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Non-Destructive Testing; Radiography and Tomography

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1. Introduction

The detection of defects in solids is a necessary part of the control of engineering systems for their safe and successful use in practical situations. This is known variously as non-destructive testing (NDT), non-destructive evaluation (NDE), non-destructive characterization, non-destructive inspection (NDI), but also as quality control, quality technology, or as non-contact measurement. However, investigations go much deeper and are much vaster in scope than the detection of gross defects, and concern all aspects of the characterization of solids, their microstructure, texture, morphology, chemical constituents, physical and chemical properties, as well as their methods of preparation. There is concern for the minutest detail which may affect the future performance of the object in service, so that all properties need to be under control and all factors understood which may lead to breakdown. Nor it is appropriate to make general statements since each study and each example must be treated individually, proceeding by the use of all known properties and information about the component. Practical situations are always involved in these examinations and it is for this reason that the solid under examination should be referred to as the Engineering Component.

The art of non-destructive testing covers all possible measurements of properties that do not damage the solids involved, so as to determine the suitability of a part for its duty without damaging it. A description of the early evolution of NDT is given by Mullins (1,2) and his review still covers most of the methods presently used. The theory and practice of the established methods are well known, and it is only their use in practical situations that is developing and evolving with time. The established test methods include radiography, ultrasonics, thermography, electrical and magnetic methods, visual testing, and microscopy. In the case of radiography, x-ray and gamma ray

are well established, but neutron, proton, ard Compton scattering need also be considered and these are described in Section 2. More detail is given to recent developments than to the established aspects of the technique, and the advances in tomography are discussed in Section 3. A series of examples are listed in Section 4. Other NDT methods covering a wide spectrum are listed with references in Section 5. Organizations concerned with NDT are described in Section 6. Many of the NDT methods are highly sophisticated, yet there are a whole series of techniques that are relatively simple. One such method is visual examination, with optical aids. These methods are stressed, since it is important not to overlook the obvious in examining an engineering component. Discussions are presented in Section 6.2 concerning NDT in the developing countries.

Applications of NDT in industry concern metal, non-metals, very small to very large objects, and stationary as well as moving components. In medicine, NDT includes mammography, NMR scans, general x-radiography, and microangiography. Non-contact measurements using sensors are important in a wide range of subjects from geology, forensic studies, aerial temperatures and weather surveys, to thickness measurements and art authentication. The examinations are concerned with flaws, defects, discontinuities, imperfections, inhomogeneities, temperature and pressure variations, topography, and surface contamination.

The situation or system can vary over such a wide range that the term NDT, by itself, is not really sufficient; it is essential to add the nature of the specific product, or material. The operator of the tests is another important factor, and operator fatigue, as well as training, represents both an essential ingredient and a severe problem affecting all aspects of NDT. Since NDT is all embracing, it is most useful to have a library of as many examples

as possible, all concerned with practical situations. For this reason, a very extensive set of examples is given in Section 4, with the appropriate references.

2. Radiography

NDT by radiography has been used extensively in industry, medicine, art authentication, forensic studies, ballistics, moving parts of machinery, geological studies, as well as many other subjects. Different radiations and particle beams can be employed having different absorption characteristics in materials, and this enables the best conditions to be chosen to obtain optimum contrast in the image. X-rays, γ-rays, neutrons, protons, electrons, α-particles, and Compton scattering have all been employed. The radiography can be by Flash X-ray systems (for studies of ballistics and moving objects), laminography and tomography for views in sections of three-dimensional objects. X-ray microscopy, autoradiography and activation analyses are all closely related topics .

X-radiography is one of the earliest NDT techniques, and indeed Röntgen in 1897 reported on the observation of weights inside of a box, and of voids in a metal object (3). X-rays are generated when high energy electrons strike a solid surface (4), as synchotron radiation (5), and by very high temperature plasma (6); these methods are discussed in (7) Chapter 7. A typical x-ray system for radiography is shown in Fig. 1 when a wide range of x-ray photon energies are generated up to a maximum corresponding to the potential difference applied to the x-ray tube (4). The diverging x-ray beam is essential for radiography, though x-rays scattered by the object can remain within the diverging beam and reach the film (or detector). X-ray tubes for NDT are discussed in reference (8). These scattered x-rays will reduce the image con-

trast which is due to absorption differences within the specimen. A system of grids is sometimes employed to eliminate the scattered rays from reaching the detector; further details are given in (9).

It is useful to consider the nature of the various factors contributing to the linear absorption (attenuation) coefficient μ, defined by

$$I(x) = I(o) \exp(-\mu x) \tag{1}$$

where $I(x)$ is the x-ray intensity at a distance x, and

$$\mu = T + \tau + \sigma + k + \pi \tag{2}$$

where T is the Thomson scattering, τ is the photoelectric effect, σ is the Compton scattering consisting of $\sigma(A)$ absorption and $\sigma(S)$ scattering, k is the pair and triplet formation, and π is the photodisintegration. The relative contributions of these factors to the attenuation of the beam depend on the photon energy and absorber composition. Below 1.022 MeV, k and π are zero; τ is the dominant factor for high atomic number atoms irradiated by low energy photons; Compton scattering is important for low atomic number specimens (9). Eq. (2) can be rewritten as

$$\mu(m) = \mu/\rho = \mu(S) + \mu(\tau) \tag{3}$$

where $\mu(m)$ is the mass absorption coefficient, ρ is the density, $\mu(S)$ is the scattering component (Compton and Thomson), $\mu(\tau)$ is the photoelectric and other effects where the energy of the x-ray photon is converted into other energy forms. The regions of relative importance of $\mu(S)$ and $\mu(\tau)$ with photon

energy and atomic species are given in Fig. 2. The variation of the absorption coefficient with atomic number Z and x-ray wavelength λ are given by the approximate empirical relationships of

$$\mu/\rho \propto Z^n \propto \lambda^m \tag{4}$$

where $n \sim 4$, and $m \sim 2.5$ except at absorption edges (4).

The detection of x-rays using films, intensifying screen, channel plates, and solid state detectors is discussed in references (7) and (9); and in an appendix of reference (10).

The quality of the radiographic image is often discussed in terms of the "unsharpness", that is the inability of a radiographic image to reproduce faithfully the boundary of a given contrast. The quality of the radiographic image is expressed also by resolving power, that is the number of lines of unit length resolved when line separation and line width are the same. This means that the unsharpness, expressed as m.m. at half-width, is inversely related to resolving power, expressed as lines per m.m.: see (9). The unsharpness of an image is made up of geometric unsharpness, screen unsharpness, and film unsharpness. The geometric unsharpness consists of effects due to the x-ray source focal spot size, motion of the object, and focal spot motion. Typical values in medical radiographs for screen unsharpness are 0.25 m.m., and film unsharpness 0.07 m.m. The geometric unsharpness depends on the focal spot size, and on the distance to the object and screen. The resulting unsharpness can be about 0.4 m.m. in typical medical radiographs.

