Assessment of Beryllium Depletion Modeling on SAFARI-1 Reactor Core Parameters in aid of OSCAR-4 Validation

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Abstract.

The build-up of ^{6}Li and ^{3}He, the strong thermal neutron absorbers or the so-called neutron "poisons", in beryllium reflector elements, due to fast neutron irradiation, is an important topic in beryllium-reflected reactors such as the SAFARI-1 research reactor. The presence of these isotopes influences the properties of beryllium, as well as the physical characteristics of the reactor. The methodology for simulating the build-up and depletion of these isotopes has been developed and applied using the OSCAR-3 neutronic code to investigate the effects on SAFARI-1 core parameters. This work uses OSCAR-4, the latest version of the OSCAR code system, to investigate the effects of these isotopes on SAFARI-1 core parameters, such as reactivity, neutron flux and power distribution. The code-simulated results are compared to experimental data, with the results of the study contributing towards the validation of the improved OSCAR-4 code system.

1. Introduction

Beryllium has a number of unique properties that make it ideal for nuclear applications, where it is used primarily for moderating and reflecting neutrons with energies above 0.7 MeV, via (n,2n) reactions in beryllium [1]. In this way, a neutron resulting from a fission reaction, which might otherwise leak out of a nuclear reactor core, may instead result in two neutrons with lower energies being sent back into the core, thereby increasing the probability of further fission reactions occurring [2].

In addition to (n,2n) reactions, neutrons with energies above 0.7 MeV also undergo (n,α) reactions in beryllium. These result in the production of ^{6}Li and ^{3}He isotopes within the beryllium material, leading to a phenomenon known as beryllium *depletion* or *poisoning* [1]. Both ^{6}Li and ^{3}He isotopes are strong absorbers of neutrons in the *thermal* range (neutrons with energies of 1 eV and below) [1], which are responsible for the vast majority of nuclear fissions that occur within a thermal nuclear reactor [2].

The buildup of ^{6}Li and ^{3}He isotopes has been shown to have a noticeable effect on reactor core parameters, with thermal microscopic absorption cross sections of around 950 barns and 5327 barns respectively [1]. Therefore, it is important to consider the possible effects that these isotopes could have when simulating the behaviour of a reactor.

2. Reflection and Depletion Reactions

The (n,2n) reaction in beryllium [3], which leads to neutron moderation and reflection, is

$$n + {}^{9}Be \rightarrow 2({}^{4}He) + 2n \ . \qquad (1)$$

The (n,α) reaction in beryllium, and the resulting reactions that lead to the formation of ^{6}Li and ^{3}He isotopes [3], are

$$n + {}^{9}Be \rightarrow {}^{6}He + {}^{4}He \qquad (2)$$

$$^{6}He \rightarrow {}^{6}Li + e^{-} + v_{e^{-}} \ (T_{\frac{1}{2}}^{6He} = 0.808 \text{ seconds}) \qquad (3)$$

$$n + {}^{6}Li \rightarrow {}^{3}H + {}^{4}He \qquad (4)$$

$$^{3}H \rightarrow {}^{3}He + e^{-} + v_{e^{-}} \ (T_{\frac{1}{2}}^{3H} = 12.33 \text{ years}) \qquad (5)$$

$$n + {}^{3}He \rightarrow {}^{3}H + p \ . \qquad (6)$$

Reactions 2 to 6 describe the processes that lead to the formation of ^{6}Li and ^{3}He isotopes, both of which have high propensities for capturing thermal neutrons [3]. Equations 5 and 6 describe a cyclical process that develops over time, with ^{3}H decaying into ^{3}He, which in turn is converted back into ^{3}H through neutron absorption. This set of reactions collectively causes neutron absorbers to burn away during reactor operation, and to build up again during shutdown periods [3].

The purpose of this work then, is to determine the impact that the modelling of beryllium depletion could have on the prediction of nuclear reactor parameters, and then specifically on the SAFARI-1 (South African Fundamental Atomic Reactor Installation 1) reactor at Necsa (described in Section 3.3). OSCAR-4 (Overall System for the Calculation of Reactors 4) is a neutronics code system utilized for the modelling of SAFARI-1 at Necsa, briefly discussed in Section 4.

