Analysis of the spatial and spectral neutron distributions of various conceptual core designs with the aim of optimising the SAFARI-1 research reactor

By

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Outline:

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2. Objective
3. Methodology
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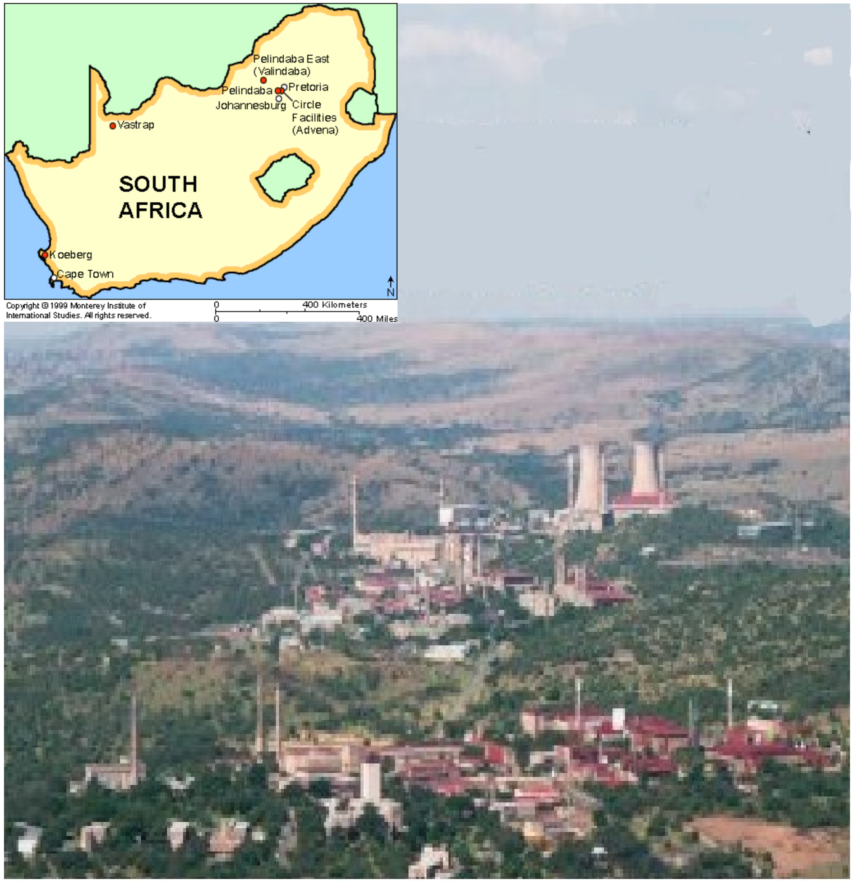
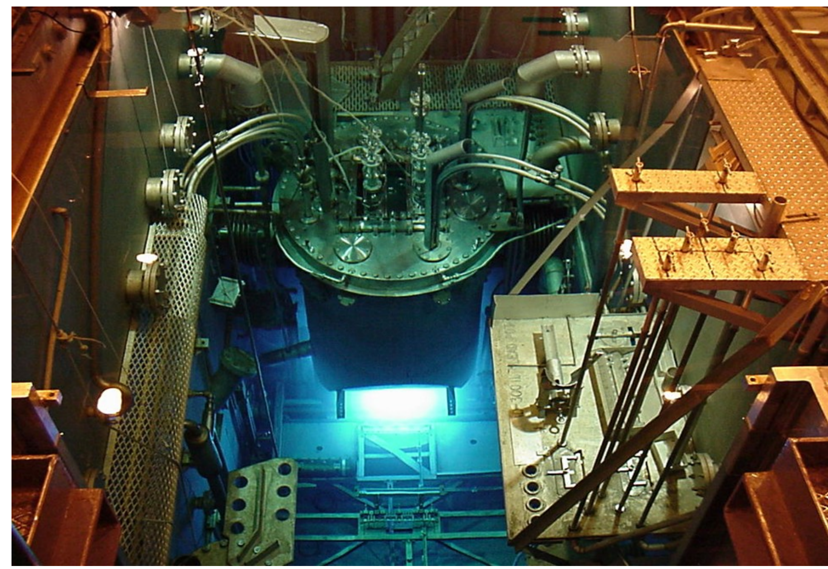
Introduction:

