Overview of Neutron Radiography Experiment at Thai Research Reactor

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ABSTRACT

Thai Research Reactor-1/Modification 1 (TRR-1/M1), first operated in 1961, remained the only nuclear reactor in Thailand. Among the unique applications available, neutron radiography has been in service for physical studies of samples. Neutron images can complement those obtained from X-ray or gamma-ray radiography due to the difference in attenuation characteristics. The current radiography facility is being planned for renovation in various aspects, including image capturing, shielding, and beam shutter, in order to achieve efficient and safe 3-D imaging capability, which will be useful for handling, for instance, archaeological and biological samples. In this work we presented the progress and future plans of the neutron radiography upgrade regarding the imaging system and the radiation shielding wall.

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INTRODUCTION

The neutron, due to its neutral electric charge, can be used as a unique probe of material as it does not get affected by electrostatic Coulomb force in the electromagnetic fields of the medium. Radiography is a non-destructive testing method which can be used to study physical information of samples (Kardjilov et al., 2011). Different characteristics between high-energy electromagnetic radiation and neutrons exist. They have different attenuation cross sections and interactions in materials. X-rays and gamma rays scatter off atoms via Compton and Thomson scattering, and can get absorbed via photoelectric absorption. High-atomic-number materials, such as metals, have high cross sections for these interactions and can therefore attenuate high-energy electromagnetic radiation effectively. Compared to X-rays and gamma rays, neutrons can penetrate metals farther. Neutrons also interact differently with isotopes of a given element. Therefore their radiographs can provide complementary information about the samples to each other. The attenuation coefficients between thermal neutrons and X-rays are compared in Fig. 1.

![Thermal neutron and X-ray mass attenuation coefficients for the elements](Figure from SHIEI, www.shiei.co.jp)

**Figure 1** Mass attenuation coefficient of different atoms as function of the atomic number. The lines are for X-rays, whereas the circles are for neutrons. (Figure from SHIEI, www.shiei.co.jp)

Located at Thailand Institute of Nuclear Technology (TINT), Thailand Research Reactor-1/Modification 1 (TRR-1/M1) has been employing, among others, a neutron radiography facility to probe the internal structures of objects. The facility is shown in the diagram in Fig. 2. The reactor has thermal neutron flux at the thermal column of about $8.90 \times 10^9$ cm$^{-2}$ s$^{-1}$ (Jan 2013). The thermal flux at the radiography area is about 4 orders of magnitude smaller. The beam size is approximately 20 cm x 20 cm.
Figure 2 (a) Current neutron radiography facility at TRR-1/M1. (b) Dimensions of the imaging area, as measured in July 2013.

Images from neutron radiographs and X-ray radiographs provide complementary information about the samples to each other (Ratanatongchai et al., 2012). Reactor neutron radiography experiments have long been conducted around the world (Dudley et al., 1999 and Tang et al., 2006) due to relatively high flux and well-established safety measures. This is in contrast to a portable system using a radioisotope where shielding can be a challenge (Picha et al., 2008). Reactor neutron radiography is a useful technique and not as widely available as X-ray radiography. Therefore, optimizing the facility at TRR-1/M1 will provide a material testing alternative to users, especially from universities and industry.

However, the current installation has a limited space and fully manual controls. Therefore, there is a plan to renovate the facility and upgrade the system to have larger working area, automatic controls, and to be able to reconstruct 3-D images efficiently.

Shielding of radiation is a crucial component of a nuclear facility. Concrete is chosen in this research due to its affordability and adaptability. Neutrons are very penetrative due to its electric neutrality. Shielding material needs to contain a moderator that efficiently absorbs the neutron energy (such as hydrogen or carbon) and an absorber to stop the neutrons completely (such as boron or cadmium). Gamma rays are usually also present. Therefore high-Z material such as barium and lead must also be a part of the shielding setup.

In this study we introduce the design of a prototype box which integrates neutron-to-photon conversion, photon reflection, and image capturing. We also discuss the plan for reconstructing the shielding walls for the facility.

**MATERIALS AND METHODS**

In order to shield the surrounding light from the environment, a box was constructed to house the
imaging system. The wooden box was painted black on the inner walls. A converter screen, terbium-activated gadolinium oxysulfide \( \text{Gd}_2\text{O}_2\text{S:Tb} \) or GADOX (X-ray Accessory Corp (XAC) Green 600 or KG6 model) was used. Compared to a previous TRR-1/M1 work (Prasing et al., 2013), the box is smaller and the converter is thinner, smaller \((25.4\times30.5 \text{ cm}^2)\), and less photosensitive than the Mitsubishi Chemical (MC) PI-200 screen in that work. The converter was affixed to a \(40\times40 \text{ cm}^2\) aluminum plate \((0.7 \text{ mm thick})\). When the beam shutter was opened, the neutrons entered through the front of the box. The converter captured the neutrons and released green photons \((545 \text{ nm})\) into the box via \((n,\gamma)\) reactions. A mirror, oriented at 45 degrees, reflected the photons toward a camera (Canon EOS 500D Digital SLR).

