Analyses of the spatial and spectral neutron distribution of various conceptual core designs with the aim of optimizing the SAFARI-1 research reactor

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Abstract. The SAFARI-1 research reactor at Pelindaba is a 45 year old 20 MW tank-in-pool type material testing reactor, and is expected to reach the end of its operating life between 2020 and 2030. The purpose of this study is to investigate various inhomogeneous neutron distributions within the core, arising from different core layouts of the SAFARI-1 reactor, which nonetheless still achieve efficiency in the operation for various design purposes, but with a lower power output. The spatial and energy neutron distribution is one of the most important parameters in the characterization of such an alternative core layout. This neutron distribution is a result of basic physics processes such as particle matter interactions, nuclear reactions, material properties, the effect of temperature and the time evolution of the system. A SAFARI-1 reference core, obtained through an equilibrium cycle calculation, is used to generate a set of safety and utilization targets against which alternative designs are measured. Alternative core layouts were developed by using a parametric study to determine the size and power level of potential candidate conceptual cores while adhering to the safety and utilization requirements. Results indicate that an alternative core with a power of 17 MW can achieve similar performance results as the current 20 MW SAFARI-1 design, by simply rearranging components in the core.

1. Introduction

The SAFARI-1 research reactor is at present (2014) the only research reactor in South Africa, utilized for both research and isotope production purposes. It utilizes a plate-type fuel element design, where the core is constructed from a lattice of fuel elements (and other components) sitting in a large pool of water. Control elements, reflector elements and irradiation channels further fill the lattice. The water serves as moderator and at the same time cools the reactor. Beam tubes are also present and stream leaking neutrons from the core to various instruments. The focus of this study is the steady-state neutron distribution within the highly heterogeneous and complex geometry of the SAFARI-1 reactor core described above. This information may be used to determine the neutron reaction rate with its surrounding material and thus estimate the depletion rate of the core fuel and modification to the core structure. For example, the total reaction rate, over some volume in the reactor and the whole energy range, for a given reaction type (k), in which a neutron-nuclear reaction occurs, can be defined in terms of the material cross section (σ), the material atomic density (N) and the neutron scalar flux (φ) as:

$$R_t = \int\int \varphi(\vec{\mathbf{r}}, N)N(\vec{\mathbf{r}})\sigma_t(\vec{\mathbf{r}}, E)d^3\vec{\mathbf{r}}dE. \tag{1}$$

In this work, these quantities (reaction rate, flux and material distribution) are resolved over a number of different potential core design concepts, in order to design an optimal core for the SAFARI-1 research reactor at Necsa. In this context, an optimal core is defined as the core geometry yielding a steady state spatial and spectral neutron flux distribution which satisfies all safety and utilization requirements throughout the operating cycle, but with a minimized power level.

2. Methodology

In this work, we proceed in three steps in order to obtain such an optimal core design. Firstly, we determine the metric for core evaluation in terms of a set of operating objectives and constraints. Secondly we determine the conceptual core characteristics for achieving the set objectives, and finally we extrapolate the conceptual core design to a detailed and realistic SAFARI-1 core layout.

2.1. Core evaluation metric

The metric for core evaluation is established by analyzing the set of defined SAFARI-1 operating objectives and investigating the sensitivity of these objectives to the reactor power level. These objectives and constraints, evaluated via numerical analyses with the OSCAR-4 code system, are defined as:

- power peaking factor: The power peaking factor is defined as the ratio of the maximum power density in a given localized region divided by the average power density in the reactor core [1]. In order to ensure that the fuel does not sustain damage, the local power density at the hottest part of the nuclear fuel should be estimated accurately.
- reactivity: The degree of change, in neutron multiplication in a nuclear reactor core, is evaluated by the reactivity in the core. The reactivity measures of interest consist of excess reactivity (additional reactivity at the beginning of cycle (BOC)), control bank worth (total absorbing capability of all the control rods), shut down margin (amount of negative reactivity available to counteract any initiating events).
- position dependent thermal flux: The thermal flux level, in a number of positions in the core, is critical to meet operating objectives. These include flux levels in general irradiation positions, in Mo-99 production positions and at the entry point of beam tubes (to support beam instruments for research purposes).
- fuel economy: The discharge mass, which is the amount of U-235 remaining in spent fuel elements, is a typical measure of fuel economy and should be minimized. It is of critical importance to operate the core in a way that minimize fuel usage, given the significant fuel cost. Generally, a reduction in power implies a reduction in fuel usage.

