Def Sci J, Vol 32, No 3, July 1982, pp 259-273

Neutron Radiography

A. R. REDDY & M. V. N. RAO
Defence Laboratory, Jodhpur-342 001

Received 5 March 1982

Abstract. The field of neutron radiography with special referenceto isotopic neutron radiography has been reviewed. Different components viz., sources, collimators, imaging systems are described. Various designs of neutron radiography facilities, their relative merits and demerits, the appropriateness of each design depending on the object to be radiographed, and economics of each technique are also dealt. The applications of neutron radiography are also briefly presented.

1. Introduction

Industrial radiography is among the most widely practised radioisotopic applications. The technique is non-destructive, highly economical and flexible to suit varied requirements. Sources emitting X-rays, gamma rays or neutrons are used for radiography. Isotopic radiographic systems are simple, completely self-contained, occupy minimum space and are mobile. They are cheap but require long exposure times. ^{60}Co, ^{137}Cs, ^{170}Tm and ^{192}Ir are amongst the important gamma sources used for this purpose.

Radiography with neutron sources (*Am-Be*, *Pu-Be*, spontaneous fission neutron sources like ^{252}Cf and reactors) is done where distinction of internal structures involving hydrogenous or low Z materials is to be made. Neutron radiography offers little or no advantage as a replacement for successful X- or gamma radiography; instead, the two techniques compliment each other and together appreciably expand the usefulness of radiography.

The major difference between neutron radiography and X-radiography is in the nature of interaction of neutrons and X- or gamma photons with matter. The attenuation coefficient of X-rays for different materials increases systematically with increasing atomic number, whereas for neutrons it varies randomly with atomic number. Fig. 1 shows a comparison of neutron (circles) and X-ray (solid lines) attenuation coefficients for various elements[1]. It can be seen that neutron attenuation by low Z materials is generally higher and by high Z materials lower. For some neighbouring elements (e.g. *Cd* and *Ag*, *Pt* and *Au*) the neutron attenuation coefficients are widely different. Because of these differences in absorption characteristics, non-destructive radiography of light elements, composites, rocket propellants, air-craft

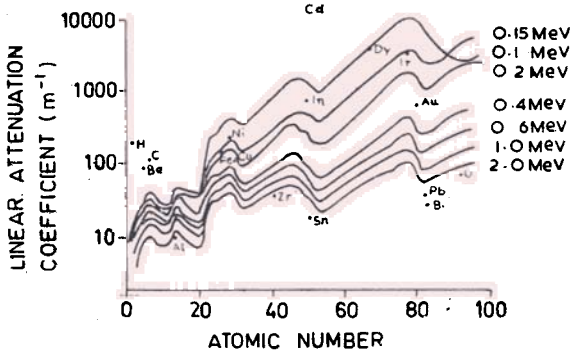

Figure 1. Comparison of X-ray (solid lines) and neutron (circles) attenuation coefficients for various elements.

components, ordnance items, oil and fuel flow in metal components of gas turbines, electronic hardware, highly radioactive specimens, biological specimens, etc., which was not feasible earlier became a possibility by use of neutrons.

Most of the original work on neutron radiography has been carried out with reactor neutrons. However, search has always been on for a more portable and compact source of adequate intensity.

The present paper is a review of the field of neutron radiography with special reference to isotopic neutron radiography.

Although in principle neutrons of all energies can be used for radiography it is the thermal neutron radiography that is more widely used.

2. Neutron Radiography Systems

A neutron radiography system mainly consists of the following major components.

2.1 *Neutron Source*

The three principal neutron sources useful for radiography are : reactor, isotopic sources and accelerators. A summary of the general characteristics of these various types of sources is given in Table[2] 1. A reactor specially designed for neutron radiography is the best neutron source for broad practical use, but an in-house reactor may not be cost-effective for ordinary production units. Accelerators used for thermal neutron radiography include low voltage Cockroft-Walton generators employing the $(d - t)$ reaction, linear accelerators employing the (p, n) reaction and Van de Graaf accelerators in which a beryllium targets is bombarded with deuterons or protons. Of the isotopic sources ^{252}Cf (Table 2) is by far the best but is limited by economics[2]. It is ideal for *in situ* work and may find substantial use particularly where only moderate resolution is needed.

^{252}Cf is a spontaneous fission neutron source with a neutron yield of 2.3×10^{12} n/sec—g and a half-life of 2.65 y.