Radiography can be contact (object close to detector), or projection (object close to x-ray source). Fresnel diffraction from sharp edges gives rise to a fringe (first maximum) at a distance x(F) in the image plane; in contact

radiography for thin specimens, about 40 μm thick, resting on the film emulsion, using x-rays of $\lambda \sim 0.1$ nm, then x(F) is about 10 nm, and similar distances apply in projection. A fringe can also occur in the image due to the total external reflection of x-rays, particularly when examination is being carried out of smooth curved surfaces (7). In general, neither Fresnel fringes nor those due to total external reflection play a role in x-radiography, and need only be considered in the case of very special x-ray microscope studies (11).

The limit of detection and contrast for projection radiography depends on the penumbra of the objects as given by simple geometry considerations from the finite size of the source. The detection limit is considered to be determined where the level of intensity between objects falls by 25%, when the resolution limit is found to be of the size of the source (11). A more precise method of consideration of the quality of radiographs uses a modulation transfer function, where Fourier analysis is used to describe the contrast boundary in the image (9). The contrast in a radiograph of an object containing different elements can be enhanced by a careful choice of λ. The contrast will depend on the differences in the mass absorption coefficients of the elements present, and these can become very large when an absorption edge change is involved. An example of this is given by Cosslett and Nixon (11) examining a specimen containing Cu and Pt, using ZnK_{α} radiation, which has a λ just above the K-absorption edge of Cu.

A handbook of essential x-ray and γ-ray data is given in reference (12). Reviews of methods of the interpretation and the sharpening of x-ray images are discussed in references (13), (14), and (15).

2.1 Flash Radiography

High speed flash x-radiography is carried out using an x-ray pulse of 3-100 ns duration, and Fig. 1 is a schematic of such a unit (16, 17, 18, 19). Peak voltages of 100 kV to over 2 MV are used, with a pulse generator (20). The spectrum from W or Mo targets consists of a short λ component (hard x-rays) with considerable penetration, and also longer λ radiation (soft x-rays) which can enhance the contrast of the image. At 100 kV peak voltage, the shortest λ are about 0.1 Å, and at 1 MV λ is about 0.01 Å; this is derived from λ Å = 12.4/V kV (4). Examples of Flash Radiography NDT are listed in Table III

2.2 γ-Radiography

γ-rays are emitted by many radioactive (RA) isotopes which can be used as γ-sources for radiography; γ-rays are x-rays of very high energy from RA sources. Some of the RA isotopes most frequently used are listed in Table I (21, 22, 23). The advantages of RA x-ray sources are relatively small size, low cost, independent of electricity and H_2O supplies, and can be monochromatic. The disadvantages are low intensity levels requiring long exposures, and the short life of the RA isotopes can require frequent replacement. Moreover, substantial shielding must be provided on a permanent basis when using RA sources. Examples of γ-ray NDT are given in Table III

2.3 Neutron Radiography

Neutron radiography complements x-radiography since the absorption characteristics are vastly different. Thus, while x-rays are more heavily absorbed by elements of high atomic number, neutron absorption varies

in an apparent random manner with atomic number so that hydrogen has one of the highest neutron absorption coefficients. Neutron radiography provides much more contrast for organic materials, and also for elements of neighboring atomic number; x-radiography is not suitable for observations of such materials. An example often presented is that of a thin wax string encased in a Pb block of thickness of 2", when the neutron radiograph reveals the presence of the string.

Neutrons are usually classified by energy as cold ($< 10^{-2}$ eV), thermal (< 0.3 eV), epithermal ($< 10^{4}$ eV), and fast (10-20 MeV). Thermal neutrons undergo capture by a nucleus to form a different nucleus; this is the basis of "Neutron Activation Analysis", to be discussed later. Fast neutrons have had very limited use for radiography to date.

Sources of neutrons are atomic reactors, spallation sources, and from RA isotopes. Lists of suitable RA isotopes and their characteristics are listed in (24, V.1, Chapt. 9). A portable neutron radiography system using Cf(252) is described in (25, Chapt. 7). This system is about the same size as a small portable x-ray system. The half-life of Cf(252) is 2.65 years, average neutron energy 2.3 MeV, giving a neutron yield of about 10^{12} neutron/second/gram; γ-rays are also present from the RA source. Thermal neutrons can be detected by a photographic method furnished with a converted screen converting neutrons to α, β, or γ rays. The screen can provide prompt emissions for direct exposures, though γ-rays from the source will be a problem since they affect the photographic film. The presence of γ-rays can be overcome, by using a transfer exposure method; the converter screen is exposed to the neutron beam, becoming radioactive, and is then transferred to a cassette and exposure of film (26).

In a typical direct exposure method, Cd screens are placed both in front of and behind the film, and a recommended combination is a front Cd screen 250 μm thick, and a back Cd screen 500 μm thick. A discussion of the merits of different types of converter screens is given in (26). Examples of neutron radiography are given in Table III.

2.4 Proton Radiography

The use of protons in radiography has been very limited and an extensive discussion of the method is given in (27). The great advantage of this technique is that very small density changes can be detected under suitable conditions, much smaller than for other radiations. Transmission of the monoenergetic proton beam through an object remains approximately constant for about 90% of the trajectory, after which the transmission rapidly drops to zero. It is during this last stage that a small variation in density can have a pronounced effect on transmission. Density changes as little as 0.05% can be detected. The protons can be detected by photographic or polaroid film, and measurements have been made with proton beams of several hundred MeV. Different procedures can be followed using proton absorption, proton scattering, or proton activation autoradiography (27). Applications include thickness measurements with accuracies possible of 2×10^{-3}%, the examination of welded Al sheets of 1/2 mm thickness, of foliage, and of biological specimens. Other examples are listed in Table III.

2.5 Activation Analysis

Elemental analysis of an object can be carried out by activation analysis (AA). Thermal neutron, γ, proton, and deuteron radiations in-

duce nuclear reactions to occur followed by the emission of γ-rays (28). The γ-rays can be detected using Ge (Li) semiconductor devices. The emitted γ-spectra, half-life of the radioactivity, and the type of radiation emitted can be used to identify the elements present (29, 30). In neutron activation analysis (NAA), neutrons are used to induce radiative capture reactions (n,γ), (n,p), (n,α), or (n,2n). Typical nuclear reactions are $Na^{23}(n,\gamma)Na^{24}$, $Al^{27}(n,p)Mg^{27}$, $P^{31}(n,\alpha)Al^{27}$, and $Cl^{35}(n,2n)Cl^{34}$. Quantitative analysis can be undertaken from the induced radioactivity, usually carried out by comparison with standards. Minimum amounts of elements that can be detected by NAA are listed in Table II.