Initial work in this regard [1], briefly described in Section 5, has indicated that the impact of modelling beryllium depletion could be significant, and of specific interest is the potential impact on the comparisons between detailed experimental measurements and calculated predictions. Such comparisons are performed at the beginning of every reactor cycle to confirm safety and utilization parameters and improvement of such predictions could prove valuable.

3. Beryllium Depletion: Case Studies

MARIA, BR2 and SAFARI-1 are three research reactors that utilise beryllium to a greater or lesser extent for neutron moderation and reflection purposes. Beryllium depletion has been an issue with these reactors, and each of them is briefly discussed in the following sections.

3.1. MARIA Reactor, Poland

The MARIA high-flux reactor, operated in Poland since 1975, consists of a beryllium matrix with fuel channels in cutouts of beryllium blocks. After an 8-year break in operation, a large negative reactivity in the order of 7% was observed within the reactor core, due to beryllium poisoning by ^{6}Li and ^{3}He isotopes. It was shown that the presence of ^{6}Li and ^{3}He resulted in modifications to flux, spectrum and power distribution, with the accumulation of these isotopes being strongly dependent on flux levels experienced by the beryllium elements in the reactor core. It was also estimated that during the period of 1975 - 1985, beryllium density reduction was 0.08% due to the desirable (n,2n) reaction shown in (1), and 0.03% due to the undesirable (n,α) reaction shown in (2) [3].

3.2. BR2 Reactor, Belgium

The Belgian Material Test Reactor (MTR) BR2 is a strongly heterogeneous high flux test reactor, which operates at a thermal power of 60 to 100 MW. BR2 reactor cycles are typically followed by long shut-down periods, which lead to poisoning of beryllium by ^{3}He. In 1978, the first beryllium matrix was replaced with a new one, and a second replacement was done in 1997. A study focusing on the effects of beryllium poisoning was done, using data from reactor core loads between April 1997 and December 2003, which highlighted the importance of accounting for beryllium poisoning for accurate reactivity predictions [4].

3.3. SAFARI-1 Reactor, South Africa

SAFARI-1 is a tank-in-pool MTR, which uses light water for cooling and moderation. Commissioned in 1965 for the purpose of testing nuclear materials, the reactor was originally fuelled with high-enriched uranium (HEU) fuel, with conversion to low-enriched uranium (LEU) fuel completed in 2009. It has a licensed operating power of 20 MW, and is now primarily used for the commercial production of ^{99}Mo, for use in the field of nuclear medicine [5].

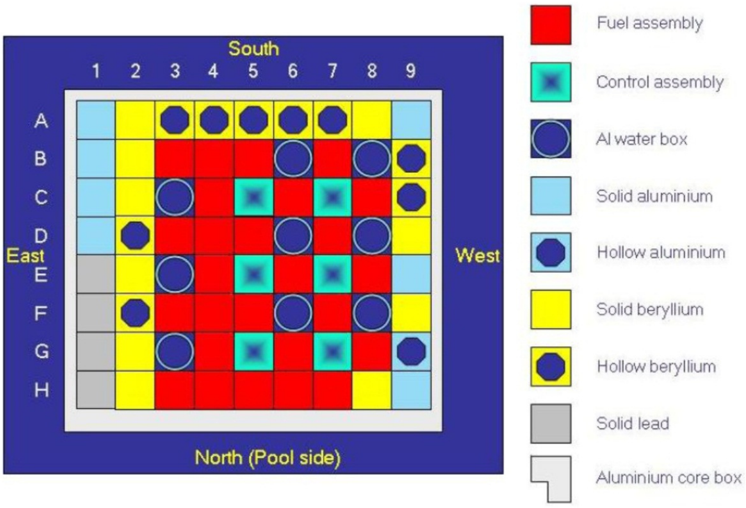


Figure 1. Schematic top view of the SAFARI-1 reactor core[5]

As shown in Figure 1, the SAFARI-1 reactor has an 8 x 9 core lattice, housing 26 fuel elements, 6 control rods, a number of solid lead shield elements, solid and hollow aluminium filler elements, as well as solid and hollow beryllium reflector elements [5].

