Scientific design of the new neutron radiography facility (SANRAD) at SAFARI-1 for South Africa

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Abstract

The final scientific design for an upgraded neutron radiography/tomography facility at beam port no.2 of the SAFARI-1 nuclear research reactor has been performed through expert advice from Physics Consulting, FRMII in Germany and IPEN, Brazil. A need to upgrade the facility became apparent due to the identification of various deficiencies of the current SANRAD facility during an IAEA-sponsored expert mission of international scientists to Necsa, South Africa. A lack of adequate shielding that results in high neutron background on the beam port floor, a mismatch in the collimator aperture to the core that results in a high gradient in neutron flux on the imaging plane and due to a relative low L/D the quality of the radiographs are poor, are a number of deficiencies to name a few.

The new design, based on results of Monte Carlo (MCNP-X) simulations of neutron- and gamma transport from the reactor core and through the new facility, is being outlined. The scientific design philosophy, neutron optics and imaging capabilities that include the utilization of fission neutrons, thermal neutrons, and gamma-rays emerging from the core of SAFARI-1 are discussed.

Keywords: Type your keywords here, separated by semicolons ; Necsa, SAFARI-1, Neutron Tomography, Upgrade

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1. Introduction

The South African Neutron Radiography (SANRAD) facility, located at the SAFARI-1 nuclear research reactor, and at beam port-2 in the reactor hall, is in operation since 1975, first applying the film technique (Gd and In), upgraded in 1995 to an electronic CCD system and finally, in 2003 until today, equipped also with a tomography capability in collaboration with the Paul Sherrer Institute (PSI) in Switzerland [1].

The facility is a product of a South African governmental initiative to upgrade national research equipment and it is part of the South African National System of Innovation. It is therefore being used by researchers and post graduate students as an analytical tool and together with a recently installed Micro-focus X-ray system [2], forms the South African National Center for Radiography and Tomography, located at Necsa.

Research was successfully conducted at the SANRAD facility and reported in many peer reviewed journals ranges from applications in the Archaeology [3,4,5], Palaeontology [6], Geosciences [7], Engineering [8,9,10] and optimization of neutron procedures for improved quantitative neutron radiography [11].

The need for optimization of the SANRAD facility toward European standards is borne from mechanical, optical and optimization needs as well as deficiencies inherit to the current facility located at beam tube no2. Due to corrosion as well as optical mismatch of the collimator system, inadequate radiation shielding that showers neighboring instruments with stray neutrons as well as a minimum functional scientific and experimental capability, the facility could not function optimally and an upgrade was proposed. The upgrade is being supported by DST-NRF-NEP-RISP funding – a national equipment funding initiative from the South African government and is in line with the National System of Innovation strategy of the government to provide necessary infrastructure for scientific research.

In this paper the scientific aspects are addressed that will optimize the facility to fit into and adhere to constraints, to current conditions on the beam port floor of the SAFARI-1 reactor and the upgrade to a more versatile facility.

2. Description of upgrade

For aging research reactors, the upgrade or installation of a new beam line facility has to deal with constraints that hinders full compliance with needs and that has to be overcome or comply with in the best possible manner. For the new South African Neutron Radiography (SANRAD) facility it is very much the case as the functionality and the size of the new facility is limited to (a) a radiation beam port that is axial to the reactor core producing a radiation beam that is rich of fission gammas and fast neutrons and (b) an area available on the beam port floor within the beam port hall area that can support the weight of the new shielding.

Due to the axial alignment of the beam port to the reactor core, the fast neutron and fission gamma radiation components of the beam have direct detrimental influence on the containment shielding properties – denser and thus heavier. However, these two components of the radiation beam will be used in a positive way to be included in the expansion for the more effective and more versatile utilization of the facility.

Currently the aperture/collimator is mounted inside the channel through the biological shielding. With the actual setup of the facility the following problems occur:

- The neutron flux distribution in the detector plane is not homogeneous. The inhomogeneity is bothering for neutron radiography measurements.
• Scattered neutrons from the shielding and the structure materials cause a high background in the measured signal.
• The beam is contaminated by a high background of fast neutrons and gamma radiation. This is due to the direct view to the reactor core.
• Neutron transmission through the radiation shielding and through gap systems causes a high background for neighbour diffraction experiments.
• Heat production due to gamma radiation in the collimator makes a cooling system necessary. The coolant (water) causes corrosion of the collimator structure.