For archeological purposes, the authenticity of ancient coins has been extensively studied by AA (29, 31, 32). One example uses the fact that the Ag coins are contaminated by Au and that, up to the 6th Century A.D., there was up to 1% of Au impurity in Ag coins. Subsequently, with improved methods of refinement, Ag coins contain much less Au. The γ-spectra from coins after irradiation by protons of energy 30 MeV, permit the Au concentration to be determined, which can be used to date the coins.

The age and provenance of oil paintings can be determined by AA. White lead $2PbCO_3 . Pb(OH)_2$, has been used in paintings throughout the ages, and the Pb purity has improved with the refinement process. During refinement, some of the Ra(226) from the U decay series, is removed, particularly in developments since the 18th Century. This means that the relative amounts of Ra(226), Pb(210), and Po(210) (of the U decay series) can be used to determine the age of paint specimens (33).

It is often important to determine the composition at great depths below the earth's surface. This can be carried out using a drill-hole,

typically 4" in diameter. A compact source of neutrons is inserted with a particle counter shielded from the source. The source of neutrons may consist of an α-particle emitter mixed with Be powder when a (α,n) reaction occurs. The neutrons activate the minerals and the γ-spectra is measured by the counter. Rocks bearing Fe have been identified by their characteristic γ-ray spectra (35).

Forensic studies have been carried out on the bullets fired in the assassination of President J.F. Kennedy (36). NAA showed similarities in the Ag and Sb content of several of the bullets found at the scene.

2.6 Shadow Autoradiography

A radioactive specimen in contact with a photographic emulsion will produce an image, and this technique, autoradiography, is used extensively to examine biological specimens, generally deliberately doped with a RA isotope. The RA isotope can be an α-emitter (Pu), or a β-emitter [I(131), Ru(106), Sr(90), and P(32)]. In Shadow Autoradiography, a preliminary shadowing of the specimen is carried out by a metal coating. Specimens examined by this technique are very diverse and include human skin and sputum, sheep thyroid, hung tissue, plant leaves, as well as radioactive powders (22, 30, 37).

2.7 Microangiography

Microangiography is the study by contact or projection x-radiography of the microcirculatory system of animals and humans, using the injection of an x-ray opaque solution. A colloidal solution of Ba, of particles sizes less than 0.5 μm, is typically used. Systems examined include the human eye, brain, and spinal cord (7, 37).

2.8 Thickness Measurements

Control of thickness during the production of objects is a desirable feature of quality control technology. Thickness can be measured by absorption or by back-scattering techniques of x-rays, γ-rays, α- or β-rays, or by x-ray fluorescence (22, 30). In the x-ray gauge, the absorption of a beam of x-rays is used to determine thickness of an object of known composition. A typical example is the use of additives in paper, such as the pigment kaolinite clay ($Al_2O_3 . 2SiO_2 . 2H_2O$) which has been controlled using the attenuation of a monochromatic x-ray beam (38). Similarly, the porosity of materials can be measured (39) as well as the observation of steam voids in water (40).

In the case of RA specimens, the absorption of the γ-rays emitted by the specimen itself can be used to control the thickness. An example of this, is the loading of U(235) reactor fuel elements, monitored by the γ-rays (184 keV) emitted by the U(235) specimen itself (41). The thickness of thin foils has been measured using a beam of α-particles (22) using a RA source which emits α-particles with a range of about 3.4 cm in air. The sensitivity can be adjusted to detect small changes in thickness of about 1%. A beam of β-particles has been used to determine the thickness of foils from rolling mills of Al and of steel, and in another use, to control the tobacco content of cigarettes; a radioactive isotope Sr(90) is used, which emits β-rays of energies up to about 1.35 MeV. There is an empirical relationship (22, 42) relating density, ρ, specimen thickness t, to the energy of the β-ray E_M MeV, where

$$\rho t = 0.45\ E_M - 0.16. \qquad (6)$$

The thickness of coatings on substrates can be measured using the back-scattering of x-rays, γ-rays, or β-rays. The sensitivity depends on the difference in atomic number between the substrate and coating materials (22). Typical measurements are of Sn, Zn, Cr, or brass coatings on steel, paint, or lacquer on metallic surfaces, rubber or plastics on calendering rolls, Se layers on Al, Ba coatings on photographic paper, plastic coatings on wires, glaze on porcelain. In the case of Sn plating on steel, the coatings can be controlled to about 10^{-6} cm, that is about 0.3 mg/cm^2.

X-ray fluorescence (30) has also been used to estimate surface conditions, and this is appropriate for elements of high atomic number when fluorescent yield is more important than the production of Auger electrons. Fluorescence is induced in the substrate and the reduction in intensity of the fluorescent beam leads to a calculated value of the thickness of the surface coating. When measurements are carried out in air, the longer fluorescent x-ray wavelengths are absorbed; the limit in air is the fluorescent radiation from Ti (Z = 22 with K_αx-rays, λ = 2.75 Å), when a path in air of about 10 cm will reduce the x-ray intensity by about 50%. Examples of fluorescent measurements of thickness are silver plating on Cu; Mo radiation (Mo $K_\alpha\lambda$ = 0.71 Å) is used which causes the Cu to fluorescence. In deriving the thickness of the Ag plating, allowance has to be made for the absorption in the coating of the incoming MoK_α x-radiation, as well as the attenuation of the CuK_α fluorescent radiation traversing the coating (4). Another application concerns the thickness of Zr cladding (about 0.01 cm thick) on U core nuclear fuel pins of diameter of about 0.3 cm; x-rays from a W target at 50 kV were used to excite

the ULα (λ = 0.911 Å). This enabled the identification of regions where the Zr cladding was less than 0.0075 cm thick (30, 43).

Autoradiography can also be used to measure coating thicknesses, and an example of this is the use of a flat U source on which sheets of Al, Zr, or stainless steel can be placed. The β-radiation of energies up to 2 MeV traverse the sheets, leading to accuracies of about 5% in thicknesses of metal sheets of about 0.5 mm (22, 44).

2.9 Other X-ray Methods

There are several other x-ray techniques used in the testing of solids. X-ray microscopy, or micro-focal radiography, is projection x-radiography using an x-ray source having a very fine spot size (7, 11, 45). These special x-ray generators are reviewed in Chapter 1 of reference (7). X-ray focal spot sizes down to 50 µm diameter have been obtained by special focusing techniques at 40-100 kV, with a target loading of 1 mA. This is achieved in metal-ceramic x-ray tubes with electrostatic focusing.

Various studies are in progress on x-ray optical systems. These are reviewed in references (46) and (47). Direct viewing of x-ray images can be carried out by fluoroscopy, using intensifiers of the x-ray image; these methods are reviewed in references (9) and (30).

