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Standard Guide for Radioscopy[1]

This standard is issued under the fixed designation E 1000; 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 E 1316.

1.3 *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:*

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 1316 Terminology for Nondestructive Examinations[2]
E 2002 Practice for Determining Total Image Unsharpness in Radiology[2]

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]

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),

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

[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.

video recording, or "still" photographs using conventional cameras. The radioscopic image may be electronically enhanced, digitized, or otherwise processed for improved visual image analysis or automatic, computer-aided analysis, or both.

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 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 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 (on the order of 0.1 millilambert or 0.343×10^{-3} cd/m^2) 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 1950's 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 (keVcp) 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, low-light-output fluorescent screens directly. The results are comparable to those obtained with the image intensifier.

5.3 In recent years (circa 1980's) new digital radiology techniques have been 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 on magnetic tape. Digital radioscopic systems use scintillator-photodetector and phosphor-photodetector sensors in flying spot and fan beam-detector array arrangements.

5.4 All of these techniques employ television presentation and can utilize various electronic techniques for image enhancement, image storage, and video recording. These advanced imaging devices, along with modern video 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.

5.5 *Limitations*—Despite the numerous advances in RRTI technology, the sensitivity and resolution of real-time systems usually are not as good as can be 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 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. 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 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:

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 100 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 iodide (thallium-activated) and sodium iodide (cesium-activated). These single crystal materials can be obtained in very large sizes (up to 30-cm or 12-in. diameter is not uncommon) and can be machined into various sizes and shapes as required. Thickness of 2 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*—The most common example of this 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 sulfide, cadmium selenide, lead oxide, and selenium. The latter two 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.

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. 1-13 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.

