Study on low density material detection capabilities of Neutron Radiography Experimental setups with neutron sources based on Nuclear Reactor and Deuterium-Tritium Generator

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ABSTRACT

Neutron Radiography (NR) is the method that is used to detect hydrogenous compounds in sealed metallic devices in aerospace applications, which are not detectable in X-Ray radiography. The experiments are carried out using two experimental facilities; one with a low-flux Neutron Radiography system using Deuterium–Tritium (D-T) neutron source and the other with a nuclear reactor as the source. Both facilities use a cooled intensified CCD based imaging system. Similar exposure times and image processing techniques such as averaging, flat field corrections etc. are used in both. Although reactor-based neutron imaging system produces images of much better quality owing to high collimator ratio, we have carried out feasibility study using D-T based neutron imaging system for qualitative imaging of neutron attenuating materials present inside SS304 or Al stepped samples. D-T generator based neutron imaging system has potential application for on-site measurements at plants/facilities where reactor source is not available. This paper presents a qualitative comparison of the detection capability of the two systems using samples prepared with SS304 and Al cases which are filled with low density compounds of variable neutron attenuation properties such as teflon, naphthalene, epoxy and wax.

Keywords: *D-T generator, neutron flux, collimator ratio, CCD, neutron imaging, attenuation*

1. INTRODUCTION

Reactor based thermal neutrons imaging is widely popular and used for various applications. However, thermal neutrons obtained from non-reactor sources such as accelerator based sources and radioisotopes are also used for neutron radiography applications where reactor sources are not available. These thermal neutrons are collimated towards a given object using collimators which are made at a particular collimator ratio (L/D ratio, where L is the distance between aperture of collimator and sample position and D is the diameter of aperture) so as to get an optimum thermal neutron flux at the object necessary to form a good quality neutron image.

NR can be used for detecting low density compounds present inside sealed metal shells to a good extent since the neutron attenuation by various low dense compounds is based on their macroscopic attenuation characteristics [1].

NR is used in detecting explosive charges present in pyro components which are mission critical items in space applications. The common explosive charges used are RDX, nitrocellulose, PETN, boron based compositions etc. If these low dense compounds are present inside these pyro components made of SS304 case, they cannot be detected in X-ray radiography. Since these explosive compounds contain elements such as hydrogen and boron which have high attenuation for thermal neutrons, the same can be detected by neutron radiography[1-3].

The neutron imaging beamline at Dhruva research reactor is developed for neutron imaging applications such as neutron radiography/tomography and phase contrast imaging[4]. The facility uses a cooled CCD neutron imaging system for radiography and tomography applications.

Koerner et. al describes the different ways of selection of neutron imaging detector systems based on CCD[5] depending on the sample material and geometry. Besides the well-known radiographic examinations with X-rays and γ-rays, neutron radiography provides an important endorsement to radiographic examinations in the field of non-destructive testing (NDT. The design considerations and calculus used in selecting the low noise, cooled CCD camera with better efficiency optics are described[6][7]. Suitable fixtures are designed to ensure safe assembly of items to be tested in D-T generator based NR set up.

White spots that pollute a neutron image obtained in CCD camera can be effectively removed by using the detection-local-removal method. This can improve the image quality. A collaborative filtering strategy is adopted to denoise and remove the gamma white spots which also helps in improving quality of CCD based neutron images[8,9].

Sungwan et. al describes optimised shielding designs for moderator and collimators for D-D and D-T based portable neutron generators[10] neutron radiography, and neutron capture therapy. In such applications of neutron generators, compactness is one of the most important issues. Since a neutron source is generated by deuterium-deuterium (D-D. Neutron radiography of pyro elements using nuclear reactor as source and indirect imaging techniques using radiographic films gave high contrast images that gives an idea of the elastomers, pyro charges etc., present inside those devices[11]. Development of a neutron radiography facility using a low flux neutron source and a CCD based imaging system with ^{6}LiF: ZnS(Ag) scintillator screen was studied so as to have a portable neutron radiography system[12].