X-ray topography is reviewed in references (34) and (48); single crystals can be examined to display dislocations, stacking faults, twinning, lattice distortions. Polycrystalline aggregates can be examined for strains, surface relief, and texture. Monochromatic x-radiation must be employed, and exposures are long, except when synchroton radiation and image intensifiers are employed.

Residual stress NDT measurements can be undertaken of polycrystalline surface layers by x-ray diffraction and the technique is reviewed in reference (49) and the principles discussed in reference (4). These measurements are very delicate, time consuming, and require extreme precision.

3. Tomography

Tomography is literally, "the picture of a slice." The differences between radiography and tomography are illustrated in Figure 3. In conventional radiography by transmission, the contrast of a defect is due to absorption differences along the total path that the x-ray traverses, as shown in Figure 3(a), and there is no attempt to determine the distance along that path of the position of the defect. Conventional radiography is by shadow projection. The position of the defect is revealed more precisely if scattered x-rays are used; see Figure 3(b). In Scattered Radiography, the region under view in the object is defined by the line of vision of the detector; this is the case using Compton scattering. Another procedure uses special motions in transmission to blur all of the object planes except the one of interest; see Figure 3(c). This is known as Laminography or Motion Tomography. A further method is Reconstructive Tomography, see Figure 3(d), where all of the planes are excluded except the one of interest, and mathematical procedures are used to reconstruct the image of the plane. In Flashing Tomosynthesis, or Multi-Radiograph Tomography, the image consists of several overlapping x-radiographs. These are unscrambled optically from the multi x-ray radiograph, see Figure 4. These methods, providing data about the 3-dimensional position of defects, are now described in more detail.

3.1 Laminography

In laminography, the x-ray source, the object, and the film are moved simultaneously, so that the projection of one particular layer of the object remains stationary relative to the film. All other layers of the object project as blurred images, since they move relative to the film (30, 50, 51, 170). The object needs to remain constant throughout the exposure, which may require a high x-radiation dose, so that this procedure is not appropriate for human beings. Different levels of the object can be viewed by adjusting the particular plane of the object in synchronism with the detector plane. Specimens examined include the variations in the wall thickness of a glass bottle (51, 170), the different levels of a complex circuit board, and the interior of a stopwatch (50).

3.2 Compton (Inelastic) Imaging

This has been applied as NDT tomography to topics as varied as microporosity in plastic explosives, and to medical studies of tumors in human tissue (52, 53). In elastic or Compton scattering results from the scattering of x-rays with a loss of energy due to recoil energy transferred to electrons. The change of wavelength $\Delta\lambda$ is given by

$$\Delta\lambda \propto (1 - \cos\phi) \tag{7}$$

where ϕ is the Compton scattering angle (42). This provides for a discrimination between the incoming x-rays and the Compton scattered x-rays of lower energy. These Compton scattered x-rays permit the monitoring of the electron density and compositional change, since the image position

is defined by the small overlap volume of the incident radiation and the scattered beam; see Figure 3(b).

Compton scattering is of sufficient intensity to be detected and differentiated from the elastically scattered radiation. The use of an industrial-type (tungsten) x-ray tube operating at 200 kV provides sufficient Compton scattered x-rays to record a suitable image on film in 2 hours of an Al casting (52). The recording time can be reduced drastically by the use of a standard x-ray image intensifier with a TV monitor when a suitable image can be obtained in less than 1 second (53). The x-ray beam in the form of a diverging fan irradiates one slice of the object; a pin-hole lens permits Compton scattered rays at 90° to enter the x-ray camera and be recorded.

With this simple system, a spatial resolution of about 1 mm is obtained of the slice of the object examined. A more advanced system has been constructed, COMSCAN (53); the x-ray tube is a standard industrial type and is operated at about 65 kV. Several collimator slits are provided, around an irradiated object, and the scattered x-rays detected by an extended array of scintillation counters of $Bi_4Ge_3O_{12}$. The volume elements of the object examined are 1 mm x 1 mm x 7 mm.

In other systems, γ-rays from RA sources have been used; e.g., Co(60) (about 200 TBq) sources, providing γ-rays of energies 1.17 and 1.33 MeV, with NaI(Te) solid state detectors. The Compton scattering can be observed at any angle, so that measurements can be carried out in an object where there is only restricted access to one side of the object.

Applications of Compton scattering tomography include examination of Al car engine components, breast cancer and its spread into surrounding tissue, examination of the human skull and jaw, the explosive charge in

shells, cooling channels in aero engine turbine blades, location of Fe bars behind 4 cm thick concrete walls, examination of the Fe base of crude oil tanks, the inspection of Fe bars and voids in concrete (52, 53).

Future developments depend on the availability of high energy x-ray sources.

3.3 Flashing Tomosynthesis

Multiple-Radiograph Tomography, or Flashing Tomosynthesis (54) requires radiographs to be taken of an object from several different angles. The reconstruction of the image of a particular layer is carried out optically, and the principle of the method is illustrated in Figure 4. The first step is the formation of a multiple image taken by flashing x-radiographs of the object using a series of x-ray sources set in the same plane, and subtending different angles at the object. A multiple image is formed, which is then decoded by projecting light through the image from a series of lenses in a pattern related to that of the x-ray sources. In Figure 4(a), and object is shown consisting of a square and a circle in different layers of the object, and illumination by three sources gives rise to a complex multiple image. Three sources of light are now projected through this complex image, in such a way that one feature of the object, here the square, superimposes in the final image; see Figure 4(b). There is a background in the image due to the non-coinciding parts of the image and this noise level can be minimized by careful selection of the pattern of the x-ray sources used, as well as the diameter of the object examined. Objects up to 60 mm in diameter have been examined, giving good images using an array of 25 x-ray tubes, when depths of 15 cm

can be portrayed in planar slices. Good images have been obtained of a phantom human head, skull, and neck (54).

3.4 Reconstructive Tomography

Mathematical procedures can be used to reconstruct the desired image plane from transmission data taken along different paths within one plane of the object, see Figure 3(d). This is known as Reconstructive Tomography (RT), Computed Tomography (CT), or Computer Assisted (axial) Tomography (CAT) (see refs. 10, 55, 56, 57, 58, 59). The various mathematical procedures are known as Iterative Least-square Technique (ILST), Algebraic Reconstructive Technique (ART), and Simultaneous Iterative Reconstruction Technique (SIRT). The data used can be x-ray transmission attenuation, but also ultrasonic (59), NMR (60), neutron transmission (59), or positron annihilation (10). The data from x-ray transmission produces a Sinogram (59), where the intensities in a sinogram are proportional to the line integral of the x-ray attenuation between the source and the detector positions.

