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Beam characterization of new neutron radiography facility at TRIGA Mark II PUSPATI research reactor

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Abstract. Characterization of neutron beam compositions is important in order to capture great radiographic images. The quality of the neutron beam has significant impacts to the radiographic images produced using that beam. Characterizing of the beam, including determination of the effective value for the thermal neutron content, scattered neutron content, gamma content, and pair production content as well as beam sensitivity, is vital for producing quality radiographic images. This paper provides a characterization of the neutron radiography's beam port (beam port 3) at TRIGA Mark II PUSPATI research reactor (RTP). The experiments to determine the effective beam contents and neutron radiograph sensitivity at the beam are based on American Society for Testing and Materials (ASTM) standards document E545. The Beam Purity Indicator (BPI) and Sensitivity Indicator (SI) are the standard used in these experiments. Neutron radiographic imaging of this standard was performed using direct radiographic method with 0.1 mm thickness Gadolinium (Gd) metal converter and film. Characterization of the beam was carried out for 10, 15, 20, 25 and 30 minutes exposure time at 750 kW reactor operating power. The standard was placed at 110 cm from the beam opening. The current neutron beam performances are compared with previous results.

1. Introduction

Neutron radiography is a non-destructive testing method similar to x-ray, but which uses neutrons as radiation source to expose the film. The quality of the neutron radiographic images and the effective beam contents of the source can be studied using ASTM standards device known as Sensitivity Indicator and Beam Purity Indicator respectively. The ASTM document E545 describes a pair of image quality indicators that have been accepted internationally as a standard for neutron radiography [1].

The BPI device measures the effective beam contents of the source including thermal neutron content, scattered neutron content, gamma content and pair production contribution. It is constructed of four simple materials which the radiographic image of the BPI on the film can give both a qualitative analysis using the human eye for a quick visual check, and a quantitative analysis from measurements using a densitometer.

The SI device has been widely utilized for indicating the sensitivity of details visible on the neutron radiograph [2]. This device has a more complex build as compare to BPI, consisting of four steps of a plastic material, with holes and gaps built in to examine the resolution available. Its values are based on the film reader's ability to see the smallest size hole or gap that can be resolved by the reader.

Both of these devices are used in this study to characterize the new neutron radiography beam at RTP. The image recorder used in this study was AGFA radiographic film together with Gadolinium converter screen of 0.1 mm thickness and aluminium cassette. The characterization of the beam was carried out for 10, 15, 20, 25 and 30 minutes exposure time at 750 kW reactor operating power. The samples were placed at 110 cm from the beam opening which give the L/D ratio at the sample position at 105.

2. Methodology

2.1. Beam Purity Indicator

The purpose of this experiment is to determine the effective beam contents of the collimated beam from beam port #3 at new neutron radiography facility at RTP. This new collimator was design to increase the L/D ratio, decrease gamma content, and has reasonable thermal neutron flux for neutron radiography. The new collimator for this neutron radiography facility is comprehensively discussed in [3]. The BPI is capable to measure the effective beam contents. The percentage of these effective beam contents can be quantitatively determined.

The BPI is made of an 8 mm thick Teflon (26 × 26 mm) plate. It has a central hole of 16 mm in diameter. At the top and bottom of the plate have two pairs of round holes (4 mm in diameter and 2 mm deep) are made to accommodate 2 mm thick boron nitride and lead discs. Square grooves (2 × 2 mm^2) are made to accommodate 12 mm long square (2 × 2 mm^2) cadmium rods. The cadmium rods included in the BPI are used to provide an indication if inherent beam resolution or sharpness. The BPI schematic design is shown in figure 1. The BPI schematic design is explained well in [4].

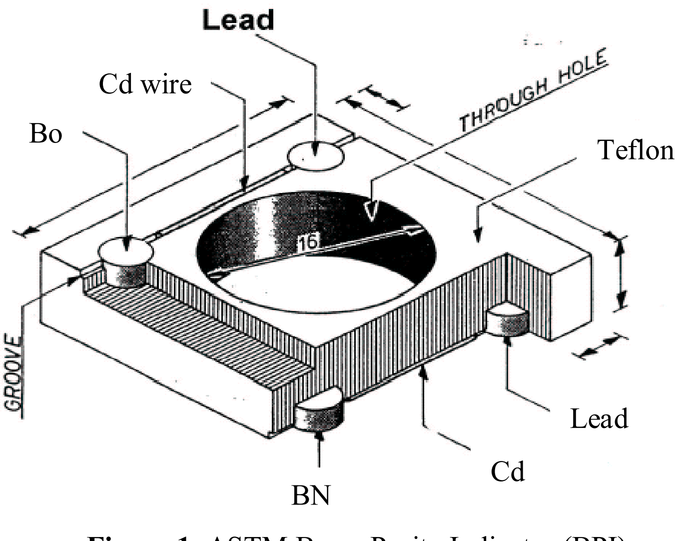

Figure 1. ASTM Beam Purity Indicator (BPI).

