UTILISATION AND UPGRADING OF THE NEUTRON BEAM LINES FACILITIES AT THE SAFARI-1 NUCLEAR RESEARCH REACTOR IN SOUTH AFRICA

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Abstract

The South African Nuclear Energy Corporation (Necsa) owns and operates the SAFARI-1 20 MW Research Reactor located near Pretoria. In the last two decades the SAFARI-1 research reactor has been successfully utilized for the production of radio-isotopes and the neutron transmutation doping of silicon. At the same time, various developments have been undertaken at the horizontal thermal neutron beam line ports. In fulfilling its statuary mandate to apply radiation technology for scientific purposes, Necsa is constantly exploring opportunities to employ the neutrons from its beam line facilities to benefit both academia and industry in research and technological development. This paper outlines the facilities available at SAFARI-1, the current initiatives to establish state-of-the–art user facilities and their application to various fields of material research.

1. INTRODUCTION

SAFARI-1 has 6 radial beam tubes from the reactor core that currently accommodate 3 instruments for the applications: Diffraction (NDIFF - Beam line BT5), Radiography (SANRAD - Beam line BT2) and Small Angle Neutron Scattering (SANS - Beam line BT1). A schematic diagram of the beam line layout is seen in Figure 1.

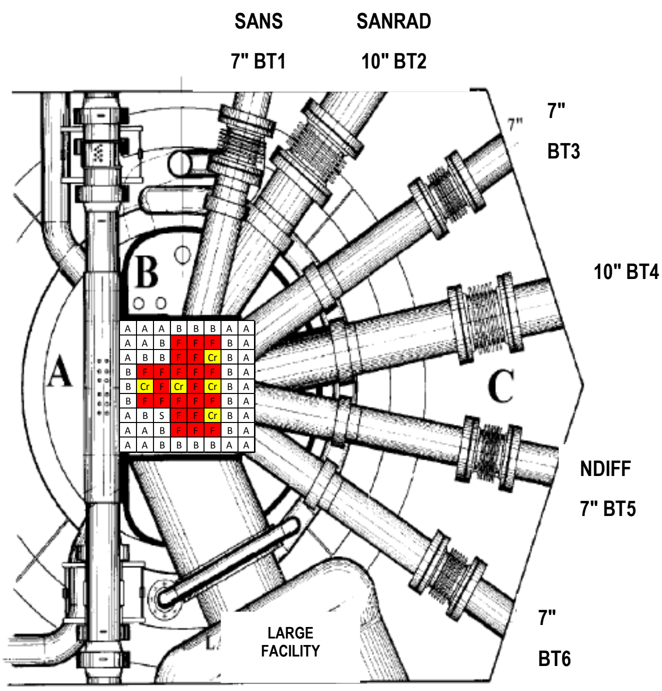

Figure 1: Top view layout of the SAFARI-1 reactor. Indicated positions refer to: A: Pool-side facility, B: In-core positions, and C: the radial beam lines.

The upgrade program of the individual beam line facilities employed extensive MCNP-X software simulation of the SAFARI-1 reactor core as well as each beam line facility to determine optimized shielding and neutron transport properties. In collaboration with the International Atomic Energy Agency (IAEA), an initiative to establish user facilities at the beam lines was launched in 2004 through Technical Cooperation (TC's) initiatives and Collaborative Research Projects (CRP's) [1,2,3,4,5]. Through expert missions to South Africa, and scientific missions of Necsa scientists to state of the art facilities in Europe, upgraded facilities are under development to be operational from 2012 hence including an online user office for management and control of users.

