Chapter 7.

Design and Development of 15 MeV Linear Accelerator based Thermal Neutron Radiography facility

This chapter mainly deals with the work on design and development of 15 MeV Linear Accelerator based thermal neutron radiography facility. The $\gamma - n$ target has been optimized based on their photonuclear threshold. The moderating properties has been studied for a few light elements to optimized best suitable moderator for radiography system. The major part of the design was to optimize the collimator for neutron beam. The main design parameters for the collimator are collimation ratio, gamma content, neutron flux, cadmium ratio, beam uniformity, etc. Based on extensive literature survey and the simulation results, the collimator design has been optimized to meet required output. To make the actual radiographs for this designed facility has been kept as a future scope. However, some of the radiographs have been taken up using the radiography facility of APSARA reactor at BARC, Mumbai for the study purpose. All the radiographs were taken by direct detection techniques.
7.1 Importance and Objective

The thermal neutrons, are valuable for studying industrial components because of their high penetration depth in materials such as steel, aluminium and zirconium. Neutrons are efficiently attenuated by only a few specific elements such as hydrogen, boron, cadmium, samarium and gadolinium and many structural materials such as aluminium, steel are nearly transparent. Neutron radiography (NR) is a powerful non-destructive testing technique frequently used either on its own or as complementary to X-ray radiography for the analysis of objects. The technique is widely used in security, engineering, medical, nuclear and industrial applications [1, 2]. Inspection of ceramics or composite materials as well as detection of aluminium alloy corrosion damage is an example of effective applications of NR.

Neutron radiography comprises two principal components namely a suitable neutron source providing high flux of uniform thermal neutron beam at image plane and a device to record the image of the object. The necessary neutron beams used today are provided by nuclear reactors, radioisotopes and accelerators sources. Nuclear reactors provide high-intensity neutron beam but are expensive, non-transportable and having radioactive waste. Radioisotope based neutron sources, produce low neutron intensity in comparison to the accelerators and nuclear reactors. Because of the compactness, easy handling, adjustable flux, no radioactive waste, less shielding requirement etc. the accelerator based neutron source offering the possibility for in-situ testing of objects. In order to enlarge the range of application of the NR technique, it is necessary to design and construct transportable systems. Such systems must be easy to operate, handle and repair. However, these systems must be properly shielded to meet the radiography rules and regulations. Therefore, the size, weight, shielding and operational conditions of the system must be optimized.

In this work, a transportable unit for radiography using the accelerator based thermal neutron source has been simulated using the Monte Carlo based FLUKA code. The aim is to optimize the design of unit in terms of photo nuclear
target, moderator thickness, collimator and shielding. Therefore, using their optimized design, a transportable NR system can be constructed with maximum and uniform thermal neutron flux at the image plane. In addition, the radiographs of some samples have been studied using the APSARA neutron radiography facility at BARC.

7.2 Literature Survey

Extensive literature review has been done for the design of the neutron radiography setup and their characteristics at other existing places. The imaging techniques and their pros and cons were also reviewed.

(i) Collimator Design

The collimator is the basic component in neutron radiography which decides the quality of the image given and hence collimator designs at the other facilities were reviewed prior to its design for the present facility. In this regard a compilation published by Neutron Radiography Working Group (NRWG), on Collimators for Thermal Neutron Radiography, compiled by J.C. Domanus has information about many different types of collimators and also has general guidelines. It consists of collimator design data from 144 publications. The following general aspects of collimator were reviewed from the compilation [3]

(a) Geometric Shape of the Collimator

The divergent beam collimator is mainly used after the conclusion of Barton in 1967 that divergent beam collimators produce highest resolution [4]. Among them the most commonly used physical form is a truncated cone or pyramid [3]. Conical (truncated cone) collimators have been used in the earlier NR facilities [5–8]. A truncated pyramid, either with a square or a rectangular cross-section is also used commonly in collimator design [9]. Collimators with convergent-divergent shape were used in facilities [10, 11]. A divergent collimator can also be constructed with several cylinders with increasing diameters [3]. Collimators are constructed in segments and then assembled together [12]. The advantage of this type of construction is each single part does not become too
heavy. Also each of the segments can be changed separately if required.

