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Characteristics of the neutron/X-ray tomography system at the SANRAD facility in South Africa

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Abstract

Through collaboration with the NEUTRA-facility at the Paul Scherrer Institute (PSI), Switzerland, a turnkey tomography system was designed specifically for the beam geometry at the South African Neutron Radiography (SANRAD) facility, located on the beam port floor of the SAFARI-1 nuclear research reactor and operated by Necsa. The new system is currently being extensively utilized in both 2D and 3D mode for various applications in general industry and institutional activities. The basic performance characteristics of its 3D tomography capability in a neutron and X-ray configuration are presented with the aid of several case studies. An X-ray source has also been commissioned to further diversify the capabilities of the facility.

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Keywords: SAFARI-1; Neutron tomography; NDE testing

1. Introduction

A South African born American physicist, Alan M. Cormack, was awarded the Nobel Prize for Physiology on Medicine 1979 for the development of the powerful new diagnostic technique of computerized axial tomography (CAT) scanning [1]. His contribution together with Godfrey Houndsfield from EMI labs utilized the mathematical transformation algorithms generated by John Radon in 1907 to produce three-dimensional reconstructed images for the medical examination of patients. Thirty years later (Jan 2003), the very first tomography reconstruction images were generated in South Africa with the aid of a neutron beam, utilizing the basic principles of CAT scanning developed by Cormack.

CAT scanning has become a common and necessary tool in hospitals for 3D diagnostic examination of humans but is generally unavailable for the scanning of industrial samples for NDE purposes. Furthermore, most medical institutions do not allow industry to operate or utilize their CAT-scanning equipment. To address this need and to complement the neutron tomography

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examinations at Necsa, the SANRAD facility [2], located at the beam port floor of the SAFARI-1 nuclear research reactor, was equipped with an X-ray source (100 kV tube) and X-ray sensitive scintillator screen. This allows the generation of complementary 3D X-ray tomographs, utilizing almost the same infrastructure as for neutrons. The characteristics of the neutron and X-ray equipment and their performance are discussed.

2. SANRAD facility

2.1. Containment

The No. 2 beam tube of the SAFARI-1 materials testing nuclear research reactor at Necsa, Pretoria, has been commissioned with a radial collimator for thermal neutron radiography. Most of the primary γ and fast neutron radiation are being removed from the beam by means of a bismuth filter. The SANRAD facility containment in the beam port hall consists of 45 cm thick high density concrete walls, lined with a 2 cm polyethylene layer and 2 cm wax layer loaded with 5% B by mass. The back wall, or beam stop, of the containment acts as an access door to the facility. It consists of layers of Fe and polyethylene, embedded in a housing of 0.5 cm layer of steel, 150 cm thick. The front surface of the beam stop is covered with 4 cm of wax loaded with 5% B by mass. The containment inside dimensions are 200 cm × 200 cm × 200 cm. The section of the roof directly above the target area can be opened to accommodate longer samples. Fig. 1 schematically shows the location of the SANRAD facility in the beam port hall of SAFARI-1 at beam port No. 2 between the current operational neutron diffraction (NDIFF at beam port No. 5) and proposed small angle neutron scattering (SANS at beam port No. 1) facilities.

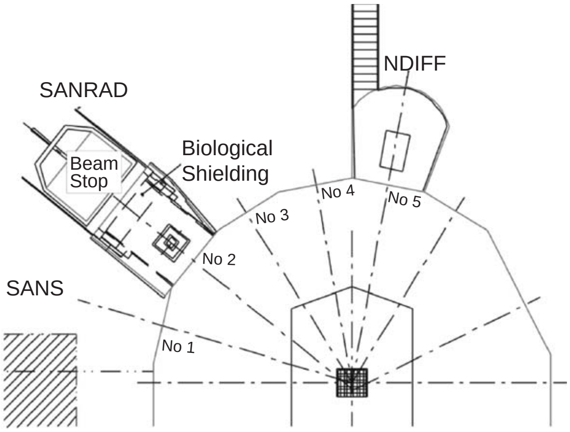

Fig. 1. Schematic layout of the location of the SANRAD facility on the beam port floor area of SAFARI-1.

2.2. Neutron beam for tomography set-up

The collimator specifications and neutron beam characteristics of the 93% thermal neutron beam for beam port No. 2 are being defined in Table 1.