These set of performance and safety parameters, that are used to ensure the viability of any proposed core, are defined and expressed as a function of typical neutronic results available from the standard calculational tools used to model the SAFARI-1 reactor. Input from the reactor managers and clients are utilized to rank these objectives in terms of priority. In order to determine the set of reference values for these parameters, two approaches are followed.
Firstly, a set of existing SAFARI-1 operating cycles are analyzed in order to quantify the current SAFARI-1 performance. Although highly realistic, these set of reference values prove difficult to utilize for theoretical comparison, given the non-constant nature of the actual operating schedule

(due to unplanned outages or varying user requirements). Therefore, an idealized equilibrium core is also constructed, based on a typical, repeatable SAFARI-1 cycle and loading definition. It is, however, important that this equilibrium reference core performs within the range of actual operating performance parameters in order to use it as an acceptable reference for evaluating alternative proposed cores.

2.2. Conceptual core design

In the next phase, a parametric study is undertaken in order to determine the relationship between core size, core power level and core performance. Parameters that are investigated include minimum core size, minimum power level, the number of fuel elements and the minimum number of production facilities. In particular, we investigate the core size and power combinations which yield acceptable maximum power density and minimum isotope yield.

We employed the constraints of not enlarging the existing SAFARI-1 core, not changing the control rod positions and not adjusting the number of isotope irradiation positions in the core. The outcome of this phase of the study is the characterization of an allowable space spanned by the dimensions of core size and core power level.

2.3. Detailed core design

Once the boundaries of allowable core size and power are established, it remains to construct a realistic SAFARI-1 core layout which falls within these parameters. This process is based on existing core flexibility, SAFARI-1 loading constraints and established know-how in core design. It is reiterated that this is not a typical design process of a new reactor core, given that a number of limitations are placed by the existing SAFARI-1 plant and its capabilities and as such any benefit provided by a new core design has to be considered in conjunction with the nature and gravity of the changes required. In particular, changes which would require significant licensing adaptations might prove problematic.

3. Modelling Tools

Reactor calculation code systems, with associated automation procedures, are crucial in the prediction of these reactor safety and utilization parameters [2]. The OSCAR-4 code system, which is the dedicated code to model the SAFARI-1 reactor, is utilized as a modelling tool in this study. OSCAR-4 [3] solves for the neutron flux distribution within the reactor in a multi-step deterministic fashion. However, the neutron transport equation is solved in 2D on the scale of each reactor component in full heterogeneous detail in order to generate component averaged cross-sections and the neutron diffusion equation is then utilized (along with these averaged cross-sections) to calculate the flux distribution on the global 3D core level. The neutron transport and diffusion equations, which are solved in this two step process within the OSCAR-4 system, are given below. The neutron transport equation, solved for each core component, may be written as:

$$\frac{1}{v}\frac{\partial \phi}{\partial t} + \nabla \cdot \vec{J}(\vec{\mathbf{r}}, E, t) + \Sigma_t(\vec{\mathbf{r}}, E)\phi(\vec{\mathbf{r}}, E, t) = \int_0^\infty dE' \Sigma_s(E' \to E,)\phi(\vec{\mathbf{r}}, E', t) + S(\vec{\mathbf{r}}, E, t). \quad (2)$$

Where, $\Sigma_s(E' \to E)$ represents the macroscopic differential scattering cross section, $\Sigma_t(\vec{\mathbf{r}}, E)$ represents the total macroscopic cross section for all interactions, v is equal to the neutron speed and $S(\vec{\mathbf{r}}, E, t)$ represents the fission source and other source terms in Equation 2. ϕ is equal to the neutron flux, $\vec{J}$ is equal to the neutron current density and E is the neutron energy. The multi-group neutron diffusion equation is utilized to determine the 3D global core flux distribution. The numerical solution schemes surrounding these equations are implemented within the OSCAR-4 code system and additional discussions on these techniques may be found in [4].

4. Results and Discussion

In this section, we present results from each of the three steps in the methodology section above.