The advantages of ^{252}Cf as an isotopic neutron source for radiography are :

(a) Low cost per neutron yield; (b) An energy spectrum which allows thermal, epithermal, and fast neutron radiography. (c) Small size, enabling the source to be placed in a portable housing system. (d) Peak thermal flux several times greater than fluxes obtained with (γ, n) sources of the same total fast neutron yield. (e) Easy adaptation to simple, safe and inexpensive water tank facility with a normal amount of shielding. (f) Minimal gamma ray background.

The main disadvantage is the requirment for frequent replacement of source because of short half-life (2.65 *y*).

A method of boosting the output of ^{252}Cf at less than a proportional increase in cost is to use a subcritical neutron multiplier in which the source is surrounded by fissile material and the neutrons emitted by ^{252}Cf cause fission events to take place in the fissile material[3] (Fig. 2). For a subcritical assembly the multiplication factor is always less than unity. Several investigators have studied the multiplication of ^{252}Cf neutrons by subcritical assemblies and have shown that flux boosting factors of 10 to 100 could be achieved with safe, uncomplicated and inexpensive devices (in comparison to low power critical reactors). It has been shown that a properly positioned ^{252}Cf source will generate a beam of useful neutrons 17 per cent greater than *Pu-Be* source of equivalent strength (1 μg ^{252}Cf needle: 2.09×10^6 n/sec; 13 *Ci* ^{239}*Pu-Be* source: 1.81×10^6 n/sec). One additional advantage of a subcritical multiplier is its ability to be turned off by removing the ^{252}Cf from the fiissile material. The neutron intensity and thus the radiological hazard could be reduced. A thermal flux level of 10^5 n/cm^2-sec at image plane could be achieved at 60 cm from the source. The salient features of one such subcritical assembly[3] is given in Table 3.

Certainly all these sources and perhaps new source concepts such as plasmas have a place in neutron radiography. The growth of neutron inspection methods in industry will depend on the availability of sources (and associated equipment) that can be used in a manufacturer's plant and in the field, just as X-radiography is used now. Radioactive sources, particularly ^{252}Cf, offer the greatest potential for field neutron radiography.

Table 1 Characteristics of thermal-neutron sources[2].

Type of source	Typical radiographic intensity (a)	Resolution	Exposure time	Characteristics
Radioisotope	10^1 to 10^4	Poor to medium	Long	Stable operation, medium investment cost, possibly portable.
Accelerator	10^3 to 10^6	Medium	Average	On-Off operation, medium cost, possibly portable.
Subcritical Assembly	10^4 to 10^6	Good	Average	Stable operation. Medium to high investment cost, portability difficult.
Nuclear reactor	10^5 to 10^8	Excellent	Short	Stable operation. Medium to high investment cost, portability difficult.

(a) Neutrons per sq. cm. per s.

Table 2. Some radioactive sources for neutron radiography[1].

Source	Reaction	Half-life	Cost in thousands of dollars	Average neutron energy (MeV)	Neutron yield (n/s-g)	Gamma dose (rads/hr at 1m)[2]	Gamma ray energy (MeV)	Comments
^{124}Sb-Be	(γ, n)	60 d	25	0.024	2.7×10^{9}	4.5×10^{8}	1.7	Short half-life and high gamma background; available as high intensity sources, low neutron energy is an advantage for thermalisation.
^{241}Am-Be	(α, n)	458 y	1500	$\simeq 4$	1×10^{7}	2.5	0.06	Easily shielded gamma output; long half-life: high cost.
^{244}Cm-Be	(α, n)	18.1 y	35[3]	$\simeq 4$	2.4×10^{9}	0.2	0.04	Long half-life; low gamma background. Source can also be used as a spontaneous fission source, with about half the neutron yield. Because ^{244}Cm is produced in nuclear fuel, this radioisotope could be widely available as a byproduct material.
^{252}Cf	Spontaneous fission	2.65 y	200[4]	2.3	3×10^{12}	2.9	0.04 0.1	Very high yield source, present cost projected/ future cost makes it attractive; small size and low energy are advantages for moderation.

1. Cost of the radionuclide only is given; The cost is normalized to source total yield of 5×10^{10} n/s.
2. The gamma ray dose is normalized to a neutron yield of 5×10^{10} n/s.
3. The cost is based on a proposed cost of $ 170/g,
4. The cost is based on the present price of $ 10/μg, unencapsulated.

