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NEUTRONIC CHARACTERIZATION OF THE SAFARI-1 MATERIAL TESTING REACTOR

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ABSTRACT

This work presents a neutronic analysis of the core in the South African Fundamental Atomic Research Installation (SAFARI-1) for future Pebble Bed Modular Reactor (PBM) fuel irradiation experiments. Monte Carlo simulation of the core with and without the rig has been performed. The results show a negligibly small reactivity worth of the rig, which is expected, due to the small amount of heavy metal loading in the pebble and the low fuel enrichment. This effect will be further investigated when the rig is extended to include more than one fuel pebble. Results further show perturbations in the neutron and photon flux as well as the power distribution in core position B6. A 50% thermal neutron flux depression is observed in position B6 due to the insertion of the rig. A 60% increase in axial photon heating values is also observed in position B6. The neutron and photon flux and power distributions in the other in-core irradiation positions (D6 and F6) are slightly affected by the insertion of this rig. Fluxes and power distributions in positions D6 and F6 will be studied in detail when they are loaded with isotope production rigs.

1. INTRODUCTION

SAFARI-1 is a 20 MW tank-in-pool material testing reactor (MTR) with capabilities and facilities to produce radioisotopes and to perform a wide range of fuel and material irradiations. The core is configured in an 8 × 9 grid with twenty six (26) fuel assembly positions and six (6) control positions [1] as shown in

Figure 1. The core and fuel element design parameters are summarized in Table 1. The reactor is moderated and cooled by light water. SAFARI-1 is in the process to convert from high

enriched uranium (HEU-93% ²³⁵U) to low enriched uranium (LEU-19.75% ²³⁵U) fuel.

A feasibility study is conducted at the South African Nuclear Energy Corporation (Necsa) for the irradiation of the fuel for PBM. Conducting such experiments requires the characterization of the core in terms of knowing the neutron and photon spatial distribution and the power distribution in the core to be able to quantify the perturbations due to the experiment. Also required, is the knowledge of the reactivity worth of the experiment as well as the effect of conducting this experiment on the core operational schedule in terms of cycle length and isotope production. The proposed pebble irradiation rig is designed to fit in an experimental position that already exists in the SAFARI-1 reactor.

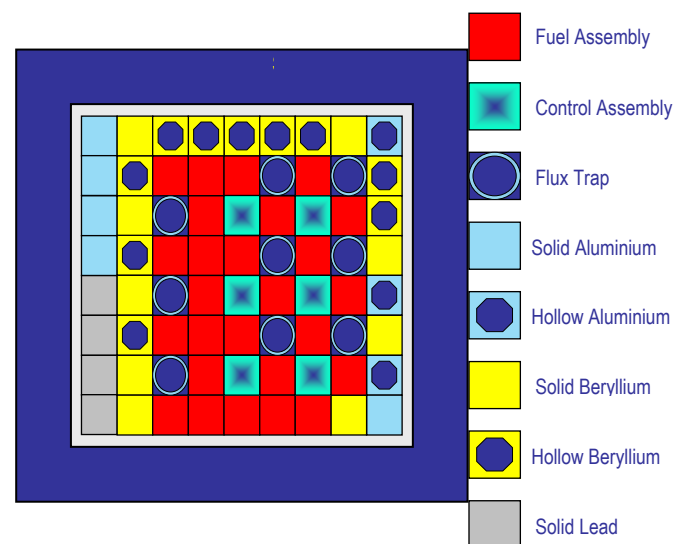


Figure 1: SAFARI-1 Core Map

Table 1: SAFARI-1 Core and Fuel Element Data

Core		
Power level	MW	20
Grid		8 × 9
Active height	cm	59.37
Number of fuel elements		26
Number of control elements		6
Fuel element		
Dimension (xyz)	cm	7.71 × 8.1 × 59.37
Type of Alloy		U ₃ Si ₂ -Al
²³⁵ U enrichment (LEU)		19.75%
²³⁵ U enrichment (HEU)		93%

The schematic design of the proposed rig is presented in Figure 2. The first containment is provided by a stainless steel (SS 316) capsule which contains the fuel pebble embedded in graphite half cups. The second containment is provided by the stainless steel rig, contained inside an aluminum water box. The gas gaps in the rig and capsule structure can be filled with mixtures of helium and neon gas to control the fuel temperature. For the purpose of this study, these gas gaps are only filled with helium.

