Standard Guide for Radioscopy[1]

This standard is issued under the fixed designation E1000; 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 is for tutorial purposes only and to outline the general principles of radioscopic imaging.

1.2 This guide describes practices and image quality measuring systems for real-time, and near real-time, nonfilm detection, display, and recording of radioscopic images. These images, used in materials examination, are generated by penetrating radiation passing through the subject material and producing an image on the detecting medium. 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 photographic film as a means for permanent recording of the image is not precluded.

NOTE 1—For information purposes, refer to Terminology E1316.

1.3 This guide summarizes the state of radioscopic technology prior to the advent of Digital Detector Arrays (DDAs), which may also be used for radioscopic imaging. For a summary of DDAs, see E2736, Standard Guide for Digital Detector Array Radiology. It should be noted that some detector configurations listed herein have similar foundations to those described in Guide E2736.

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 6.

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E747 Practice for Design, Manufacture and Material Grouping Classification of Wire Image Quality Indicators (IQI) Used for Radiology

E1025 Practice for Design, Manufacture, and Material Grouping Classification of Hole-Type Image Quality Indicators (IQI) Used for Radiology

E1316 Terminology for Nondestructive Examinations

E1742 Practice for Radiographic Examination

E2002 Practice for Determining Total Image Unsharpness and Basic Spatial Resolution in Radiography and Radioscopy

E2736 Guide for Digital Detector Array Radiology

2.2 *National Council on Radiation Protection and Measurement (NCRP) Standards:*

NCRP 49 Structural Shielding Design and Evaluation for Medical Use of X-rays and Gamma Rays of Energies up to 10 MeV[3]

NCRP 51 Radiation Protection Design Guidelines for 0.1–100 MeV Particle Accelerator Facilities[3]

NCRP 91, (supercedes NCRP 39) Recommendations on Limits for Exposure to Ionizing Radiation[3]

2.3 *Federal Standard:*

Fed. Std. No. 21-CFR 1020.40 Safety Requirements for Cabinet X-Ray Machines[4]

2.4 *Aerospace Industries Association Document:*

NAS 410 Certification & Qualification of Nondestructive Test Personnel[5]

2.5 *ASNT Documents:*[6]

SNT-TC-1A Recommended Practice for Personnel Qualification and Certification in Nondestructive Testing

ANSI/ASNT-CP-189 ASNT Standard for Qualification and Certification of Nondestructive Testing Personnel

2.6 *CEN Documents:*[7]

EN 4179 Aerospace Series—Qualification and Approval of Personel for Non-Destructive Testing

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

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from NCRP Publications, 7010 Woodmont Ave., Suite 1016, Bethesda, MD 20814.

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

[5] Available from Aerospace Industries Association of America, Inc. (AIA), 1000 Wilson Blvd., Suite 1700, Arlington, VA 22209-3928, http://www.aia-aerospace.org.

[6] Available from American Society for Nondestructive Testing (ASNT), P.O. Box 28518, 1711 Arlingate Ln., Columbus, OH 43228-0518, http://www.asnt.org.

[7] Available from CEN-European Committee for Standardization, Rue De Stassart 36, Bruxelles, Belgium B-1050, http://www.cen.eu

2.7 *ISO Documents:*[8]

ISO 9712 Non-destructive Testing—Qualification and Certification of NDT Personnel

3. Summary of Guide

3.1 This guide outlines the practices for the use of radioscopic methods and techniques for materials examinations. It is intended to provide a basic understanding of the method and the techniques involved. The selection of an imaging device, radiation source, and radiological and optical techniques to achieve a specified quality in radioscopic images is described.

4. Significance and Use

4.1 Radioscopy is a versatile nondestructive means for examining an object. It provides immediate information regarding the nature, size, location, and distribution of imperfections, both internal and external. It also provides a rapid check of the dimensions, mechanical configuration, and the presence and positioning of components in a mechanism. It indicates in real-time the presence of structural or component imperfections anywhere in a mechanism or an assembly. Through manipulation, it may provide three-dimensional information regarding the nature, sizes, and relative positioning of items of interest within an object, and can be further employed to check the functioning of internal mechanisms. Radioscopy permits timely assessments of product integrity, and allows prompt disposition of the product based on acceptance standards. Although closely related to the radiographic method, it has much lower operating costs in terms of time, manpower, and material.

4.2 Long-term records of the radioscopic image may be obtained through motion-picture recording (cinefluorography), video recording, or "still" photographs using conventional cameras, or direct digital streaming and storage of image stacks to internal or external hard drives, or directly to RAM locations, if sufficient RAM is present in the computer. The radioscopic image may be electronically enhanced, digitized, or otherwise processed for improved visual image analysis or automatic, computer-aided analysis, or both.

4.3 Computer systems enable image or frame averaging for noise reduction. For some applications image integration or averaging is required to get the required image quality. As an add-on, an automatic defect recognition system (ADR) may be used with the radioscopic image.

4.4 *Personnel Qualification*—Personnel performing examinations to this standard shall be qualified in accordance with a nationally or internationally recognized NDT personnel qualification practice or standard such as ANSI/ASNT CP-189, SNT-TC-1A, NAS 410, ISO 9712, EN 4179 or similar document and certified by the employer or certifying agency, as applicable. The practice or standard used and its applicable revision shall be identified in the contractual agreement between the using parties.

5. Background

5.1 Fluorescence was the means by which X-rays were discovered, but industrial fluoroscopy began some years later with the development of more powerful radiation sources and improved Fluoroscopic screens. Fluoroscopic screens typically consist of phosphors that are deposited on a substrate. They emit light in proportion to incident radiation intensity, and as a function of the composition, thickness, and grain size of the phosphor coating. Screen brightness is also a function of the wavelength of the impinging radiation. Screens with coarse-grained or thick coatings of phosphor, or both, are usually brighter but have lower spatial resolution than those with fine grains or thin coatings, or both. In the past, conventional fluorescent screens limited the industrial applications of fluoroscopy. The light output of suitable screens was quite low and required about 30 min for an examiner to adapt his eyes to the dim image. To protect the examiner from radiation, the fluoroscopic image had to be viewed through leaded glass or indirectly using mirror optics. Such systems were used primarily for the examination of light-alloy castings, the detection of foreign material in foodstuffs, cotton and wool, package inspection, and checking weldments in thin or low-density metal sections. The choice of fluoroscopy over radiography was generally justified where time and cost factors were important and other nondestructive methods were not feasible.

5.2 It was not until the early 1950s that technological advances set the stage for widespread uses of industrial fluoroscopy. The development of the X-ray image intensifier provided the greatest impetus. It had sufficient brightness gain to bring fluoroscopic images to levels where examination could be performed in rooms with somewhat subdued lighting, and without the need for dark adaption. These intensifiers contained an input phosphor to convert the X-rays to light, a photocathode (in intimate contact with the input phosphor) to convert the light image into an electronic image, electron accelerating and focusing electrodes, and a small output phosphor. Intensifier brightness gain results from both the ratio of input to output phosphor areas and the energy imparted to the electrons. Early units had brightness gains of around 1200 to 1500 and resolutions somewhat less than high-resolution conventional screens. Modern units utilizing improved phosphors and electronics have brightness gains in excess of 10 000× and improved resolution. For example, welds in steel thicknesses up to 28.6 mm (1.125 in.) can be examined at 2 % plaque penetrameter sensitivity using a 160 constant potential X-ray generator (kVcp) source. Concurrent with image-intensifier developments, direct X-ray to television-camera tubes capable of high sensitivity and resolution on low-density materials were marketed. Because they require a comparatively high X-ray flux input for proper operation, however, their use has been limited to examination of low-density electronic components, circuit boards, and similar applications. The development of low-light level television (LLLTV) camera tubes, such as the isocon, intensifier orthicon, and secondary electron conduction (SEC) vidicon, and the advent of advanced, low-noise video circuitry have made it possible to use television cameras to scan conventional, high-resolution,

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[8] Available from International Organization for Standardization (ISO), ISO Central Secretariat, BIBC II, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, http://www.iso.org.

low-light-output fluorescent screens directly. The results are comparable to those obtained with the image intensifier.

5.3 In the 1980s new digital radiology techniques were developed. These methods produce directly digitized representations of the X-ray field transmitted by an examination article. Direct digitization enhances the signal-to-noise ratio of the data and presents the information in a form directly suitable for electronic image processing and enhancement, and storage. Digital radioscopic systems use scintillator-photodetector and phosphor-photodetector sensors in flying spot (pencil beam), fan beam-detector, or cone beam array arrangements.

5.4 All of these techniques employ live monitor display presentation and can utilize various electronic techniques for image enhancement, image storage, and video or data recording. These imaging devices, along with video and data stream processing and analysis techniques, have greatly expanded the versatility of radioscopic imaging. Industrial applications have become wide-spread: production examination of the longitudinal fusion welds in line pipe, welds in rocket-motor housings, castings, transistors, microcircuits, circuit-boards rocket propellant uniformity, solenoid valves, fuses, relays, tires and reinforced plastics are typical examples. Additionally the use of full automatic defect recognition systems for automotive casting inspection using integrated or averaged images and an appropriately powered computer leads to a large cost reduction.

5.5 *Limitations*—Despite the numerous advances in radioscopic imaging technology, the sensitivity and resolution of real-time systems usually are not as good as can be obtained with longer exposures obtained with film. In radiography the time exposures and close contact between the film and the subject, the control of scatter, and the use of metallic screens make it relatively simple to obtain better than 2 % penetrameter sensitivity in most cases. Inherently, because of statistical limitations dynamic scenes require a higher X-ray flux level to develop a suitable image than static scenes. In addition, the product-handling considerations in a dynamic imaging system mandate that the image plane be separated from the surface of the product resulting in perceptible image unsharpness. Geometric unsharpness can be minimized by employing small focal spot (fractions of a millimetre) X-ray sources, but this requirement is contrary to the need for the high X-ray flux density cited previously. An alternative may be a micro-focus source and image integration with a computer system; the limitation in spatial resolution will be the size of the focal spot, and in contrast-to-noise ratio, the available integration time for one resulting image. Furthermore, limitations imposed by the dynamic system make control of scatter and geometry more difficult than in conventional radiographic systems. Finally, dynamic radioscopic systems require careful alignment of the source, subject, and detector and often expensive product-handling mechanisms. These, along with the radiation safety requirements peculiar to dynamic systems usually result in capital equipment costs considerably in excess of that for conventional film radiography. The costs of expendables, manpower, product-handling and time, however, are usually significantly lower for radioscopic systems.

6. Safety Precautions

6.1 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.