The experiments were conducted with exposure time of 10, 15, 20, 25 and 30 minutes. The BPI was attached to the film cassette with aluminium tape and exposed to the radiations beam with AGFA radiographic film embedded with Gadolinium foil. The position of upper and lower Boron Nitrate disc, Lead disk and Cadmium wire was well defined. After finished the exposure, the radiographic film was processed manually in the dark room. Next, the optical density of the BPI images was visualized and measured at six measuring location using X-Rite 361T optical density measurement. The average value of optical density was recorded. The percentage of the effective beam contents and interaction characteristic of neutron and gamma recorded on the radiographic film was calculated using the ASTM equations as follows:

$$Themal\ neutron\ contents, C = [\frac{D_5 - (higher\ value\ of\ D_1\ or\ D_2)}{D_5}] \times 100 \quad (1)$$

$$Scattered\ neutron\ contents, S = [\frac{(D_1 - D_2)}{D_5}] \times 100 \quad (2)$$

$$Gamma\ contents, \gamma = [\frac{D_6 - (lower\ value\ of\ D_3\ or\ D_4)}{D_5}] \times 100 \quad (3)$$

$$Pair\ production, P = [\frac{(D_3 - D_4}{D_5}] \times 100 \quad (4)$$

From the neutron radiographs of the BPI, the following film densities are to be measured:

D_1 – Density under the lower boron nitride disc.
D_2 – Density under the upper boron nitride disc.
D_3 – Density under the lower lead disc.
D_4 – Density under the upper lead disc.
D_5 – Density under the centre of the hole.
D_6 – Density under the Teflon body.

2.2. Sensitivity Indicator

The purpose of the sensitivity measurement is to determine the details visible to the neutron radiography system by evaluating the neutron radiographic image of the sensitivity indicator. This device is one of several devices used for qualitative determination of the sensitivity of detail visible on a neutron radiograph.

The SI is a step-wedge device containing gaps and holes of known dimensions. This device has 4 shims and it has 4 holes which marked as A, B, C and D. Shim D is covered with lead and shim A, B and C are covered with cast acrylic resin. The thickness of the shim and its diameter for shim A, B, C and D are 0.13 mm, 0.25 mm, 0.51 mm and 0.25 mm respectively. The cast acrylic resin step separated by aluminum spacers with gap size marked as G. The G values are 0.25 mm, 0.13 mm, 0.10 mm, 0.076 mm, 0.051 mm, 0.025 mm and 0.013 mm. The SI must be enclosed with aluminum cover to protect from dust. The SI schematic design is shown on figure 2. The SI schematic design is comprehensively discussed in [2].

The SI was exposed together with BPI for the same exposure time. This pair of image quality indicators can give a basis for evaluating both the facility at which the film was radiograph, and the resolution of the film itself. The BPI and SI was placed no less than one inch from any edge of the film to avoid the edge effects of captured gamma from the conversion screen. Same as BPI, the orientation of the SI was well defined. The thickest step in the wedge should be placed away from the BPI. The resolution of the film can be subjectively determined by examination of the holes and gaps. The visual examination of the neutron radiograph of the sensitivity indicator, the G and H values was recorded.

The experimental setup for both BPI and SI are shown in figure 3. The exposure factors for this experiment including the diameter of the beam inlet aperture, the distance between inlet aperture to sample, L/D ratio, type of film, exposure time and type of converter are stated in table 1.