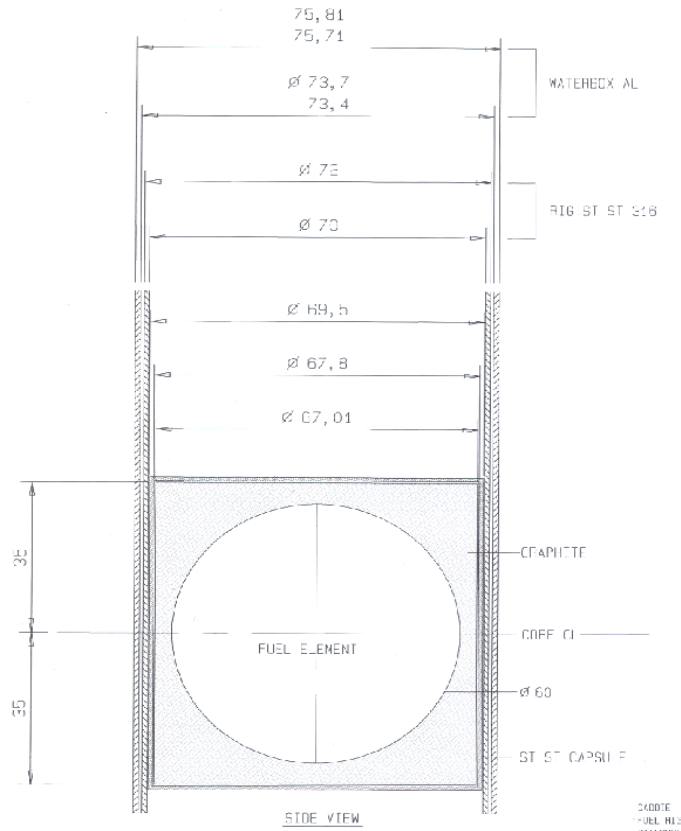


Figure 2: A Section through the Proposed Rig

The pebble, 6.0 cm in diameter, consists of two regions. The inner fuel region (2.5 cm radius) is composed of about 15 000 TRISO-type coated fuel particles embedded in a graphite matrix. The fuel region is surrounded by a fuel free graphite shell (3 cm radius) [2]. Figure 3 shows the schematics of the coated fuel particle with all the coating layers.

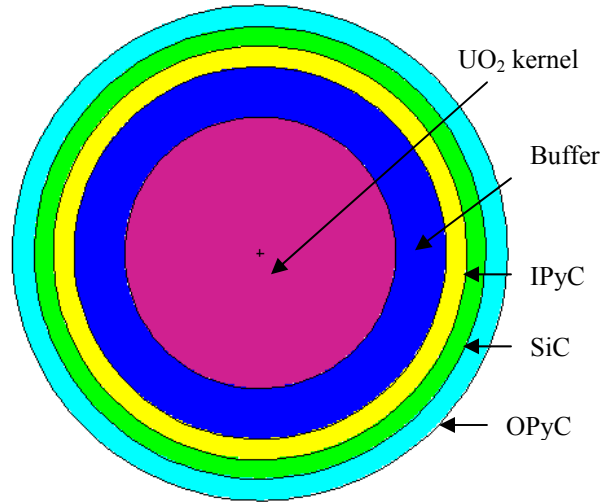


Figure 3: Schematic Design of a Coated Fuel Particle

The composition and the dimensions of the typical fuel pebble are given in Table 2 below.

