PLASMA STABILIZATION CONDUCTING SHELLS AND THEIR IMPACT ON TBR AND ACTIVATION IN CLiFF DESIGN

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ABSTRACT

Plasma stabilization and plasma elongation are best achieved by keeping a stabilizing shell as close as possible to the plasma. In CLiFF design, a 2-cm-thick flowing liquid layer is placed in front of a solid FW and is thought to be used as an active conduction shell if its conductance is relatively high such as with liquid lithium. On the other hand, higher conductance is achieved by solid shells (e.g. Cu, Al, FS, W, V alloy). In the present study, the adverse effect of this stabilizing shell (whether it is liquid or solid material) on tritium breeding ratio (TBR) is investigated. Among the design features that quantify this effect are: the type of breeder and structure, the degree of Li-6 enrichment, the material and thickness of the shell, and whether or not there is a front beryllium multiplying zone in the blanket. Additionally, the presence of a solid conducting shell near the FW will impose a safety concern in the case of LOCA. The present study addresses this concern and comparison of the level of decay heat and waste disposal rating is made among the candidate materials for the stabilizing shell.

I. INTRODUCTION

In the thin Convective Liquid Flow First Wall (CLiFF) blanket concept, a 2 cm-thick liquid layer is flowing poloidally from top to bottom in front of a solid first wall.[1] This concept is among several liquid and solid FW concepts under investigation in the Advanced Power EXtraction (APEX) study that is currently in progress for exploring innovative concepts for high power density application.[2-3] Plasma kink mode stabilization and plasma elongation can be achieved by introducing a conducting shell near the FW. Plasma shaping with a close shell and liquid walls could potentially eliminate the need for current drive and neutral beams, while keeping feedback loops behind the shield.[4] The liquid layer in front of solid FW in CLiFF concept can in principle be used as a conducting shell but solid shells exhibit higher conductance.

The introduction of the conducting shell near the FW will have an adverse impact on the tritium breeding ratio, TBR, particularly if the liquid breeder used, such as Flibe[1], has marginal tritium breeding capability. Such an impact is highly system-dependent. Among the important variants in the design features that determine this effect are: (1) Location of the conducting shell (in front of the FW or deeper in the blanket), (2) The type of breeder and structure, (3) The degree of lithium enrichment, (4) The type and thickness of solid conducting shell (e.g. Cu, Al, FS, W, V alloy), (4) Whether or not there is already a FW to act as a structural support and the conducting shell is placed in front of it, and (5) Whether or not there is a front beryllium-multiplying zone in the blanket. Furthermore, chosen as a solid, the conducting shell placed near the FW will impose a safety concern due to the additional decay heat generated in the case of LOCA. These issues are investigated in the following sections and comparison is made to identify the best candidate material to be used as a stabilizing shell with the least impact on TBR and decay heat while having the lowest waste disposal rating.

II. CALCULATIONAL PROCEDURES

The 1-D calculational model for CLiFF used in the present comparative analysis is shown in Refs. 1 and 2. The model includes the geometrical details of the inboard (I/B) and outboard (O/B). Liquid breeder of 2 cm-thickness is flowing poloidally and covers a solid wall layer of 0.5 cm-thickness. The blanket and shield follow this solid wall. The dimensions are those corresponding to the ARIES-RS design.[5] The blanket thickness is 60 cm-thick on the O/B (40 cm-thick on the I/B). It consists of 90% liquid breeder and 10% structure. High-temperature (H.T.) shield follows the blanket and consists of 95% structure and 5% liquid. Its thickness is 30.5 cm on the O/B side and 28 cm on the I/B side. After a 2 cm-thick gap, the low-temperature shield follows with a thickness of 30.5 cm (O/B) and 28 cm (I/B). It consists of 95% structure and 5% liquid breeder. The vacuum vessel and TF coils follow the shield. The calculations were performed with ANISN code[6] along with 46:21 neutron-gamma multi-group cross section data library based on FENDL-1 data base[7] with an average neutron wall load of 10 MW/m^2 on the O/B and 7 MW/m^2 on the I/B. For the activation calculations, the ONEDANT code[8] was used along with the activation code DKR-PULSAR2.0[9] and the FENDL/A-2.0 data library.[10]

II. IMPACT OF THE CONDUCTING SHELL ON TRITIUM BREEDING

Flibe has been used as the breeding material and the flowing liquid layer in the original exploration of the CLiFF concept[2] although other breeders were examined for better tritium breeding potential.[1] Ferritic steel (FS) and SiC have also been considered as the structure material. Because Flibe exhibits marginal TBR, a beryllium-multiplying zone was incorporated in the blanket to enhance TBR[1]. In the following, the impact of the conducting shell on TBR under these various design features is given.

