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Radiographic Testing at Lawrence Livermore National Laboratory

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Lawrence Livermore Laboratory

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Abstract

Radiographic testing is a nondestructive inspection technique which uses penetrating radiation. The Nondestructive Evaluation (NDE) Section at Lawrence Livermore National Laboratory has a broad spectrum of equipment and techniques for radiographic testing. These resources include low-energy vacuum systems, low- and mid-energy cabinet and cell radiographic systems, high-energy linear accelerators, portable x-ray machines and radioisotopes for radiographic inspections. For diagnostic testing the NDE Section also has real-time and flash radiographic equipment.

Introduction

Radiographic testing is the most widely used technique of the Engineering Sciences Division's Nondestructive Evaluation Section (NDE) at Lawrence Livermore National Laboratory (LLNL). Radiography is performed at both Livermore (Building 327 and 239) and Site 300 (Building 809 and 823). Field work is also performed out-of-doors or in other facilities. Applications of radiography include the inspection of raw materials, fabricated parts and assemblies in support of LLNL programs, field inspections of components and assemblies, inspection under environmental conditions, real-time radiography of dynamic systems, and flash radiography of very rapid dynamic events.

This report discusses the radiographic capability of the NDE Section. This capability is described primarily in terms of the wide range of x-ray and gamma-ray sources used to provide the appropriate radiographic service for various situations. The sources are listed in Appendix A. Real-time and flash radiographic equipment is also discussed.

Basic Radiographic Testing

The radiographic technique uses an open setup, as shown in Fig. 1.* Radiation passes through the object, and the spatially modulated beam, containing information about the internal condition of the object, is detected. The radiation source is selected for energy and intensity such that the attenuation of radiation is a reasonable number of half-value layers and the exposure time is not prohibitively long. The attenuation of radiation is given by

$$I = I_0 e^{-(\mu/\rho)\rho t} \quad ,$$

where I is the transmitted radiation intensity, I_0 is the primary radiation intensity, μ/ρ is the mass attenuation coefficient, ρ is the material density, and t is the object thickness. The value of μ/ρ is a function of material and energy. The mass attenuation coefficient has units of cm^2/g and the liner attenuation coefficient (μ) has units of cm^{-1}.

Figure 2 shows how μ/ρ increases with atomic number. Figure 3 shows the variation of μ/ρ with energy for three materials. The total attenuation coefficient is composed of photoelectric, Compton and pair-production effects.

A half-value layer (HVL) is the thickness of material required to reduce the radiation intensity by a factor of two

$$HVL = 0.693/\mu \quad .$$

*All figures appear at the end of the report.

The appropriate energy for radiography is normally that which represents about five half-value layers.

The most common radiation source for radiography is the x-ray machine. X rays are generated when electrons at high energies are slowed in a target material generating Bremsstrahlung radiation. This radiation has a continuous energy spectrum with a peak at the accelerating potential for the electrons. Characteristic spectral lines will also be present as a function of the target material. Figure 4 shows the photon energy spectrum of an 80-kV_p x-ray machine. The effective energy of the spectrum for radiography is at about half the peak kV value. If the beam is passed through a filter, the spectrum will be shifted to higher energies. This is called beam hardening and, of course, takes place as the beam passes through the object.

Radioactive isotopes are also used as sources of radiation for radiography. The radioisotopes emit gamma rays when they decay from excited states. Figure 5(a) and 5(b) show the spectrum of emission for the two most common radiography sources: ^{192}Ir and ^{60}Co. The spectrums show the characteristic lines of emission, which contrasts with the continuous spectrum of x-ray machines. The intensity of radiation from these isotopes is listed in Table 1.

The source, object and detector arrangement are determined not only by object geometry but by radiographic geometry. Figure 6 shows the geometric effects for unsharpness and magnification in the image depending on setup. In most circumstances a small focal spot, large source-to-film distance, and small object-to-film distance are desired to minimize geometric unsharpness in the image.

Collimation is an important part of the configuration. It reduces the radiation field to the area of interest and prevents radiation from other directions being scattered by the object or surroundings and being recorded as noise on the detector. Scattered radiation can appear from all directions, but particularly from the back. Since the detector will absorb only a small fraction of the primary beam at mid energies and higher, there is a large quantity of scatter off walls behind the object and film. This backscatter can be minimized by using a beam trap and having the film relatively far away from the nearest wall (a method usually used with high energies) or by backing the film with a shield, such as a lead plate (used with mid energies). Figure 7 shows the degree of scatter in the attenuation of photons for several materials as a function of photon energy.

The radiographic imaging detector is x-ray film or, in the case of real-time radiography, a video imaging system. The film types and characteristics normally used in the NDE Section are listed in Table 2. Table 3 is a comparison of some performance characteristics of the films.

Table 1. Intensity of radiation from isotope sources.

Isotope	Half-life	R/hr at 1 m/Ci	Practical specific activity (Ci/g)	Theoretical specific activity (Ci/g)
^{60}Co	5.2 years	1.35	400	1 200
^{192}Ir	74 days	0.55	500	10 000

Table 2. Industrial radiographic film types (ASTM E94).

Film type	Speed	Contrast	Graininess	NDE example
1	Low	Very high	Very low	Kodak SR, DR, M, T
2	Medium	High	Low	Kodak AA
3	High	Medium	High	–
4	Very high	Very high	Depends on fluorescent screen	Dupont NDT 91

Table 3. Film performance characteristics.

Film type	Relative speed		Grain size[a] (μm)
	$80\ kV_p$	^{60}Co	
Kodak AA	100	100	0.54
T	65	55	0.54 + 0.23
M	45	30	0.23
DR	15	12	0.22

[a] G. T. Liv, D. M. Alger, and S. R. Bull, *Materials Evaluation*, February 1982, p. 220.

Low-Energy X-Ray Machines

Low-energy radiography (50 kV_p and less) is performed in a special room of Building 327. The power supply allows radiography from 5 to 50 kV_p. The peak current rating is 30 mA; however, at low kV the current should not exceed 1 mA/kV. Two x-ray heads are available, one for use in air and one for use in vacuum. Both have beryllium window x-ray tubes to minimize the low-energy x-ray absorption in the tube. The tube used in air normally shoots toward the floor and is adjustable in source-to-film distance up to 1.2 m. Figure 8 shows the vacuum radiography unit. This unit is used when radiography is performed on thin, light materials, usually at energies below 15 kV_p. The maximum source-to-film distance is 0.45 m. The film for vacuum radiography is nearly always used bare (no cassette). This practice requires the low-energy radiography room to be a darkroom. Spectroscopic plates may be used when extra high resolution in the image is needed. The low-energy radiography room must be a clean room. Dust particles on the object will be imaged and appear as flaw indications in the radiograph. Occasionally, to be certain that indications are not due to dust, the object is moved and a second exposure is taken. Another precaution against misinterpreting artifacts as indications is the use of double film loads.

The Site-300 facility also has a 50-kV_p x-ray unit in an x-ray cabinet. This machine is used for work on explosive material, usually less than 15 mm thick.

Mid-Energy X-Ray Machines

The mid-energy x-ray equipment runs from 150 kV_p to 400 kV_p units. The Livermore Building 327 facility has two cabinet systems, shown in Fig. 9. The cabinet unit on the left is 150-kV_p with a 1.2-m-maximum source-to-film distance and the unit on the right is 300-kV_p with a 1.5-m-maximum source-to-film distance. The cabinets are lined with lead and have interlocked lead-shielded doors. Personnel may stand beside the cabinets during radiography. The radiography configuration is vertical. The objects are placed on top of the film cassette/pack on the cabinet shelf. The cabinet units are used for radiography of welds, castings and formed parts. Site 300's Building 809 also has a similar 150-kV_p cabinet that is used for radiography of explosives.