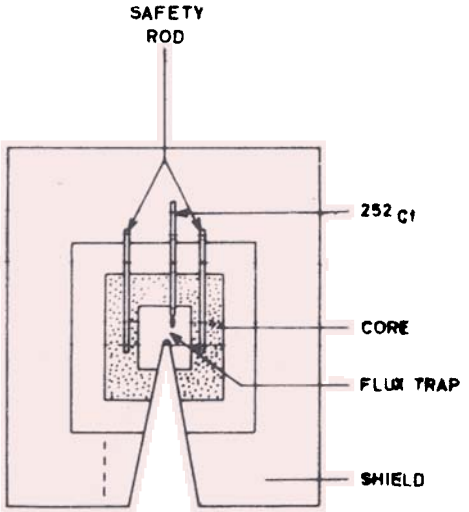

Figure 2. Schematic diagram of a subcritical neutron multiplier with Californium-252.

Table 3. Salient features of a CFX subcritical assembly from IRT Cornoration[3].

^{252}Cf source	1 mg
^{235}U loading	1500 g
Uranium enrichment	93.4 per cent
Fuel form	Clad metal plates
Moderator	Polyethylene
Maximum k_{eff}	0.990
$\triangle k$ *eff* increase for 20-g ^{235}U sample	0.004
Control poison	Cadmium, *Al* clad
Thermal flux	3×10^8 n/cm^2-sec
Fast flux	6×10^8 n/cm^2-sec
Thermal flux multiplication	30
Equivalent ^{252}Cf sources	30 mg
Radiography collimator ratio (*L*/D)	50 or greater
Thermal flux at film plane	2×10^5 for $L/D = 50$
Dose rate at shield surface	Less than 10 mR/hr
Fission power level	3.8 W_t

All these sources yield primarily fast neutrons. For thermal neutron radiography it is necessary to slow down these fast neutrons. The slowing down or thermalization is normally done by sorrounding the source with different moderating materials such as water, deuterium, paraffin, plastic etc. Efficiency of thermalisation depends upon the emitted neutron spectrum. The higher the energy of the emitted neutron, the more number of collisions are required for its thermalization. Ratio of the fast neutron yield (n/sec) to peak thermal flux achieved after thermalisation (n/cm^2-sec) could be defined as the thermalization factor. It varies widely for different sources of neutrons, viz. from 45 for ^{124}Sb-*Be* source, to 100 for ^{252}Cf source, to 600–1000 for 14 MeV *d-t* neutrons; it gives an indication of the physical size of the neutron source after thermalization[4].

2.2 *Collimator for ^{252}Cf Radiographic Facility*

After moderation the thermal neutron flux tends to peak at a short distance from the source. The neutrons move in all possible directions in the moderating medium and must be extracted out of the moderator by a suitable collimator. The simplest way of collimating the thermal neutrons is to use a long tube, slightly divergent or conical, lined from inside with a highly neutron absorbing material like cadmium or boron. Neutrons travelling towards the collimator walls are then absorbed and only those travelling along the collimator axis emerge out as a defined beam. It is important that the inner end of a collimator is precisely located at a point in the moderator where the thermal flux is maximum.

Two factors are important in collimator design, namely the diameter D of the inner end and the length[5] L. It is seen from Fig. 3, that the geometric unsharpness of the image is directly proportional to the ratio D/L, while the thermal flux available at the collimator outlet is proportional to $(D/L)^2$. The geometric unsharpness should be small (that is D/L should be small) for high resolution work. However this reduces the available neutron flux at the specimen, requiring very long exposure time. Thus the two requirements, high resolution and large thermal flux at object plane, are contradictory to each other and a compromise on one or the other is therefore necessary.

The quality of thermal neutron radiography with ^{252}Cf is limited by the intensity of the collimated flux and the gamma ray background, for example, 1.3×10^{13} gamma photons per second per gram of ^{252}Cf. While ^{252}Cf emits about 2.3×10^{12} n/sec-g typical collimation losses reduce the intensity of a beam by about 10^5. For a 1 mg ^{252}Cf source the maximum thermal beam would then be about 2.3×10^4 n/sec-cm^2. To reduce the background radiation, either the source-to-film distance must be large or shielding material must be used. Introduction of shielding material is a more practical proposition.

One of the materials which has good neutron and gamma attenuation properties is lithium-lead (*Li–Pb*), an intermetallic compound[6]. The material combines the neutron absorption characteristics of lithium and gamma attenuation characteristics of lead (Table 4).