Macroscopic cross section of compounds can be calculated to understand their neutron attenuation properties[13]. The use of sensitivity indicators and beam purity indicators for analysing the quality of neutron radiographs is well explained in ASTM-E545-14. But for CCD based neutron images using a low flux neutron source, the use of reference replica sample only could be used for quality assessment[14]. Various other neutron imaging applications such as phase contrast imaging, energy selective NR/tomography using thermal/cold neutrons and possible scattering corrections using point scattered functions are explained[15-18]. Advanced researches in the area of Neutron tomography is in lithium ion cells and batteries where complimentary information to X-ray Computed tomography are now possible[19,20].

In the present research, neutron radiography is carried out at two setups based on two different types of neutron sources namely nuclear reactor and Deuterium- Tritium (D-T) based accelerator source. Metallic samples made of SS304 and Aluminium of different wall thickness and same inner diameter are used. Compounds having different macroscopic cross-sections for thermal neutrons is used. Neutron Radiography of these samples are carried out in both NR setups keeping similar thermal neutron flux at the sample location. NR images from both setups are studied case to case and are described in this paper.

2. EXPERIMENTAL DETAILS

The experiments are performed in the D-T based NR set up, at Vikram Sarabhai Space Centre (VSSC), Thiruvananthapuram, India described elsewhere[1,3] and reactor-based NR set up at Bhabha Atomic Research Centre (BARC), Mumbai, India. For the reactor-based set-up, the neutron beam line generated by the Dhruva reactor, BARC is used[4]. The thermal neutron flux at the position of sample is 4 x 10^{7} $ncm^{-2}s^{-1}$ with L/D ratio of 160. For the present experiment, the neutron flux at the sample is reduced to 1 x 10^{4} $ncm^{-2}s^{-1}$ by using a suitable aperture at the input of the collimator. The corresponding L/D ratio was accordingly increased to 1500. The neutron imaging detector for both test set ups consists of 0.4 mm thick ^{6}LiF: ZnS(Ag) scintillator, mirror and 16-bit cooled intensified CCD camera.

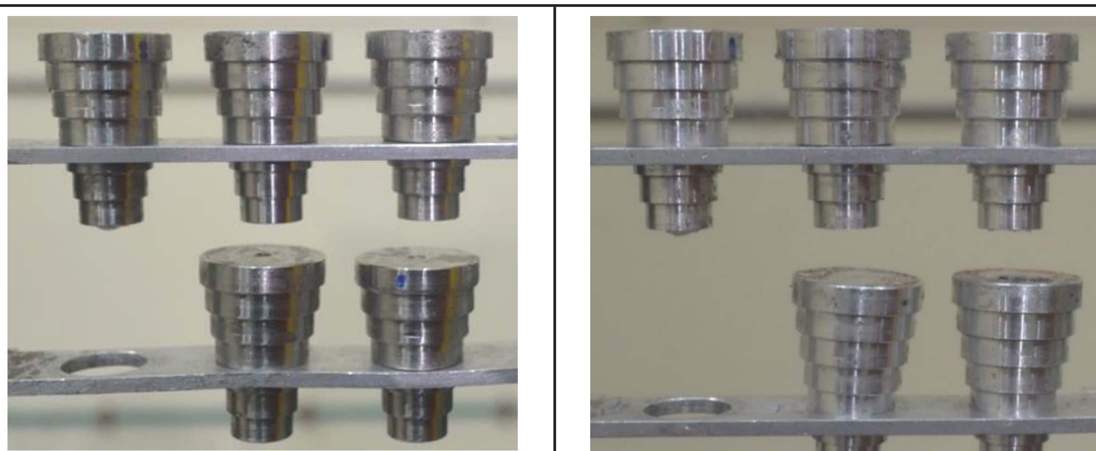
It is a known fact that the quality of the D-T generator-based neutron image cannot be equal to that of reactor-based image due to reduced neutron flux and low L/D ratio. Studies are carried out to evaluate the NR images of same test specimens under both setups with same imaging units to understand the difference in the image quality obtained. When the application of NR is limited to the detection of presence of hydrogenous materials inside metallic casing, a D-T generator-based NR set up is sufficient as it is easy to install and operate. On the other hand, for detection of defects in the hydrogenous materials and accurate sizing of them, it is essential to have a nuclear reactor-based NR setup.