Radiography in shielded rooms (x-ray caves or cells) is available with mid-energy machines. The 150-kV_p x-ray cell in Building 327 is shown in Fig. 10. The x-ray head is on a portable stand. Normally the beam is used horizontally, although it is capable of shooting toward the floor or at odd angles. Alignment of the x-ray beam with the object can be performed with a surveyor's transit, as shown in the figure, or, as it is more routinely performed, with a laser-beam system mounted on the tube head. Similar facilities are available for 300-kV_p machines in Buildings 239 and 809 and a 400-kV_p unit in Building 327. The fixturing for the x-ray heads differs, the higher-energy units having significantly larger heads.

The mid-energy equipment is used for objects requiring radiation from 50 kV_p to 400 kV_p (corresponding roughly to thicknesses of 6 mm of aluminum to 20 mm of iron). The film technique uses ready-pack film (sheets of x-ray film in light-tight paper envelopes supplied by the manufacturer) up to about 125 kV_p. Above 125 kV_p, lead-pack (paper envelopes with a lead oxide layer against the film) or lead screens in paper cassettes are used. At the higher energy the lead serves as an intensifier by undergoing a photoelectric effect.

The photoelectron is recorded by the film more readily than the primary photon. The typical lead screen loading uses a 125-μm front lead screen (on the source side of the film) and a 250-μm back lead screen. When two films are required in the film load a 75-μm lead screen is placed between them in the cassette, in addition to the front and back screens. The satisfactory use of lead screens requires good contact with the film. The film cassettes are therefore often placed inside plastic bags to which a vacuum is applied. Such an apparatus is shown above the object table in Fig. 10.

High-Energy Systems

The NDE Section high-energy x-ray machines run from 1 MeV to 13 MeV. Two 1-MeV resotrons are in use—one in Building 327 and the other at Building 809. These machines use a resonating high-voltage transfer at 180 Hz, with a half-wave self-rectified x-ray tube. The transformer is cooled with sulfur hexafluoride (SF_6) in a tank (1.5 m long by 0.9 m in diameter). The transformer coils are in a cylindrical stack. Electrons are accelerated down a central tube of the stack, into an anode extension, and strike a water-cooled tungsten target. The machine may be operated in a transmitted- (forward) or a reflected-beam mode. The focal spot size in the transmission mode is about 10 mm in diameter. The intensity of the radiation beam is a function of the angle, as shown in Fig. 11. The quality of the radiation (the energy spectrum) is also affected by the angle, as shown in Fig. 12 in terms of the half-value layer for lead.

Figure 13 shows the Building 327 1-MeV machine in the radiography cell. A special D-38 collimator has been added to the extended anode for the reflected beam operation of the unit. Parts and assemblies are radiographed with this unit. The 1-MeV unit at Site 300 is used in the transmission-beam mode for radiography of large explosive pieces.

Linear accelerators used for radiography use a tuned resonant waveguide to accelerate electrons to high energy. Electrons from an electron gun are injected into a standing-wave accelerator structure (a copper structure of variable length). A magnetron (rf oscillator) supplies power to the waveguide. Pulses of 4.5 μs duration from a modulator and pulse transformer are fed to the electron gun and magnetron at 80–320 pulses/s. The electrons travelling at near-relativistic velocities strike a tungsten target to generate x rays. The high energy of the electrons and x rays cause a predominate forward beam intensity of the radiation. Figure 14 shows how the intensity falls off as a function of angle for linear accelerators.

Radiography with high-energy machines is performed in large bays to reduce the effect of radiation scattered from walls. Figure 15 shows the 4-MeV linear accelerator bay. A laser alignment beam is used to position the film and object in the x-ray beam. The usual film load consists of 0.5-mm front lead screen and a single emulsion fine-grain film. Neither back screen nor emulsion on the back side of the film is used. Undetected primary radiation is free to travel large distances (8 to 16 m) into beam traps to avoid backscatter noise in the image. The typical source-to-film distance is 6 m. With the 2-mm focal spot size of the 4- and 8-MeV linear accelerators, the geometric unsharpness is quite small, even for large objects.

The 8-MeV linear accelerator is shown in Fig. 16. This unit has an adjustable collimator on the x-ray head. The collimator, shown in the closeup of Fig. 16(b), is made of 67-mm thick tungsten/copper alloy jaws on motorized lead screws.

Linear accelerators are used for the radiography of thick sections of material. Table 4 lists half-value layers for various materials. The use of high-energy x rays flattens the image (reduces the

Table 4. Half-value layers (mm) at linear accelerator energies.

Material	Energy 4 MeV	8 MeV	15 MeV
Tungsten (18 g/cm^3)	9.4		7.9
Lead (11 g/cm^3)	16.5	15.2	14
Steel (7.8 g/cm^3)	26	31.0	33
Aluminum (2.7 g/cm^3)	77	99	104
Concrete (2.4 g/cm^3)	83	115	120
Solid Propellant (1.7 g/cm^3)	115	150	193
Lucite (1.2 g/cm^3)	175	220	279

contrast) between materials and so is useful even on assemblies of relatively light materials in some cases. This effect is shown in the higher-energy curve of Fig. 2.

At Site 300, a 13-MeV linear accelerator is available, as shown in Fig. 17. This unit is different from the 4- and 8-MeV machines, because it uses a traveling- rather than a standing-waveguide. Electrons enter the waveguide from an electron gun and are accelerated on a traveling wave along the guide. The high-energy electrons exit the guide and are bent 90° and focused on a tungsten target. The focal spot size is 1 mm, with an output of about 2000R/min at 1 m. The target current is 120 mA. The pulse width is 3.5 μs, at 150–320 pulses/s.

This machine is used for the radiography of assemblies and explosives. It is designed to be transportable to field locations. The accelerator unit is built as a box within a box on the carriage, to protect against hazardous environments. A control trailer for operation of the machine is located remotely.

Isotope Radiography

Isotopes can be used for radiography in the laboratory or in the field. The NDE Section has a number of sources, listed in Appendix A. The ^{60}Co source containers are of three types: Picker Cyclops, Tech Ops 520 and Tech Ops 680. The Cyclops operates with a motor-driven shutter mechanism and adjustable collimator. These units provide a well-collimated, high-intensity beam of radiation. They can hold up to 2000 Ci of cobalt. The Tech Ops 520 is a 1000 Ci unit. This unit uses a remote manual cable drive to expose the source so no electrical power is needed. The Tech Ops 680 ^{60}Co containers hold up to 100 Ci. They use remote manual cables to position the source in a guide tube.

The ^{192}Ir containers for 100 Ci source sizes, are much smaller than the ^{60}Co containers, because the energy is lower. Gamma Industries "pipeliners" and a Tech Ops 664 container are used. The pipeliner uses a manual turnscrew to open the source to the exposure position. The 664 uses remote manual cables and source guide tubes. Figure 18 shows the Cyclops, 680, Pipeliner, and 664 containers for isotopes.

Isotope sources emit radiation continuously, with fluctuations due only to the statistical nature of the decay process. Because there is a decay process, the sources lose intensity with time. ^{60}Co has a half-life of 5.2 years and ^{192}Ir a half life of 74 days. The sources are therefore cycled for replacement on a frequency of about 1–2 half-lives.

Portable X-Ray Machines

The NDE Section has a number of portable x-ray machines for laboratory and field use in the low- to mid-energy range. Portable x-ray sources are usually limited in field applications by duty cycles which require them to be off a portion of the time to provide satisfactory cooling of the target. Also, the targets are generally larger than equivalent-energy laboratory units. The units used by the NDE Section are listed in Appendix A.

The Picker ranger (100-kV$_p$) unit has a portable cooling system that allows it to be used in the field under continuous operation at high (10 mA) current ratings. The Andrex 250-kV$_p$ machine can operate continuously when attached to a water cooling system in a laboratory environment. The Picker hot shot units may be operated continuously at low-keV, low-mA ratings. However, at the highest ratings there must be a sufficient time off before repeating the exposure cycle. These machines use air cooling and are therefore relatively simple in design. The x-ray head weighs 26 kg. The 300-kV$_p$ Sperry machine is a large unit with a 36-kg head. The machine has its own cooling system, allowing it to be operated continuously.