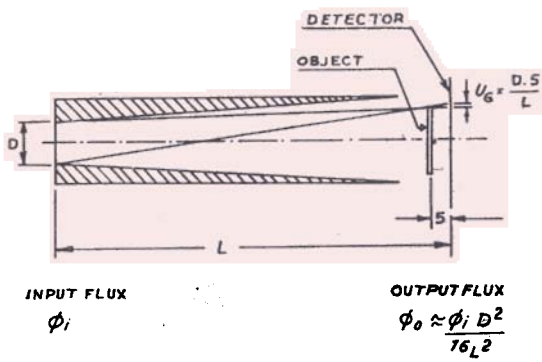

Figure 3. Two important factors in a collimator design, viz. geometric unsharpness (U_G) and output thermal neutron flux (ϕ_0). For high resolution U_G should be small and for short exposure times the ϕ_0 should be large. Both these requirements are contradictory.

Table 4. Thermal neutron and gamma interaction characteristics of Lithium, Lead and Lithium-Lead

	Li	*Pb*	*Li=Pb*
Molecular weight	6.94	207.19	214.13
Density g/cm³	0.534	11.34	8.0
Thermal neutron absorption and scattering coefficients			
$\sum_{\text{Abs}}^{2200}$ cm^{-1}	3.39	0.006	1.65
$\sum_{\text{scat, cm}^{-1}}^{2200}$	0.065	0.363	
Attenuation coefficient of gamma photons of MeV energy (cm^{-1})	0.027	0.776	0.54

In a typical design of neutron radiography facility, the neutron moderation is done by way or polyethylene[7]. The moderator is a cube of 60 cm on each side. The collimator is a cone with 1.5 mm thick cadmium lining the inner wall of the conical hole in the paraffin moderator (Fig. 4), The inlet and outlet apertures are 5 cm and 15 cm in diameter respectively. To reduce gamma contamination the inner wall of the cadmium cone has been lined with a 6 mm thick cone of lead. To further reduce the gamma ray component reaching the film plane, 2.5 cm of bismuth (two plugs each of 12.5 cm thick) was placed in the collimator adjacent to the inlet aperture. Also a flat 1.6 cm thick lead gamma shield was added around the collimator opening to shield the entire face of the moderator. To improve the quality of the thermal neutron beam

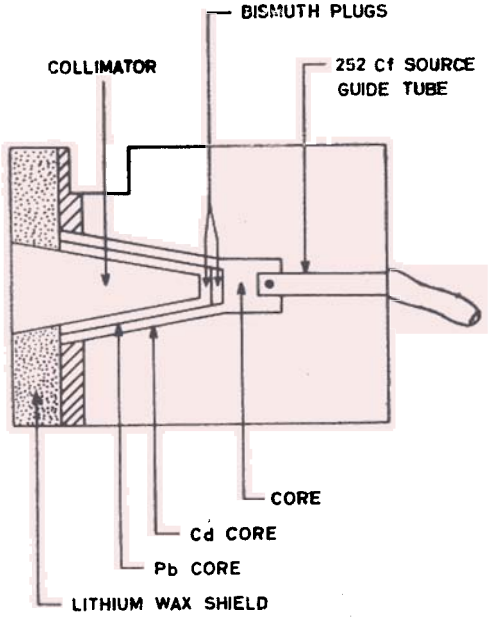

Figure 4. Schematic diagram of a typical radiography facility using Californium-252 and an optical Collimator design.

reaching the film plane, a 15 cm thick lithium-loaded paraffin slab (50 wt per cent lithium hydroxide monohydrate) was also added to absorb stray neutrons emanating from the face of the moderator. The ^{252}Cf source guide tube was inserted at the centre of the moderator via a cylindrical hole directly opposite and along the axis of collimator. A L/D ratio of 20 (fixed) has been used. Characteristics of the system are:

Source size	10.4 mg
Total neutron yield	2.5×10^{10} n/sec.
Peak thermal neutron flux at moderator centre n/cm^2-sec	1.14×10^8
Thermal flux at film plane (1000 cm)	1.2×10^4 n/cm^2-sec
Cadmium ratio at moderator Centre	5.1
Cadmium ratio at film plane	2.1
Gamma dose rate at film plane	0.24 mR/sec
Neutron-to-gamma ratio at film plane	5×10^4 n/cm^2 per mR
L/D Ratio	20

A new polyethylene moderator with a gadolonium oxide collimator has been developed and has replaced the paraffin moderator-cadmium collimator system. The thermal neutron flux at the film plane per milligram of ^{252}Cf has increased by $1\frac{1}{4}$ times because of increased[7] hydrogen density (from 0.891 g/cm^3).