Table 2: Dimensions and Material Properties of Typical PBMR Fuel

Property	Value	
Enrichment	9.8 weight percent ²³⁵ U	
Kernel material	UO ₂	
U mass per kernel	0.62 mg	
U mass per pebble	9 g	
Layer	Dimensions (μm)	Density (g/cm ³)
Kernel	500*	10.8
Buffer	93#	1.01
Inner Pyrolytic Carbon (IPyC)	38#	1.86
SiC	35#	3.19
Outer Pyrolytic Carbon (OPyC)	40#	1.89

* Diameter

Thickness

2. METHODOLOGY

Calculations were performed with Monte Carlo N-Particle (MCNP-5) code, version 1.4 using continuous energy ENDF/B-VI cross section data libraries at 300 K and the thermal $S(\alpha,\beta)$ data for water and graphite. MCNP5 is a three dimensional general purpose code with the capability to model very complex geometries accurately and to perform criticality and shielding calculations. The code can be used to simulate neutron, photon and electron transport, coupled and uncoupled [3]. All the calculations were performed for beginning of SAFARI-1 cycle (BoC) 0803-1.

2.1 Geometry Modeling

An MCNP5 model of the present reactor core was established to calculate the core configurations and to study optimization alternatives. The model describes the fuel assemblies by individual fuel plates and uses 17 axial positions along the height of the fuel. The six control rods and the molybdenum thimble tubes are also modeled explicitly together with the beryllium reflectors. The software code, OSCAR3-MCNP5 INTERface (OSMINT) [4], developed at Necsa is a link between the core depletion code OSCAR-3 and MCNP5 is used in this study to generate a core that is assumed to be correct in space and time.

The modeling of the pebble fuel poses a challenge due to the double heterogeneity of the fuel and the random distribution of CFPs in the fuel region of the pebble. The CFPs and the pebble were modeled using the specifications in Table 2. All the layers were modeled explicitly. The stochastic arrangement of CFPs in the fuel region was approximated, taking advantage of the lattice handling capability in MCNP5 [3], by placing the CFPs on a three dimensional hexahedral (triangular) lattice. The lattice constants (pitch, etc) were carefully determined to preserve the mass of uranium in the kernel and the whole pebble.

2.2 Reactivity

It is important from a safety point of view to have knowledge of the reactivity insertion (positive or negative) due to experiments done at any point in time in the reactor core. Reactivity is defined as:

$$\rho = \frac{k_{\text{eff}} - 1}{k_{\text{eff}}} \quad (\text{i})$$

In equation (i), k_{eff} is the core criticality value (multiplication factor) calculated in MCNP at the beginning of cycle (BoC) 0803-1. Two calculations were performed, one for a core with a rig in position B6 and second for a core without a rig in B6. The calculations were performed with 100 000 source histories per cycle, an estimate of k_{eff} of 1.0, skipping 15 cycles

before averaging k_{eff} and accumulating tallies and a total of 415 cycles (i.e. KCODE 100000 1.0 15 415).

The reactivity worth of the irradiation rig is therefore determined as

$$\Delta\rho = \rho(\text{core with a rig}) - \rho(\text{core without a rig}) \quad (\text{ii})$$

2.3 Flux

The neutron and photon flux were calculated with MCNP5 for a core with and without a rig. MCNP flux tallies are normalized to one source particle [3], in order to achieve flux tallies in the correct units ($\text{n/cm}^2\cdot\text{s}$), criticality calculations are normalized using the steady power level of the reactor (i.e. 20 MW in the SAFARI-1 reactor) using equation (iii) to give number of fissions/watt-sec:

$$\left(\frac{1 \text{ joule/sec}}{\text{watt}}\right) \left(\frac{1 \text{ MeV}}{1.602 \times 10^{-13} \text{ joules}}\right) \left(\frac{\text{fission}}{\text{Q MeV}}\right) = \# \left(\frac{\text{fissions}}{\text{watt-sec}}\right) \quad (\text{iii})$$

The core average Q-value is calculated with the F7 tally (the track length estimate of fission heating in a cell), and after normalization, it was divided by the core average fission rate.

$$\text{Neutron source strength} \left(\frac{\text{neutrons}}{\text{sec}}\right) = \# \left(\frac{\text{fissions}}{\text{watt-sec}}\right) \times P(\text{watt}) \times \bar{\nu} \left(\frac{\text{neutrons}}{\text{fission}}\right) \quad (\text{iv})$$

A flux mesh tally was used to calculate the axial neutron and photon fluxes in the core and the irradiation positions.