Real-Time Radiography

A special technique in radiography is to replace the film-detection method with a real-time imaging technique. The most common method of real-time imaging is the use of a fluorescent screen to convert x ray to light and to collect the light with an intensifier/television camera combination. The Delcalix real-time imaging system (diagrammed in Fig. 19) uses this approach. The Delcalix system has an interchangeable fluorescent screen to allow the experimenter to match the screen characteristics to the objectives of the experiment. The light from the screen is reflected in a mirror and collected to an intensifier by an efficient concentric mirror lens system (.65 f stop). The intensifier is then coupled to an image isocon camera. The large optics of the Delcalix allows for a large input image area (320 mm diameter). The intensifier can be electronically focused to either the full input diameter or, to present an enlarged image on the monitor, to the central 160 mm. The NDE Section has three Delcalix units. Figure 20(a) shows two of the units being positioned in the 150-keV x-ray cave in preparation for a material transfer experiment. The control area is shown in Fig. 20(b).

Real-time radiography is used primarily for diagnostics of dynamic systems. The video frame rate is 30/s. Events which take place over several seconds to several minutes are ideal. Video tape-recording, stop-frame playback, and image enhancement are all used to aid in the data recording and interpretation.

Scattered radiation seriously degrades real-time images (more so than in film radiography) and so special care must be taken. The large inherent unsharpness in real-time systems as compared to film allows magnification techniques to be used (see Fig. 6), because geometric unsharpness is not necessarily the controlling factor. The separation between object and screen in the magnification mode reduces the scatter problem.

Another real-time radiography system is the x-ray-sensitive vidicon (XRV) camera. This is a vidicon camera that is modified by changing the light-sensitive tube to one that is x-ray-sensitive; the input window is changed to beryllium and the target increased in its sensitivity to x rays (normally using a PbO layer). The XRV has a small imaging area (9 x 12 mm) and is used in the low- to mid-energy range. It requires a high dose-rate input (about 100 R/min). The resolution capability of the XRV is very good; it can resolve 13-μm gold wires in electronic components.

Figure 21 shows a setup with the XRV, remote-control staging table, collimator, and x-ray head. The remote-control stage is a useful tool for real-time imaging. The part is mounted on a rotating table which is above a horizontal and vertical stage combination. The remote-control movement allows an operator to select the part locations for inspection. This feature can provide 100% inspection of the part (as opposed to selected angles in film radiography) or allow positioning for ideal alignment, after which a higher quality film technique can be applied.

Flash Radiography

The NDE Section provides a service in flash radiography for imaging rapid dynamic events. This technique is used as a diagnostic tool for experiments on ballistic devices, shaped charges, explosives, etc. The equipment available includes a 2.3-MeV x-ray unit, a three-head 180-keV system and a three-head 150-keV system.

The 2.3-MeV machine is shown in Fig. 22. Like all the flash x-ray equipment, it uses a field-emission x-ray tube. The focal spot size is 5 mm in diameter. The pulse width is 30 ns with an intensity of 75 mR at 2 m/pulse. This unit has been used for radiography of thick (155 mm) sections of propellant material and shadowgraph radiography of projectiles at 50 m source-to-film distance.

The 150-keV and 180-keV systems are shown in Fig. 23(a) and 23(b). They have 70-ns pulse widths, 3-mm focal spot size and intensities of 40 mR at 0.2 m per pulse. They are used primarily for shadowgraphs of high-velocity projectiles.

Because the dose rate per pulse at the film plane is so low (between 0.1 and 1 mR), a very fast imaging process is needed. Type 4 film with fluorescent screens is therefore used (Table 2). Special techniques of loading the films in protective cassettes to avoid damage due to blast and shrapnel are also needed in flash radiography.

Summary

Radiographic testing involves a spectrum of equipment and applications. Equipment ranges from very-low-energy vacuum systems to very-high-energy linear accelerator machines. Testing may be performed in the laboratory environment or in the field. Testing extends beyond inspections to include diagnostic techniques, such as real-time and flash radiography.

The NDE Section provides a broad range of radiographic services to support the various programs at LLNL. Equipment ranging from World War II vintage to state-of-the-art is maintained and used. The ongoing effort to continually upgrade and improve radiographic testing is an important part of the programmatic support.

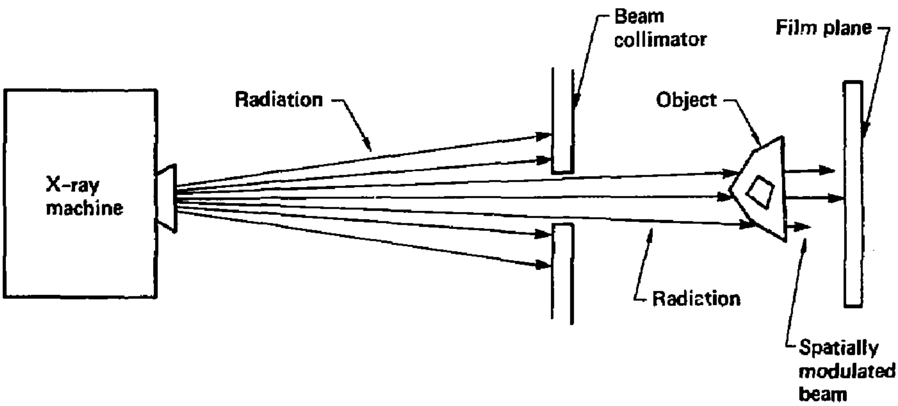

Figure 1. Radiographic setup with an x-ray machine, beam collimator, object and film detector plane.

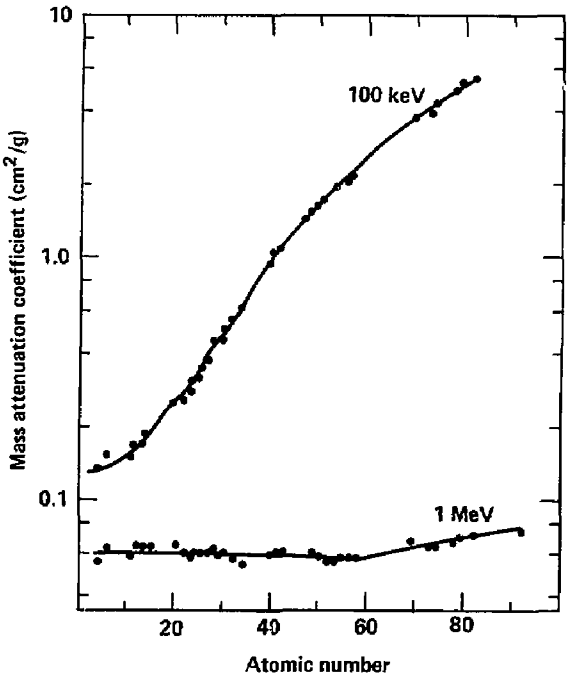

Figure 2. Mass attenuation coefficient versus atomic number at 100-keV and 1-MeV photon energies.

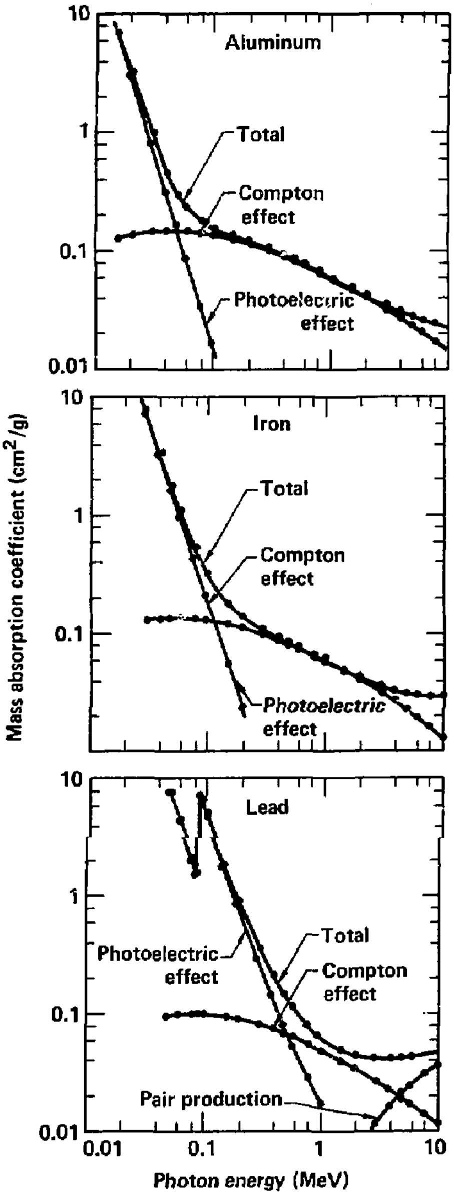

Figure 3. Mass attenuation coefficient as a function of photon energy for aluminum, iron, and lead.