The beam lines are developed in support of research activities within the South African National System of Innovation (NSI) as well as such activities suitable for international and regional collaboration [6]. The first includes the higher educational sector and other government funded research institutions The research activities are multidisciplinary and includes non-destructive testing, *in-situ* analysis of various properties and characteristics of condensed matter, materials and engineering components. Of specific interest is the establishment of a core capability in the field of nuclear materials research in support of the nuclear energy industry. In approaching this multi-disciplinary challenge it has also been recognized that it is extremely important to provide a suite of complimentary beam line analytical services to the client, for example: X-ray diffraction, X-ray radiography (including X-ray micro-focus), small angle X-ray scattering, scanning electron microscopy and delayed neutron activation analysis. Applications within the NSI are as important to Necsa as in-house research, and the beam line facilities have comprehensive analytical programmes supporting cultural heritage, environmental sciences, geological- and mineralogical sciences, archaeological studies, and a number of biological and forensic science applications. Furthermore, an integral part of the research and development programme is to provide training opportunities to local and international clients (mainly post graduate students) and to participate in international research collaborations.

The beam lines play an integral role in the training of scientists and engineers up to post-graduate level and offers fundamental and applied research opportunities for the scientific community in the Southern African Region.

2. UPGRADE INITIATIVES

The neutron beam line facilities at Necsa have a long history of utilisation since commissioning in the 1970's. The neutron beam lines have been dedicated to neutron diffraction (residual stress, powder diffraction, magnetism and crystallography), neutron radiography/ tomography, small angle neutron scattering and prompt gamma-ray neutron activation analysis. Three of these facilities are presently undergoing major upgrades so that they can provide a scientifically competitive service to academia and industry. A schematic top view of the new beam line facilities layout in relation to the SAFARI-1 reactor hall is depicted in Fig.2. A description of the technical details of the upgrades follows below:

2.1. SANS

The initial SANS instrument was located on the tangential beam port. The tangential beam tube was sacrificed during the early 1990's to accommodate a commercial project to secure the operational history of SAFARI-1. With assistance from the IAEA, in the form of a Technical Cooperation (TC) Agreement and a Collaborative Research Project (CRP), it was aimed at re-establishing a basic SANS centre at the No.1 radial beam tube. A minimal system should be in operation by early 2012 (phase 1) with a fully operational facility scheduled for operation in 2013 (phase 2).

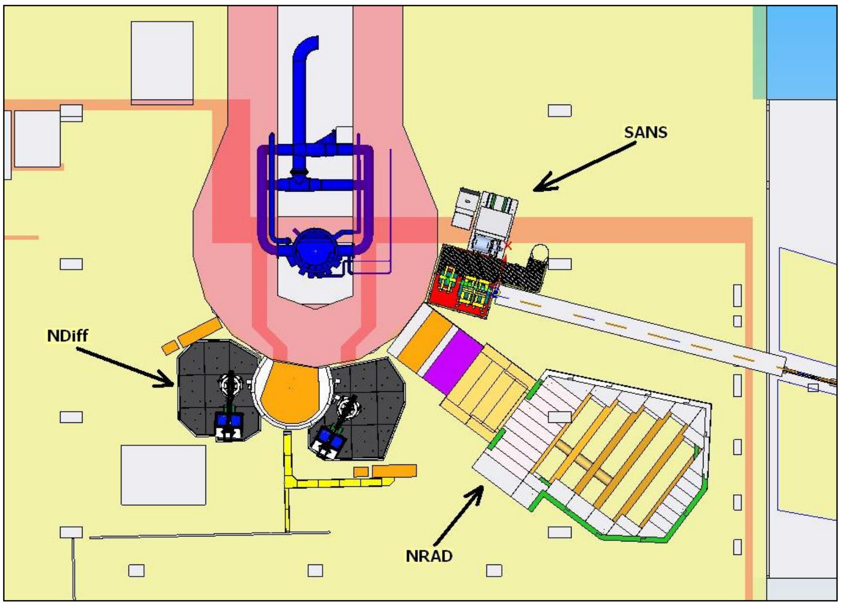

Figure 2: Top view layout of the beam line facilities in the SAFARI-1 reactor hall. The second phase of the SANS development will extend through the containment wall on the Eastern side of the reactor hall.

