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Neutron Radiography

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1. Introduction

A few years after the discovery of neutron by James Chadwick in 1932, H. Kallman and E. Kuhn started their work on neutron radiography in Germany using neutrons from a small neutron generator. Due to the second World War, their first publication was delayed until 1947. However, the first report on neutron radiography was published by Peters in 1946, a year before Kallman and Kuhn's. After research reactors were available, in 1956 Thewlis and Derbyshire in UK demonstrated that much better neutron radiographic images could be obtained by using intense thermal neutron beam from the reactor. Specific applications of neutron radiography were then started and expanded rapidly particularly where research reactors were available.

The radiographic technique was originally based on metallic neutron converter screen/film assembly. Neutron converter screen and film were gradually improved until early 1990's when computer technology became powerful and was available at low cost. Non-film neutron radiography was then possible to be used for routine inspection of specimens. After 2005, imaging plate specially designed for neutron radiography was available and could provide image quality comparable to the best image quality obtained from the gadolinium foil/film assembly with relative speed approximately 40 times faster. Nevertheless, neutron radiography has not been widely employed for routine inspection of specimen in industry like x-ray and gamma-ray radiography due to two main reasons. Firstly, excellent image quality still needs neutrons from nuclear reactor. Secondly, neutron radiography is only well-known among the academic but not industrial people. It is actually excellent for inspecting parts containing light elements in materials even when they are covered or enveloped by heavy elements. Nowadays, neutrons from small neutron generator and californium-252 source can give neutron intensity sufficient for modern image recording system such as the neutron imaging plate and the light-emitting neutron converter screen/digital camera assembly.

2. Principle of neutron radiography

Neutrons are fundamental particles which are bound together with protons within the atomic nucleus. Neutron is electrically neutral and has mass of nearly the same as a proton i.e. about 1 u. Once a neutron is emitted from the nucleus it becomes free neutron which is not stable. It decays to a proton and an electron with a half-life of 12 minutes.

Neutron radiography requires parallel beam or divergent beam of low energy neutrons having intensity in the range of only 10^4 – 10^6 neutrons/cm^2-s to avoid formation of significant amount of long-lived radioactive isotope from neutron absorption within the specimen. The transmitted neutrons will then interact with neutron converter screen to generate particles or light photons which can be recorded by film or any other recording media. Free neutrons emitted from all sources are fast neutrons while neutron radiography prefers low energy neutrons. To reduce neutron energy, neutron sources are normally surrounded by large volume of hydrogeneous material such as water, polyethylene, transformer oil and paraffin. Neutron collimator is designed to bring low energy neutron beam to the test specimen. As illustrated in Figure 2, attenuation coefficient of gamma-ray increases with increasing of the atomic number of element while attenuation coefficients of neutron are high for light elements like hydrogen(H), lithium (Li) and boron(B) as well as some heavy elements such as gadolinium (Gd), cadmium(Cd) and dysprosium (Dy). In contrast, lead (Pb) has very high attenuation coefficient for gamma-ray but very low for neutron. Neutron radiography therefore can make parts containing light elements; such as polymer, plastic, rubber, chemical; visible even when they are covered or enveloped by heavy elements.

Neutrons may interact with matter in one or more of the following reactions.

i. Elastic scattering: (n, n) reaction

Neutron collides with the atomic nucleus, then loses its kinetic energy. It should be noted that neutron loses less kinetic energy when it collides with a heavy nucleus. In contrast, it loses more kinetic energy when collides with a light nucleus. Hydrogen(^{1}H) is therefore the most effective neutron moderator because it is the lightest nucleus having mass almost the same as neutron (~1u). Elastic scattering is most important in production of low energy or slow neutrons from fast neutrons emitted from the source for neutron radiography. Water, paraffin and polyethylene are common neutron moderators. In fact, hydrogen-2 (^{2}H, so called "deuterium") is the best neutron moderator due to its extremely low neutron absorption probability. Heavy water (D_2O) has neutron absorption cross section only about 1/500 that of light water (H_2O) but heavy water is very costly.

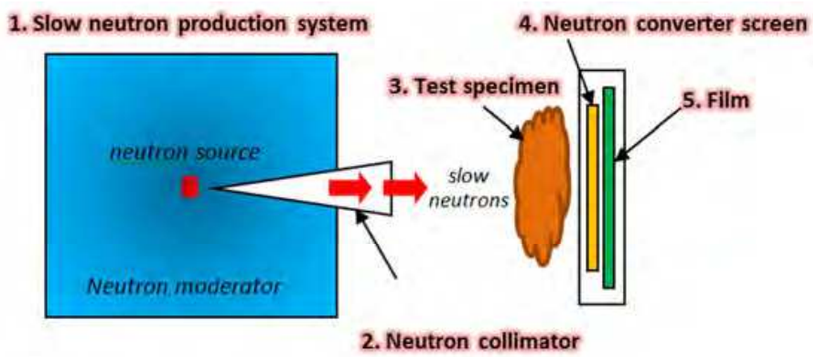


Figure 5 Neutron radiography major components

Fig. 1. Major components of typical neutron radiography system

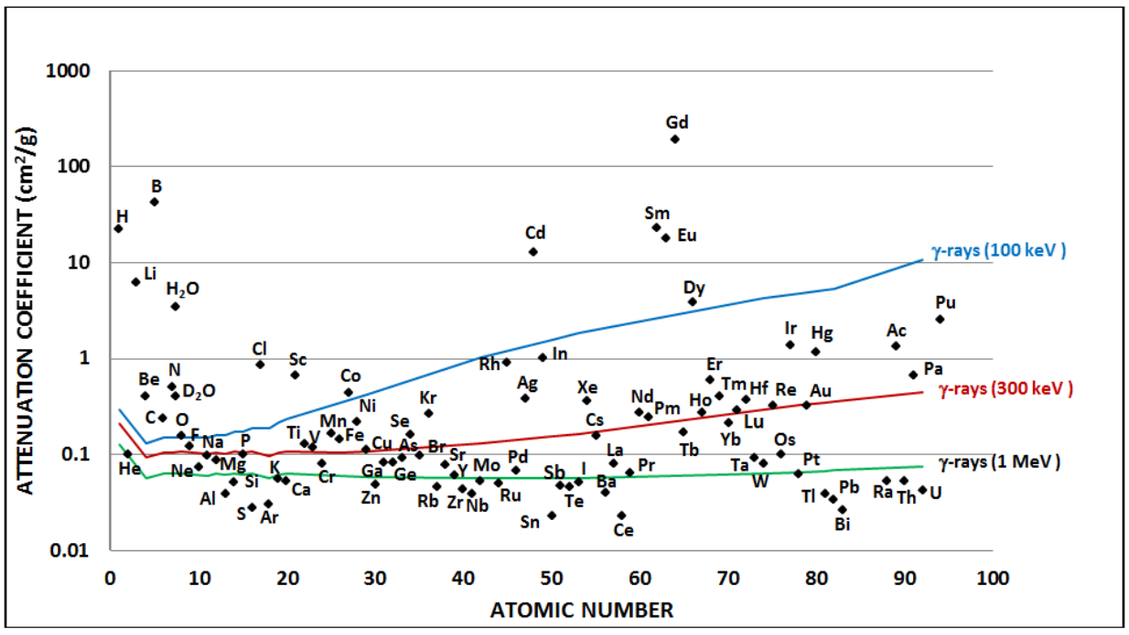


Fig. 2. Mass attenuation coefficients for thermal neutrons (♦) and gamma-rays as a function of atomic number of elements (reproduced from [3] with some modifications)

ii. Inelastic scattering: (n, n') or (n, n'γ) reaction

Similar to elastic scattering but when a neutron collides with the atomic nucleus it has enough kinetic energy to raise the nucleus into its excited state. After collision, the nucleus will give off gamma-ray(s) in returning to its ground state. Even inelastic scattering also reduces energy of fast neutron but this is not preferable in neutron radiography because it increases in contamination of gamma-rays to the system.

iii. Neutron capture: (n, γ) reaction

A neutron can be absorbed by the atomic nucleus to form new nucleus with an additional neutron resulting in increasing of mass number by 1. For example, when cobalt-59 (^{59}Co) captures a neutron will become radioactive cobalt-60 (^{60}Co). The new nucleus mostly becomes radioactive and decays to beta-particle followed by emission of gamma-ray. Some of them are not radioactive such as ^{2}H, ^{114}Cd, ^{156}Gd, and ^{158}Gd. A few of them only decay by beta-particle without emission of gamma-ray such as ^{32}P. This reaction plays a vital role in neutron radiography when metallic foil screen is used to convert neutrons into beta-particles and gamma-rays.

iv. Charged particle emission: (n, p) and (n, α) reactions

Most of charged particle emission occurs by fast neutrons except for the two important (n, α) reactions of lithium-6 (^{6}Li) and boron-10 (^{10}B). The ^{6}Li(n, α)^{3}H and ^{10}B(n, α)^{7}Li reactions play important roles in neutron detection and shielding. In neutron radiography, these two reactions are mainly employed to convert neutrons to alpha particles or to light. The (n, p) reaction is not important in neutron radiography but it may be useful when solid state track detector is selected as the image recorder.

v. Neutron producing reaction: (n, 2n) and (n, 3n) reactions

These reactions occur only with fast neutrons which require a threshold energy to trigger. They may be useful in neutron radiography particularly when utilizing 14-MeV neutrons produced from a neutron generator. By inserting blocks of heavy metal like lead (Pb) or uranium (U) in neutron moderator, low energy neutron intensity can be increased by a factor of 2 – 3 or higher from (n, 2n) and (n, 3n) reactions.

vi. Fission: (n, f) reaction

Fission reaction is well-known for energy production in nuclear power plant and neutron production in nuclear research reactor. A heavy nucleus like uranium-235 (^{235}U), plutonium-239(^{239}Pu) undergoes fission after absorption of neutron. The nucleus splits into 2 nuclei of mass approximately one-half of the original nucleus with emission of 2 – 3 neutrons. When uranium (U) is used to increase neutron intensity by the above (n, 2n) and (n, 3n) reactions, fission reaction also contributes additional neutrons to the system. The degree of contribution depends on the ratio of uranium-235 to uranium-238 in uranium.

Attenuation of neutron by the specimen depends on thickness and the attenuation coefficient similar to gamma-ray as follows.

$$I_t = I_0 \exp(-\Sigma t) \quad (1)$$

Where

I_t is the transmitted neutron intensity (n/cm^2-s)
I_0 is the incident neutron intensity (n/cm^2-s)
t is the specimen thickness (cm)
Σ is the macroscopic cross section (cm^{-1})

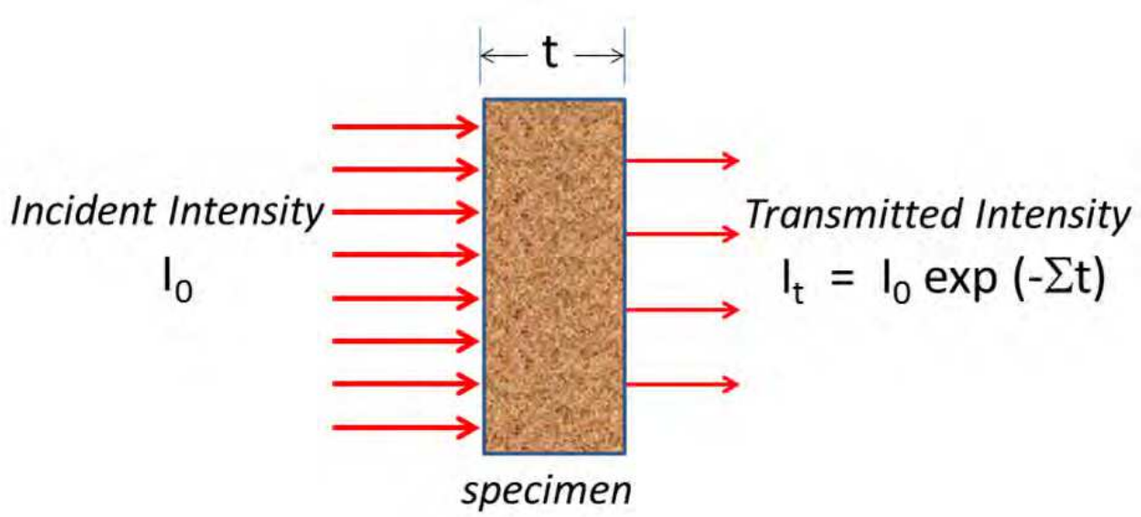


Fig. 3. Attenuation of neutrons by specimen

Σ is equivalent to the linear attenuation coefficient of gamma-ray (μ) and is the characteristic of elements in the specimen. Σ and μ are the product of atom density of elements contained in the specimen (in atoms/ cm^3) and their effective microscopic cross sections (σ) to the reactions of interest (in cm^2). σ is the effective cross section, not the actual physical cross section of the nucleus. It indicates probability of occurrence for each neutron interaction. For examples, $\sigma_{(n,\gamma)}$ indicates the probability of (n, γ) reaction and σ_s indicates the probability of scattering reaction which combines elastic (n, n) and inelastic (n, n′) scattering cross sections. Σ and σ of pure elements and common compounds or mixtures (such as water, heavy water and concrete) can be found in literatures. Figure 4 illustrates percentage of 0.0253 eV neutron transmission through different kinds of material having thickness of 1 cm.

