Designation: E1000 − 16

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

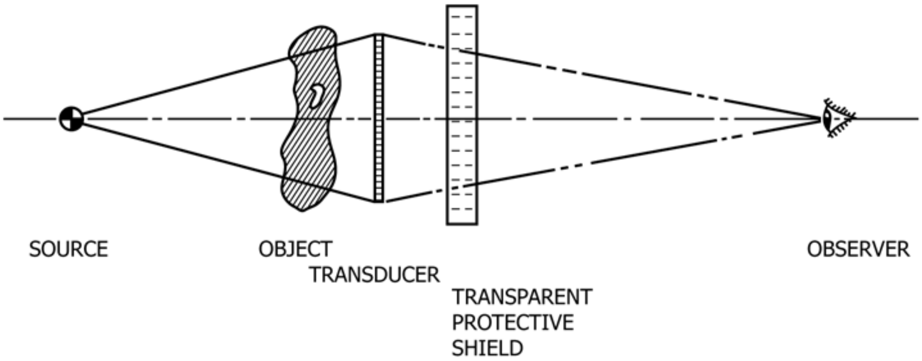


FIG. 1 Basic Fluoroscope

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

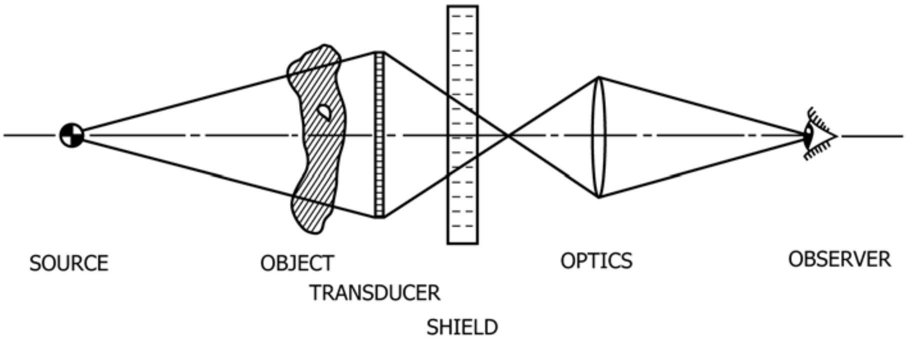


FIG. 2 Fluoroscope with Optics

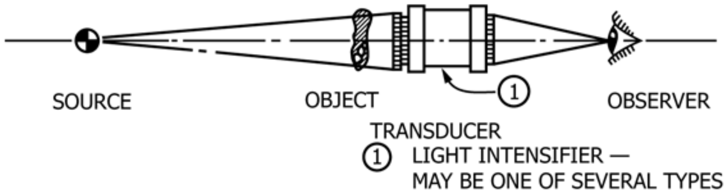


FIG. 3 Light-Intensified Fluoroscope

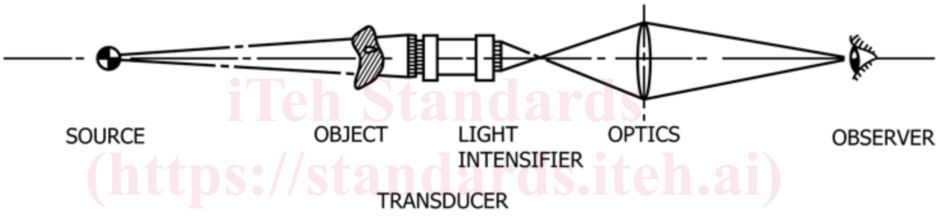


FIG. 4 Light-Intensified Fluoroscope with Optics

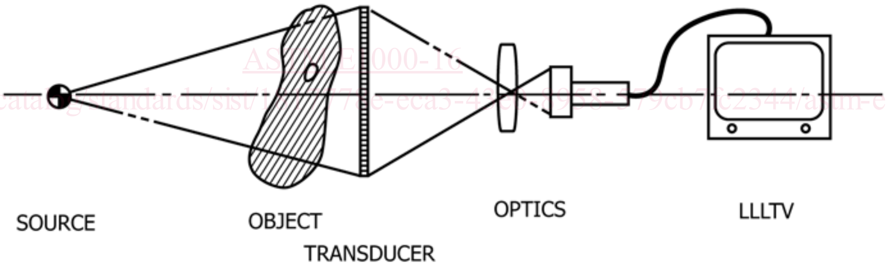


FIG. 5 LLLTV Fluoroscope

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

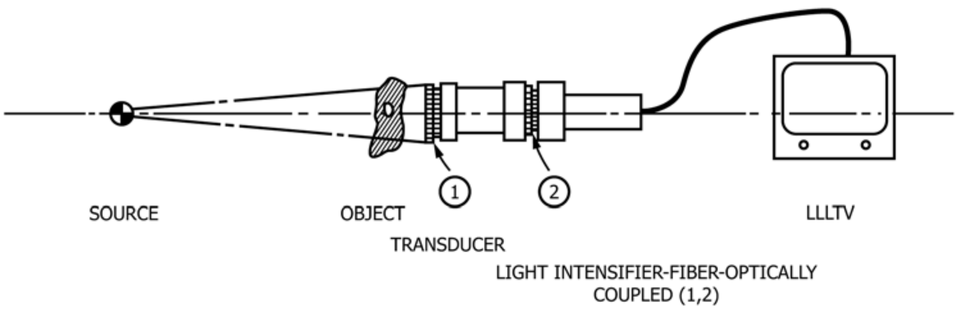
9.1.2 Usable isotope sources have energy levels from 84 keV (Thulium-170, Tm^{170}) up to 1.25 MeV (Cobalt-60, Co^{60}). With high specific activities, these sources should be considered for special application where their field mobility and operational simplicity can be of significant advantage.