For the detection of the neutron beam and the formation of a photon image, a neutron scintillation screen (6LiF/ZnS:Cu,Al,Au) is being used [3].

2.3. X-ray beam for tomography set-up

A 100 kV X-ray tube can be inserted in the beam port region of the facility (Fig. 2). The X-ray power supply is located outside the SANRAD

Table 1

Distance from aperture (L)		2465 mm
Beam diameter at outlet of collimator		300 mm
Neutron flux[a] at object in center of beam [n cm^{-2} s^{-1}] at 20 MW reactor power & pinhole (D) = 21 mm		1.2×10^7
Approximate collimation ratio L/D for 3 separate pinhole apertures:		
	$D = 6$ mm	500
	$D = 10$ mm	300
	$D = 21$ mm	150
Theoretical geometric unsharpness with sample detector distance: 600 mm		
	$D = 6$ mm	0.95 mm
	$D = 10$ mm	1.6 mm
	$D = 21$ mm	3.3 mm
Beam divergence at		
	$D = 6$ mm	0.9°
	$D = 10$ mm	1.5°
	$D = 21$ mm	3.2°

[a] Based on Au activation foils.

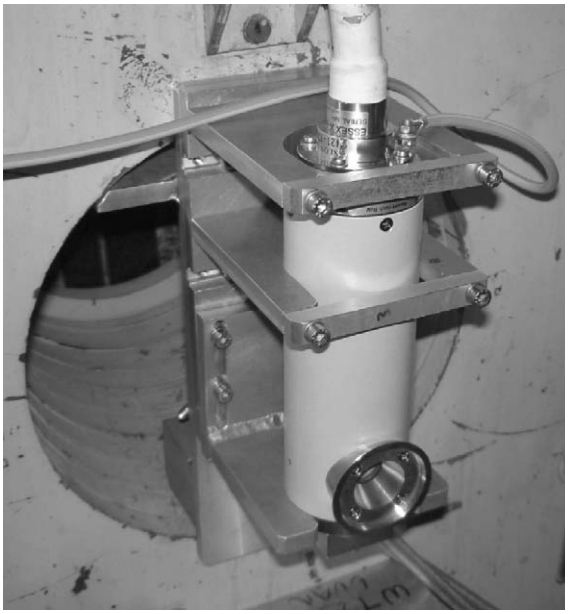

Fig. 2. X-ray tube inserted in neutron port to substitute the neutron beam.

containment with the control panel in the laboratory next to the PC containing the frame grabber card. Any applied change to the voltage or current is directly observed on the PC as a change in the quality (brightness/contrast) of the image. The characteristics of the X-ray beam and imaging properties are being defined in Table 2.

For the detection of the X-ray beam and the formation of a photon image, an X-ray sensitive scintillation screen (gadolinium oxysulfide) is being used [3].

2.4. Tomography equipment

The tomography imaging setup shown in Fig. 4 consists of a Peltier-cooled CCD camera inside a light-tight box.

An aluminum-coated mirror (45° reflection) reflects the photon image from a scintillator screen, mounted onto the front end of the box, through a lens, mounted on the camera, onto the CCD chip. Various lenses are utilized to improve on the spatial resolution of the images, especially for small samples.

Table 2

Distance from aperture to scintillator (L) (mm)		1000
Cone beam diameter at scintillator (mm)		~728
X-ray tube voltage (Continues)		0–100 kV
Approximate collimation ratio L/D for focal spot D		
	$D = 1$ mm	800
	$D = 3$ mm	266
Geometric unsharpness [mm] with sample thickness 5 cm and sample distance = 600 mm from focal spot:		
	$D = 1$ mm	0.07 mm
	$D = 3$ mm	0.20 mm
Beam divergence		40°

Table 3 depicts the spatial resolution obtained by the system for the various SMC-Pentax lenses.

The Peltier-cooled (1024 × 1024 pixel) CCD camera (DV434-BV) from Andor Technology [4] has an output of 16-bit images at a rate of 2 μs/pixel (approximately 2.2 s readout/frame). The chip can be cooled to −75 °C to obtain a low dark current of less than 0.05 electrons/pixel/s.