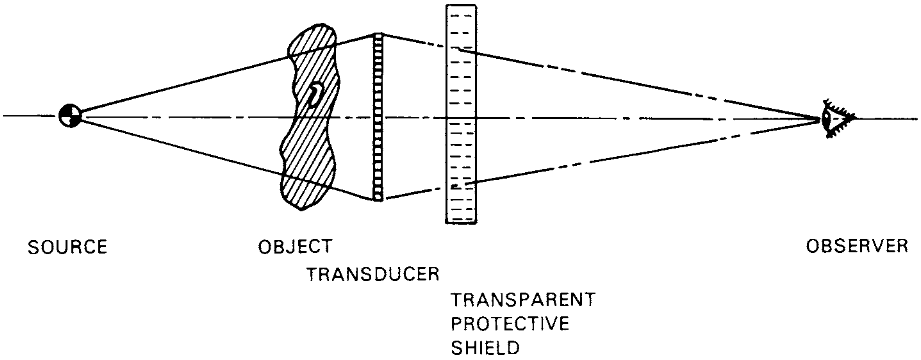


FIG. 1 Basic Fluoroscope

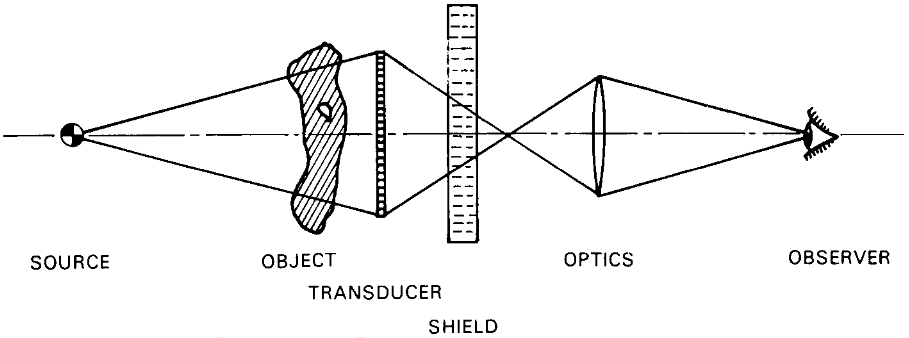


FIG. 2 Fluoroscope with Optics

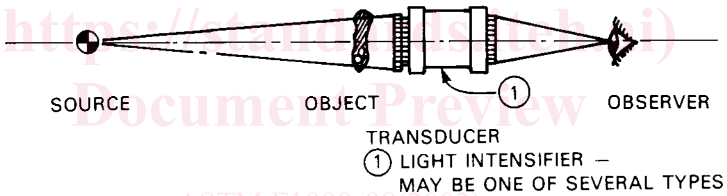


FIG. 3 Light-Intensified Fluoroscope

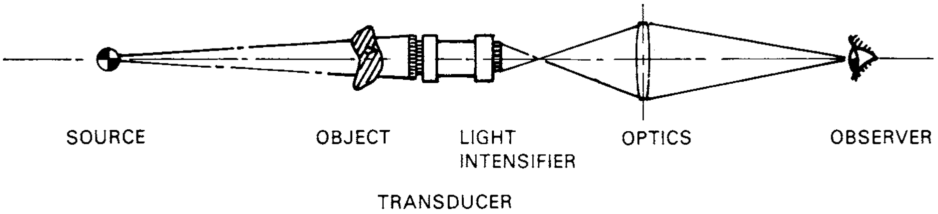


FIG. 4 Light-Intensified Fluoroscope with Optics

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 420 keV. Energy sources from 1 MeV and above may be the Van de Graaff generator and the linear accelerator. High energy sources with large flux outputs make possible the real-time examination of greater thicknesses of material.

9.1.2 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.

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 420 keV, the X-ray units

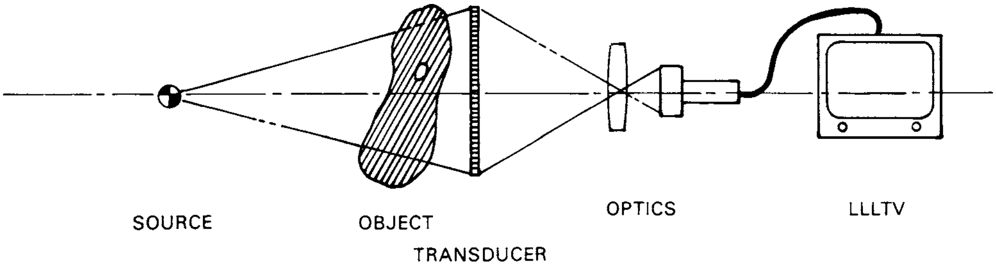
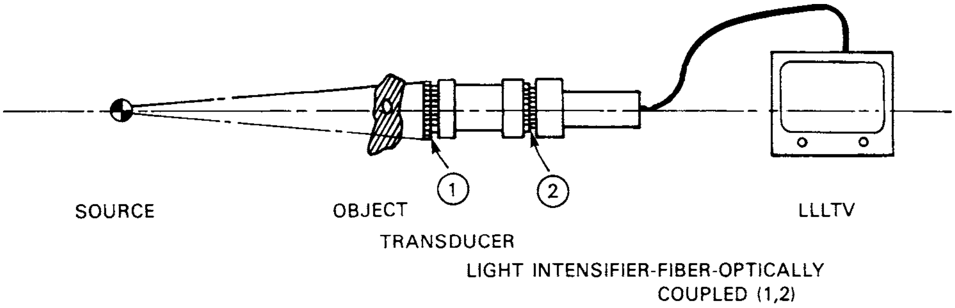
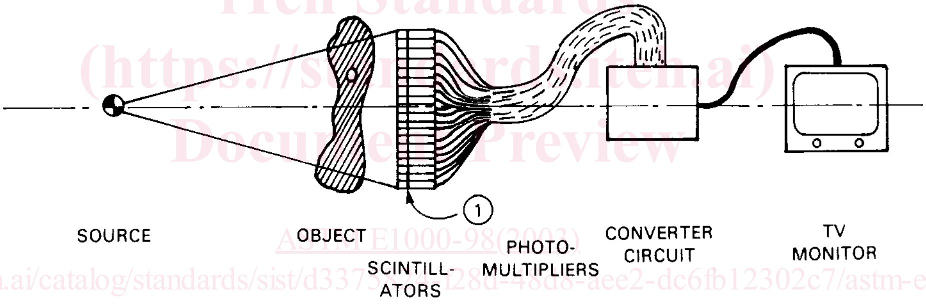


FIG. 5 LLLTV Fluoroscope



① ② GEOMETRIC OPTICS OR FIBER OPTICS IS USED FOR THESE INTERFACES, DEPENDING ON TYPE OF TRANSDUCER AND CCTV

FIG. 6 Light-Intensified LLLTV Fluoroscope



① SCINTILLATOR ARRAY MAY BE AN AREA OR A LINE. IN LATTER CASE, RELATIVE MOTION REQUIRED TO GENERATE SCANNING. IN SOME CASES, X-RAY BEAM MAY BE COLLIMATED AND SCANNED

FIG. 7 Scintillator Arrays, TV Readout

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 420-keV equipment operates down to about 85 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.