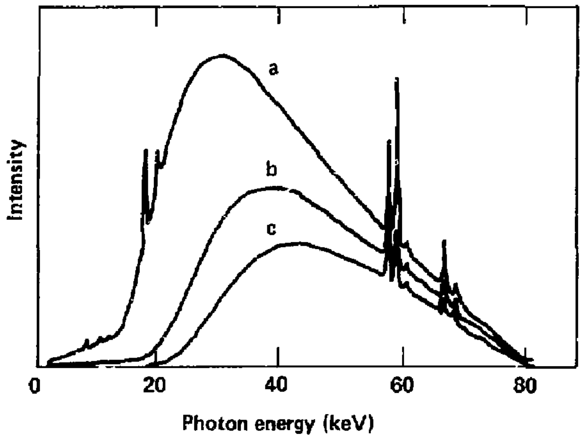

Figure 4. Measured spectrum from an 80-kV$_p$p x-ray machine at (a) no filtration, (b) 2.5 mm aluminum filtration, and (c) 5.0 mm aluminum filtration.

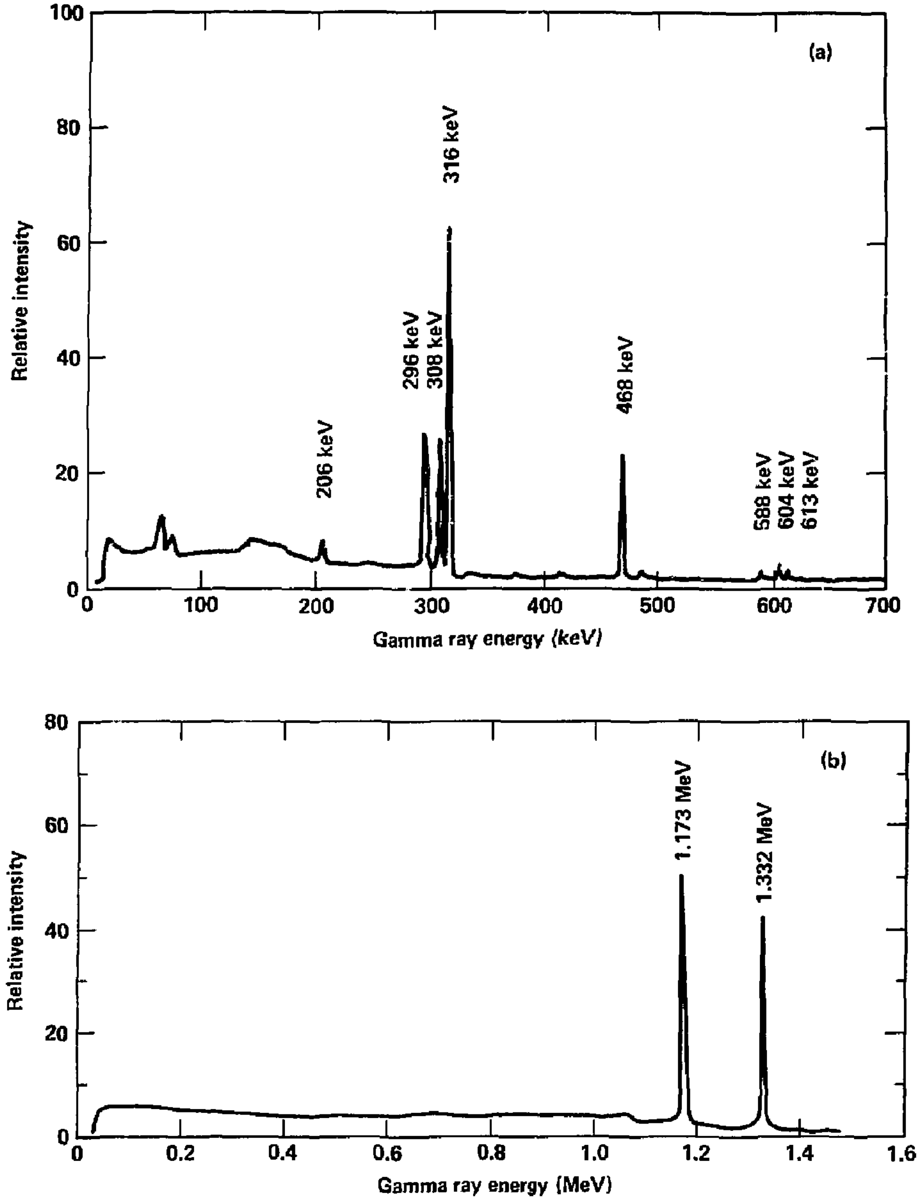

Figure 5. (a) Spectrum of emission from ^{192}Ir. (b) Spectrum of emission from ^{60}Co.

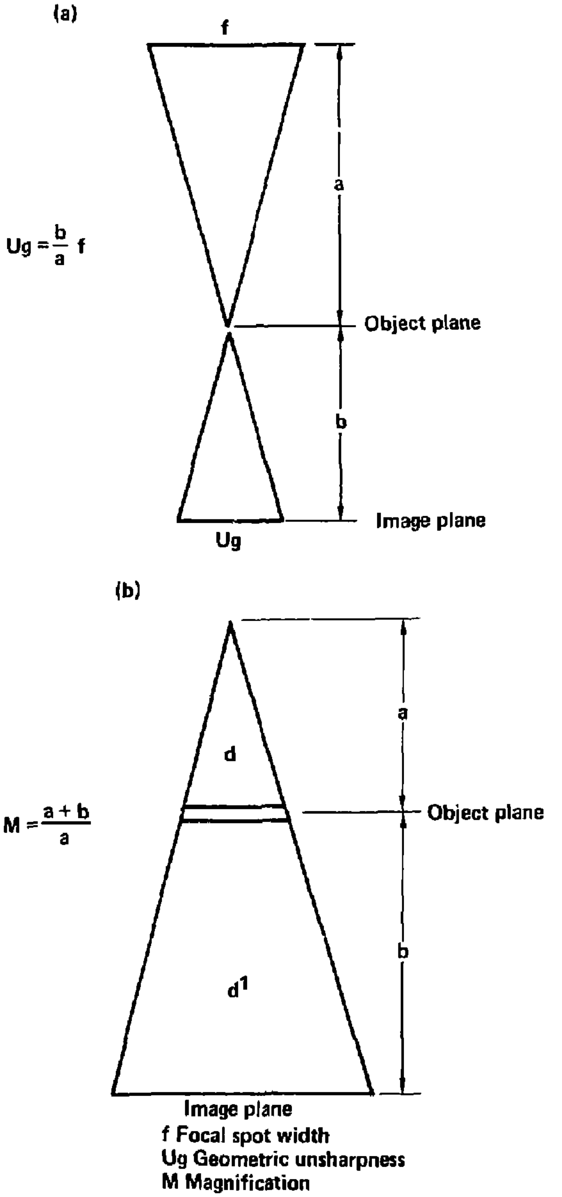

Figure 6. Radiographic geometry consideration for (a) geometric unsharpness and (b) image magnification.