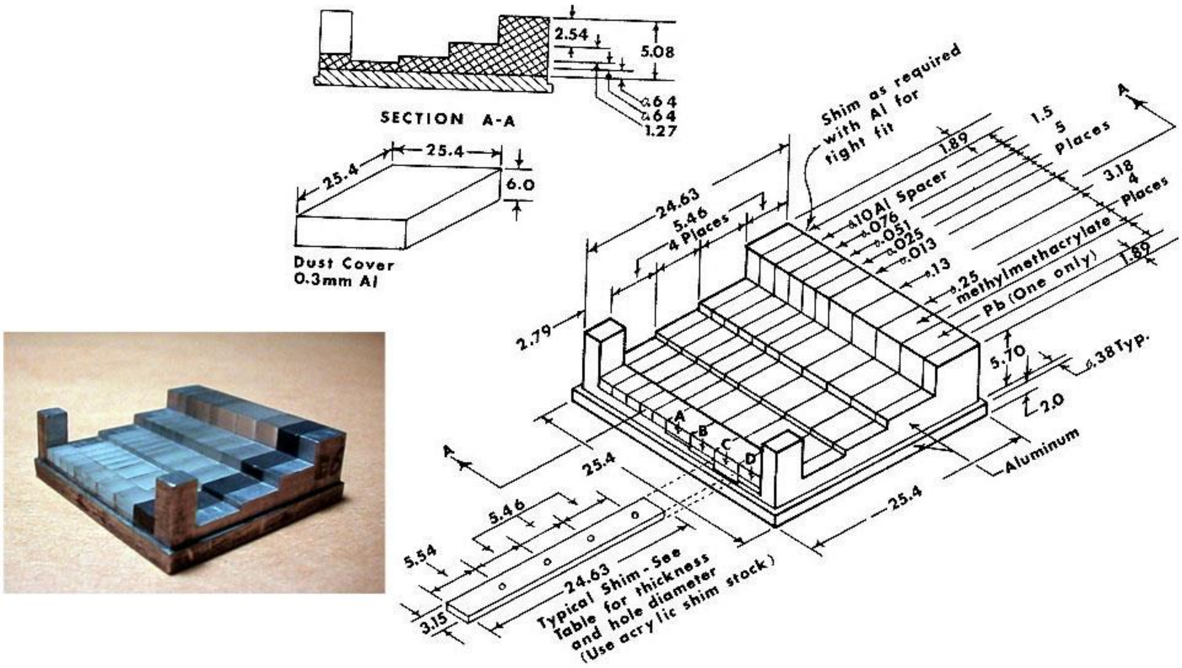

Figure 2. ASTM Sensitivity Indicator (SI).

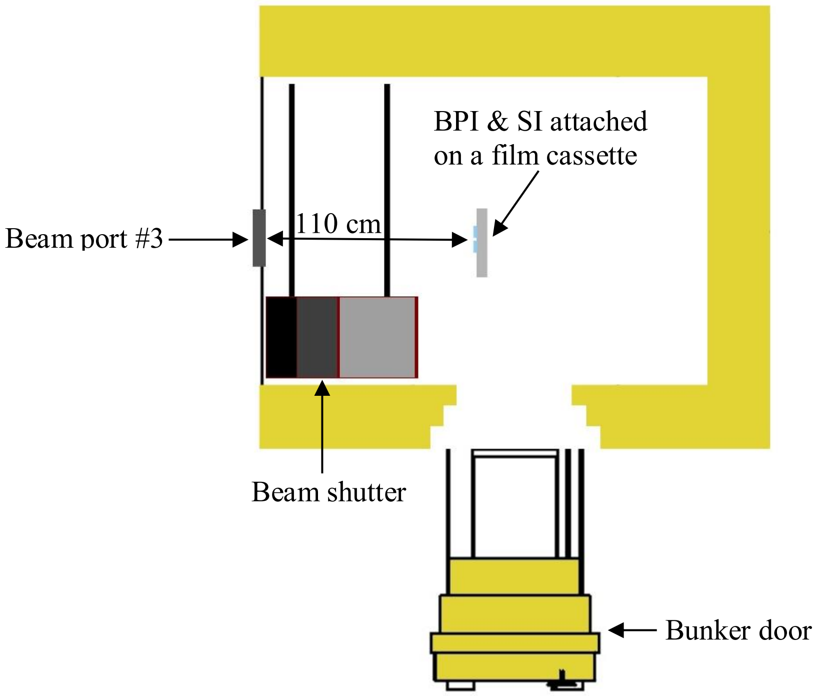

Figure 3. Experimental setup for BPI and SI.

Table 1. The exposure factors for the neutron radiograph.

Factors	Values
Diameter of the beam inlet aperture, D	3 cm
The distance between inlet aperture to sample, L	314.4 cm
The L/D ratio	105
Type of neutron converter	Gadolinium foil with 0.1 mm thickness
Type of film	AGFA radiographic film
Exposure time	10, 15, 20, 25, 30 minutes

3. Results and Discussion

3.1. Beam Radiation Composition

The effective beam contents in the new collimated beam of the neutron radiography facility at RTP are shown in table 2.

Table 2. Radiation contents in the new collimated beam at NR facility at RTP.

