

THE DEVELOPMENT OF MONOCHROMATIC NEUTRON TOMOGRAPHY SYSTEM AT LOW FLUX RESEARCH REACTOR

NOR ABIDIN ASHARI¹, JUNITA MOHAMAD SALEH², MOHD ZAID ABDULLAH³, ABDUL AZIZ MOHAMAD⁴ & RAFHAYUDI JAMRO⁵

Abstract. A new monochromatic neutron tomography system was built utilizing the Malaysia Nuclear Agency 1MW TRIGA MARK II research reactor located at Bangi, Selangor. The CCD camera was used in data capturing and the system was evaluated using an experimental phantom made from spark plug. Reconstruction was based on the filtered back-projection and the iterative approach. Altogether 25 projections were used in the reconstruction and results discussed.

Keywords: Monochromatic, neutron tomography, CCD camera, filtered back-projection, iterative, image reconstruction

Abstrak. Satu sistem tomografi monokromatik neutron telah direka bentuk di reaktor penyelidikan 1MW TRIGA MARK II milik Agensi Nuklear Malaysia (Nuklear Malaysia) yang terletak di Bangi, Selangor. Kamera CCD digunakan dalam proses pengumpulan data dan sistem ini dinilai dengan menggunakan palam pencucuh. Pembinaan semula imej dijalankan berasaskan kaedah *filtered back-projection* dan lelaran. Keseluruhannya, 25 data projeksi digunakan dalam proses pembinaan semula imej.

Kata kunci: Monokromatik, tomografi neutron, kamera CCD, filtered back-projection, lelaran, pembinaan semula imej

1.0 INTRODUCTION

Neutron tomography (NT) has become one of the indispensable tools for obtaining information about the inner structure of an inspected object, or the internal behaviour of an industrial process. This relatively new imaging technique has found many applications in industry particularly the automotive and aviation sectors [1,2]. Tomography refers to cross-sectional imaging of an object from either transmission or reflection data collected by illuminating the object from many different directions. One of the most important aspects in NT is the image reconstruction method.

^{1,2&3}School of Electrical and Electronic Engineering, Universiti Sains Malaysia, Engineering Campus, 14300 Nibong Tebal, Pulau Pinang. Email: norabidin@nuclearmalaysia.gov.my

^{4&5}Malaysian Nuclear Agency, Materials Technology Group of Industrial Technology Division, 43000 Bangi, Selangor, Malaysia

Image reconstruction involved the reconstruction of a two-dimensional function from its projection. The problem of image reconstruction was studied extensively by Austrian Mathematician Radon and solutions proposed [3]. The reconstruction was based on a transmission measurement, in which the attenuation of the neutron beam from a beam port (*i.e.* source) was detected and recorded by a detector. Depending on the required resolution the object is either rotated discretely by 180 degree or 360 degrees. The processing was done by assuming that the radiation beam produced by the source is very narrow and behaved monochromatically. The attenuation of a beam that traverses a two-dimensional field of matter can be described by a two-dimensional linear attenuation coefficient $u(x,y)$ and calculated by the well known line integral, along the path of beam as follows:

$$I = I_0 e^{(-\int \mu(x,y)) ds} \quad (1)$$

One projection is the total set of such line integrals covering the whole field. The mathematical solution is to reconstruct the two-dimensional function from its projections. The methods and procedures on how to solve this problem are discussed thoroughly by Kak and Slaney [4]. The conventional tomography uses the attenuation of intensity (transmitted or emitted intensity, change of electric fields, resistances, etc), magnetic fields (nuclear magnetic resonance tomography) and time as the imaging signals. In addition to transmission and attenuation effects, neutron beam also experiences other interactions such as scattering, depolarization and change of phase. These interactions can also be used for tomographic applications [5]. The image reconstruction is an inverse process based on the procedure of filtered back-projection (FBP) [4, 6]. Assuming that the effect due to absorption is minimal then the quality of the reconstruction depends only on the number of projections [4]. This assumption is only valid if and only if the refraction effect is minimised and hence ignored. Nevertheless, the FBP can still be used if this condition is not fulfilled but required substantial modification as previous research has demonstrated [5]. Meanwhile the iterative reconstruction refers to a method in which an image is successively updated starting from a given arbitrary model until a final acceptable image is produced. Generally this process involved minimization of some kind of function which is usually defined as the error between measured and calculated values. Once an agreement is reached or the error is lowered than the threshold limit then the image accepted as an approximation to the actual representation.