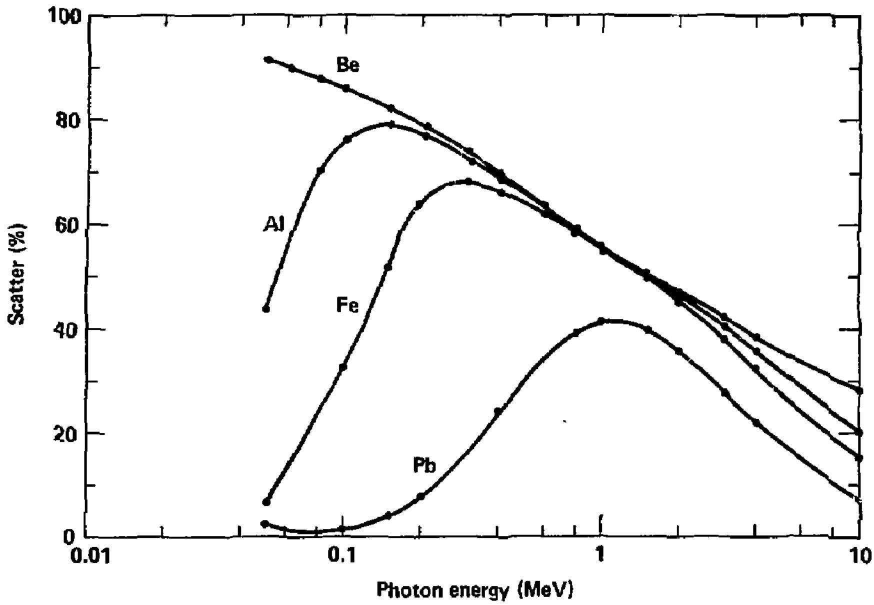

Figure 7. Scatter in the attenuation of radiation for several materials as a function of photon energy.

Figure 8. Low-energy radiography room with vacuum chamber and 50-kV$_p$ head. The 50-kV$_p$ x-ray head for use in air is in the right foreground.

Figure 9. X-ray cabinet units and radiography laboratory area in Building 327.

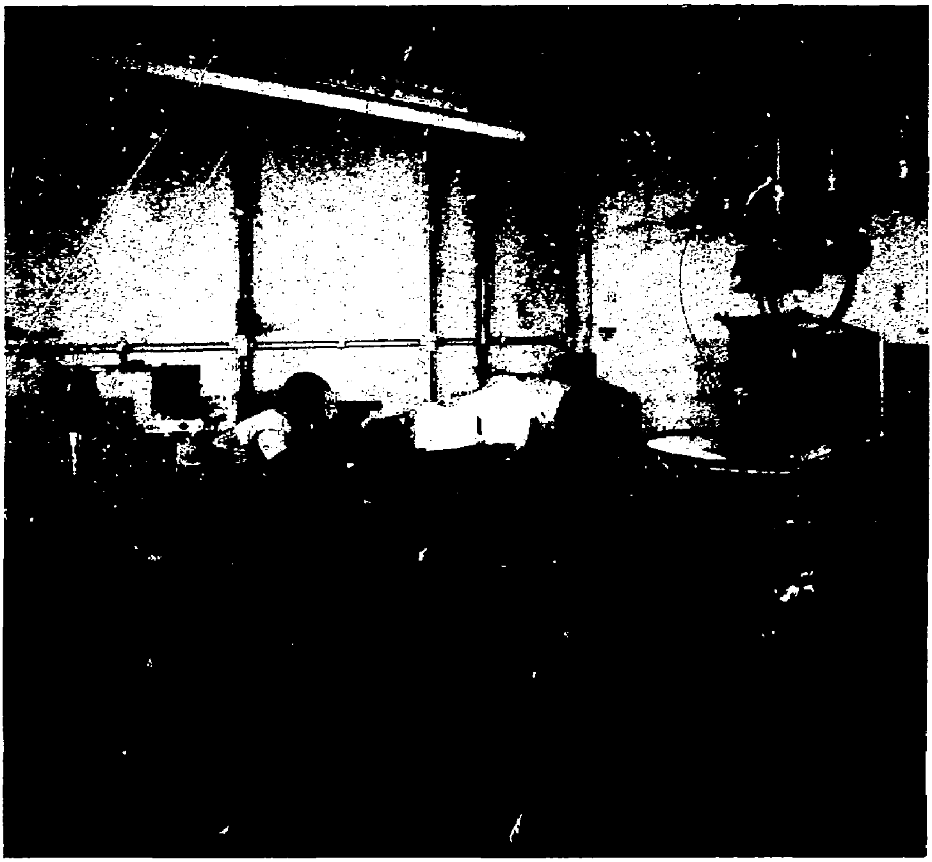

Figure 10. 150-kV$_p$ x-ray cell.

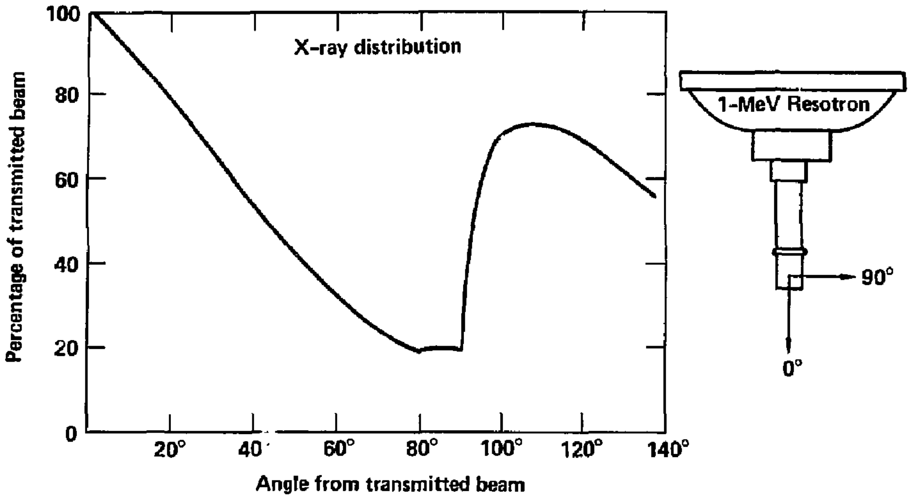

Figure 11. Relative intensity of the beam as a function of angle for the 1-MeV General Electric Resotron.

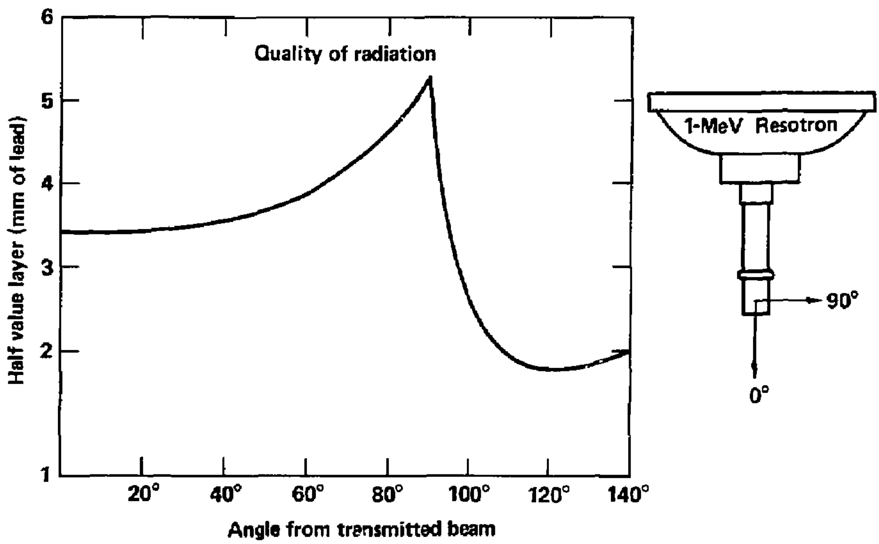

Figure 12. Half-value layer of lead versus angle for the 1-MeV General Electric Resotron.