2.4 Power

The core power distributions were also calculated using the F4 mesh tally. It takes advantage of the feature of calculating power distributions in regions which are composed of more than one material. Instead of entering the material card in the tally multiplier (FM) card, a zero is entered and MCNP searches for the correct materials for that region of interest [3]. These calculations are done to determine the power perturbation introduced by the rig. Once the power distributions are known, they can be input into thermal hydraulic calculations to determine the temperature distribution.

3. RESULTS AND DISCUSSION

3.1 Reactivity

Criticality calculations were performed for BoC 0803-1 and it was found that the reactivity worth due to insertion of a rig containing just one fuel pebble is negligibly small. The

effect of the rig will be fully investigated when the number of fuel pebbles in the rig is increased.

3.2 Flux

3.2.1 Neutron Flux in the Core

The average neutron and photon flux energy dependent distribution in the SAFARI-1 core are presented in Figure 4 and Figure 5 respectively.

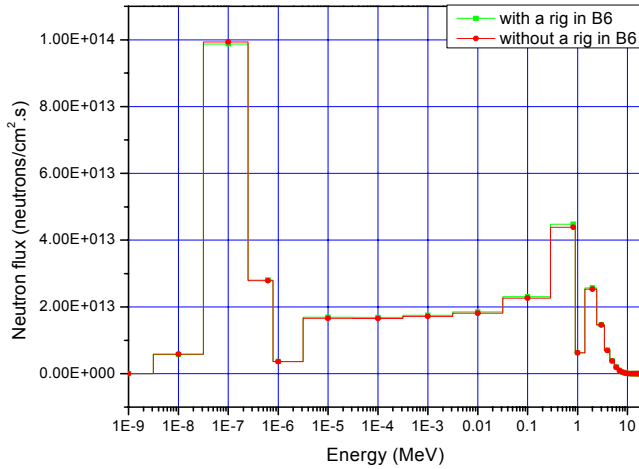


Figure 4: Neutron Flux in SAFARI-1 for the Core with and without the Rig in Position B6

An initial decrease of less than 1% in the neutron flux is observed in the thermal energy region. This is mainly due to absorption of thermal neutrons in the fuel region of the pebble during the fission process. A subsequent 2% increase in the neutron flux is observed in the epithermal energy range. The neutron flux in the fast energy range is increased by about 2% when this rig is inserted. This increase can be attributed to the contribution from the fast neutron emission of the fuel pebble and mainly due to the displacement of the water moderator by the rig. The amount of U-238 introduced by the insertion of this rig is insignificantly small to influence the thermalization process in the whole core, although this effect will be studied once the core is loaded with a rig containing more than one fuel pebble.

Figure 5 is representative of the core photon flux spectrum. It is observed from this graph that the insertion of the pebble irradiation rig in position B6 of the core shows no significant perturbation on the photon flux spectrum.