In practice, there are a number of tractable algorithms, which have been developed to solve the above inverse problem. These include the back-projection, iterative and analytical methods [7].

2.0 EXPERIMENTAL PROCEDURE

A monochromatic NT experiment has been performed using a Small Angle Neutron Scattering (SANS) facility available at Triga Mark II research reactor. The

monochromatic neutron beam was obtained by transmitting a neutron beam produced by the reactor core via beryllium filter and highly oriented pyrolytic graphite (HOPG) monochromator. The wavelength of the monochromatic neutron beam, λ was approximately 0.5 nm. A schematic diagram of the SANS collimation and shielding system is shown in Figure 1.

The radiation channel is made-up of 10 mm diameter collimator. The channel was able to generate the neutron and as well as the gamma particles. The neutron flux available at the sample place was 1×10^4 n/cm²s with the ratio between the length and the diameter of the collimator (L/D) was maintained at approximately 40.

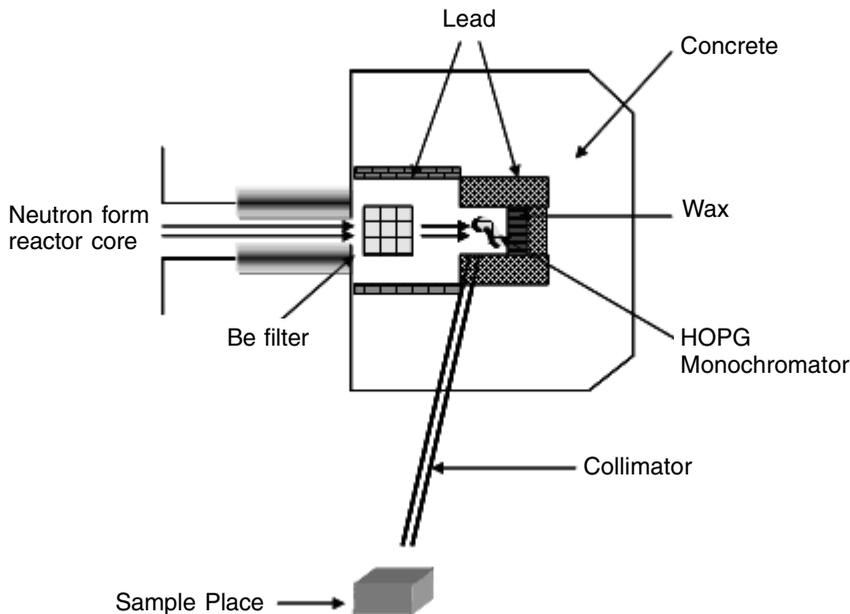


Figure 1 Top view schematic diagram of a SANS collimation system

The neutrons were detected using neutron scintillation panel. This panel is primarily made from Li with adequate composition of ZnS and Ag. The panel was 0.4 mm in thickness and mounted in front of the camera so that the image could be directly viewed by a cooled Charge Couple Device (CCD) camera. The later was assembled by Photonic Science and marketed under the brand name Cool View FDI camera. The camera was equipped with a sensitive array of 1032×1384 pixels and the frame rate could be automatically adjusted using Image Pro Express software. The firewire cable was used to connect the PC and the camera. In this set-up, each pixel acts as an equivalent high sensitivity elementary neutron detector with 12-bit readout A/D conversion.

For the purpose of testing, an ordinary spark plug was chosen as a target to be imaged. The setup is shown in Figure 2. The test object was placed on a on a motor driven turn-table and connected to PC via serial cable.