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:*

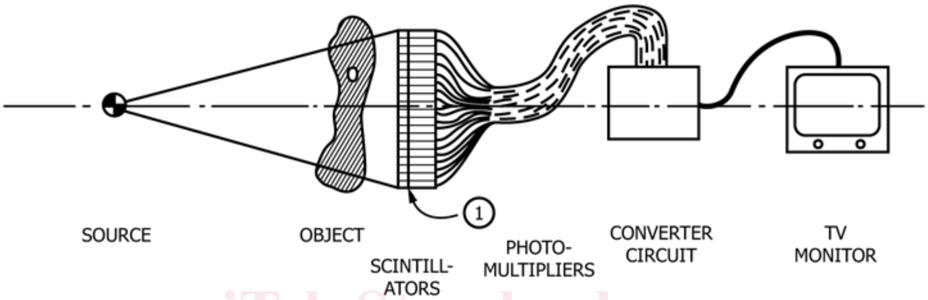
9.2.1 *Low Energy*—The radiation source selected for a specific examination system depends upon the material being examined, its mass, its thickness, and the required rate of examination. In the energy range up to 750 keV, the X-ray units have an adjustable energy range so that they are applicable to 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.



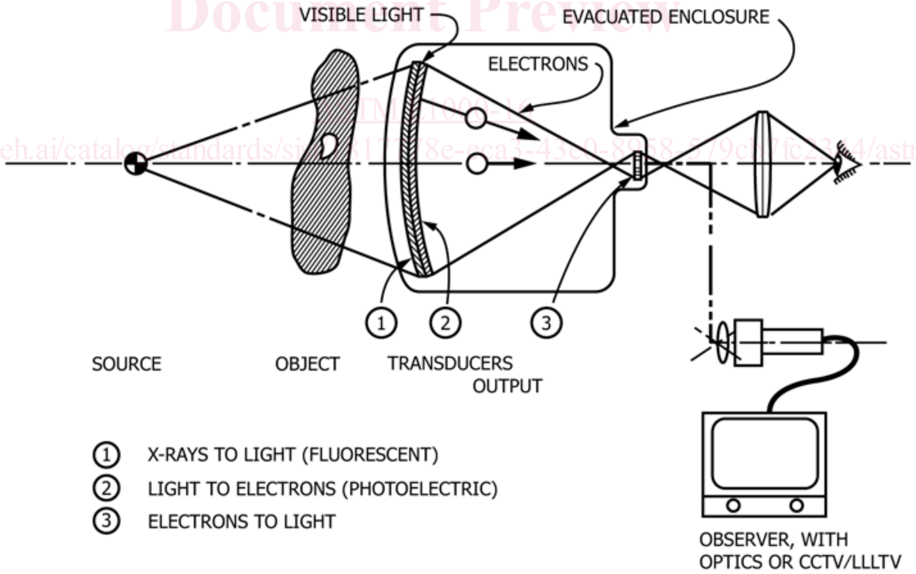
① ② GEOMETRIC OPTICS OR FIBER OPTICS IS USED FOR THESE INTERFACES, DEPENDING ON TYPE OF TRANSDUCER AND CCTV

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



① X-RAYS TO LIGHT (FLUORESCENT)
② LIGHT TO ELECTRONS (PHOTOELECTRIC)
③ ELECTRONS TO LIGHT

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.