Phase 1 of the facility upgrade consist of a 2 metre long neutron guide insert into the beam port, to enable extraction of a neutron beam (40 x 40 mm^2), which after having passed cryogenically cooled Bi and Be filters (to remove fast neutrons and gamma-rays transmitted from the reactor core) will enable monochromation and selection of neutron wavelengths from 4 Å to about 14 Å in conjunction with a mechanical velocity selector. The sub-thermal neutrons are then collimated to a target station and the scattered neutrons detected in a detection chamber consisting of a 60 x 60 cm^2 array of position sensitive neutron detectors.

Phase 2 of the facility upgrade include the installation of a 25 m long curved neutron guide through the wall of the reactor building and an inclusion of a 10 m long scattering chamber which will be located at the outside of the reactor building to minimise radiation background noise (see Figure 3).

Recent investigations at the Budapest Neutron Centre SANS facility on wool samples have provided an indication of the potential scope of the Necsa SANS facility.

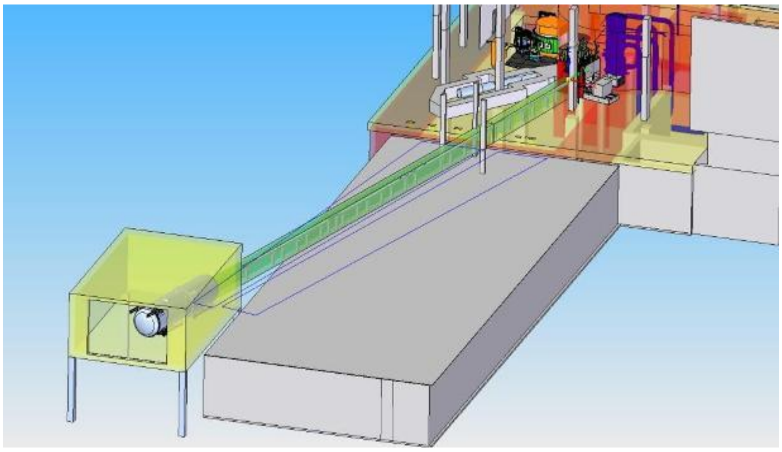

Figure 3: Artistic impression on SANS Phase 2 extending through the Eastern wall of SAFARI-1 building with curved neutron guide and doubled scattering chamber.

2.2. NDIFF

The first generation neutron diffraction instrument at SAFARI-1 was in operation on beam tube 5 from the early 1970s up to 2007. A new upgraded facility, as depicted in Fig.4 is under development, catering for substantially improved scientific capability including:

- Maximisation of the useful thermal neutron flux at the sample position of the neutron diffraction instruments, through the redesign and simplification of the primary beam shaper (PBS) layout and associated service channels inside BT5;
- Minimisation of the background radiation levels outside the monochromator chamber by removing unwanted radiation well before it enters the chamber. This is achieved by the improved PBS design, incorporation of a sapphire filter, as well as the installation of additional shielding layers external to the chamber;
- Establishment of instrumentation floors external to the monochromator chamber that have a surface flatness better than 20 μm/m;
- Provision of utilities to accommodate two independent neutron diffraction instruments, i.e. specifically optimised as a neutron strain scanner and a neutron powder diffraction facility;
- Implementation of new instrument control systems for the independent operation of these two neutron diffraction instruments. Each instrument has in excess of 25 motion stages that are all equipped with encoders for optimal positional accuracy in conjunction with microstepping of the stepper motors.