A view of the SAFARI- 1 reactor building

NECSA site





SAFARI- 1 reactor Core

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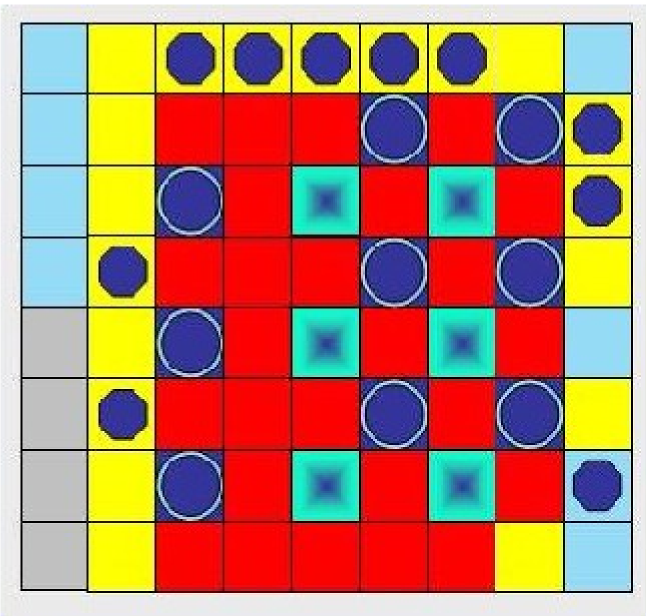
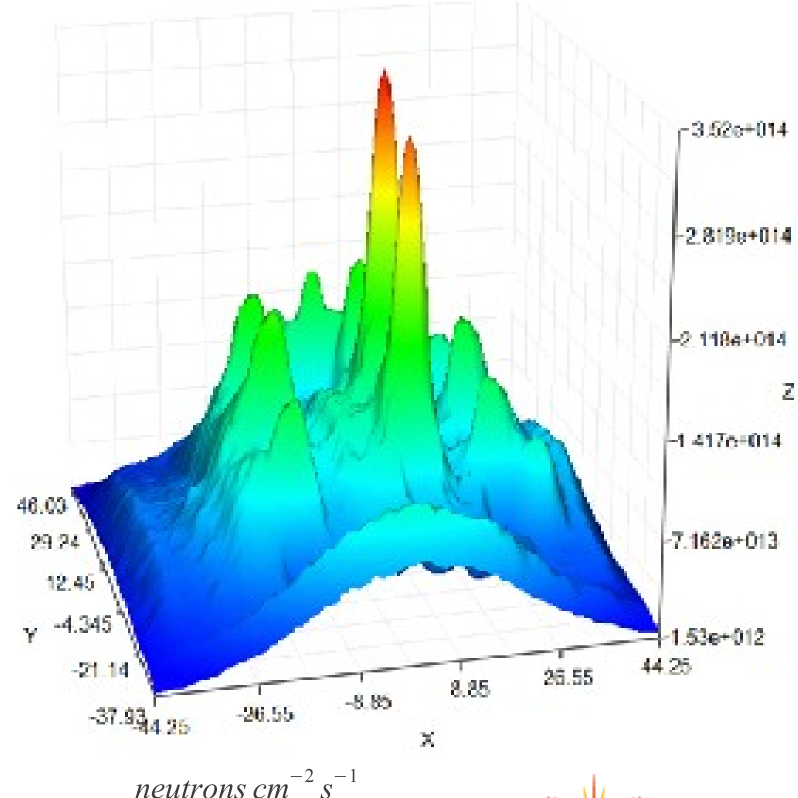
Introduction:

Schematic layout of SAFARI-1 Reactor core



Typical neutron flux in SAFARI-1 the reactor core

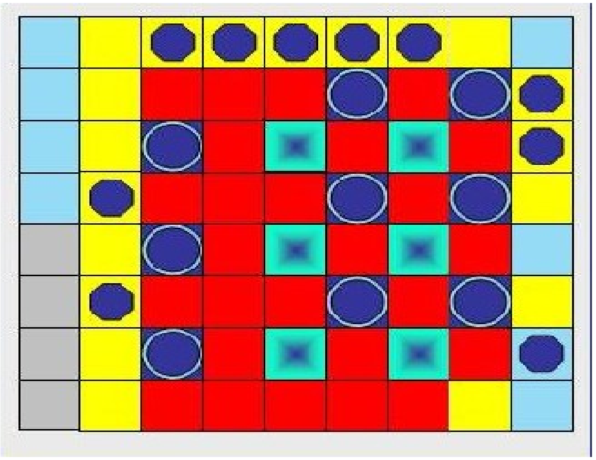


Introduction:

- SAFARI-1 is currently the only nuclear research reactor in South Africa, and it is approaching its end of life.
- SAFARI-1 is used for research and isotope production purposes.
- There is a need to investigate the possibility of extending SAFARI-1 operating lifetime for as long as it is economical and safe.
- A possible way of extending the operating lifetime of SAFARI-1 is to reduce its operating power.
- This is achieved by reducing the average neutron distribution and reshaping the neutron distribution.
- Hence various alternative SAFARI-1 core design are proposed and their neutronic properties are evaluated.
- As mentioned before, the safety must be maintained and also the utilization must not be compromised.

Objective:

This work aims to propose and evaluate various core geometry configurations in order to find an acceptable optimal core layout operating at a reduced power.



Study

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Proposed Core:

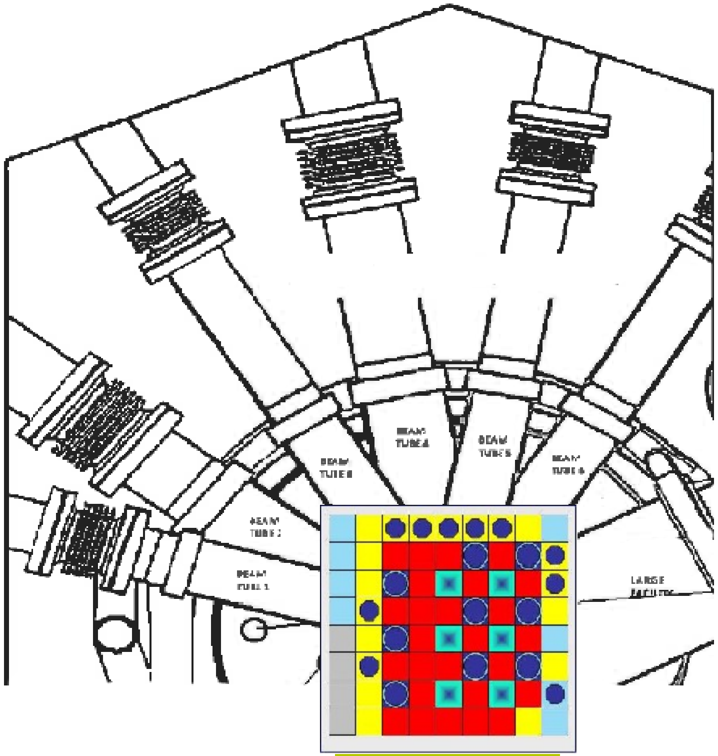
1. Determine the metric for core evaluation
2. Core Size (how many fuel assemblies)
3. Core power
4. Core arrangement

Methodology: Core evaluation metric

- The following set of SAFARI-1 performance and safety objectives are defined and quantified via numerical analysis with the OSCAR-4 code system.

1. Core reactivity $\rho = \frac{k-1}{k}$ (2 Objectives)
2. Fluxes φ = n v ($neutrons\ cm^{-2} s^{-1}$) (13 Objectives)
3. Power peaking factors. (1 objective)
4. Fuel economy

- These objectives are a function of the neutron distribution within the reactor core.



Silicon facility

Methodology: Core evaluation metric

- Existing SAFARI-1 operating cycles are analysed in order to quantify the current SAFARI-1 performance. Although highly realistic, this set of reference values proves difficult to utilize for theoretical comparison, given the non-constant nature of the actual operating schedule.

- An idealised equilibrium core model is developed, based on a typical, repeatable SAFARI-1 cycle and loading definition.