D-T based NR set up is designed for carrying out NR of explosive filled samples and hence the electrical fittings are flameproof in nature and the whole set up is installed in a RCC walled enclosure. The facility also houses object manipulator setups which can be operated remotely from a control room and the whole process can be viewed using CCTV cameras in the control room. The facility is specifically designed so as to assemble maximum number of pyro devices at a stretch for NR. This ensures limited entry to the area for assembly/disassembly thus reducing the secondary exposure to the operators as far as possible.

Since explosive filled samples are not permitted to test in this reactor-based NR set up, the studies are restricted to non-explosive compounds.

3. SAMPLE PREPARATION

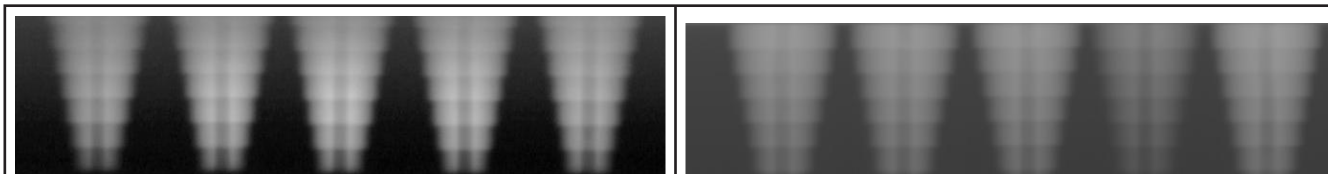
Specimens used are made of SS 304 and Aluminium of length 35 mm, outer diameter (OD) varying from 12 to 24 mm in steps of 2 mm and with height of 5 mm for each step. A 3 mm diameter hole is drilled in each of these samples at its centre. Four such samples each of SS304 and Aluminium are filled with teflon, naphthalene, epoxy and wax respectively. Specimens used are made of SS 304 and aluminium of length 35 mm, outer diameter (OD) varying from 12 to 24 mm in steps of 2 mm and with height of 5 mm for each step. A 3 mm outer diameter hole is drilled in each of these samples at its centre. Four such samples each of SS304 and aluminium are filled with teflon, naphthalene, epoxy and wax respectively. A fifth sample each of SS304 and aluminium stepped sample is kept unfilled for comparison. Fig. 1a and b shows the SS304 and aluminium stepped samples kept in specific object holding fixtures used in the D-T based NR facility at VSSC.



(a) (b)

Fig. 1: (a) SS 304 and (b) aluminium samples filled with teflon, naphthalene, epoxy and wax along with one unfilled sample.

The stepped samples are radiographed using a 450 kV X-ray machine. The radiograph obtained for each sample is digitised and the images of filled samples are compared with corresponding unfilled samples (Fig. 2a and b).



(a) (b)

Figure 2: (a) X-ray image of SS 304 samples which are filled with teflon, naphthalene, wax, empty and epoxy respectively (left to right), (b) X-ray image of Aluminium samples which are filled with teflon, naphthalene, wax, empty and epoxy respectively (left to right)

Due to the low dense nature of the compounds filled in the samples, the presence of these compounds in their respective location cannot be distinguished from the X-ray radiographic images. Specimens replicate the charged region of certain pyro elements used in satellites and launch vehicles, where the presence of charge in its specified location has to be confirmed by neutron radiography to ensure predicted performance. The wall thickness of the component along with the material with which it is made of has significant effect on NR results.

The low dense explosive compounds used in pyro elements have certain macroscopic attenuation cross-section for neutrons based on the constituent elements present in it. Table 1 gives the macroscopic cross-section of teflon, naphthalene, epoxy and wax respectively.