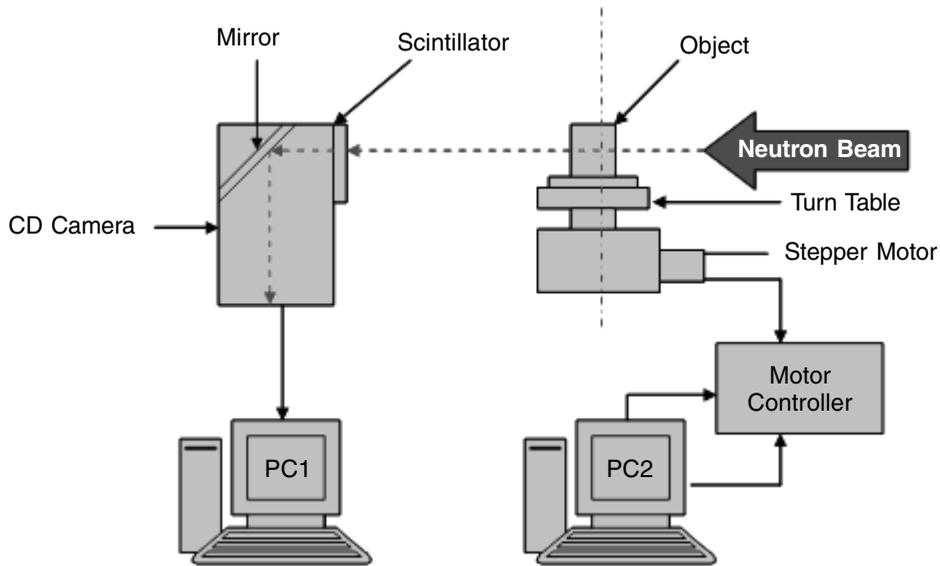


Figure 2 Experimental setup for NT system

The tomographic tests were performed using a 1032×1384 image matrix with a field of view of 30 mm^2 . Altogether data from 25 projections were recorded by rotating the turn-table over 180 degree and at discrete step of 7.2 degree. The imaging process was carried out using two-reconstruction methods; the FBP and iterative methods. The reconstruction software used to obtain the two-dimensional planar reconstructions was the Donner Package for Reconstruction Tomography which is available free from Lawrence Berkeley Lab [8]. However, the software was slightly modified since only translation scanning was needed to perform reconstruction. In this application the beam size was comparable to the object diameter. Hence, all parallel data could be recorded from one single projection.

3.0 RESULTS AND DISCUSSION

3.1 Object Investigated

The target chosen for verification of the experimental setup and data acquisition was an automobile spark plug. Figure 3 shows a schematic diagram of a spark plug. The centre electrode is made up of nickel alloy with manganese, chrome and silicon. Its metal shell is made of stainless steel, covering the inner materials of the spark plug.

Altogether 25 image projections were acquired and reconstruction attempted using the FBP and iterative algorithm previously described. Problems encountered during experiments included the poor signal-to-noise ratio of the acquired data. This was mainly due to exposure time that had to be limited during data capturing. Hence, some correction (so-called pre-processing) procedures were applied to the data prior to reconstruction.

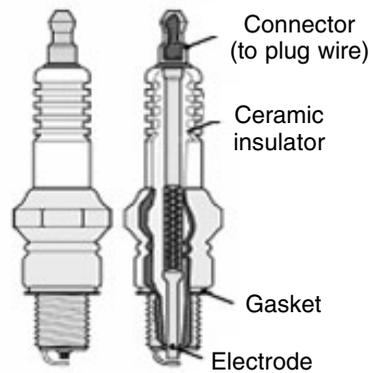


Figure 3 Example of a spark plug used in this study

3.2 Pre-processing of Radiographs

The pre-processing procedures performed to correct the distorted projected images are as discussed below:

- (i) *Cropping*: This procedure extracts the relevant area of the projections containing the sample object.
- (ii) *Intensity correction*: This pre-processing stage is needed to achieve a rather constant average background intensity.
- (iii) *Uniformity correction*: This is done to eliminate non-uniform sensitivity of the detector plate in the field of view.
- (iv) *Threshold median filtering*: This process is done to eliminate high-intensity pixels.

3.3 Image Reconstruction of the Spark Plug

Once all parameters needed for reconstruction were obtained, the data were then transferred to a Pentium 4 PC, which performed tomographic reconstruction on selected slice and required dimension. For this reconstruction, 692×692 pixels dimension was used. Figure 4 shows the interface of the NT system in Nuclear Malaysia.

Figure 5 shows the projection image from one of the sequences obtained during the experiment after post-processing. The exposure time for each projection was 2 minutes and the time needed to acquire all projection data was approximately 3 hours. The acquisition time was relatively longer due to the fact most of the data capturing process were implemented manually. For practical applications both the exposure and acquisition time need to be substantially shortened. This can be achieved through automation and the use of high-speed stepper motor.

Although the signal-to-noise for the image was 2.3277, the qualities of the reconstructed images were rather poor. This need to pre-process the measured data further worsened the problem.