Element or Molecular	Atomic number	Nominal Density (g/cm^3)	σ_a, barns	Σ_a, cm^{-1}
Boron	5	2.3	759	97.23
Carbon(graphite)	6	1.60	3.4×10^{-3}	2.728×10^{-4}
Heavy water		1.105	1.33×10^{-3}	4.42×10^{-5}
Water		1.0	0.664	0.02220
Aluminum	13	2.699	0.230	0.01386
Iron	26	7.87	2.55	0.2164
Copper	29	8.96	3.79	0.3219
Silver	47	10.49	63.6	3.725
Gadolinium	64	7.95	49000	1492
Dysprosium	66	8.56	930	29.50
Gold	79	19.32	98.8	5.836
Lead	82	11.34	0.170	5.603×10^{-3}

Table 1. Microscopic and macroscopic cross sections of some elements and compounds [4]

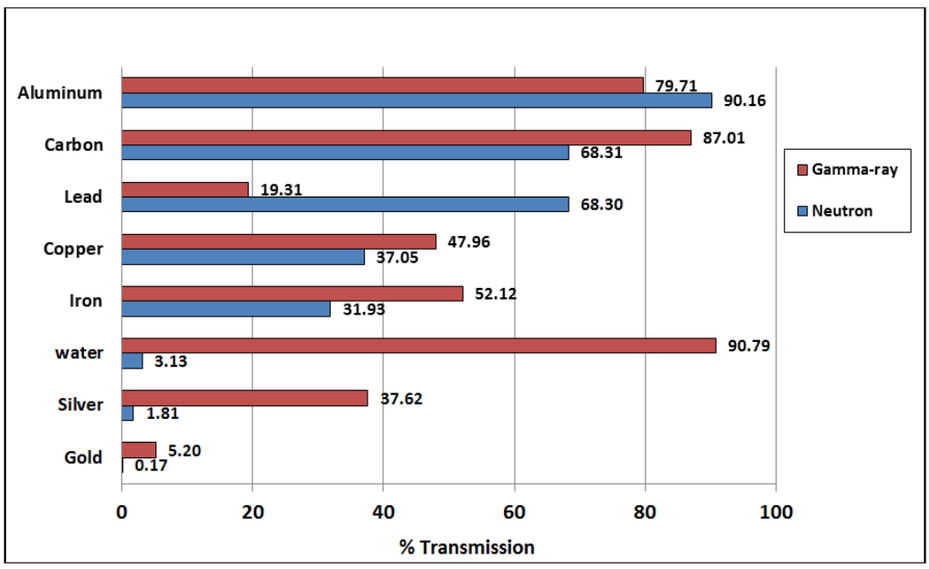


Fig. 4. Comparison of 0.0253 eV neutron and 0.5 MeV gamma-ray transmission through materials having thickness of 1 cm

3. Neutron sources

Neutron sources for neutron radiography can be divided into 3 groups. These are radioisotope source, electronic source and nuclear reactor.

i. Radioisotope neutron source

Nowadays, two radioisotope sources are appropriate and available for neutron radiography i.e. americium-241/beryllium (^{241}Am/Be) and californium-252 (^{252}Cf). ^{241}Am/Be produces neutron from (α, n) reaction by bombardment of beryllium (Be) nucleus with alpha particles from ^{241}Am. The average neutron energy and the neutron emission rate are approximately 4.5 MeV and 2.2 x 10^6 neutrons/second per 1 curie (Ci) of ^{241}Am with a half-life of 432 years. ^{241}Am/Be can be available up to several tens curies of ^{241}Am. ^{252}Cf emits neutrons from spontaneous fission with average neutron energy of 2 MeV and the emission rate of 4.3 x 10^9 neutrons/second per curie or 2.3 x 10^6 neutrons/second per microgram of ^{252}Cf. ^{252}Cf has a half-life of 2.6 years and is the best radioisotope source for neutron radiography due to its extremely high neutron output, low average emitted neutron energy and small size.

ii. Electronic neutron source

Particle accelerator and neutron generator are neutron emitting sources produced by nuclear reactions. Particles are accelerated to a sufficient energy and brought to hit target nuclei to produce neutrons. Compact neutron generators are now available for field use with neutron emission rate of 10^9 to 10^{12} neutrons per second. The reactions below are commonly used to produce neutrons.

$$_1D^2 + {}_1D^2 \rightarrow {}_0n^1 + {}_2He^3 + 3.28 \text{ MeV}, \quad \textit{so called "DD Reaction"}$$

$$_1T^3 + {}_1D^2 \rightarrow {}_0n^1 + {}_2He^4 + 17.6 \text{ MeV}, \quad \textit{so called "DT Reaction"}$$

$$_1D^2 + {}_4Be^9 \rightarrow {}_0n^1 + {}_5B^{10} + 4.35 \text{ MeV}$$

$$_1H^1 + {}_4Be^9 \rightarrow {}_0n^1 + {}_5B^9 - 1.85 \text{ MeV}$$

Energy of fast neurons produced from the above reactions is monoenergetic and depends on the incoming particle i.e. ^{1}H and ^{2}D. The DT reaction is a well-known fusion reaction for generating 14 MeV neutrons.

iii. Nuclear reactor

Nuclear reactor generally produces neutrons from fission reaction of uranium-235 (^{235}U). The fission neutron energy is in the range of 0 – 10 MeV with the most probable and the average energy of 0.7 and 2 MeV respectively. Fission reactions take place in the nuclear reactor fuel rods which are surrounded by neutron moderator. The moderator reduces the neutron energy to thermal energy or slow neutron. Due to its high slow neutron intensity in the reactor core of about 10^{12} – 10^{14} neutrons/cm^2 per second, good collimation of neutron beam can be easily obtained to give excellent image quality for neutron radiography.

Maximum neutron flux in moderator is a function of neutron emission rate from neutron source and neutron energy. Thermalization factor, as shown in Table 3, is the ratio of the

neutron emission rate (in neutrons per second, s^{-1}) to the maximum neutron flux (in neutrons per second per square centimeter, cm^{-2} s^{-1}) in moderator. Neutron flux in water moderator per a neutron emitted from the neutron source at any distances can be obtained from Figures 6 and 7. For example, the thermalization factor of ^{252}Cf obtained from Table 3 is 100. The neutron emission rate of ^{252}Cf is 2.3×10^6 neutrons per microgram. If a 500 mg ^{252}Cf is used, the maximum flux in water can be calculated from $500 \times 2.3 \times 10^6/100 = 1.15 \times 10^7$ cm^{-2} s^{-1}. From a graph in Figure 6 for ^{252}Cf, the maximum flux is at 1 cm distance from the source which indicates the neutron flux of about 1×10^{-2} per a neutron emission from ^{252}Cf. Thus, the maximum neutron flux can be calculated from $(500 \times 2.3 \times 10^6) \times (1 \times 10^{-2}) = 1.15 \times 10^7$ cm^{-2} s^{-1}. Neutron flux at other distances can also be obtained from Figure 6. It should be noted that the thermalization factor increases with increasing emitted neutron energy from the source.

As mentioned earlier, neutron radiography requires low energy neutrons. The lower neutron energy gives better image contrast. Fast neutron or high energy neutrons emitted from the source are slowed down by moderator such as water to produce slow or low energy neutrons. The slow neutron energy in moderator is dependent of moderator temperature and the energy distribution follows Maxwellian's for gas molecules and particles. The slow neutron is therefore called "thermal neutron". "Cold neutrons" can be produced by cooling the moderator/collimator down, such as with liquid helium, to obtain better image contrast. The cadmium ratio of cold neutrons is indicated in Table 2 where infinity (∞) means there is no epicadmium neutron (energy > 0.5 eV) in the beam.

Source	Comments
Radioisotope	constant neutron output, low cost, maintenance free, no operating cost, low neutron flux/long exposure time, acceptable image quality, mobile unit is possible
Accelerator	moderate cost, moderate operating and maintenance cost, medium neutron flux/medium exposure time, good image quality, mobile unit is possible for small neutron generator
Nuclear Reactor	constant neutron output, high cost, high maintenance and operating cost, high neutron flux/short exposure time, excellent image quality, mobile unit is impossible

Table 2. Neutron sources and their general characteristics

Source	Emitted neutron energy (MeV)		Normal thermal neutron flux (cm^{-2} s)		Therma-lization factor	L/D ratio	Cd ratio
	Range	Mean	in moderator	at specimen			
Radioisotope							
- ^{241}Am/Be (50 Ci)	0 – 10	4.5	10^8	10^3 - 10^4	400	30-50	5-20
- ^{252}Cf (1 mg)	0 - 10	2.0	10^9	10^3 – 10^5	100	50-100	5-20
Accelerator							
- ^{2}D(d, n)^{3}He	2.7	2.7	10^8 – 10^9	10^4 – 10^5	200	20-30	5-20
- ^{3}T(d, n)^{4}He	14.1	14.1	10^8 – 10^9	10^4 – 10^5	600	20-30	5-20
- ^{9}Be(p, n)^{9}B	1.15	1.15	10^8 – 10^9	10^4 – 10^5	50	20-30	5-20
- ^{9}Be(d, n)^{10}B	3.96	3.96	10^8 – 10^9	10^4 – 10^5	100	20-30	5-20
Nuclear Reactor	0-10	2.0	10^{11} - 10^{14}	10^6 – 10^8	100	100-300	100-∞

Table 3. Neutron sources and their technical characteristics [2, 6]

