Overview of the Conceptual Design of the Upgraded Neutron Radiography Facility (INDLOVU) at the SAFARI-1 Research Reactor in South Africa

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Keywords: Neutron Radiography, SAFARI-1, INDLOVU, Necsa

Abstract. The research and economic value of neutron beam line facilities are increasingly appreciated as is evident from the number of new facilities being planned and commissioned worldwide. In order to provide local researchers with world-class capabilities, the South African Nuclear Energy Corporation SOC Ltd. has embarked on the upgrade of the neutron beam line instruments at the SAFARI-1 nuclear research reactor which entails, inter alia, a novel, multi-functional neutron radiography (NRAD) facility, named INDLOVU (acronym for "**I**maging **N**eutron **D**evice to **L**ocate the **O**bscure and **V**isualise the **U**nknown" and also the Zulu name for elephant). The basic design of the facility has been developed and construction will commence after the required licensing authorizations have been obtained. The INDLOVU NRAD facility comprises of a number of subsystems. However, this article describes and highlights some of the more important subsystems and components in terms of their importance, functionality and operational interconnection with other subsystems.

Introduction

The design, construction and commissioning of neutron radiography (NRAD) facilities are generally non-trivial and expensive and therefore should aim right from the start to be competitive, complementary, state of the art, optimal for a given facility, multifunctional but also flexible.

The IAEA Research Reactors database contains updated information on current neutron radiography facilities located at nuclear research reactors (RR) [1] while NRAD facilities at spallation sources (SS) are summarized in the International Society for Neutron Radiography (ISNR) database [2]. A total of 72 NRAD RR facilities in 38 countries and 5 NRAD SS facilities in 2 countries are listed of which 15 NRAD facilities are classified as operational user facilities. Also listed is development and/or upgrading of 10 RR NRAD facilities and development of 3 new SS NRAD facilities (IMAT in UK; VENUS in USA [3]; ODIN in Sweden).

Of the 18 countries that participated at the WCNR-11 (this conference) only 2 countries made presentations on existing activities for building and/or upgrading of NRAD facilities to be operational in the near future. However, there is a potential in 9 other countries for the development of new NRAD facilities. The closure of BERII in Berlin in 2020 with the subsequent loss of a highly productive NRAD facility at the Helmholtz Institute, sketch a scenario of limited available NRAD user facilities over the next 5 years. This makes the upgrade of the thermal spectrum limited South African Neutron Radiography (SANRAD) facility towards the planned multi-functional INDLOVU NRAD facility, an important capacity generating development and milestone for South Africa and the international NRAD user community.

Necsa has been planning the upgrade since 2005 starting with an IAEA supported expert mission to identify the shortcomings of the old SANRAD facility. It was followed by several IAEA supported expert missions to FRMII, Germany as well as a MCNP-X optimization study which was based on the findings of the IAEA expert mission [4]. Additionally, guidelines for the improvement, optimization and implementation of NRAD facilities as compiled and suggested by Lehmann [5] were incorporated in the design of the INDLOVU NRAD facility. This includes optimal radiation protection, large space provisioning at experimental infrastructure, options for beam limitation and energy selection, maximized radiation beam intensity, an L/D > 250 and a homogeneous radiation beam spatial distribution.

Since 2013, several ISNR related conference articles were published on the planned enhancements of the old SANRAD facility [6] towards an improved new INDLOVU NRAD facility. These included articles on the concrete characteristics of the shielding design, which was based on that of the ANTARES facility at FRMII in Germany, and experimental evidence was provided as to the shielding integrity w.r.t. radiological safety [7]. The initial envisaged scientific design philosophy, neutron optics (collimation ratios) and imaging capabilities of the facility were also presented at ITMNR-8 and described elsewhere [8].

After several engineering design changes were approved to meet local criteria and manufacturing requirements, the final design of the INDLOVU NRAD facility has been optimized and nearly concluded. The physical dimensions of INDLOVU are as follows: Average height of 3.20 m with a maximum of 5 m at the secondary shutter and collimators. The width and length are 7.411 m and 13.573 m respectively. As indicated in the schematic overview in Fig. 1, the facility has been subdivided into several subsystems which are now discussed in separation and in relation to each other.

