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

M. BELAL
South African Nuclear Energy Corporation (Necsa),
Radiation and Reactor Theory Section,
Pretoria,
South Africa

W.J. STYRDOM
South African Nuclear Energy Corporation (Necsa),
SAFARI-1 research reactor,
Pretoria,
South Africa

Abstract

The aspects that were considered in the evaluation of the status of the beryllium reflector elements and the justification for the replacement are safety and operational related. The safety considerations were carefully examined against what is stated in the safety requirements document IAEA NR-S-4, and the following safety related functions were deduced as where the beryllium elements are deemed to be a contributor to their fulfillment, the maintenance of a constant core configuration, and the structural integrity of the core. These safety requirements are essential to the fulfillment of the shutdown and cooling safety functions. Furthermore on the topic of safety considerations is the accumulation of the highly radioactive Tritium that may leak through a cracked or broken element and threatens workers and public health. Operational considerations are 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, the operational experience, and the replacement criteria by other research reactors. The three former considerations could be realized as related neutronics contributors to the operational performance and the later related to the safety considerations stated above. Against the above background, this paper presents an overview of the Beryllium reflector replacement evaluation with regard to fast neutron impact on ductility, swelling, bowing and subsequent operational difficulties. Lastly the paper highlights safety measures put in place to ensure a well controlled replacement exercise.

1. INTRODUCTION

Beryllium is a light weight material with a unique combination of structural, chemical and especially neutron absorption characteristics that make it a highly desirable material for application as a neutron reflector in a neutron reactor [1,2]. Presently beryllium reflectors found application in the reactors at Petten [3], BR2-MOL [4], the ATR at Idaho [5], JMTR Japan [6], Maria reactor in Poland [7], to name a few.

Unfortunately the unique neutron and material characteristics are negatively affected by fast neutron irradiation. High energy neutron exposure results in (n,α) and (n,2n) reactions, resulting in the formation of neutron absorbing poisons such as ^{6}Li and ^{3}He (high absorption cross sections) [4]. In the case of SAFARI, the formation of vast quantities of poisons may lead to a reduced thermal flux in the adjacent irradiation positions.

The good structural characteristics of beryllium are negatively affected by the formation of gaseous atoms of helium and tritium. The volumes of gas formed contribute to the swelling behaviour of the material and adds to the reduction of the ductility of the reflectors, to an extent where the beryllium become embrittled [8-11]. As a matter of interest, the amount of helium formed is approximately 22 cm^3 (STP) per cm^3 of beryllium per 10^{22} cm^{-2} (E_n>1 MeV) [2]. It was thus important to consider the beryllium status at SAFARI-1, knowing that during its operation history, the beryllium was never replaced. Although it is difficult to find a replacement strategy in literature, the following replacement guidelines were encountered:

— It is reported that Petten [3] replaced their reflectors after a fast fluence of approximately 5×10^{22} cm^{-2}. It must be mentioned that the decision to replace was based on operational experience, such as handling problems;
— BR2 adopted an upper limit of 6.4×10^{22} cm^{-2} , for future replacements [4];
— Missouri reactor [12] based their replacement on the power (MWd) accumulated before they observed cracks in the beryllium for the first time.

The above mentioned fast fluence values seems rather high if compared to other reported observations on mechanical property changes;

— Fluences of 10^{20} cm^{-2} lead to a reduction of ductility at irradiation temperatures of less than 100°C [2];
— Beryllium irradiated to a fluence of 10^{21} cm^{-2} and tested at temperature below 100°C, exhibits increased yield strength and nil ductility [8].

2. FAST FLUENCE AND DIMENSIONAL CHANGE

Neutronic calculations were performed for SAFARI using MCNP5 and MCNPX with the CINDER module [13]. Based on mostly a representative HEU core indicate that fluences of approximately 6×10^{21} and 3×10^{22} cm^{-2} could be expected at various localised sections in the reflectors. The representative core is defined as the core that has the highest fast flux in the beryllium elements. The maximum fast fluence (cm^{-2}) values calculated per volume sections (77.1–81.0×10 mm^3) of the beryllium are presented in Table I.