With the maximum neutron flux for the facility (20 MW and $D = 21$ mm), the exposure time for the full set of 180 projections in 180 angular degrees is 15 min for the wide aperture lens. For the smallest field of view (FOV) lens combination, the comparative exposure time is approximately 1.5 h. Per projection, the exposure times are 25 and 5 s for a wide and small FOV respectively in order to optimize the image dynamic range in each setup to 65,536 (16bit) gray scales per pixel.

To obtain similar high dynamic range for one X-ray radiograph at optimum conditions (100 kV, 15 mA), the exposure time is 0.4 s. For a set of 180-projections acquisition, the X-ray tomographic imaging time is about 4 min.

The sample is positioned on top of a rotary stage fixed onto a tilting table, which is in turn fixed to an x-axis positioning stage. Fig. 3 shows the translation table setup in the beam showing the stepper motors for the translation and rotation.

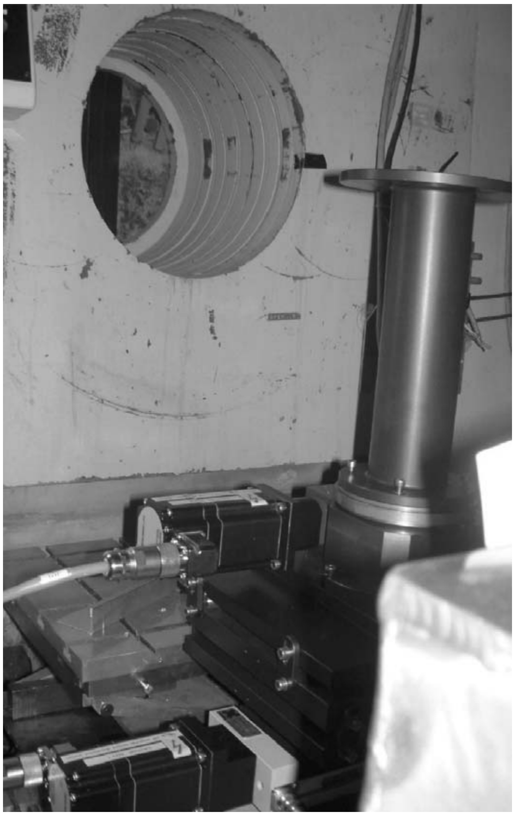

Fig. 3. Photograph of the sample-positioning table for tomography.

The system further consists out of two computers for frame grabbing and coordination of the rotation. The necessary software to automatically scan a sample up to 300 projections and reconstruct and image the reconstruction in 3D, is housed in 2 Pentium-IV computers (2.7 GHz/1.5 Gbytes RAM). The reconstruction of samples is done in terms of 3D voxel units, with minimum dimensions of $200 \times 200 \times 200\,\mu m$. Fig. 4. depicts a schematic diagram of neutron tomography set-up.

2.5. Tomography procedure

Careful calibration of the system has to be performed for good quality tomography reconstructions. The lens is optimally focused by means of the edge response function of a thin Gd-foil in contact with the scintillator. The position of the

Table 3

Pentax lens	Field of views (FOV) (mm)	Spatial resolution (pixels/mm)[a]
A 50 mm/F1.2	250 × 250	3.8
FA 100 mm/F2.8	130 × 130	7.7
FA 135 mm/F2.8	100 × 100	10.3

[a] Measured for a 2D image–pixel resolution.

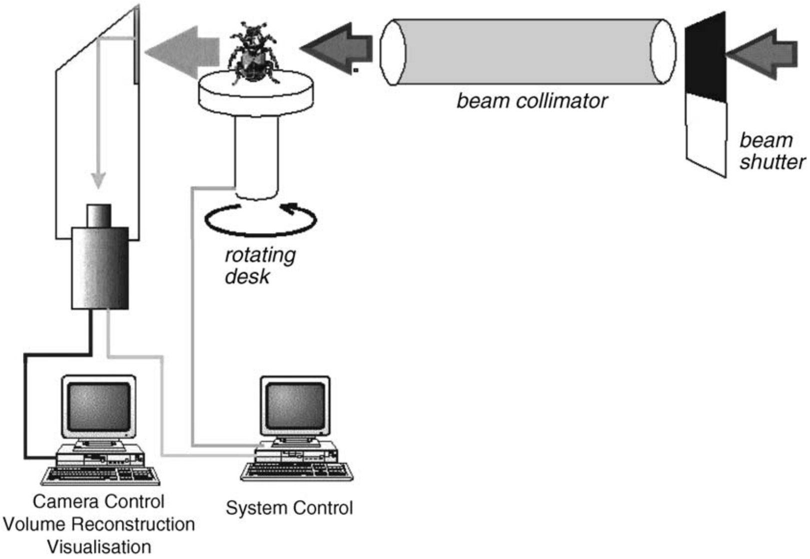

Fig. 4. Schematic diagram of the tomography set up at the SANRAD facility.