The principle of these methods is illustrated in Figure 5; see (56). The object is considered as subdivided into an array of cells as in Figure 5(a). The contributions of the i^{th} cell in the j^{th} array are considered in the observed sinogram, so that the object is replaced by an array of cells, in each of which it is required to determine the relative density of matter. Any observation will provide the effect of the sum of the i^{th} cells along the direction of the j^{th} ray. The process to do this is illustrated in Figure 5(b), which is a simplified case of how the observations can be unraveled to arrive at the original object densities. The original object and ray measurements are shown in Figure 5(b). One

method of procedure is presented schematically using additive corrections. Starting from zero in all cells, one can correct each ray sum to approach the observed values.

Practical examples of reconstructive tomography are body scans (57), mamography (by ultra sonic transmission) (59, 61), nuclear fuel bundles inside a reactor by neutron tomography using 20 neutron radiographs (59), aerospace structures by x-ray tomography (62), and turbine blades and vanes (63).

3.4 Other Tomographic Techniques

Tomography can also be carried out by:

1. Positron Annihilation Tomography; see refs. (10, 64, 65, 66)
2. Radionuclide Tomography; see ref. (10)
3. γ-ray Tomography; see ref. (10)
4. NMR; see refs. (67, 68, 69, 70, 71)
5. Ultra-sonics; see refs. (55, 72, 73, 74, 75).

4. Examples of Radiography and Tomography

A wide range of examples of NDT are listed in Table III, covering Industrial, Medical, General Interest, and Scientific subjects.

A few special interest cases are examinations of "The Statue of Liberty", "The Liberty Bell", and forensic studies on the bullets used at the "Assassination of President Kennedy". Because of the great interest of these studies, very full details have been published, and so provide very useful, fully documented examples of NDT.

During the recent renovation of the Statue of Liberty, in the harbor of New York, USA, γ-radiographic measurements were made of crucial parts of the

original steel structural framework (76). A radioactive source of 3.7×10^{12} Bq of Ir(192) was used, when 5 min. exposures were required.

The "Liberty Bell" in Philadelphia has been γ-radiographed when the famous crack could be clearly seen (76). A source of 2.5×10^{13} Bq of Co(60) was used. The large size of the bell required the radioactive source to be placed at a considerable distance of about 5 m, to provide a full size radiograph. As a consequence, long exposures of about 36 hours were required.

Forensic studies have been carried out on the bullets fired in the assassination of President J.F. Kennedy (36). NAA showed similarities in the Ag and Sb content of several of the bullets found at the scene. This fact can be used in reviewing the number of guns involved in the assassination. The article (36) describes the complete procedure for the NAA of the bullets.

Besides the examples listed in Table III, many others are given in the published proceedings of the conferences and symposia held in recent years, and many of these are listed in ref. (77). Other review references are (24, 78, 79, 80, 81, 82, 83, 84, and 85).

A useful review of all metallurgical NDT is given in ref. (86), and in ref. (77) is given an extensive discussion of all types of metallurgical processes and the appropriate NDT. Several examples of NDT during World War II are given in ref. (87).

5. Other NDT Methods

There are a very large number of methods applied as NDT, and general reviews are given in refs. (21, 23, 77, 85, 86). These many methods are listed in Table IV with references to their description and applications.

6. Organizations Concerned With NDT

6.1 International and European Organizations

Table V gives the names and addresses of organizations closely related to NDT, concerning standardization, quality control, testing of materials, as well as NDT. Other organizations deal with radiation protection; data on radiological procedures are given in refs. (12, 88, 89, 90, 171-174). The American and the International Institutes of Welding are listed, since NDT is such an important factor in the examination of welds.

Table VI lists national societies that are members of or associated with the International Committee for Non-destructive Testing (ICNDT) which is based in Columbus, Ohio, USA.

There are many organizations concerned with standards, and indeed all countries of the world are full members or correspondent members of the International Organization for Standardization (ISO), (see Table V). A recent review of standards for NDT is given in ref. (91).

6.2 NDT in Developing Countries

Many countries, both developed and developing, of the world are members of ICNDT (see Table VI), and so are in touch with developments in NDT. The education of NDT technicians is of considerable importance, since the quality of NDT is only as reliable as that of the worker; this is discussed in several papers in ref. (85). The American Society for NDT (ASNT) has published a series of study handbooks on the training of technicians; see ref. (92). Much information is given, in review form,

in reference (77) on NDT - literature, publications, societies, technical data, examples of defects, standards, and other related matters.

Many of the NDT techniques are highly sophisticated, and these have been discussed in this review. However, there are also many of the essential NDT methods that are relatively simple, extremely effective, and can be established at low cost. A few of these methods include leak testing, liquid penetrant, acoustic, radiography, visual. Introductory texts have been published on these by ASNT (92). Elementary reviews and texts are given in refs. (21, 22, and 86). Useful periodicals are published regularly on NDT, such as ref. (168 and 169). Useful handbooks on x-ray protection and related matters are published by the National Bureau of Standards, Washington, D.C., USA (see refs. 171-174).

The developing countries listed in Table VI, which adhere to the ICNDT, are in a good position to undertake NDT under the best circumstances possible, and it would be a great advantage for any country to have a national NDT society, and to participate to the fullest extent with both ICNDT, as well as with the other international organizations; ISO, IIW, RILEM (all listed in Table V).

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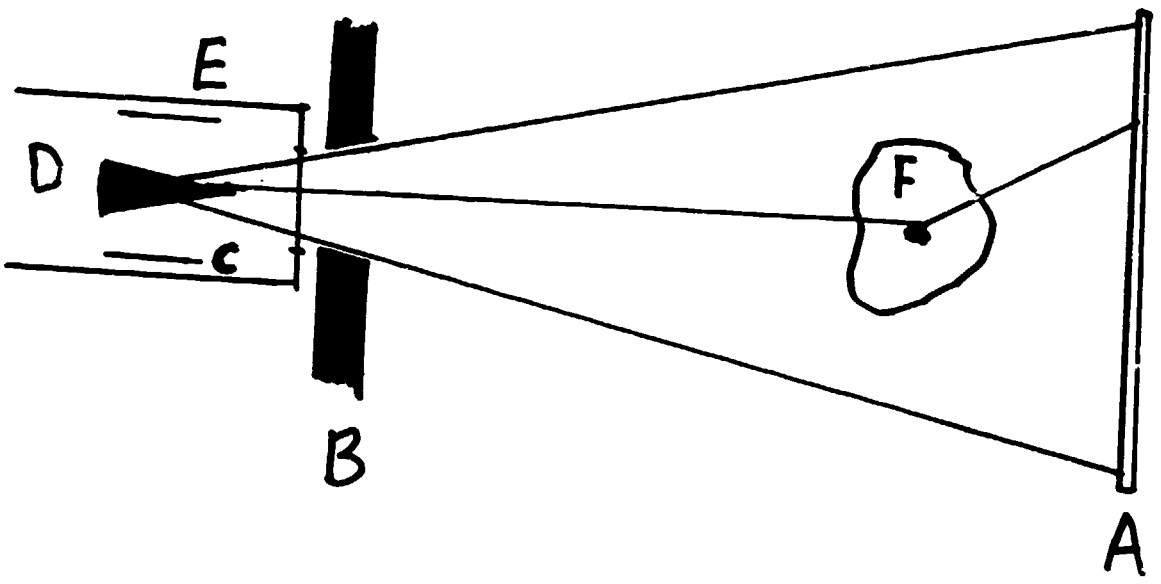

Figure 1. Schematic of X-ray Unit for Radiography. A, Detector; B, Collimator; C, Cathode; D, Target (shaped to project a small source size); E, X-ray Tube; F, object. A beam of x-rays leaves the source, D, and diverges through the defining screen, B, to the detector, A, which may consist of an intensifying screen and x-ray film. Scattered x-rays from the object, F, can attain the detector, reducing contrast in the image. The target is usually W, at a high voltage, from about 50 kV to several MV.

