March 2, 2000

To: Mike Kotschenreuther and the APEX-core Group
From: Mahmoud Z. Youssef
RE: Effect of including a Conducting Shell on the TBR
DOC Ref: Effect of conducting shell_MZY-3-00

Introduction:

Recent calculations I performed were given to Mike Kotschenreuther showing the impact on tritium breeding ratio (TBR) upon including 1-2 cm-thick solid conducting shell in front of the first wall instead of the convective liquid layer in the CliFF design.of last year [Flibe (25%Li-6)/Ferritic Steel]. In the system for which these calculations were performed, the adverse impact on TBR was small (several %) and manageable. When these results were discussed in the recent Innovative Confinement Concepts workshop, some of the audience raised a concern that the impact should be more severe and they recommended him to speak to the people who do the neutronics analysis for ARIES [LiPb (90%Li-6/SiC]. The purpose of this memo is to resolve this difference in opinion. In fact, when independent investigations were performed by the neutronics team in U. of Wisconsin (Dr. M. Sawan) on similar system, the two independent calculations are very consistent. Before presenting my results, it is very important to bear in mind that the impact of the inclusion of the conducting shell on the TBR is highly dependent on the system under consideration. Among the important variants in the design features of this system are:

(a) Location of the conducting shell (in front of the FW or deeper in the blanket)
(b) The type of breeder and structure (e.g. in ARIES we have LiPb(90%Li-6)/SiC VS Flibe(25%Li-6)/FS in old CliFF design, and Flibe(natural)/SiC with a beryllium multiplier in recent CliFF design of APEX).
(c) The degree of lithium enrichment.
(d) The type of solid conducting shell (e.g. Cu, Al, FS, W, V alloy)
(e) Whether or not there is already a FW to act as a structural support and the conducting shell is placed in front of it.
(f) Whether or not there is a front beryllium-multiplying zone in the blanket.

The most important neutronics features from the calculations that follow are:

(a) Removing the liquid 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). In the later 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.

(b) Placing W as a conducting shell at the FW in front of the beryllium multiplying zone gives the largest adverse impact on TBR (up to ~-30% for 2 cm shell). The least impact is with V and Al conductors (~-12% for 2 cm shell).
(c) Placing W as a conducting shell at the FW in 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.
(d) Obviously placing the conducting shell deeper in the blanket will have marginal adverse effect on TBR.

These features with their explanations are given below for three cases. The radial build of the system is given in Figure 0-a and 0-b. The blanket system is 60cm thick on the OB side and ~40cm-thich on the IB side. The shielding is ~ 60cm thick. There is always a layer of 0.5 cm thick as a FW on both the OB and IB (as opposed to 1-2 cm conducting shell in front of it) which act as the structural support. The vacuum vessel and the TF coil are included in the model.