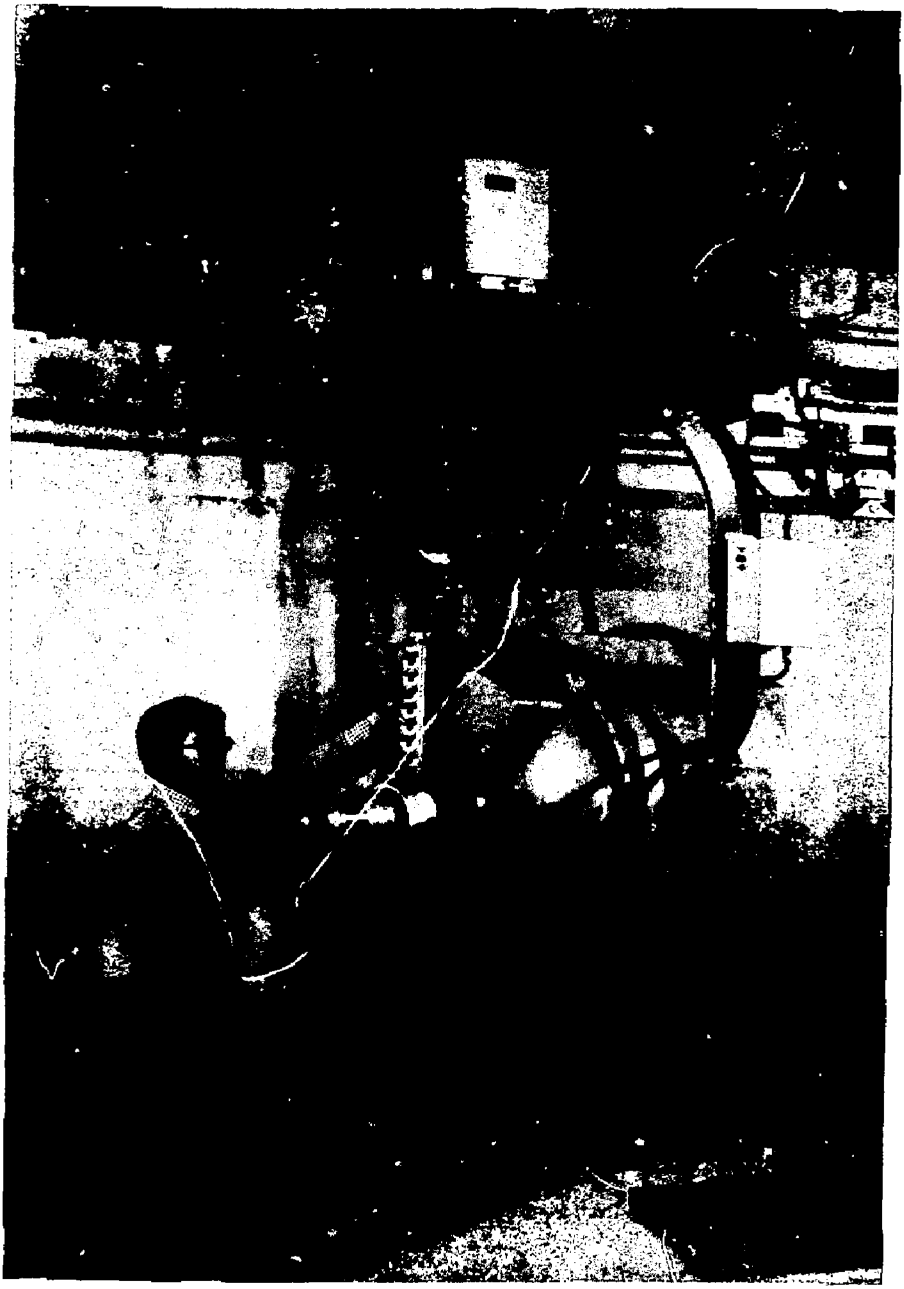

Figure 13. 1-MeV General Electric Resotron.

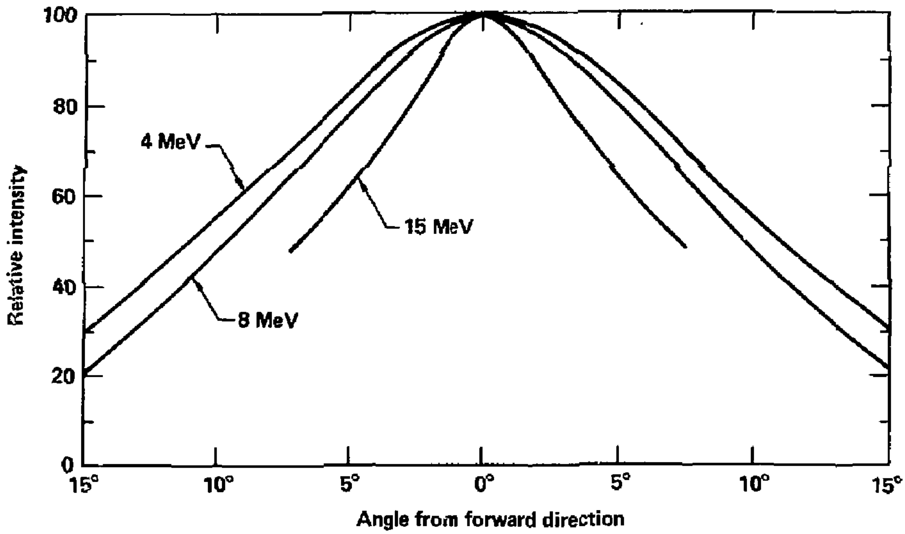

Figure 14. Intensity of radiation as a function of angle from linear accelerators.

Figure 15. 4-MeV linear accelerator and radiography bay.

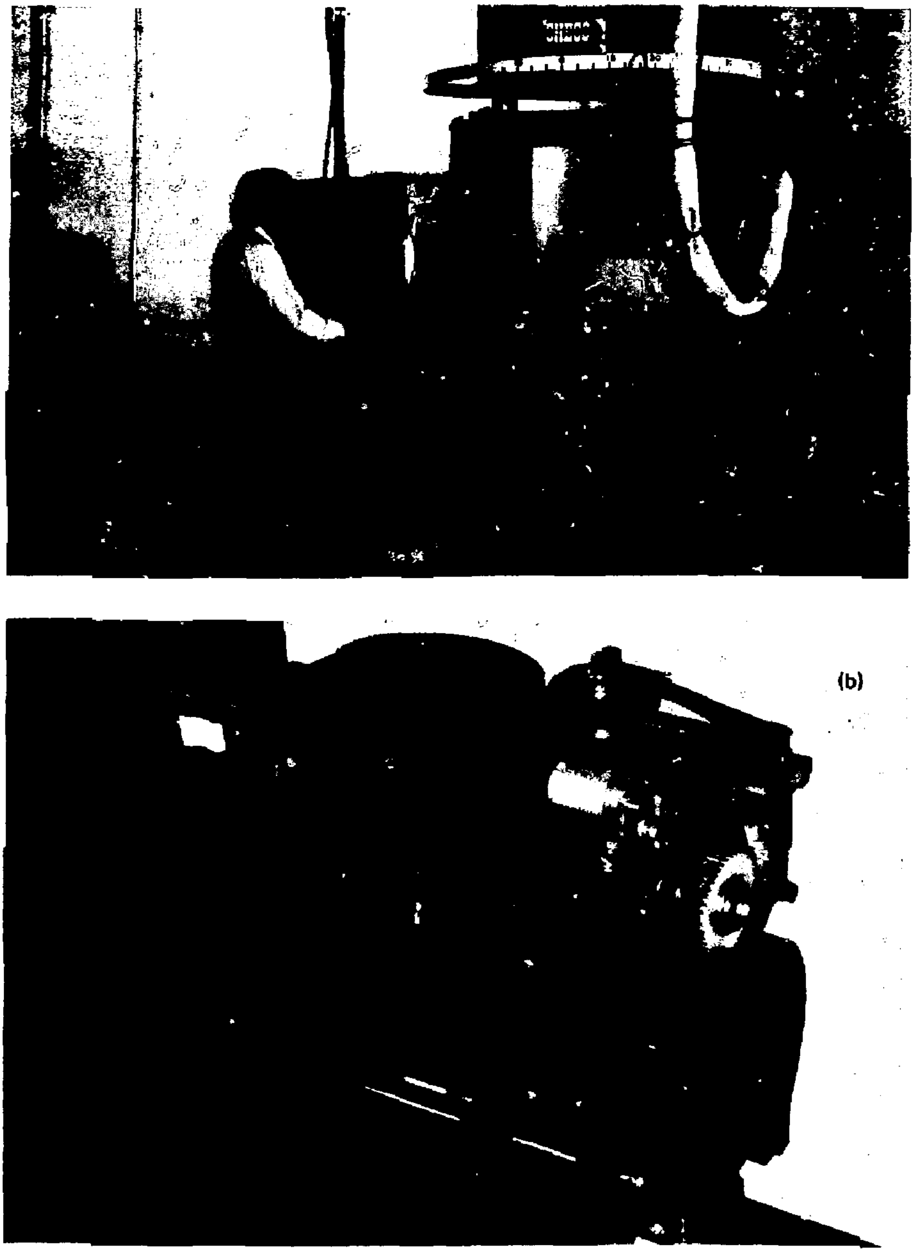

Figure 16. 8-MeV linear accelerator: (a) x-ray head, (b) variable collimator.