Table 1: Macroscopic cross-section of teflon, naphthalene, epoxy and wax[1]

Compound	Chemical Formula	Molecular Mass, A (gmol^{-1})	Total Cross-section, $\sum\sigma_i$ (barns/ molecule)	Macroscopic Cross-section of compound, $\sum_c$ (cm^{-1})
Teflon	C_2F_4	100.02	24.7	0.15
Naphthalene	$C_{10}H_8$	128.17	348	1.63
Epoxy	$C_8H_{10}O_3$	154.17	426	1.66
Wax	$C_{20}H_{42}$	282.56	1670	3.56

4. RESULTS AND DISCUSSION

Fig. 3a shows D-T generator-based NR image of an empty sample made of SS304 material and the region of interest is filled with teflon, epoxy, naphthalene and wax. The empty portion is distinguishable in the image. The noise levels are high when compared to the NR image of the same sample taken in a nuclear reactor-based setup which is shown in Fig. 4a. The edges of samples are sharp and the empty portion of it is very clear in reactor based NR image.

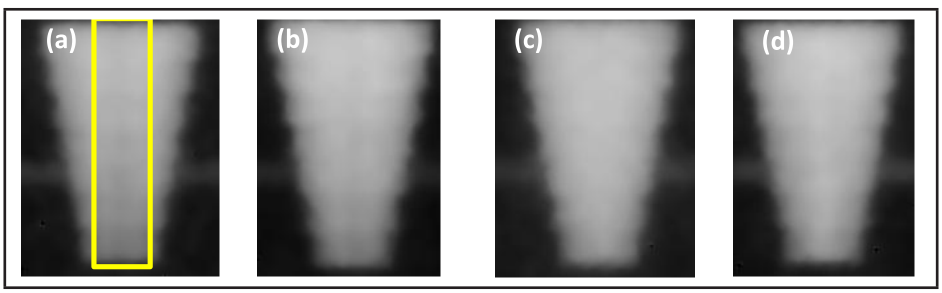


Figure 3: NR image of SS 304 samples taken in D-T generator based set up filled with (a) empty (b) Teflon (c) Naphthalene (d) Wax (e) Epoxy[1]

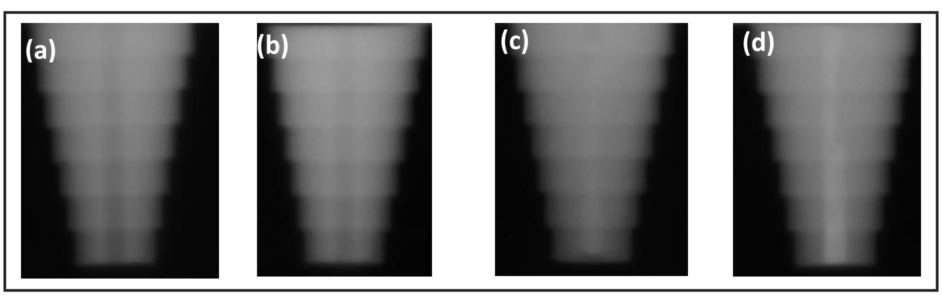


Figure 4: NR image of SS 304 samples taken in Nuclear Reactor based set up filled with (a) empty (b) Teflon (c) Naphthalene (d) Wax (e) Epoxy

In Fig. 3b and 4b, NR image of samples filled with teflon is shown. Teflon has a macroscopic cross-section 0.148 cm^{-1}, which is low neutron attenuation. Hence there is only a slight increase in grayscale value when compared to the empty region (Fig. 3a). Hence, it is evident that materials with low neutron attenuation like teflon is difficult to be detected when filled in SS304 stepped sample.

In Fig. 3c and 4c, NR images of the specimen filled with naphthalene is shown. The grayscale value in the naphthalene filled region is higher than its surroundings. But the contrast obtained is very low in the case of D-T generator-based NR system. A stepped sample without hole may also be giving a similar appearance. Hence in this case, absence of such a compound in the sample alone could be detected. On the other hand, in reactor based setup, NR shows a clear image of the naphthalene filled region upto an OD of around 18mm. Beyond this, the naphthalene filled region is not clearly distinguishable from its surroundings.

Wax is distinguishable in D-T based setup, since it has a relatively high macroscopic cross-section of 3.558 cm^{-1}. Its presence can be easily identified when compared to empty sample (Fig.3d). The reactor based set up shows a good grayscale value difference and hence a good contrast for the image of wax filled region as seen in Fig.4d. Apart from detection, the reactor based NR setup gives details about the pores and partly filled regions in the wax filled sample. Moreover, the images are sharp and less noisy.