(b) Materials of the walls and their lining

The most important item of each collimator is its lining. Unlike charged particles, neutrons cannot be focused. Hence the neutron beam must be collimated by suitable lining in the collimator. To prevent stray neutrons from reaching the radiographed object and to reduce the scattering of neutrons within the collimator lining must be done with neutron absorbing material. The materials suitable for this purpose are: boron, cadmium, dysprosium, europium, gadolinium and indium [3]. The effectiveness of these materials varies with the neutron energy spectrum. The use of boron is recommended because it gets less activated, which facilitates maintenance of the collimator [3]. Generally, boron in the form of Boral (B4C) is used in the collimator. The collimator lining for many old NR facilities in Europe is given in Ref. [13]. The collimator walls are made up of either aluminium (sheet or cast) or stainless steel [3]. The following is the list of material which has been used before in NR facilities for collimator lining [3].


Boron nitride is also a material which can be used in the collimator as it is easy to machine and therefore unlike boral, complicated shapes can be easily cut of it. As it can be observed there are many choices for the lining of the collimator. There is no explicit advantage of one above the other. Also the thickness of these materials can be varied. Hence suitability must be decided based on the requirement, availability and the cost of the lining.

(c) Filling of the Collimator

The neutron beam gets attenuated by 5% per meter in a collimator filled with air [13]. This reduces the flux at the image plane and also results in more scattering of neutrons which produces blurring of the image. This attenuation can be decreased to less than 1% per meter when helium is used as the filling
gas [13]. The use of argon as the filling gas has also been reported [14].

(d) Gamma and Neutron Filters

To filter out the gamma rays from the beam, lead and bismuth filters are used [3]. As long as 200-mm thick lead and bismuth filters have been used to suppress the gamma rays [12, 15]. The effectiveness of the gamma filter is defined by the $N/\gamma$ (or N/G) ratio. The ratio varies from facility to facility depending upon the imaging technique followed. But the deleterious effect of gamma rays on the image also depends on the object to be radiographed [16]. The least recommended value is about $5 \times 10^4 \text{ n} \cdot \text{cm}^{-2} \cdot \text{mR}^{-1}$ [17]. But with the development of new gamma insensitive neutron detection plates a ratio less than this can also be justified.

Neutron filters are also required to filter out the fast neutrons from the beam. Single crystal sapphire (Al$_2$O$_3$), silicon, quartz and bismuth act as fast neutron filters [18–20]. Sapphire (Al$_2$O$_3$) is an effective fast-neutron filter because its transmission for neutrons of wavelengths less than 0.04 nm (500 meV) is less than 3% for a filter thickness of 100-mm [18]. It is also an effective filter of thermal neutrons with wavelengths less than about 0.1 nm, since there is a great density of high-order reflections available to scatter the incident beam [18]. It has been shown that high quality single-crystal sapphire at room temperature is a better fast neutron filter than silicon and quartz even when they are cooled to liquid nitrogen temperature [21]. Single crystal bismuth along with being a gamma filter is also a good neutron filter. A Bi crystal cut along the [111] plane has been shown to have a thermal neutron window [20].

(ii) Detector Systems

X-ray films with a neutron absorbing converter screens have been traditionally used as detectors in neutron radiography. Although good spatial resolution ($\sim 20 \mu\text{m}$) can be obtained from films, there are many drawbacks which demand new detection systems. In addition, there are new detection systems with more flexible performances especially with respect to time resolution, dynamic range and quantitative information from the images. Apart from film, presently
the following neutron detection systems are available [22]: CCD-camera detection systems, Intensified camera systems, Amorphous silicon flat panels, Pixel detectors.

7.3 Neutron Radiography

Radiography with neutrons began shortly after the discovery of the neutron in 1932. The initial experiments in neutron radiography were performed in Germany in the late 1930s by H. Kallmann and E. Kuhn. The findings of that study, published several years after the work was finished [23] and reported in several patents, conclusively showed the primary potential value of radiography with slow neutrons, and indicated several useful methods of performing neutron radiography.