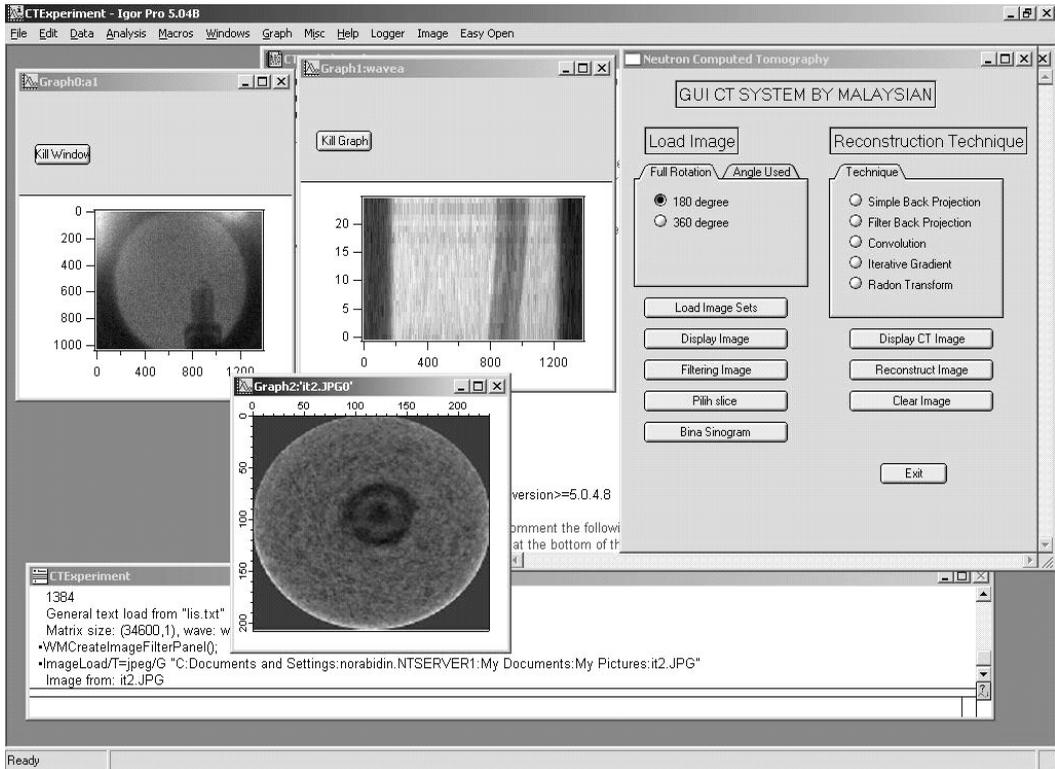


Figure 4 Tomographic reconstruction interface

The exposure time for the CCD camera was 2 minutes per radiograph. Image reconstructions were performed using FBP and iterative algorithm. Hanning window with cut-off frequency of 0.2 was used in both reconstructions. The relaxation step for iterative reconstruction was set to 5 and each method took less than a minute to produce one tomogram. However, the reconstruction time for FBP was slightly shorter than iterative reconstruction.

Figure 6 shows the cross-section images of the spark-plug obtained from this study. Figures 6(a) and 6(d) show tomographic images corresponding to cross-section line marked as 'x' in Figure 5. This section is where the spark gap is located. Meanwhile Figures 6(b) and 6(e) show the images of metal thread and electrode corresponding to cross-section line marked as 'y' in Figure 5. Finally, Figures 6(c) and 6(f) show the images of stainless steel shell and insulator corresponding to cross-section line marked as 'z' in Figure 5.

The metal (stainless steel) shell and electrode are well imaged. It can also be seen that the dimensions and the relative attenuation coefficients of the target have been accurately reconstructed. The electrode and metal shell are quite transparent to neutrons and therefore are rather indistinguishable. These preliminary results demonstrate the feasibility of NT system developed using Nuclear Malaysia SANS's