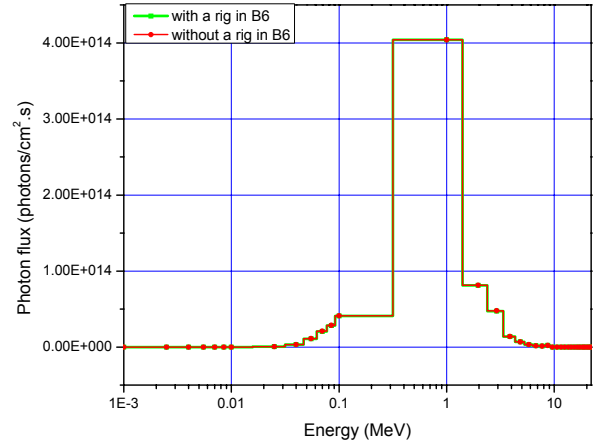


Figure 5: Photon Flux in SAFARI-1 for the Core with and without the Rig in position B6

3.2.2 Neutron Flux in the Irradiation Positions

The axial profile of the total neutron flux in the in-core irradiation position B6 is presented in Figure 6 for the two different core configurations: firstly position B6 is filled with water and secondly for position B6 loaded with the pebble irradiation rig.

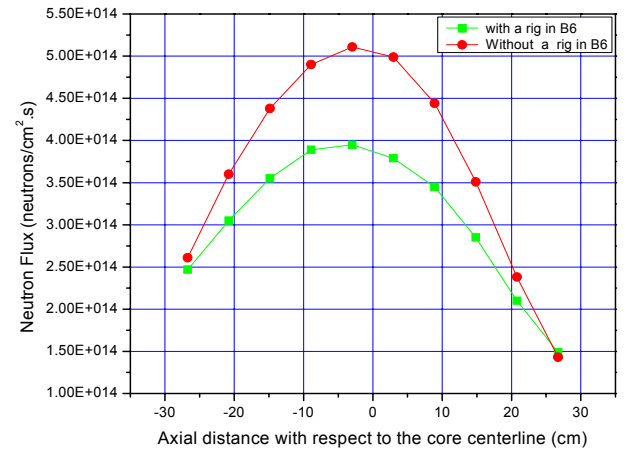


Figure 6: Total Axial Neutron Flux in the Core Position B6 filled with water (red) and loaded with a rig (green)

The loading of the pebble irradiation rig in position B6 of the core leads to a 20% depression in the axial neutron flux profile. This is mainly due to the replacement of the water moderator in position B6 with rig material. The other two in-core irradiation positions D6 and F6 only show less than 1% increase in the total axial neutron flux.

The axial profile of the total photon flux in the in-core irradiation position B6 is presented in Figure 7 for two different core configurations as studied for the neutron flux profile above.

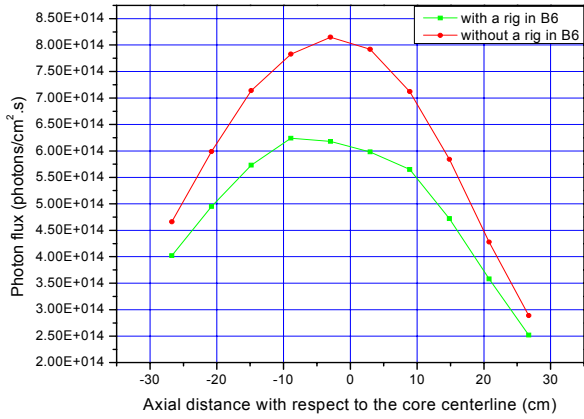


Figure 7: Total Axial Photon Flux in the Core Position B6 filled with water (red) and loaded with a rig (green)

The total axial photon flux profile in position B6 is reduced by up to 20% due to the loading of the rig and the absorption of the photons in the rig materials. This effect is more pronounced in the region straddling the core centerline ± 10 cm, where there is lots of helium gas and graphite. In position D6, there is a reduction of less than 1% in the photon flux in the region ± 10 cm about the core centerline and an increase of 1% in the other regions. Position F6 also shows an overall increase of less than 1% in the axial neutron flux.

The energy dependence of the flux in position B6 is presented in Figure 8 and Figure 9 for the neutron and photon flux respectively.