Figure 17. 13-MeV linear accelerator.

Figure 18. Isotope source containers, left to right: Gamma Industries Pipeliner, Tech Ops 660, Tech Ops 680, and Picker Cyclops.

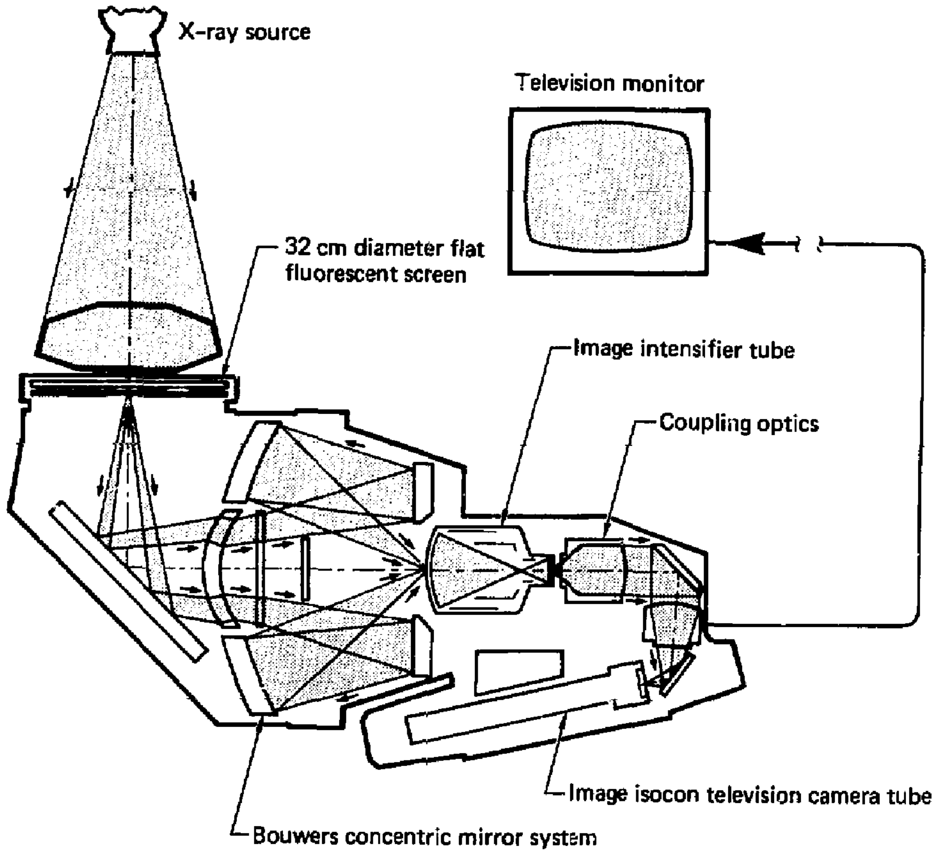

Figure 19. Delcalix real-time imaging system.

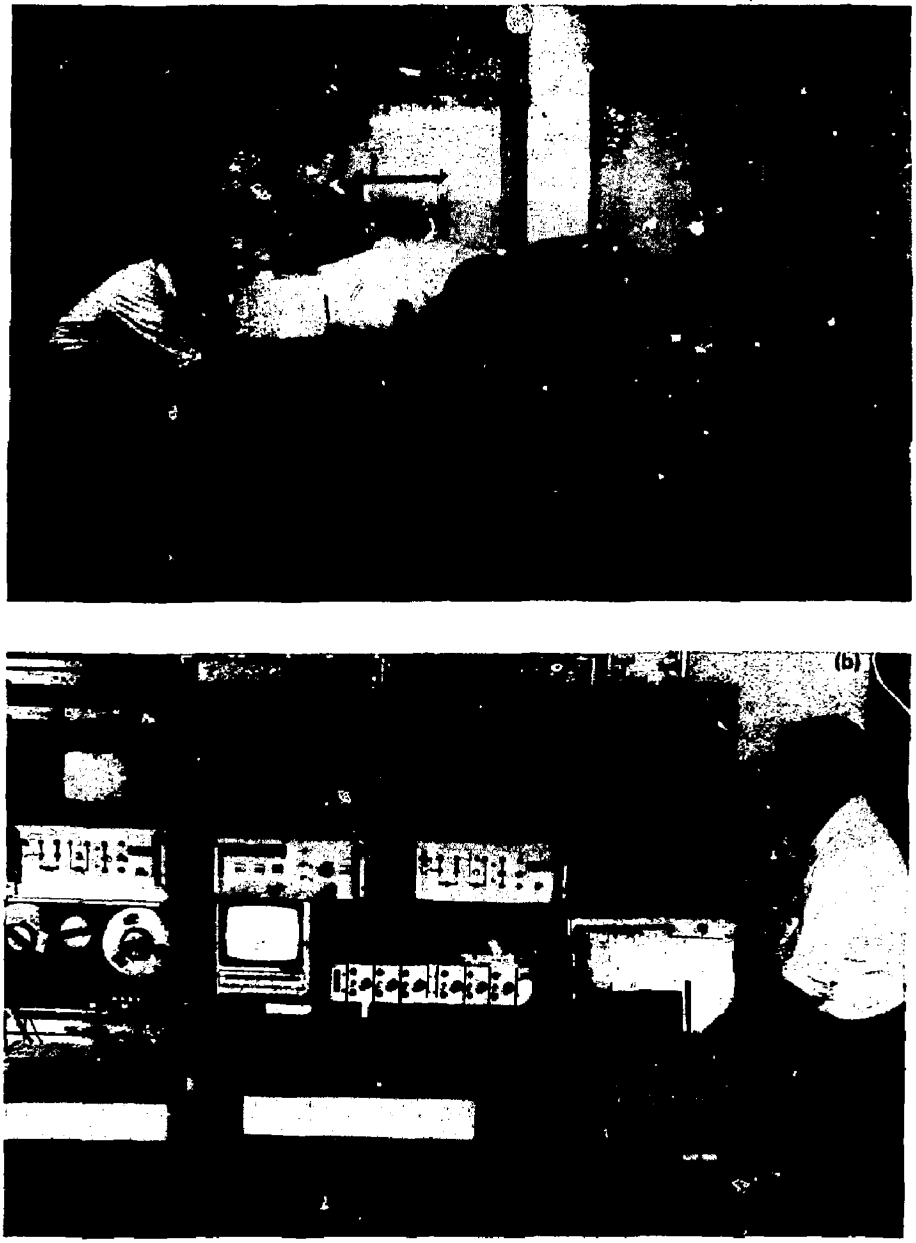

Figure 20. Delcalix imaging systems for a material transfer experiment: (a) 150-keV cave, (b) control room.