4. The OSCAR Code System

The OSCAR code system was developed at Necsa, primarily to provide support for SAFARI-1. There are currently two versions of OSCAR which are being actively maintained and developed by Necsa personnel, namely OSCAR-3 and OSCAR-4 [6].

4.1. The OSCAR-3 Code System

OSCAR-3 is a core neutronics calculational system, based on modern nodal methods. It is the present production code system for the SAFARI-1 reactor, and is the primary tool for performing fuel management calculations. These include *Core Follow* and *Reload* calculations. Core Follow calculations keep track of the isotopic inventory or material composition in the reactor core by following the depletion history of each burnable material. Reload calculations ensure that all safety and utilisation parameters for the coming cycle are within acceptable ranges [6].

4.2. The OSCAR-4 Code System

OSCAR-4 has a number of major improvements over OSCAR-3, resulting from the need to incorporate a number of specialised models, methods and features, and this required a fundamental restructuring of the system. Once OSCAR-4 has been fully validated and licensed, it is likely to replace OSCAR-3 as the production code for SAFARI-1. This work is performed with OSCAR-4, in aid of its validation [6].

5. Beryllium Depletion Modelling at SAFARI-1

In a study completed at Necsa in 2011 [1], OSCAR-3 was used in combination with a number of other tools, to simulate beryllium depletion in the SAFARI-1 reactor over a period of 45 years. The impact of beryllium depletion was evaluated on some typical, integral reactor parameters. A key result of [1] was the generation of a set of number densities for ^{3}He and ^{6}Li, for each beryllium element.

In this work, we use the number densities from [1] to determine the impact of beryllium depletion on a multi-cycle set of 6 reactor cycles, looking specifically at reactivity measurements, 3D flux measurements and control rod calibration experiments, using OSCAR-4, with its improved models [5]. A subset of these results are presented in this work. This will help to confirm the depletion level of the SAFARI-1 beryllium reflectors, as predicted by [1], as well as aiding the validation of the OSCAR-4 code system for use as a production code. The work was performed in two stages, given below.

5.1. Four-Node Model

A 2D model was created in OSCAR-4, consisting of four individual blocks, or *nodes*. In the first case, pure nuclear-grade beryllium was assumed, with the model treated as a reference. In the second case, depleted beryllium was assumed, using typical number densities for ^{3}He and ^{6}Li [1]. This model was used to gain some initial insight into the possible effects that may result when simulating depleted beryllium. Due to space constraints, results of this part of the study are not included here.

5.2. SAFARI-1 Operating Cycle Studies

Six consecutive SAFARI-1 cycles (C1001-1 to C1006-1) were chosen and simulated using OSCAR-4. For the first run, pure beryllium was assumed throughout; this run was treated as a reference. For the second run, depleted beryllium was assumed throughout, using average number densities for ^{3}He and ^{6}Li, derived from results of [1].

Results of these two runs are shown in Figures 2 to 5.

6. Results and Discussion of Operating Cycle Results

Operating cycles of SAFARI-1, spanning the first six cycles of 2010, were selected as a representative multi-cycle set for the sake of this analysis. At the time of submission, all relevant safety and utilization parameters, as well as experiments had been modelled for pure beryllium (termed Old Model) and depleted beryllium (termed New Model). The comparison to measured data is still in progress. This section thus describes the relative effects of beryllium depletion products on OSCAR-4 models.

Figures 2 - 4 show a subset of results obtained during this analysis and depict the difference in the given parameters introduced by including the improved beryllium poison modelling in OSCAR-4. In particular, Figures 2 and 4 show, respectively, the impact on the predicted excess

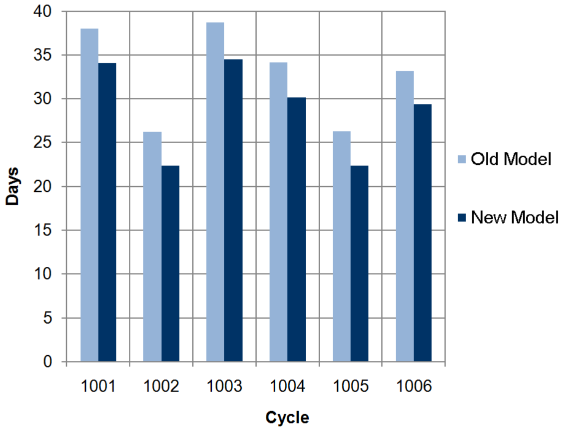


Figure 2. Cycle length.