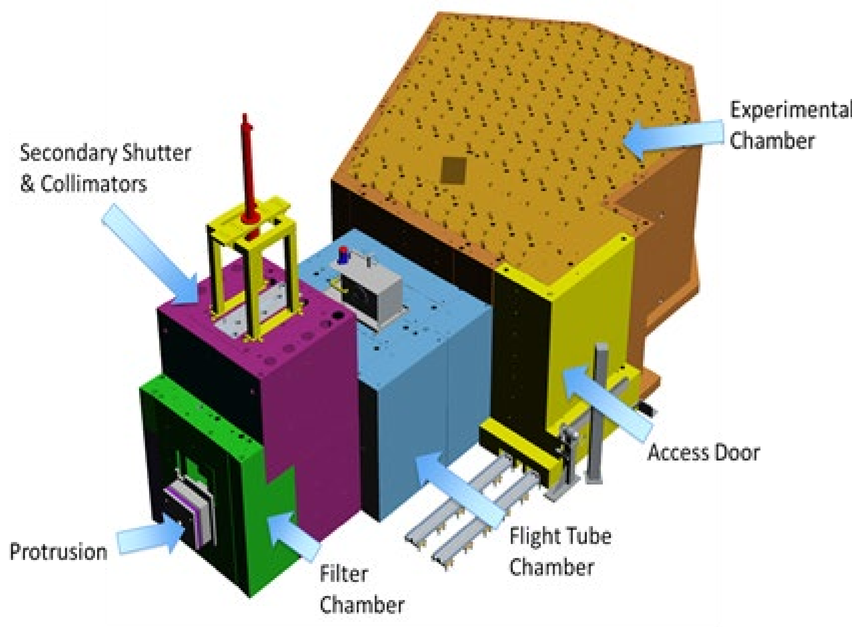

Fig. 1. Schematic model of the INDLOVU NRAD facility with its subsystems and weight (Tonnes)

Filter Exchange chamber:	~18T	(Green)
Secondary Shutter:	~82T	(Purple)
Flight Tube Chamber:	~78T	(Blue)
Experimental Chamber:	~353T	(Brown & Yellow)

Materials Research Proceedings **15** (2020) 11-16 https://doi.org/10.21741/9781644900574-2

Beam tube, Primary Shutter and Protrusion (Fixed Collimator)

The No-2 beam tube is located radial to the SAFARI-1 nuclear research reactor core thus allowing the full neutron and gamma ray spectrum to be guided through the 3.4 m long, 30 cm diameter tube towards the outside of the biological shield. Normally, during long term instrument shutdown, the tube is fitted with a concrete plug and cooled with circulating water. However, during maintenance of the filter chamber, the beam tube will only be filled with water, and, together with the primary shutter, provide adequate shielding from the reactor core. During normal operations the beam tube will be filled with He to allow uninhibited neutron transmission.

The primary shutter consists of a 0.8 m thick layered Fe and B-PE structure, which pneumatically slides horizontally and latches into discrete opened or closed positions. The primary shutter fails in a closed position through a spring mechanism. Between the shutter and the filter exchange chamber, a layered Fe and B-PE structure with a fixed cone-shaped hole is inserted to provide initial collimation of the usable radiation beam. This hole is extended to the outside of the biological shield via another Fe and B-PE laminated extension structure, which serves as the connection interface between the reactor's biological shield and NRAD shielding. Using the opening of the hole as a fixed collimator, an L/D = 125 is achieved.

Filter Exchange Chamber

A set of three uncooled filter materials, Bi, Sapphire (Al_2O_3) and B-PE, is located inside the filter exchange chamber. Each filter can individually be moved into or out of the radiation beam using either the Data Acquisition & Control System (DACS) or manually via chains from outside the chamber. This design concept adds to the multi-functionality of INDLOVU and allows for the radiation beam to be manipulated and thus exhibiting an applicable radiation composition for a specific experiment through a selected combination of any of the filters.

Secondary Shutter and Collimators

The collimator-shutter assembly consists of a 123 cm thick vertical sliding block with a concrete section and three fixed B-Fe collimators stacked on top of each other (Fig. 2). The collimators have fixed apertures of 12 mm, 24 mm and 42 mm and provide L/D ratios of 800, 400 and 250 respectively. The collimator-shutter assembly also acts as a secondary radiation shutter comprising of 125 cm thick high density concrete.