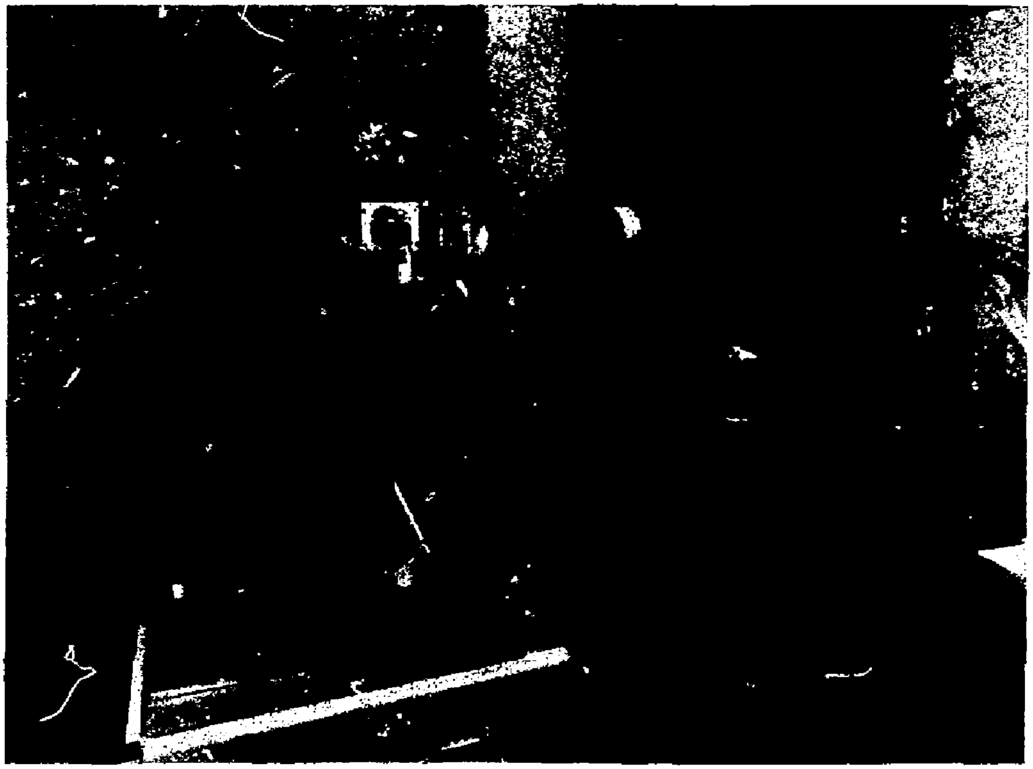

Figure 21. X-ray-sensitive Vidicon camera set up with a remote-control object stage, collimator, and x-ray head.

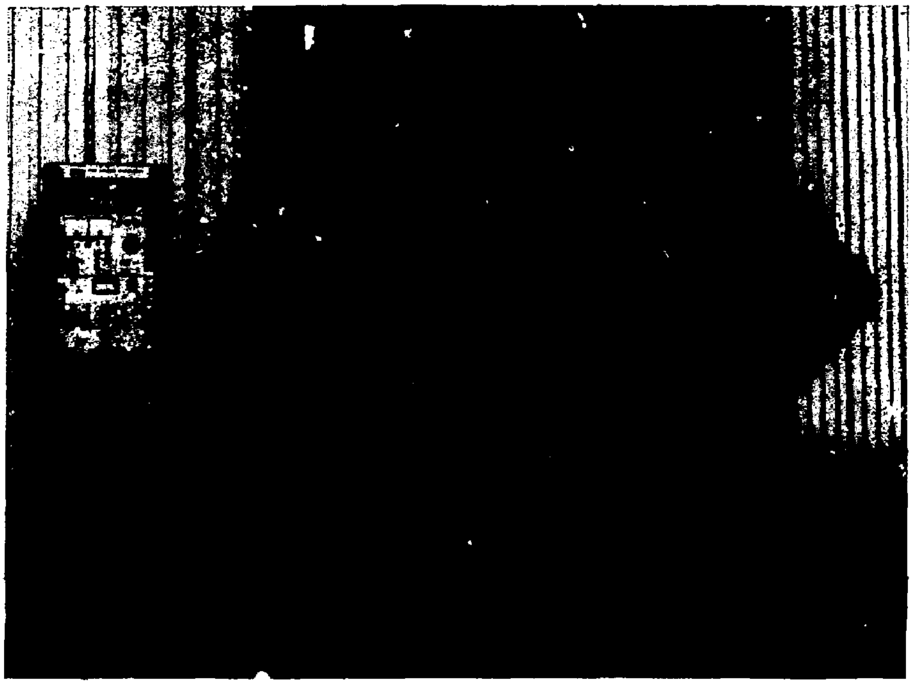

Figure 22. 2.3-MeV flash x-ray system.

(a)

(b)

Figure 23. Flash x-ray systems: (a) 150-keV three-head system, and (b) 180-keV three-head system.

Appendix A

Table A1. NDE radiation sources (low- and mid-energy range).

Energy	Manufacturer	Location	Operating range	Focal spot size (mm)
50 kV_p	Picker	Livermore B-327 A Cave	5-50 keV 30 mA	1.5 × 1.5
50 kV_p	Philips	Site 300 B-809 FS Cabinet	10-50 keV 15 mA	1.5 × 1.5
150 kV_p	Norelco	Livermore B-327 E Cave	25-150 keV 4 mA (small FS) 20 mA (large FS) Rod anode tube 50-150 keV 15 mA	0.4 × 0.4 3.0 × 3.0 1.5
150 kV_p	Siefert	Livermore B-327 G Cabinet	50-150 keV 4 mA (small FS) 12 mA (large FS)	0.6 × 1.2 2.3 × 3.0
150 kV_p	Norelco	Site 300 B-809 SS Cabinet	50-150 keV 8 mA	1.5 × 1.5 4.0 × 4.0
300 kV_p	Norelco	Livermore B-327 H Cabinet	100-300 keV 4 mA (small FS) 10 mA (large FS)	1.4 × 1.9 4 × 4
300 kV_p	Norelco	Livermore B-239 R Cell	100-300 keV 4 mA (small FS) 10 mA (large FS)	1.6 × 1.6 2.5 × 4
300 kV_p	Norelco	Site 300 B-809 KS Cell	50-300 keV 8 mA (large FS)	1.5 × 1.5 4.0 × 4.0
400 kV_p	Siefert	Livermore B-327 J Cell	100-400 keV 8 mA	3 × 3.5

Table A2. NDE radiation sources (high-energy range).

Energy	Manufacturer	Location	Output	Focal spot size
1 MeV	General Electric	Livermore B-327 Y Cell	60 R/min at 1 m	10 mm diameter transmitted beam
1 MeV	General Electric	Site 300 B-809 VS Cell	60 R/min at 1 m	10 mm diameter transmitted beam
4 MeV	Varian	Livermore B-239 Z Cell	400 R/min at 1 m	2 × 2 mm
8 MeV	Varian	Livermore B-239 X Cell	2000 R/min at 1 m	2 × 2 mm
13 MeV	Varian	Site 300 B-823 WS Cell	2000 R/min at 1 m	1 × 1 mm

Table A3. NDE radiation sources (portable x-ray machines).

Energy	Manufacturer	Number of units	Operating range	Focal spot size (mm)
110 kV_p	Picker (Hot Shot)	4	20-110 keV 4 mA	0.5 × 0.5
100 kV_p	Picker (Ranger)	1	20-100 keV 10 mA	0.25 × 1.2
250 kV_p	Andrex	1	50-250 keV 5 mA	3.0 × 3.0
300 kV_p	Triplett & Barton	1	50-300 keV 10 mA	3.4 × 4.7

Table A4. NDE radiation sources (isotope sources).

Isotope	Container type	Number of units	Maximum load (Ci)	Container weight (kg)	Typical size of source (mm)
^{60}Co	Picker Cyclops	2	2000	1000	5 × 12
^{60}Co	Tech Ops 520	1	1000	1040	4 × 9
^{60}Co	Tech Ops 680	4	100	184	2.5
^{192}Ir	Pipeliners (Gamma Industries)	4	100	14	3.3
^{192}Ir	Tech Ops 664	1	100	20	3.2

DPH/ks