7.3.1 Basic physics of neutron radiography

Neutron radiography is an imaging method where the objects are penetrated by neutron and corresponding information is obtained about the inner structure. It is non-destructive technique. Its principle is the same as X-ray Radiography. X-ray interacts with electron cloud around the nucleus. The extent of X-ray interaction can be expected to increase with atomic number, since the electron cloud density increases with atomic number. Neutron beams on the other hand are uncharged, so that the neutron has high penetrating power. Since neutron is one of the building blocks of atomic nuclei, it interacts with nuclei to an extent which depends on the existence of stable configurations of neutrons and protons in the nuclei of the object. For a very few types of nuclei, the addition of a neutron forms a particularly stable configuration so that the probability of interaction for these materials is very high. Thus, in general, neutrons penetrate materials easily but some materials are exceptions to this rule and will be imaged readily and will also obviously be essential elements in neutron detectors. The variation in the mass-attenuation coefficients $\mu/\rho$ are plotted as a function of atomic number of the attenuating element for both X-rays (about 120 keV energy) and slow neutrons are shown in Figure 7.1 [24]. The figure demonstrates
the differences in attenuation of neutrons and X-rays for the elements. The absorption coefficient of thermal neutrons is quite different from and unrelated to that of X-ray photons. It is observed from the figure that the neutrons can penetrate high density materials, which are opaque to X-rays, thus allowing the inspection of objects obstructed by a dense martial. Furthermore, the attenuation of thermal neutrons (relative to X-rays) is pronounce for lighter elements, such as hydrogen, carbon and their compounds that comprise the base for many organic materials.

**Figure 7.1:** Mass-attenuation coefficients (cm$^{-2}$·g$^{-1}$) for the elements as a function of atomic number for both X rays (solid line) and thermal neutrons (circles) [24].

The X-ray radiography has some merits/demerits which neutron radiography has not. At some situation such as distinguishing between elements of similar atomic weight and isotopes of the same element and avoiding the interference of gamma radiation of the irradiated materials by using the indirect imaging method, so neutron radiography is a only available non destructive method [25]. A major advantage of using slow neutron radiography over X-ray radiography is the attenuation difference in the respective material [23]. For example, the high attenuation of slow neutrons in elements such as hydrogen, lithium, boron, cadmium, and several rare earths means that these materials can readily be shadowed with neutrons even when they may be combined in an assembly with some high
atomic weight material such as steel, lead, bismuth, or uranium. Although, the heavy material would make X-radiography difficult, neutron radiography should yield a successful inspection. Further, the differences in slow neutron attenuation often found between neighboring materials in the periodic table offer an advantage for neutron radiographic discrimination between materials that have similar X-ray attenuation characteristics. This advantage is illustrated in Figure 7.1. For neutrons, it is more convenient to have the relationship between attenuation coefficient and cross section, as follows:

$$\mu = N\sigma_t = N(\Sigma_a + \Sigma_s)$$  \hspace{1cm} (7.1)

where $N$=number of nuclei per cm$^3$ of attenuating material, $\Sigma_t$ = total cross section (cm$^2$), equal to the sum of absorption and scattering cross sections $\Sigma_a + \Sigma_s$, and $\mu$ = linear attenuation coefficient (cm$^{-1}$).

In radiographic situations, radiation that transmitted through the object being examined is recorded so that those areas in which radiation has been removed, either by absorption or by scattering, may be observed. The above equations are valuable in assessing the relative change in transmitted radiation intensity that might be obtained for several materials and thicknesses within an object of interest.

The neutron radiographic applications are those involving hydrogenous and metallic assemblies such as metal-jacketed explosives, adhesive-bonded assemblies, fluids in metal structures, components such as rubber, plastic, wax, or paper in metal assemblies, and hydride deposits in metals. In addition, neutron inspections of such diverse objects as boron filament composite materials, brazed assemblies, cadmium plating, and heavy metal assemblies appear attractive.

Most work in neutron radiography has been performed with thermal neutrons because neutrons within that energy range exhibit the useful attenuation characteristics and because such neutrons can be obtained with relative ease from a variety of neutron sources.

The basic requirements for a neutron radiography system are a neutron source, a neutron collimator and suitable neutron detectors.
7.3.2 The Neutron Source

These fall into four categories: reactor sources, radioisotope sources, accelerator sources and neutron emitting spontaneously fissionable nuclides. The Table 7.1 shows the details about different type of neutron source and their advantages and disadvantages.