Verification of the influence of the different structure elements of the facility and optimization of the facility is done by help of Monte Carlo simulations. A 3-D model of the simulated NRad facility is shown in fig-1:

The aims of the optimisation of the new radiography and tomography facility are to achieve:
• Highest possible neutron flux in the detector plane.
• A homogeneous neutron illumination in the detector plane within an area of 35 cm x 35 cm.
• Low background of scattered neutrons and gamma radiation around the detector system.
• Low background radiation level outside the facility (low background for neighbour experiments, radiation protection requirements).
• A low cost, volume, and weight radiation shielding. Simulated in Fig.3
• Utilize all radiation types emerging from the beam port (Fast neutrons, Thermal neutrons, Fission gammas) for radiography.

A high neutron flux in the detector plane is important in order to reach a statistical relevant signal even within small exposure times. Especially for dynamic radiography of non periodic systems it is essential to have a high neutron flux. The homogeneous illumination in the detector plane (see Fig. 1, "full illumination") is desirable in order to get the same counter statistics at each location of the projection and for optimal use of the dynamic range of the detector system in the whole detector area.

Fig. 1: Schematic overview of the beam geometry of a neutron radiography facility

The homogeneous illumination should be obtained within an area of 35 cm x 35 cm. The secondary neutron source (entrance window of the beam tube) has a circular shape. Hence fully illumination in the detector plane will also occur in a circular area. To obtain the desired area of 35 cm x 35 cm, the radius of the fully illuminated area has to be at least 24.7 cm (Fig. 2).
Fig. 2: In order to obtain the desired fully illuminated area of 35 cm x 35 cm, the radius of the fully illuminated area has to be 24.7 cm.

![Diagram showing the relationship between the radius and the area.](image)

\[ r = \sqrt{l^2 / 2} = 24.7 \text{cm} \]

Fig. 3: A simulated schematic diagram of the new SANRAD facility.

In the following paragraphs, scientific evaluation and description of the following aspects of the upgrade, which is unique to this facility but also concepts taken from the ANTARES facility at FRMII, Germany[12], are discussed - L/D Ratio, radiation filters, Field of View (FOV) and Shielding.

2.1. L/D (Collimation) ratio.

The Collimation ratio is the most important physical parameter and driver for the success and characteristics of a neutron radiography facility. The size of the penumbra, the neutron flat field size / Field-of-View (FOV), neutron flux on the detector plane and shielding properties are all dependant on the position/distance of the collimator from the source and/or the aperture opening size (D) and/or the distance the collimator is from the detector (L).
Due to corrosion problems and thus leaking of water into the front beam port, dictates that the collimator should be located at the outside of the SAFARI-1 biological shield. This move allows only for a flat field of view of 35cm x 35cm as there is a limit in L (distance of detector plane to collimator (D)). Fig 4 depicts the 3D simulated view of the collimator/2nd Shutter assembly.

Fig. 4: 3D schematic simulation of the collimator assembly.

The collimator / shutter combinations allows for the neutron beam to be stopped, to be fully opened or to be collimated with 3 x collimator shutter apertures that allows for 3 different L/D ratio’s and thus different neutron flux at the detector plane with the collimator position fixed at 451cm from the source (reactor core). Table-1 below shows the collimator settings of the new facility and predicted neutron flux.

Table 1. Collimator settings and parameters.

<table>
<thead>
<tr>
<th>Collimator aperture (D) (mm)</th>
<th>L/D ratio</th>
<th>Predicted maximum neutron flux – all energies and no filtering (n.cm(^{-2}).sec(^{-1}))</th>
<th>Radiation Flat Field size on detector (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0(Close)</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>42</td>
<td>250</td>
<td>7 x 10(^7)</td>
<td>37,3</td>
</tr>
<tr>
<td>21</td>
<td>500</td>
<td>2 x 10(^7)</td>
<td>43,4</td>
</tr>
<tr>
<td>13.1</td>
<td>800</td>
<td>8 x 10(^6)</td>
<td>47,5</td>
</tr>
<tr>
<td>138 full open</td>
<td>76</td>
<td>1 x 10(^9)</td>
<td>9,4</td>
</tr>
</tbody>
</table>

2.2. Radiation filters[13]

Through applying certain combinations of radiation filters, which are selectable for a specific application to be used to make the new facility versatile in its application, fast neutrons, thermal neutrons, cold neutrons or gamma rays can be selected from the initial fission spectrum beam of radiation originating from the SAFARI-1 core.

Bismuth is used as gamma filter due to its high atomic number (Z=83; density: 9.78g/cm\(^3\); melting point: 271.3°C). There is nearly no advantage in using bismuth instead of lead for pure gamma shielding,
but bismuth is advantageous when the neutron/gamma ratio in a neutron beam should be increased due to its low thermal neutron attenuation. Bismuth the thermal neutron transmission strongly depends on the material properties as e.g. temperature and the crystal structure. Due to neutron photon interactions the thermal neutron transmission is increased by cooling the filter material and using a single crystal.