	Paraffin	*Polyethyelene*
Thermal neutron flux at film plane (100 cm) n/cm^2-sec	1.2×10^4	2.35×10^4
Cadmium ratio at film plane	2.1	2.6
^{252}Cf in mg	9.79	8.49
Film plane flux per mg ^{252}Cf	1.23×10^3	2.77×10^3
L/D ratio	20	20
Mean density (g/cm^3)	0.891	0.962

2.3 *Imaging*

Neutrons themselves do not affect a photographic plate, and neutron radiographs cannot be made directly. Instead, images are formed through a suitable neutron-to-charged particle converter screen held adjacent to photographic film (the direct exposure method) or on a screen that becomes activated and is later placed adjacent to a photographic film activation—transfer method).

Direct exposure neutron radiography

In direct exposure neutron radiography, the convertor screen and the film are both exposed together to the neutrons, just behind the specimen under test. The converter screen must have a high thermal neutron capture cross-section and emit radiations like alpha, or soft beta particles or visible light. It is these secondary radiations which form the image on the film much in the same way as the intensifying screens in

X-radiography. The canverter screens are normally used as back screens, i.e. the screen is placed behind the film, to reduce the scattering of secondary radiations inside the screen to a minimum.

The most widely used screen for this technique is thin gadolinium ($\sim$ 12μm thick). Gadolinium has a high neutron absorption cross-section and emits 70 keV electrons. These low energy elecrons are easily stopped in the film emulsion with minimum spread, thereby giving high resolution capacity ($<$ 10 μm). Typical neutron intensity required for an optical density of 1.5 on crystallex film is about 3×10^8 n/cm^2.

Scintillators made with ^6Li or ^{10}B, *ZnS* and a binding material are the fastest converter screens (about 100 times faster than *Gd*). However, resolution capability is poorer ($\sim$ 50 μm) due to finite size of *ZnS* grains.

The limit of exposure time is set by the gamma radiation level present in the beam. Most of the photographic neutron detectors using converter screens require an exposure of 10^5 n/cm^2 sec to equal the film response to 1 mR of ^{60}Co gamma radiation. A neutron to gamma intensity ratio of at least 10^5 n/cm^2/mR is therefore necessary to minimise the gamma interference in the radiograph[5].

The thermal neutron radiographs taken with ^{252}Cf source are of a quality at least equal to those with ^{241}Am-*Be* and ^{242}Cm-*Be* sources[2]. Some of the scintillator-film combinations used are given below.

(i) ^6Li-*Zns* scintillator screens with radiographic films and with polaroid photographic films. Exposure time 10 min with type 52 film to 10 sec with type 57 film; (ii) Kodak Blue brand film and NE 425 scintillator; (iii) Kodak AA film and NE 425 scintillator; (iv) Kodak Blue Brand film and glass scintillator similar to NE 900 scintillator; (v) Kodak AA film and glass scintillator similar to NE 900 scintillator; (vi) Boron loaded Zns scintillator.

Activation transfer neutron radiography

If the specimen itself is radioactive (e.g. nuclear fuels, reactor components) or the thermal neutron source has an unfavourable neutron to gamma ratio (much less than 10^5 n/cm^2/mR), direct exposure method has limitations, High gamma background causes excessive film fogging, resulting in a poor quality radiograph (lack of contrast and detail). In such circumstances activation transfer neutron radiographic technique is used. In this method, a converter screen is exposed alone to the neutron beam and becomes radioactive on neutron absorption. A latent image of the specimen is formed on the screen which is then transferred from the beam area to a photographic film in a remote place and allowed to decay. The secondary radiations now expose the film resulting in a radiograph which is free from gamma interference.

The main requirements for such a transfer screen are high neutron absorption cross-section and moderate as well as convenient half life after activation. The three most commonly used materials are *In*, *Dy* and *Au*.

This radiography method was demonstrated to be possible with a 3.83×10^8 n/sec ^{252}Cf source if less of collimation and long exposure times are used. A film density of 0.62 was obtained using 0.13 mm Dysprosium foil, Kodak Royal blue films, 1.5 m $\times$ 1.5 m $\times$ 9 m collimator, saturation exposure, and transfer times of a few hours. Lead screens 0.25 mm thick were adjacent to the film during transfer[9].

Some of the activation combinations used are given below:

(i) Three gadolonium secreens of different sizes and small lead screen mounted in the casettee to be in contact with Du Pont NDT-75 film (exposure 1 to 2 hr). (ii) Kodak type R single-emulsion film (S lower-fine grain type) and gadolinium back-screens (exposure 16 hr). (iii) Transfer exposure methods with indium and dysprosium foils, Kodak Blue Brand and AA films and a neutron flux of 3×10^3 n/cm²-sec. (iv) Gadolinium with either Ilford Industrial GX-ray film or Kodak Royal Blue film is less sensitive and requires 8 hr exposure. Kodak Trix film requires exposure of about 1 hr.