Exposure time	10 minutes	15 minutes	20 minutes	25 minutes	30 minutes
Thermal neutron contents, C	22.73%	50.00%	60.23%	61.86%	63.43%
Scattered neutron contents, S	4.55%	4.41%	2.27%	2.06%	2.24%
Gamma contents, γ	0.91%	4.41%	1.14%	1.03%	1.49%
Pair production, P	2.73%	0.00%	2.27%	1.03%	1.49%

From the table 2, it is shown that the scattered neutron contents, gamma contents and pair production (secondary radiation) have lower percentage when the exposure time higher than 20 minutes. Meanwhile, the thermal neutron contents are increased as the exposure time increases because more thermal neutron can be converted and captured by the film when longer exposure time was used. The thermal neutron content is within in an acceptable range between 50.00% to 63.43% as per ASTM [1] confirming that new neutron radiography facility at RTP is in good working conditions. Besides, the 10 minutes exposure time shows it does not have sufficient thermal neutron contents for conducting neutron radiography. The highest value of secondary radiation of scattered neutron, gamma rays and pair production are found to be 4.55%, 4.41% and 2.73% respectively. This results showed that, the secondary radiation is in acceptable range as recommended by ASTM [1].

Figure 4 and figure 5 shows the comparison of the effective beam contents obtained from previous NR facility [5] with the results obtained from new NR facility. From figure 4, the graph showed that the thermal neutron contents from new neutron radiography facility have lower percentage as compared to old neutron radiography facility, especially at 10 minutes exposure time. There are several factors that might contribute in decreasing the thermal neutron contents in new neutron radiography facility. The first factor is smaller beam inlet aperture used in the new collimator [3]. New neutron radiography collimator was design to increase the L/D ratio of the facility, hence the design is made in such a way that it has small beam inlet aperture, D and high length of L. This relation can be expressed with equation below:

$$\frac{Flux\ at\ enterance}{Flux\ at\ exit} = \frac{\phi_0}{\phi} = 16\left(\frac{L}{D}\right)^2 \quad (5)$$

From the equation, it is clear that neutron flux/neutron contents at the exit of the collimator drops with increasing collimator length L, and rises when the inlet aperture, D is made larger. The other factor that might contribute in decreasing the thermal neutron contents is fuel burnup in the reactor core. However, the thermal neutron contents in new NR facility at RTP still in acceptable range as per ASTM. In the other hand, figure 5 showed that new neutron radiography facility has slightly better performance in managing the secondary radiation especially at 25 minutes exposure time.

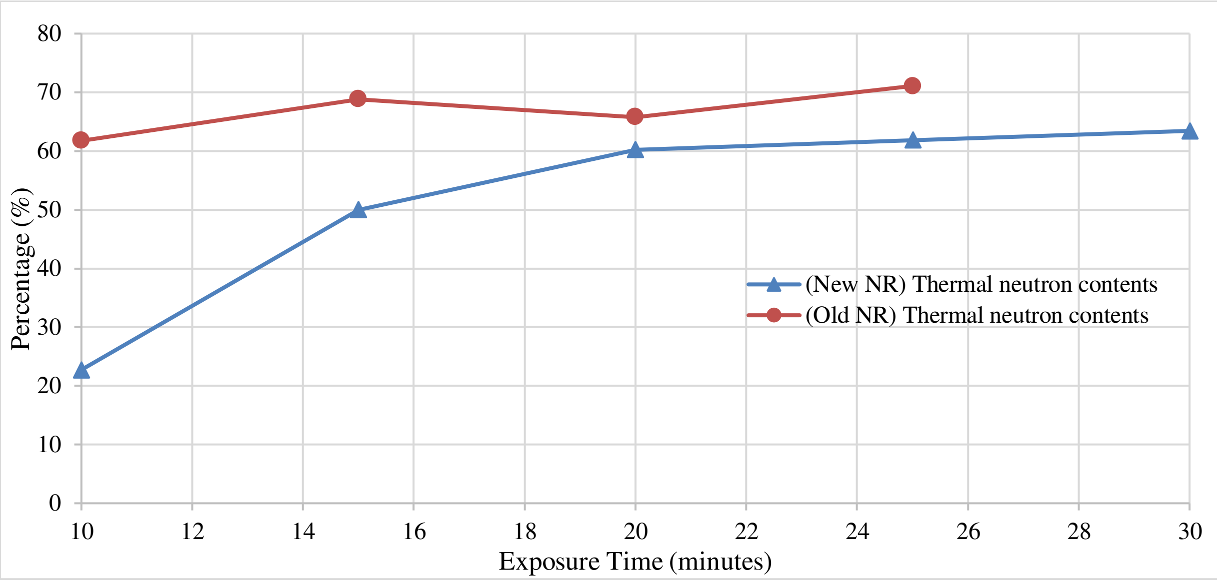

Figure 4. Comparison of thermal neutron contents of new neutron radiography facility with old facility.

