by x-rays or gamma radiation.

1.3 The values stated in SI units are to be regarded as the standard. The inch-pound units given in parentheses are for information only.

1.4 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.* For specific safety precautionary statements, see Section 7.

2. Referenced Documents

2.1 *ASTM Standards:*

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[1] This guide is under the jurisdiction of ASTM Committee E-7 on Nondestructive Testing and is the direct responsibility of Subcommittee E07.01 on Radiology (X and Gamma) Method.

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E 142 Method for Controlling Quality of Radiographic Testing[2]
E 747 Practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology[2]
E 1025 Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiology[2]
E 1817 Practice for Controlling Quality of Radiological Examination by Using Representative Quality Indicators (RQIs)[2]

2.2 *Federal Standard:*

Fed. Std. No. 21-CFR 1020.40 Safety Requirements for Cabinet X-Ray Machines[3]

3. Summary of Guide

3.1 This guide outlines the practices for the use of CR methods and techniques for materials examination. It is intended to provide a basic understanding of the method and the techniques involved. The selection of a storage phosphor imaging plate, radiation source, and radiological techniques, which are necessary in achieving user CR performance requirements, is described.

4. Significance and Use

4.1 This guide establishes an introduction to the theory and use of CR. The X-, gamma-ray detector discussed in this guide is a storage phosphor imaging plate, hereafter referred to as SPIP. The SPIP, which is the key component in the CR process, differentiates CR from other radiologic methods. This guide is a tutorial standard, and therefore it does not present specified image quality levels as would be used to address the acceptance or rejection criteria established between two contracting parties, for example, NDT facility or consumer of NDT services, or both. It is not a detailed how-to procedure to be used by the NDT facility or consumer of NDT service, or both.

4.2 Table 1 lists the general performance, complexity, and relative cost of CR systems.

5. Background

5.1 Inspired by the success of computed tomography (CT), new methods of radiologic imaging have been developed that utilize recent advances in electronics and computer technologies to realize better image quality, and to evolve new imaging modalities. These are generally in a category in which the X-ray sensor is mainly either the conventional image intensifier and television-camera combination or the linear array sensor as used in CT. The basic quality of the digital image is not limited by digital processing but in large measure by the performance of the sensor itself in regard to spacial resolution and signal to noise ratio.

5.2 The earliest written reference to fluorescence, the phenomenon which causes materials to emit light in response to external stimuli, dates back to 1500 B.C. in China. This phenomenon did not attract scientific interest until 1603, when the discovery of the Bolognese stone in Italy led to investigation by a large number of researchers. One of these was Becquerel, who, in his 1869 book *La Lumiere*, revealed that he had discovered the phenomenon of stimulated luminescence in the course of his work with phosphors.

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[2] *Annual Book of ASTM Standards*, Vol 03.03.

[3] Available from Standardization Documents Order Desk, Bldg. 4, Section D, 700 Robbins Ave., Philadelphia, PA 19111-5094, Attn: NPODS.

TABLE 1 Computed Radiology (PSL Method)

Availability	Good
Equipment needed	Phosphor storage imaging plate, plate reader and work station
Usual readout methods	Electronics/visual
Other readout methods	Film
Practical resolution	Dependent on application and equipment
Contrast sensitivity in %	Dependent on energy and material
Useful kVcp range	
Min	10kV
Max	32MeV
Optimum kVcp	As low as practical
Maximum field of view	14[in] × 17[in]
Relative sensitivity to X rays	Extremely high
Relative cost	Low to moderate
Approximate useful life	Five years or determined by handling
Special remarks	Digital and versatile