4.1. Definition of the reference core

As stated, both the actual SAFARI-1 operating cycles and an idealized equilibrium core model were utilized to determine the set of reference values for the safety and utilization objectives identified. Table 1 identified the set of objectives in column 1, lists the values of these objectives from an actual (and typical) SAFARI-1 operating cycle in column 2 and provides the corresponding values from the idealized equilibrium reference core in column 3. An equilibrium core is obtained when a particular fuel loading pattern is applied to a series of cycle calculations until core parameters, such as core reactivity, U-235 distribution and flux distribution converge from cycle-to-cycle. The loading pattern employed in this case is that the fuel with the highest mass is placed in a core position with a lower flux, in order to limit excessive power peaking in high power fuel assemblies. The convergence parameter used to determine when the equilibrium is reached is the end-of-cycle (EOC) k-eff. EOC k-eff values converge at the 30th cycle in the multi-cycle set and the equilibrium oscillates between an even cycle and odd cycle. This two-step equilibrium appears due to the loading of fresh control elements as one fresh control element is loaded only every second cycle. This is done to follow the typical approach employed at SAFARI-1.

Calculated results presented in Table 1 show that all the reference core safety and utilization parameters reasonably match those of the actual SAFARI-1 reactor operating cycle. With these results it can be concluded that this equilibrium core model is suitable for use as a reference core against which alternative core designs can be measured. This reference core was constructed by loading 3 fresh elements in a given cycle, and then loading 3 fresh fuels and one fresh control element in the following cycle. Considering ten operating cycles per year, this implies the usage of 30 fuel elements and 5 control elements per year.

4.2. Conceptual parametric study

Figure 1 demonstrates the results of the parametric study conducted to determine the acceptable range of core sizes and power levels. In order to evaluate the various cases, the reference SAFARI-1 core model was utilized as a basis (represents the intersection point of 20 MW with a core size of 29 fuel elements - 26 standard fuel and six followers counted as a half element each). This core model was then adapted in both power level and core size to evaluate all other combinations of these parameters. For a decreasing core size, fuel elements were systematically removed and replaced with water filler elements. For each core concept obtained, the values of power peaking and Mo-99 production were determined.

The Mo-99 yield and the power peaking factor values obtained from the neutronic evaluation of the proposed core concepts are listed in Tables 2 and 3. Based on results of all such core evaluations, an overlapping area bounded by the upper power level constraints of maximum power density and lower power level constraints of minimum isotope production was developed and is demarcated by area BCDG. We thus expect that any core within this demarcated area would yield, for the selected combination of power level and core size, a viable alternative to the current SAFARI-1 arrangement of 29 fuel elements at 20 MW.

The upper boundary of the allowable area is limited by line AC, which results from the maximum power density limitation. This line was obtained based on the current acceptable maximum power density in the SAFARI-1 core, utilizing the current cooling capacity. Line CD occurs due to the intention of reducing the current SAFARI-1 power and thus limiting the target power level to below 20 MW. Similarly, line DG occurs since the intention is to reduce the current SAFARI-1 core size. Line BG indicates the lower limit which retains an acceptable level of isotope production.

Table 1. Summary results of safety and utilization parameters

Parameters	SAFARI-1	Reference core	17 MW core	Limit
Calculated cycle length (days)	36.69	44.92	36.84	$>$ 29.96
Max Mo-99 yield	0.02 Ci	9.01 Ci	5.78	
Excess reactivity ($)	7.97	10.06	8.23	
Control bank worth ($)	29.49	32.22	37.72	$>$ 20.00
Shut-down margin ($)	18.89	20.43	27.96	
Min individual RW ($)	2.92	2.52	4.00	$>$ 2.00
Power peaking factor	3.32	3.41	2.27	$<$ 3.50
Peak power density (W/cm^3)	565.24	589.16	451.37	
Assembly with peak power ensity	B5	B5	C7	
BOC bank position (cm)	51.45	46.50	49.68	
EOC bank position (cm)	66.37	62.08	68.16	
Target plate worth ($)	2.62	1.73	1.52	
BOC bank with target plate (cm)	46.05	42.88	47.88	$>$ 39.53
BOC equilibrium Xe bank (cm)	56.72	52.76	56.30	
Number of rigs in the core	7	7	7	
Silicon facility 1 fluxes $(n/cm^2/\mathrm{s})$	2.66	1.78	3.54	
Core box fast flux $(n/cm^2/\mathrm{s})$	1.69	0.97	2.40	
Max IPR1 flux $(n/cm^2/\mathrm{s})$	9.00	9.00	9.00	
Max IPR2 flux $(n/cm^2/\mathrm{s})$	7.86	7.17	8.83	
Beam tube 5 flux $(n/cm^2/\mathrm{s})$	1.82	1.86	1.92	
Beam tube 2 flux $(n/cm^2/\mathrm{s})$	$6.30\mathrm{E}10^{-15}$	$5.78\mathrm{E}10^{-15}$	$6.43\mathrm{E}10^{-15}$	
Beam tube 1 flux $(n/cm^2/\mathrm{s})$	0.33	0.35	1.26	
Number of fuel	26	26	22	
Control rods	6	6	6	
Power level	20.00 MW	20.00 MW	17.00 MW	