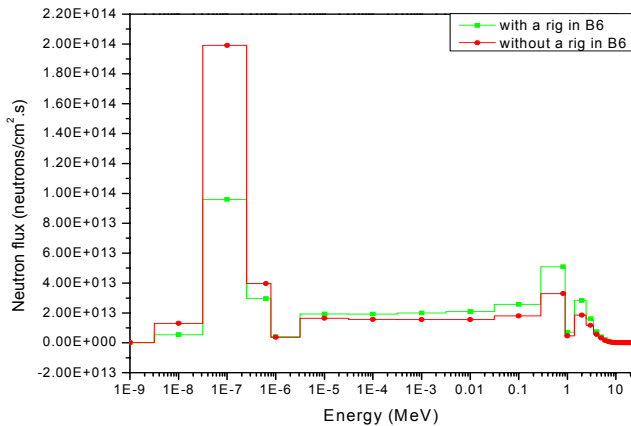


Figure 8: Energy Dependent Neutron Flux in the Irradiation Position B6 filled with Water (red) and loaded with a Rig (green)

In Figure 8, a 50% neutron flux depression in the thermal energy range is noticed due to the displacement of the water moderator in position B6 by the rig. Position B6 also shows close to 50% enhancement of the neutron flux in the fast energy range due to the emission of fast fission neutrons from the fuel region of the pebble and reduced moderating effects. The neutron fluxes in the other two in-core irradiation positions (D6 and F6) are slightly perturbed, with an overall increase of less than 1% in the energy dependent neutron flux.

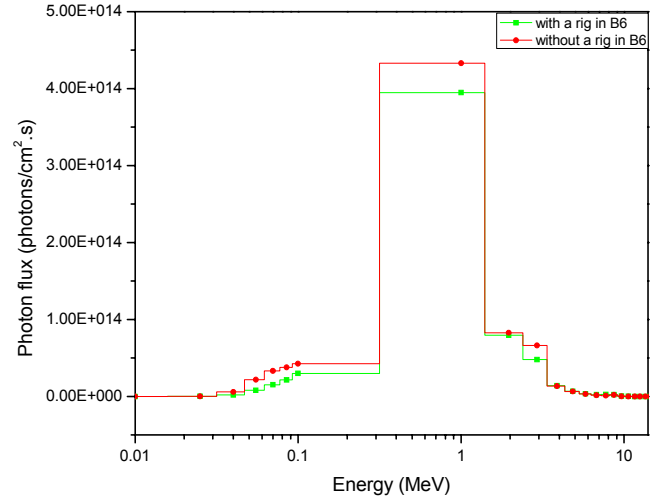


Figure 9: Energy Dependent Photon Flux in the Irradiation Position B6 filled with Water (red) and loaded with a Rig (green)

In Figure 9, the perturbation on the photon flux profile introduced by loading the rig in core position B6 is more pronounced in the energy range between 0.01 and 10 MeV. This can be attributed to the absorption of photons in the rig structures

3.3 Power Distributions

The power distribution in the core is studied to determine whether the insertion of the rig results in a shift in the position where power peaking occurs. The axial power distributions are presented in this study although this effect can be explained better with a core power distribution map.

3.3.1 Core Power Distribution

The total axial core power distribution is presented in Figure 10 for neutron heating. The axial neutron heating profile in the core is enhanced by up to 4% when the rig is loaded in position B6. The photon and fission axial heating profiles were also calculated and were found to differ by less than 1% with and without the rig in B6.

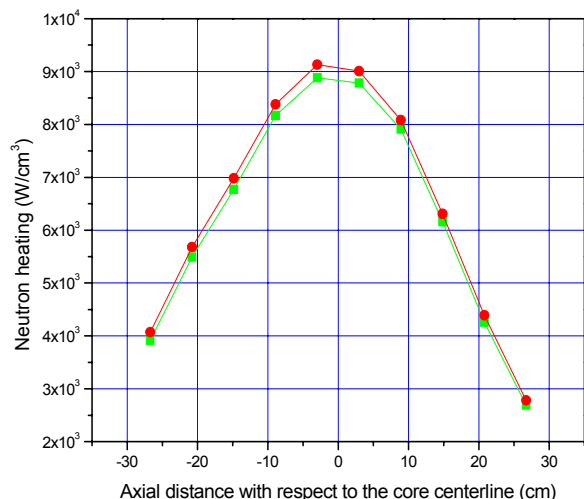


Figure 10: Axial Neutron Heating in the Core without a Rig in B6 (Green) and with a Rig in B6 (Red)