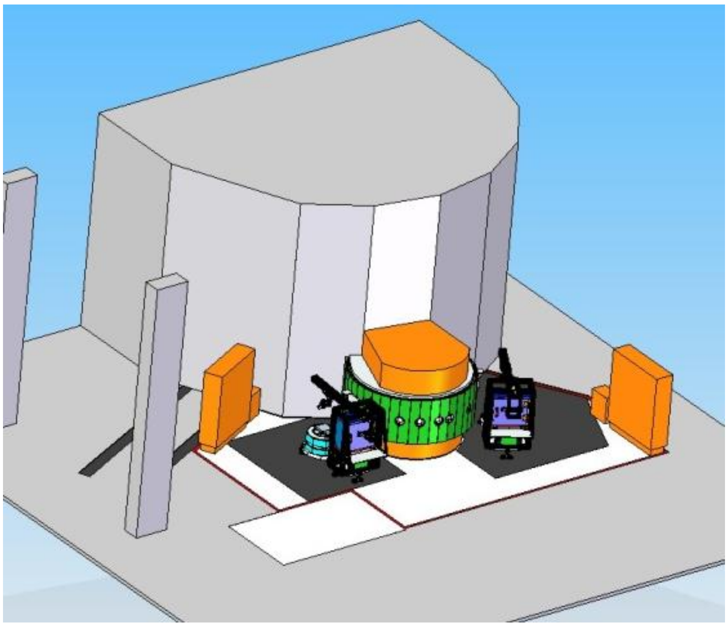

Figure. 4: Top view of the NDIFF instrument locations, utilities channel (grey lines leading from the monochromator chamber to the air conditioned computer workstations, as well as from this channel towards the motion control cabinet of the powder diffraction instrument) and electronic racks are shown.The electronic racks (accommodating servers and/or analogue electronics) are shown by smaller orange rectangles while the motion control cabinets are shown by larger orange rectangles. The dark grey floor areas indicate the location of the special instrumentation floors with surface flatness to within 20 μm/m.

Using extensive Monte Carlo based modelling [7-9], the following have been determined:

- The optimum incident neutron beam shape and dimensions through the PBS to deliver maximal useful thermal neutron flux specific to the NDIFF applications.
- The most effective readily available radiation absorption materials for the construction of the PBS.
- Improved shielding efficiency of the monochromator chamber with the primary purpose to minimise background radiation levels external to the monochromator chamber.

2.3. NRAD

The first generation neutron radiography facility was in operation on BT4 from the early 1970s up to 2000. The facility was relocated to BT2 to accommodate expansion of the NDIFF applications. This facility has since been in operation whilst a new, upgraded facility is under development since 2005. The new facility was planned in collaboration with, and based on design aspects of the ANTARES neutron radiography facility at FRM-II, Germany. The program encompasses improvement of the overall scientific and operational performance through:

- Simplification of the collimation system to minimise maintenance and expand its lifetime. The new collimator will be placed external to the beam tube and 5 meters from the reactor core, on the floor in the reactor hall.
- Maximisation of the neutron flux on the detector plane through neutron optics design that will maximize the solid angle facing the core.
- Extensive improvement of the shielding design through MCNP-X simulation to reduce the dose rate, not only from a safety regulatory perspective but also to reduce the neutron and gamma background to the nearby NDIFF- and SANS facilities which are adversely influenced by high background radiation levels emanating from stray neutrons leaking from the inadequate shielding properties of the current NRAD facility (Fig-5).
- Expansion of the analytical capabilities from thermal neutron radiography to include fast neutron radiography, gamma-ray radiography with the possibility of dynamic studies. The introduction of filters such as Bismuth and Sapphire, polyethylene and Pb that will allow beam spectrum tailoring to improve the application scope considerably.

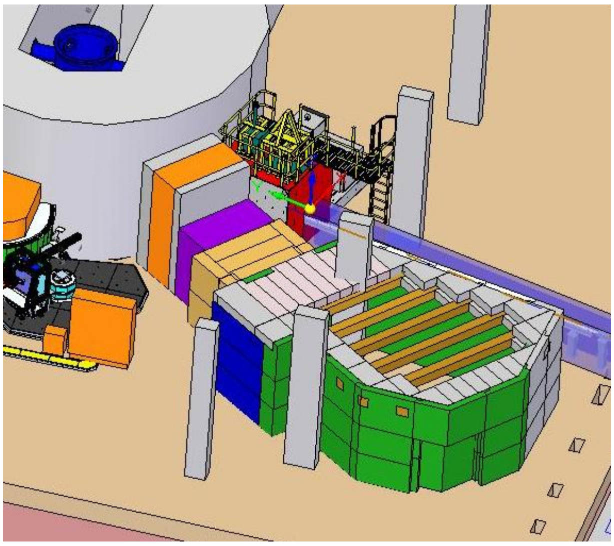

Figure. 5: 3-Dimensional view of the NRAD facility

3. UTILISATION

In this section we provide a brief description of the application scope of the SAFARI-1 neutron beam line facilities, with reference to findings and research published in peer reviewed papers.

