THE STATUS OF THE BERYLLIUM REFLECTOR IN THE SAFARI-1 RESEARCH REACTOR

By:

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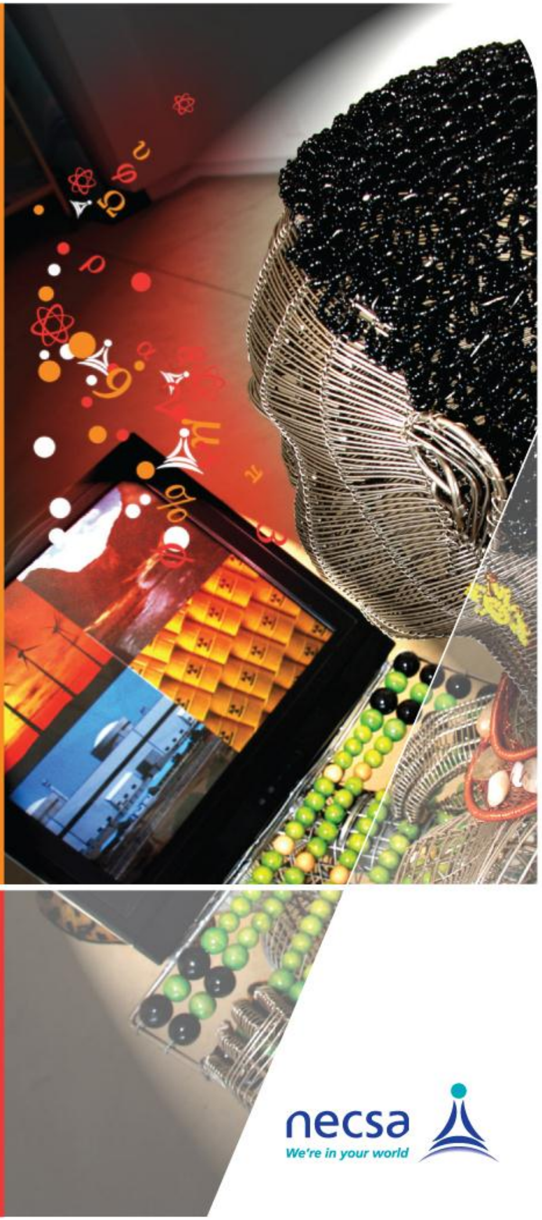

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Contents

Introduction

- Aspects that were considered are safety and operational related.

- The safety considerations:
  - the maintenance of a constant core configuration,
  - the structural integrity of the core, and
  - the accumulation of the highly radioactive products.

- The operational considerations:
  - the reflection efficiency of the elements,
  - the impact on the core performance and on the in-core fuel management,
  - the handling of the embrittled elements, and
  - the replacement criteria by other research reactors.

Replacement Criteria by Other RRs

- Fast Fluence:
  - Petten replaced at fast fluence > 5 x 10^{22} n.cm^{-2}.
  - BR2 adopted an upper limit of 6.4 x 10^{22} n.cm^{-2}.
  - Missouri based their replacement on the accumulated power before they observed cracks.

- Observations on Mechanical Property Change:
  - Fluences of 10^{20} n.cm^{-2} lead to a reduction of ductility.
  - Beryllium irradiated to a fluence of 10^{21} n.cm^{-2} exhibits increased yield strength and nil ductility.

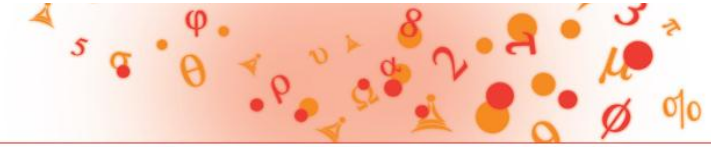
Developing SAFARI-1 Criteria

- Fast Fluence
  - Fluences of approximately 6 x 10^{21} and 3 x 10^{22} n.cm^{-2} could be expected at various localised sections in the reflectors.
- Swelling
  - The swelling behaviour of beryllium, for irradiations at temperatures below 75 degree C, as a function of fast fluence (E_n > 1MeV) can be determined by the following equation;