7. Interpretation and Reference Standards

7.1 Reference radiographs produced by ASTM and acceptance standards written by other organizations may be employed for radioscopic examination as well as for radiography, provided appropriate adjustments are made to accommodate for the differences in the fluoroscopic images.

8. Radioscopic Devices, Classification

8.1 The most commonly used electromagnetic radiation in radioscopy is produced by X-ray sources. X-rays are affected in various modes and degrees by passage through matter. This provides very useful information about the matter that has been traversed. The detection of these X-ray photons in such a way that the information they carry can be used immediately is the prime requisite of radioscopy. Since there are many ways of detecting the presence of X-rays, their energy and flux density, there are a number of possible systems. Of these, only a few deserve more than the attention caused by scientific curiosity. For our purposes here, only these few are classified and described.

8.2 *Basic Classification of Radioscopic Systems*—All commonly used systems depend on two basic processes for detecting X-ray photons: X-ray to light conversion and X-ray to electron conversion.

8.3 *X-ray to Light Conversion–Radioscopic Systems*—In these systems X-ray photons are converted into visible light photons, which are then used in various ways to produce images. The processes are fluorescence and scintillation. Certain materials have the property of emitting visible light when excited by X-ray photons. Those used most commonly are as follows (see section 10.6.3.1 for additional discussion on image intensifiers):

8.3.1 *Phosphors*—These include the commonly used fluorescent screens, composed of relatively thin, uniform layers of phosphor crystals spread upon a suitable support. Zinc cadmium sulfide, gadolinium oxysulfide, lanthanum oxybromide, and calcium tungstate are in common use. Coating weights vary from approximately 50 mg/cm^2 to 200 mg/cm.^{2}

8.3.2 *Scintillators*—These are materials which are transparent and emit visible light when excited by X-rays. The emission occurs very rapidly for each photon capture event, and consists of a pulse of light whose brightness is proportional to the energy of the photon. Since the materials are transparent, they lend themselves to optical configurations not possible with the phosphors used in ordinary fluorescent screens. Typical materials used are sodium iodide (thallium-activated), cesium

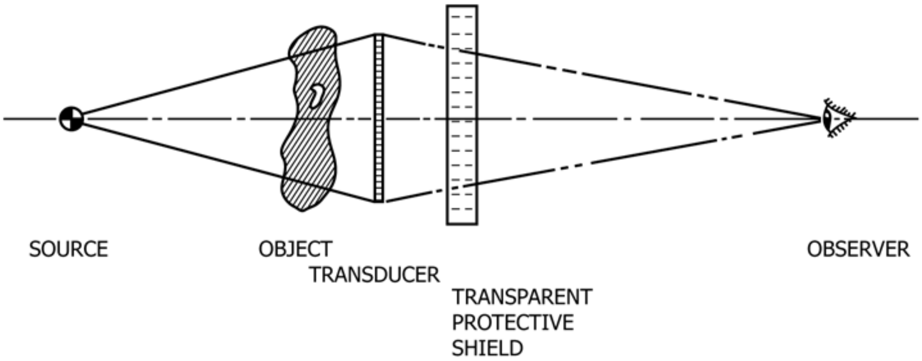

FIG. 1 Basic Fluoroscope

iodide (thallium-activated) and sodium iodide (cesium-activated). These single crystal, transparent or translucent ceramic materials can be obtained in very large sizes (up to 45-cm or 17-in. diameter is now possible) and can be machined into various sizes and shapes as required. Thicknesses of 0.1 to 100 mm (0.08 to 4 in.) are customary.

8.4 *X-ray to Electron Conversion—Radioscopic Systems*—X-ray photons of sufficient energy have the ability to release loosely bound electrons from the inner shells of atoms with which they collide. These photoelectrons have energies proportional to the original X-ray photon and can be utilized in a variety of ways to produce images, including the following useful processes.

8.4.1 *Energizing of Semiconductor Junctions*—The resistance of a semiconductor, or of a semiconductor junction in a device such as a diode or transistor, can be altered by adding free electrons. The energy of an X-ray photon is capable of freeing electrons in such materials and can profoundly affect the operation of the device. For example, a simple silicon "solar cell" connected to a microammeter will produce a substantial current when exposed to an X-ray source.

8.4.1.1 If an array of small semiconductor devices is exposed to an X-ray beam, and the performance of each device is sampled, then an image can be produced by a suitable display of the data. Such arrays can be linear or two-dimensional. Linear arrays normally require relative motion between the object and the array to produce a useful real-time image. The choice depends upon the application.

8.4.2 *Affecting Resistance of Semiconductors*—One technology used for direct X-ray-to-electron device is the X-ray sensitive vidicon camera tube. Here the target layer of the vidicon tube, and its support, are modified to have an improved sensitivity to X-ray photons. The result is a change in conductivity of the target layer corresponding to the pattern of X-ray flux falling upon the tube, and this is directly transformed by the scanning beam into a video signal which can be used in a variety of ways.

8.4.2.1 Photoconductive materials that exhibit X-ray sensitivity include cadmium telluride (CdTe), zinc cadmium telluride (CdZnTe), cadmium selenide, lead oxide, selenium, gallium arsenide, and silicon. Some of these have been used in X-ray sensitive TV camera tubes. Cadmium sulfide is commonly used as an X-ray detector, but not usually for image formation. Selenium, CdTe, and CdZnTe (CZT) have been formed over thin film transistor (TFT) arrays, and are read-out directly in solid state imaging devices. These later devices with solid state read-out circuitry are more appropriately defined as Digital Detector Arrays (DDAs), see E2736. Whereas the former devices where the direct converter is coupled with camera tube technology are treated as radioscopic devices.

8.4.3 *Microchannel Plates*—These consist of an array or bundle of very tiny, short tubes, each of which, under proper conditions, can emit a large number of electrons from one end when an X-ray photon strikes the other end. The number of electrons emitted depends upon the X-ray flux per unit area, and thus an electron image can be produced. These devices must operate in a vacuum, so that a practical imaging device is possible only with careful packaging. Usually, this will mean that a combination of processes is required, as described more completely in 8.5.

8.5 *Combinations of Detecting Processes—Radioscopic Systems*—A variety of practical systems can be produced by various combinations of the basic mechanisms described, together with other devices for transforming patterns of light, electrons, or resistance changes into an image visible to the human eye, or which can be analyzed for action decision in a completely automated system. Since the amount of light or electrical energy produced by the detecting mechanism is normally orders of magnitude below the range of human senses, some form of amplification or intensification is common. Figs. 1-11 illustrate the basic configuration of practical systems in use. For details of their performance and application see Section 10. Table 1 compares several common imaging systems in terms of general performance, complexity, and relative costs.

9. Radiation Sources

9.1 *General:*

9.1.1 The sources of radiation for radioscopic imaging systems described in this guide are X-ray machines and radioactive isotopes. The energy range available extends from a few keV 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 750 keV. Energy sources from 1 MeV and above may be the Van de Graaff generator, linear accelerator, or the betatron. High

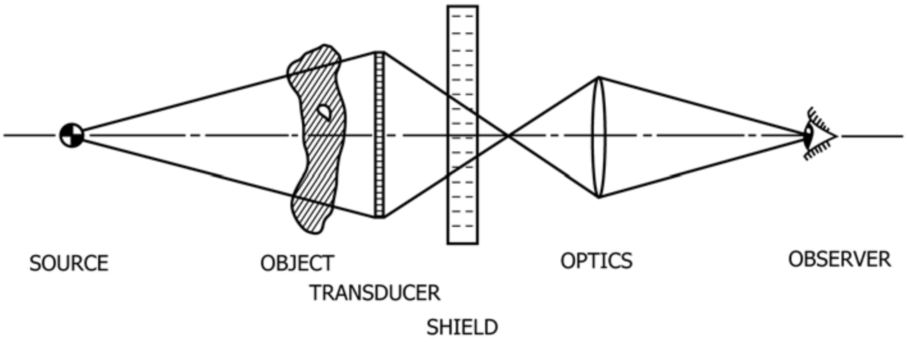

FIG. 2 Fluoroscope with Optics

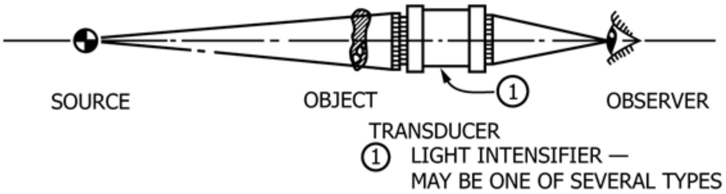

FIG. 3 Light-Intensified Fluoroscope

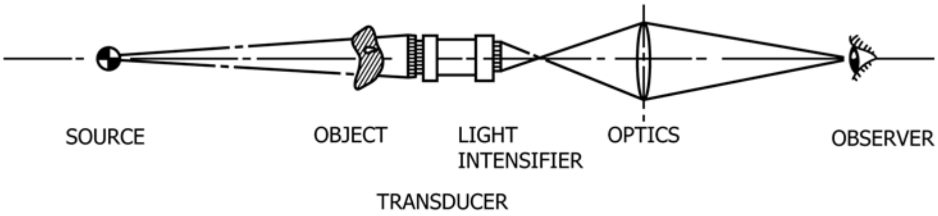

FIG. 4 Light-Intensified Fluoroscope with Optics

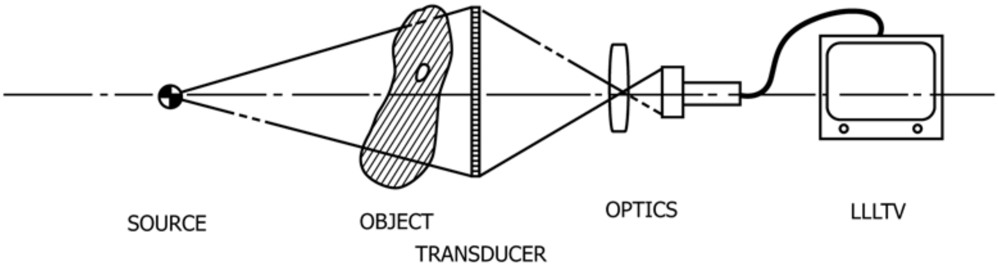

FIG. 5 LLLTV Fluoroscope

energy sources with large flux outputs make possible the real-time examination of greater thicknesses of material.

9.1.2 Usable 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.

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

9.2 *Selection of Sources:*

9.2.1 *Low Energy*—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 750 keV, the X-ray units have an adjustable energy range so that they are applicable to a wide range of materials. Specifically, 50-keV units operate down to a few keV, 160-keV equipment operates down to 20 keV, and 450-keV equipment operates down to about 25 keV. A guide to the use of radiation sources for some materials is given in Table 2.