3.1 NDIFF

Powder diffraction at SAFARI-1 is applied to the investigation of crystallographic phenomena of polycrystalline systems in conjunction with the Rietveld whole profile refinement technique, as well as the investigation of magnetic phenomena in materials by exploiting the magnetic moment of the neutrons. With reference to the latter, many investigations have already been conducted of the magnetic phenomena in dilute alloys of Cr [10-15].

Non destructive residual stress investigations using neutron strain scanning is a well established technique internationally that is widely accepted and implemented by industry today [16-18]. This stems from the solid fundamentals in technique benchmarking employed and continuous expansion programs (European NET: European Network on Neutron Techniques Standardization for Structural Integrity, coordinated by European Commission – Joint Research Centre which joins partners from research institutes, academic media and industry within the framework of a sustained research program of experiments and modelling related to welding residual stress assessment) to integrate its utilization with more traditional techniques and software modelling finite-element based approaches. Neutron strain scanning provides an ideal experimental technique to test theories.

Neutron strain scanning, residual or applied, enables determination of the tri-axial stress condition existing in the interior of most materials of industrial importance which includes alloys of magnesium, titanium, aluminium, steel, as well as ceramics, metal matrix composites, etc. The technique utilizes a well defined and characterized small gauge volume, typically a 1 mm^3 cube (can be tailored to any size or geometry matched to the information resolution required) to selectively illuminate a small volume within the sample interior within which the lattice plane spacing of the material microstructure is then averaged. Strain profiling through the volume of a component is done by precise positioning of the sample (to within 50-100 μm) to the centre of the gauge volume using high precision orthogonal sample positioning stages in conjunction to the sample orientation with reference to the diffraction geometry. This enables precise depth profiling as well as independent strain component investigation. The strains are derived with reference to an unstressed condition. Conversion from strain to stress is done by incorporating the elasticity constants of the chemical phase under consideration.

Examples of results from investigations performed for industrial collaborations are autofrettaged thick walled steel tubes, cermet composites under in-situ loading conditions, laser forming of mild steel samples and tri-axial stress conditions in automotive helical coil springs.

3.2 NRAD

Neutron radiography (NRAD) is a non-destructive materials investigative imaging technique that is extensively utilised at beam line facilities at nuclear research reactor centres worldwide. At steady-state neutron sources, such as the SAFARI-1 research reactor, it is most effectively applied for investigating material macrostructural properties in an imaging (2D-radiography and 3D-tomography) geometry.

The existing facility at BT2 has investigated a wide range of applications ranging from archaeological, geological (petrochemical) and mineralogical objects to civil (concrete) and mechanical (engine components) engineering samples, materials such as composites and corrosion studies. Neutrons are particularly well suited for studies of water transport through a variety of structures, including porous media. Through combination of imaging techniques and quantitative radiography the knowledge of the dynamics and characteristic parameters of such phenomena can be studied comprehensively. Examples of different research applications of the neutron radiography facility, in a number of the fields mentioned, can be found in the proceedings of the 9th World Conference on Neutron Radiography held in South Africa in 2010 [23].

4. CONCLUSION

Neutron beam techniques provide a powerful and unique complementary means (compared to complementary or alternative techniques) to aid researchers in many different fields of study. The growing awareness of this fact amongst South African researchers, has led to a marked increase in users and to a growing level of sophistication in the nature and types of experiments conducted at the neutron facilities located on the beam port floor of the SAFARI-1 nuclear research reactor. Although neutron beam line activities can be applied over the full spectrum of science and engineering, the quality of work often relies on a measure of specialisation on the part of the instrument scientist. It is therefore important to maintain a focussed approach and manage the skills portfolio accordingly. For instance, many basic application skills overlap, but each specialised applications requires the instrument scientists to acquire a level of understanding of the complementary techniques already available in the particular field in order to improve knowledge addition through application of neutrons. The upgrading initiatives on 3 of the beam lines as well as examples of areas of focus of research at the Necsa beam line facilities have been provided.