### Table 7.1: Different types of neutron sources generally used for neutron radiography [26].

<table>
<thead>
<tr>
<th>Source type</th>
<th>Neutron flux (n/cm²·s)</th>
<th>Beam dia. (cm)</th>
<th>Reference</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor based</td>
<td>~ 10⁹ to 10¹⁰</td>
<td>20 to 80</td>
<td>[27], [28]</td>
<td>highest thermal neutron flux and resolution</td>
<td>high gamma content, not portable, problem of radioactive waste</td>
</tr>
<tr>
<td>Radioisotope</td>
<td>~ 10³ to 10⁵</td>
<td>10</td>
<td>Am-Be</td>
<td>semi portable and completely reliable</td>
<td>less flux, shielding problem</td>
</tr>
<tr>
<td>based</td>
<td></td>
<td></td>
<td>[29], [30]</td>
<td></td>
<td>The system can not make OFF</td>
</tr>
<tr>
<td>Accelerator</td>
<td>~ 10⁵ to 10⁷</td>
<td>20 to 30</td>
<td>5.5 MeV Linac on a Be [31] 2.5 MeV D ions on a Be [32]</td>
<td>transportable, no radioactive waste good resolution</td>
<td>less fluxcompare to reactor</td>
</tr>
<tr>
<td>based</td>
<td></td>
<td></td>
<td>[31], [32]</td>
<td></td>
<td>not portable, looses neutron flux</td>
</tr>
<tr>
<td>spontaneous fission</td>
<td>~ 10⁵ to 10⁷</td>
<td>20</td>
<td>²⁵²Cf [33] [34]</td>
<td>Semi portable, poorer resolution</td>
<td>problems of availability</td>
</tr>
</tbody>
</table>

One of the major loss mechanisms in all the systems is the need to moderate the fast neutrons from the source, from their creation energy (typically in the range 20 keV-14 MeV) down to thermal energies (0.025 eV). This is because most materials have a 1/ν (ν= neutron velocity) response to an incoming neutron beam, so that there is little contrast between materials for fast neutrons compared with the large resonances in the thermal range. This has been experimentally investigated by Berger (1970).

7.3.3 Neutron Collimation

Since moderated neutron sources are isotropic, it is essential to introduce some spatial order into the neutron beam used for radiography. Because neutrons are uncharged, focusing to the degree required by utilizing the magnetic moment of the neutron is not feasible. Collimation is achieved by positioning one end of a tube lined with neutron absorber at or near the position of maximum thermal flux in the moderator and allowing the neutrons to stream along the tube.
Neutron radiography collimators typically included some or all of the following components:

1. **An illuminator**: It provides a uniformly intense source of neutrons

2. **Beam filters**: It removes unwanted radiations from the beam

3. **Aperture**: The aperture must prevent thermal neutrons from entering the beam except through the hole. As such, it is made out of strongly absorbing materials. Holes are most usually round or square

4. **Gamma shielding**: It stops most of the gamma rays

5. **Collimator walls**: It helps to define the beam direction

6. **Filling gas**: It improves the beam transport and reduce scattering.

The un-sharpness of a point in the object projected on the image screen is a function of the ratio \( L/D \) where \( L = \) length of collimator, \( D = \) diameter of aperture plane and the neutron flux reaching the object is a function of \( D^2/L^2 \). The highest quality beams from nuclear reactors typically have \( L/D \) ratios of 150 but conservation of flux in lower output accelerator and radioisotope based system dictates the use of \( L/D \) ratios of 18 to 30, with a resultant loss in picture quality. The lowest practical value of \( L/D \) is 10. To prevent ingress of unwanted neutrons, the collimators are usually lined with cadmium or boron compounds. The methods of neutron collimation are simple and direct, and that resolution is attained only at the expense of loss of neutron intensity. When collimating the beams from low flux sources, it has been found useful to keep the neutron absorbing lining at least 7 cm from the end of the lined tube to avoid over-depression of the peak flux [26].

### 7.3.4 Detectors and detection techniques for neutron radiography

Unfortunately, the direct photographic effect of neutrons is negligible. So that all methods rely on intermediate conversion of the neutron information
pattern into a form which can efficiently record by an ordinary radiographic film. The detection techniques split themselves into two classes, (a) transfer detectors and (b) prompt detectors.

**Transfer detectors:** In this technique a thin (0.005 in thick), flat foil of a potentially radioactive metal (dysprosium and indium) is placed in the attenuated neutron beam behind the specimen. The neutron information pattern is then built up as a radioactivity pattern in the foil with a time constant depending on the half life of the foil. Later on the radioactive foil is placed in contact with conventional X-radiographic film which creates latent image centres [35] in the film which are developed in the normal manner to produce a radiograph.

**Direct detectors** In this technique the neutron radiation is converted instantaneously into actinic radiation, usually either light or electrons. A thin (0.001 in thick), flat sheet of gadolinium metal which emits low energy (∼ 70 keV) electron radiation under neutron bombardment, is placed in the attenuated neutron beam behind the specimen and radiographic film. The neutron information pattern is built on gadolinium which accordingly emits electrons. The backscatter electrons generated in Gadolinium forms the image on X-radiographic film which are developed in the normal manner to produce a radiograph.