Table 2. The power peaking factor in the reference core and the proposed core concepts

Core	power peaking factor
Reference core	3.41
17 MW core	2.72
16 MW core	3.20
15 MW core	3.18

Table 3. The molybdenum-99 yield in the reference core and the proposed core concepts

Position	17MW core % change in Mo-99 yield	16MW core % change in Mo-99 yield	15MW core % change in Mo-99 yield
Total Mo-99 yield	1.81	-7.85	-14.26
Max. Mo-99 yield	-2.86	-6.03	-11.91

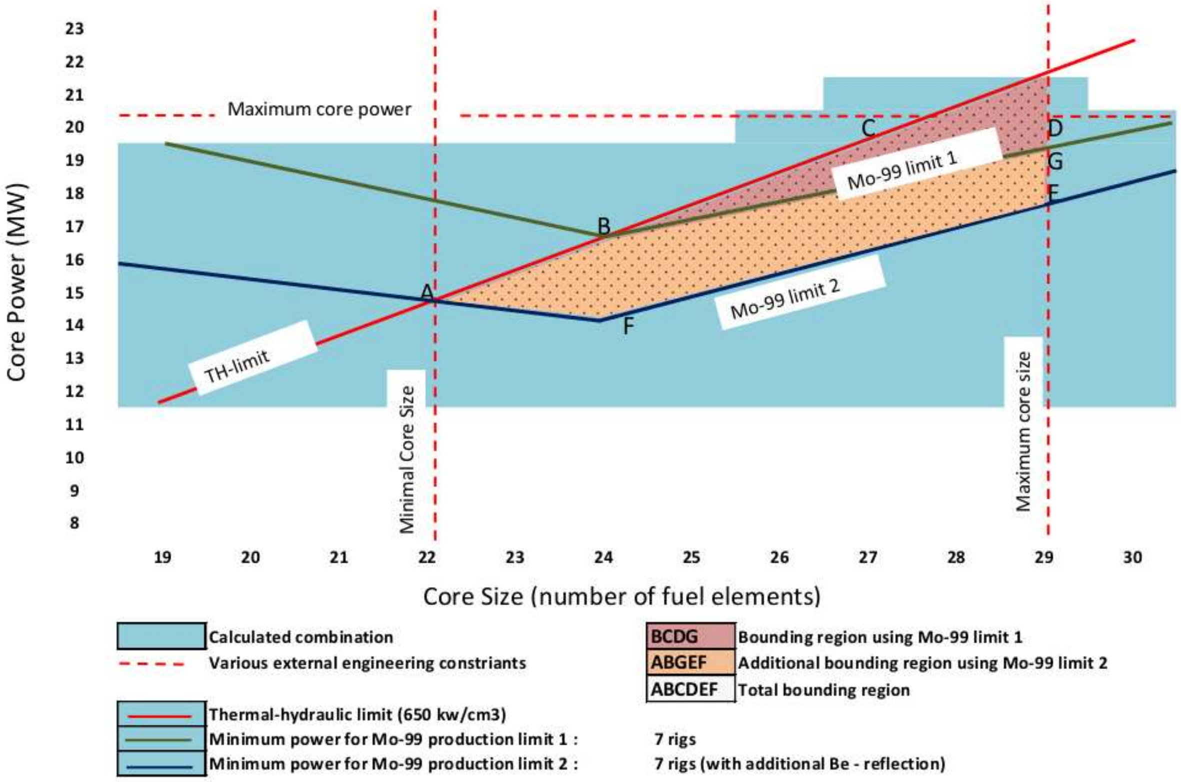

Figure 1. Result of Parametric study

Note further that a second, less restrictive, lower power limit in isotope production is possible if all excore positions are filled with Beryllium reflector elements. This limit, referred to in the graph as "+Reflection" allows even lower power cores to be potentially viable and enlarges the legal area to the space indicated by ABCDEF. This occurs because the additional Beryllium elements reduce leakage in the core and as such provides reactivity. This enlargement of the space does not require any significant core changes other than the cost of a number of additional Beryllium elements and is quite attractive.

To illustrate how this graph can be utilized, we now choose the intersection point of 17MW with 25 fuel elements as our first proposed core and consider it in the next section. As can be seen from the allowable area in the graph, 17 MW is quite a conservative choice and it might be possible to operate a 25 element core at around 15 MW. Nevertheless, as a first application of this study, we investigate the 17 MW core as a viable option with some margin.

4.3. Evaluation of proposed detailed core