Filmless Radiography

Both direct exposure method and activation transfer technique require costly films or dark-room equipment. Two techniques are cited below which do not require films and are of recent development.

(a) *Track Etch Radiography*

In this technique ^6Li, ^{10}B or ^{235}U loaded screens are used to convert thermal neutrons to charged particles or fission fragments. When these secondary particles which have high specific ionization fall on certain plastics, they cause radiation damage along their paths. When selectively etched with suitable chemicals the damage becomes visible and a radiograph results. The advantages of this method are that it is completely gamma insensitive, has no limit on exposure, has good resolution characteristics and is simple to adopt. The main disadvantage is that it has a poor contrast.

Kodak Pathe' (France) is marketing cellulose nitrate films coated on both sides with a thin layer of lithium-borate[5]. Typical exposures for a good radiography require 10^9 n/cm².

(b) *Electronic Image Recording Thermal Neutron Radiography*

In addition to the metal film combinations, or solid state track etch detector screen systems, electronic image recorders have also been tested for neutron radiography. These recorders were developed for an immediate inspection of objects during any manipulation or movement.

A small 200 μg ^{252}Cf source with an inexpensive shielding consisting of plates of borated wood and gypsum as well as lead, a divergent collimator of L/D ratio 20:1 and a thermal flux level of 4.7×10^2 n/cm²-sec has been used in combination with the following commercial components for electronic image recording thermal neutron radiography[10].

(i) A neutron scintillator screen containing a mixture of ^6Li-ZnS (Ag) in an inorganic matrix (Type NE 426).

(ii) A three stage electrostatic image intensifier *H* XX 9955 with an overall gain in brightness of 3×10^4 which views the scintillator by using a sensitive optic bus system (objective 1:10).

(iii) A Secondary Electronic Conduction (*SEC*) television camera tube *SEC H-1004* which is fiber optically coupled to the rear output face plate of the image intensifier. The *SEC* tube gives possibility to accumulate single events—which may be indiscernible in normal scanning periods of 1/25 seconds—into an image. By scanning of *SEC* target after an appropriate integration time (several seconds) the image can be released and observed in a monitor coupled with the video output of the camera.

A comparison of neutron fluences necessary for obtaining a discernible radiographic image with various neutron image recorders points to a remarkable reduction of the exposure time by using the electronic imaging system (Table[10] 5).

Table 5. Various neutron image recorders and their comparison.

(a) Neutron photographic image recorders

Material	Type	Reaction	Ionising Rad.	Film
Ne 426	^{6}LiF-$ZnS(Ag)$	$^{6}Li(n, \alpha)\ ^{3}H$	α	Illford *HP* 4
Gd	Foil (0.1 mm)	$^{155}Gd(n, \gamma)\ ^{156}Gd$ $^{157}Gd(n, \gamma)\ ^{158}Gd$	β^-	Structurix *D* 7
Dy	Foil (0.1 mm)	$^{164}Dy(n, \gamma)\ ^{165}Dy$ $^{164}D(n, \gamma)\ ^{165}Dy$	β^-	Structurix *D* 7

(b) Comparison between various neutron image recorders

Recorder system	Exposure time for discernible images	Minimum fluence (n/cm^2)
Gd — structurix *D* 7	90 minutes	2.5×10^6
NE 426 — *HP* 4	2.5 minutes	7×10^4
NE 426 — *SEC* System	10 seconds	4.7×10^3

2.4. *Assessment Standards for Neutron Radiography*

As neutron radiography is still a relatively new field, no universally accepted standards exist, although *ASTM* has approved a standard method for determining image quality in neutron radiography. The method consists of two types of indicators: (i) a beam purity indicator (*BPI*) and (ii) a sensitivity indicator[5].

The *BPI* consists of a block of boron nitride with 3 drilled holes. One hole contains a thin disc of boron nitride, the second contains a disc of boron nitride and lead and the third hole is open. By proper densitometric measurements of the image of *BPI*, the thermal neutron, scattered neutron, equithermal neutron and low energy gamma ray content of the beam can be determined.

The sensitivity device is a set of 4 indicators, called Type *A*, *B*, *C* and *D* indicators. All the four are made of cast acrylic resin stop wedges. Type *A* indicator has a set of holes in each step and the sensitivity level is determined by the smallest observable hole and thickness of the corresponding absorbers in the indicator. Type *B* consists of

differing diameter nylon rods, Type *C* is a slot gauge with varying width groves in the steps and Type *D* is a gap gauge.