TABLE I: LOCAL MAXIMUM FLUENCE PER BERYLLIUM ELEMENT

Core position	Fast fluence	Core position	Fast fluence
A2	6.65E+21	C2	1.91E+22
A3	2.25E+22	C9	1.94E+22
A4	2.43E+22	D2	1.99E+22
A5	1.25E+22	D9	1.99E+22
A6	1.91E+22	E2	2.25E+22
A7	1.94E+22	F2	2.43E+22
A8	1.16E+22	F9	1.87E+22
B2	1.56E+22	G2	2.18E+22
B9	1.25E+22	H2	1.84E+22
-	-	H8	2.89E+22

It is thus evident that the accumulated fast fluences in the SAFARI-reflectors do not exceed the Petten criteria, but sections in all of them exceed the nil ductility criteria, as mentioned above.

During a private communication it was mentioned that the (γ,n) reaction in the beryllium elements, may contribute approximately another 5% in fast flux, therefore the fast fluxes, fluences and swell dimensions were scaled up by 5% to account for the (γ,n) reaction contribution to the poisons build-up in the beryllium[14)].

3. 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[4,9];

$\Delta L/L = 0.00185 \times (\Phi.t)$ where,

$\Phi.t$ = fast fluence in units of 10^{22} $n.cm^{-2}$

L = dimension of reflector, as indicated in Table II below.

This formula can be used to predict the swelling for fluences less than 6.4×10^{22} $n.cm^{-2}$. At fluences higher than this value, an accelerated swelling behaviour occurs, resulting in swelling values higher than predicted by this formula[4]. The total gap between the beryllium parts of the reflectors is shown in table II. The swell limit that can be tolerated can be defined as follows; if two adjacent reflectors swell to the same extent, the maximum swell ($\Delta L/2$) that can be allowed is less than half of the Be-reflector gap size. To avoid total gap closure, swelling to 90% of the gap can be tolerated. The fluence required to reach the swell limit can be calculated from the following formula:

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

and is reported in Table II.

TABLE II: RELEVANT PHYSICAL PARAMETERS EFFECTING SWELL

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

Figure 1 shows the determined swell in each element, with the highest at 0.4mm. It is evident from figure 1 that none of the reflectors are theoretically close to the swell limit. Of greater concern is the fact that although the theoretical assessment (as above) 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 than indicated above.

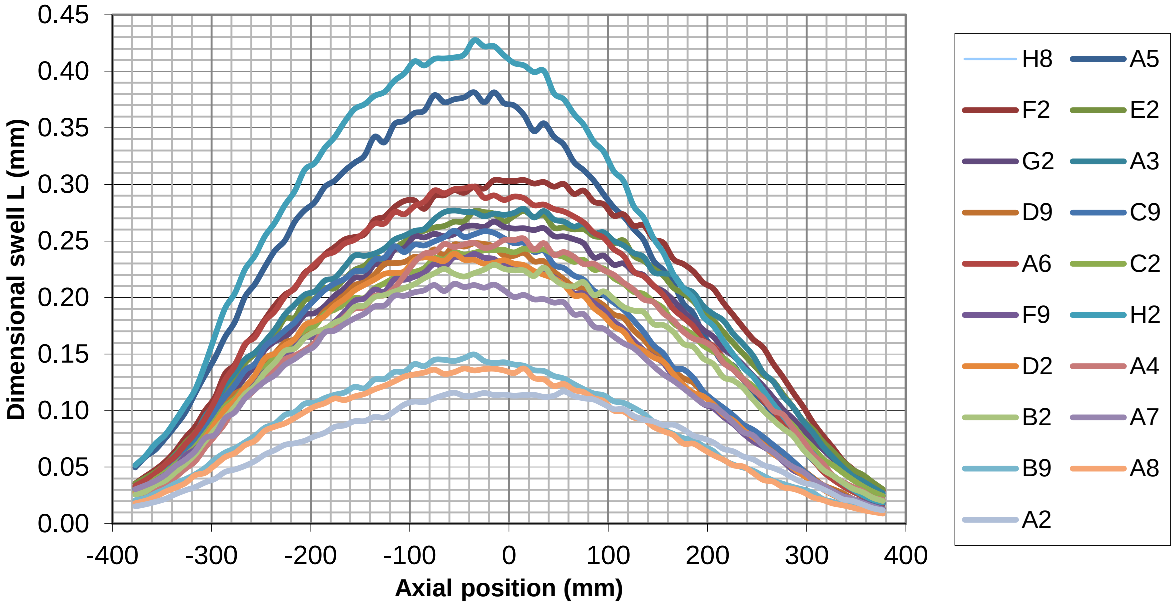

FIG. 1. Axial dimensional swell for each beryllium element. Each element was divided into 10 mm axial segments to calculate the swell in each segment.