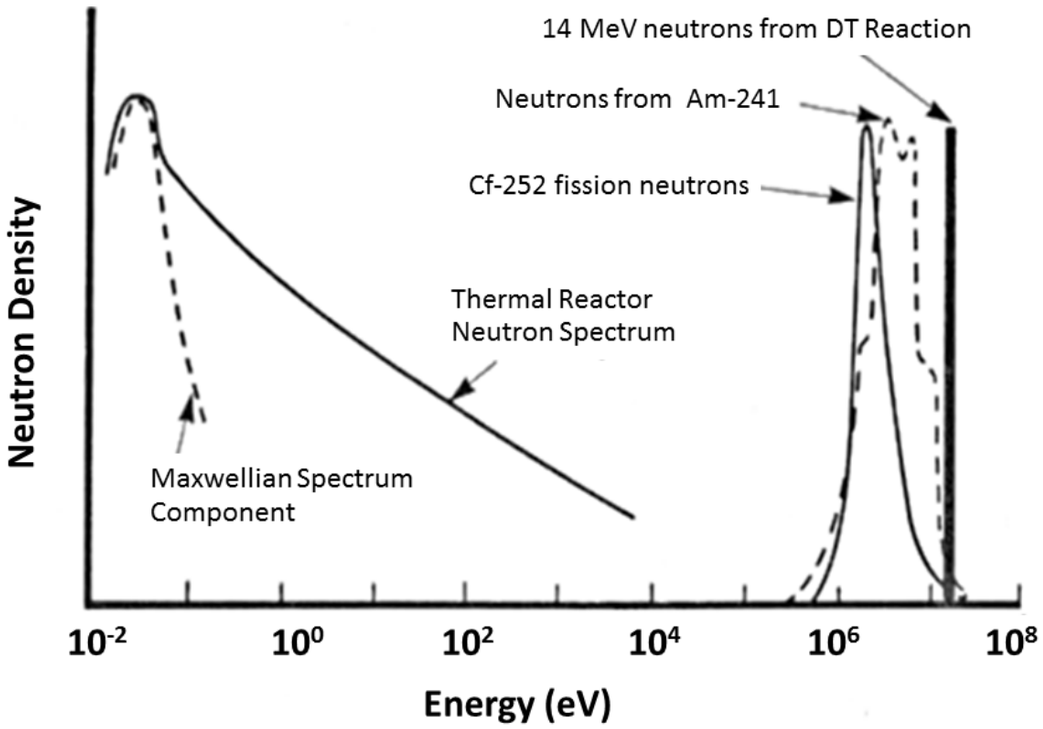


Fig. 5. Energy spectra of neutrons from neutron sources (reproduced from [5])

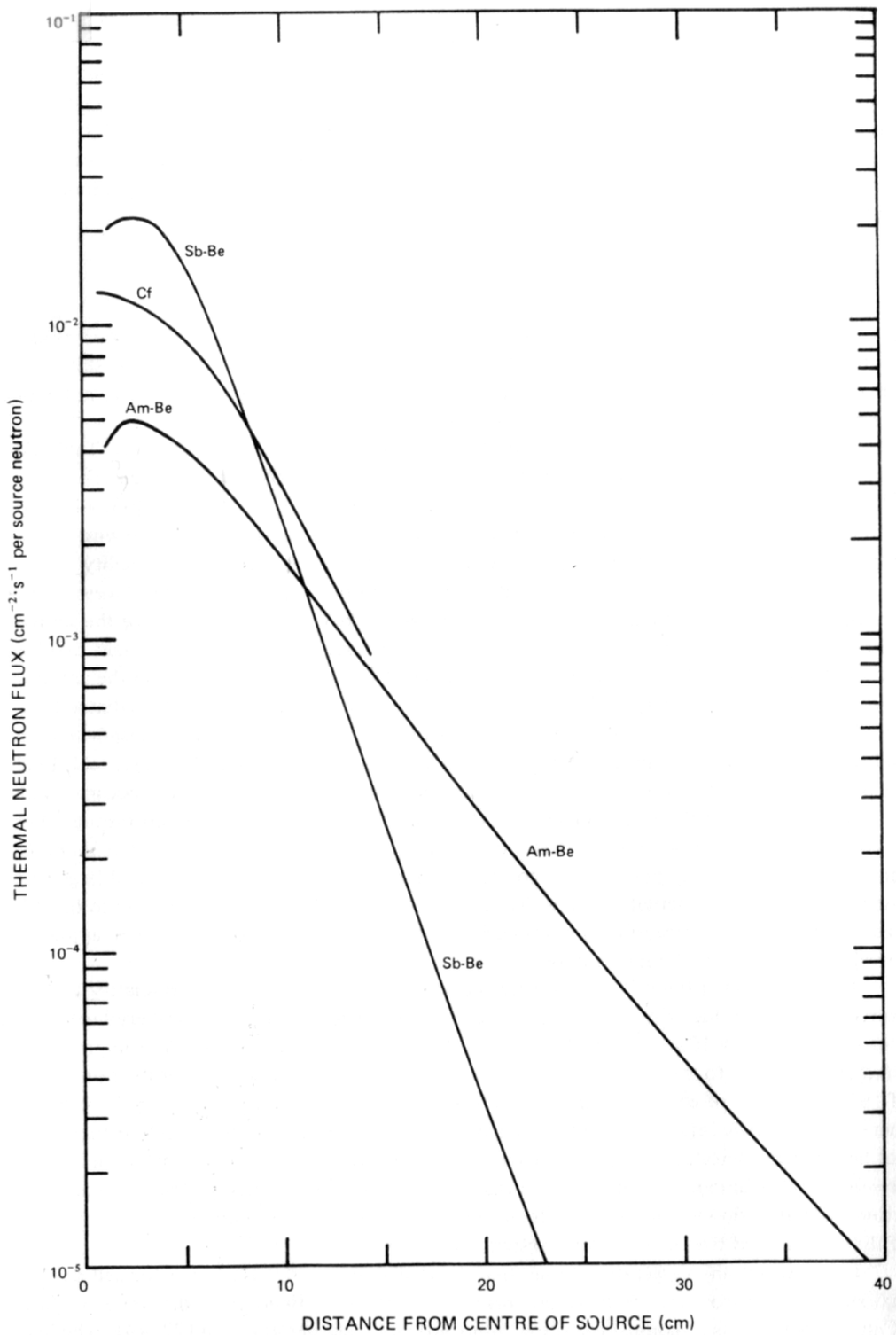


Fig. 6. Neutron flux in water per source neutron emitted from radioisotope neutron sources [6]

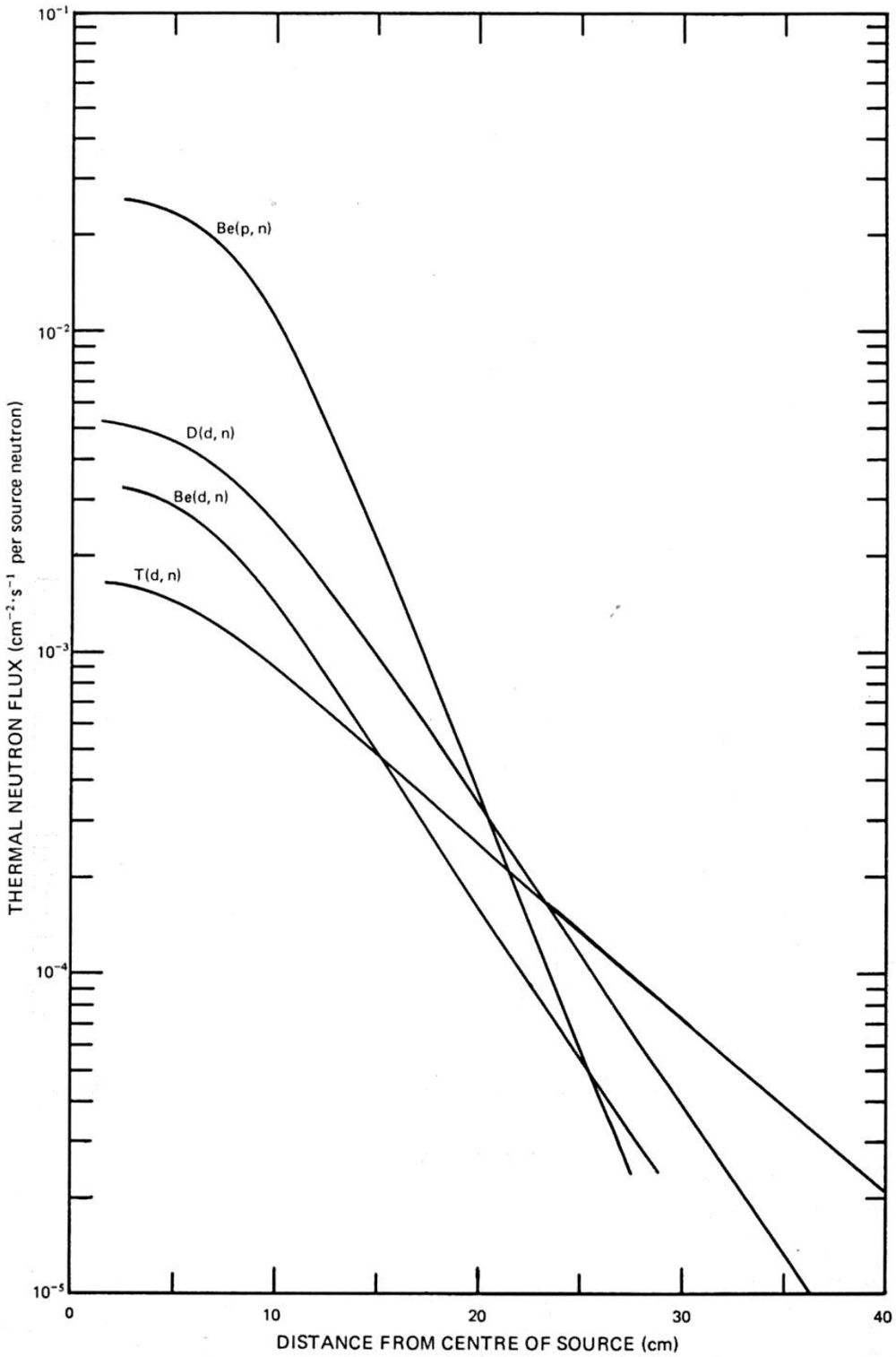


Fig. 7. Neutron flux in water per source neutron emitted from neutron producing accelerators [6]

4. Neutron collimators

Neutrons in moderator are scattered in all directions which are not suitable for radiography. Neutron collimator is a structure designed to extract slow neutron beam from the moderator to the specimen. Ideally, parallel neutron beam is preferred because it gives best image sharpness. If this is the case, Soller or multitube collimator is used. However, divergent collimator is easier to construct and gives good image sharpness depending on the geometrical parameters as will be discussed later.

i. *Soller or multitube collimator*: This collimator is constructed with neutron absorbing material; such as boron, cadmium and gadolinium; as illustrated in Figure 8 so as to bring parallel neutron beam to the test specimen. Neutrons can only get into the collimator from one end which is in the moderator then get out to the other end. Neutrons those are not travel in parallel with the collimator axis will hit the side of the tube or plate and are then absorbed allowing only neutrons travelling in parallel with the tube axis to reach the test specimen. This type of collimator is applicable to nuclear reactor where input neutron intensity to the collimator is high. The drawbacks are that the pattern of parallel plates or tubes may be seen on the image and it is more costly to construct in comparison to the divergent collimator.

ii. *Divergent collimator*: Divergent collimator is designed in the way that neutrons are allowed to get into the collimator only through a small hole from one end then diverge at the other end. The collimator is lined with neutron absorber to absorb unwanted scattered neutrons. It is easy to construct and can be used with non-reactor neutron source like radioisotope and accelerator where slow neutron input is low. The drawback is that image sharpness may not be as good as the Soller collimator. For low neutron intensity as in radioisotope system, neutron output at the specimen position can still be increased by making part of the collimator on the input or source side free from neutron absorber as shown in Figure 10. Neutrons can thus enter the collimator through this part resulting in increasing of neutron intensity. From experience with ^{241}Am/Be and ^{252}Cf sources, neutron intensity can be increased approximately by 10 - 60 % and the cadmium ratio can also be increased from about 5 to 20. In doing so, the image contrast is significantly improved while the image sharpness is a little poorer.