3.3.2 Power Distribution in the Irradiation Positions

The axial neutron heating in position B6 of the core is presented in Figure 11 for the two core configurations: firstly with position B6 filled with water and secondly loaded with a rig.

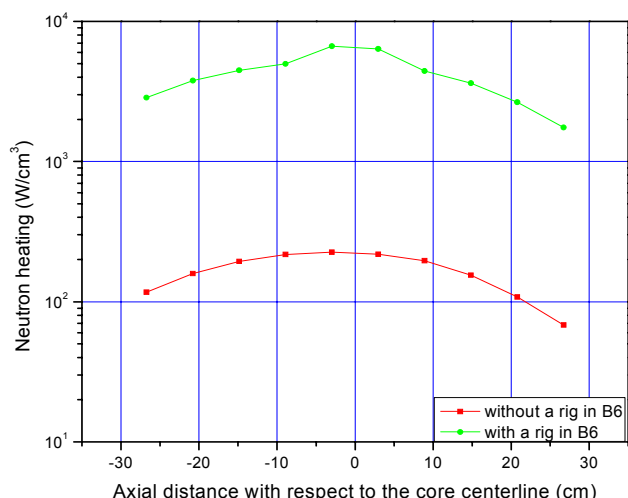


Figure 11: Axial Neutron Heating in the Irradiation Position B6 filled with Water (red) and loaded with a Rig (green)

The axial neutron power distribution is clearly enhanced in position of B6 of the core due to the introduction of the rig. Neutron heating values were found to increase by one order of magnitude in position B6 where the rig is loaded. This can be attributed to the introduction of materials in B6, the rig and the pebble, with high absorption cross sections for neutrons. Position D6 shows about 1% variation in the neutron heating

values in the region ± 15 cm about the core centerline and a 2% variation elsewhere. In position F6, a variation of less than 2% in the neutron heating values is observed. The neutron heating values are also enhanced in the regions where water in position B6 is replaced by helium as contained in the rig.

An MCNP study was performed in core position B6 to determine neutron heat deposition in a sphere filled with water in one case and filled with helium in the other case. The study has revealed that neutron heating in a helium sphere is small in the thermal energy range compared to neutron heating in water. In the fast energy region, a helium sphere in position B6 deposits more neutron heat compared to a sphere filled with water. It can therefore be concluded that the enhanced neutron heating values in position B6 with a rig loaded is due to neutron absorption in the resonances of helium.

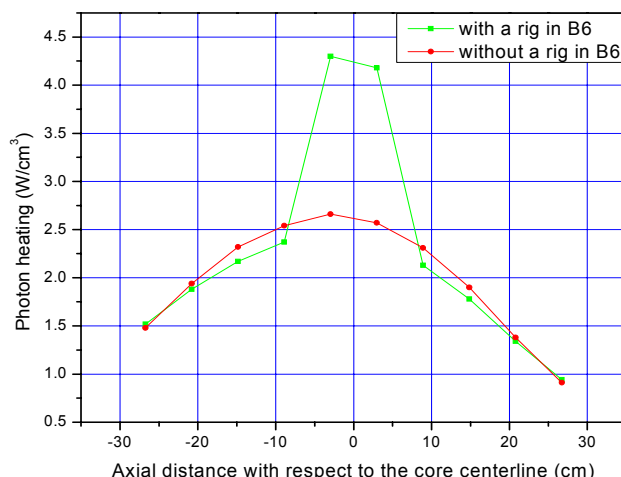


Figure 12: Axial Photon Heating in the Irradiation Position B6 filled with Water (red) and loaded with a Rig (green)

Figure 12 represent the total axial photon power distribution in positions B6. A 60% increase in the photon axial power distribution is observed and more pronounced in the region ± 3 cm about the core centerline, with perturbations of less than 10% elsewhere. The increase in the photon heating values in B6 around the core centerline is mainly due to the loading of the rig with materials that have high absorption cross sections for photons as well as photon production in the fuel region of the pebble following the fission process. The overall perturbation in the photon axial heating profiles is less than 1% in position D6 and F6.