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.

4. OPERATIONAL EXPERIENCE

During the November 2010 shut down problems were encountered to reload the core. The following photo (figure 2) was taken during the operation, as 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 (figure 2);
- Polishing of the grid plate element ports;
- Exchanging a fuel element with another one, due to physical damage at the end adaptor.

FIG. 2. Photo taken during the November 2010 shut down.

Although bowing might contribute to the “tight” core theory, it cannot be solely the reason for the reload problem encountered, due to the following;

- Unfortunately due to time constraints the above mentioned actions were done simultaneously and thus the resultant success is due to a combined effect;
- According to the Reactor operations manager the total core were unpacked and reloaded with the previous shut down, without any problems. Neither bowing nor swelling can in three weeks time account for such dramatic dimensional changes.
- 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.

5. BOWING MODEL

With respect to the above mentioned observations a more detailed evaluation in terms of radial and axial flux gradients were required to address the bowing effect, if any. The results in figure 1 assumed a constant radial flux through each axial layer, which results only in swell of the beryllium elements. Therefore, it was necessary to perform this qualitative analysis to identify the present shape of the elements. A beryllium element was modelled as shown in figure 3 and figure 4 shows the fast flux gradients in each layer that was used for this stress analysis.

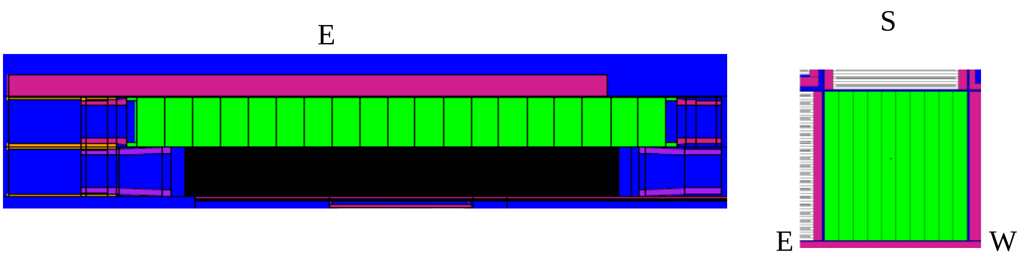

FIG. 3. SAFARI-1 MCNP model showing the axial layers of the Be elements (left), and radial layers (right).

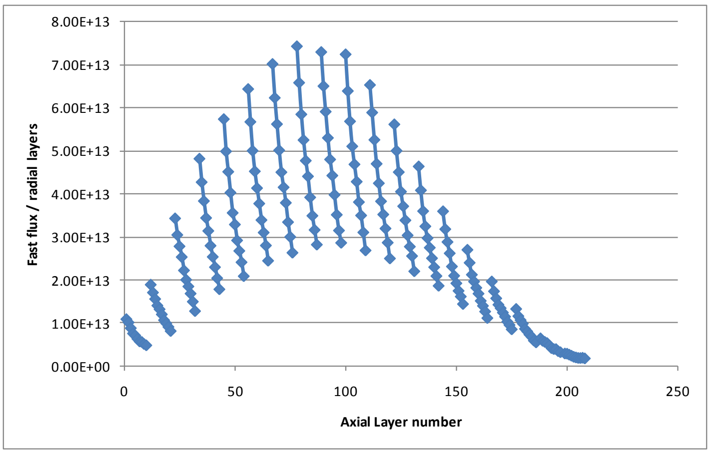

FIG. 4. (Axial-radial) fast flux gradient used for bowing estimation.

The loads incorporated in this analysis are gravity, pressure and a lower end fixed support. The material properties were used in the isotropic conditions[15,16)]. The resultant swell-bow effect is depicted in figure 5.

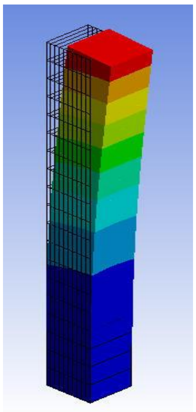

FIG. 5. Dimensional swell-bow of the highest exposed beryllium element (H8) – max of 9.8 mm.