5.2.1 Photo stimulated luminescence (PSL) is a phenomenon in which a phosphor that has ceased emitting light because of the removal of the stimulus once again emits light when excited by light with a longer wavelength. The phenomenon is quite common since photostimulable phosphors cover a broad range of materials—compounds of elements from Groups IIB and VI (for example, ZnS), compounds of elements from Groups 1A and VIIA, VIIB and V VIB (for example, alkali halides), diamond, Groups 2A and VIIA, VIIB and V VIB (for example, barium fluorohalides—Ba FX-EU^{2+} X=Br, I, etc.), oxides (for example, Zn2Si04:Mn and LaOBr:Ce, Tb), and even certain organic compounds. The materials therefore lend themselves to data storage because the stimulus or primary excitation could be used to write data to the material, the light or secondary excitation to read the data back. Storage phosphor imaging plate (IP) is a name given to a two-dimensional flexible sensor that can store a latent image obtained from X rays, electron beams or other types of radiation, using photostimulable phosphors (P.P.), and then sequentially reproduces them as a digital file by releasing the PSL with a laser beam, piping the PSL to a photomultiplier tube (PMT) and then digitizing the resulting electrical signal.

5.3 With the introduction of photostimulable luminescence imaging systems in the early 1980's, CR was born by the combination of this highly advanced photographic technology with recent advances in computer technologies.

5.4 CR can utilize various software algorithms for image enhancement and optical disks for digital file storage. This advanced imaging system greatly expands the versatility of radiology. Potential industrial applications include production examination of aircraft components, welds in rocket-motor housings, castings, transistors, microcircuits, circuit-boards, valve positions, erosion and corrosion of pipes, integrity of pipe welds, solenoid valves, fuses, relays, tires, reinforced plastics and automotive parts.

5.5 *Limitation*:

5.5.1 *Handling Characteristics*—Potentially, a CR imaging plate may be erased and reused thousands of times. The primary limiting factor, as is the case with lead intensifying screens, is physical handling. Frequency of handling, bending and cleaning determines the plate's useful lifespan.

6. Interpretation and Reference Standards

6.1 *Acceptance Standards*—As written by other organizations for film radiography may be employed for CR inspection provided appropriate adjustments are made to accommodate the differences represented by the CR data files.

6.2 *ASTM Reference Standards*—Reference digital image standards, complementing existing ASTM reference film radiographic standards must be developed. Subcommittee E07.01 work aimed at developing such standards is underway.

7. Safety Precautions

7.1 The safety procedures for the handling and use of ionizing radiation sources must be followed. Mandatory rules and regulations are published by governmental licensing agencies, and guidelines for control of radiation are available in publications such as the Fed. Std. No. 21-CFR 1020.40. Careful radiation surveys should be made in accordance with regulations and codes and should be conducted in the examination area as well as adjacent areas under all possible operating conditions.

8. Radiation Sources

8.1 *General*:

8.1.1 The sources of radiation for CR imaging systems described in this guide are X-ray machines and radioactive isotopes. The energy range available extends from a few kV to 32 MeV. Since examination systems in general require high dose rates, X-ray machines are the primary radiation source. The types of X-ray sources available are conventional X-ray generators that extend in energy up to 420 kV. Energy sources from 1 MeV and above are generally represented by linear accelerators.

8.1.2 Useable isotope sources have energy levels from 84 keV (Thulium-170, Tm^{170}) up to 1.25 MeV (Cobalt-60, Co^{60}). With high specific activities, these sources should be considered for special application where their field mobility and operational simplicity can be of significant advantage.

8.1.3 The factors to be considered in determining the desired radiation source are energy, focal geometry, wave form, half life, and radiation output.

8.2 *Selection of Sources*:

8.2.1 *Low-Energy Sources*—The radiation source selected for a specific examination system depends upon the material being examined, its mass, its thickness, and the required rate of examination. In the energy range up to 420 kV, the X-ray units have an adjustable energy range so that they are applicable to a wide range of materials. Specifically, 50-kV units operate down to a few kV; 160-kV equipment operates down to 20 kV; and 420-kV equipment operates down to about 85 kV.

8.2.2 *High-Energy Sources*—The increased efficiency of X-ray production at higher accelerating potentials makes available a large radiation flux, and this makes possible the examination of greater thicknesses of material. High radiation energies in general produce lower image contrast, so that as a guide the minimum thickness of material examined should not be less than 2.5 half-value layers of material. The maximum thickness of material can extend up to 10 half-value layers.