A. CLiFF Design with Flibe/FS Structure (No Beryllium Multiplying Zone)

This system is the initial CLiFF design concept and is not optimized for TBR enhancement. The blanket (60 cm OB, 40 cm IB) does not include a front Be multiplying zone and consists of 90% Flibe and 10% FS structure. The shield consists of 5% Flibe and 95% FS. Lithium is enriched to 25%Li-6. The local TBR is as follows:

TBR = 1.16 (with the liquid convective layer)
TBR = 1.156 (without the liquid convective layer) – less than 1% drop

The effect of including the conducting shell of thickness d cm in front of the bare FW (TBR=1.156) is shown in Fig.1 and 2. The following can be seen from these figures:

- The largest adverse effect on local TBR is with Aluminum (-5% at d=1 cm, -8.5% at d=2 cm).
- The decrease in TBR upon including copper or ferritic steel conductors is comparable (-2% at d=1 cm, -4% at d=2 cm).
- The inclusion of either tungsten or vanadium alloys improves local TBR (in case of W, TBR maximizes around d=1 cm) due to neutron multiplication. Neutrons end up being absorbed mainly in Li-6 which is ~25% of Li. If natural Li is used, TBR drops, especially with W since tritium breeding from Li-7 will decrease [W(n,2n) reactions compete with Li-7(n,n'α)t reactions at high-energy neutrons.

B. CLiFF Design with Flibe/SiC Structure (No Beryllium Multiplying Zone)

In this system, the TBR decrease upon replacing FS structure with SiC. The effect of Li-6 enrichment can be seen from Fig. 3. As shown, local TBR is marginal and a neutron-multiplying zone is needed to improve TBR. The Flibe/FS combination gives larger TBR at all Li-6 enrichment than Flibe/SiC combination. Local TBR in the case of Flibe/FS peaks around 25% Li-6 enrichment whereas it always decreases with Li-6 enrichment in the case of Flibe/SiC. The local TBR with natural lithium is as follows:

TBR = 1.13 (with the liquid convective layer)
TBR = 1.085 (without the liquid convective layer) - ~4% drop (more than in case A above)

Taking the bare FW case (TBR=1.085), Fig. 4 shows the impact on TBR upon including the conducting shell in front of the FW. Table 1 summarizes the change in TBR.

In this system, tungsten has the worse impact on TBR. TBR drops by ~ 9% at d=2m. Since natural lithium is used, adding the W(n,2n) reactions leads to a decrease in Li-7(n,n'α)t reactions. The TBR could improve if Li is enriched to 25% Li-6 as was shown in case A above. This is because the W(n,2n) reactions improve TBR if there is no beryllium multiplier and with enriched lithium. Note in particular that the absolute value for the TBR with natural Li drops below unity in this case (TBR=0.99) which is absolutely unacceptable from tritium self-sufficiency viewpoint. Copper and Aluminum have similar impact (~ -7% at d=2 cm). The least impact is with ferritic steel (~ 2% at d=2 cm). The inclusion of a vanadium shell improves TBR in this system by ~ 3% at d=2cm.

C. CliFF Design with Flibe/SiC Structure (With Beryllium Multiplying Zone)

Including a front beryllium multiplying zone (60%Be, 30%Flibe natural, 10%SiC) is a must to improve TBR and ensure that tritium self-sufficiency condition is met. Figure 5 shows how TBR improves as the thickness of this multiplying zone increases up to the total blanket thickness (60-cm O/B, 40 cm I/B). Local TBR increases drastically and the effect is more pronounced in the Flibe/SiC combination than in the Flibe/FS case. Local TBR can be larger in with Flibe/SiC than with Flibe/FS (Contrary to the no Be case). At front Be zone thickness of ~10 cm, local TBR seems adequate (TBR = 1.5) with SiC structure. It was also shown that increasing Li-6 enrichment in this has an adverse effect on TBR if SiC is used as the structural material. The TBR in this case is:

TBR = 1.5 (with a convective liquid layer)
TBR = 1.54 (without a convective liquid layer)- ~3% improvement in TBR.