Sapphire (Al₂O₃; density: 3.95 g/cm³ - 4.03 g/cm³) is used widely as filter material due to its high thermal neutron transmission and the resonances of Al in the epithermal and fast energy region. A poly crystal is being applied without cooling – thus increase the thermal neutron transmission and filter the higher energy neutron spectrum.

By selecting the Bismuth and Sapphire filters simultaneously, a more “clean” thermal neutron beam will be transmitted without a high gamma ray component (due to Bi filtering) and fast neutron (due to Sapphire filtering) component.

At beam port 2 of the SAFARI-reactor the neutron beam is contaminated by a high background of gamma radiation. During neutron radiography measurements this background is bothering and therefore Bi-filtering is applied. However, the gamma radiation of the reactor core could be also used for gamma radiography. In this case neutrons would be a bothering background. A polyethylene filter (CH₂; ρ=0.92g/cm³) which increases the gamma/neutron ratio in the beam will be applied because polyethylene has a low gamma attenuation coefficient (it consists of elements with low atomic number) and a high neutron attenuation coefficient.

By placing a polycrystalline beryllium neutron filter and a single crystal bismuth gamma-ray filter in a white spectrum fission radiation beam, a beam of neutrons of energies below 0.005 eV is obtained. The emergent beam is relatively free of fast neutrons and gamma rays. [14] Although the neutron flux in the cold spectrum, being created through applying the Be-filter, will be very low and thus increase the acquisition time, it is worthwhile as scanning can continue overnight. Table 2 depicts the different filter combinations for delivering different energy radiation beams and intensities to the imaging plane.

Table 2. Filter combinations to generate different radiation spectra

<table>
<thead>
<tr>
<th>Radiation type needed</th>
<th>Bismuth (monocrystal cooled) (10cm) (Gamma Filter)</th>
<th>Sapphire (10cm)</th>
<th>Beryllium (10cm)</th>
<th>Borated PE (10cm)</th>
<th>Cd (1mm)</th>
<th>Predicted Radiation flux (Worst case with no collimator) (n.cm⁻².sec⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal neutrons</td>
<td>IN</td>
<td>IN</td>
<td>OUT</td>
<td>OUT</td>
<td>OUT</td>
<td>4.20 x 10⁶</td>
</tr>
<tr>
<td></td>
<td>IN</td>
<td>OUT</td>
<td></td>
<td></td>
<td></td>
<td>1.07 x 10⁸</td>
</tr>
<tr>
<td></td>
<td>OUT</td>
<td>IN</td>
<td></td>
<td></td>
<td></td>
<td>7.50 x 10⁶</td>
</tr>
<tr>
<td>Fast neutrons</td>
<td>IN</td>
<td>OUT</td>
<td>OUT</td>
<td>OUT</td>
<td>IN</td>
<td>6.50 x 10⁷</td>
</tr>
<tr>
<td>Cold neutrons</td>
<td>IN</td>
<td>IN</td>
<td>IN</td>
<td>OUT</td>
<td>IN</td>
<td>Speculating</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>~1.00 x 10⁴</td>
</tr>
<tr>
<td>Gamma rays (Primary fission gamma rays)</td>
<td>OUT</td>
<td>OUT</td>
<td>OUT</td>
<td>IN Thermalise fast neutrons</td>
<td>IN Capture Thermal neutrons</td>
<td>1.90 x 10⁹</td>
</tr>
<tr>
<td>Full fission spectrum (for dynamic studies)</td>
<td>OUT</td>
<td>OUT</td>
<td>OUT</td>
<td>OUT</td>
<td>OUT</td>
<td>N: 1.90 x 10⁹</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Gamma: 1.95 x 10⁹</td>
</tr>
</tbody>
</table>
2.3. Shielding.

The background of scattered neutrons has to be minimised because scattered neutrons cause a signal in the detector without gain of information about the specimen. The same holds for generated gamma radiation from the region around the detector system. The radiation shielding of the facility have to keep the neutron and gamma background radiation level around the facility to a minimum. No major background contribution for other experiments in the reactor hall must be caused by the facility and the radiation protection requirements have to be fulfilled.

For the worst case scenario, when dynamic studies are performed in a high flux of radiation, a full white fission spectrum of radiation (neutrons and gammas) should be contained. The recipe obtained from the ANTARES neutron radiography facility in Munich was adopted as it has a proven record that it can be functional at the new SANRAD facility. The basic shielding format consist of 20mm Borated Polyethylene, 1cm Fe steel casing, 60cm to 80cm high density (4.7g/cc) concrete (mix of Hematite, Colemanite, Steel shot) and 1cm Fe steel casing.

Acknowledgements

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