The dimensional change indicated in figure 5 shouldn't be considered as the current expected situation, due to the fact that other competing factors are not taken into account which will suppress the dimensional outward movement of each volume element. It would be therefore necessary to perform a more detailed analysis to determine the more realistic final dimensional change[17)].

The measured dimensional change of two selected beryllium elements is shown in figure 6. 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. However, figure 6 shows that some elements were bowed, which indicate less rotation during their lifetime when compared to the elements that showed only swelling. The bowing effect has a much higher impact on the dimensional change, which according to the criteria in Table II has caused the closure of the water gap between two beryllium elements or a beryllium element and a fuel plate/side plate.

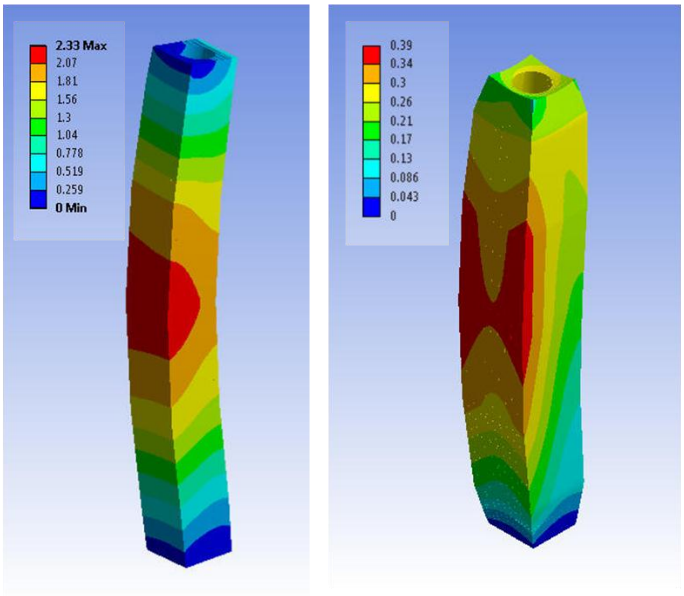

FIG. 6. The measured dimensional change of selected beryllium elements – bowed element (left scaled to x16), swelled element (right scaled to x110).

6. PRESENT REFLECTOR AND RELOAD IMPLICATION

Due to a lack of information regarding the impurity content of the present (before 1965) material, the impurity content was taken as reported in the early literature[2)], for material of the 1970 period.

An Equivalent Boron Content (EBC)* evaluation of the reported impurities resulted in a value of less than 2ppm. A neutronic study was performed where the inventories were calculated for pure and impure Beryllium. The results 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.

The impacts of the impurities as a function of concentration on the thermal flux in the adjacent core positions were also investigated. Thermal flux depression of up to 5% can be expected at impurity concentrations of 35 ppm.

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.

---

*The elemental content was converted according to ASTM: C1233-03 to an EBC value[18)].

On the other hand, the small variation in the safety parameters (<1% PPF) indicated the possibility of replacing all beryllium elements with no need for a specific beryllium replacement scheme.

7. OPERATIONAL AND SAFETY CONSIDERATIONS

In order to assist the replacement procedure, an extrapolation was performed on the predicted neutronics parameters, and a step-wise replacement was followed. In this step-wise replacement, only two elements of the highest reactivity worth and with relatively high accumulated poisons were first replaced and their reactivity worth was compared with the predictions. Once verified, the final replacement of all the elements commenced.

The EBC, in units of ppm, is shown in figure 7 for each beryllium element, resulting in an estimated average EBC of 35 ppm. The EBC was used in all calculations for the extrapolated reactivity worth and impact on the core. With the expected average 35ppm EBC in the elements the impact is less than 5% as indicated above.

	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	

FIG. 7. The EBC (ppm) for each Beryllium element

Beryllium elements in core positions D2 and F2 were selected for the reactivity worth measurements due to their high worth positions and the relatively high accumulated poisons. The reactivity worth of the accumulated poisons in D2 and F2 when the positions are filled with the old versus new beryllium was expected to be of the order of 16.7 cents.

An extrapolation of the predicted poisons content in the beryllium element was performed, and that is by increasing the EBC in the entire beryllium elements while calculating the D2+F2 reactivity worth (up to 40 cents), and the associated impact on the core when all elements are replaced. The extrapolation was carried out with increasing the EBC until the impact on the core was identified to be high, with an associated D2+F2 reactivity worth of 40 cents.