Epoxy resin is filled partially in the last sample. It is filled from top and bottom leaving the middle region empty. Only traces of epoxy are expected in the middle region of the sample. NR of the sample using both setups could identify the partially filled region. However, in reactor-based system, the exact location up to which epoxy is filled can be clearly distinguished (Fig. 3e and 4e).

Fig. 5a and b shows the surface plot of NR images of empty SS304 samples taken in D-T generator-based setup and nuclear reactor-based setup respectively. The sharpness of the reactor-based NR image is clearly seen in the surface plot.

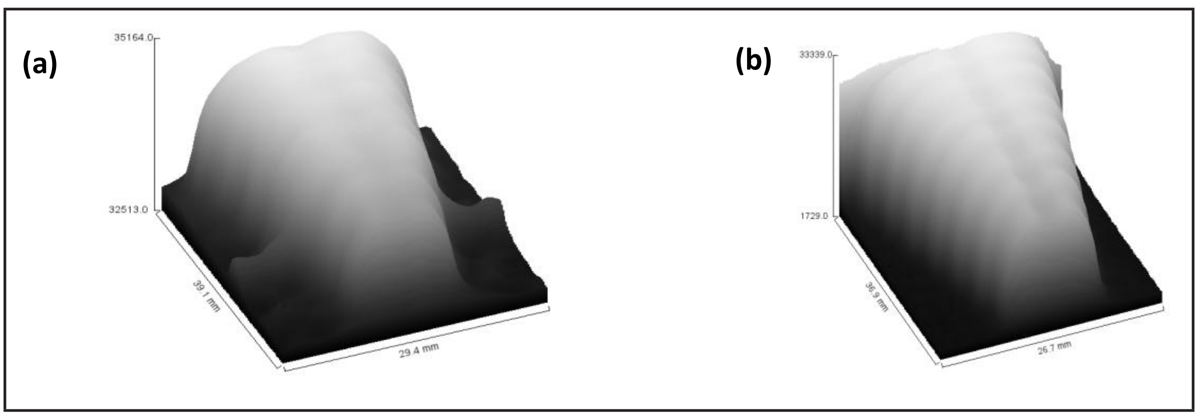


Figure 5: Surface plot of NR images of empty SS 304 samples taken in (a) D-T generator based setup[1] (b) Nuclear Reactor based setup

The basic purpose of carrying out NR in pyro elements used in space application is detection of explosive charge. This requirement can be met with both neutron imaging set ups. To obtain high resolution images with low noise and good contrast, a nuclear reactor-based NR set up is essential.

Hence it is inferred that if compounds of macroscopic cross-section above 1.6 cm^{-1} is present in the specimen, both the NR setups are capable of distinguishing them from a sample containing compounds of macroscopic cross-section less than 0.14 cm^{-1} or empty. It could be noted that in D-T generator/nuclear reactor-based NR setup, it is difficult to characterize specimens filled with compounds of macroscopic cross-section above 1.6 cm^{-1} since the difference in grayscale levels produced by these compounds present in sample with its background is very low.

4.1. Effect of change in case material

To understand the effect of attenuation cross-section offered by SS 304 to thermal neutrons, exact replica samples are made with aluminium. Same compounds used in above experiments are filled in these aluminium samples. Aluminium cases are nearly transparent in NR image due to low attenuation offered[1]. The following study helps in understanding the neutron attenuation by compounds in a better way.

Fig. 6a and 7a shows the NR images of the empty samples taken in both NR setups. The sharpness and contrast of the NR image of reactor setup is much better. The empty region is distinguishable in both.