The reason for the increase in TBR in the bare solid wall case is the fact that the presence of the 2 cm liquid layer tends to moderate the neutrons energy which has an adverse effect on multiplication through Be(n,2n) reactions. The change in TBR in the bare FW case upon including a conducting layer at the front is shown in Fig. 6 and the change in TBR is summarized in Table 2.

Tungsten has the worse impact on TBR. TBR drops by ~ 30% at d=2cm and the absolute value becomes TBR=1.08, which is not acceptable to meet tritium self-sufficiency condition. Tungsten has a large (n,2n) cross-section (~ 2 barns at 14 MeV) but its threshold energy is high (E_{th}= ~7 MeV). Although beryllium has lower (n,2n) cross-section at 14 MeV (~0.5 barns) but its threshold energy is much lower (E_{th}= ~2 MeV). Thus, the presence of W degrades the effectiveness of beryllium as a neutron multiplier.

Copper is the next element that has adverse effect on TBR in this design. The drop is ~ 20% at d=2cm. The corresponding drop with FS is ~ 15%. The effect of Al and V alloy is comparable (-12% decrease in TBR at d=2cm).

III. ACTIVATION ANALYSIS FOR THE CONDUCTING SHELL

A. Calculational Procedures

Activation analyses were performed to assess the waste disposal ratings of the candidate stabilizing shell alloys as well as the decay heat after shutdown. Calculations are performed assuming neutron wall loading of 7 and 10 MW/m^2 at the inboard and outboard first walls, respectively. The analysis used the ORNL low activation ferritic steel (LAFS) 9Cr-2WVTa as a structure material and Flibe as breeding material. The stabilizing shell is assumed to be 2-cm thick and placed immediately behind the liquid first wall or deep inside the blanket at 30 cm from the liquid first wall. The shell was assumed to survive for 3 FPY. The following five materials are analyzed for use as a stabilizing shell:

- The ORNL (9Cr-2WVTa) ferritic steel alloy.
- The V-4Cr-4Ti alloy.
- The W-5Re alloy.
- The Al-6061 alloy.
- The Glidcop-Al15-DS-Cu alloy.

B.Decay Heat Generation in the Stabilizing Shell

Decay heat generation in the stabilizing shell is an important source of safety concern. The amount of decay heat induced in the stabilizing shell during an accident, like a loss of coolant accident (LOCA) is a safety concern and could impact the overall thermal response of the structure. Hence, it is desirable to select a stabilizing shell alloy with the lowest possible decay heat generation. Figures 7 and 8 show the specific decay heat generated in the different alloys immediately behind the first wall and at 30 cm from the liquid first wall, respectively. As shown, the W-5Re alloy generates the highest amount of decay heat during the first year following shutdown. Most of the decay heat is induced by the ^{187}W ($T_{1/2}$ = 23.9 h), ^{185}W ($T_{1/2}$ = 74.8 d), ^{188}Re($T_{1/2}$ = 16.94 h), and ^{186}Re ($T_{1/2}$ = 3.77 d). The Al-6061 alloy is the second leading generator of decay heat during the first day following shutdown if the stabilizing shell is located immediately behind the first wall. This is caused by the generation of ^{24}Na ($T_{1/2}$ = 14.96 h) via the high-energy ^{27}Al (n,α) reaction. As shown in figure 8, the level of decay heat generated in the Al-6061 alloy drops in comparison to other alloys if the stabilizing shell is located at 30 cm from the liquid first wall due to the soften neutron spectrum.