sample, vertically and horizontally as well as in the centre of the rotation table is checked utilizing the imaging software and display on the PC.

At least 3 flat field images (images without a sample in the beam) as well as 3 background images (images when the beam is closed) are taken with an area of interest setting large enough to show the whole sample including unattenuanted beam region outside the object's projection. Any number of angular sampling intervals within 180° for neutron tomography and 360° for X-ray tomography respectively is chosen on the TOMO-CONTROL PC LabView software interface that controls the stepping of the sample rotation automatically in sequence with the sampling of projections.

After image acquisition the 16-bit unassigned integer data (each projection) is corrected for the following: "white spot" speckle noise elimination, exposure normalization and flatfield- and background-correction. For neutron images, this reconstruction procedure is performed with an IDL-software package [5]. A filtered Fast Fourier Transformation back projection algorithm optimized by PSI is applied. The reconstruction time on the 2.7 GHz/1.5 Gbytes RAM PC takes approximately 2 min for 180 projections of 512 × 512 pixel size. The IDL software allows for the generation of x-, y- and z-slicing images of every slice in JPEG or MPEG format.

For X-ray images, the reconstruction procedure is performed with OCTOPUS [6], a cone beam reconstruction software package that corrects the images due to the divergence of the X-ray beam in the geometry set-up. The VGStudio MAX-2.1 software from Volume-Graphics [7] is used for the 3D rendering, segmentation and visualization of the reconstructed volume data.

3. Examples of tomography investigations at SANRAD

3.1. Mechanical engineering (application in reverse engineering)

To demonstrate the penetration power of neutrons through dense materials and the 3D reconstruction capability of the system in the mechanical engineering community, three phantoms were manufactured from Pb, Al and STST (25 × 25 × 40 mm) with two × 5 mm holes, two × 2 mm holes and one 1 mm hole drilled into the samples. The 2-mm hole was filled with an electrical cord while the one 5-mm hole was filled either with water or a 1 mm Cu cable. The neutron reconstruction on the STST sample, as seen in Fig. 5 is sliced in the x-direction revealing the 1 mm Cu wire located in the 5-mm hole. The voxels of the STST can be made electronically transparent as Fig. 6 shows the electrical cord and water respectively.

The photo in Fig. 7 shows a combustor (Ti/Ni/Al alloy) reverse engineered by the tomographic system to enable determination of the inner dimensions non-destructively. The reconstruction and slicing of the sample (Fig. 8) show all the passages and holes inside the sample.

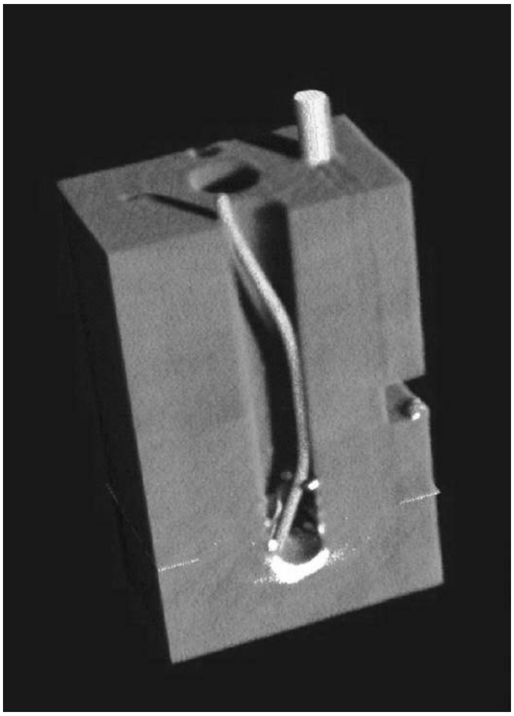

Fig. 5. Neutron tomographic reconstruction of STST phantom showing the copper cable in the 5 mm hole.