The fuel pebble is expected to be irradiated at high temperatures. In order to achieve that, the pebble is placed in a graphite half-cups, surrounded by helium gas contained in a stainless steel rig.. The increased gamma heating in the region of the pebble as shown in Figure 12 makes it feasible that high temperature pebble irradiation environment can be achieved but

this can only be confirmed as final after a thermal hydraulic analysis.

3.3.3 Pebble Power Calculations

The neutron, photon and fission power in the fuel region of the pebble were also calculated at BoC 0803-1. These results are presented in Table 3.

Table 3: Results of Pebble Power Calculations

Pebble power (W)	
Fission	Photon
3803	119

The heat calculations in the pebble were performed using the F4 tally with a MODE n p card to account for neutron induced photon production. The following reaction cross sections (in units of barns) and reaction numbers were used: for neutron heating: 1 (for the total neutron cross section), 4 for the neutron heating number in MeV/collision; for photon heating: 5 for the total cross section and 6 for the photon heating number in MeV/collision and for fission heating: 6 for the fission cross section and 8 for the fission Q value in MeV/fission [3].

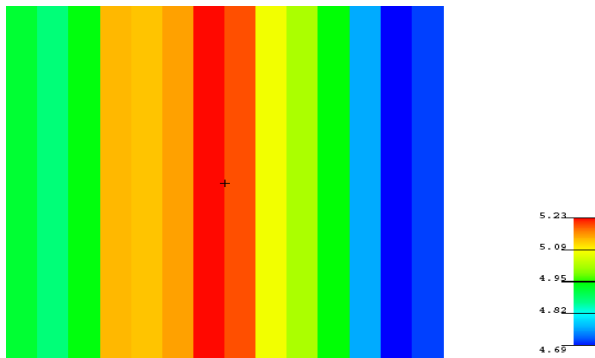


Figure 13: Axial photon heating (W/cm^3) in the graphite half cup section of the rig

Figure 13 is representative of the axial heating profile in the graphite section of the rig with results ranging from $4.69 \text{ W}/\text{cm}^3$ to $5.23 \text{ W}/\text{cm}^3$. The mesh region spans the entire position B6 in the x and y dimension and axially from -3.5 to 3.5 cm to include the entire graphite half-cup. The finer mesh also shows that the high temperature irradiation environment for the pebble can be achieved pending thermal hydraulic calculations.

4. CONCLUSIONS AND FUTURE WORK

The SAFARI-1 reactor has been characterized through calculations of the neutron and photon flux and power distributions in the whole core and in the different positions. The study has shown that the insertion of the pebble irradiation contributes a positive reactivity, which is negligibly small due to the amount of fissile material in the fuel pebble as well as the corresponding low enrichment. Perturbations were observed in the spatial flux and power distributions and they were more pronounced in position B6 of the core where this rig is loaded. It can only be concluded after a thermal hydraulic calculation has been performed, whether the 60% increase in photon heating values in position B6 of the core will ensure envisaged high temperature irradiation environment for the fuel pebble.

In future, the following aspects will be addressed:

- This model will be expanded to address a rig containing up to four fuel elements;
- The effect of insertion of this rig on the operational schedule and how isotope production is affected will also be quantified.
- Pebble power calculations will be performed at the middle and at the end of cycles.
- The use of high temperature cross sections in the pebble region.

5. REFERENCES

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