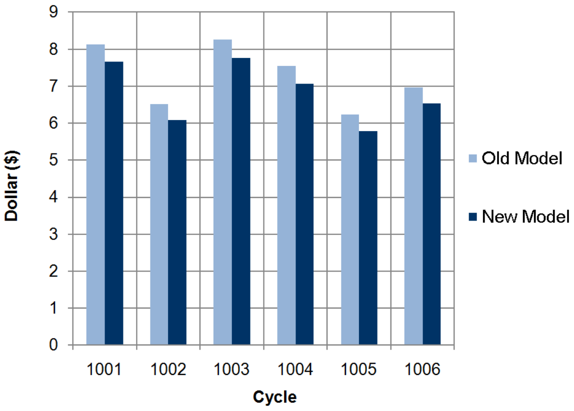


Figure 3. Excess reactivity.

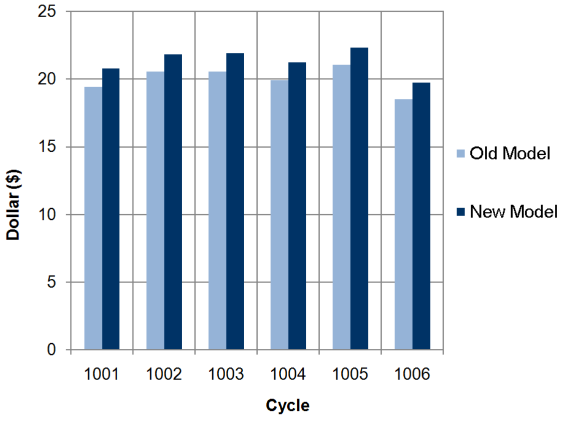
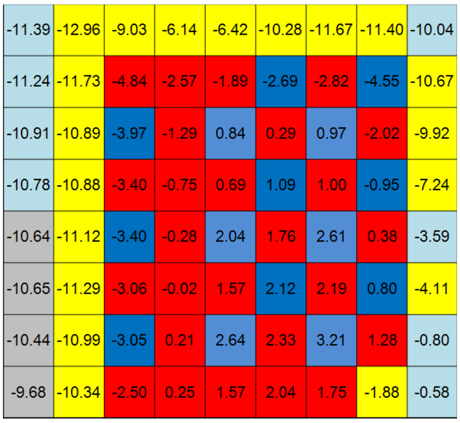


Figure 4. Shutdown margin.



-11.39	-12.96	-9.03	-6.14	-6.42	-10.28	-11.67	-11.40	-10.04
-11.24	-11.73	-4.84	-2.57	-1.89	-2.69	-2.82	-4.55	-10.67
-10.91	-10.89	-3.97	-1.29	0.84	0.29	0.97	-2.02	-9.92
-10.78	-10.88	-3.40	-0.75	0.69	1.09	1.00	-0.95	-7.24
-10.64	-11.12	-3.40	-0.28	2.04	1.76	2.61	0.38	-3.59
-10.65	-11.29	-3.06	-0.02	1.57	2.12	2.19	0.80	-4.11
-10.44	-10.99	-3.05	0.21	2.64	2.33	3.21	1.28	-0.80
-9.68	-10.34	-2.50	0.25	1.57	2.04	1.75	-1.88	-0.58

Figure 5. Flux tilt.

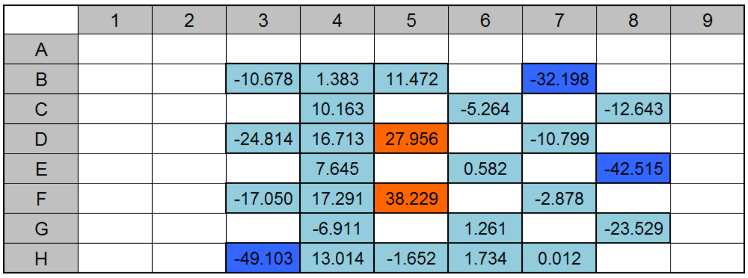
reactivity and the predicted shutdown margin, both at the beginning of cycle (BOC). Figure 5 shows, for cycle C1001-1, the tilt introduced in assembly averaged thermal flux by the new model.