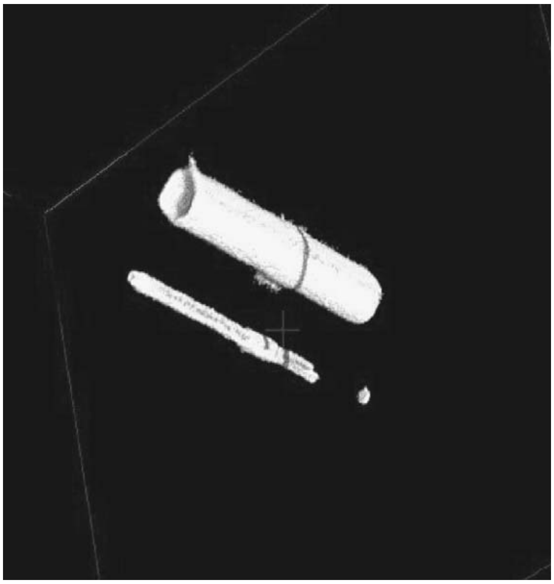

Fig. 6. STST set electronically transparent to reveal water and electrical cord.

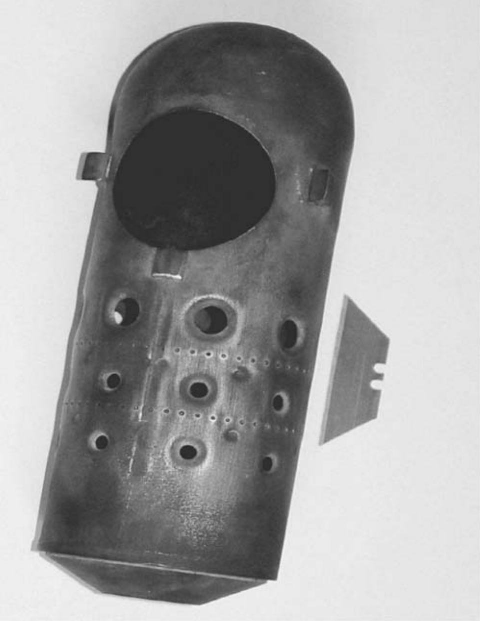

Fig. 7. Photo of combustor.

3.2. Geology

Graphical 3D neutron examination of geological samples reveals the 3D distribution of mineral deposits as well as veins or cracks in the sample (Figs. 9 and 10). Important geological information such as the distribution of minerals, location of cracks and voids or even the location, size and distribution of granules can be revealed without destroying the sample.

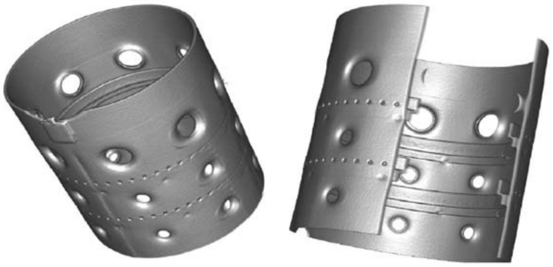

Fig. 8. Reconstruction of middle section of combustor and x-coordinate slicing.

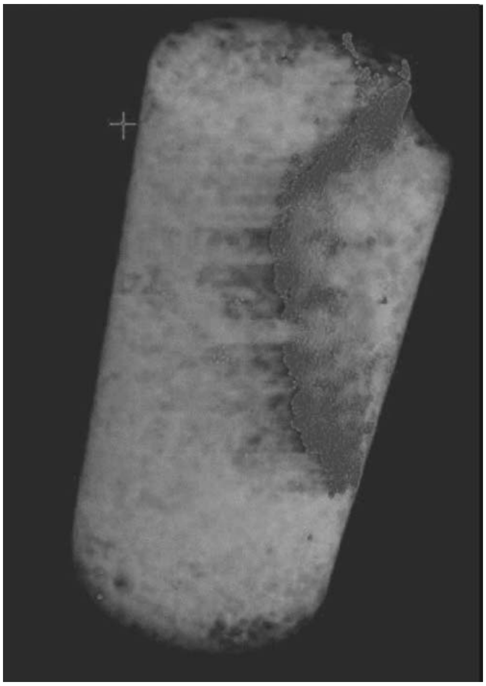

Fig. 9. Neutron reconstruction to make transparent a geological sample.