Moreover, when the reactor shuts down and prior the replacement, He-3 builds up. It was estimated that this effect will increase the average EBC in the elements from 35.09 to 35.7, which is insignificant and contributes by less than 5 cents to the core reactivity excess. Table III shows the measured and calculated reactivity worth. Due to the good agreement with the predicted D2+F2 reactivity worth and therefore the associated impact on the core, the final replacement of all the elements was conducted, and the comparison with the total reactivity worth still showed good agreement.

TABLE III: MEASURED AND PREDICTED REACTIVITY WORTH

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

Furthermore, flux measurements were conducted with cobalt and nickel foils in the hollow beryllium elements, for the same core, before (old elements core) and after (new elements core) the replacement of all beryllium elements. Table IV shows the calculated to measured flux ratios. The high ratios in the old elements core could be due to the absence of the axial distribution of beryllium poisoning elements in the calculation model (only a uniform distribution of EBCs was modelled). Nevertheless, this consistent comparison provides confidence in the predicted impact on the core. The criticality error between the old and new element cores was less than 10 cents.

TABLE IV: 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

8. CONCLUSIONS

The aspects that were considered in this report for the replacement of the Beryllium elements 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. This aspect deals with the change in properties of the beryllium elements due to mainly fast neutron irradiation, in terms of the quantification of the embrittlement profile as well as cracks location and dimensional changes. The importance of this aspect is to ensure a constant core configuration, and the structural integrity of the reactor core, on which the beryllium dimensional or property changes would impact.

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. Moreover, 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.

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. Breakage during normal handling of the reflectors, resulting in the release and spread of contamination products can be ill afforded. Moreover, the measured dimensional changes have shown that possible water gap closure has occurred.

ACKNOWLEDGEMENTS

Here we acknowledge W Vlok for the development of the measuring rig and performing the dimensional measurements.

REFERENCES

[1] TOMBERLIN, T.A., "Beryllium – A Unique Material in Nuclear Applications", 36th International SAMPE Conference, 2004.
[2] BEESTON, J.M., "Beryllium Metal as a Neutron Moderator and Reflector Material", Nuclear Engineering and Design **14** (1970) p 445.
[3] AHLF, J., ZIJP, W., "Upgrading Activities for the HFR Petten", IAEA-SM-310/54.
[4] KOONEN, E., "Experience Gained from the BR2 Beryllium Matrix Replacement and Second Matrix Surveillance Programme," IAEA-SM- 310/68.
[5] DURNEY, J.L., CROUCHER, D.W., "Replacement of Core Components in the Advanced Test Reactor," IAEA-SM- 310/21.
[6] HANAWA, Y., et al., "Manufacturing of Neutron Reflector Frame for JMTR", 2nd International Symposium on MTRs, Idaho Falls.
[7] ANDRZEJEWSKI, K., et al., "Beryllium Poisoning in the Maria Reactor," International Meeting on Reduced Enrichment for Research and Test Reactors, Budapest, 1999.
[8] STONEHOUSE, A.J. "Physics and Chemistry of Beryllium", J Vac Sci Technology **A4(3)** (1986) p 1163.
[9] BEESTON, J.M., "Mechanical Properties of Irradiated Beryllium", Journal of Nuclear Materials **195**(1992) p 102.
[10] SANNEN, L., "Helium Content and Induced Swelling of Neutron Irradiated Beryllium", Fusion Engineering and Design **29** (1994) p 470.
[11] BEESTON, J.M., et al., "Comparison of Compression Properties and Swelling of Beryllium Irradiated at Various Temperatures," Journal of Nuclear Materials **122/123** (1984) p 802.
[12] MCKIBBEN, C.J., Missouri reactor, private communication, 2010.
[13] LOS ALAMOS NATIONAL LABORATORY, "MCNP–A General Monte Carlo N-Particle Transport Code," MCNP5 1.5 & MCNPX2.6.
[14] RIDIKAS, D. Private communication, International Atomic Energy Agency 2010.
[15] MATWEB, "Beryllium [Online]," http://www.matweb.com, (2010).
[16] HEARN, E.J., "Mechanics of Materials," 3rd ed, Butterworth-Heinemann (2010).
[17] JANSEN, E., Private communication, South African Nuclear Energy Corporation, 2010.
[18] ASTM: C1233-03, "Standard Practice for Determining Equivalent Boron Contents of Nuclear Materials."