From these graphs we conclude that the inclusion of beryllium poisons has a significant impact on these important utilization and safety parameters. It can be seen from Figure 2 that the old beryllium model implies a significant over estimation of the predicted cycle length. As such, the new model could potentially improve fuel economy, and thus cost, since the cycle planning calculations are used to determine the number of fresh fuel elements to load [5].

Figures 3 and 4 show a shift between the old and new models in the balance between the excess reactivity (amount of positive reactivity available at BOC) and the shutdown margin (the amount of negative reactivity available at BOC). This indicates that the old beryllium model has overestimated the core reactivity by about one dollar [2]. The shutdown margin is one of the primary safety parameters in reactor analysis [2], and correcting the estimation of this parameter by one dollar is definitely an important model improvement.

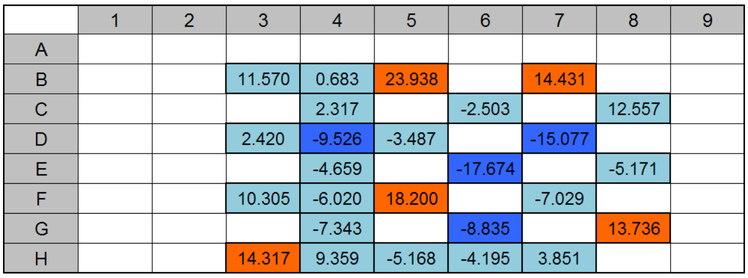
Figure 5 shows the impact of the beryllium depletion products on the flux tilt. Since the beryllium reflector elements are not symmetrically placed about the core [5], it is expected that such a tilt would exist and that it is largely responsible for the impact on the parameters in the previous figures. Figure 5 shows that the introduction of additional neutron poisons in the beryllium positions decreases the flux in areas adjacent to them, and hence lifts the flux elsewhere. The typical change in fuel elements is around 3-5%, with flux differences of up to 10% seen in beryllium elements themselves.

Low power flux measurements (LPFM) in all the fuel assemblies are performed prior to the reactor start-up of each cycle. The reactor becomes critical at very low power and a length of copper wire is inserted into each fuel assembly and control rod follower along its axial centreline and over the full height of the assembly. The axial activity profile of each wire is obtained on a dedicated counting device. The experimental data is then processed for comparison to the OSCAR-4 calculated results. Tables 1 and 2 show the differences between the calculated and the measured LPFM for both the old and the new model, for operating cycle C1001-1.



	1	2	3	4	5	6	7	8	9
A									
B			-10.678	1.383	11.472		-32.198		
C				10.163		-5.264		-12.643	
D			-24.814	16.713	27.956		-10.799		
E				7.645		0.582		-42.515	
F			-17.050	17.291	38.229		-2.878		
G				-6.911		1.261		-23.529	
H			-49.103	13.014	-1.652	1.734	0.012		

Table 1. Calculated and LPFM comparison for pure (old) Be (Measured - Calculated)



	1	2	3	4	5	6	7	8	9
A									
B			11.570	0.683	23.938		14.431		
C				2.317		-2.503		12.557	
D			2.420	-9.526	-3.487		-15.077		
E				-4.659		-17.674		-5.171	
F			10.305	-6.020	18.200		-7.029		
G				-7.343		-8.835		13.736	
H			14.317	9.359	-5.168	-4.195	3.851		

Table 2. Calculated and LPFM comparison for depleted (new) Be (Measured - Calculated)

In general the comparison of fuel elements adjacent to the beryllium reflector (Table 2) shows improvements. The flux tilt due to beryllium reflector poisoning, seen in Figure 5, tends to improve code-to-experimental data comparison. More extensive experimental comparisons will be included in the presentation.

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