9.3 *Source Geometry*:

9.3.1 The physical size of the source of radiation is a parameter that may vary considerably. One reason is the dominating unsharpness in the radiation detector, which can be of the order of 0.5 to 0.75 mm [0.02 to 0.03 in.]. Thus, 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. 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

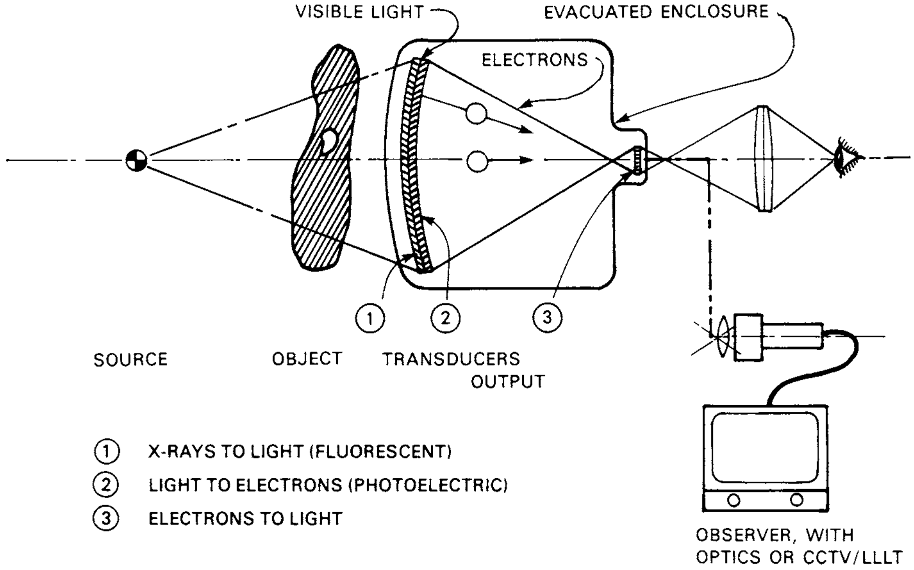
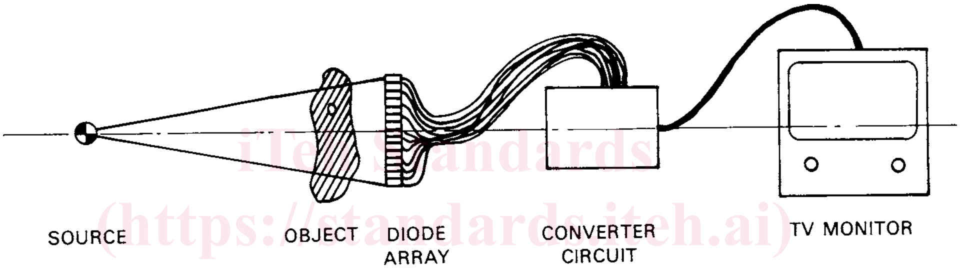
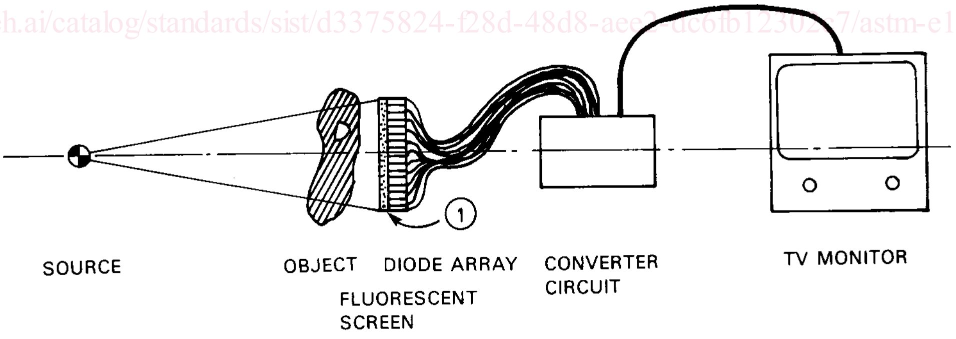


FIG. 8 X-ray Image Intensifier



NOTE: DIODE ARRAY MAY BE A LINE OR AN AREA. IF IT IS A LINE, RELATIVE MOTION IS REQUIRED TO PRODUCE AREA SCANNING.