8.3 *Source Geometry*:

8.3.1 Although the physical size of the source of radiation is a parameter that may vary considerably, the radiation sensor is generally the principal source of unsharpness.

9. CR Storage Phosphor Imaging Plate

9.1 A CR storage phosphor imaging plate (SPIP) is described as a reusable detector (flexible or rigid) that stores penetrating radiation energy as a latent image.

9.2 When X-ray photons pass through an object, they are attenuated. At low-to-medium energies this attenuation is caused primarily by photoelectric absorption, or Compton scattering. At high energies, scattering is by pair production (over 1 MeV) and photon photonuclear processes (at about 11.5 MeV). As a result of attenuation, the character of the flux field in a cross-section of the X-ray beam is changed. Variations in photon flux density and energy are most commonly encountered, and are caused by photoelectric absorption and Compton scattering.

9.3 By analyzing this flux field, we can make deductions about the composition of the object being examined, since the attenuation process depends on the number of atoms encountered by the original X-ray beam, and their atomic number.

9.4 The attenuation process is quite complex, since the X-ray beam is usually composed of a mixture of photons of many different energies and the object may be composed of atoms of many different kinds. Exact prediction of the flux field falling upon the SPIP is therefore, difficult. Approximations can be made, since the mathematics and data are available to treat any single photon energy and atomic type, but in practice great reliance must be placed on the experience of the user. In spite of these difficulties, successful CR SPIP's have been developed, and perform well. The criteria for choice depend on many factors, which, depending on the application, may, or may not be critical. Obviously, these criteria will include the following factors.

9.4.1 *Field of View*—The field of view of the SPIP and its resolution are interrelated. The resolution of the SPIP is fixed by its physical characteristics, so if the X-ray image is projected upon it full-size (the object and image planes in contact), the resultant resolution will be approximately equal to that of the SPIP. When SPIP resolution becomes the limiting factor, the object may be moved away from the SPIP, and towards the source to enlarge the projected image and thus allow smaller details to be resolved by the same SPIP. As the image is magnified, however, the detail contrast is reduced and its outlines are less distinct. (See 10.3.) It is apparent, also, that when geometric magnification is used, the area of the object that is imaged on the SPIP is proportionally reduced. As a general rule, X-ray magnifications should not exceed 5x except when using X-ray sources with very small (microfocus) anodes. In such cases, magnifications in the order of 10 to 20x are useful. When using conventional focal-spot X-ray sources, magnifications from 1.2 to 1.5 provide a good compromise between contrast and resolution in the magnified image.

9.4.2 *Inherent Sensitivity*—The basic sensitivity of the SPIP may be defined as its ability to respond to small, local variations in radiant energy to display the features of interest in the object being examined. It would seem that an SPIP that can display intensity changes on the order of 1 to 2 % at resolutions approaching that of film radiography would satisfy all of the requirements for successful CR imaging. It is not nearly that simple. Often good technique is more important than the details of the imaging system itself. The geometry of the system with respect to field of view, resolution and contrast is a very important consideration as is the control of scattered radiation. Scattered X rays entering the imaging system produce background similar to fogging in a radiograph. This scatter not only introduces radiant energy containing no useful information into the imaging system but also impairs system sensitivity and resolution. Careful filtering and collimation of the X-ray beam and control of back scatter, are vital to good CR.

9.5 *Physical Factors*—The selection of a CR imaging system for any specific application may be affected by a number of factors. Environmental conditions such as extremes of temperature and humidity, the presence of loose dirt and scale and oily vapors can all limit their use, or even preclude some applications. In production-line applications, system reliability, ease of adjustment, mean-time-between-failures, and ease and cost of maintenance are significant factors.

9.6 *X-Ray to Photostimulable Luminescence*—For the purpose of CR, the SPIP is a phosphor-coated plastic sheet of material that "holds" the X-ray image information, then releases it as photostimulable luminescent light when the phosphor is stimulated by laser light of a specific wavelength.