- This equilibrium core performance and safety objectives values must match those of actual operating performance parameters in order to use it as an acceptable reference for evaluating alternative core.

Comparison of SAFARI-1 and equilibrium model

Parameters	SAFARI-1	Reference core
Maximum achievable cycle length(days)	44.92	42.35
Maximum Mo-99 yield	699.30 Ci	632.70 Ci
Total Mo-99 yield	3873.90 Ci	3751.80 Ci
Excess reactivity	10.06	10.09
Control bank worth	32.22	30.67
Shut-down margin	19.3	18.90
Minimum individual rod worth	2.52	3.40
Relative power peak	3.41	2.85
Peak power density (W/cm^3)	589.16	489.54
Assembly with peak power density	B5	B7
BOC bank position (cm)	46.50	48.38
EOC bank position (cm)	62.08	63.26
Target plate worth (dollar)	1.73	1.68
Target plate Peak power (kW)	17.22	16.68
BOC bank with target plate (cm)	42.88	44.76
BOC equilibrium Xe bank (cm)	52.76	53.53
Number of rigs in core	7	7
Number of fuel	26	26
Control rod	6	6
Power level	20.00 MW	20.00 MW

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Methodology: Parametric study

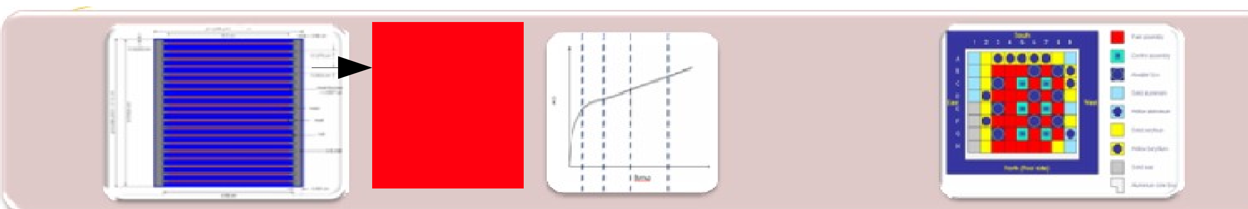
- A parametric study is performed to investigate parameters such as:
  1. Minimum core size
  2. Minimum power level
  3. Number of fuel elements and
  4. Required number of production facilities.

- Given a core size and power level we propose a realistic core arrangement.

Modelling Tools:

- The OSCAR-4 code system, which is the dedicated code to model SAFARI-1 reactor, is utilized as a modelling tool in this study.

- OSCAR-4 solves for the neutron flux distribution within the reactor in a multi-step deterministic fashion. It uses the integral transport equation for assembly calculation and the nodal diffusion method for full core calculation.



CROGEN	CROLIN	CORANA
<u>HEADE</u>	<u>POLX</u>	<u>MGRAC</u>
Collision probability based	Second order fitting for point data per state parameter	Static Nodal diffusion methods for global core calculations
Production of few group homogenized cross-sections	Burnup, Fuel temp, Moderator temp	Multi-Group Analytic Nodal Method

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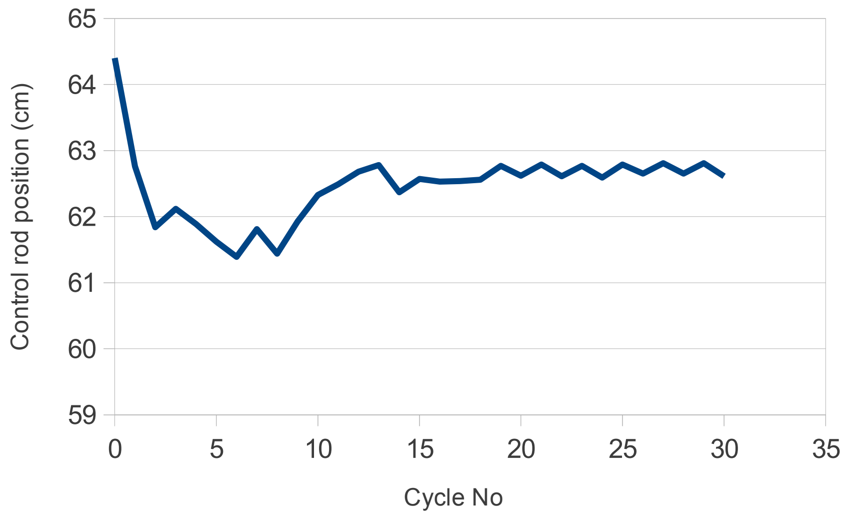
Results: Obtaining an equilibrium core

- Equilibrium utilizes the
  3 fresh, 0 control
  3 fresh, 1 control loading pattern.