9.2.2 *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 three-half value layers of material. The maximum thickness of material can extend up to ten-half value layers. Table 3 is a guide to the selection of high-energy sources.

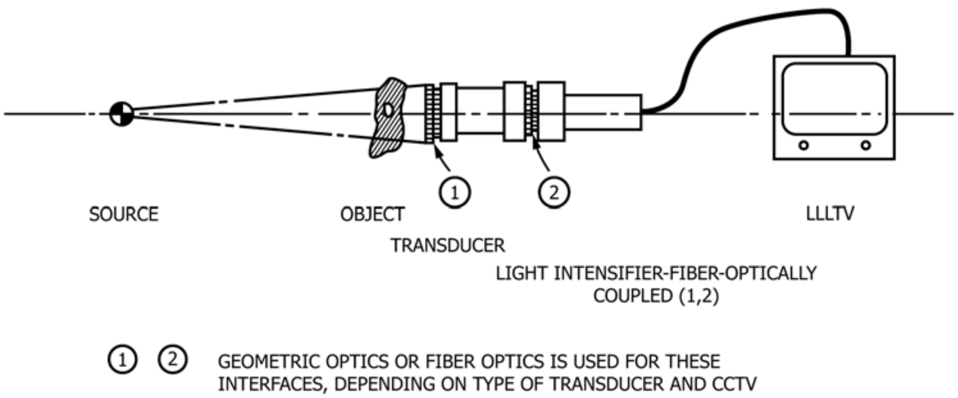

FIG. 6 Light-Intensified LLLTV Fluoroscope

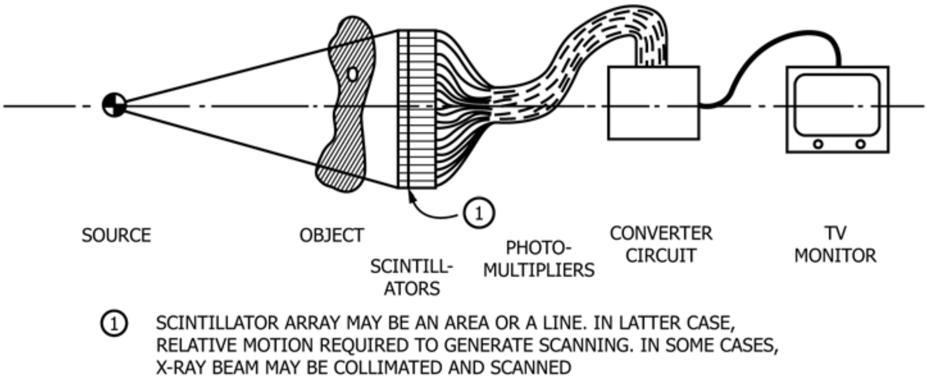

FIG. 7 Scintillator Arrays, TV Readout

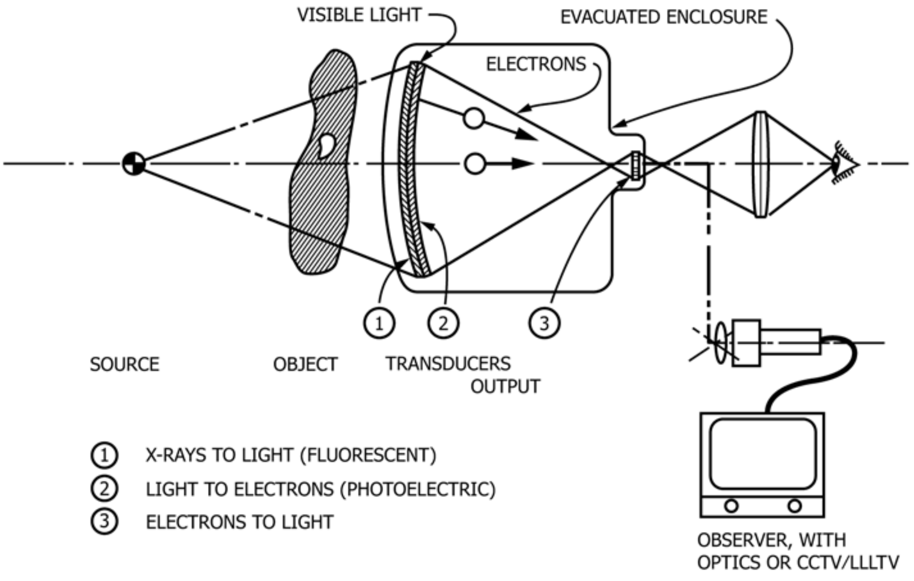

FIG. 8 X-ray Image Intensifier

9.3 *Source Geometry:*

9.3.1 While an X-ray tube with a focal spot of 3 mm (0.12 in.) operating at a target to detector distance of 380 mm (15 in.) and penetrating a 25-mm (1-in.) thick material would contribute an unsharpness of 0.2 mm (0.008 in.), a detector unsharpness of 0.5 to 0.75 mm would still be the principal source of unsharpness.

9.3.2 The small source geometry of microfocus X-ray tubes permits small target-to-detector spacings and object projection magnification for the detection of small anomalies. The selection of detectors with low unsharpness is of particular advantage in these cases to the reduce the focal spot-detector distance (FDD). With high magnification, the focal spot size would be the principal source of unsharpness.

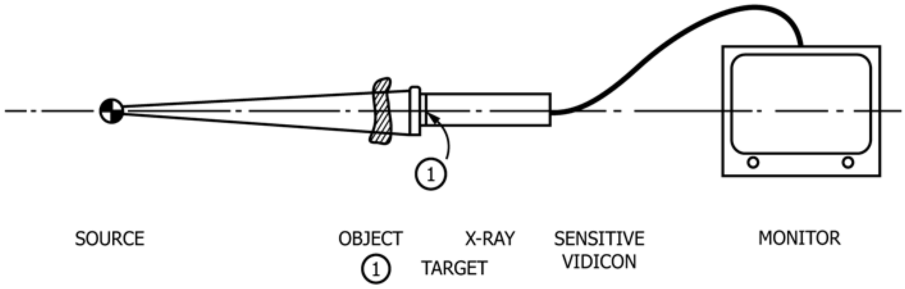

FIG. 9 X-ray Sensitive Vidicon

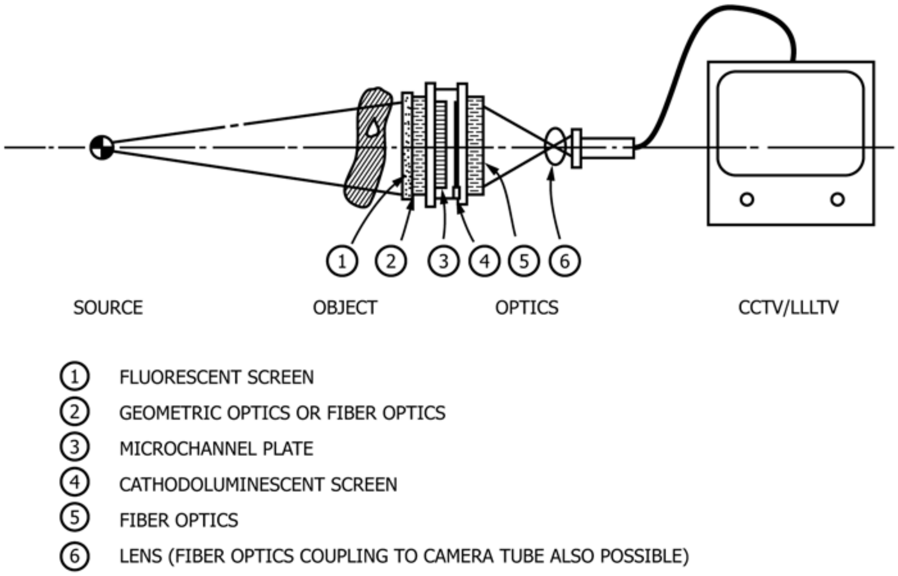

FIG. 10 Microchannel Plates

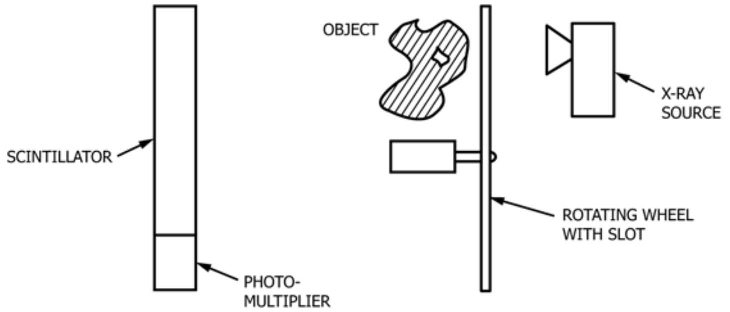

FIG. 11 Flying Spot Scanner

9.3.3 Where isotopes are to be evaluated for radioscopic systems, the highest specific activities that are economically practical should be available so that source size is minimized.

9.4 *Radiation Source Rating Requirements:*

9.4.1 The X-ray equipment selected for examination should be evaluated at its continuous duty ratings, because the economy of radioscopic examination is realized in continuous production examination. X-ray units with target cooling by fluids are usually required.

9.4.2 High-energy sources, for example linear accelerators, which can operate at pulse rates up to 400 pulses per second, may produce interference lines. These lines can be minimized by the design of the real-time systems. Other lower energy X-ray generators operate with pulse rates of more than 10,000 pulses/sec, thus the influence on real-time imaging is negligible.

9.4.3 The radiation flux is a major consideration in the selection of the radiation source. For stationary or slow-moving objects, radiation sources with high outputs at a continuous duty cycle are desired. X-ray equipment at the same nominal kilovolt and milliampere ratings may have widely different radiation outputs. Therefore in a specific examination requirement of radiation output through the material thickness being examined should be measured.

TABLE 1 Comparison of Several Imaging Devices
(new instrumentation and configurations to meet a similar need are continually being invented and commercialized)

NOTE 1—The data presented are for general guidance only, and must be used circumspectly. There are many variables inherent in combining such devices that can affect results significantly, and that cannot be covered adequately in such a simple presentation. These data are based upon the personal experiences of the authors and may not reflect the experiences of others.