9.7 *Photostimulable Luminescence (PSL) Phosphors*:

9.7.1 Photostimulable Luminescence (PSL) phosphors incorporate special properties differing from those previously known. Although PSL has some characteristics similar to those of fluorescent phosphors, it has an altogether different mode for light emission. Subsequent to exposure to X- or gamma radiation, the PSL phosphor stores the radiation photons, then releases a visible luminescence upon stimulation by laser light.

9.7.2 When coated on a suitable support, the PSL phosphor satisfies a basic concept of X- or gamma SPIP which stores the initial radiation information then releases that information when desired. Some PSL phosphors currently in use incorporate groups of very small crystals of barium fluorohalide containing a trace of bivalent europium as a luminescence center or alkaline-earth sulfide doped with cerium and samarium. These phosphors are uniformly coated on a plastic substrate or polyester support base.

9.7.3 Radiologic exposure of the SPIP is performed the same as that for film radiography, consequently no special handling or enclosure equipment is required. Lead screens are recommended to minimize scattered radiation and provide a level of intensification for applications that normally require them in film radiography. The exposed SPIP is scanned with a laser beam of appropriate wavelength while it is being conveyed with high accuracy in an SPIP reader. Reading sensitivity and sensitivity range can also be selected according to the end use. PSL light, released upon laser excitation, is collected through a light collection guide to a photomultiplier tube (PMT), and converted to analog electric signals. These same analog electric signals are subsequently digitized. An illustration of this process is shown in Fig. 1.

9.7.4 Photostimulable Luminescence SPIPs are commercially available (accompanying a phosphor reader) in specific sizes.

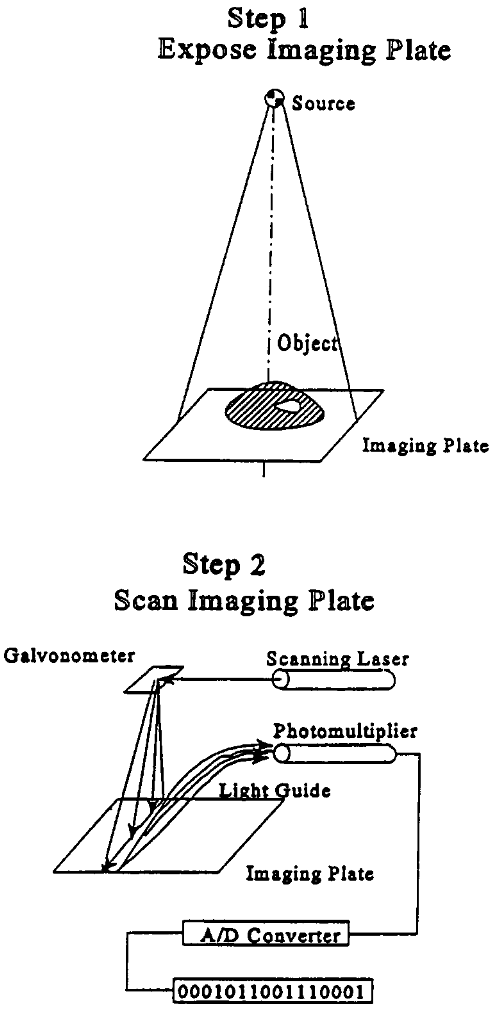

FIG. 1 CR Imaging Process

Spatial resolution is a function of the SPIP size, granularity and readout laser spot size. SPIP size is chosen depending on the end use application.

10. Image Quality Considerations

10.1 Image quality is governed by two factors, image contrast and resolution. These factors are interrelated in a complex manner which will be partially discussed here. Radiologic sensitivity, as indicated by the conventional IQI, measures contrast and resolution. In this section a number of different approaches to assessing image quality are presented. Care must be exercised in selecting a method since the question that must be satisfied is: "Does the system have the capability for detecting the discontinuities of interest?"