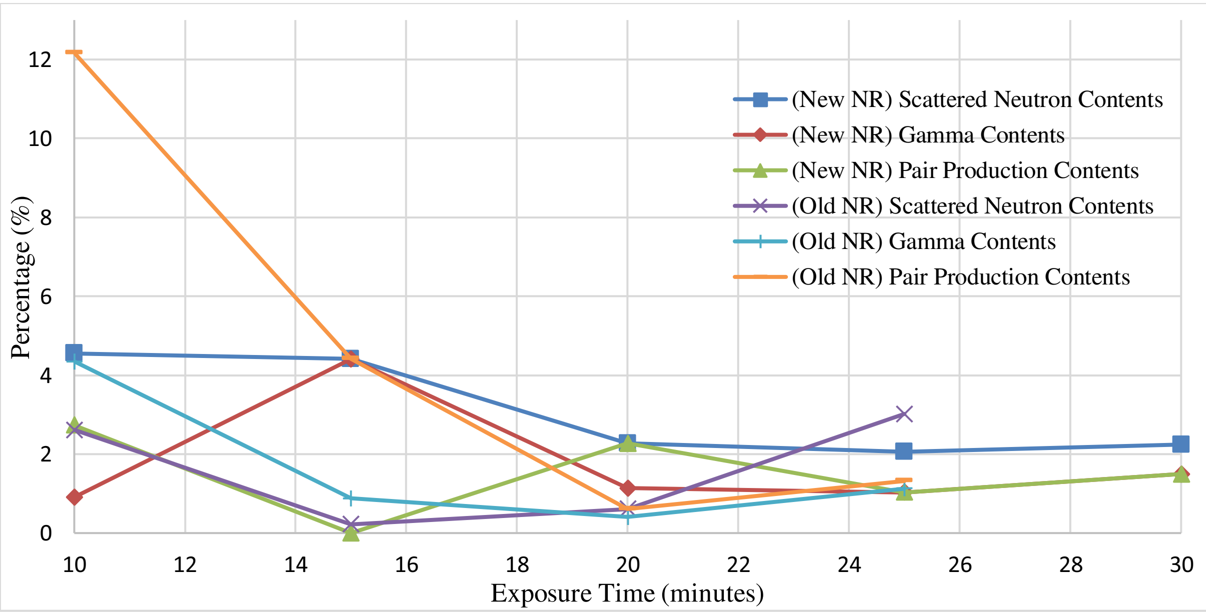

Figure 5. Comparison of secondary radiation composition of new neutron radiography facility with old facility.

3.2. Radiographic Sensitivity

As discussed earlier, the visibility of all holes (H) and gaps (G) on the neutron radiograph of SI device is important criteria to determine whether the system can produce good quality radiograph or not. It was observed that the maximum holes that can be seen in the radiograph was 4 H. The 4 H was visible at exposure times of 20, 25, 30 minutes, while 15 minutes exposure time only have 3 visible H and lastly 1 H for 10 minutes exposure time. These results showed that the radiograph did not achieve the minimum value of H for good quality radiograph. Good quality radiograph should obtain at least 6 H. However, all of the 7 G can be clearly seen on all of the radiograph. These present results of G and H measurement are shown in Table 3 and Table 4 respectively. As compared to previous study by [5], the old NR managed to produce radiograph with 6 H and 7 G at exposure time of 10, 15, 20, and 25 minutes. This results were due to slightly lower thermal neutron contents as compared to previous facility.

Table 3. Radiographic sensitivity (Gap)

Exposure time (minutes)	**Visible gaps (G)** **Spacer** (mm)						
	0.25	**0.125**	**0.0125**	**0.025**	**0.050**	**0.075**	**0.10**
10	yes	yes	yes	yes	yes	yes	yes
15	yes	yes	yes	yes	yes	yes	yes
20	yes	yes	yes	yes	yes	yes	yes
25	yes	yes	yes	yes	yes	yes	yes
30	yes	yes	yes	yes	yes	yes	yes

Table 4. Radiographic sensitivity (Hole)

Exposure time (minutes)	**Number of visible holes (H)**
10	1
15	3
20	4
25	4
30	4

4. Conclusion

The effective beam contents and image quality of the new neutron radiography facility at RTP are obtained from this study. The results have showed that the new neutron radiography facility at beam port #3 at RTP is capable for neutron imaging system in non-destructive application. However, the quality of the radiographic image can be improved in order to meet the minimum requirement for best neutron radiography facility. Based on the results, it showed that this new facility can produce radiographic image with excellent contrast, but has slightly lower sharpness. This experiment can be extended with different L/D ratio for future studies.

5. References

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