REFERENCES

[1] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA CRP SAF 11510 "Development and practical utilization of small angle neutron scattering applications."

[2] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA TC project SAF/1002 "Establishing a small-angle neutron scattering center."

[3] INTERNATIONAL ATOMIC ENERGY AGENCY, "Neutron scattering corrections for neutron radiography," IAEA Research contract 2455/RBF, IAEA CRP SAF 12455 “Development and improved sources and imaging systems for neutron radiography.”

[4] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA TC project SAF/3004 “Upgrading of SAFARI-1 beam line facilities.”

[5] INTERNATIONAL ATOMIC ENERGY AGENCY, IAEA CRP RC 1023 “Development and applications of the technique of residual stress measurements in materials.”

[6] STRYDOM, W.J., VENTER, A.M., FRANKLYN, C.B., DE BEER, F.C., “The Role of SAFARI-1 in Industry and Academia,” Physica Scripta **T97** (2002) 45–49.

[7] ŠAROUN J., KULDA, J. “RESTRAX — A program for TAS resolution calculation and for scan profile simulation,” Physics **B 234–236** (1997) 1102–1104.

[8] ŠAROUN J., KULDA, J. “Monte Carlo simulations and data analysis for three-axis neutron spectrometers,” Nuclear Physics Insttute of the Academy of Sciences of the Czech Republic, http://neutron.ujf.cas.cz/restrax/ (Last accessed 17 December,

2011).

[9] MCNP – A General Monte Carlo N-Particle Transport Code, BREISMEISTER J.F., Ed, Radiation Safety Information Computational Center (RSICC), Oak Ridge (1977).

[10] Introduction to the Characterization of Residual Stress by Neutron Diffraction, HUTCHINGS, M.T., WITHERS P.J., HOLDEN, T.M., LORENTZEN, T., Eds, Taylor and Francis, London (2005).

[11] Analysis of residual Stress by Diffraction using Neutron and Synchrotron Radiation, FITZPATRICK, M.E., LODINI, A., Eds, Taylor and Francis, London (2003).

[12] Neutrons and Synchrotron Radiation in Engineering Materials Science, REIMERS, W., PYZALLA, A.R., SCHREYER, A., CLEMENS, H., Eds, Wiley-Vch Verlag GmbH & Co, Hoboken, (2008).

[13] "Neutron Diffraction Measurements of Residual Stress in a Shrink-fit Ring and Plug", WEBSTER, G.A., Ed, VAMAS Report No. 38 (2000).

[14] OHMS, C., et al., "The European Network on Neutron Techniques Standardization for Structural Integrity – NeT," Proceedings of ASME PVP 2008, July 27-31, 2008, Chicago, ASME, Chicago (2008).

[15] VENTER, A.M., DE SWARDT, R.R., KYRIACOU, S.J., "Comparative measurements on autofrettaged cylinders with large Bauschinger reverse yielding zones." Journal of Strain Analysis **35** (2000) 459.

[16] VENTER, A.M., de Swardt, R.R., "Residual strain investigations in autofrettaged tubes," Journal of Neutron Research **12** (2004) 1.

[17] UNDERWOOD, J.H., et al., "Stress calculations for autofrettaged tubes compared with neutron diffraction residual stresses and measured yield pressure and fatigue life," Proceedings of ASME Pressure Vessel and Piping Division Conference, 2007.

[18] VENTER, A.M., LUZIN, V., HATTINGH, D., "Characterisation of residual stresses associated with the production steps of cold coiled spring steel samples," Proceedings of the International Conference on Neutron Scattering, 2011.

[19] Proceedings of the 9th World Conference on Neutron Radiography ("The Big-5 on Neutron Radiography"), Nuclear Instruments and Methods in Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment, **651** 1 (2011), 1–336.