- This implies 30 fuel elements per year and 5 control elements.

Results of the parameter used to determined when the equilibrium is reached.



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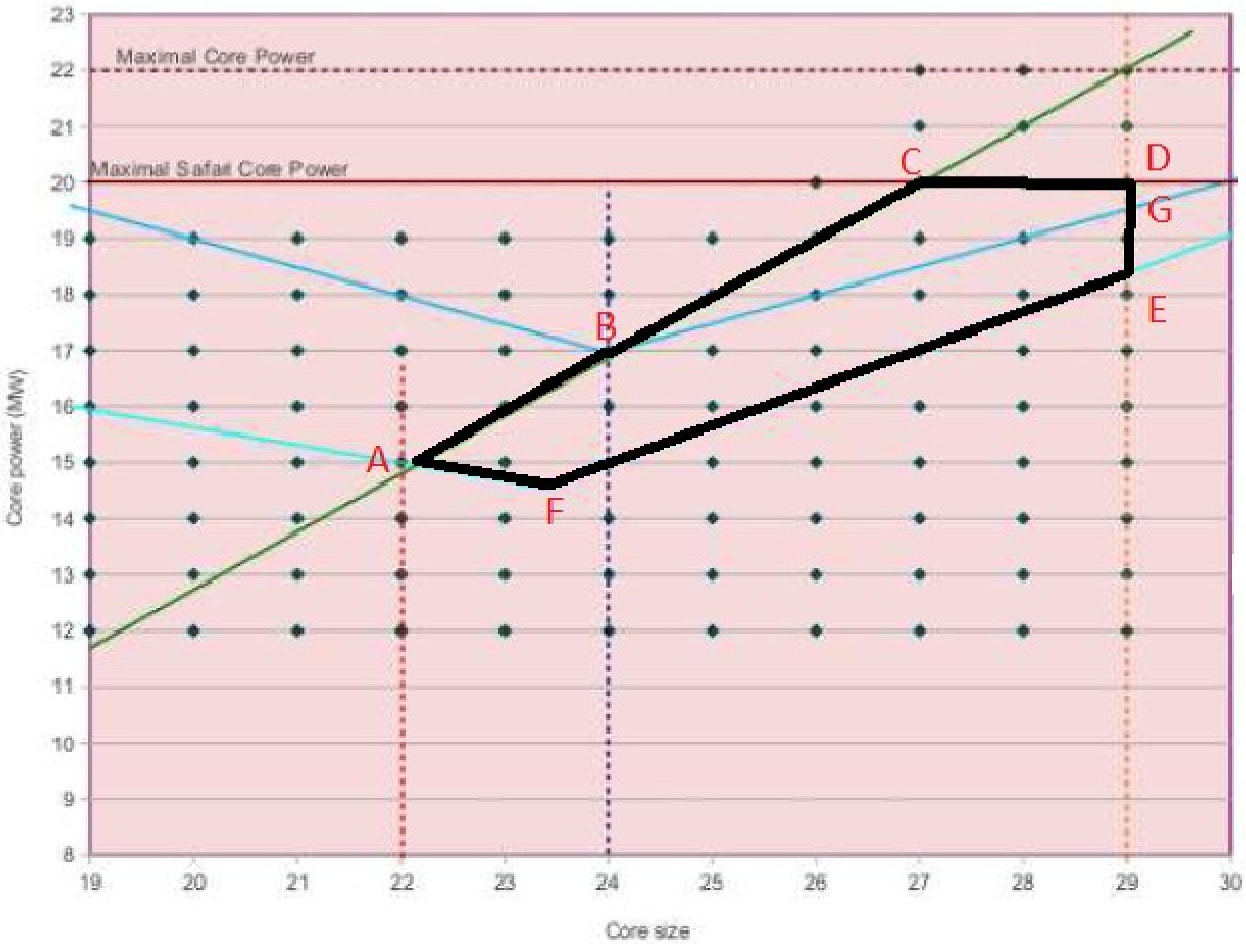
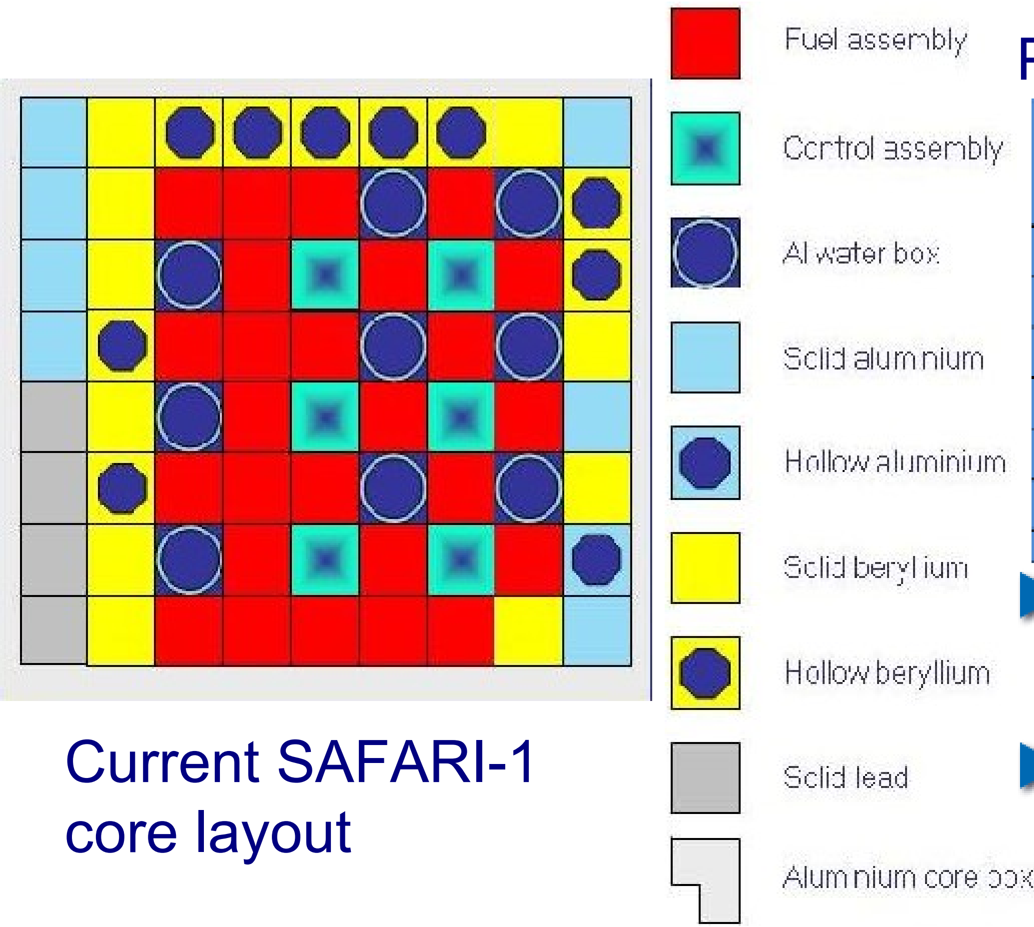
Results: Results of the Parametric study