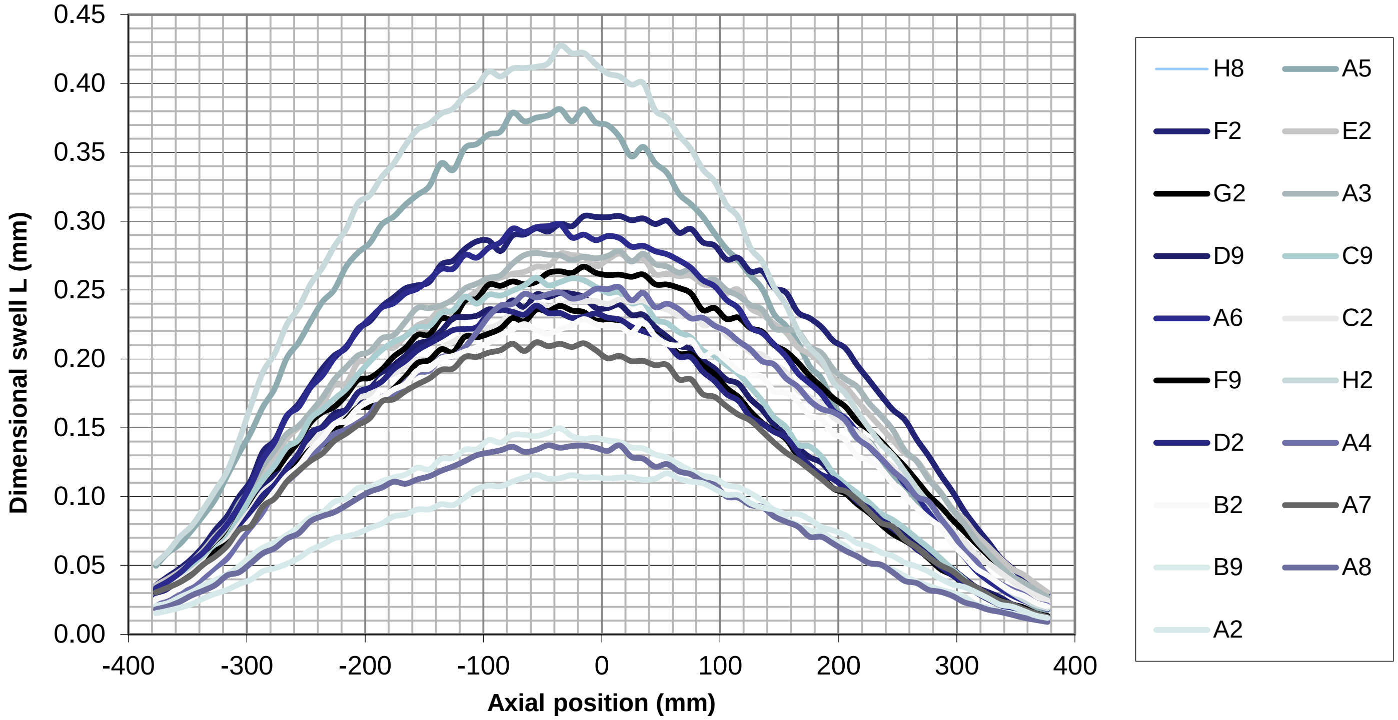
$$\Delta L/L = 0.00185 \times (\Phi.t) \qquad \Phi.t < 6.4 \times 10^{22}\ \mathrm{n.cm^{-2}}.$$

$$\text{Swell limit} = \Delta L/2 = 0.5 \times 0.00185 \times (\Phi.t) \times L$$

Direction	**Gap**	**Dimension**	**Maximum ΔL**	**Swell fluence limit ($\Phi t * 10^{22}$) n.cm^{-2}**
North - South	1.09	79.91	0.98	6.63
East - West	1.27	75.82	1.14	8.13



Developing SAFARI-1 Criteria



Axial dimensional swell for each beryllium element. Each element was divided into 10 mm axial segments to calculate the swell in each segment.

Developing SAFARI-1 Criteria

- The accumulated fast **fluences do not exceed the Petten criteria**, but sections in all of them exceed the nil ductility criteria.

- It is evident that **none of the reflectors are theoretically close to the swell limit**. Of greater concern is the fact that although the theoretical assessment may not provide adequate proof for replacement, the practical reality in terms of buckling, mechanical damage due to handling and wear and tear may proof otherwise. Moreover, this swell assessment assumes the gas produced follows the same axial and radial profile of the neutron fluence, however in practice, this gases experience diffusion mechanisms, and may form local stresses in other locations that affect the actual swell/bow characteristics and could result in higher dimensional changes and swell characteristics.