	Fluorescent Phosphors	X-ray Scintillating Crystals	X-ray Image Intensifier	X-ray Vidicon	Microchannel Plates	Flying Spot/Line Scanners
Availability	excellent	excellent	excellent	good	fair	fair
Auxiliary equipment needed	shielding glass, optics	shielding glass, optics LLLTV^A	CCTV, optics^A	CCTV^A	fluorescent screen, special packaging, CCTV, output phosphor	fluorescent phosphor or scintillating crystals, special electronics, digitizers
Usual readout methods	Visual	computer monitor(s)	computer monitor(s)	computer monitor(s)	computer monitor(s)	electronic/visual
Other readout methods	none	none	direct	none	none	none
Practical resolution, usual readout, lp/mm	up to 4.5	10	4	20	20	10
Minimum large-area contrast sensitivity, %	2	1	2	5	5	1
Useful keVcp						
range, min	25	25	5	20	15	25
range, max	300	10 MeV	10 MeV	250	2 MeV	15 MeV
Optimum keVcp	120	200	100	75	100	NA
Field of view, maximum	no practical limit	229-mm (9-in.) dia	305-mm (12-in.) dia	9.53 × 12.7 mm (⅜ × ½ in.)	76-mm (3-in.) dia	no limit
Relative sensitivity to X-rays	low	medium	high	low	medium	high
Relative cost	low	high	medium	low	high	high
Approximate useful life	10 years	indefinite	3 years	5 years	5 years	5 years
Special remarks	very simple	high quality image	very practical	limited to small thin, objects	Rarely used	No longer used

^{A} Low-light level television (LLLTV) is a sensitive form of closed circuit television (CCTV) designed to produce usable images at illumination levels equivalent to starlight (10^{-1} to 10^{-4} lm/m^2 or 0.343 × 10^{-4} to 0.343 × 10^{-7} cd/m^2).

TABLE 2 Radiation Sources for Aluminum and Steel^A

kV or Isotope	Aluminum, mm (in.)	Steel, mm (in.)
40	5.1–12.8 (0.2–0.5)	...
70	12–30 (0.5–1.2)	3–7.5 (0.12–0.3)
100	20–50 (0.8–2)	6.25–15.6 (0.25–0.62)
200	33.5–83.8 (1.3–3.3)	8–20 (0.32–0.8)
300	...	15–45 (0.6–1.8)
420	...	18–45 (0.71–1.8)
Thulium 170	...	3 (0.12)
Ytterbium 169	...	4 -15 (0.15 – 0.59)
Selenium 75	...	8 - 20 (0.31 – 0.78)
Iridium 192	...	26 (1.02)

^{A} The minimum thickness of material at a given energy represents two-half value layers of material while the maximum thickness represents five-half value layers. The use of a selected energy at other material thicknesses depends upon the specific radiation flux and possible image processing in the radioscope system.

TABLE 3 High-Energy Radiation Sources for Solid Propellant and Steel

MeV	Steel, mm (in.)	Solid Propellant, mm (in.)
1.0	46.0–107.0 (1.8–4.2)	198.0–462.0 (7.8–18.2)
2.0	57.0–133.0 (2.24–5.24)	267.0–620.0 (10.5–24.4)
4.0	76.0–178.0 (3–7)	358.0–836.0 (14.1–32.9)
10.0	99.0–231.0^A (3.9–9.1)	495.0–1156.0 (19.7–45.5)
15.0	99.0–231.0 (3.9–9.1)	553.0–1290.0 (21.8–50.8)
Cobalt-60	57.0 (2.24)–180 (7.08)	267.0–620.0 (10.5-24.4)

^{A} There is no significant difference in the half-value layers for steel from 10 to 15 MeV.

10. Imaging Devices

10.1 An imaging device can be described as a component or sub-system that transforms an X-ray flux field into a prompt response optical or electronic signal.

10.2 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 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 scatterings.

10.3 By analyzing this flux field, deductions can be made 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.

10.4 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 composed of atoms of many different kinds. Exact prediction of the flux field falling upon the imaging device 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, many successful imaging devices 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 devices.

10.4.1 *Field of View of Imaging Device*—The field of view of the imaging device, its resolution, and the dynamic inspection speed are interrelated. The resolution of the detector 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 detector. When detector resolution becomes the limiting factor, the object may be moved away from the detector, and towards the source to enlarge the projected image and thus allow smaller details to be resolved by the same detector. As the image is magnified, however, the detail contrast is reduced and its outlines are less distinct. (See 11.3.) It is apparent, also, that when geometric magnification is used, the area of the object that is imaged on the detector is proportionally reduced. Consequently the area that can be examined per unit time will be reduced. As a general rule, X-ray magnifications should not exceed 5× except when using X-ray sources with very small (microfocus) anodes. In such cases, magnifications in the order of 10 to 20× 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.

10.4.2 *Inherent Sensitivity of Imaging Device*—The basic sensitivity of the detector may be defined as its ability to respond to small, local variations in radiant flux to display the features of interest in the object being examined. It would seem that a detector that can display density changes on the order of 1 to 2% at resolutions approaching that of radiography would satisfy all of the requirements for successful radioscopic 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 and scattered light in the optical 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, control of backscatter, and appropriate use of light absorbing materials in the optical system are vital to good radioscopy. The low-resolution, low-contrast visible light images produced by the detector may pose special problems in the choice of optical components. For example, a lens that would be an excellent choice for photography may be a poor choice to couple a low-light-level imaging camera to a fluorescent screen.

10.4.2.1 This brief treatment just touches on a complex subject. When designing an imaging system, the reader should consult other references.

10.5 *Physical Factors*—The selection of a radioscopic 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 strong magnetic fields in the proximity of image intensifiers and cameras, 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. Furthermore, the size and weight of imaging system components as well as positioning and handling mechanism requirements must be considered in system design, and interact with cost factors in selection of a system.

10.6 *X-ray to Light Conversion—Radioscopic Systems*—For the purpose of radioscopy, a fluorescent screen can be described as a sheet of material that converts X-ray photons into visible light through energy transitions in the material as the X-ray energy is absorbed and cascades to lower energy radiation. At these lower discrete energies in the screen, the material goes into an excited state, that upon relaxation emits some of that energy as light. Screen materials were known even before the discovery of X-rays or radioactive materials, since substances which "glow in the dark" have been known for centuries. In fact, it was a fluorescent screen that was the key to the discovery of X-rays. However, enormous improvements have been made in understanding, manufacturing, and applying screens. Although the basic physical phenomena involved are similar, it is convenient for our purposes to divide screens into two groups, fluorescent phosphors and scintillating crystals.

10.6.1 *Fluorescent Phosphors:*

10.6.1.1 A fluorescent screen is a layer of phosphor crystals deposited on a suitable support backing, with a transparent protective coating or cover. The crystals used have the ability to absorb energy from an X-ray photon and re-emit some of that energy in the form of visible light. The amount of light produced for a given X-ray flux input is termed the *brightness* (luminance) of the screen. The number of light photons emitted per unit exposure is the *conversion efficiency*. *Resolution* is the ability to show fine detail (for high contrast objects), and *contrast* is the detectable discernible change in brightness with a specified change in input flux. This is often specified as the minimum percentage thickness change in the object which can be detected. Image quality indicators (IQI) are commonly used to make these tests. Most phosphors used in screens have limited ability to transmit the light they produce without scattering or refraction due to their size, shape, coatings, and

TABLE 4 Properties of Some Common Fluorescent Screens[A]

No.	Formula	Name	Relative Brightness With Attenuation[B]								Resolution[C]	Color
			Soft Spectrum			Medium Hard Spectrum		Harder Spectrum		Hardest Spectrum		
			50 keVp	100 keVp	150 keVp	100 keVp	150 keVp	100 keVp	150 keVp	150 keVp	lp/mm (in.)	nm
1	$CaWO_4$	calcium tungstate		6	13	2	8	1	2	0.5	1.2 (30)	violet ~420
2	ZnCdS	zinc cadmium sulfide	3.5	46	120	22	65	7	25	3	2.0 (50)	green ~540
3	ZnCdS	zinc cadmium sulfide	8	122	320	50	160	16	60	5	0.8 (20)	green ~540
4	$Gd_2O_2S_j$	gadolinium oxysulfide	5	89	250	43	150	16	65	12	1.6 (40)	yellow-green ~550
5	LaOBr	lanthanum oxybromide	1	19	50	8	29	3.5	13	2	1.2 (30)	blue ~460

[A] These are for illustrative purposes only. The X-ray tube used had beryllium window and fractional focal spot.

[B] All these measurements were made under identical conditions.

[C] The higher numbers indicate better resolution. These are approximately lp/mm (lp/in.).

other factors, and are not truly transparent. Thus the light that is produced by the lowermost layers is somewhat distorted by passage through the layers above. Consequently thicker phosphors that have, in general, increased ability to absorb X-rays, and thus produce more light, usually produce brighter images with lower resolution, as compared to thin screens of the same material.

10.6.1.2 The contrast of a fluorescent screen is influenced by the scattering of light and X-rays within the structure of the screen itself, and to a larger extent by the relative response of the screen to direct and scattered X-rays. The scattered X-rays, particularly those scattered at large angles, consist of lower energy photons, to which the screen is more sensitive. This has the effect of reducing the contrast.

10.6.1.3 In usual applications, the contrast of the fluorescent image for large areas (such as the outline of an IQI) is limited by the contrast capability of the eye. Practical experience is that the lower observable limit is that change in brightness caused by a 1 % change in thickness of the object. Smaller differences may be possible with digitization and image processing techniques.

10.6.1.4 All fluorescent screens exhibit some persistence or afterglow. This is a function of the phosphor and activator used and to this extent may be somewhat controlled by the manufacturer. It is usually of the order of 10^{-5} s for calcium tungstate ($CaWO_4$) screens and 10^{-2} for zinc sulfide (ZnS). Rare earth screens with terbium^{3} (Tb^{3}) and europium^{3+} (Eu^{3+}) activators have about the same persistence (10^{-2} s), but other activators such as Ce^{3+} can produce characteristic decay times as short as 10^{-6} to 10^{-9} s. The relationship between brightness and resolution is clearly shown in Table 4.

10.6.1.5 These screens are commercially available and the choice of screen will be governed by the requirements of the user, who must make a compromise choice between brightness, resolution, keV range, and apparent *color* of the image. The apparent color of the fluorescent image is important both in the directly viewed and electronically scanned systems. Matching of spectral content to the response of the human eye or that of a detector such as a camera is significant in low-light-level systems, and can affect both sensitivity and "noise" figures. Those most commonly used are phosphors numbered 2, 3, 4, and 5 in Table 4. Two thicknesses of the ZnCdS and Gd_2O_2S screens are shown to illustrate the range of sensitivity (brightness) and resolution available. As would be expected, the brightest screen, No. 3, has the lowest resolution except when the X-ray beam is strongly attenuated (see data for ¼-in. (6.2-mm) steel, for example). Then, screens 4 and 5 are preferable. As these few examples show, the choice of screen for a particular application is not simple, and the best available data from various suppliers should be studied before making a choice.