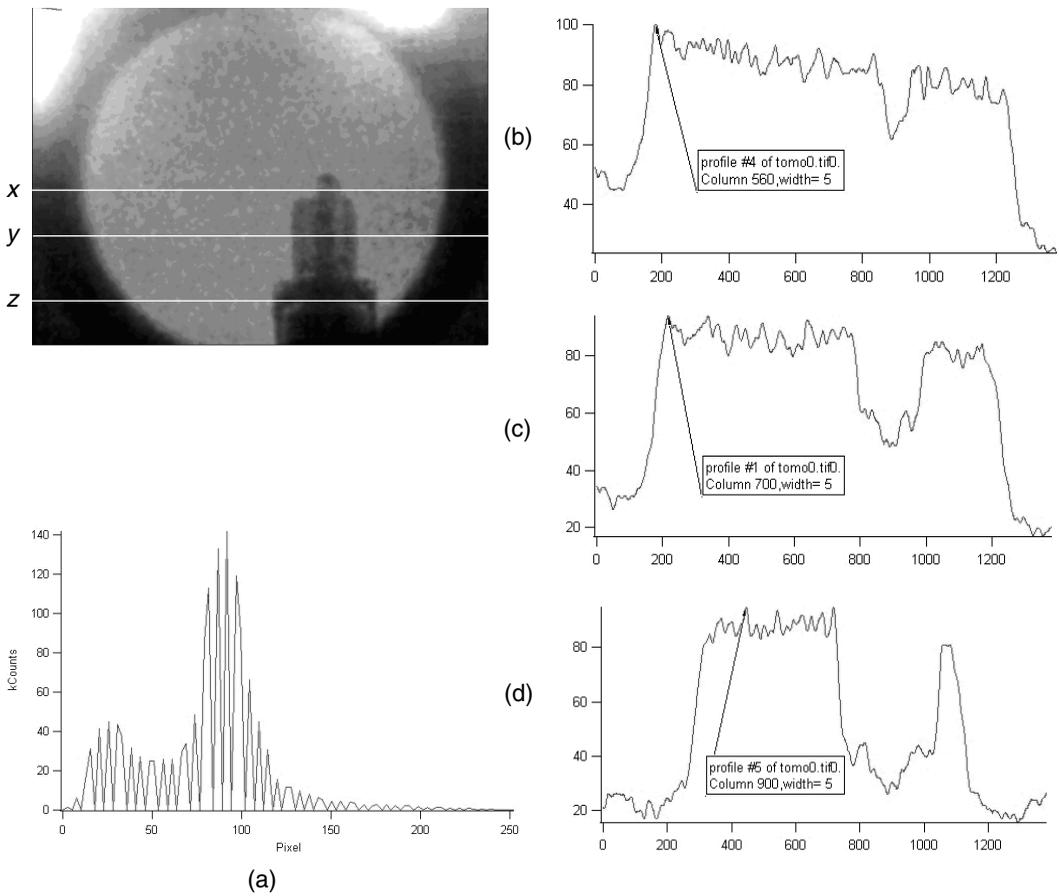


Figure 5 Radiographic image after post processing, showing pixel distribution for (a) the image, (b) cross-section x , (c) cross-section y , and (d) cross-section z

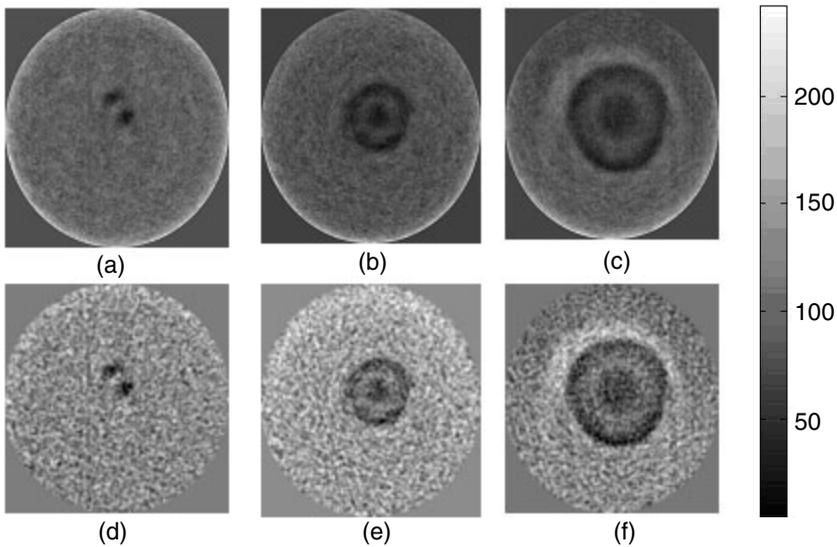


Figure 6 Tomograms of a spark plug, (a), (b) and (c) were reconstructed using the iterative technique and (d), (e) and (f) were reconstructed using the FBP technique

facility for application involving tomographic imaging. The quality of reconstructed images can further be improved by appropriately designing filter functions or by developing a more sophisticated reconstruction algorithm.

4.0 CONCLUSION

A new monochromatic NT facility was designed and constructed at the TRIGA MARK II research reactor site. The specific aim of the present work was to set-up the neutron tomographic facility at Nuclear Malaysia. The tomographic images obtained were based on the filtered back-projection and iterative methods. Taking account the limited number of projection and the use of low neutron flux, these methods produced fairly good images and comparable to images produced by other similar facilities in this region. The results demonstrated the feasibility of performing neutron-based tomographic imaging using SANS's facility available at Nuclear Malaysia.

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