Developing SAFARI-1 Criteria

- The impact of fast neutron fluence on the ductility is in general a function of the material fabrication process. It is thus problematic to quantitatively evaluate the ductility of the present reflectors, due to the fact that the fabrication process for the reflectors is an unknown.

- At best it can be assumed that mechanical failure due to embrittlement can be expected at the predicted accumulated fluences.

Operational Experience

- During the November 2010 shut down problems were encountered to reload the core.
- An indication that bowing of the elements could form part of the problem.
- Operations-personnel succeeded to reload the core after the following steps were carried out;
  - Replacement of the Be-reflectors in position A3 and A4;
  - Polishing of the grid plate element ports;
  - Exchanging a fuel element with another one, due to physical damage at the end adaptor.

Photo taken during the November 2010 shut down

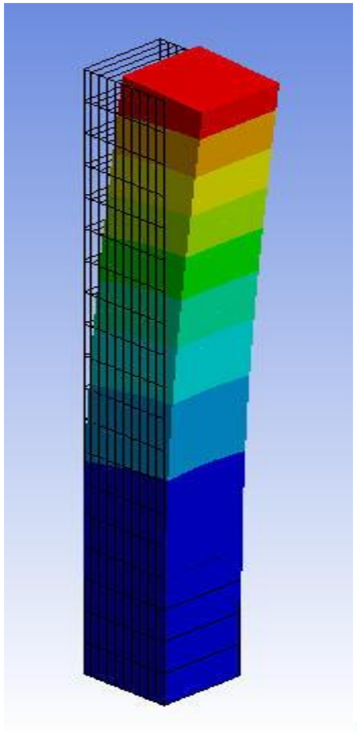
Cont. Operational Experience

- It cannot be solely the reason for the reload problem encountered, due to the following;
  - The total core were unpacked and reloaded with the previous shut down, without any problems.
  - The effect observed in the photo can also be due to the "play" in the fit in the grid plate, a straight reflector tilt effect, instead of a bowed reflector.

Photo taken during the November 2010 shut down

Bowing Model

- A more detailed evaluation in terms of radial and axial flux gradients were required to address the bowing effect, if any.
- Swell calculations assumed a constant radial flux through each axial layer, which results only in swell of the beryllium elements.
- The loads incorporated in this analysis are gravity, pressure and a lower end fixed support.
- Other competing factors are not taken into account which will suppress the dimensional outward movement of each volume element.



Dimensional swell-bow of the highest exposed beryllium element (H8) – max of 9.8 mm.

Present Reflector and Reload Implication

- The results of neutronic assessment indicate the following;
  - that the formed Helium-3 and lithium-6 from beryllium dominate the impurity content;
  - that the initial impurities present in fresh material remains present to some (40%) degree, if expressed in EBC;
  - that the EBC of the present reflectors after 45 years of service may exceed 35 ppm;
  - that there is a build-up of radioactive nuclides where the highest is tritium.

	1	2	3	4	5	6	7	8	9
A		27.0			37.1	32.4	39.3	31.0	
B		39.3							31.4
C		35.2							38.6
D		**37.1**							36.7
E		32.2							
F		**34.6**							35.9
G		32.8							
H		40.0						35.9	

The EBC (ppm) for each Beryllium element

Present Reflector and Reload Implication

- Two implications can be expected, and require evaluation:
  - the beryllium replacement procedure; and
  - the in-core fuel management procedure.

- The estimated accumulated error in the burn-up and flux predictions were 15%, contributed by un-poisoned beryllium modelling in the core simulator. This makes the predicted flux variation between poisoned and un-poisoned element core to be in-significant. This indicated no need either to update the reload designs, or a change in the fuel management procedure.

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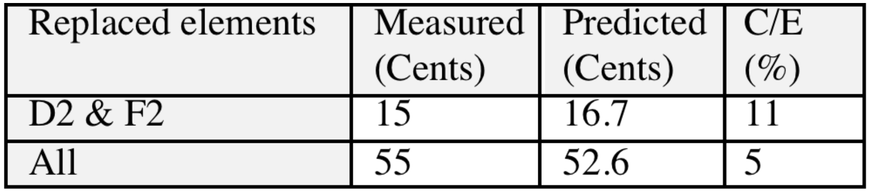
Operational and Safety Considerations

- An extrapolation was performed on the predicted neutronics parameters, and a step-wise replacement was followed.
- Beryllium elements in two core positions were selected for the reactivity worth measurements.
- The extrapolation was carried out with increasing the EBC until the impact on the core was identified to be high, with an associated reactivity worth of 40 cents.
- Due to the good agreement with the predicted reactivity worth and therefore the associated impact on the core, the final replacement of all the elements was conducted.