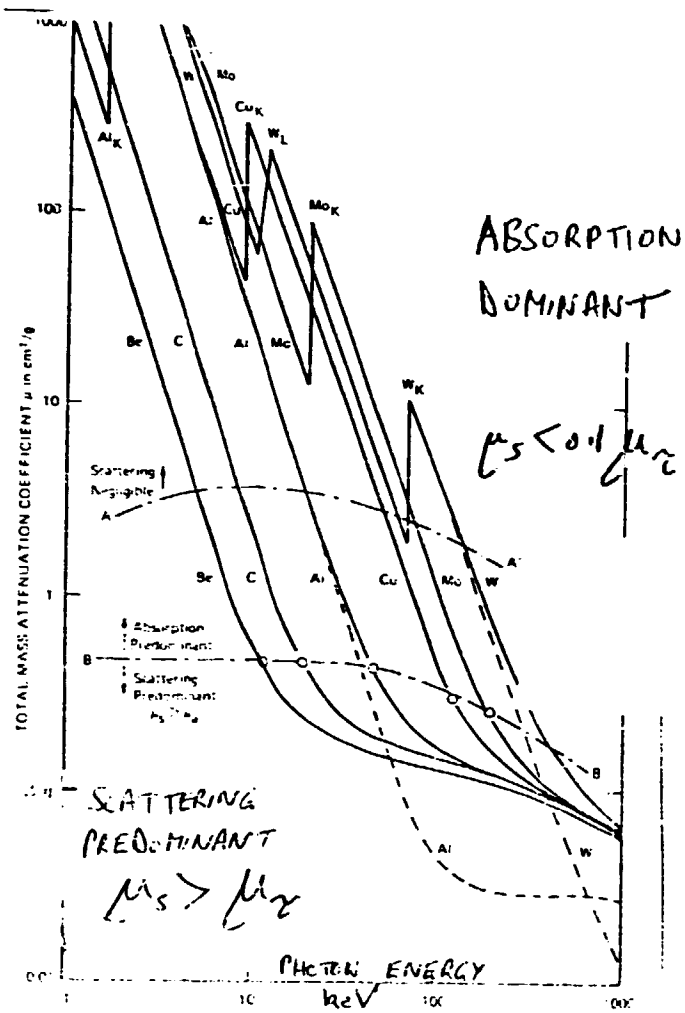

Figure 2. Absorption Processes

Relative importance of $\mu(s)$, due to all scattering processes, and $\mu(\tau)$, due to all true absorption processes, with photon energy and atomic number, where the mass absorption coefficient:

$\mu(m) = \mu(s) + \mu(\tau)$; see text, and Ref. (20).

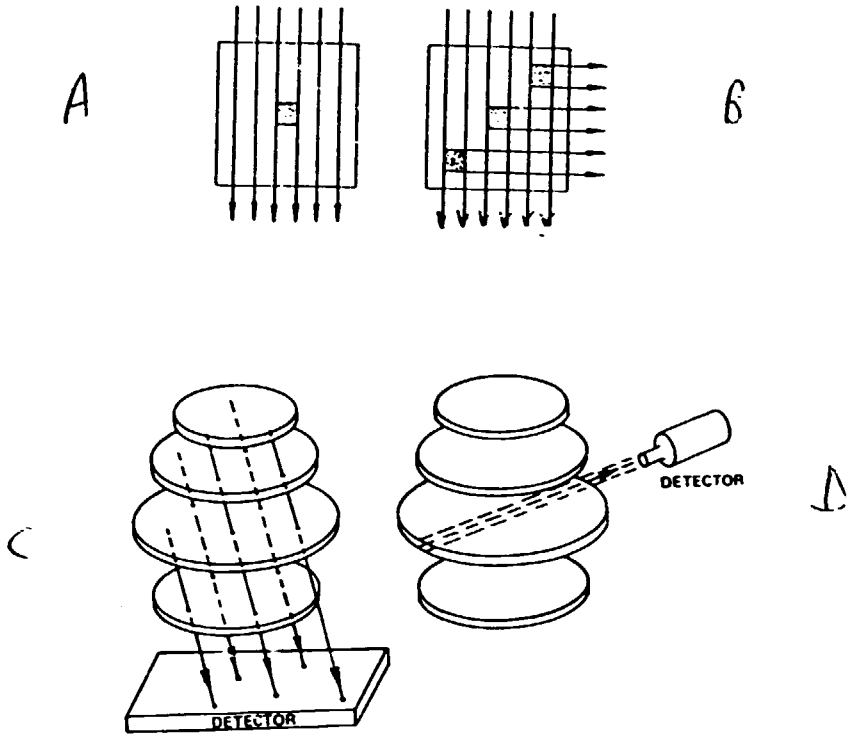

Figure 3. Diagrams Illustrating (A) Conventional Shadow Radiography by Transmission, (B) Scattered Radiography at 90° Where the Line of Vision of the Detector Will Define the Volume Under View in the Object, (C) Laminography, Where Relative Motions of Object and Detector Cause All But One Plane to be Blurred, (D) Reconstructive Tomography, Where Many Observations are Carried Out From Different Angles Within One Plane; (see Refs. 52 and 56).