10.2 *Image-Formation Basis*:

10.2.1 Contrast is a direct result of X-ray attenuation by the object. Fig. 2 shows how a thickness change ΔX produces an X-ray intensity profile. This scheme is idealized where the effects of unsharpness due to scatter, screens, electronics, etc. are not considered. Based on the attenuation equation, the intensity for mono-energetic radiation is as follows:

$$I = I_o e^{-\mu x} \tag{1}$$

Taking the derivative and substituting I results in:

$$\frac{\Delta I}{I} = \mu \Delta x \tag{2}$$

$\frac{\Delta I}{I}$ can be considered the object contrast.

10.2.2 Unsharpness due to geometry, and SPIP tend to reduce contrast and make it more difficult to define edges. Fig. 2 shows how the intensity profile is affected by unsharpness where the image of the sharp step edge is blurred. If the unsharpness is much smaller than a void *d* (Fig. 3), the contrast is not reduced and the edges in the image are easily defined. If the void is smaller than the unsharpness, then the contrast is reduced. It is possible to make the unsharpness so large that the void image is not resolved.

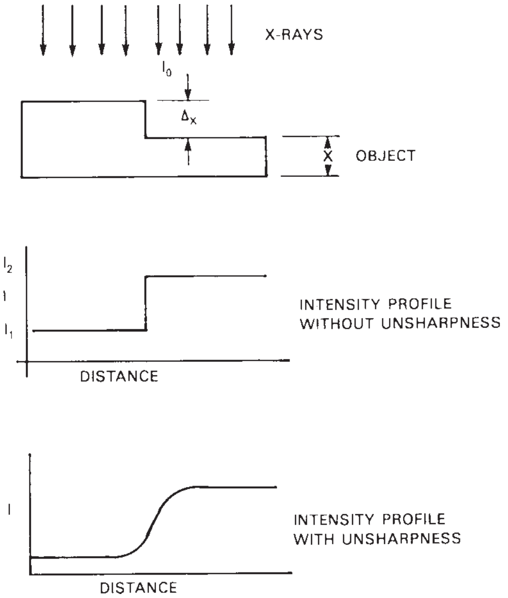

FIG. 2 X-ray Absorption and Unsharpness

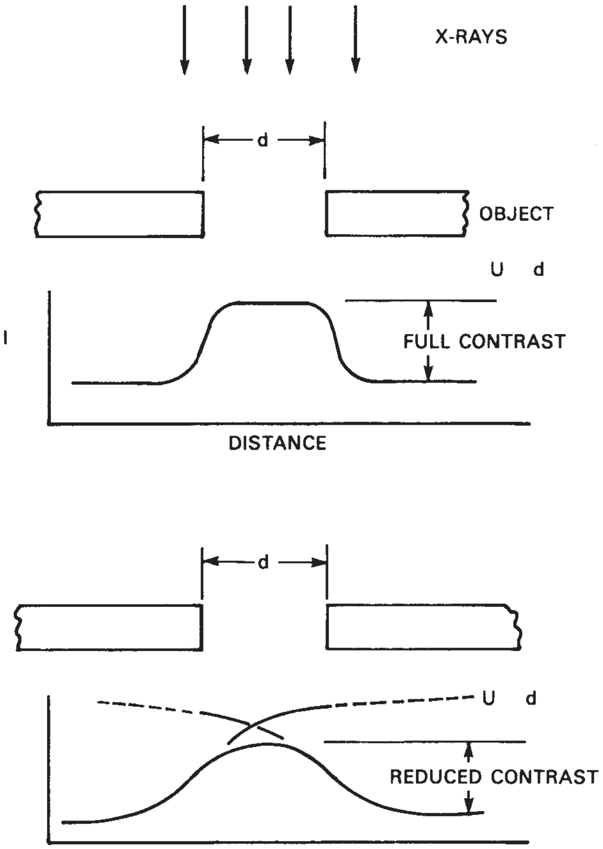

FIG. 3 Effect of Geometric Unsharpness on Image Contrast

10.2.3 Fig. 4 shows Klasens[4] method for determining unsharpness from a measured curve. This technique has produced good results and is generally accepted. According to Klasens, the total unsharpness, U_T, is equal to the cube root of the sum of the cubes of unsharpness due to geometry, Ug, and the unsharpness due to the SPIP, U_P:

$$U_T = (Ug^3 + U_P{}^3)^{1/3} \tag{3}$$

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[4] Kiesens, H. A., “Measurement and Calculation of Unsharpness Combinations in X-Ray Photography”, Phillips Research Reports, Vol 1, No. 4, August 1946, pp. 241–249.