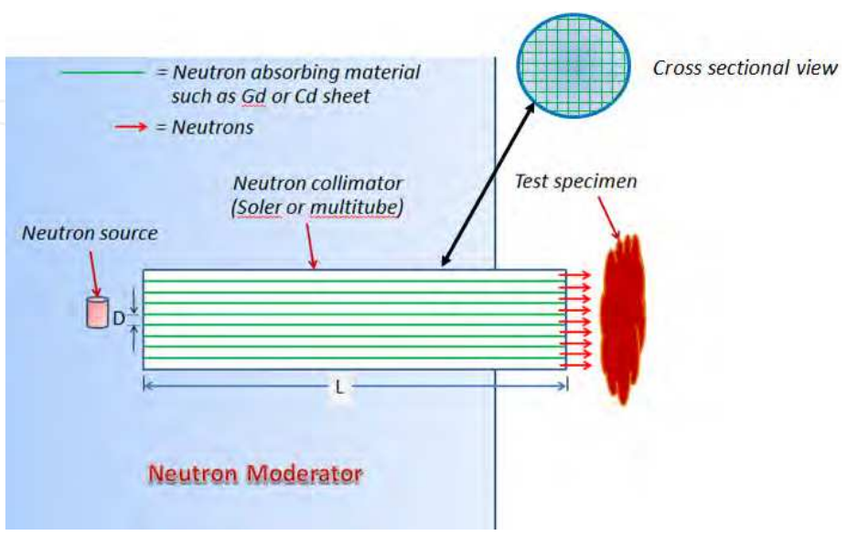


Fig. 8. Multitube neutron collimator

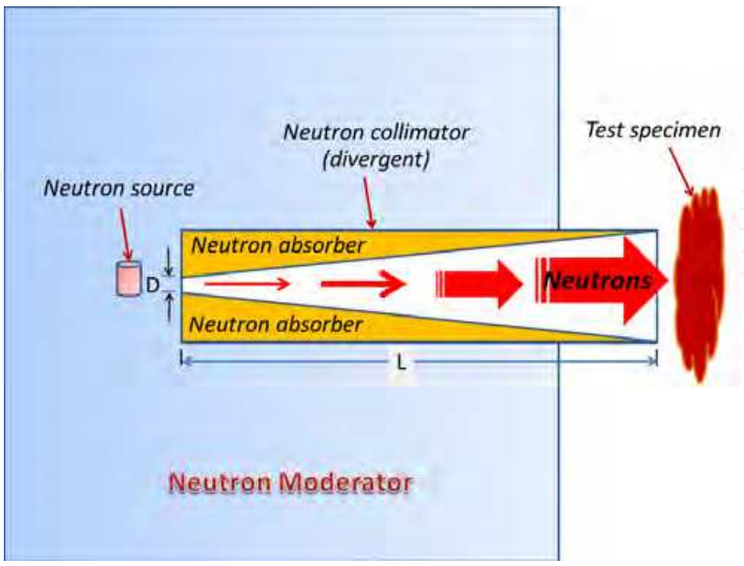


Fig. 9. Divergent neutron collimator allowing neutrons to get into the collimator only through the hole of diameter "D"

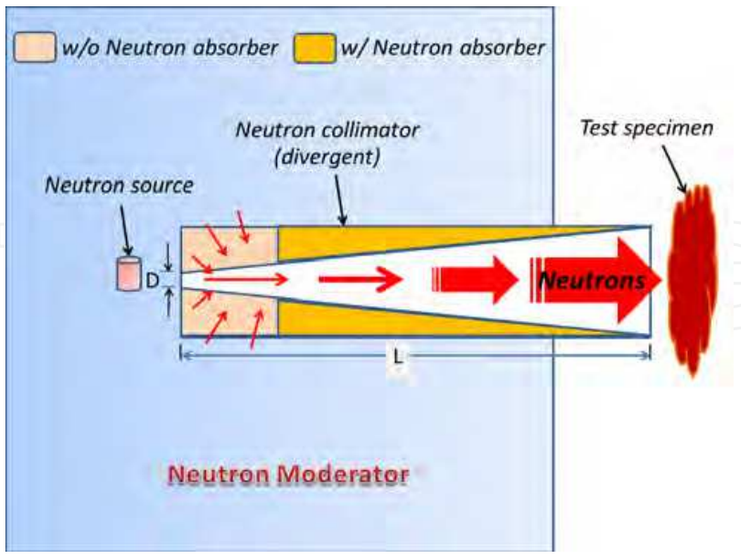


Fig. 10. Divergent neutron collimator with part of the source side contains no neutron absorber allowing more neutrons to get into the collimator

5. Neutron radiographic techniques

After neutrons pass through the specimen they interact with the converter screen to produce radioisotope, alpha particle or light which can be recorded by film, imaging plate, optical camera or video camera. Image recording medium must be selected to match with the particles or light emitted from the neutron converter screen so as to obtain the maximum efficiency. The neutron converter screen/image recording device assemblies commonly used in neutron radiography are described below.

i. *Metallic foil screen/film*: Metallic foil with high neutron cross section is employed to convert slow neutrons to beta-particles, gamma-rays and/or conversion electron while industrial x-ray film is normally used as the image recorder. Gadolinium (Gd) foil is the best metallic screen for neutron radiography in terms of having extremely high neutron absorption cross section, giving the best image resolution and not becoming radioisotope after neutron absorption. ^{155}Gd and ^{157}Gd are found 14.9 and 15.7 percent of natural Gd isotopes with neutron absorption cross sections of 61,000 and 254,000 barns respectively. ^{155}Gd and ^{157}Gd absorb neutrons then become ^{156}Gd and ^{158}Gd correspondingly which are not radioactive. Prompt captured gamma-rays emitted during neutron absorption can cause film blackening. More importantly, prompt gamma-rays may hit atomic electrons resulting in ejection of electrons from the atoms (so called "conversion electron") which are more effective to cause film blackening. It should be noted that less than a few percentage of gamma-ray photons cause film blackening. Electrons and beta-particles are preferred because they interact with film much more than gamma-rays.

Film may be replaced by imaging plate (IP) which has more than 10 times faster speed than the x-ray film. Gd foil/x-ray film requires relatively high neutron exposure thus it is not possible to carry out neutron radiography with low neutron flux system using radioisotope. About 5 years ago, Fuji started to produce neutron imaging plate by adding Gd into the imaging plate which can give the image quality comparable to that from the Gd foil/x-ray film assembly with approximately 50 times reduction of neutron exposure. It is therefore possible to be used with low neutron flux system.

Other metallic foil screens can also be used (as listed in Table 4) but the image quality is not as good as that obtained from Gd. This is mainly because low energy electrons emitted from Gd have very short ranges resulting in much better image sharpness. In case of having large gamma-ray contamination in the neutron beam and specimen containing gamma-ray emitting radioisotopes, dysprosium (Dy) is often used. To avoid gamma-ray exposure to x-ray film, the transfer method must be applied by exposing only the Dy screen with transmitted neutrons from the specimen. During exposure, radioisotopes ^{165m}Dy and ^{165}Dy are formed with half-lives of 1.26 minutes and 2.3 hours respectively. The Dy foil is then removed from the neutron beam and placed in close contact with an x-ray film to produce a latent image. The film density or film darkness is corresponding to the activity of Dy radioisotopes formed in each part of the Dy foil.

Formation of radioisotope from neutron irradiation follows the equation below.

$$A = n\sigma\phi (1 - e^{-\lambda T}) \quad (2)$$

Where A is the radioactivity of radioisotope formed in disintegration per second (dps) after completion of neutron irradiation. n is the number of original stable isotope atoms. σ is the neutron absorption cross section of the original stable isotope in cm^2. ϕ is the neutron flux in cm^{-2} s^{-1}. λ is the decay constant of the radioisotope formed in s^{-1} and T is the irradiation time in second (s).

The decay constant (λ) can be obtained from :

$$\lambda = 0.693/T_{1/2} \quad (3)$$

where $T_{1/2}$ is half-life of the radioisotope. Form equation (1), more than 96 % of the maximum radioactivity can be obtained if the irradiation time is greater than 5 times of the half-life.

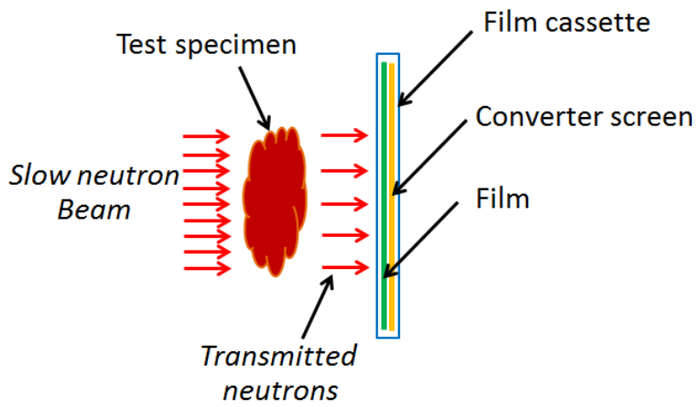


Fig. 11. Illustration of direct exposure method

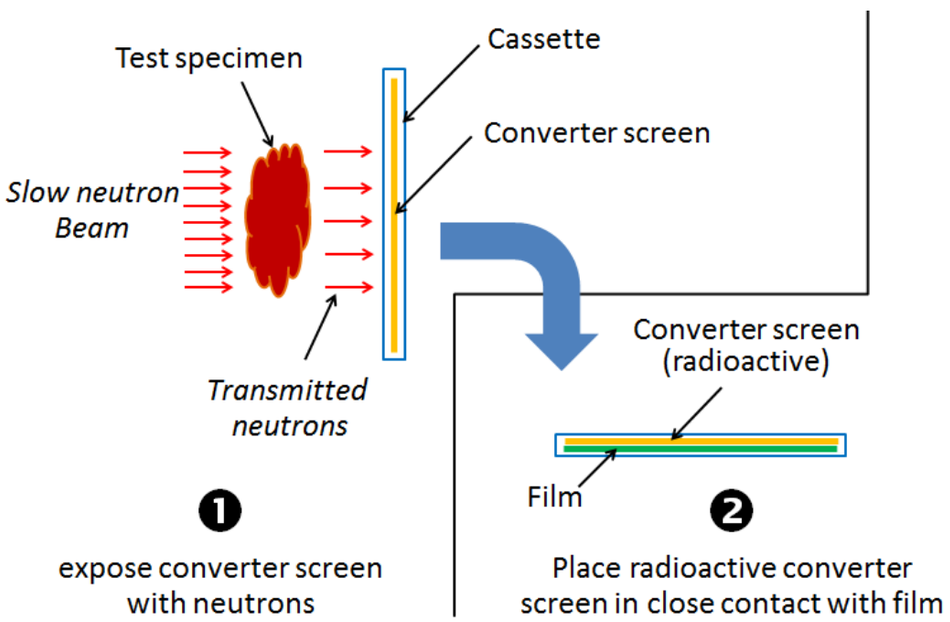


Fig. 12. Illustration of two steps of indirect or transfer exposure method

Material	Mode of Production of active Isotope	Cross-section (barns)	Half-life	Major particle emitted	Direct or Transfer technique
Lithium	$Li^{6}(n, \alpha)H^{3}$	935	Stable	α	Direct
Boron	$B^{10}(n, \alpha)Li^{7}$	3,837	Stable	α	Direct
Rhodium	$Rh^{103}(n, \gamma)Rh^{104}$	144	43 s	β-	Direct
	$Rh^{103}(n, n)Rh^{103m}$		57 min	x-ray	
	$Rh^{103}(n, \gamma)Rh^{104m}$	11	4.4 min	β-	
Cadmium	$Cd^{113}(n, \gamma)Cd^{114}$	20,000	Stable	γ	Direct
Indium	$In^{115}(n, \gamma)In^{116}$	45	14 s	β-	Transfer
	$In^{115}(n, \gamma)In^{116m}$	154	54 min	β-	
Samarium	$Sm^{149}(n, \gamma)Sm^{150}$	41,500	Stable	γ	Direct
	$Sm^{152}(n, \gamma)Sm^{153}$	210	46.7 h	β-	
Gadolinium	$Gd^{155}(n, \gamma)Gd^{156}$	58,000	Stable	e-	Direct
	$Gd^{157}(n, \gamma)Gd^{158}$	240,000	Stable	e-	
Dysprosium	$Dy^{164}(n, \gamma)Dy^{165}$	800	2.3 h	β-	Transfer
	$Dy^{164}(n, \gamma)Dy^{165}$	2,000	1.26 min	β-	