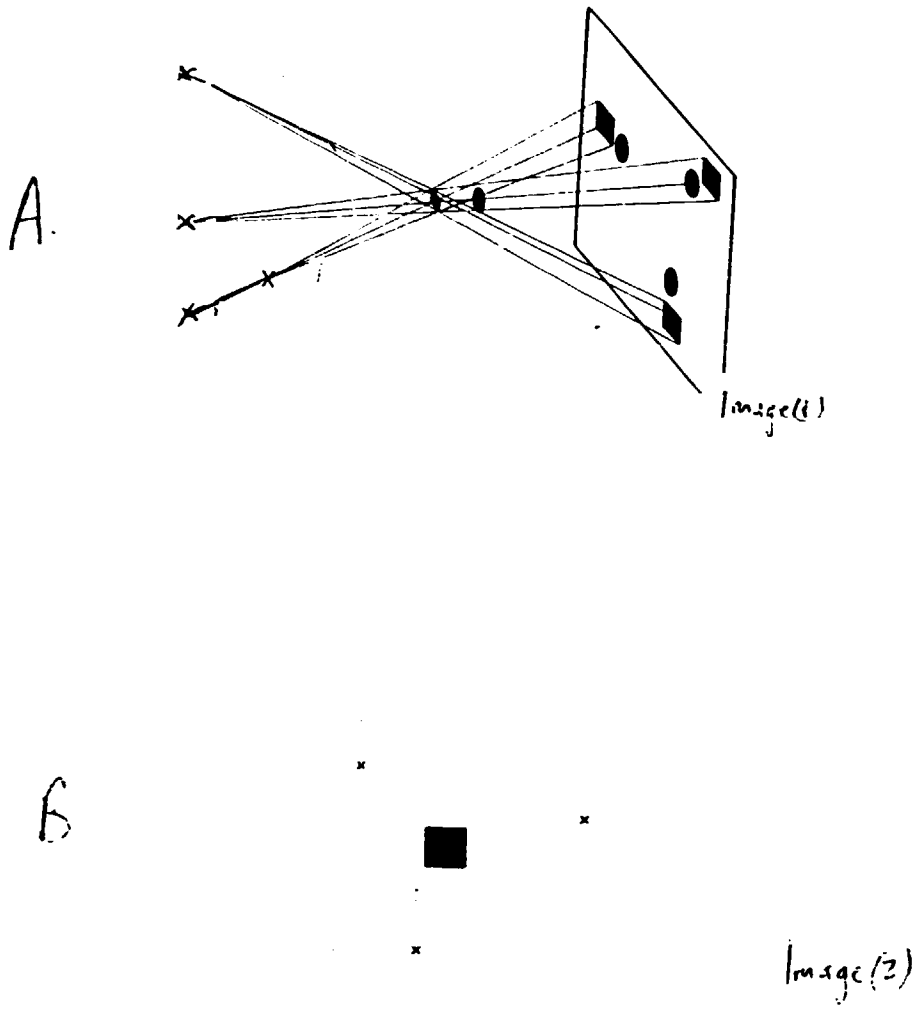

Figure 4. Flashing Tomosynthesis, or Multiple Radiograph Tomography

As an illustration, an object consisting of a square and a circle at different layers are illuminated by three sources resulting in a multiple image, Fig. 4A. Three light sources project image (1) so that the square part of the object is superimposed in image (2). The remainder of the image gives rise to background noise; see text and ref. (54).

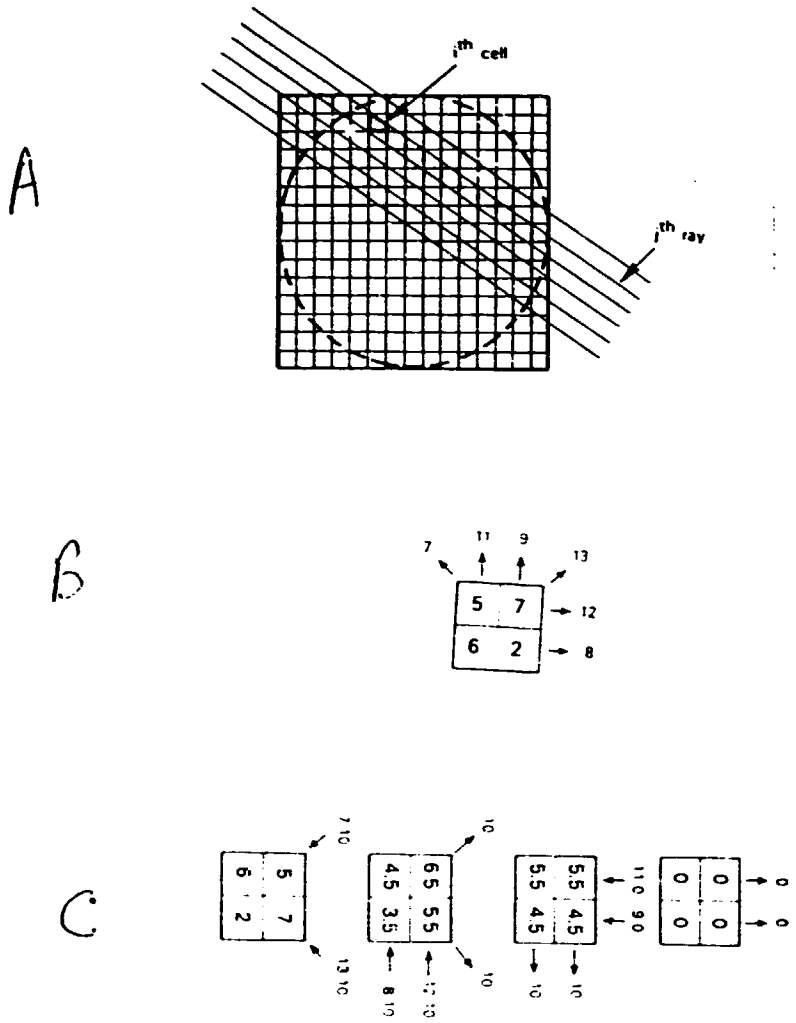

Figure 5. Illustration of Iterative Reconstruction Tomography.

A. The object is considered as an array of small volumes (voxel). The j^{th} ray sums the effects due to the voxels along its path.

B. Simple object of 4 voxel (pixel in 2D). The ray sums are given.

C. Additive Correction Scheme; see text and ref. (56).

Table I.

Radioactive Isotope	Half-Life	γ-rays (MeV)	Effective Source Size Diameter (mm)	Radioactive Source Strength $Ckg^{-1}s^{-1}Bq^{-1} \times 10^{-19}$	Steel Plate Thickness Limit (cm)
$^{60}_{27}Co$	5.3 years	1.17, 1.33	3	20	15
$^{192}_{77}Ir$	74 days	0.21-0.61	0.5	5	10
$^{169}_{70}Yb$	31 days	0.053-0.309	0.3	2	-

Radioactive Isotopes Used as Sources for γ-radiography (see Ref. (23)).

Table II.