The Glidcop Cu alloy is another producer of significant amount of decay heat. The copper alloy becomes the leading generator of decay heat at times exceeding one year following shutdown. Most of the decay heat is dominated by the two copper isotopes ^{66}Cu ($T_{1/2}$ = 5.1 min), and ^{64}Cu ($T_{1/2}$ = 12.7 h). The low activation ferritic steel and vanadium alloys produce the least amount of decay heat, with the V-4Cr-4Ti alloy being the most attractive alloy. The decay heat induced in the ORNL LAFS is dominated by the two manganese isotopes, ^{56}Mn ($T_{1/2}$ = 2.578 h) and ^{54}Mn ($T_{1/2}$ = 312.2 d), as well as the ^{187}W isotope. On the other hand, the decay heat induced in V-4Cr-4Ti is mostly due to ^{51}Ti ($T_{1/2}$ = 5.76 min), and ^{48}Sc ($T_{1/2}$ = 43.7 h).

C. Waste Disposal Ratings

The waste disposal ratings (WDR) of the stabilizing shell were assessed according to both the NRC 10CFR61 and Fetter waste disposal concentration limits (WDL). The 10CFR61 regulations assume that the waste disposal site will be under administrative control for 100 years. The dose at the site to an inadvertent intruder after the 100 years is limited to less than 500 mrem/year. The WDR is defined as the sum of the ratio of the concentration of a particular isotope to the maximum allowed concentration of that isotope taken over all isotopes and for a particular class. If the calculated WDR • 1 when Class A limits are used, the radwaste should qualify for Class A segregated waste. The major hazard of this class of waste is to individuals who are responsible for handling it. Such waste is not considered to be a hazard following the loss of institutional control of the disposal site. If the WDR is > 1 when Class A WDL are used but • 1 when Class C limits are used, the waste is termed Class C intruder waste. It must be packaged and buried such that it will not pose a hazard to an inadvertent intruder after the 100 years institutional period is over. Class C waste is assumed to be stable for 500 years. Using Class C limits, a WDR > 1 implies that the radwaste does not qualify for shallow land burial. Fetter developed a modified version of the NRC's intruder model to calculate waste disposal limits for a wider range of long-lived radionuclides which are of interest for fusion researchers than the few that currently exist in the current 10CFR61 regulations. Fetter's model included more accurate transfer coefficients and dose conversion factors.

Tables 3 and 4, show the waste disposal ratings of the different stabilizing shells immediately behind the first wall and at 30 cm from the liquid first wall, respectively. The dominant nuclides are given between brackets. The waste disposal ratings are given following a cooling period of ten years. As shown in Table 3, only stabilizing shells made of ferritic steel and V-4Cr-4Ti alloys would qualify for disposal as low level waste according to the two waste disposal limits used in this analysis. The WDR of both alloys are dominated by contribution from the niobium impurities in both alloys. The waste disposal ratings of the W-5Re alloy are also dominated by the niobium impurities. The W-5Re alloy used in this analysis contains 10 wppm of niobium impurities. Limiting the level of niobium impurities in the W-5Re alloy to less than 1 wppm could reduce the alloy WDR below the Class C limits according to 10CFR61. The Al-6061 will also qualify for disposal as Class C waste according to the 10CFR61. The reason is that ^{26}Al, which has no limits in 10CFR61, dominates the WDR. On the other hand, due to the low limits allowed for ^{26}Al by Fetter, Al-6061 is the worst performing stabilizing shell. The WDR of the Glidcop Cu is too high. As shown in the table, the high 10CFR61 WDR limits are caused by ^{63}Ni produced by the ^{63}Cu (n,p) reaction. ^{63}Ni contribution to the Fetter waste disposal limits is minimal due to the fact that it is given higher allowable limits by Fetter. Finally, results in Table 5 show that even though the WDR are more moderate the conclusions regarding alloys suitability are not changed.

IV. CONCLUDING REMARKS

The adverse effect on TBR due to the inclusion of a conducting shell in front of the solid FW is highly system-dependent. Among the design features that quantify this effect are the type of breeder and structure, the degree of lithium-6 enrichment, the type of solid conducting shell (e.g. Cu, Al, FS, W, V alloy), and whether or not there is a front beryllium multiplying zone in the blanket. It is shown that removing the front Flibe convective layer itself (2m thick) can drop TBR by less than 1% (FS structure) and by ~4% (SiC structure) if no front beryllium multiplying zone is deployed. On the other hand, TBR increases (by ~3%) if a beryllium multiplying zone is implemented in the system (SiC structure with natural lithium). In this case, the presence of the convective layer degrades the multiplication effect of Be through Be(n,2n) reactions due to neutron moderation by the layer.