Table 4. Characteristics of Some Possible Neutron Radiography Converter Materials [2, 7]

Radioisotope decays exponentially according to its half-life. If A_0 is the radioactivity of the radioisotope after completion of neutron irradiation, the radioactivity at any time t can be calculated from

$$A_t = A_0 \ e^{-\lambda t} \tag{4}$$

For Gd foil, no radioisotope is formed during neutron irradiation. Emission of prompt gamma-rays and conversion electrons follows neutron absorption by ^{155}Gd and ^{157}Gd at the rate of $n\sigma\phi$ per second. In case of Dy foil, ^{165m}Dy and ^{165}Dy are formed with the radioactivity following equation (2). After removal from the neutron facility, ^{165m}Dy and ^{165}Dy will decay with half-lives of 1.26 minutes and 2.3 hours respectively. Film is exposed to emitted radiation while placing in close contact with the radioactive foil. Build-up and decay of a radioisotope is illustrated graphically in Figure 13.

ii. *Light emitting screen/film*: Light-emitting screen is a mixture of scintillator or phosphor with lithium-6 (^{6}Li) and/or boron-10 (^{10}B). Neutrons interact with ^{6}Li or ^{10}B to produce alpha-particles via (n, α) reaction. Light is then emitted from energy loss of alpha-particles in scintillator or phosphor. Light sensitive film, digital camera or video camera can be used to record image. This makes real-time and near real-time radiography possible. The most common light-emitting screen is NE426 available from NE Technology which is composed of ZnS(Ag) scintillator and boron compound. Gadolinium oxysulfide (terbium) [Gd_2O_2S (Tb), GOS] and lithium loaded glass scintillator are also common in neutron radiography. GOS itself is a scintillator. Conversion electrons as well as low energy prompt gamma-rays emitted from interaction of neutrons with Gd cause light emission. Glass scintillator is sensitive to

charged particles such as alpha- and beta-particles. Lithium is added into the glass scintillator so that alpha-particle will be emitted from $^{6}Li(n, \alpha)^{3}H$ reaction resulting in emission of light.

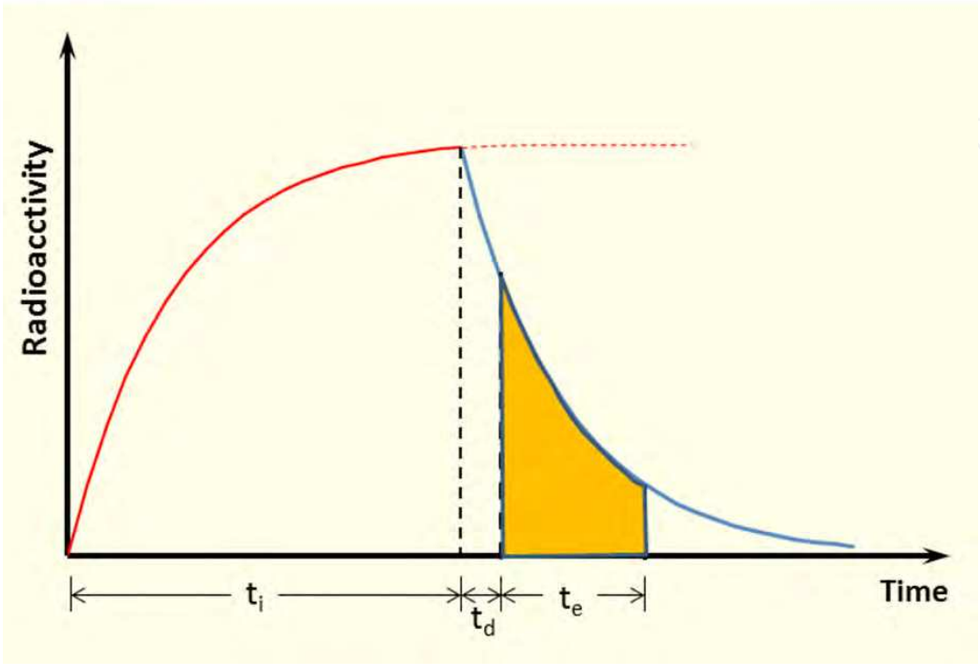


Fig. 13. Graphical illustration of build-up and decay of radioactivity of a radioisotopein neutron converter screen using indirect or transfer method

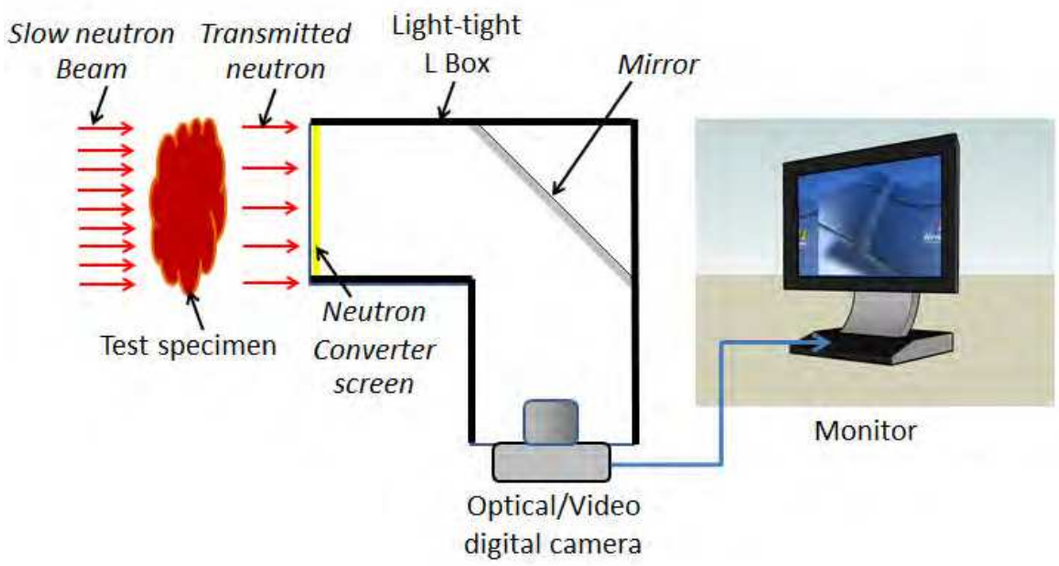


Fig. 14. Real-time or near real-time neutron imaging system using light-emitting neutron converter screen

Light-emitting screen offers highest speed but gives poorest image sharpness comparing to other screen/film assemblies. This is the only type of screen that can be used with low neutron flux system using radioisotope neutron source. From experience, photographic film is more suitable with the light-emitting screen than industrial x-ray film by the following two main reasons. Firstly, photographic film is less sensitive to gamma-ray. As a result, it gives better image contrast particularly when neutron beam is contaminated by large fraction of gamma-rays. Secondly, photographic film is cheaper and easily available.

iii. *Alpha-emitting screen/track-etch film*: Alpha-emitting screen is made of lithium and/or boron compound. Particles emitted from $^{6}Li(n, \alpha)^{3}H$ and $^{10}B(n, \alpha)^{7}Li$ reactions interact with track-etch film (or so called "solid state track detector, SSTD)") to produce damage tracks along their trajectories. The detector is later put into hot chemical solution to enlarge or "etch" the damage tracks. After etching, the damage tracks can be made visible under an optical microscope with a magnification of x 100 up. Radiation dose and/or neutron intensity can be evaluated by counting number of tracks per unit area. The area where track density is so large becomes translucent while the area with low track density is more transparent. The degree of translucence depends on track density resulting in formation of visible image on the film. However, contrast of the image is poor while sharpness is comparable to the Gd foil/x-ray film assembly. Methods for viewing the image is needed to improve image contrast such as reprinting the image on a high contrast film. It has been reported that the simplest method is to scan image on the track-etch film using a desktop scanner [8]. Track-etch film is not sensitive to light, beta-particle and gamma-ray. The alpha-emitting screen/track-etch film assembly can therefore be used to radiograph radioactive specimens by the direct method. No darkroom is needed for film processing. Kodak LR115 Type II, CA80-15 Type II and CN85 Type B have been widely used during the past two decades. They are cellulose nitrate films coated with lithium metaborate ($Li_2B_4O_7$). The optimum etching condition is 10 - 40 % sodium hydroxide (NaOH) at 60 ^{0}C for a duration of 30 – 40 minutes. Later, BE-10 screen of 93 % enriched boron-10 in boron carbide (B_4C) form manufactured by Kodak became available and has been widely used since then due to its highest neutron conversion efficiency. Kodak LR115, CA8015 and CN85 cellulose nitrate film without lithium metaborate are used with the BE-10 screen. CR39 plastic or poly(alyl diglycol) carbonate is also available and is used extensively for alpha detection due to its higher track registration efficiency. The CR39/BE-10 assembly will probably become the most common in track-etch neutron radiography.

6. Applications of neutron radiography: Facilities and sample images

Neutron radiography has been employed for non-destructive testing of specimens. Parts of test specimen containing light elements; such as rubber, plastic, chemicals; can be made visible even when they are covered or enveloped by heavy elements. Nuclear reactor gives the best thermal or cold neutron beam for neutron radiography as can be seen in Tables 3 and 6. The cadmium ratio is normally greater than 10 and can be as high as 300 or even infinity if required. The L/D ratio is always greater than 100 which indicate excellent image sharpness. Nuclear research reactor generally provides excellent beam ports for neutron experiments including for neutron radiography. All neutron converter screen/image

recorder assemblies mentioned above can be employed for inspection of specimens but the exposure times vary considerably. Neutron exposure for some converter screen/film assemblies can be estimated by using the curves in Figure 15.

Converter Screen	Emitted Particles	Recording Medium	Comment
Metallic foil screen			
- Gd foil	electrons	Industrial x-ray film	Best image quality, needs high neutron exposure
- Dy foil	Beta-particles, Gamma-rays	Industrial x-ray film	Best for transfer method, good image quality, needs high exposure
Light-emitting screen			
- NE426 - GOS - ^{6}Li loaded glass scintillator	Light	Photographic film, Industrial x-ray film, Optical or video camera	Fastest speed, needs low exposure, acceptable image quality, allows real-time or near real-time imaging
Alpha-emitting screen			
- $Li_2B_4O_7$	Alpha-particles	Track-etch film e.g. CR39, cellulose nitrate	Good image quality, needs high exposure, low contrast, requires image viewing technique, does not require a darkroom for film loading and processing
- BE-10			

Table 5. Common neutron converter screens and image recording media

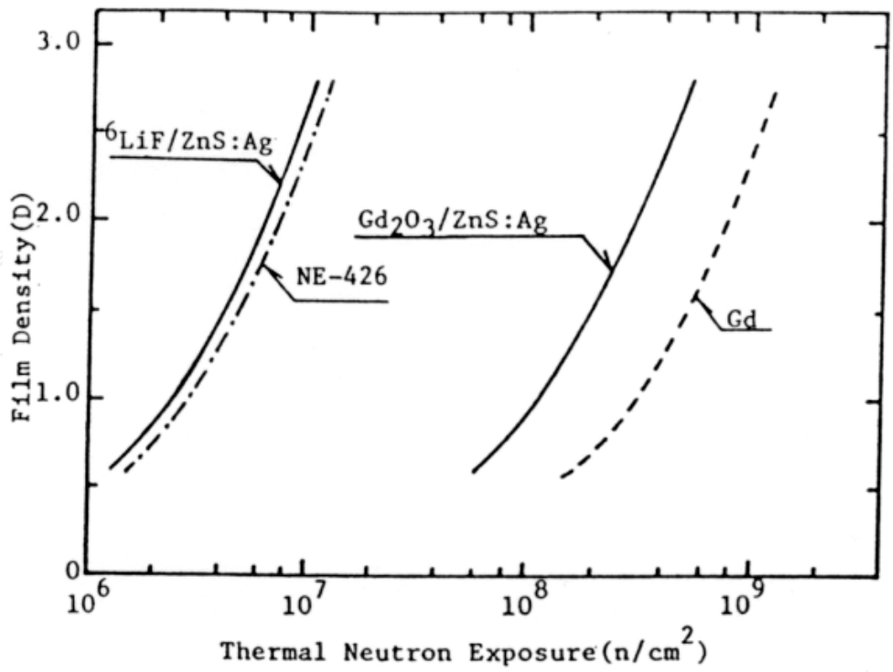


Fig. 15. Thermal neutron exposure required film for radiography [9]

For example, total thermal neutrons per square centimeter required for Gd metallic foil screen/film and NE-426 light emitting screen/film assemblies to make a density of 1.5 on film are approximately 5.5 x 10^8 and 5 x 10^6 respectively. If neutron flux at the specimen position is 10^6 cm^{-2} s^{-1}, the exposure time needed for the two screens are 550 and 5 seconds respectively.