In normal use, only the *BPI* and the Type *A* gauge are used on a neutron radiograph. *ASTM* designation of quality level includes the thermal neutron content, the scattered neutron content and the hole gauge sensitivity. Typical values for these parameters respectively are 70 per cent, 15 per cent and 10 per cent which denotes a smallest hole size of 0.25 mm in absorber thickness of 1.57 mm.

3. Applications of Neutron Radiography

(1) (a) *Inspection of aircraft and aircraft components*

Neutron radiography technique is capable of non-destructive inspection of a number of aircraft components, some of which are not amenable for X- or gamma radiography. For example:

(i) *Detection of hidden corrosion*: The ability to detect surface corrosion[11] in aircraft structure is perhaps the most important asset of neutron radiography. Most surface corrosions form an oxide of the metal which is porous and very light. If exposed to the atmosphere it absorbs moisture and may eventually convert to the hydroxide of the metal. In some cases the corroded area is exposed to oil or grease. The presence of very small quantities of hydrogenous substances (oil, grease, jet fuel, hydroxide or water) in the corroded area allows neutron radiography. Inspection by X-rays of such surface or hidden corrosions is futile.

Neutron radiography is also able to detect surface corrosion under a coat of paint. Although the paint on the surface appears to be uniform, corroded spots are easily identified. Such capabilities to inspect surface or hidden corrosions result in considerable cost saving by eliminating the need for disassembly or paint removal before inspection.

^{252}Cf-based neutron radiography systems have identified areas of surface and intergranular corrosion in the bushing areas of nose landing gear struts. The size and depth of a stress corrosion cracking defect in the landing gear could be defined.

(iii) *Examination of adhesive bonds*: Neutron radiography is capable of distinguishing between materials with different neutron absorption coefficients. For a bondline[12] of uniform thickness, variations in the radiograph film contrast indicate variations in absorber uniformity. Such variations could be the result of voids or inclusions. Conversely contrast variations could indicate that uniform bond line thickness had not been achieved. Voids may be fissures or bubbles extending from adherent to adherent or may be localized within a portion of the glue line. Inclusions may have absorption coefficients either greater or less than that of the adhesive. Low coefficients will cause the inclusion to appear as a void; inclusions which have high absorption coefficients are readily recognised as such. Voids were easily detected in bondlines prepared with a uniformly doped adhesive. They appear as light areas in a neutron radiograph positive. The per cent void area can be estimated within 5 to 10 per cent by visually estimating the per cent light area in the radiograph.

The neutron radiography shows prominently the adhesive material whereas the X-radiography shows the metallic core. Therefore it is possible to detect voids as well as adhesive poor and adhesive-rich regions.

To enhance imaging and to improve radiographic contrast, chemically inert gadolinium oxide (Gd_2O_3) which readily interacts with neutrons is added to adhesives. The adhesives are then used to bond very thin sheets of aluminium alloys (0.16 mm thickness) into laminates. Bond thicknesses are around 0.13 mm. The Advanced Technology Centre, Inc., U. S. A., used a mobile neutron radiography system with a thermal neutron flux level of 10^4 n/cm^2-sec (from a 2.8 mg ^{252}Cf source) to detect voids at the critical upper (skin to spar) and the centre (skin to skin) bond lines.

Accurate prediction of strength of bond line under stress becomes possible if the void content of the adhesive bonds or the bonded area could be determined. Neutron radiography of Gd_2O_3 modified adhesive bond lines can just provide that information rapidly (radiographs in 30 min with Kodak AA X-ray films) and aid in the decision of servicibility of critical bond lines (refer data given below). It should be mentioned that the modified adhesive (one part epoxy adhesive with 5 per cent Gd_2O_3) itself has lower strength than the unmodified one (by about 10 per cent).

Table 6. Neutron radiographic inspection data for laminated primary structure test specimens

Specimen assembly identification	Neutron radiography bondline inspection results		Neutron radiography serviceability assessment	Experimental verification of critical bondline strength
	Skin to spar	Skin to skin		
A	Void free	Void free	Good	6740
L	Extensive void fraction	Void free	Poor	3360
M	Extensive void fraction	Extensive void fraction	Poor	
N	Void free	Extensive void fraction	Satisfractory	

(iii) *Water in honey-comb* : The presence of water in the honey-comb cells[11] is rather difficult to estimate by conventional techniques. Neutron radiography provides a sensitive and simple inspection technique for such detection. The smallest quantity of water in a cell of a honey-comb panel detected by ^{252}Cf neutron radiography system is 10 μl.