Placing tungsten as a conducting shell at the FW in a system that does not deploy beryllium as a multiplier will have lesser adverse impact on TBR (~-8-10%) if Flibe breeder uses natural lithium. However it improves TBR by ~+2-3% if 25%Li-6 enrichment is used.

In the latest CLiFF design, a front beryllium multiplying zone (60%Be, 30%Flibe, 10% SiC) of a thickness of 10 cm is most likely to be adopted to improve TBR. Natural lithium gives the largest local TBR in this case (TBR=1.5). Without the convective layer (TBR=1.54), using tungsten as the conducting shell gives the largest adverse impact on TBR (up to ~-30% for shell thickness d=2 cm) and the absolute value becomes TBR=1.08, which is not acceptable to meet tritium self-sufficiency condition. Copper is the next element that has adverse effect on TBR in this design. The drop is ~ 20% at d=2cm. The corresponding drop with FS is ~ 15%. The least impact is with V and Al conductors (TBR drops by~-12% for 2 cm shell). Obviously placing the conducting shell deeper in the blanket will have marginal adverse effect on TBR.

The tungsten alloy generates the highest amount of decay heat during the first year following shutdown. The Al-6061 alloy is the second leading generator of decay heat during the first day following shutdown if the stabilizing shell is located immediately behind the first wall. However, the level of decay heat drops in comparison to other alloys if the stabilizing shell is located at 30 cm from the liquid first wall due to the soften neutron spectrum. The Cu alloy is another producer of significant amount of decay heat. The low activation ferritic steel and vanadium alloys produce the least amount of decay heat. In addition, these two alloys also would qualify for disposal as low-level waste since their waste disposal ratings (WDR) are the least. The WDR of the W-5Re alloy are above unity based on both 10CFR61 and Fetter criteria. Limiting the level of niobium impurities to less than 1 wppm could reduce the alloy WDR below the Class C limits according to 10CFR61. The Al-6061 will also qualify for disposal as Class C waste according to the 10CFR61 but according to Fetter's limits, Al-6061 is the worst performing stabilizing shell. The WDR of the Cu alloy is too high based on both 10CFR61 and Fetter's limits.

The results given here assume a conducting shell thickness of 1 cm or 2 cm for the several investigated solid alloys. In reality, the required thickness will vary, depending on the conductance of the solid material use for the conducting shell. The results cited here however could be used as guidance to have rough estimates for the change in the response under consideration (e.g. TBR, decay heat, WDR) for other thickness for the conducting shell.

Table 1: The % change in TBR upon including a conducting shell of thickness d
(Flibe with nat. Li/SiC structure- no Be multiplying zone)

Material of Conducting shell	d= 1 cm	d=2 cm
Cu	-3.4%	-6.6%
Al	-3.7%	-6.8%
Ferritic Steel	-0.51%	-1.8%
W	-6.6%	-8.6%
V	+1.8%	+2.5%

Table 2: The % change in TBR upon including a conducting shell of thickness d
(Flibe with nat. Li/SiC structure- with 10 cm front Be multiplying zone)

Material of Conducting shell	d= 1 cm	d=2 cm
Cu	-12.6%	-20.3%
Al	-6.5%	-11.8%
Ferritic Steel	-8.8%	-15.3%
W	-25.2%	-30%

Table 3. Class C Waste Disposal Ratings behind the First Wall.

Alloy	Fetter	10CFR61
ORNL FS	0.97 (^{94}Nb, ^{99}Tc)	0.42 (^{94}Nb)
V-4Cr-4Ti	0.4 (^{26}Al, ^{94}Nb)	0.47 (^{14}C, ^{94}Nb)
W-5Re	29.9 (^{94}Nb, ^{108m}Ag, ^{186m}Re)	11.6 (^{94}Nb)
Al-6061	412 (^{26}Al)	0.34 (^{63}Ni)
Glidcop Cu	23.3 (^{108m}Ag, ^{26}Al)	329 (^{63}Ni)

Table 4. Class C Waste Disposal Ratings 30-cm Inside the Blanket.