From the result of the parametric study (Figure 1) a potential realistic core which can operate at 17 MW with 25 fuel assembly is selected and evaluated from the neutronic perspective. The layout of the SAFARI-1 core and the proposed core may be seen in Figure 2. It represents a 15 percent power reduction as compared to the current SAFARI-1 reactor operating power (20 MW). All parameters for this core are calculated and compared to the set limits and targets and is used to complete column 4 of Table 1. Note from the core layout that we have utilized the option of flooding the ex-core regions with beryllium elements in order to introduce some additional reactivity. Removed fuel elements, which facilitated the reduction of the number of

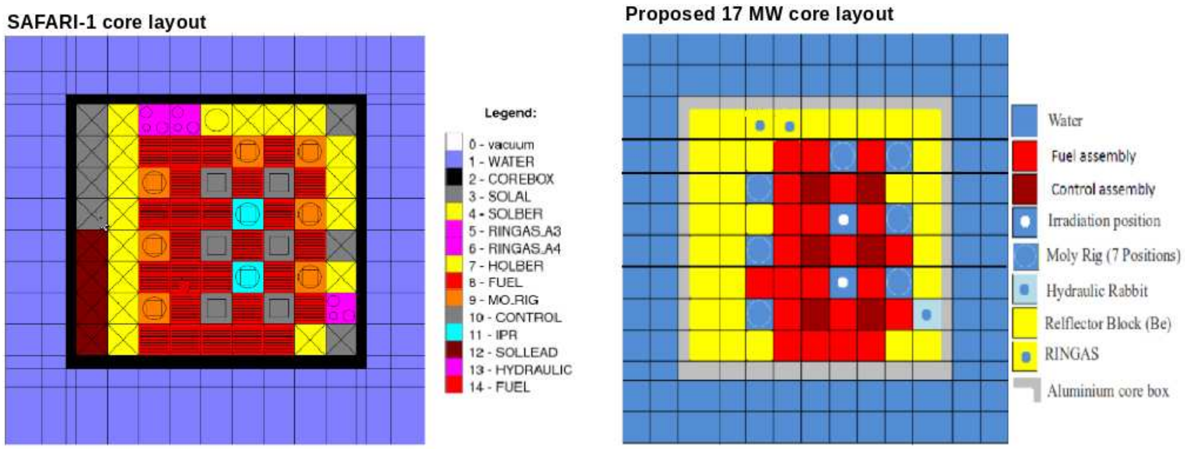

Figure 2. The Proposed 17 MW core layouts

fuel from 29 to 25, have also been filled with beryllium elements.

From the evaluation of this 17 MW core it can be seen that the reactivity, power density and production requirements all meet expectation, as is suggested by the preceding parametric study. It may be concluded that it is indeed possible to operate the SAFARI-1 reactor at a reduced power level, whilst maintaining the capabilities of the current core. Such a power decrease would save in fuel cost and potentially provide some life extension to the reactor.

5. Conclusion

The result present in Table 1 shown that an alternative core with a power of 17 MW can achieve similar performance as the current 20MW SAFARI-1 design, by simply rearranging components in the core. Additional power reduction may only be possible if more significant core design changes are allowed, but studies concerning such core concepts are still underway.

6. References

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