(iv) *Turbine blades*: Inspection of aircraft engine turbine blades[11] for the presence of residual core material from the original casting process or coke deposits from jet fuel in the cooling passage is an important application. Ceramic core material, particularly when doped with gadolinium, is easily detected by neutron radiography. Carbon is a good scatterer of neutrons and hence is easily imaged by neutrons. Therefore detection of coke in the cooling passages is made by neutron radiography while inspecting blades after they have been in service. Fuel manifolds, ignitors and

other such aircraft engine components are also inspected by this technique for coke deposits.

(v) *Advanced composits materials*: The development and wide-spread use of advanced composites[12] in aircraft structures calls for new inspection techniques. Neutron radiography is capable of inspecting composites such as tungsten boron fibres in an aluminium matrix, post-cover assembly comprising of a curved aluminium plate with a phenolic fibre-glass frame bonded with adhesive at the edge of and on both sides of a peripheral flange in the aluminium plate.

(vi) *Inspection of critical bearings for lubricants*: The ability of neutrons to readily image lubricating oils and greases makes neutron radiography an effective technique for inspecting critical bearings to ensure proper lubrication without disassembly.

(vii) *Neutron radiography systems for field use*: Two distinct applications for aircraft maintenance can be foreseen.

(*i*) A unit designed to be stationed at each aircraft maintenance establisment to radiograph the aircraft components either to identify defective components or to assure quality of repair.

(*ii*) A truly mobile unit to inspect components of an aircraft without disassembly.

(b) *Munition components*

The hand granade fuse[13], adapter, cartridge case, and squib switches are all standard munition items and are routinely radiographed with X-rays. But because neutron radiography can distinguish the low-density organic materials inside metal enclosures much more easily, it has been shown to have its own special merits. Several hundred explosive booster assemblies have been radiographed at the Picatinny Arsenal of the U. S. Department of Army, Dover, NJ with ^{252}Cf neutrons (10 mg, paraffin moderator) for their proper assembly. The presence of explosive filler inside the small steel end cup could easily be seen by neutron radiography. Conventional X-radiography is not a success in inspecting this due to inadequate sensitivity to the low density organic explosive filler.

Cases where cartridges (40 mm thick aluminium housed) were filled with insufficient levels of propellant powder could easily be discerned.

Acknowledgement

Authors' grateful thanks are due to Shri A. Nagaratnam, Director, Defence Laboratory, Jodhpur and Shri J. V. Ramana Rao, Head, Isotope Laboratory, for their helpful discussions and encouragement.

References

1. Lewcock, A. I., *Phys. Technol.*, **10** (1979), 74.
2. Berger, H., 'Caliofrnium-252 as a Source for Thermal Neutron Radiography', *in* Proceedings of an International Symposium on Californium-252 Utilization, held in Paris, April 26–28, 1976, (Eds. R. L. Berger, W. R. Cornman), CONF-760436, Vol. II, V-1 to V-14. U. S. Department of Energy.

3. Preskitt, C. A., Crosbie, K. L., Larsen, J. E. & Joseph John, 'The Californium Multiplier (CFX)' *in* Proceedings of an International Symposium on Californium-252 Utilization, held in Paris, April 26–28, 1976, (Eds. R. L. Berger, W.R. Cornman) CONF-760436, Vol. II, 2-123 to 2-144, U. S. Department of Energy.
4. Hawkesworth, M. R. 'On the Economics of Neutron Production', Neutron Radiography News Letter (Am. Society for Non-Destructive Testing, Evanston, Illinois **12** (1971), 20.
5. Dande, Y. D., 'Neutron Radiography—A New NDT Technique', Private Communication, 1980.
6. University of Texas at Austin, Californium-252 Progress, No. 2, 15, 1972.
7. Picatinny Arsenal, Californium-252 Progress, No. 9, (1971), 14.
8. Argonne National, Laboratory, Californium-252, No. 2, 23, 1970.
9. General Dynamics Corporation, Californium-252, No. 5, 18, 1970.
10. Meier, H. & Albrocht W., 'Problems and Limits of 252 *Cf* Neutron Radiography', *in* Proceedings of an International Symposium on Californium Utilization, held in Paris, April 26–28, 1976, (Eds. R. L. Berger, W. R. Cornman) CONF–760436 Vol. II, V–15 to V–32, U. S. Department of Energy.
11. Intercom Rad Tech and Naval Development Centre, Californium-252, No. 17 (1974), 36.
12. Advanced Technology Centre, Inc., Californium-252, No. 22 (1978), 22.
13. Picatinny Arsenal, Californium-252, No. 11, (1972), 16.