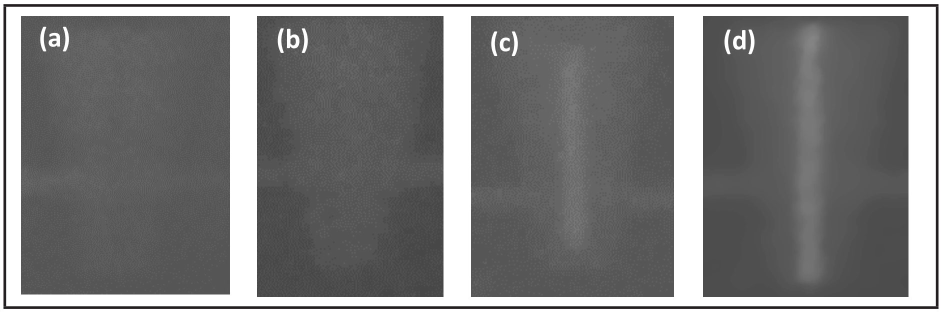


Figure 6: NR image of Al samples taken in D-T generator based set up (a) unfilled and those filled with (b) Teflon (c) Naphthalene (d) Wax (e) Epoxy[1]

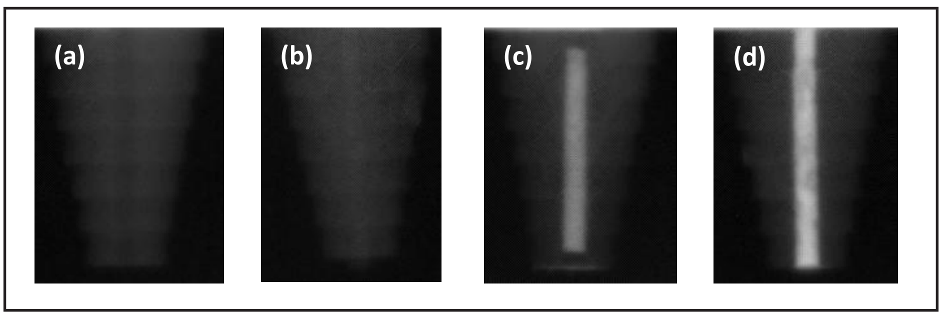


Figure 7: NR image of Al samples taken in Nuclear Reactor based set up (a) unfilled and those filled with (b) Teflon (c) Naphthalene (d) Wax (e) Epoxy

Fig. 6b and 7b shows the NR images of the sample filled with teflon recorded in both NR setups. The compound is not well distinguishable in D-T based set up whereas reactor based setup shows a comparatively better grayscale value difference in the teflon filled region with respect to its surroundings.

Fig.6c and 7c shows naphthalene filled in the samples and are distinguishable in both setups very clearly. The empty portions at top and bottom of samples are seen sharp with definite boundaries in the reactor-based setup whereas D-T generator based set up shows the absence of naphthalene alone at top and bottom.

Similar is the case with wax, which is also clearly distinguishable in both the setups as shown in Fig. 6d and 7d. But in addition to presence of wax, reactor based set up shows the voids and difference in packing of wax in the sample. This shows that defects inside the charge also could be detected by this setup.

In order to understand the capability of the two NR systems to detect unevenness or absence of the compound, epoxy resin is filled unevenly in the samples. Fig.6e and 7e shows the NR images. D-T based setup has detected the information about the filled and empty regions of epoxy resin. The setup shows good sharpness at the edges of the resin filled portion. But NR image from reactor setup clearly gives a picture of filled and unfilled regions as well as regions which has traces of epoxy resin flown inside.

Fig. 8a and b shows the surface plot of the empty Al samples. The plot shows the sharpness of the NR image from a reactor based set up.