Minimum Amounts of Some Elements Detectable by
Thermal Neutron Activation Analysis, Under Normal Conditions, (see refs. 29, 30)

Element	mg	Element	mg	Element	mg
A	1	Cs	10^{2}	Ir	10^{-2}
Ag	0.1	Cu	10	K	10^{2}
Al	1	Dy	10^{-3}	Kr	10^{2}
As	10	Er	10	La	10
Au	1	Eu	10^{-2}	Mg	10
Ba	10	F	10	Mn	10^{-1}
Bi	10^{4}	Ga	1	Mo	10
Br	1	Gd	10	Na	10
Cd	100	Ge	10	Nb	1
Ce	10^{3}	Hf	10^{3}	Ni	10^{2}
Cl	1	Hg	10^{-1}	Os	10^{2}
Co	1	I	10^{-1}	P	10^{3}
Cr	10^{3}	In	10^{-2}	Pb	10^{4}

Table II, (continued)

Element	mg	Element	mg
Pd	10	Te	10
Pt	10	Ti	10^2
Rb	10	Tl	10
Re	1	V	10^{-1}
Rh	10^{-2}	W	10
S	10^4	Xe	10^2
Sb	10	Y	10^2
Sc	10^{-2}	Yb	10
Se	1	Zn	10^2
Si	10^2	Zr	10^3
Sn	10		
Sr	10		
Ta	10^2		
Tb	10^2		

Table III.

Examples of Radiography and Tomography

A. Industrial

Reference	Technique	Subject Examined
7	Projection Radiograph Microfocal X-ray Unit X-ray Microscopy	Integrated Circuit. Incomplete Interface Bonding.
93	Neutron Radiography	Combination Lock in Steel and Light Metals.
25	Neutron Radiography	Adhesive Bonded Metal Honeycomb-Plastic Structure.
25	Neutron Radiography	Explosive Train Devices. Explosive Material in Pyrotechnic Devices.
25	Neutron and X-ray Radiography	Cooling Tubes in Turbine Blades.
25	Neutron Radiography	Bolts on Aircraft Wing. Corrosion on Aircraft Wing Skin. Aircraft Fuel Tanks.
29	Neutron Activation Analysis	Traces of Metal.
35	Neutron Activation Analysis, Using Small Source.	Geological Drill-hole Analysis at Depths in the Earth's Crust.
30, 38	X-ray Gauge (Absorption)	Mass Per Unit Area of Inorganic Coatings on Paper.
39	X-ray Gauge	Porosity of Specimens.
40	X-ray Absorption	Steam Voids in H_2O.
30, 94	γ-ray Absorption	Thickness of Coatings (various)
22	γ-ray Gauge (Absorption)	Hot Steel Strip Thickness

Reference	Technique	Subject Examined
41	γ-ray Emission	Reactor Fuel U(235) Loading by Monitoring γ-radiation.
22	β-ray Absorption	Thickness Control Rolling Operation.
95	β-ray Transmission	Cigarette Industry Control of Tobacco Content.
22	Back-Scattering γ-rays	Thickness of Steel Plates.
22	Back-Scattering β-rays	Thickness: Sn, Zn coatings on steel; paint, lacquer on metallic surfaces; rubber, plastics on calendering rolls; Se on Al; Ba coating on photographic paper; Cr or brass on steel; filters in paper and plastic; porcelain glaze; plastic coatings on wire; Ni or Cr coatings on metals.
22	X-ray Back-Scattering	Thickness: electroplated metal films, evaporated coatings; pigment layers.
22, 30, 43, 94	X-ray Fluorescence	Thickness: Ag-plated Cu; Cd-plating Fe; Zr cladding of U nuclear fuel elements. Range of metal coatings on metal substrates.
51	X-ray Laminography	Wall Thickness of Glass Bottle.
50	X-ray Laminography	Different Planar Views of Printed Circuit Board, Stop-watch.
86	All Techniques	Forgings, Castings, Steel Bars and Billets, Wrought Tubular Products, Weldments, Brazed Assemblies, Soldered Joints, Adhesive Bonded Joints, Threaded Fasteners, Pressure Vessel Pipelines
59, 96, 97	Neutron Tomography	Nuclear Fuel Bundle.
62, 63	X-ray Tomography (420 kV Source)	Aerospace Structure, Turbine Blade.
63, 98, 99	γ-ray Tomography	Concrete, Timber, Steel Structures.
100, 101, 102, 103, 109	Radiography	Pipe Welding, Nuclear Industry Materials, Structural Ceramics, Concrete.

Reference	Technique	Subject Examined
19, 104, 105, 106	Vibrothermography Thermal Wave, U.S.	Composite Materials.
107	U.S. Robot Controlled	Cracks in Nuclear Reactors.
108	TV Holography	Engineering Structures; Vibrations of Car Door.
16, 17, 18, 19, 20	Flash Radiography	Ballistics, Moving Machinery, Projectiles, Phase Transformations.
44	γ-Absorption	Density Measurements.
45	X-ray Microfocus	Ceramics.
27	Proton Radiography	Thickness Al Foil, Leaves, Al Weld.
52, 53	Compton Imaging	Al Casting, Explosives.

Table III, (continued)

D. Scientific

Reference	Technique	Subject Examined
7	X-radiography	Coelocanth Scales With Denticles and Microtubes.
48	X-ray Topography	Fracture Surface Mo Single Crystal Transformation Studies, Crystal Growth Features.
49	X-ray Diffraction Residual Stress Technique	Subsurface Residual Stress, Hardness, Cold-work Effects in Steels, and Other Metals.

Table IV.

Other NDT Methods and References

Technique	References
Acoustic Emission	23, 77, 82, 167
Dynamic and Vibrational Analysis	152, 153
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Xonics Electron Radiography	161

Table V.

International, American and European Organizations
of Standardization, Quality Control, and NDT

1. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)
   1 rue de Varembé, case postale 56, CH-1211 Genève 20, Switzerland
   (Committee on Nondestructive Testing (ISO/TC135) - All countries of the world are full members or correspondent members of ISO.)

2. INTERNATIONAL COMMISSION ON RADIATION UNITS AND MEASUREMENTS (ICRU)
   7910 Woodmont Avenue, Suite 1016, Washington, D.C. USA

3. INTERNATIONAL COMMISSION ON RADIOLOGICAL PROTECTION (ICRP)
   Dr. F.D. Sowby, Clifton Avenue, Sutton SM2 5PU, ENGLAND

4. INTERNATIONAL INSTITUTE OF WELDING (IIW)
   54 Princess Gate, Exhibition Road, London SW7 2PG, ENGLAND

5. EUROPEAN ORGANIZATION FOR QUALITY CONTROL (EOQC)
   P.O. Box 2613, CH-3001, Berne, SWITZERLAND

6. USA NATIONAL COMMISSION ON RADIATION PROTECTION
   P.O. Box 4867, Washington, D.C. 20008, USA

7. AMERICAN SOCIETY FOR TESTING MATERIALS (ASTM)
   1916 Race Street, Philadelphia, PA 19103, USA
   (Special Technical Publications cover many aspects of NDT.)

8. AMERICAN SOCIETY OF MECHANICAL ENGINEERS (ASME)
   United Engineering Center, 345 East 47th Street, New York, NY 10017 USA
   (Special Publications cover many NDT practices.)

9. AMERICAN WELDING SOCIETY
   550 NW LeJeune Road, Miami, FL 33126 USA