Other detection techniques include, the track etch detector and Thermoluminescent detectors.

### 7.4 Design Goals

The design of the collimator will affect fundamental properties of the resulting neutron beam very directly. The design choices that are made must recognize the relationship between all of the various components and features. The key issues in the design of any facility for neutron imaging include peak thermal flux, L/D ratio, thermal to fast neutron flux ratio (also called the cadmium ratio), thermal neutron to gamma ratio, flux uniformity and imaging method.

The parameters most important to the quality of the image data are the following

(i) **Collimation Ratio (L/D):** The ratio of the length of collimator to diameter
of the aperture. This ratio directly determines the relationship between sample thickness and image sharpness and links the neutron flux at the aperture with that at the image plane through an inverse square relationship.

\[
\phi_i = \frac{\phi_a}{16 \left( \frac{L}{D} \right)^2}, \quad \mu_G = t \left( \frac{L}{D} \right)
\]  

(7.2)

where, \( t \) = sample thickness, \( \phi_i \) = neutron flux at the image plane, \( \phi_a \) = neutron flux at aperture, and \( \mu_G \) = geometric unsharpness.

(ii) **Beam Divergence**: It is an indicator of the amount of blurring that will be present in the resulting images. The half angle of beam divergence is an important measure of the usefulness of the beam near its periphery and is given by

\[
\theta = \tan^{-1} \left( \frac{\frac{1}{2} I}{L} \right)
\]  

(7.3)

where, \( I \) is the maximum dimension of the image plane (usually a diagonal). If the neutron beam diverges very rapidly to a large size, then the outer portion of the image produced will suffer significant distortion. Conversely, if the beam is very long or if the image size is small, then the outer portion of the image will be less distorted.

(iii) **Gamma content**: The intensity of gamma radiation in the beam affects the amount of biological shielding required, determines whether or not direct-method neutron radiography is possible, and influences the quality of generated neutron radiographs. Radiographically, the absolute intensity of gamma radiation is less important than is the relative contribution of gamma rays to the generation of the image as compared to the contribution from neutrons. Therefore, a useful characteristic of a neutron beam is the \( n/\gamma \) ratio, which is typically such that:

\[
\frac{n}{\gamma} \geq 10^6 \frac{n}{cm^2.mR}
\]  

(7.4)

This condition ensures that gamma-ray contribution to the generation of the image will be small relative to that from neutrons.
(iv) Neutron Flux: The overall neutron flux will largely determine the exposure time, or available temporal resolution of the system. The scattered neutron content is vitally important to the sharpness of the images. Careful design of the collimator to capture scattered neutrons, will minimize this component of the beam.

7.5 Design of 15 MeV Linear Accelerator Based Thermal Neutron Source

15 MeV electron beam of Linear Accelerator has been used for the design of thermal neutron radiography facility. Based on the results estimated in the Chapter 3, the $e^{-}\gamma$ target has been optimized to tungsten target having thickness 4.2 mm for the production of bremsstrahlung radiations. The forward directed bremsstrahlung radiations are then collimated and allowed to fall on the $\gamma-n$ target. To optimized the $\gamma-n$ target, materials those having photo nuclear reaction threshold below 15 MeV were simulated in FLUKA and the integrated neutron fluence was calculated for different thickness of $\gamma-n$ target. The different materials such as beryllium, iron, lead, tantalum, tungsten were simulated for various target thickness and the variation in integrated neutron fluence is shown in Figure 7.2. In addition, the results are also simulated for the most commonly used $e^{-}\gamma$ target (W-Cu). In general, it is observed from figure that the neutron fluence increases with thickness upto certain thickness and then decreases with increase in thickness of $\gamma-n$ target. In an individual target, the lead produces the highest neutron fluence at thickness of 4 cm. Even though the photo nuclear reaction threshold for beryllium (1.66 MeV) is less than lead (7.37 MeV) it produces less number of neutrons because of the cross section of ($\gamma,n$) reaction with beryllium is lower than lead. The bremsstrahlung spectrum generated from the tungsten target has contain maximum number of bremsstrahlung radiation of energy less than 7.37 MeV. Therefore, to utilized lower energy bremsstrahlung radiation ($E < 7.37$ MeV), it was decided to use combine target of beryllium with lead (since lead is producing maximum neutron fluence in an individual target).
The thickness for both the targets were kept same. The variation of neutron fluence with thickness for Be+Pb target is shown in Figure 7.2. It is observed that the Be+Pb target generates highest neutron fluence at 8 cm thickness. The neutron spectra for beryllium (4 cm thick), lead (4 cm thick) and combine target of beryllium + lead (4 cm Be + 4 cm Pb) is shown in Figure 7.3. The integrated neutron fluence for individual beryllium, lead and combine beryllium + lead is $3.045 \times 10^{-7}$, $1.124 \times 10^{-6}$, $2.099 \times 10^{-6}$ (n–cm$^{-2}$–sec$^{-1}$)/e– and mean energy is 150, 562, 400 keV respectively.