FIG. 9 Semiconductor (Diode) Array



① GEOMETRIC OR FIBER OPTICS MAY BE USED AT THIS INTERFACE. AREA SCANNING REQUIRES RELATIVE MOTION, IF LINE DETECTOR USED.

FIG. 10 Semiconductor (Diode) Array with Fluorescence

economy of radioscopic examination is realized in continuous production examination. X-ray units with target cooling by fluids are usually required.

9.4.2 The wave form of X-ray units up to 420 keV are mostly of the full-wave rectified or the constant potential type. The full-wave rectified units give 120 pulses per second which can present interference lines on the television monitor. Similarly the high-energy sources which can operate at pulse rates up to 300 pulses per second produce interference lines. These lines can be minimized by the design of the real-time systems.

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

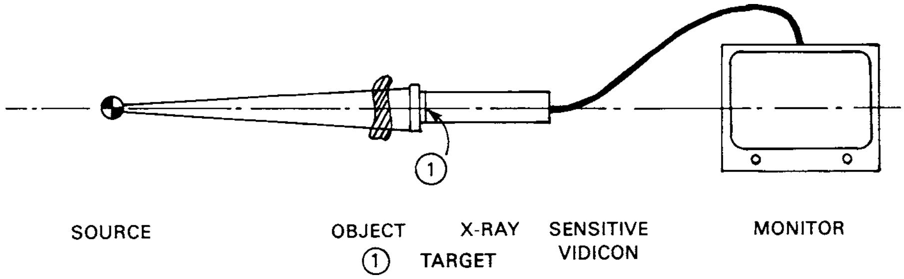
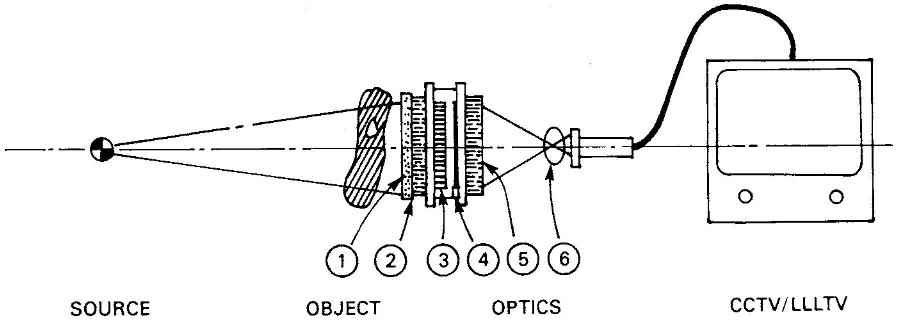


FIG. 11 X-ray Sensitive Vidicon



① FLUORESCENT SCREEN
② GEOMETRIC OPTICS OR FIBER OPTICS
③ MICROCHANNEL PLATE
④ CATHODOLUMINESCENT SCREEN
⑤ FIBER OPTICS
⑥ LENS (FIBER OPTICS COUPLING TO CAMERA TUBE ALSO POSSIBLE)

FIG. 12 Microchannel Plates

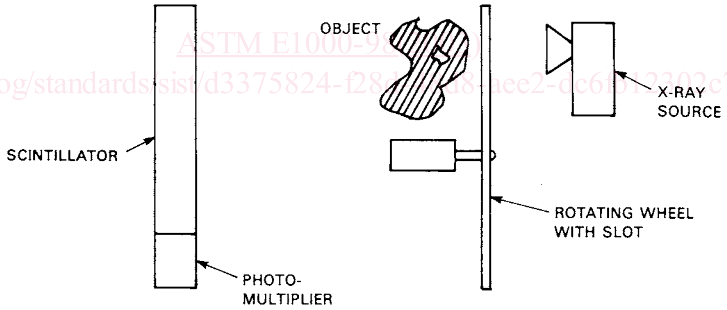


FIG. 13 Flying Spot Scanner

requirement of radiation output through the material thickness being examined should be measured.