When a 1 mg (1000 μg) Cf-252 is used as in Table 6, the maximum neutron flux in water will be 1000 μg x (2.3 x 10^6 s^{-1} μg^{-1})/100 = 2.3 x 10^7 cm^{-2} s^{-1}. The neutron flux at the specimen position for a circular cross-section, divergent collimator with an L/D of 12 (as in Table 6) can be calculated from:

$$\Phi_{exit} = \Phi_{source} (D/L)^2/16 \quad (5)$$

$$\Phi_{exit} = 2.3 \times 10^7 (1/12)^2/16 = 9.98 \times 10^3 \approx 10^4 \text{ cm}^{-2}\text{ s}^{-1}$$

Where Φ_{source} and Φ_{exit} are neutron fluxes at the source side and the specimen position respectively. The neutron flux obtained from calculation agrees with the value in Table 6. Thus, the exposure time required for the Gd metallic foil screen/film and NE-426 light emitting screen/film assemblies to make a density of 2.0 on film will be 5.5 x 10^4 and 500 seconds respectively. It is therefore impossible to use the Gd foil screen/film assembly with Cf-252 source. However, the neutron flux can still be increased by leaving part of the collimator on the source side without neutron absorber. The neutron flux will then be increased by a factor of (1 + 2a/L), where a is the length of the collimator without neutron absorber. For example, if the length of the total collimator (L) is 30 cm and the part without neutron absorber (a) is 10 cm, the neutron flux is increased by a factor of [1 + (2 x 10)/30] =

1.67 or 67 %. The exposure time will then be reduced from 500 seconds to 300 seconds. In doing so, the cadmium ratio is increased from about 5 to 15 -20 resulting in significant improvement in image contrast but the image sharpness is gradually reduced [10]. Use of the second neutron converter screen can also decrease the exposure time by a factor of up to 2.2 as shown in Table 7. During the past decades, the image recording devices have been rapidly improved in speed as well as graininess including film, imaging plate (IP), digital optical camera, digital video camera, CCD and CMOS chips. The new devices allow radiographers to perform non-film neutron radiography with neutron generator and Cf-252 neutron sources. The Fuji neutron imaging plate offers speed several ten times faster than that of the Gd/film assembly with comparable image quality [11-13]. The light-emitting screen coupled with a digital camera with light sensitivity from ISO 1600 and time integration mode makes non-film neutron radiography by Cf-252 possible. An image intensifier or a microchannel plate (MCP) is useful for real-time or near real-time neutron imaging in low flux system. Examples of neutron radiographic images taken from different neutron facilities and by different techniques are illustrated in Figures 18 to 23.

Source	Collimator		Typical beam characteristics		
	Position	Base flux ($cm^{-2} \cdot s^{-1}$)	Intensity ($cm^{-2} \cdot s^{-1}$)	L/D ratio	Cd ratio
Multi-purpose research reactor	Radial	10^{14}	10^{8}	250	2-5
	Tangential	10^{13}	10^{7}	250	10-50
	Cold source	2×10^{11}	10^{6}	100	∞
Radiography reactor	Radial	10^{12}	10^{6}	250	2-5
	Tangential	4×10^{11}	2×10^{6}	100	10-50
Be(d, n); 3 MeV, 400 μA	Radial	3×10^{9}	2×10^{5}	33	5-20
Be(γ, n); 5.5 MeV, 100 μA	Radial	4×10^{8}	8×10^{4}	18	5-20
T(d, n)+ U; 120 keV, 7 mA	Radial	10^{8}	2×10^{4}	18	5-20
^{252}Cf ; 5 mg + sub-critical Reactor assembly	Radial	3×10^{9}	2×10^{5}	18	5-20
^{252}Cf ; 1 mg	Radial	2×10^{7}	10^{4}	12	5-20

Table 6. Examples of common neutron radiography facilities [2, 6]

Converter Foil	Technique	Foil Thickness (μm)		Relative Speed
		Front	Back	
Rh/Gd	Direct	250	50	5.3
Rh/Rh	Direct	250	250	4.7
Gd/Gd	Direct	25	50	3.7
In/In	Direct	500	750	3.7
Dy/Dy	Direct	150	250	3.7
Cd/Cd	Direct	250	500	3.3
Ag/Ag	Direct	450	450	2.7
Dy	Direct	-	250	2.5
Gd	Direct	-	25	2.4
Cd	Direct	-	250	2.2
Rh	Direct	-	250	2.1
In	Direct	500	-	1.7
Dy	Transfer	250	-	16.4
In	Transfer	50	-	11.2

Remark : The relative speed for the direct and transfer methods are not comparable

Table 7. Relative Speed of Neutron Converter Screens [2]