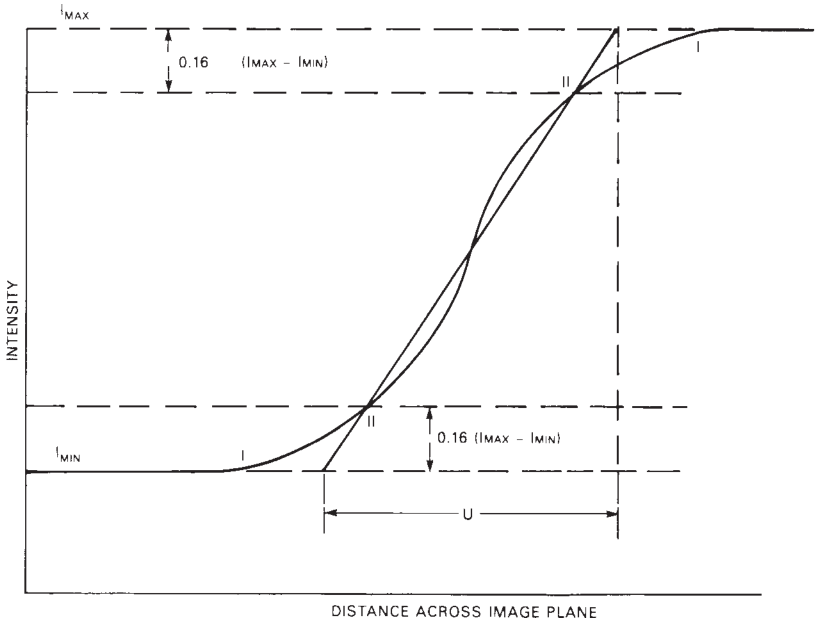

FIG. 4 Klasens' Equivalent Blur

10.2.4 *Modulation Transfer Function*:

10.2.4.1 One way to evaluate a system is by measuring the modulation transfer function (MTF). This is a measure of sinusoidal amplitude modulation as a function of spatial frequency. A plot of the two variables will give a curve representing the frequency response of a system thereby making comparisons of different systems possible. A typical MTF curve is shown in Fig. 5 where at low frequencies the MTF approaches 100 % and falls off as the frequency is increased.

10.2.4.2 There are several techniques for measuring MTF; some use direct measurement with a test object and others use a measure of the point spread function and mathematically convoluting this with a sine function, thereby constructing the MTF curve.

10.3 *X-Ray Scatter*:

10.3.1 X-ray scatter is a problem in CR systems just as it is in film radiography. When an X-ray beam is directed through an object some of the rays are absorbed, some are scattered, and some pass straight through. Electrons of the atoms comprising the object scatter radiation in all directions. The scatter is lower energy and less penetrating than the primary beam. The amount of scatter is related to the material and the intensity of the primary beam, in accordance with the following relation:

$$I_s = KI \tag{4}$$

where:

I_s = scattered radiation,
K = scattering factor, and
I = intensity of primary beam.

10.3.2 Typical exposure curves for aluminum at 80 kV with and without transmitted scatter are shown in Fig. 6. From such data the scattering factor can be determined. The scattering ratio is given by (1 + K) where this value reduces contrast sensitivity.

10.3.3 Scatter can be minimized even though it cannot be completely eliminated. The following recommendations should be followed.