The neutron spectra calculated in forward, orthogonal and backward direction for combine target of beryllium + lead is shown in Figure 7.4. It is observed from the figure that in backward direction the neutron fluence is more as compared to forward and orthogonal direction. The integrated neutron fluence for Be+Pb is $2.099 \times 10^{-6}$, $1.846 \times 10^{-6}$, $2.798 \times 10^{-6}$ n–cm$^{-2}$–sec$^{-1}$ at forward, orthogonal and backward direction respectively. Since the backward direction gives maximum neutron fluence, the respective target was divided into two parts. First part of the target was mounted before the neutron collimator and subsequently second one was mounted after the collimator opening. Both
the targets were mounted along the incident electron beam axis.

Next in the design is to optimize the moderator. The moderating properties for various materials are shown in Table 7.2. The moderator material must
Table 7.2: Properties of the moderator materials studied.

<table>
<thead>
<tr>
<th>Material</th>
<th>Chemical Composition</th>
<th>Density (g.cm(^{-3}))</th>
<th>ξ (log energy loss)</th>
<th>ξΣs (cm(^{-1}))</th>
<th>R(_m)</th>
<th>TF (cm(^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light Water</td>
<td>H(_2)O</td>
<td>1.0</td>
<td>0.920</td>
<td>1.35</td>
<td>71</td>
<td>88</td>
</tr>
<tr>
<td>Heavy Water</td>
<td>D(_2)O</td>
<td>1.1</td>
<td>0.509</td>
<td>0.176</td>
<td>5670</td>
<td>425</td>
</tr>
<tr>
<td>Beryllium</td>
<td>Be</td>
<td>1.85</td>
<td>0.209</td>
<td>0.158</td>
<td>143</td>
<td>170</td>
</tr>
<tr>
<td>Graphite</td>
<td>C</td>
<td>1.60</td>
<td>0.158</td>
<td>0.060</td>
<td>192</td>
<td>2570</td>
</tr>
<tr>
<td>Beryllium Oxide</td>
<td>BeO</td>
<td>3.025</td>
<td>0.173</td>
<td>0.131</td>
<td>181</td>
<td>180</td>
</tr>
<tr>
<td>Paraffin</td>
<td>C(<em>{25})H(</em>{52})</td>
<td>0.89</td>
<td>0.917</td>
<td>1.69</td>
<td>64</td>
<td>63</td>
</tr>
<tr>
<td>High Dens. Polyethylene</td>
<td>C(_2)H(_4)</td>
<td>0.98</td>
<td>0.914</td>
<td>1.80</td>
<td>64</td>
<td>56</td>
</tr>
<tr>
<td>Zirconium Hydride</td>
<td>ZrH(_2)</td>
<td>5.61</td>
<td>0.843</td>
<td>1.52</td>
<td>50</td>
<td>63</td>
</tr>
</tbody>
</table>

have properties like high average logarithmic energy loss (ξ), large moderating ratio \(R_m\), large scattering cross section, and small value of thermalization factor. Thermalization factor is defined as

\[
TF(\text{cm}^2) = \frac{\text{Fast neutron yield (n} - s^{-1})}{\text{Peak thermal flux (n} - \text{cm}^{-2} - s^{-1})}
\]  

(7.5)

The geometric configuration use for the optimization of moderator is shown Figure 7.5. Electron beam is started at the center and emits isotropically.