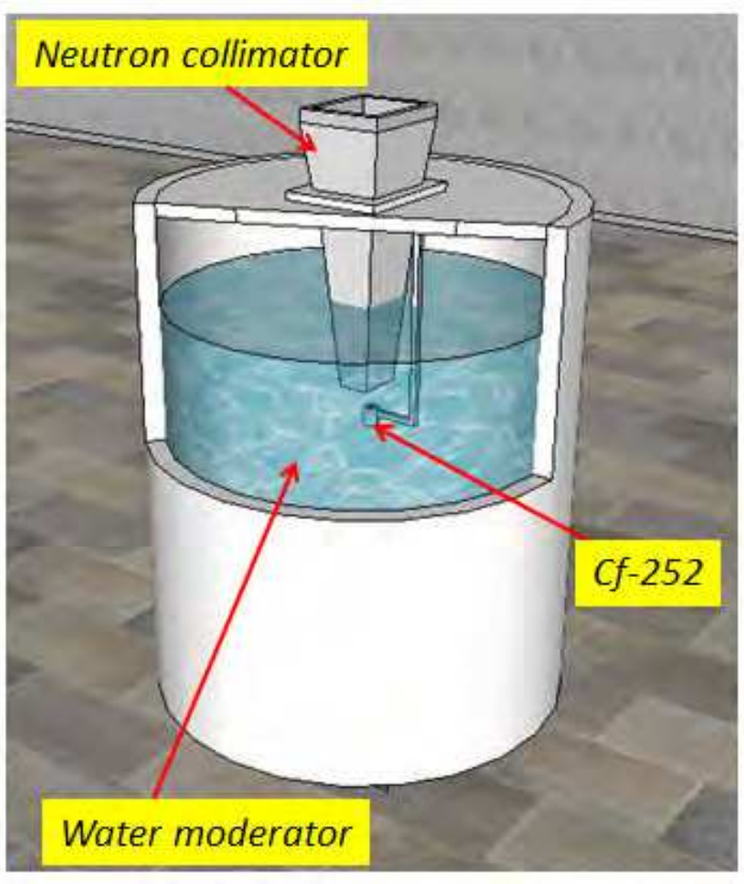


Fig. 16. An example of Cf-252 based neutron radiography system

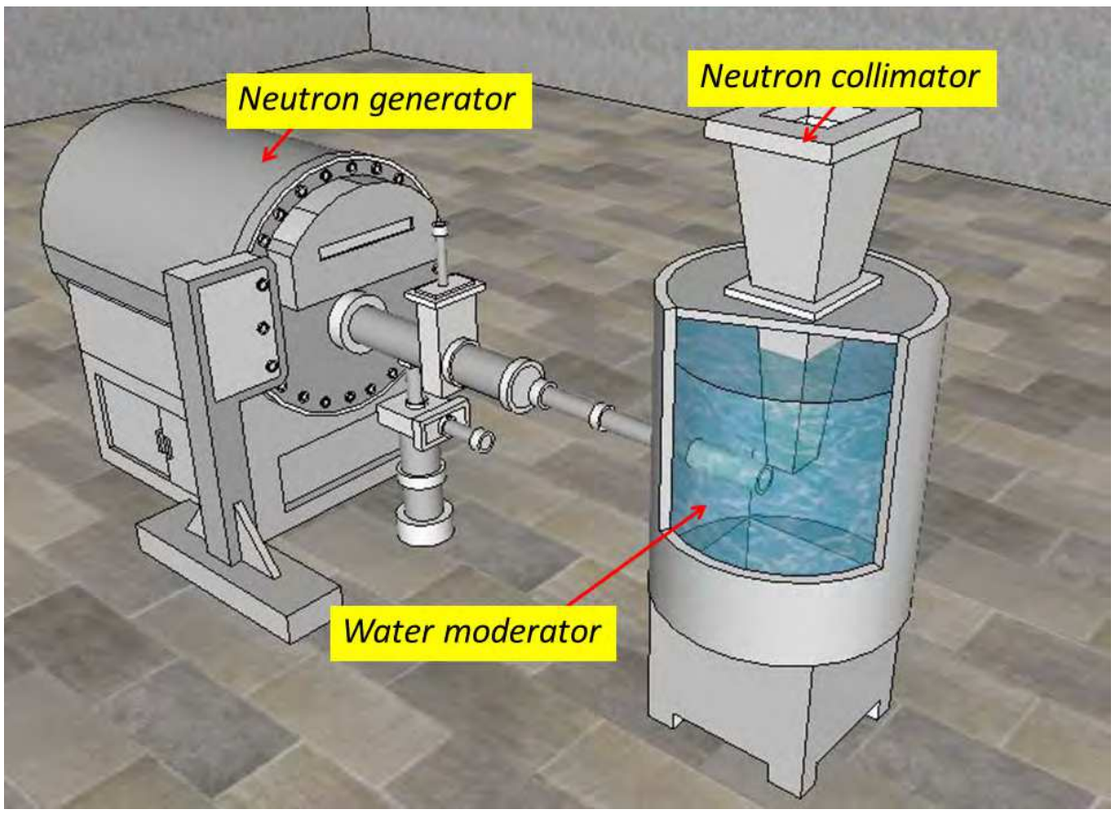


Fig. 17. An example of neutron generator based neutron radiography system

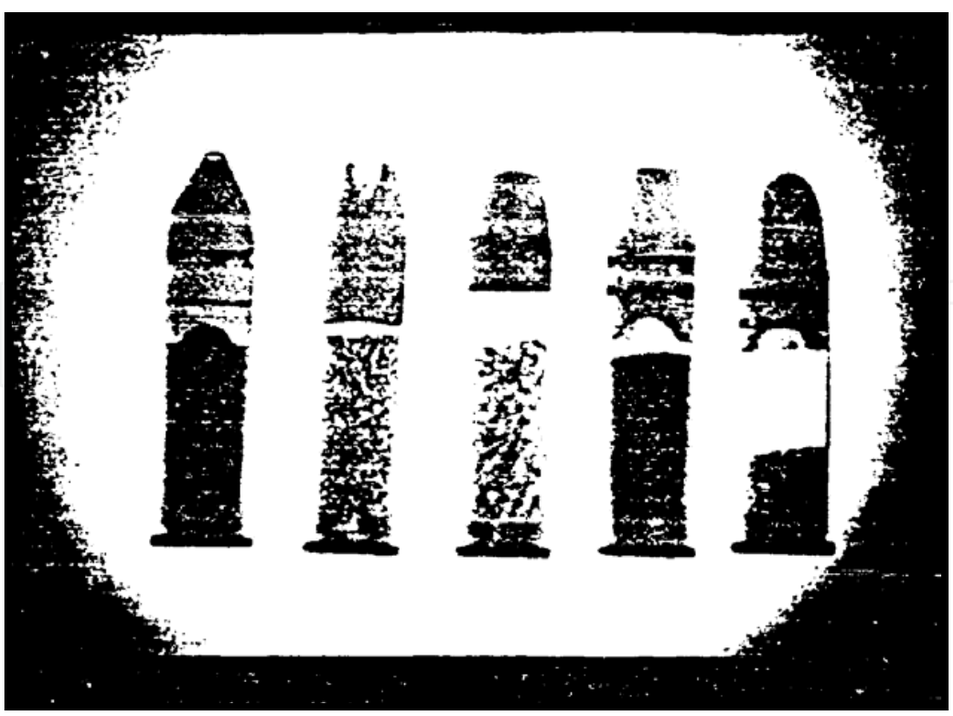
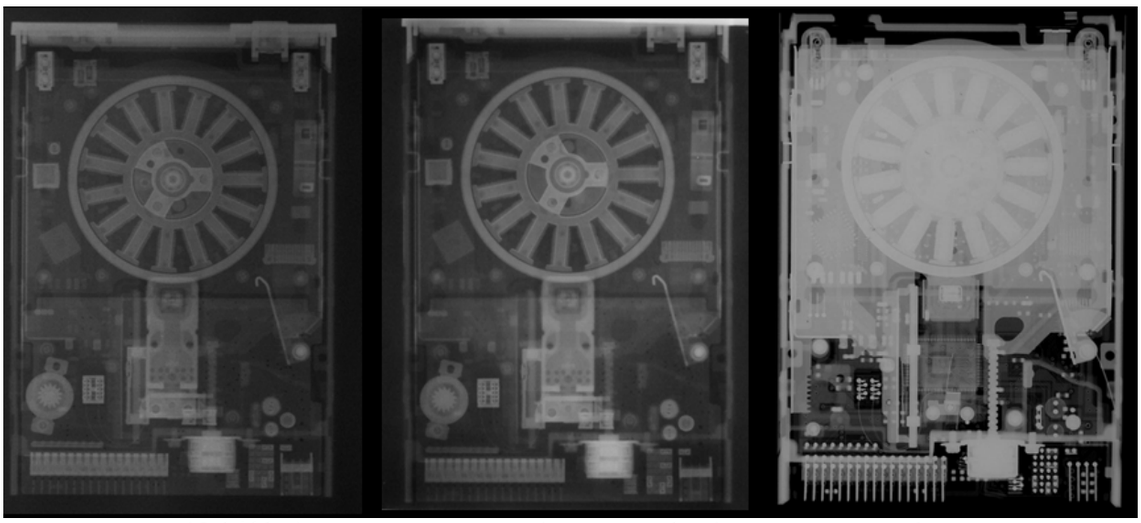


Fig. 18. A neutron radiograph of pistol bullets [14] (research reactor, Gd foil/film technique)



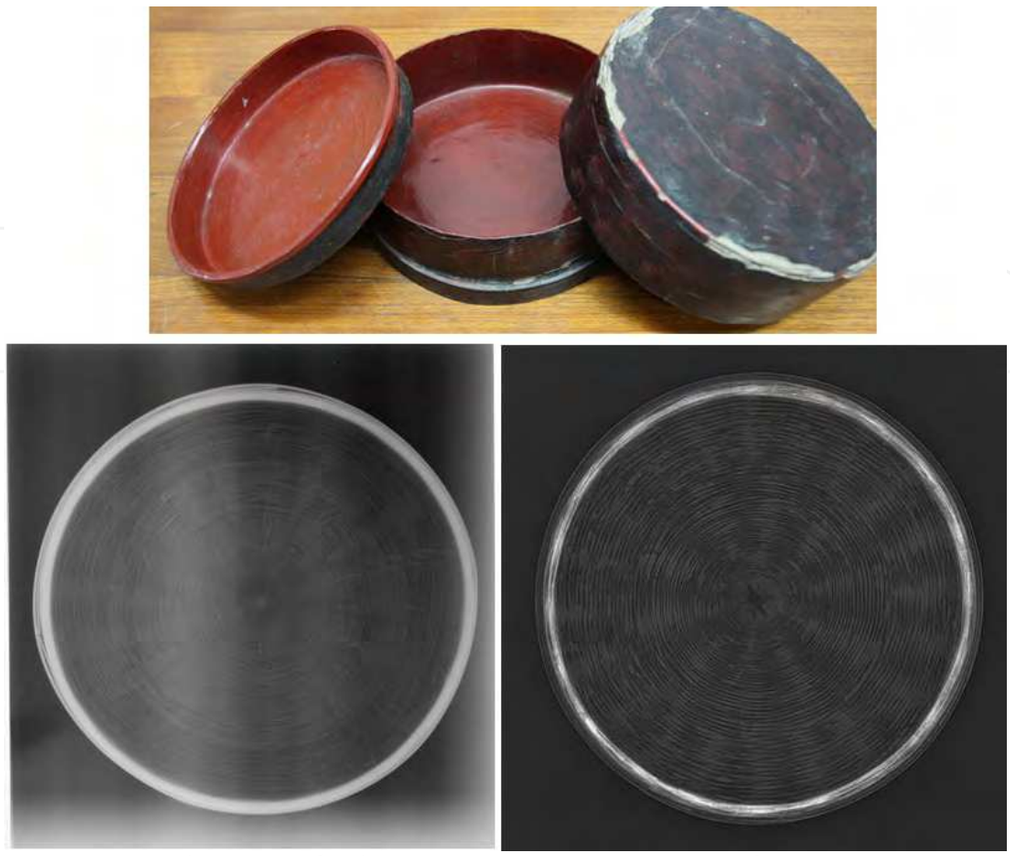
Neutron(Gd/film) Neutron (imaging plate) X-Ray

Neutron(Gd/film) Neutron (imaging plate) X-Ray

Fig. 19. Neutron radiographs with a floppy disk drive (above) and RS-232 connectors (below) using neutron beam from a TRIGA Mark III research reactor in comparison with x-ray radiograph [12]

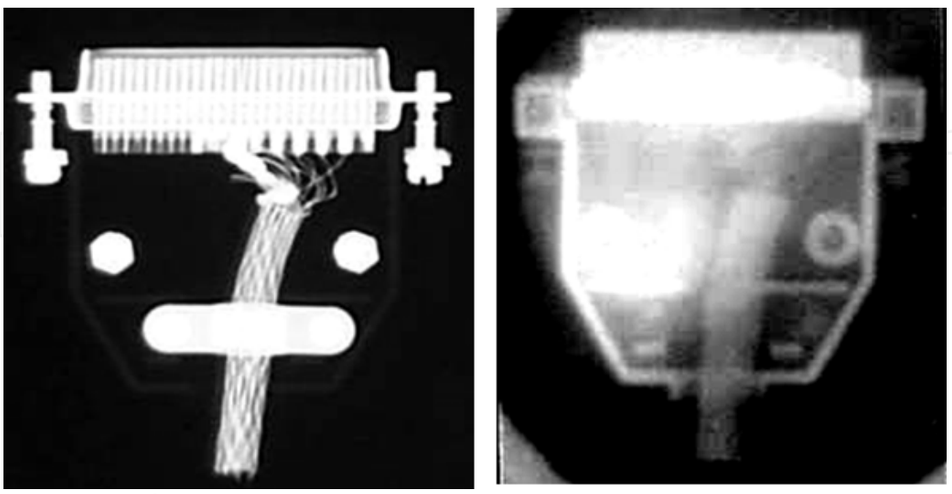
Neutron (imaging plate) X-Ray

Fig. 20. Neutron radiograph of a Buddha statue using neutron beam from a TRIGA Mark III research reactor in comparison with x-ray radiograph [13] (Clay can be clearly seen in the middle part of the body in the neutron radiograph)



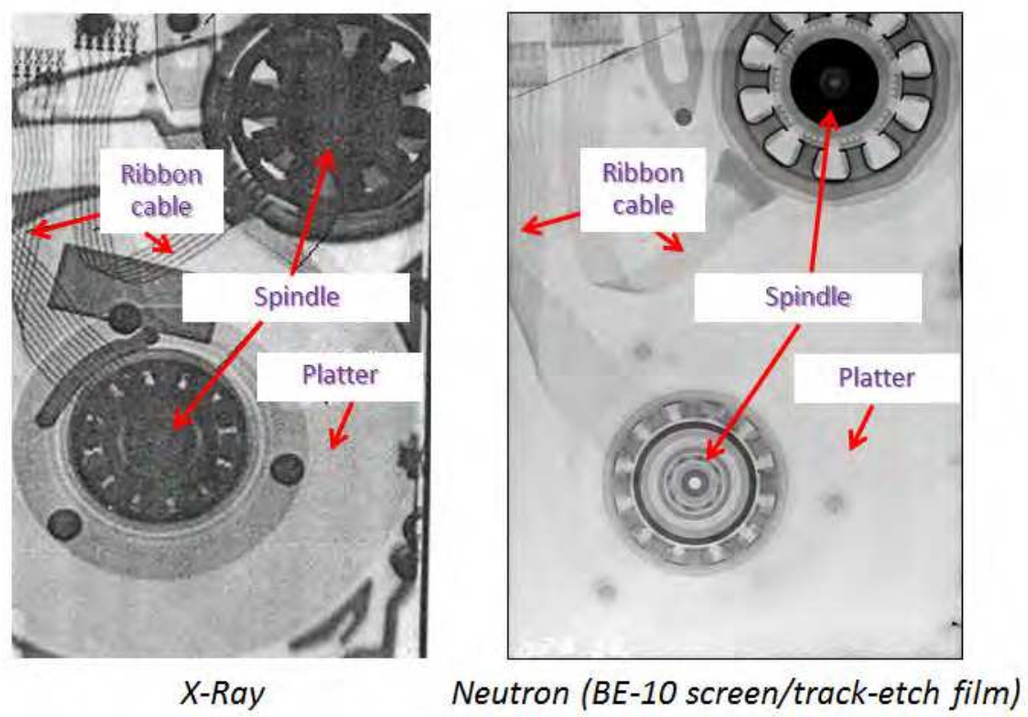
Neutron (imaging plate) X-Ray

Fig. 21. Neutron radiograph of an ancient lacquerware using neutron beam from a TRIGA Mark III research reactor in comparison of x-ray radiograph [13] (Pattern of embroidered bamboo thread can be seen clearer in the neutron radiograph)



X-Ray Neutron

Fig. 22. Neutron radiograph of an RS-232 connector using low intensity neutrons from Cf-252 and NE426 light-emitting screen/photographic film [15]



(a) (b)

Fig. 23. Neutron radiograph (b) of a hard disk drive using neutrons from a research reactor in comparison with x-ray radiograph (a) [16] (The neutron radiograph from the track-etch film was scanned by using a desktop scanner with a shiny polished metal sheet used as the light reflecting surface.)

7. Quality control of neutron radiographic image

Quality of neutron radiograph is affected by various factors not only the L/D ratio and the cadmium ratio as mentioned previously but also the gamma-ray content, the geometric unsharpness, type of converter screen, type of image recording medium and film processing. The image sharpness is improved with increasing of the L/D ratio while the image contrast is improved with increasing of the cadmium ratio. The gamma-ray content in neutron beam will deteriorate the image contrast. The other factors affect the neutron radiographs in the same way as in x-ray and gamma-ray radiography. The ASTM Beam Purity Indicator (BPI) and the ASTM Sensitivity Indicator (SI) are common neutron beam quality indicators as illustrated in Figures 24 and 25 respectively. Department of Nuclear Engineering of Chulalongkorn University also developed a neutron beam quality indicator, so called "CU-NIQI", as illustrated in Figure 26. The CU-NIQI is used with a 3 mm thick lead (Pb) plate to determine gamma-ray content. The quality indicators are based on the same principles. Teflon and polyethylene are hydrogeneous materials used for indicating proportion of slow neutrons to fast neutrons. Cadmium and boron are good neutron absorbers used for indicating proportion of neutrons of energy below 0.5 eV to beyond 0.5 eV. Lead strip or wire is the indicator for gamma-ray content. Film density readings at the positions corresponding to those materials can be used to evaluate quality of the neutron beam.