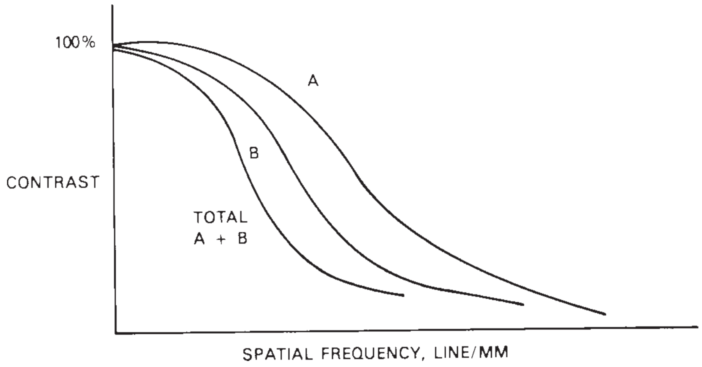

FIG. 5 Modulation Transfer Curve

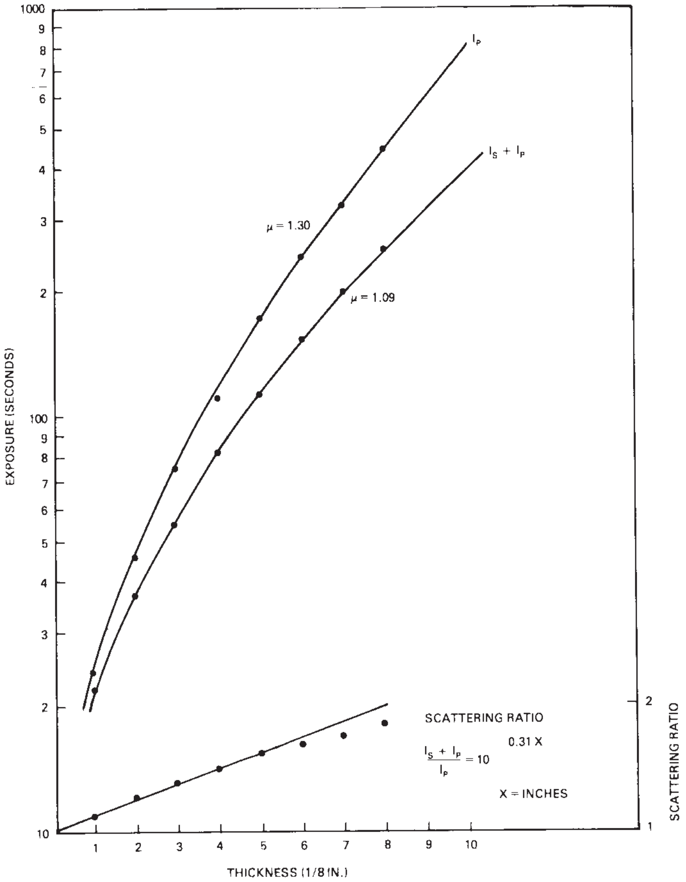

FIG. 6 Exposure Curves for Aluminum

10.3.3.1 Use masks or diaphragms to limit the X-ray beam to the subject area.

10.3.3.2 Protect against back scatter and scatter from external objects by placing the tube or screen in a shielded position.

10.3.3.3 Use filters where possible to eliminate low-energy scatter.

10.4 *Image Quality Indicators*:

10.4.1 A number of different devices, such as wires, plaques, steps, mesh, etc., have been used to measure image quality. The same principles apply for CR systems as for other radiological methods. Some CR systems may require several devices, such as IQIs and wire mesh, to assure the proper image quality. And, in those instances when these IQ devices are inadequate in controlling the quality and repeatability of the CR image, or, when representative criteria levels of the acceptance or rejection of images of discontinuities are important, Representative Quality Indicators (RQIs) may be used.

10.4.2 *Plaque Type*—This IQI is described in Test Method E 142 and Practice E 1025. It consists of a plaque with three drilled holes with diameter equal to one, two, and four times the plaque thickness (1T, 2T, and 4T). The minimum plaque thickness is 0.127 mm (0.005 in.) and the minimum hole diameters are 0.25 mm (0.010 in.), 0.5 mm (0.020 in.) and 1 mm (0.040 in.) for the 1T, 2T, and 4T holes. Most codes require the detection of the 2T hole in a plaque that is 2 % of the object thickness.