Alloy	Fetter	10CFR61
ORNL FS	0.46 (^{94}Nb, ^{99}Tc)	0.24 (^{94}Nb)
V-4Cr-4Ti	0.18 (^{94}Nb)	0.26 (^{94}Nb, ^{14}C)
W-5Re	13.7 (^{94}Nb, ^{108m}Ag, ^{186m}Re)	9.7 (^{94}Nb)
Al-6061	33.4 (^{26}Al)	0.08 (^{63}Ni)
Glidcop Cu	4.7 (^{108m}Ag)	78.1 (^{63}Ni)

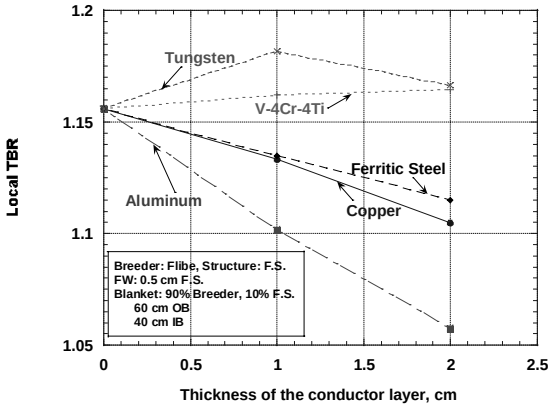

Fig. 1: Local Tritium Breeding Ratio, TBR, as a function of the Thickness of the Conducting Shell Placed in Front of the First Wall

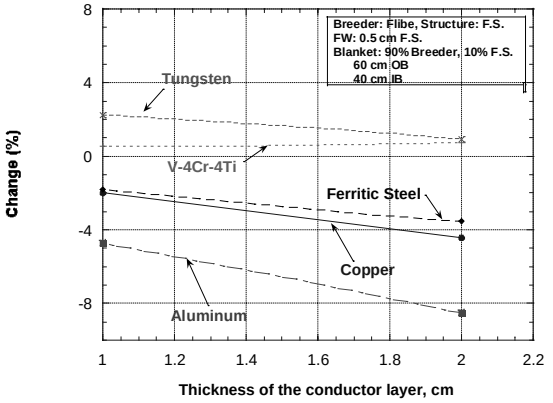

Fig. 2: Percent Change in Local TBR as a Function of the Thickness of the Conducting Layer Placed in Front of the First Wall

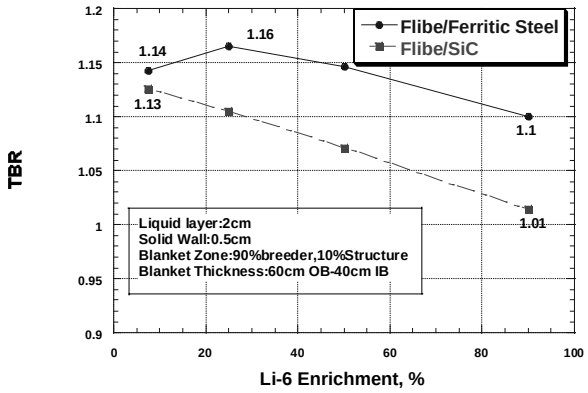

Fig. 3: Effect of Structure Type- Local Tritium Breeding Ratio, TBR, as a Function of Li-6 Enrichment

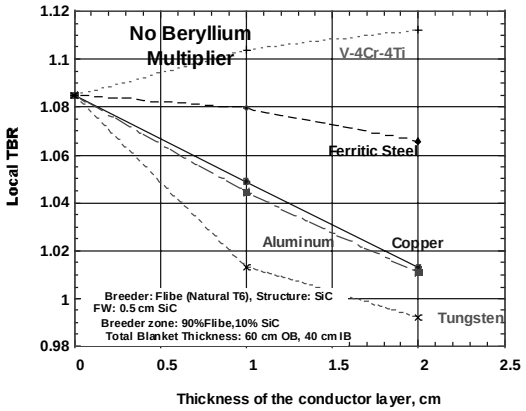

Fig. 4: Local TBR as a Function of the Thickness of the Conducting Shell (CLiFF Configuration: Flibe/SiC-No Beryllium Multiplying Zone)