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, 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.

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

TABLE 1 Comparison of Several Imaging Devices (circa 1980's)

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	Semiconductor Arrays	X-ray Vidicon	Microchannel Plates	Flying Spot/Line Scanners
Availability	excellent	good	excellent	good	good	fair (1980)	fair (1983)
Auxiliary equipment needed	shielding glass, optics LLLTV^A	shielding glass, optics LLLTV^A	CCTV, optics^A	fluorescent screen, optics special electronics	CCTV^A	fluorescent screen, special packaging, CCTV, output phosphor	fluorescent phosphor or scintillating crystals, special electronics, digitizers
Usual readout methods	Visual LLLTV	LLLTV	CCTV	CCTV	CCTV	CCTV	electronic/visual
Other readout methods	none	none	direct	none	none	none	none
Practical resolution, usual readout, lp/mm	up to 4.5	10	4	20	20	20	10
Minimum large-area contrast sensitivity, %	2	1	2	10	5	10	1
Useful keVcp							
range, min	25	25	5	20	20	15	25
range, max	300	10 MeV	10 MeV	150	250	2 MeV	15 MeV
Optimum keVcp	120	200	100	100	75	100	NA
Field of view, maximum	no practical limit	229-mm [9-in.] dia	305-mm [12-in.] dia	25.4 × 25.4 mm [1 × 1 in.]	9.53 × 12.7 mm [⅜ × ½ in.]	76-mm [3-in.] dia	no limit
Relative sensitivity to X-rays	low	medium	high	medium	low	medium	high
Relative cost	low	high	medium	medium	low	high	high
Approximate useful life	10 years	indefinite	3 years	indefinite	5 years	5 years	5 years
Special remarks	very simple	high quality image	very practical	new	limited to small thin, objects	new	new

[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 Low-Energy Radiation Sources for Aluminum and Steel^A

keV	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]
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 real time 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]
Cesium-137	51.0 [2]	...
Cobalt-60	57.0 [2.24]	...

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

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 television (LLLTV) 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 television 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, without use of external energy sources. 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. 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 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.

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 can produce characteristic decay times as short as 10^{-6} 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

TABLE 4 Properties of Some Common Fluorescent Screens[A]

			Relative Brightness With Attenuation[B]								Resolution[C]	Color
			¼-in. Aluminum			Aluminum		Aluminum		¼-in. Steel		
No.	Formula	Name	50 keVcp	100 keVcp	150 keVcp	100 keVcp	150 keVcp	100 keVcp	150 keVcp	150 keVcp	lp/in. [mm]	nm
1	$CaWO_4$	calcium tungstate		6	13	2	8	1	2	0.5	30 [1.2]	violet ~420
2	ZnCdS	zinc cadmium sulfide	3.5	46	120	22	65	7	25	3	50 [2.0]	green ~540
3	ZnCdS	zinc cadmium sulfide	8	122	320	50	160	16	60	5	20 [0.8]	green ~540
4	$Gd_2O_2S_j$	gadolinium oxysulfide	5	89	250	43	150	16	65	12	40 [1.6]	yellow-green ~550
5	$Gd_2O_2S_j$	gadolinium oxysulfide	3.5	61	175	30	105	11	50	5	60 [2.4]	yellow-green ~550
6	LaOBr	lanthanum oxybromide	1	19	50	8	29	3.5	13	2	30 [1.2]	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 wires/inch.

of spectral content to the response of the human eye or that of a detector such as a television 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_2Sj 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, there are 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.) More complex optical viewing systems use 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 closed-circuit television (CCTV) readout, with the TV 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 of a material which fluoresces when irradiated by X-rays, with short pulses of light being emitted for each photon absorbed. The practical difference between fluorescent screens and scintillation screens is that the latter are optically clear and homogenous slices of a single crystal, and are normally much thicker.

10.6.2.2 Since we have noted that larger or thicker crystals 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. Common industrial use of such single crystal screens is quite recent. 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 LLLTV. 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.