10.4.3 *Wire Type*—This IQI consists of a graded set of wires where the diameter size increases by a factor of 1.26 as described in Practice E 747. The visibility of the essential wire determines the sensitivity of the system. The smallest wire is 0.005 in., thereby limiting their usefulness for thin materials. Since the cross section of the wire is round, it is not affected by position.

10.4.4 *Duplex Wire System*—The duplex wire system consists of parallel pairs of high-density wire with the space equal to the wire diameter and is used to measure total radiologic unsharpness. The diameters of successive wire pairs increase by a factor of 1.26. The visibility of the space between the wires is used as a criterion for determining unsharpness. Thus the diameter of the wire pair where the space is no longer visible determines the unsharpness. This device works satisfactorily at energies below 250 kV.

10.4.5 *Mesh*—Wire mesh is a good device for indicating resolution. For this purpose, a graded U.S. Standard Sieve Series (ASME Specifications) in the range of Nos. 40 and 80 can be used. As an example, a No. 50 sieve has 50 lines per inch and an opening of 0.297 mm (0.0117 in.) which approximates the condition for equal width lines and spaces. Unfortunately, their use is limited to low-energy X rays since the mesh is made of brass or stainless steel.

10.4.6 *RQIs*—This image quality indicator is described in Practice E 1817. It provides documented evidence that CR images have the quality level necessary to reveal those non conformances for which the parts are being examined by ensuring adequate spatial resolution and contrast sensitivity in the area(s) of interest.

11. Display and Recording Devices

11.1 *General Considerations*:

11.1.1 The usual display for CR systems is graphic, and it is important to control as closely as possible the parameters that contribute to critical visual inspection. The display must have sufficient size, color, brightness, contrast, and resolution to meet the minimum image-quality-indicator sensitivity levels established by specification.

11.2 *Direct Viewing*:

11.2.1 The CR image produced on a monitor is viewed directly. With the minimization of ambient lighting and sufficient dark adaptation, consistent large-area contrast sensitivity can be obtained at light levels greater than 2.5 millilamberts (8.75×10^3 cd/m^2). Below 2.5 millilamberts, the sensitivity of the eye decreases by approximately a factor of two per decade of light-level reduction.

11.3 *Electronic Displays*:

11.3.1 Advances in electronics and digital techniques are revolutionizing graphic displays. Monitor presentation of the CR image markedly increases the technical and operational flexibility of CR imaging systems, and the incorporation of image enhancement, digitizing, and color-indexed signal-level indications have further improved the analytical aspects of the method. The display may be in the form of stored images, a digitized matrix, or a multicolored display in which imperfections are highlighted by color. These developments then lead to image analysis. At present, digitally enhanced displays are available.

11.3.1.1 *Display Concepts*—The use of CRT for display of the image requires that certain fundamental principles be observed in the design of the system. Aside from the selection of the CRT system and the consideration of image enhancement and storage techniques, the specification of screen size, and viewing conditions are highly important. Attention to these details can result in a measurable improvement in system sensitivity and operator effectiveness.

11.3.1.2 *Viewing Conditions*—For optimum operator performance, beneficial effects may be achieved by arranging the CRT viewing to be performed in subdued light and that no glare is reflected from the face of the monitor. Also, the operator's position with respect to the screen, the operating controls, and his report forms should be selected to avoid undue motion and strain. Finally, the examination area should be adequately shielded for radiation protection.

12. Recording

12.1 Permanent records of the image are often required. Several methods are presently available.

12.1.1 *Digital Tape Recording*—CR systems employ digital conversion techniques that utilize digitally recorded tapes for bulk storage of image information. These systems produce digital data files in a matrix of picture elements or "pixels". The digitized format lends itself to computer-controlled display, reading, analysis, and storage. Digital signals may be stored on magnetic tape, and they are compatible with the new laser recording systems which offer even greater storage efficiencies and life.

12.1.2 *Other Recording Techniques*—Electronic interfaces are available for CR systems to produce paper facsimile photographs and laser print films.

13. Keywords

13.1 calibration; computed radiology; configuration; electronic; imaging plate; module; nondestructive; photostimulable luminescence; storage phosphor

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