![Figure 7.5: Geometric configuration for moderating materials](image-url)
The electron interacts with $e - \gamma$ target sphere and generates bremsstrahlung radiation. Then the bremsstrahlung radiations interact with $\gamma - n$ target sphere to generate neutrons through photonuclear reaction. Further, they scattered in moderating material of radius ($r_m$) and subsequently detected at the detecting sphere. The moderation efficiency, defined as the flux of thermal neutrons obtained in the moderator per neutron source rate is shown in Figure 7.6. The normalized thermal neutrons flux, $\phi_{th}$, for paraffin ($C_{25}H_{52}$), High density polyethylene (HD-PE) ($C_2H_4$), zirconium hydride ($ZrH_2$) and light water ($H_2O$) is about the same, since they possess approximately the same number of hydrogen atoms per unit volume. In association with these materials, the flux of thermal neutrons decreases very rapidly as the radius of the moderating sphere increases. For moderators with higher moderating ratios ($R_m$), such as beryllium (Be), beryllium oxide (BeO), heavy water ($D_2O$) and graphite (C), a gradual decrease is observed as a function of moderating radius, due to lower absorption of thermal neutrons. The flux of thermal neutrons is greater for Be and BeO, than for $D_2O$ and C, because the Be-based materials possess larger macroscopic scattering cross sections, $\Sigma_s$.

Since HD-PE shift the fast neutron energy to thermal energy very quickly,
therefore, the polyethylene has been optimized as a moderator. The schematic of the optimized thermal neutron radiography facility is shown in Figure 7.7. The

![Schematic diagram of the optimized thermal neutron radiography facility. Not to the scale. Dimensions are in mm](image)

**Figure 7.7:** Schematic diagram of the optimized thermal neutron radiography facility. Not to the scale. Dimensions are in mm
optimized $e-\gamma$ and $\gamma-n$ targets (two parts) are placed in the electron beam axis for the generation of neutron. The position at which the peak of the thermal neutron flux occurs is observed using polyethylene as a moderator. It is found that at 4.5 cm distance from the first $\gamma-n$ target, the peak of thermal neutron flux is observed. To minimize the gamma content at image plane, neutron collimator has been designed in perpendicular direction to the incident beam. Especially, the collimator opens at the beam axis to get the maximum neutron fluence. The neutron absorbing lining of collimator has been started at 30 cm from the beam axis. To minimize the gamma contamination in the thermal neutron beam, the lead having 5 cm thickness was kept as a gamma filter. Moreover, the second $\gamma-n$ target was placed at 1.5 cm from collimator along the electron beam axis.

The best results derived on variation of $L$ and $D$ are given in Table 7.3. In optimization process of collimator, collimator length $L$, inlet aperture $D$ and diameter of the collimator inlet next to the image plane, $D_o$, were varied in order

<table>
<thead>
<tr>
<th>$D_c$ cm</th>
<th>$L$ cm</th>
<th>$D_o$ cm</th>
<th>$\phi_{th}$ n−cm$^{-2}$−s$^{-1}$</th>
<th>$\theta$ (°)</th>
<th>$L/D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>16</td>
<td>22</td>
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to attain the maximum thermal neutron flux at the image plane. The table also shows the divergence angle of the beam ($\theta$). From the results it was optimized to use L/D ratio of the collimator equal to 18, diameter of the aperture 5 cm and length of the collimator 90 cm. The thermal neutron flux calculated on the image plan is $3.1 \times 10^4$ n–cm$^{-2}$–s$^{-1}$ at 80 $\mu$A current of 15 MeV electron beam. The neutron spectra calculated on the aperture and image plane is shown in Figure 7.8.

The neutron spectra calculated on the aperture and image plane is shown in Figure 7.8.

![Graph showing neutron energy spectrum](image)

**Figure 7.8:** Neutron energy spectrum calculated at aperture and image plane for the optimized design of 15 MeV accelerator based thermal neutron radiography facility.

The specifications of the optimized 15 MeV accelerator based neutron radiography facility are as follows

1) Useful beam area = 22 cm × 22 cm square cone
2) Thermal neutron flux = $3.1 \times 10^4$ n–cm$^{-2}$–s$^{-1}$
3) L/D ratio = 18
4) Neutron / gamma ratio = $1 \times 10^5$ n–cm$^{-2}$–mR$^{-1}$
5) $e–\gamma$ target = Tungsten
6) $\gamma – n$ target = beryllium in combination with tungsten
7) moderator = high density polyethylene
8) X-ray shielding = lead
9) Neutron shielding = Polyethylene with Cadmium lining.