10.6.1.6 In using fluorescent screens, historically there have been two options for viewing the image. Direct optical viewing can be as simple as covering the screen with a sheet of leaded glass of the required thickness and looking directly at the image. (See Fig. 1.) This option has since given way to fully electronic viewing. This older methodology employed optical viewing systems with the use of mirrors or lenses, or both, to position the operator out of the direct path of the X-ray beam or even at some distance. (See Fig. 2.) The quality of the image in direct viewing is not degraded if reasonable care is taken in the choice of the optical components used, but the light level must be high and this may be difficult to achieve, unless some form of light intensification is used (see Fig. 3 and Fig. 4).

10.6.1.7 Most modern systems employ electronic readout, with a camera and lens taking the place of the human eye (see Fig. 5). These are very flexible and convenient systems. Some loss of original signal quality inevitably occurs, but the convenience, the possibility of increased brightness and the possibility of manipulation of the electronic image usually more than compensate for this loss. Various types of CCTV and LLLTV systems are used, including those with light intensification added (see Fig. 6). Fluorescent screens are rugged and durable and have useful lives of several years with reasonable care. They should not be exposed to mechanical abrasion, or high temperatures. Their conversion efficiency increases markedly as the temperature is reduced. These factors should be considered for the specified operating environment.

10.6.2 *Scintillation Crystals:*

10.6.2.1 Scintillators are generally understood to be optically clear crystals, transparent or translucent ceramics of a material which fluoresces when irradiated by X-rays, with

TABLE 5 Properties of Single Crystal Fluorescent Screens

Material	Thickness, mm (in.)	Diameter, mm (in.)	Resolution	Brightness[A]			
				Contrast	100 keV	120 keV	140 keV
Cesium Iodide (Thallium), CsI (Tl)	0.5–6.5 (0.020–0.250)	25–230 (1–9)	10 lp/mm	1 %	1.6	1.9	2.1

[A] Factors relative to gadolinium oxysulfide ($Gd_2O_2S_j$) with 13 mm (½ in.) aluminum absorber.

short pulses of light being emitted for each photon absorbed. The practical difference between fluorescent screens and scintillation screens is that the latter are bulk solids and are normally much thicker than phosphors.

10.6.2.2 Since we have noted that larger or thicker crystals or ceramics in a screen more readily absorb X-ray photons, and that the thickness of such screens must be limited by practical considerations of particle size and thus resolution, the advantage of a thicker screen that is still capable of good resolution and contrast is evident. They have high efficiencies, particularly at higher kilovoltages, compared to phosphor screens, excellent resolution, and very good contrast. Special precautions in preparation and packaging are required to control internally scattered light and to protect them from chemical or mechanical damage. Typical specifications are shown in Table 5.

10.6.2.3 The light produced has a spectral response in the visible region similar to the human eye. Such screens have been used with good efficiency at X-ray energies up to several million electronvolts. At approximately 160 keV, the X-ray attenuation of the Cesium Iodide (Thulium), CsI(T1) crystal 0.250-in. thick is approximately 85 % and approximately 65 % at 320 keV. They are thus very efficient at converting X-rays into light and are normally lens coupled to a light intensifier or a camera. Due to the thickness of the crystals in the region in which the light is produced, special precautions are required in designing the optics. It is clear that a lens with a good depth of focus is necessary to avoid blurring of the image at the edges relative to the center of the screen. Further, screens show better edge resolution if the angle subtended by the lens is small. This becomes more of a problem with large-diameter, thick screens. The choice of lens, for these reasons, becomes critical. The general arrangements used are shown in Fig. 5 and Fig. 6.

10.6.2.4 The resolution (lp/mm) is the true resolution of the screen, but this is rarely realized using camera readout, since the camera resolution will normally be the limiting factor. With a high resolution camera or multi camera systems the screen resolution can be realized. When using light intensifiers, a further loss in resolution and contrast will result. With high-quality light intensifiers this loss will be small, but noticeable. Large diameter intensifiers will normally yield superior results, all else being equal. The resolution and contrast change using a screen thickness in the ranges shown in Table 5. For low kilovoltage, a thinner screen should be used to optimize contrast and resolution. The spreading of the light from each point where an X-ray photon is absorbed is reduced in thinner screens, which increases the resolution and contrast. This effect will be more noticeable at the edge of a large field and is also affected by the optics used.

10.6.2.5 The commercially available screens are usually packaged in circular metal frames with an X-ray transparent but visible light opaque cover or window on the source side, and an optical grade thick glass window on the viewing side. Overall thickness of the package is approximately 25.4 mm (1 in.).

10.6.2.6 The scintillators must be protected against temperature extremes, thermal shock, and mechanical abuse. Some screens (for example, sodium iodide) are hygroscopic and should be hermetically sealed. The larger sizes are expensive due to the high cost of the raw material.

10.6.2.7 Arrays of smaller scintillating crystals have been used for some applications, particularly where resolution is not critical, but high sensitivity is required. Baggage inspection is a common application (see Fig. 7).

10.6.3 *X-Ray Image Intensifier:*

10.6.3.1 This device is commonly used for radioscopic imaging. (See Table 6 for the properties of an X-ray image intensifier.) The basic conversion process is fluorescence, but the fluorescent screen is contact-coupled to a photocathode inside a vacuum envelope. The photoelectrons thus produced are accelerated and focused onto a much smaller output phosphor where the photoelectrons produce a very bright visible image; typically 10 000 or more times brighter than that formed on the input phosphor (see Fig. 8).

10.6.3.2 Image intensifier tubes consist of a large evacuated glass envelope with the X-ray input end usually 152, 230, or 305 mm (6, 9, or 12 in.) in useful diameter, suitably packaged in a metal housing, including a high-voltage power supply. The output end of the tube is normally designed to be optically coupled to a camera for readout.

10.6.3.3 These tubes normally have specially structured C_sI(T1) input screens about 0.254 mm (0.010 in.) thick coupled optically (usually by evaporation) to a photocathode. The electron pattern formed is accelerated and focussed upon a small (approximately ½-in. (13-mm) diameter) output phosphor screen made of very fine-grained zinc sulfide (ZnS) crystals on the opposite end of the tube. Because the electron image is minified by a factor of almost 18 for a 9-in. tube (input phosphor) there is a geometric intensification of over 320×. In addition, the photoelectrons gain energy through the approximately 30 keV applied to the tube. Each accelerated electron produces about 100 visible photons resulting in a very bright visible light image at the output phosphor, enabling readout with a relatively inexpensive camera. This may be coupled with a relay lens system, or used directly with fiber-optic face plates. Some tubes have been made with the camera and X-ray image intensifier permanently joined together as one piece of glass. This is not prudent because it is inflexible, and the life and replacement cost of the two major components are greatly different.

10.6.3.4 It is not difficult to damage the phosphors with excessive exposure to X-rays, so in many applications good

TABLE 6 Properties of a Typical X-Ray Image Intensifier[A]

Brightness gain	10 000 or more
(Compared to a standard screen exposed to the same X-ray field.)	
Limiting resolution	5 lp/mm
Contrast sensitivity	2 %
Modulation for resolution of 2 lp/mm	50 %
Large area contrast	12:1
(This is the ratio of image brightness without and with a lead mask covering the central 10 % of the input area. "Blooming" of the image can be a problem with these tubes, and this ratio is related to this effect).	
Optimum kVp (there is approximately a 20 % fall-off at 70 kVp and 120 kV)	90 kV
Geometric distortion at edges (compared to center of image)	25 %
Brightness fall-off at edges (compared to center of image)	20 %

[A] X-ray image intensifiers are moderately rugged devices, but since they are glass enclosed, they must not be treated roughly. They are sensitive to magnetic fields, which will distort the internal electron paths and cause defocusing and distortion of the image.

masking of the parts becomes very important. Like most self-contained high-vacuum devices they have a limited useful life (two to five years).

10.7 *X-ray to Electron Conversion*—A number of radioscopic imaging devices depend upon this process, directly or indirectly. In most cases the electron is freed inside a transducer layer, and the result is indirect.

10.7.1 One device of this type with some history of successful application, is the X-ray sensitive vidicon (see Fig. 9, 10.7.2, and 12.3.4).

10.7.2 *Changing Resistance of Semiconductors*—The practical example of this mechanism is the X-ray sensitive vidicon (see Fig. 9).

10.7.2.1 These make use of a lead oxide target layer in a vidicon-type TV camera tube. The tube face-plate needs to be transparent to low-energy X-rays, rather than visible light, as is normally the case. Beryllium face plates are common.

10.7.2.2 The sensitive area of a standard 25.4-mm (1-in.) vidicon is only 9.5 by 13 mm (3⁄8 by 1⁄2 in.) in dimension, so that a very small field of view is obtained. Some tubes have been made with larger areas, but it is difficult to obtain circuitry to use with them, and they have not become popular.

10.7.2.3 Since this area is small and is scanned by a 525-line raster, resolution is theoretically somewhat under 0.025 mm (0.001 in.). In practice, resolutions of 0.025 to 0.05 mm (0.001 to 0.002 in.) are readily obtainable. Resolutions of 0.013 mm (0.0005 in.) are obtainable in high-contrast images.

10.7.2.4 The response of the lead oxide target layer to X-ray photons is low, since it is very thin. Large fluxes are required to produce useable images, and since these must normally be achieved by using kilovoltages higher than one would prefer, the contrast suffers accordingly. Contrast sensitivity of 2 % is difficult to achieve.

10.7.2.5 The obvious application of the device is the imaging of small objects with high contrast (such as the small metal wires used to connect integrated circuit chips to headers in a plastic package). Readout is through a display, and the system is relatively inexpensive.

10.7.3 *Microchannel Plates*—These are readily available.

10.7.3.1 They consist of a thin plate (approximately 3 mm) made of a very large number of very small diameter (approximately 15-µm) glass tubes fused together side by side. Each tube is in effect a miniature electron multiplier. If an electron is introduced at one end, under the axially applied high voltage it is accelerated and ricochets off the walls of the tube, each time producing more than one secondary electron. Each of these in turn generates more electrons as it strikes the wall of the tube. The overall result is that approximately 10 000 electrons come out of the tube for each one which enters the opposite end. More than one plate can be used in a series to produce electron gains that are even greater. The efficiency of detection for X-ray photons is approximately 2 % up to approximately 420 keV. The maximum size of the plates is somewhat limited by the state of technology.