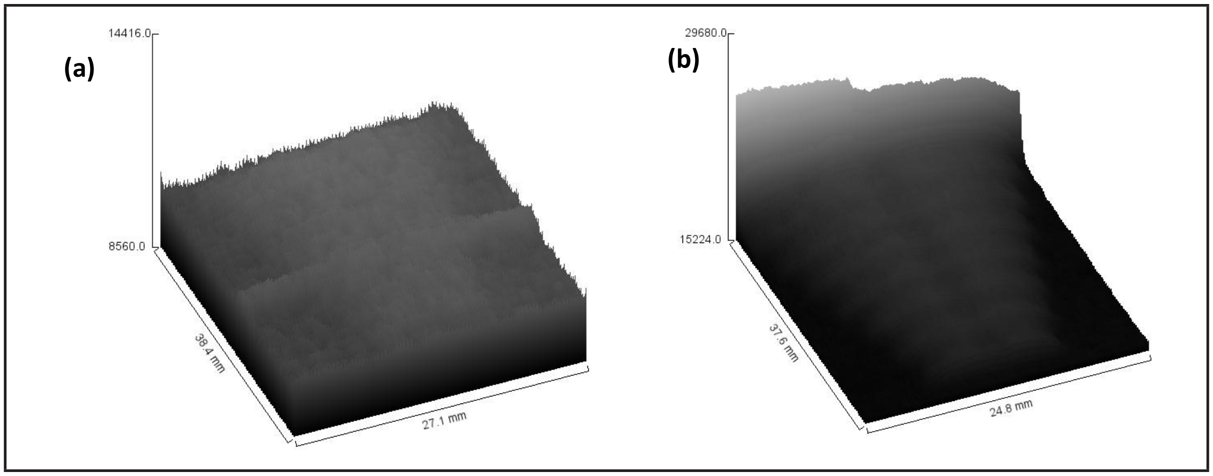


Figure 8: Surface plot of NR images of empty Al samples taken in (a) D-T generator based setup[1] (b) Nuclear Reactor based setup

5. CONCLUSION

The study shows that a nuclear reactor based NR setup with high L/D ratio is far ahead in terms of the image quality in comparison to a D-T generator based NR setup. The sharpness, contrast and grayscale value difference between compounds with variable macroscopic attenuation cross-sections given by reactor based setup is very good. The reactor based setup is capable of detecting even the traces of neutron attenuating compounds present in the samples. Since reactor based NR facilities are not feasible to be installed at certain locations due to safety considerations, NR has to be carried out using alternate neutron sources, such as D-T generator based systems that are portable in nature. Such a system has a limitation in terms of maximum neutron flux and L/D ratio achievable. But the system is very convenient to be installed in an RCC walled enclosure-based neutron radiography setup due to their small size, ease of handling and reduced safety considerations. Also, unlike a reactor based setup, D-T generator based system can be operated like an X-ray machine by switching the neutron emission ON/OFF as and when required. All these factors reduce the possibilities of radiation exposure to operators to a great extent. The setup is capable of performing the basic purpose of carrying out neutron radiography for space application which is detection of hydrogenous or other neutron attenuating low dense compounds and its characterisation qualitatively.

REFERENCES

[1] G. N. Namboodiri, M. C. Santhosh Kumar, M. Nallaperumal, S. Umasankar, and G. Levin, Detection and characterisation of low dense charges inside metallic devices used in space applications by neutron radiography. J. Nondestruct. Eval. 39, 16 (2020). https://doi.org/10.1007/s10921-020-0657-7

[2] S. Bishnoi, T. Patel, R. G. Thomas, R. Jilju, P. S. Sarkar, and B. K. Nayak, Study of tagged neutron method with laboratory D-T neutron generator for explosive detection, Eur. Phys. J. Plus 135, 428 (2020). https://doi.org/10.1140/epjp/s13360-020-00402-y

[3] G. N. Namboodiri, M. Joseph, M. C. Santhosh Kumar, M. Nallaperumal, K. K. Moideenkutty, M. Arumugam, L. Mohan Kumar, J. Jayaprakash, X-ray computed tomography and thermal neutron radiography for detection of low dense compounds inside pyro elements used in space applications. Eur. Phys. J. Plus 136, 945 (2021). https://doi.org/10.1140/epjp/s13360-021-01910-1

[4] M. Shukla, T. Roy, Y. Kashyap, S. Shukla, P. Singh, B. Ravi, T. Patel, S.C. Gadkari, Development of neutron imaging beamline for NDT applications at Dhruva reactor, India. Nucl. Instruments Methods Phys. Res. Sect. A. 889, 63–68 (2018). https://doi.org/10.1016/j.nima.2018.01.097

[5] S. Koerner, E. Lehmann, and P. Vontobel, Design and optimization of a CCD-neutron radiography detector. Nucl. Instruments Methods Phys. Res. Sect. A. 454, 158–164 (2000). https://doi.org/10.1016/S0168-9002(00)00819-6

[6] R. C. Lanza, S. Shi, and E. W. McFarland, A cooled CCD based neutron imaging system for low fluence neutron sources. IEEE Trans. Nucl. Sci. 43, 1347–1351 (1996). https://doi: 10.1109/23.507063

[7] M. Dinca and M. Pavelescu, Calculus for a neutron imaging system based on a CCD camera. Rom. Journ. Phys. 51, 363–370 (2006).