KEY

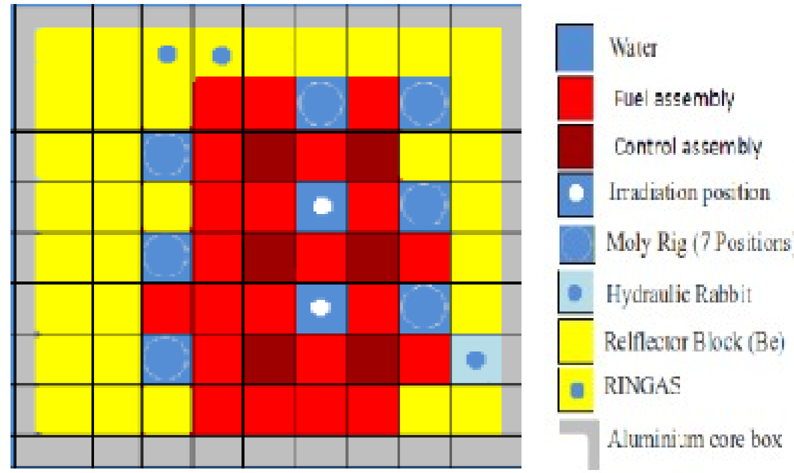
- Minimal power for 3463.20Ci with seven moly positions **(BG)**
- Minimal power for 3463.20Ci with seven moly position + Reflection **(AFE)**
- Thermal-Hydraulic Limit **(AC)**
- Minimal core size
- Minimal core size at minimal power for 3463.20Ci with seven moly positions
- Maximal core size

Results:



Current SAFARI-1 core layout

Proposed 17 MW core layout



- Proposed 17 MW core utilizes the 3 fresh, 0 control 2 fresh, 1 control loading pattern.
- This implies 25 fuel elements per year and 5 control elements, saving 5 fuel elements.

Results: Summary results of safety and utilization parameters

Parameters	SAFARI-1	Reference core	proposed concept	Limit
Calculated cycle length (days)	44.92	42.35	36.84	$>$ 29.96
Maximum Mo-99 yield	699.30 Ci	632.70 Ci	679.32	>650.00 Ci
Total Mo-99 yield	3873.90 Ci	3751.80 Ci	3943.83	
Excess reactivity	10.06	10.09	8.23	
Control bank worth	32.22	30.67	37.72	$>$ 20.00
Shut-down margin	19.3	18.90	27.96	$>$ 16.11
Minimum individual rod worth	2.52	3.40	4.00	$>$ 2.00
Relative power peak	3.41	2.85	2.72	$<$ 3.50
Peak power density (W/cm^3)	589.16	489.54	451.37	
Assembly with peak power density	B5	B7	C7	
BOC bank position (cm)	46.50	48.38	49.68	
EOC bank position (cm)	62.08	63.26	68.16	
Target plate worth (dollar)	1.73	1.68	1.52	
Target plate Peak power (kW)	17.22	16.68	18.29	$<$ 26.50
BOC bank with target plate (cm)	42.88	44.76	47.88	$>$ 39.53
BOC equilibrium Xe bank (cm)	52.76	53.53	56.30	
Number of rigs in core	7	7	7	
Number of fuel	26	26	22	
Control rod	6	6	6	
Power level	20.00 MW	20.00 MW	17.00 MW	

Conclusion:

- The results show 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.
- This design saves 5 fuel elements per year

- Additional power reduction may only be possible if more significant core design changes are allowed, but studies concerning such core concepts are still underway.

- Some lost flexibility is noticeable due to decrease in cycle length.

References:

- Man Gyun Na, Dong Won Jung, Sun Ho Shin, Kibog Lee and Yoon Joon Lee October 2004 *Estimation of the Nuclear Power Peaking Factor Using In-core Sensor Signals* vol 36 Number 5 (Korean: Nuclear Society) pp 420–429
- Wagner F. S. 1982 G*lobal optimization method applied to the nuclear reactor core design* (Anderson Alvarenga de Moura Meneses Claudio do Nascimento Abreu Pereira) pp 441–456
- Prinsloo R. H., Moloko L., Stander G., Theron S., Tomasevic D. I., Reitsma F. and Mulle E. 2009 OSCAR-4 *Tutorial documentation* (NECSA Internal RRT document) (South Africa: South Africa Nuclear Energy corporation)
- Stander G., Prinsloo R. H., Muller E. and Tomasevic D. I. 2008 *OSCAR-4 Code System Application to the SAFARI-1 Reactor* (Proceedings of the International Conference on Reactor Physics, Nuclear Power, Interlaken, Switzerland, September 14-19).

Thank you