Flight Tube Chamber

Lead and B-10 disks are used as additional filter materials to tailor the radiation beam to the experimental requirements, and are positioned in the flight tube chamber just after the collimators. The B-10 disk is small enough to be fast moving to capture the thermal radiation beam in three modes of operation: (a) manually, to absorb the thermal neutron beam during radiography setup to minimize extreme sample activation, (b) automatically, to shut the thermal neutron beam during the tomography process to minimize extreme sample activation and (c) to be used as a thermal neutron filter in combination with the other radiation filters, to obtain either a more prominent gamma-ray, or fast neutron radiation spectrum.

Fig. 2. Three B-Fe collimators: with different aperture openings (D) of 12 mm, 24 mm and 42 mm respectively.

Materials Research Proceedings **15** (2020) 11-16 https://doi.org/10.21741/9781644900574-2

The radiation flight tubes are cylindrical aluminum channels, comprising of five individual sections aligned along the optical axis, extending from the fast shutter mechanism up to the translation table and sample stage (Fig. 3). The tube sections have each a different diameter,

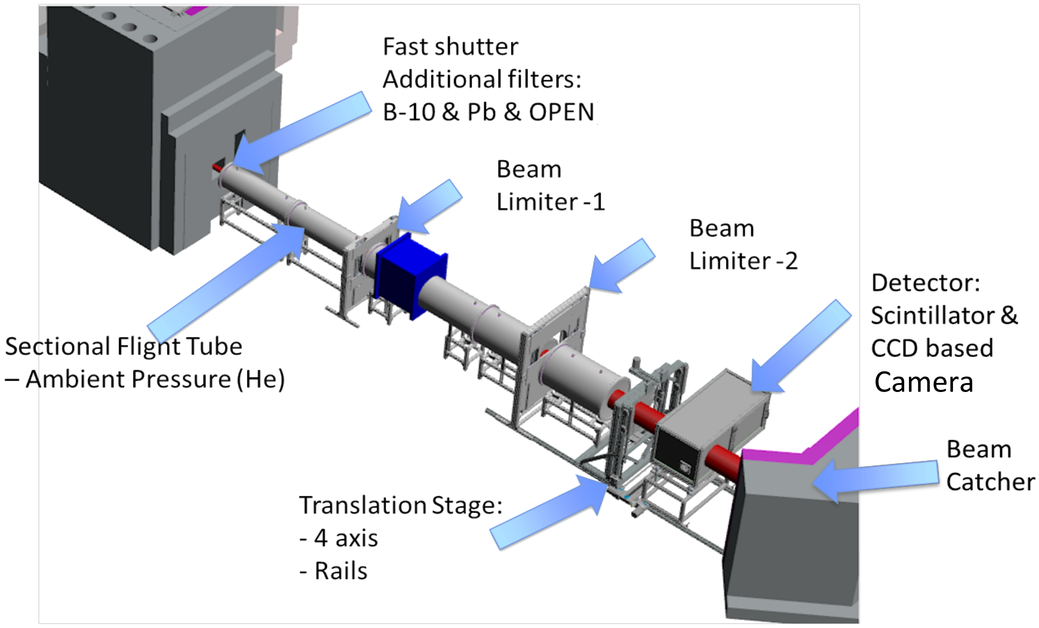

Fig. 3. Schematic diagram of the instrumentation in the flight tube chamber and experimental chamber.

increasing towards the detector to accommodate the beam divergence. He at ambient pressure as fill gas allows uninhibited neutron transport by excluding unwanted radiation scatter from air. The tube sections can be separated and removed to enable installation of additional neutron optic elements (e.g. a periscope) in the future. The mobility of the tube sections allows for the movement of the detector system towards the source for an increase in radiation flux for the envisaged addition of a micro-focus neutron camera.

Two beam limiters, a primary limiter inside the flight tube chamber and a secondary limiter fixed to the translation table in the experimental chamber, define the desired cross sectional area of the radiation beam to be dimensionally similar to the outer bounds of the sample.