10.7.3.2 The resolution is a function of "pore size" and center-to-center spacing of the tubes. Two-stage plates with spacings of 32 µm (0.0013 in.) and a diameter of 75 mm (3 in.) are available. The resolution claimed for this model is 9 lp/mm. Other models are available with resolutions up to 32 lp/mm.

10.7.3.3 A microchannel plate must be operated in a high vacuum, and thus suitable packaging requires an X-ray transparent entrance window. The electrons produced at the output end must be converted into a useable image, and this is normally done by using a thin ZnS screen, which converts them into visible light. The resultant fluorescent image can then be viewed by usual means.

10.7.3.4 Since the efficiency of these devices for direct X-ray detection is quite low, and the gain is very high, a very "noisy" image is to be expected. By adding another transducer in front of the microchannel plate to convert X-rays into electrons or ultraviolet radiation (to both of which the plate is much more sensitive), an improvement in image quality can be expected.

10.8 *Combinations of Detecting Processes*—As will be noted from the previous descriptions, many combinations of the various detecting processes, read-out devices, and image processing equipment are possible.

10.8.1 Such combinations can range from the very simple case of adding a large magnifying lens in front of a fluorescent screen to very elaborate systems combining the latest state-of-the-art hardware in solid-state electronics optics and nuclear physics.

10.8.2 A sensible "rule of thumb" in using transducers to change an X-ray field into some other useable display or electrical signal is that each such conversion stage somewhat degrades the information. An exception is the electron conversion that takes place between the photocathode and the output screen of an X-ray image intensifier, where many electrons are released by each photon. Therefore, the more complex the system is, the greater the care that must be taken in the design and fabrication of each step in the process, and thus, the greater the cost.

10.8.3 Among the many problems to be solved in complex systems can be listed:

10.8.3.1 Careful suppression of scattered X-rays.

10.8.3.2 Careful choice of the first transducer (fluorescent screen, etc.) to match both the input X-ray energy and the succeeding transducer input.

10.8.3.3 Optics must be very carefully designed to optimize modulation transfer function of the total system and to control scattered light.

10.8.3.4 Electronics must be linear, stable, and as noise free as possible.

10.8.3.5 Each stage in a multistage process must be considerably better than appears necessary, since losses are multiplicative.

10.8.3.6 When using a human observer, the system must be designed to match the physiology of human vision.

10.8.3.7 Nonlinear transducers can sometimes be used to very good advantage to enhance the transfer of information (example: Isocon TV camera tube). This is referred to at times as gamma modification.

10.8.4 Processing of electronic information is difficult without losing some information at the present state-of-the-art. Processing, such as low-pass filtering, can substantially improve the viewing by reducing high frequency noise. Since video pick-up is the first stage of processing it makes manipulation of the X-ray image information possible. Log gain amplifiers, image reversal, black-white compression or expansion all can be used to improve the viewing level for operator perception. Furthermore, the digitized information can be processed and stored and is particularly amenable to computer-controlled reading, display, and analysis.

11. Image Quality Considerations

11.1 Image quality is governed by two factors, image contrast and resolution. These factors are inter-related in a complex manner which will be partially discussed here. Radiographic sensitivity as indicated by the conventional IQI measures contrast and, to a limited degree, 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?

11.2 *Image-Formation Basis:*

11.2.1 Contrast is a direct result of the X-ray attenuation by the object. Fig. 12 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 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.

11.2.2 Unsharpness due to scatter, geometry, and screen (detector) tend to reduce contrast and make it more difficult to define edges. Fig. 12 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. 13), 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 in the image is not resolved.

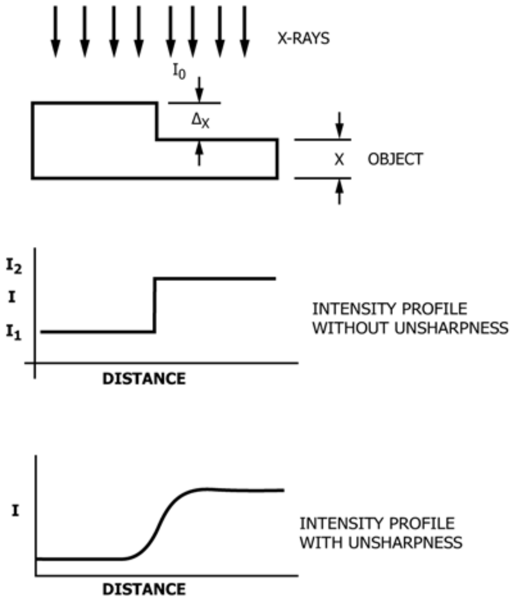

FIG. 12 X-ray Absorption and Unsharpness

11.2.3 Fig. 14 shows Klasen's[9] method for determining unsharpness from a measured curve. This technique has produced good results and is generally accepted. The most difficult part of this method is to obtain the measured curve. This can be done by imaging a "knife" edge on the system and:

(*a*) Photographing the results from the screen, a microdensitometric trace can be made from the film.

(*b*) Photographing the results from the screen with a digital camera; measure the signal with a line profile function.

(*c*) Using a frame grabber and digitizing the camera signal; measure the signal with a line profile function.

(*d*) On the video image, a "line-grabber" oscilloscope can be used.

11.2.4 Unsharpness values due to geometry, screens, etc. can be combined by the following expression:[10]

$$U_T = \sqrt[3]{U_g{}^3 + U_s{}^3 + \ldots} \tag{3}$$

U_T = total unsharpness,

U_g = geometrical unsharpness, and

U_s = screen unsharpness

This expression was developed empirically and yields a good approximation.

11.2.5 *Modulation Transfer Function:*

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[9] Klasens, H. A., "Measurement and Calculation of Unsharpness Combinations in X-ray Photography," *Philips Research Reports*, Vol 1, No. 4, August 1946, pp. 241–249.

[10] Robert F. Wagner et. al.: Toward a unified view of radiological imaging systems; Part I (1974) Medical Physics, vol. 1, issue 1, p. 11 and Part II (1977) Medical Physics, vol. 4, issue 4, p. 279.

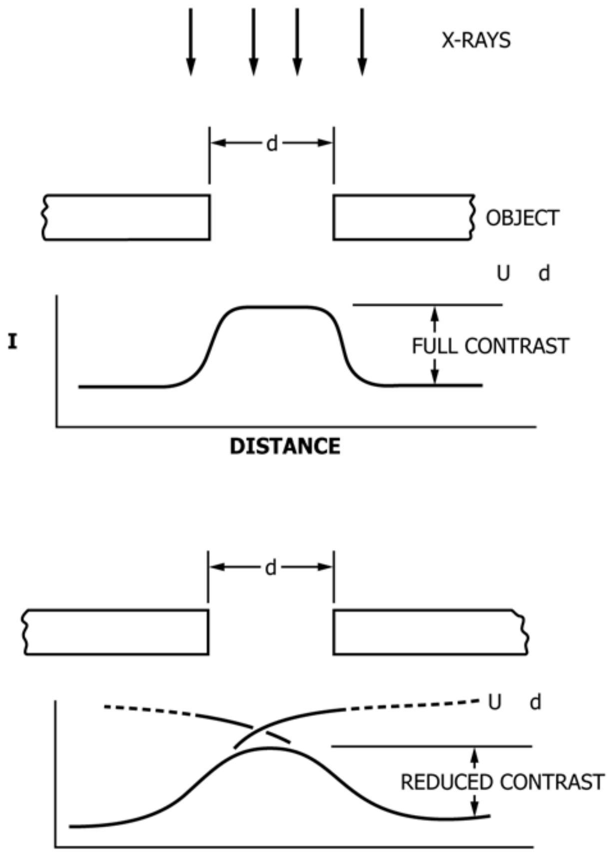


FIG. 13 Effect of Geometric Unsharpness on Image Contrast

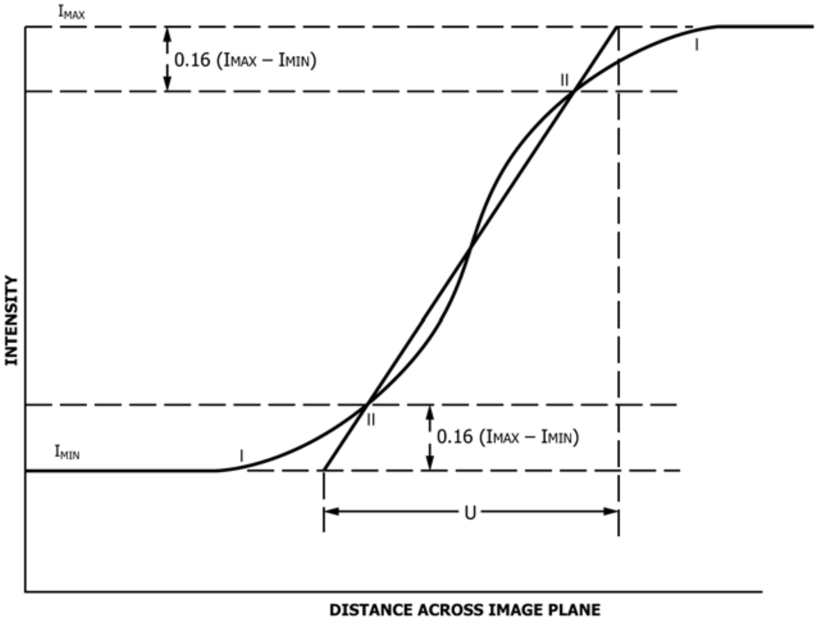


FIG. 14 Klasens' Equivalent Blur

11.2.5.1 One way to evaluate a system is by measuring the modulation transfer function (MTF). This is a measure of spatial frequency as a function of contrast. 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. 15 where at low frequencies the contrast approaches 100 % and falls off as the frequency is increased.

11.2.5.2 There are several techniques for measuring MTF; some use direct measurement with a test object and others use

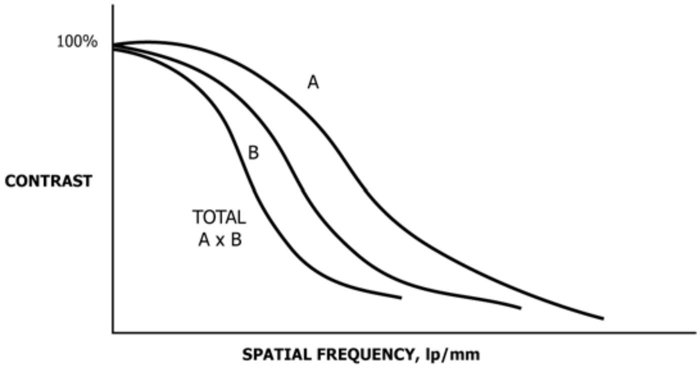


FIG. 15 Modulation Transfer Curve

A—MTF caused by geometric unsharpness
B—MTF caused by detector screen unsharpness
A × B—MTF of the combined source and detector unsharpness

a measure of the point spread function and mathematically convoluting this with a sine function, thereby constructing the MTF curve.