Measured and Predicted Reactivity Worth



Replaced elements	Measured (Cents)	Predicted (Cents)	C/E (%)
D2 & F2	15	16.7	11
All	55	52.6	5

Operational and Safety Considerations

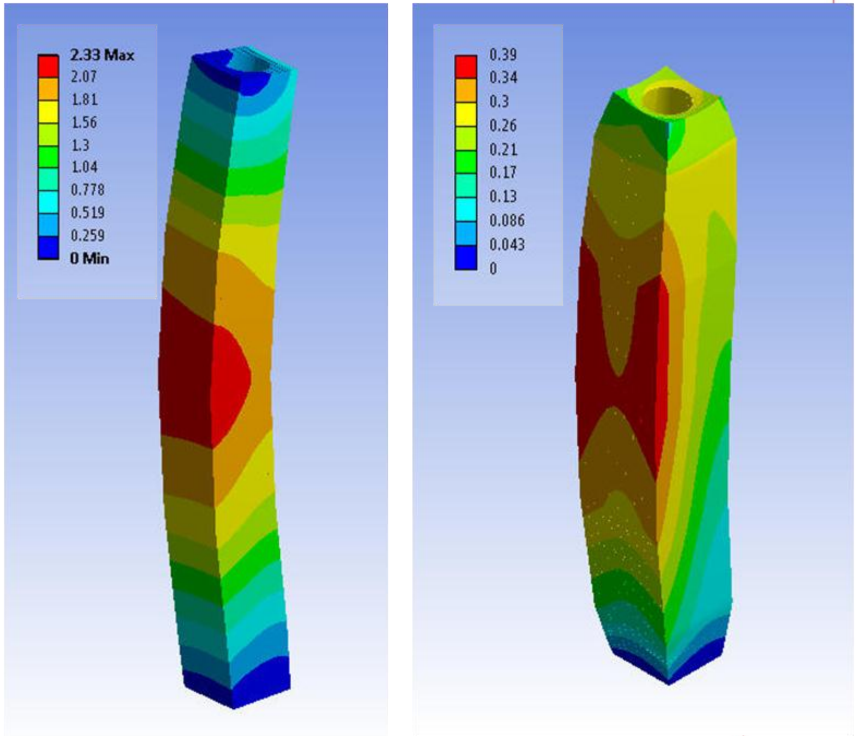
- Flux measurements were conducted in the hollow beryllium elements, for the same core, before (old elements core) and after (new elements core) the replacement of all beryllium elements .
- This consistent comparison provides confidence in the predicted impact on the core.

Calculated to measured flux ratios in the old and new beryllium elements

Beryllium position	Old elements core C/E		New elements core C/E	
	Thermal flux	Fast flux	Thermal flux	Fast flux
A5	0.22	-0.31	0.13	0.00
D2	0.19	-0.37	0.14	-0.07

Measured Dimensional Change

- Due to the lack of the historical records of the elements regarding time spent in various core positions, shuffling and rotation, it is not possible at this stage to compare it with the theoretical predictions mentioned above.
- The bowing effect has a much higher impact on the dimensional change, which according to the criteria has caused the closure of the water gap between two beryllium elements or a beryllium element and a fuel plate/side plate.



The measured dimensional change of selected beryllium elements – bowed element (left scaled to x16), swelled element (right scaled to x110)

Conclusions

- The aspects that were considered do not include the quantitative assessment of the main contributor to justify the replacement, due to the lack of historical records, data, and the resources to perform such a study.

- Based on the fact that the accumulated fast fluences of the present reflectors exceed the nil ductility criteria as found in the literature, indicating that serious embrittlement can be expected, it was recommended that SAFARI-1 must proceed with the replacement of its beryllium reflectors.

- The accumulated absorbers (helium and lithium) in the beryllium elements would not have any significant impact on the core neutronic characteristics and therefore, no beryllium reload scheme or change in the fuel management strategy was required.

Conclusions

- The approximation in the modelling of beryllium poisoning was sufficient, where the error in predictions (fluxes and reaction rates) increase for local parameters compared to e.g. criticality values, to a maximum within the poisoned beryllium elements itself.

- The measured dimensional changes have shown that possible water gap closure has occurred!

Thank You