[8] C. Zhao, Y. Yan, Y. Wang, and S. Qiao, White spots noise removal of neutron images using improved robust principal component analysis. Fusion Eng. Des. 156, 111739 (2020), https://doi.org/10.1016/j.fusengdes.2020.111739

[9] C. Zhao, Y. Yan, H. Li, T. Zhang, and S. Qiao, An effective gamma white spots removal method for CCD-based neutron images denoising. Fusion Eng. Des. 150, 111375 (2020). https://doi.org/10.1016/j.fusengdes.2019.111375

[10] S. Yun, C. W. Lee, D. W. Lee, S. Kim, B. Jung, D. Chang, H. G. Jin, C. W. Shin, An optimization study for shielding design of D-D and D-T neutron generators. Fusion Eng. Des. 146, 531–534 (2019). https://doi.org/10.1016/j.fusengdes.2019.01.014

[11] N. Raghu, V. Anandaraj, K. V. Kasiviswanathan, and P. Kalyanasundaram, Neutron radiographic inspection of industrial components using KAMINI neutron source facility, AIP Conf. Proc., 989, 202–205 (2008). https://doi.org/10.1063/1.2906066

[12] A. Sinha, B. D. Bhawe, C. G. Panchal, A. Shyam, M. Srinivasan, and V. M. Joshi, High sensitivity neutron imaging system for neutron radiography with a small neutron source. Nucl. Instruments Methods Phys. Res. Sect. B. 108, 408–412(1996). https://doi.org/10.1016/0168-583X(95)01158-7

[13] J.C. Domanus, Practical Neutron Radiography (Kluwer academic publishers, Dordrecht, 1992)

[14] ASTM E545-19, Standard Test Method for Determining Image Quality in Direct Thermal Neutron Radiographic Examination, ASTM International, West Conshohocken, PA. (2019). https://doi.org/10.1520/E0545-19

[15] N. Kardjilov (2003), Further developments and applications of radiography and tomography with thermal and cold neutrons. PhD thesis.

[16] N. Kardjilov, F. De Beer, R. Hassanein, E. Lehmann, and P. Vontobel, Scattering corrections in neutron radiography using point scattered functions. Nucl. Instruments Methods Phys. Res. Sect. A. 542, 336–341 (2005). https://doi.org/10.1016/j.nima.2005.01.159

[17] R. Hassanein, E. Lehmann, and P. Vontobel, Methods of scattering corrections for quantitative neutron radiography. Nucl. Instruments Methods Phys. Res. Sect. A. 542, 353–360 (2005). https://doi.org/10.1016/j.nima.2005.01.161

[18] R. Hassanein (2003), Correction methods for the quantitative evaluation of thermal neutron tomographys. PhD Thesis. https://doi.org/10.3929/ethz-a-005273682

[19] M. Strobl, I. Manke, N. Kardjilov, A. Hilger, M. Dawson, J. Banhart, Advances in neutron radiography and tomography. J. Phys. D: Appl. Phys. 42, 243001 (2009). https://doi.org/10.1088/0022-3727/42/24/243001

[20] R. F. Ziesche, T. Arlt, D. P. Finegan. T. M. M. Heenan, A. Tengattini, D. Baum, N. Kardjilov, H. Markötter, I. Manke, W. Kockelmann, D. J. L. Brett, P. R. Shearing, 4D imaging of lithium-batteries using correlative neutron and X-ray tomography with a virtual unrolling technique. Nat. Commun. 11, 1–11 (2020). https://doi.org/10.1038/s41467-019-13943-3