11.3 *Geometrical Considerations:*

11.3.1 An obstacle to the implementation of real-time systems is the large grain size of screens, that is, the problem is inherently one of definition. This difficulty may be minimized by *X-ray projection magnification*. X-ray projection enlargement is shown graphically in Fig. 16(*a*) where the magnification factor v is defined:

$$v = 1+\frac{b}{a} \tag{4}$$

where b is the object-screen distance and a is the focal-object distance.

11.3.2 The penumbral image due to a finite focal spot size (φ) is defined as unsharpness due to geometry, U_g, and is illustrated in Fig. 16(*b*),

$$U_g = \frac{b}{a}\varphi\text{, or} \tag{5}$$

$$U_g = \varphi(v-1) \tag{6}$$

11.3.3 It is generally agreed that penumbral images are not dependable; the limiting case for an umbral image is illustrated in Fig. 16(*c*), which may be written:

$$\frac{d}{\varphi} = \frac{b}{a+b} \tag{7}$$

where d is the discontinuity width assumed equal to the discontinuity depth Δx for an absorber thickness x.

11.3.4 It follows that $v{\cdot}d \geq U_g$ for optimum definition on a perfect screen. In a similar fashion it can be shown that the minimum discontinuity size d multiplied by the magnification factor v must be equal to or larger than the unsharpness due to the fluoroscopic screen:

$$v{\cdot}d > U_f \tag{8}$$

11.3.5 It will be assumed for this derivation that $v{\cdot}d = U_f$ is the limit; actually the limit is somewhat higher. In other words, the size of the minimum discontinuity observable is controlled by both types of unsharpness, $v{\cdot}d > U_T$. The total unsharpness, U_T, is equal to the cube root of the sum of the cubes of the unsharpness due to geometry, U_g, and the unsharpness due to the fluoroscopic screen U_f or,

$$U_T = \sqrt[3]{U_g^{\,3}+U_f^{\,3}} \tag{9}$$

11.3.6 From Eq 9, Eq 5, and Eq 4 the critical size of detail in the general case is,

$$d = \frac{1}{v}\sqrt[3]{\varphi^3(v-1)^3+U_f^{\,3}} \tag{10}$$

Writing this expression in the non-dimensional form,

$$\frac{d}{U_f} = \frac{1}{v}\sqrt[3]{(v-1)^3\frac{(\varphi)^3}{U_f^{\,3}}+1} \tag{11}$$

11.3.7 This relationship is shown graphically in Fig. 17. The ratio d/U_f is plotted as a function of projection magnification v for various values of φ/U_f. The interpretation of Fig. 17 will be simplified by assuming a fluoroscopic unsharpness U_f value of 1.0 mm. Then the minimum observable discontinuity size in millimetres is given as a function of magnification for several values of focal spot size, φ in millimetres. It is seen that for a focal spot width φ of 2 mm there is little practical advantage to be gained from enlargement; the peak improvement of 22 % at an enlargement of 1.4 is lost at enlargements of 1.7 or more.

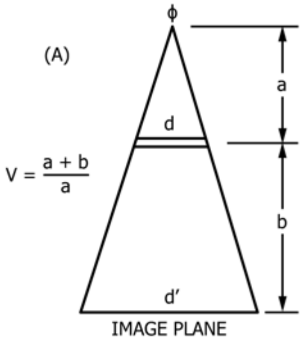
11.3.8 For a focal spot size φ of 1 mm a peak improvement of 59 % occurs at a magnification of 2. Between 1.5 and 3 the improvement is at least 43 %. For a 0.5-mm spot size the peak improvement would be 142 % at a magnification of 3.8; for a magnification of about 2 or more, the improvement would be 100 % or better.

11.3.9 In general, the optimum magnification v_m for any screen unsharpness U_f and focal spot width φ is given by:

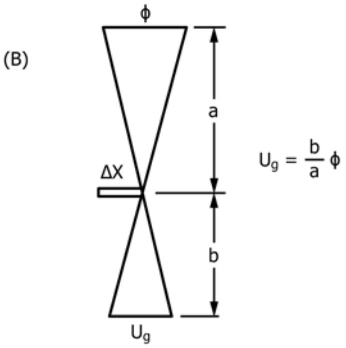
$$v_m = 1+\left(\frac{U_f}{\varphi}\right)^{3/2} \tag{12}$$

The smallest observable discontinuity, d_m, is then given by:

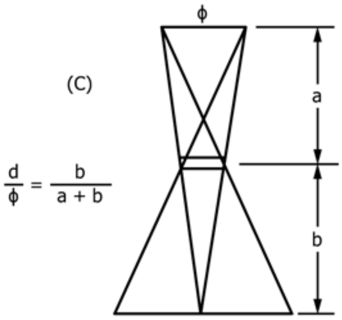
$$d_m = \frac{U_f}{v_m^{\,2/3}} \tag{13}$$



(A) X-RAY PROJECTION ENLARGEMENT



(B) UNSHARPNESS DUE TO GEOMETRY, U_g



(C) LIMITING CONDITION FOR UMBRAL IMAGE

ϕ = FOCAL SPOT WIDTH

U_g = PENUMBRAL IMAGE WIDTH

ΔX = d = DEFECT

V = MAGNIFICATION

FIG. 16 Diagrams of X-ray Projection

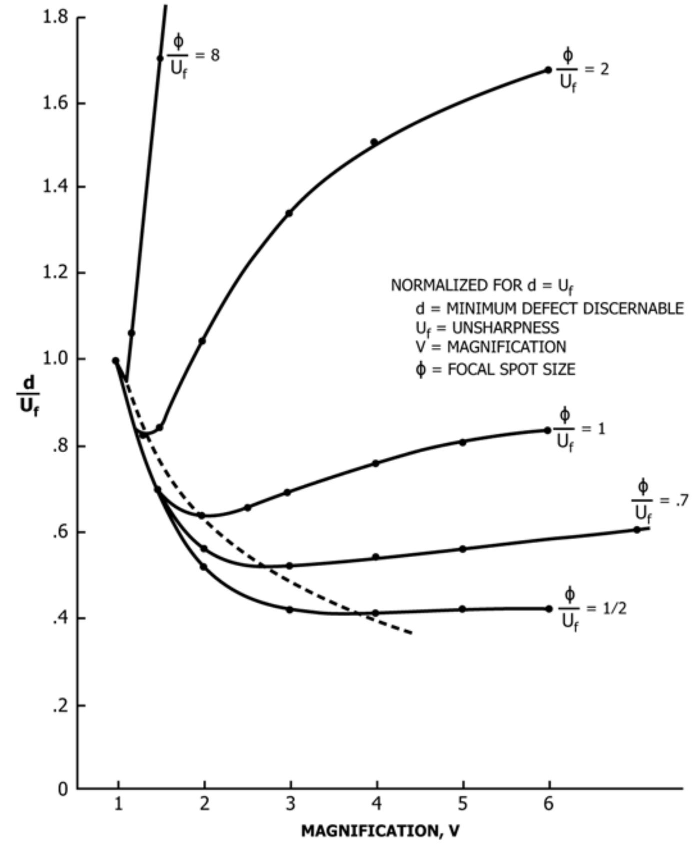


FIG. 17 Defect Discernibility Curves

The dashed line in the figure represents the optimum magnification v_m (see section 11.3.9, Eq 12).

11.4 *X-Ray Scatter:*

11.4.1 X-ray scatter is a problem in radioscopic systems just as it is in 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 of 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:

$$K = \frac{I_s}{I_p} \tag{14}$$

where:

K = scattering ratio,
I_s = scattered radiation, and
I_p = intensity of primary beam.

11.4.2 Typical intensity curves for aluminum at 80 kVp with and without transmitted scatter are shown in Fig. 18. From such data the scattering ratio K can be determined. The build-up factor is given by $(1 + K)$. The object contrast (2) is reduced by the build-up factor, resulting in a degraded contrast sensitivity.

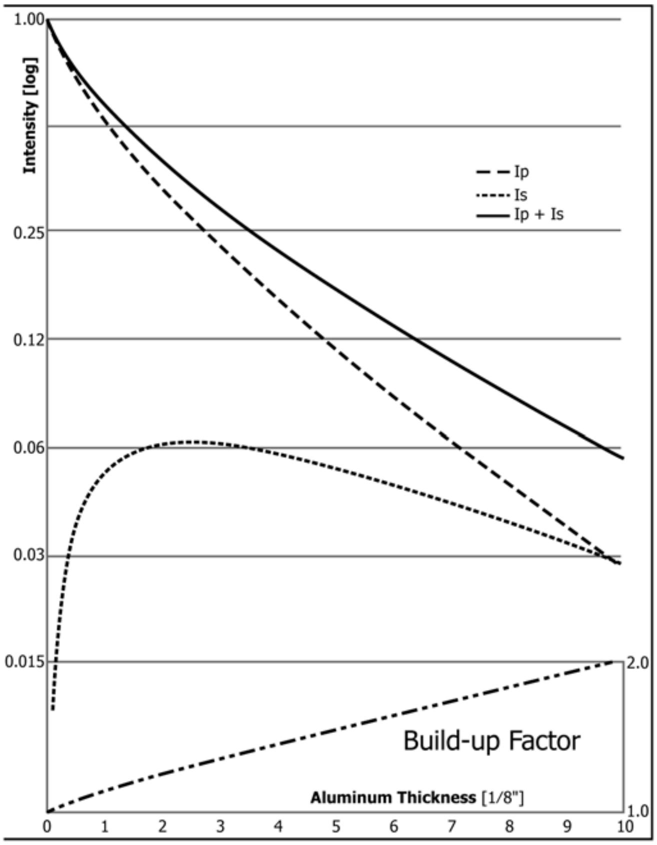


FIG. 18 Intensity Curves for Aluminum at 80 kVp

11.4.3 Scatter can be minimized even though it cannot be completely eliminated. Scatter will reduce with the square of the distance to the detector. For example, at 100 kVp the signal of an aluminum plate is 40% less when the plate is moved 100 mm away from the detector; the signal from scatter is reduced down to <5%. The following recommendations should be followed.