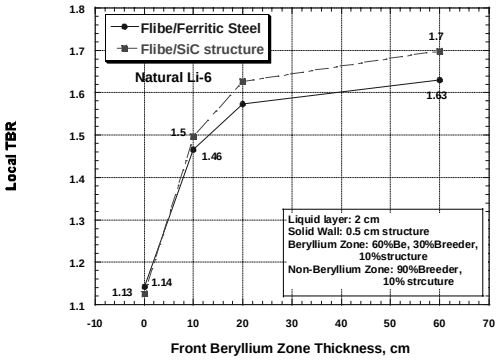

Fig. 5**:** Effect of including a front beryllium-multiplying zone on TBR- natural lithium is used

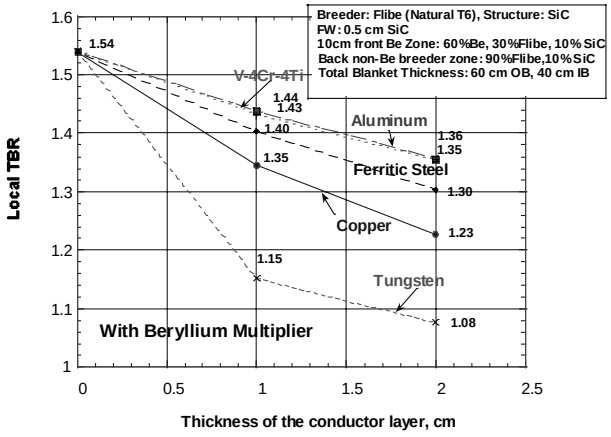

Fig 6: Local TBR as a Function of the Thickness of the Conducting Shell (CLiFF Configuration: Flibe/SiC-With Beryllium Multiplying Zone)

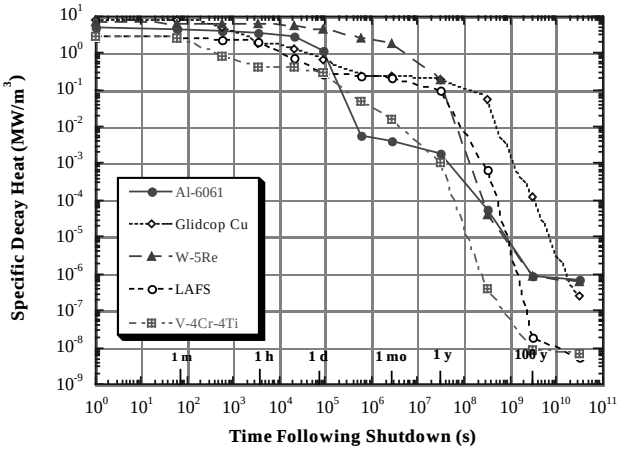

Fig. 7: Decay Heat Generated in the Stabilizing Shell Located Immediately Behind the First Wall.

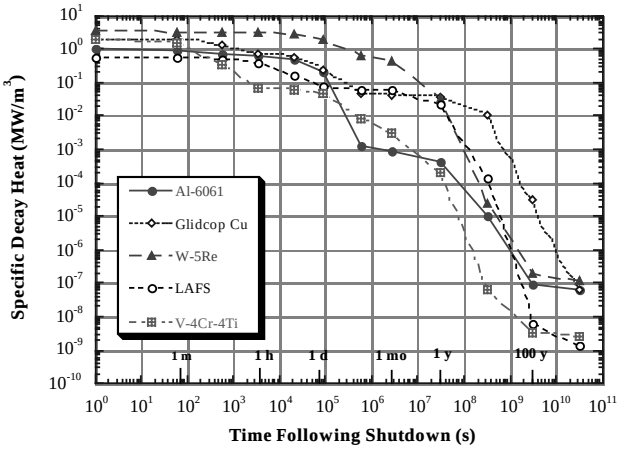

Fig. 8: Decay Heat Generated in the Stabilizing Shell Located at 30 cm from the Liquid the First Wall.

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