3.3. X-ray radiography

To investigate the X-ray tomography capabilities, a small bale of wool phantom (20 cm × 20 cm × 20 cm),

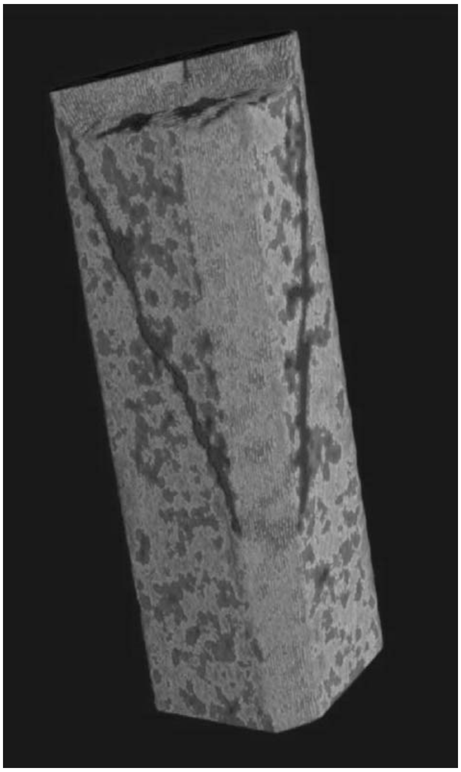

Fig. 10. Neutron reconstruction: geological sample sliced.

with density of 4 g/cc containing several "contaminants", was radiographed. Fig. 11 shows the transmission 2D X-ray radiograph through this sample under investigation and the contaminants (concrete, washer, screw, paper clip, nut and string of nylon) clearly recognizable.

Due to the divergence of the X-ray beam and the imaging geometry, tomography was unsuccessful—with the contaminants deformed and unrecognizable. The Octopus reconstruction software to correct for these artifacts created due to the beam divergence was at the time of the experiment still under investigation and not yet implemented.

3.4. *Quantitative investigations*

The digital format of the data allows also for data quantification. Quantitative neutron radiography requires an exact relation between the measured neutron attenuation and the real macroscopic attenuation coefficient for every point of the sample. In this way quantitative information about the material composition or the sample thickness can be obtained. In correlation to conventional techniques, neutron radiography has the potential to determine the distribution of, for example, porosity in porous media.

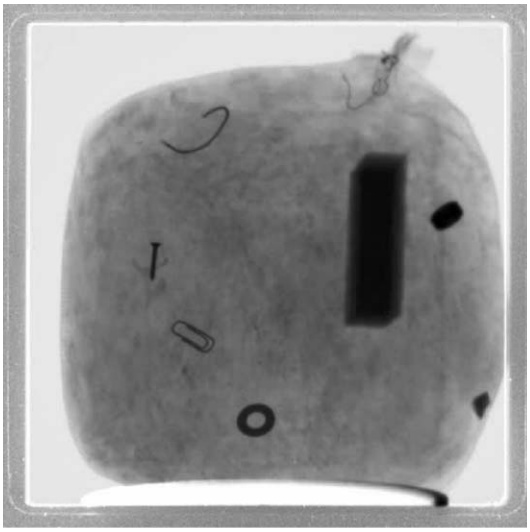

Fig. 11. X-ray transmission radiograph (2D) of contaminants in a wool bale.

4. Conclusion

The availability of a neutron tomography system, complemented by an X-ray tomography scanning system at Necsa, makes not only South Africa the only facility of this kind in Africa but also in the Southern hemisphere. This unique non-destructive facility has the capability to reveal information to South African industry and academia, which was never before available.

The system, installed at No. 2 beam port, called the SANRAD facility of the SAFARI-1 nuclear research reactor at NECSA, provides 3D data on a non-destructive basis utilizing neutrons and X-rays. Utilization and implementation of this technology into many field of application are being investigated.

The SANRAD facility is available to any industry that wishes to utilize neutrons or X-rays in a tomographic manner. Collaboration with the academic community in all research fields is sought, as the facility is perfectly suited for post-graduate research.

Acknowledgments

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[8] http://neutra.web.psi.ch/.