### 7.6 Experiment carried out on reactor based Neutron Radiography

To get an right hand experience with neutron radiography, a APSARA reactor based radiography facility at Bhabha Atomic Search Center, Mumbai, was used in the present study. The neutron radiography has been actively pursued by Solid State Division since early seventies for various applications, using the 400KW swimming pool type reactor, was used as the neutron source. In this facility the thermal neutrons from the reactor are collimated by divergent cadmium lined aluminium collimator with a L/D ratio of 90. A cadmium shutter facility was used for opening and closing of the beam. The specimen can be mounted about 60 cm from the collimator followed by a cassette containing neutron converter and X-ray film. The whole setup is properly shielded to avoid any radiation exposure to the operator. The important parameters of the facility are as follows:

- Useful beam area = 15 cm dia
- Thermal neutron flux = $1 \times 10^6$ n–cm$^{-2}$s$^{-1}$
- Gamma radiation level = 4 R/h
- Cadmium ratio = 6.3
- Neutron / gamma ratio = $9 \times 10^5$ n–cm$^{-2}$mR$^{-1}$
- Neutron converter screens = Gd 25 µm thick, Kodak Cn85-B

Using this facility the radiography of various samples has been taken up. The exposure time kept for the formation of radiograph was 3 to 4 min and effect on the image quality was observed. For 4 min of exposure time the image developed on the radiograph is more clearer. Therefore, all the radiographs were taken up at 4 min exposure time. Radiographs of the following samples were taken and they are shown in Figure 7.9 and Figure 7.10 respectively. The details discussion of the radiography are the following:

1) On an aluminium plate, MOSFET and IC’s were mounted and respective radiograph is shown in Figure 7.9(a). Corresponding photograph of the sample
Figure 7.9: Radiographs of the samples taken using APSARA reactor based neutron radiography facility and their corresponding photographs.

is also shown in figure Figure 7.9(b). It is observed from the radiograph that the internal circuitry of IC is seen very clearly.

(2) On an aluminium plate, the name ‘UNIPUNE’ was made and subsequently boric powder was filled inside the gap of the UNIPUNE word and its radiograph was taken which is shown in Figure 7.9(c). Corresponding photograph of the
sample is also shown in Figure 7.9(d). It is clearly observed from the radiograph that due to the presence of boron there is no attenuation of neutron beam on the converter screen.

(3) On an aluminium plate, drills were made vertically having different diameters and they are respectively filled with LiCl₂ and boric powder. The radiograph of the sample is shown in Figure 7.9(e) and corresponding photograph is also shown in Figure 7.9(f). The first and third drill hole was filled with LiCl₂ and second and fourth drill hole was filled with boric powder. The difference of attenuation in both the sample are observed.

(4) Packets of sugar, urea, NaNO₃ were mounted on the aluminium plate and the radiograph was taken as shown in Figure 7.9(g). Corresponding photograph of the sample is also shown in figure Figure 7.9(h). The respective attenuation of neutrons are observed.

(5) A radiograph of silver key-chain was taken and is shown in Figure 7.10(a).

(6) A radiograph of hydrophobic plant was taken and is shown in Figure 7.10(b).

Figure 7.10: Radiographs of the samples taken using APSARA reactor based neutron radiography facility.
7.7 Conclusion

A successful study on the design of 15 MeV Linear accelerator based thermal neutron radiography facility was carried out. The optimized design of radiography provide thermal neutron flux of \(3 \times 10^4\) \(\text{n cm}^{-2} \text{s}^{-1}\) at 80 \(\mu\)A current of electron beam. L/D ratio is 18, the beam size is of 22 \(\times\) 22 cm on image plane and the neutron to gamma ratio is \(1 \times 10^4\) \(\text{n cm}^{-2} \text{mR}^{-1}\). A divergent type collimator of cadmium lining has been optimized in the proposed neutron radiography facility. Moreover, few radiograph have been studied using APSARA reactor based neutron radiography at BARC as an right hand experience and understanding.

7.8 Future Scope

An optimized design of the 15 MeV Linear Accelerator based thermal neutron radiography facility is finalized and the work of development of the facility is in progress at SAMEER, Mumbai. The collimation and detection technique of the radiography facility is understood very well and the setup will be ready in near future. Once the facility gets ready then the radiographs of various samples will be taken and their results will be compared with the radiographs already taken using APSARA reactor based neutron radiography at BARC. Further, the accelerator based radiography facility can be explored to use various industrial and aerospace applications.
Bibliography


List of Publications