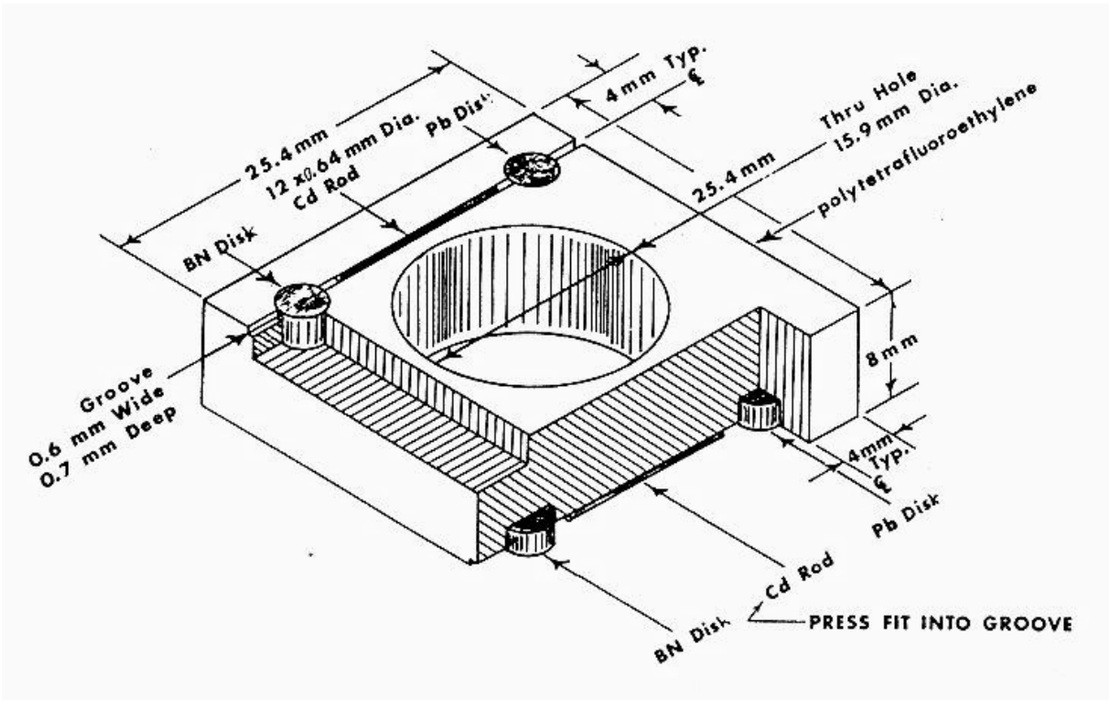


Fig. 24. The ASTM Beam Purity Indicator [2]

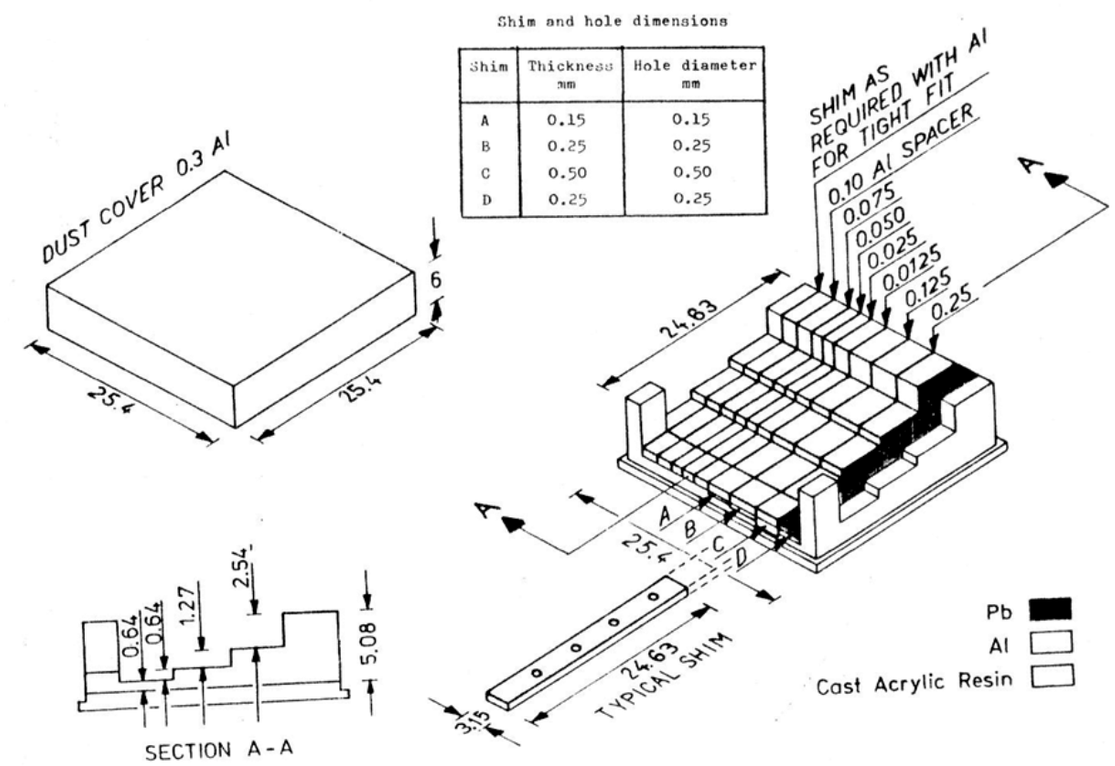
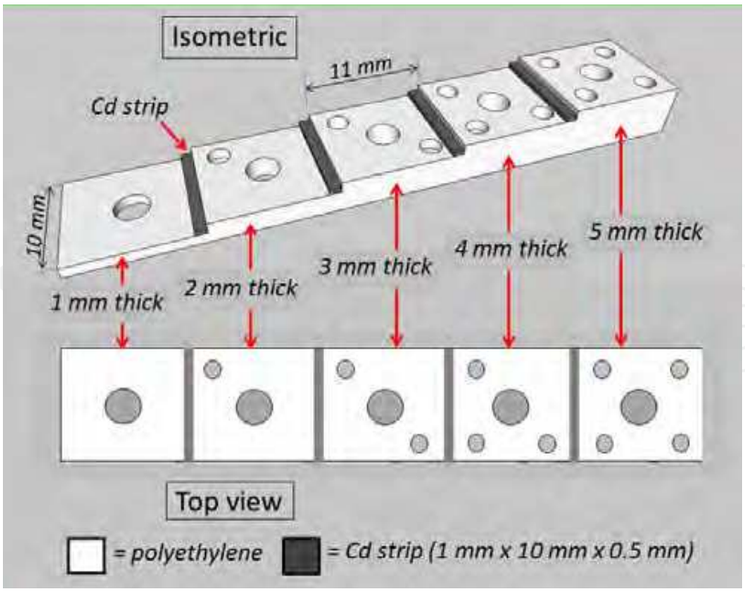


Fig. 25. The ASTM Sensitivity Indicator [2]



Diameter of the central through hole = 3 mm, diameter of hole no. 1 - 4 = 2 mm.
Depth of hole no. 1, 2, 3 and 4 are 1, 2, 3 and 4 mm respectively.

Fig. 26. The CU-NIQI Neutron Beam Purity Indicator developed by the Department of Nuclear Engineering of Chulalongkorn University

8. Methods for determining neutron exposure

In practice there is no standard procedure for constructing an exposure curve for neutron radiography as in x-ray and gamma-ray radiography. For specific application, the radiographer can first begin with trial and error to choose the best exposure. Without knowing the specimen composition and thickness to determine the neutron attenuation, the exposure cannot be obtained. The best method, so far, is to measure transmitted neutron intensity by using a small neutron detector at a few positions behind the specimen before placing the screen/film assembly. The transmitted neutron intensity is inversely

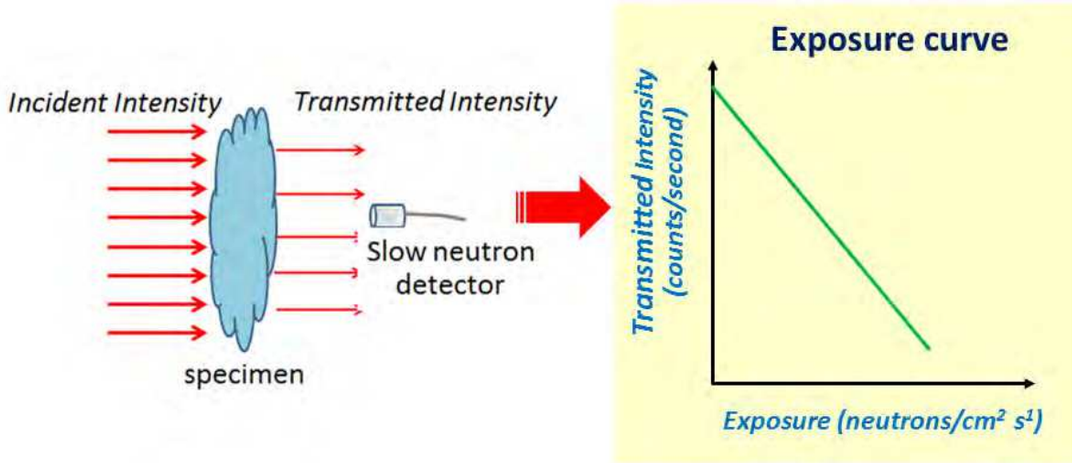


Fig. 27. Illustration of a method for determining the neutron exposure by measuring transmitted neutron intensity with a small neutron detector

proportional to the exposure. In doing so, the radiographer do not need to perform decay and distance corrections. This method can also be applied in x-ray and gamma-ray radiography by changing the neutron detector to x-ray/gamma-ray detector.

9. Acknowledgements

The author would like to express his deepest gratitude to Mr. JateChan Channuie and Mr. Kittiwin Iaemsumang for their assistance in the preparation of the figures and the tables in this chapter. Thanks are also extended to my eldest daughter, Miss Katriya Chankow, and my wife, Mrs. Julie Chankow, for their times spent in correcting the English translation.

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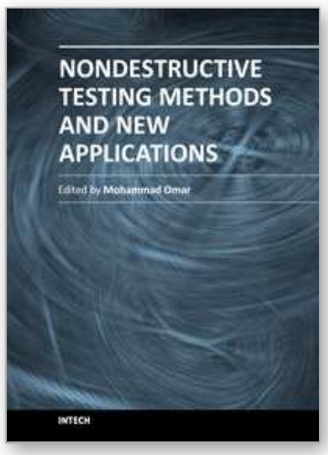

Nondestructive Testing Methods and New Applications

Edited by Dr. Mohammad Omar

ISBN 978-953-51-0108-6
Hard cover, 264 pages
Publisher InTech
Published online 02, March, 2012
Published in print edition March, 2012

Nondestructive testing enables scientists and engineers to evaluate the integrity of their structures and the properties of their materials or components non-intrusively, and in some instances in real-time fashion. Applying the Nondestructive techniques and modalities offers valuable savings and guarantees the quality of engineered systems and products. This technology can be employed through different modalities that include contact methods such as ultrasonic, eddy current, magnetic particles, and liquid penetrant, in addition to contact-less methods such as in thermography, radiography, and shearography. This book seeks to introduce some of the Nondestructive testing methods from its theoretical fundamentals to its specific applications. Additionally, the text contains several novel implementations of such techniques in different fields, including the assessment of civil structures (concrete) to its application in medicine.

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