Experimental Chamber

The flight tube extends into the experimental chamber and ends just before the secondary beam limiter. The experimental chamber mainly houses the sample translation table and neutron detection system. The sample table is mounted on rails which are fixed to the floor and positioned in front of the camera box. These rails enable macro set-up whereby the entire table can manually be moved parallel to the beam and locked in position. The table is equipped with high precision stepper motors to allow four degrees of freedom needed to position the sample in the center of the beam. These stages are parallel and tangential to the beam, vertical translation and rotation. During sample setup, the necessary controls are available to the operator within the experimental chamber enabling the safe initial positioning of the sample. This minimizes sample activation during operation as only minor positioning adjustments will be required while the sample is exposed to the radiation beam. The relative position of the sample w.r.t. the center of the beam and detector only becomes known during operation when the shutters are opened and a radiograph is acquired.

Materials Research Proceedings **15** (2020) 11-16 https://doi.org/10.21741/9781644900574-2

The first phase of implementation of the detection system entails the installation of a CCD-based digital camera housed in a light-tight a camera box. The box is positioned on rails which enables it to be manually moved parallel to the incoming radiation beam. A removable scintillator screen is attached to the front of the camera box. Two different sized scintillators can be accommodated namely 35 × 35 cm^2 and 10 × 10 cm^2. Various scintillator materials are available depending on the application and incident radiation beam spectrum needed. These are 0.05 mm or 0.10 mm thick ZnS:Cu/6-LiF screens, a 0.01 mm thick (GADOX) Gd_2O_2S:Tb/6LiF: 80/20 screen and a 1.5 mm thick PP30 (30% ZnS:Cu) converter. A maximum neutron flux of 1 × 10^9 neutrons.cm^{-2}.s^{-1} is envisaged, utilizing the full radiation spectrum – see Fig.4 from a McStas simulation of the homogeneous flat radiation field envisaged [9].

A mirror reflects the photons emanating from the scintillator at 90° towards the removable lens of the CCD camera. As the camera is mounted on a translation stage, the optimal field of view (FOV), which is dependent on the size of the sample and the required spatial resolution, can be selected through electronic means by changing the camera to scintillator distance. A focusing protocol can be initialized from NRAD DACS to enable automatic focusing of the lens. The camera box is ventilated and temperature monitored which enables automated shutdown of camera when the temperature exceeds the upper operational limit. The second phase sees the implementation of an additional detection system positioned closer to the reactor core where the intensified neutron flux (but smaller FOV) will enable a micro neutron CT capability.

The transmitted radiation beam finally terminates in a beam catcher/dump constructed of a layered system of B-PE, Pb and Cd to minimize the radiation scatter onto the detector and thus decreases the background signal.

Safe Operation

Entry to the experimental chamber is through a manual sliding door and is constrained by an independent, separate, hard wired interlocking system that controls the operation of the shutters. A “Last man out” procedure requires the last person leaving the experimental chamber to activate a device (located at the far end within the experimental chamber) with a safety key. The door should then be locked (using the same key) in the closed position within a time limit to render the shutters operational. In addition, the door can only be unlocked when the shutters are fully closed. The status of the shutters is available to the operator on the status screen of the client control computer, a mimic panel next to the access door as well through red and green indication lights placed at strategic positions on the outside of the experimental chamber. These lights are visible from the NRAD control room as well as from the SAFARI-1 control room.

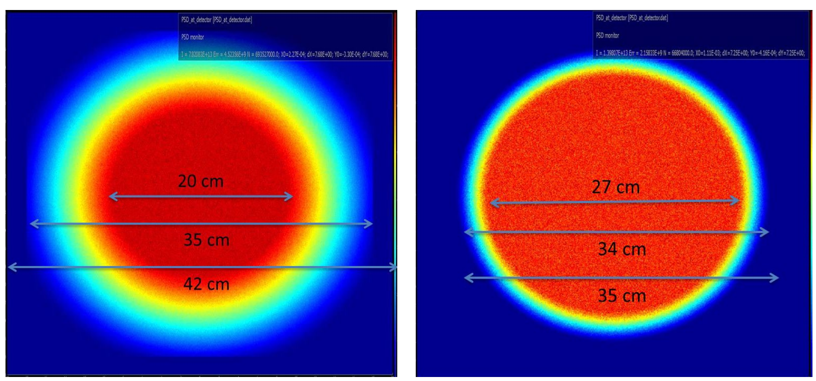

Fig. 4 McStas simulation of the Flat Field sizes and homogeneity achieved by two apertures of INDLOVU:

Aperture:	42 mm	13 mm
L/D:	250	800
Flat Field	20 cm	27 cm
Total Field:	42 cm	34 cm
Screen size:	35 cm	35 cm

Instrument Control

All motorized stages are controlled by the ANSTO implementation of the SINQ Instrument Control Software (SICS) [10]. SICS allows batch scripting of instrument parameters thereby allowing experimental sequences to be pre-programmed. This DACS functionality enables maximum facility utilization with minimum personnel.

Conclusion

The envisaged INDLOVU NRAD facility will be a unique and highly competitive analytical instrument for the neutron sciences communities of South Africa and abroad. It will offer advanced radiography/tomography functionality by exploiting the high radiation flux available at the SAFARI-1 research reactor. INDLOVU will be unique in its application as it can perform not only neutron radiography using various energy ranges, but also perform radiography utilizing a gamma-ray radiation beam. The INDLOVU beam line instrument will expand the local and international scientific and industrial user community as a multi-functionality analytical tool complementary to X-ray tomography. Future upgrades will include the installation of a periscope for monochromatic neutron radiography and tomography as well as a micro tomography capability.

Acknowledgements

The research and development for the NRAD upgrade at the SAFARI-1 nuclear research reactor was sponsored by the Department of Science and Technology’s National Research Foundation (NRF 75433) and the Department of Energy (FUN-DOE-001). The authors would like to thank Dr’s Grunauer, Schillinger and Schultz from FRMII, at the Technical University of Munich for the fruitful technical discussions and continuing support for the development of the future INDLOVU.

References

[1] IAEA, “IAEA Research Reactor Data Base.” [Online]. Available: http://nucleus.iaea.org/RRDB/. [Accessed: 15-Dec-2018].

[2] “International Society for Neutron Radiography (ISNR).” [Online]. Available: https://www.isnr.de/index.php/facilities/user-facilities. [Accessed: 15-Dec-2018].

[3] H. Bilheux, K. Herwig, S. Keener, and L. Davis, “Overview of the Conceptual Design of the Future VENUS Neutron Imaging Beam Line at the Spallation Neutron Source,” *Phys. Procedia*, vol. 69, pp. 55–59, 2015. https://doi.org/10.1016/j.phpro.2015.07.007

[4] F. Grünauer, “RS-RAD-REP-14001: Monte Carlo Simulations for the SAFARI-1 Reactor and its Instrumentation: Part C: Neutron Radiography Facility.,” 2009.

[5] E. Lehmann, Neutron Imaging Facilities in a Global Context, *J. Imaging*, vol.3, no.4, p.52, 2017. https://doi.org/10.3390/jimaging3040052

[6] F. De Beer, “Neutron and X-ray Tomography at Necsa,” *Jounal South African Inst. Min. Metall.*, vol. 108, no. OCTOBER, pp. 1–8, 2008.

[7] F. C. De Beer, M. J. Radebe, B. Schillinger, R. Nshimirimana, and M. A. Ramushu, “Upgrading the Neutron Radiography Facility in South Africa (SANRAD): Concrete Shielding Design Characteristics,” *Phys. Procedia*, vol. 69, no. October 2014, pp. 1–9, 2015. https://doi.org/10.1016/j.phpro.2015.07.017

[8] F. C. De Beer, F. Gruenauer, M. J. Radebe, T. Modise, and B. Schillinger, “Scientific design of the new neutron radiography facility (SANRAD) at SAFARI-1 for South Africa,” *Phys. Procedia*, vol. 43, pp. 34–41, 2013. https://doi.org/10.1016/j.phpro.2013.03.004

[9] http://www.mcstas.org/ (Visited 20 Dec 2018)

[10] H. Heer, M. Könnecke, and D. Maden, "The SINQ instrument control software system," *Physica B: Condensed Matter*, vol 241-243, pp 124-126, 1997. https://doi.org/10.1016/S0921-4526(97)00528-0