Because of the darkness inside the light-tight box, the camera focus was set manually prior to the exposure by estimating the distance from the converter to the camera. The camera ISO, which determines how much sensitive to light it is, was initially set to 100, whereas the focal ratio (F-number) was 5.6. The camera was set on top of the box facing downwards, and held in place by a foam slab. The exposure time was varied and two converter screens were used. The shutter was controlled manually via Canon EOS software.

For the image quality analysis, the samples shown in Fig. 3 are used. A beam purity indicator (BPI) is a small polytetrafluoroethylene block that contains boron nitride disks, lead disks, and cadmium wires. It is used to measure the relative gamma and neutron composition in the beam. Boron absorbs thermal neutrons while lead absorbs gamma rays and X-rays. A sensitivity indicator (SI) consists of steps of different thicknesses of aluminum. It has holes inside as visual cues. SI allows the measurement of the penetration depth of the beam.

![Figure 3 Test objects. (Left) Clockwise from top-left: a lead block, a beam purity indicator, a sensitivity indicator, a cadmium strip. (Right) Diagram of BPI indicating locations of BN and Pb discs.](image)
Another important issue concerning the radiography facility is the shielding. Currently, blocks of concrete were stacked and used as the wall. This wall takes up a lot of space and is prone to dislocation. A new wall is under planning and needs to be more stable, thinner, and its gamma and neutron shielding effectiveness must be more uniform. Different compositions of radiation shielding concrete have been done in the past. Based on the recent literature (Esen et al., 2011, Akkurt et al., 2010, Kharita et al., 2011, Mostofinejad et al., 2012) we select some various compositions of barite (BaSO₄), boron, cement, and water for first-stage testing and simulation.

RESULTS AND DISCUSSION

The setup described above was used to obtain neutron radiographs using the reactor. All images (shown in Fig. 4) are taken with these camera settings: ISO = 100, F-number = 5.6.

![Figure 4](image)

**Figure 4** Left to right, top to bottom: MC screen 92 s exposure, XAC screen 90 s exposure, XAC screen 150 s exposure, and XAC screen 240 s exposure.

From the results (Fig. 5) it is found that these images are not clear enough to utilize the BPI, the lead block or the sensitivity indicator. The cadmium strip can be used to quantify contrast, defined as a relative difference between the gray value of the bright area and dark area. When the exposure time increases, the image contrast also increases but more noise is observed.
Figure 5 Horizontal gray values from the neutron images, obtained using rectangular averages (left). Legends: s1 = thick GADOX screen, s2 = thin GADOX screen. Exposure times are listed in seconds.

The shielding study is an ongoing work in parallel to the imaging system development. In the first stage, we produced a small batch of barite concretes using different percentages of barite. Gamma shielding tests were conducted when the slabs finished setting. The calculation of attenuation coefficient, using a standard Co-60 source, yields the results for different composition ratios as listed in Table 1. The gamma and neutron shielding simulations were done using the 10-MeV neutron beam. In a preliminary simulation study, we found that a 10 cm thick block of barite concrete in conjunction with 1 10 cm thick block of boron concrete was able to reduce the highest energy flux by about 84% and lowest energy flux by 29%.

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<td>attenuation coefficient (cm^-1)</td>
<td>0.131+/-.003</td>
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CONCLUSION

Facility upgrade is in order as current safety and efficiency limitations prevent neutron radiography from being fully utilized as a non-destructive testing technique at 51-year-old Thai Research Reactor-1/Modification 1 at TINT. As the first step toward the renovation, we obtained images by using a proof-of-concept, semi-real-time, imaging system. A light-tight box setup enables experimenters to acquire images in shorter time than those using a digital imaging plate or a film. This helps cut down the time needed for taking multiple images for further processing. However, existing manual operation is still far from ideal and needs to be improved. An integrated camera system is
planned for the future.

Exposure time has significant effects on the image quality. Limitation of camera extended operation and radiation exposure to the equipment and personnel were found to be important challenges in conducting experiments.

We explored the use of barite aggregate as gamma shielding material in concrete, and boron compounds as the neutron absorber. The preliminary measurement yielded positive results. However, more testing, of both physical and nuclear aspects, is required to acquire the final concrete compositions that can be used in the reactor neutron radiography facility. For this large-scale plan, TINT is looking forward to forming collaboration to achieve the goal.

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REFERENCES