11.4.3.1 Use a distance to the detector of >100mm (Aluminum) or 250mm (Steel) when the focal spot is small enough.

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

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

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

11.5 *Image Quality Indicators:*

11.5.1 A number of different devices, such as wires, plaques, steps, mesh, etc., have been used to measure image quality. The same principles apply for radioscopic systems as for film radiography. Since most radioscopic systems are resolution limited, a greater emphasis is placed on devices that measure resolution. Therefore, many systems require several devices, such as IQIs and wire mesh, to assure the proper image quality.

11.5.1.1 It is important to have a method that can adequately indicate image quality especially in complex electronic imaging systems where drift may occur, and where resolution can differ in the vertical or horizontal direction.

11.5.2 *Plaque Type*—This IQI is described in Test Method E1742 and Practice E1025. 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). Most codes require the detection of the 2T hole in a plaque that is 2 % of the object thickness.

11.5.3 *Wire Type*—These consist of a graded set of wires where the diameter size increases by a factor of 1.26 as described in Practice E747. The visibility of the essential wire determines the sensitivity of the system. Since the cross section of the wire is round, it is not affected by position.

11.5.4 *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 radiographic unsharpness. The diameters of successive wire pair 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 400 keV. See Practice E2002 for duplex wire system description.

11.5.5 *Mesh*—Wire mesh is a good device for indicating resolution. For this purpose, a graded U.S. Standard Sieve Series (ASME Specifications) in the 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. The mesh can also be used as a means to measure the spatial distortion across a detector field of view.

12. Display and Recording Devices

12.1 *General Considerations:*

12.1.1 The usual display for radioscopic 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. These levels are usually poorer for the dynamic mode than for the static mode of examination. For instance, a 4-2-*T* sensitivity may be acceptable while the product is in motion, but a higher sensitivity of 2-2-*T* would be necessary for critical examination when the product is stopped. The display must, therefore, be selected on the basis of both dynamic and static performance parameters. One critical parameter that is common to many fluorescent screens is after-glow or image persistence. This lag phenomenon tends to enhance the contrast of static images, but causes smearing and loss of resolution in the dynamic image. Lag is also common in cameras and screens and, under low-light-level conditions, can be very noticeable. A small amount of lag is generally unavoidable, but it should be kept to a minimum. The color of many fluorescent screen images is designed to peak at the maximum sensitivity of the eye; about 550 nm. This is important when directly viewing conventional fluoroscopic screens, which have very low-light output. A person can see well and without discomfort at daylight intensities from about 1.1 to 540 millilamberts (3.5 to 1719 cd/m^2). For critical viewing, 10.8 to 21.6 millilamberts (34.4 to 68.8 cd/m^2) are necessary. The size, contrast, and resolution of a fluoroscopic image are interrelated, and the optimum size is usually determined experimentally. In most cases, the image magnification (based on actual product dimensions) ranges from 1.2 to 1.5. Image magnification is also important in dynamic systems where apparent speed increases directly with magnification, requiring an appropriate increase in the field of view or in the speed of response by the operator. Some specifications require that an IQI of the appropriate size be read "definitively" at operating speed. Care in control of all of these factors is essential not only in maintaining the required image quality, but in reducing operator fatigue and possible errors. System design, selection of display, and the control of the size, color, contrast, and resolution of an image require knowledge of the interaction of these parameters and their effect on the examiner.

12.2 *Direct Viewing:*

12.2.1 The radioscopic image developed on a fluoroscopic screen or at the output of an image intensifier may be viewed directly or through some suitable optical system. 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. The brightness of high-resolution fluoroscopic screens, however, is only on the order of 0.1 millilambert (0.318×10^{-3} cd/m^2), and their sensitivity ranges from 5 to 10 % in steel. Modern image intensifiers have brightness gains on the order of 10 000× and greater, bringing the light level well into the range suitable for critical viewing. With image intensifiers, 2 % sensitivity can be achieved routinely under production conditions.

12.2.2 Directly viewed X-ray imaging systems usually employ lenses, mirrors, leaded glass, and frosted-glass viewing screens for radiation protection and to provide an output image out of the line of transmitted and scattered radiation. The optical systems may also provide magnification for image-size optimization. Typical optical systems include leaded glass, flat or curved mirrors, refracting optics, or a combination of these elements.

12.3 *Electronic Displays:*

12.3.1 Video presentation of the radioscopic image markedly increased the technical and operational flexibility of radioscopic 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 real-time or stored video images, a digitized matrix, or a multicolored display in which imperfections are highlighted by color. These developments allow easier image analysis and printouts of salient information.

NOTE 2—Video test patterns can be utilized to ensure the display is operating properly and meets required contrast and spatial resolution.

12.3.2 *Video monitors* are routinely used to present a radioscopic image to the examiner and can provide many advantages:

12.3.2.1 Transfer of the image to a remote location for radiation protection and improved viewing conditions,

12.3.2.2 Amplification of image brightness to levels where visual contrast sensitivity is improved, reducing requirements for dark adaptation and ambient lighting restrictions,

12.3.2.3 Modification of the system gamma to produce greater contrast sensitivity,

12.3.2.4 Production of multiple remote images of differing characteristics from the same input image through electronic processing,

12.3.2.5 Processing of the image signal electronically to provide real-time image enhancement, and

12.3.2.6 Processing of the image signal electronically to provide pattern recognition capability, often linked with digital-computing techniques.

12.3.3 *Types of Cameras*—Video systems employ a variety of cameras, each providing differing characteristics in sensitivity, resolution, contrast, lag, light-level range, blooming, required radiation protection, noise, spectral response, and complexity. Selection of the type to utilize is dependent upon the system-design constraints. The more common types of cameras include tube based cameras (recently obsolescent) and solid state cameras (CCDs and CMOS). For completeness, a list of the tube-based cameras is listed below. For a discussion on CCD and CMOS cameras, see E2736.

12.3.3.1 Vidicons, especially plumbicons or silicon-target types, are used at higher light levels (about 0.1076 lm/m^2 or 10^{-2} fc) and are commonly interfaced with X-ray image intensifiers. The vidicon is characterized by its simplicity, ruggedness, and small size. Its target area is the same as a 16-mm photographic frame. It is simple to adjust and quite stable. The dynamic range of a plumbicon is approximately 200:1 compared to 70:1 for the vidicon, making it more flexible for varying scene intensities.

12.3.3.2 Secondary electron-coupled (SEC) vidicons employ an internal initial stage of target amplification, using a secondary target. They are similar in performance to isocons, are less complex, but differ in lag and require special protection circuitry to prevent target destruction from overloading. Primary use is for low-light level, low-contrast applications down to 1.076×10^{-4} lm/m^2 (10^{-5} fc).

12.3.3.3 Image orthicons and image isocons are return beam tubes with internal electron multipliers. The orthicon is useful to light levels of about 1.076×10^{-3} lm/m^2 (10^{-4} fc) and the isocon is useful to 1.076×10^{-4} lm/m^2 (10^{-5} fc). The isocon provides the best noise performance and resolution of all tubes for low-light levels and static scenes, but degrades for moving scenes and is highly complex. Both orthicons and isocons exhibit little target overloading damage. Both the image orthicon and isocon camera tubes must be carefully adjusted for optimum performance, the isocon being the most difficult and requiring a skilled technician. Both are temperature sensitive and should be operated under stabilized conditions. The dynamic range for the isocon is about 1000:1.

12.3.4 *X-Ray Sensitive Video Camera*—Several versions of television cameras are available that respond directly to X-rays, requiring no extra conversion means or optics. These television cameras can provide good performance, but are relatively not as responsive to X-rays as other transducers and are limited in image size and sensitivity. The most common types are vidicons; at lower keV levels, beryllium input windows are employed for the vidicons. Their primary use is in electronic components and low-density materials inspection.

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

12.3.5.1 *Video Monitor Screen Size Versus Viewing Distance*—The critical viewing distance for video is defined as that distance at which two picture elements can just be resolved as separate entities. As an example, for a 525-line video display, this distance is about 4× the height of the picture, and it is generally conceded that viewing distances of 4 to 8× the screen are suitable for critical viewing without undue fatigue. Four times screen height is equivalent to 2.4× the screen diagonal measurement, and for a 356-mm (14-in.) monitor, the viewing distance would be 853 mm (33.6 in.). This value should be considered a minimum, and the screen size and viewing distances selected accordingly. When operating controls it may be advisable to go to a smaller screen.

12.3.5.2 *Scan Format*—Video monitors for radioscopic employing LCD, CRT, LED, Plasma or other emerging techologies should be selected to have at least the pixel density similar to that of the imaging system such that at unity display magnification, each x-ray pixel is displayed on the monitor. This may not be the case if the radioscopic camera density, and data transfer rates begin to increase beyond the display pixel density technology. Where possible the pixel aspect ratios of the imaging system, and the display should be the same.

12.3.5.3 *Viewing Conditions*—In the foregoing, factors such as screen size and masking have been noted as affecting operator performance. Similar beneficial effects may be achieved by arranging that the monitor viewing be done 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 booth should be adequately shielded for radiation protection, air conditioning, and have adequate window space so that the area surrounding the station can be checked from within the booth.

12.4 *Recording*—Permanent records of the image are often required. Several methods are presently available.

12.4.1 *Photographic Recording*—Static photographs may be made of either directly viewed or video monitor presentations, with the photographic factors adjusted for the light level. Also, a radiographic film may be inserted in front of the detector to obtain a radiograph. Cinefluoroscopy usually requires the use of some type of intensifier or amplification because of the low-light quanta available per frame. Typical setups for either should include means to identify the film number, location, date, and related factors desired. The sensitivity and quality of static photographs will generally exceed that of the live presentation because of film integration and the film log ratio curve (gamma).

12.4.2 *Video Tape Recording, Analog*—Although growing obsolete, systems employing cameras may be interfaced with video tape recorders to record the electronic signal from the image, either statically or dynamically. The quality of the video-tape recording is dependent on the relative bandpass of the system and recorder. For recording of static scenes, the use of a video-graphic storage terminal to integrate the television image with slow-scan readout to the recorder can result in significant improvement of the videotaped signal. Identification of the recording may be superimposed on the electronic signal or may be added to a separate recording channel.

12.4.3 *Digital Tape Recording*—There are many forms of digital recording, and many new technologies will certainly emerge in the future. Current technologies record digital data streams, image stacks, and raw video to hard drives, internal or external, RAM, to CDs, and to DVDs.

12.4.4 *Other Recording Techniques*—Electronic interfaces are available for video systems to produce paper facsimile photographs by means of slow-scan readout for static scenes. Similar paper facsimiles may be produced by computer systems. The gray scale and resolution of these reproductions is excellent.

13. Keywords

13.1 configuration; electronic; module; non-destructive; radioscopy; real-time