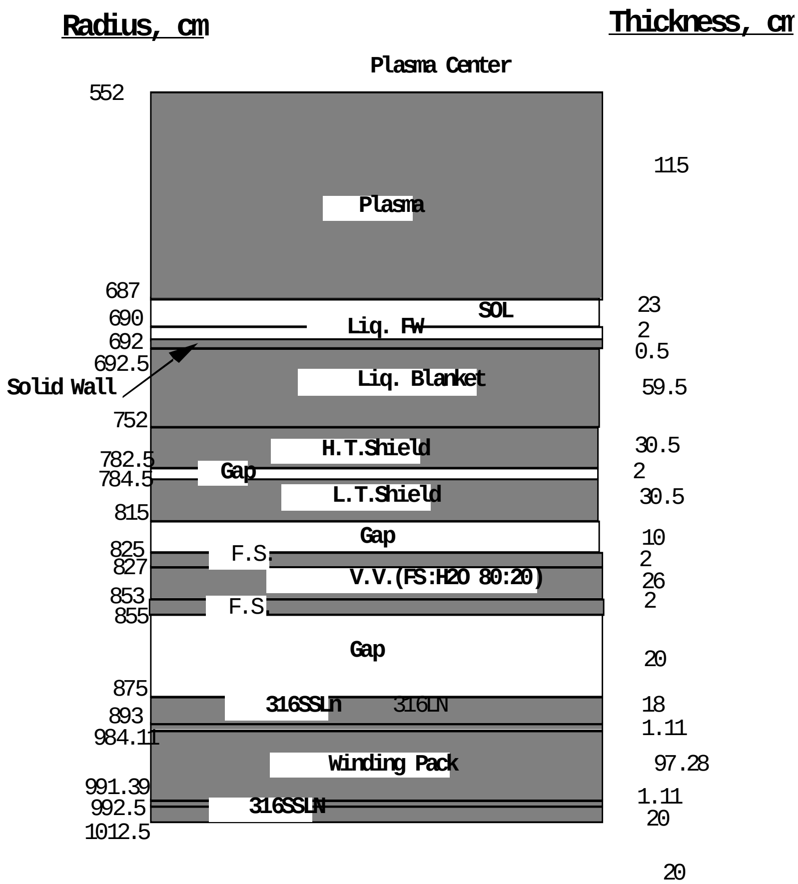
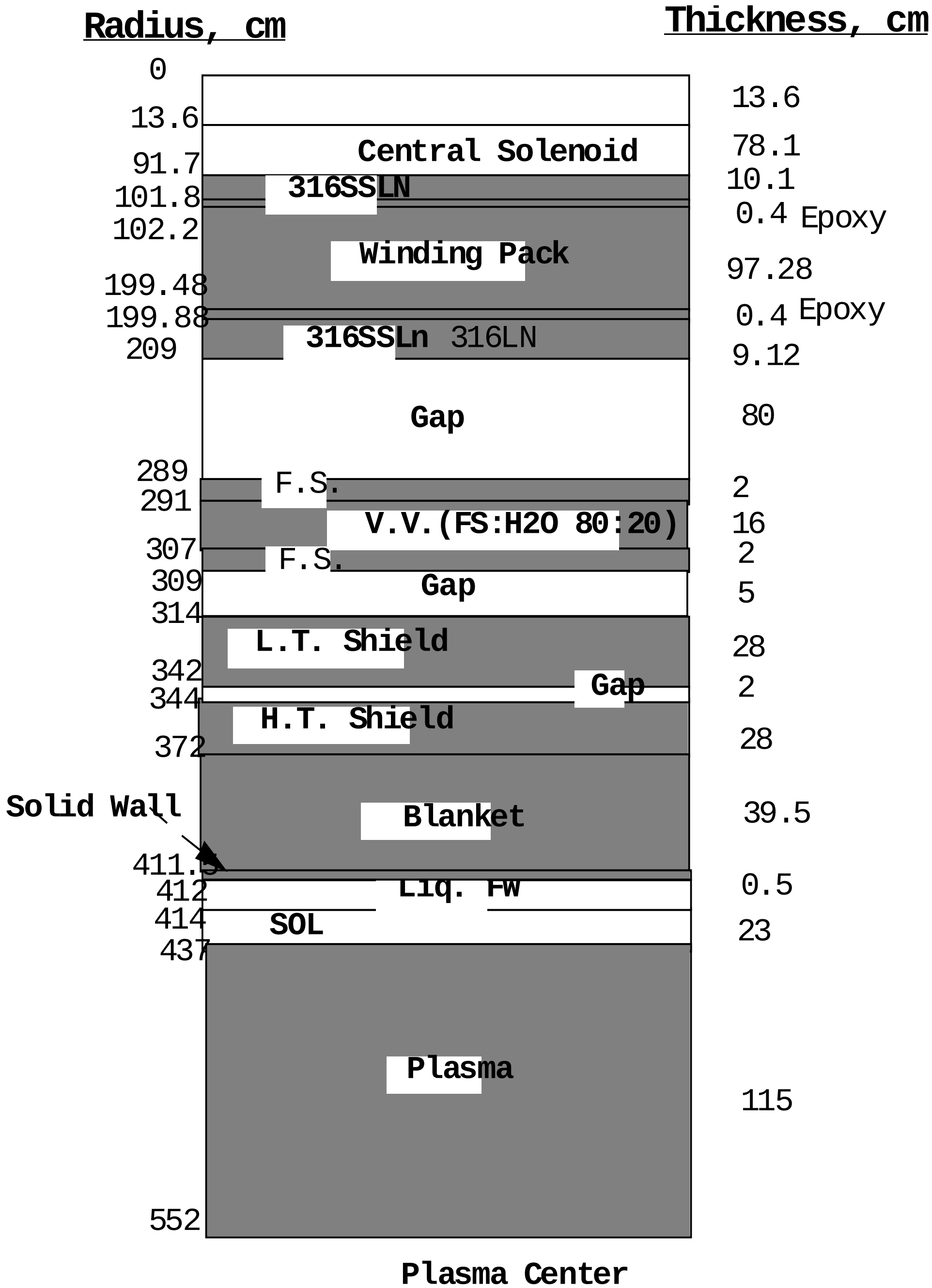


Fig:0-a Radial Build of the O/B CLiFF Concept



High Temp. Shield:15% strc.(V),80%strc.(FS),5
Low Temp. Shield:95% strc.(FS),5%Liq.
Blanket :90%Liq.,10%strc.

Fig:0-b Radial Build of the FFI/B

(A) CliFF design with Flibe/FS structure (No beryllium multiplying zone)

This system is the old CliFF design and is not optimized for TBR enhancement. Ferritic steel is used as the structure. The blanket (60 cm OB, 40 cm IB) does not include a front Be multiplying zone and consists of 90% Flibe and 10%F.S. structure. The shield consists of 5% Flibe and 90% 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 FW 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'a)t reactions at high-energy neutrons.

Fig. 1: The Local TBR as a Function of the Thickness of the Conductor Layer Placed in Front of the FW

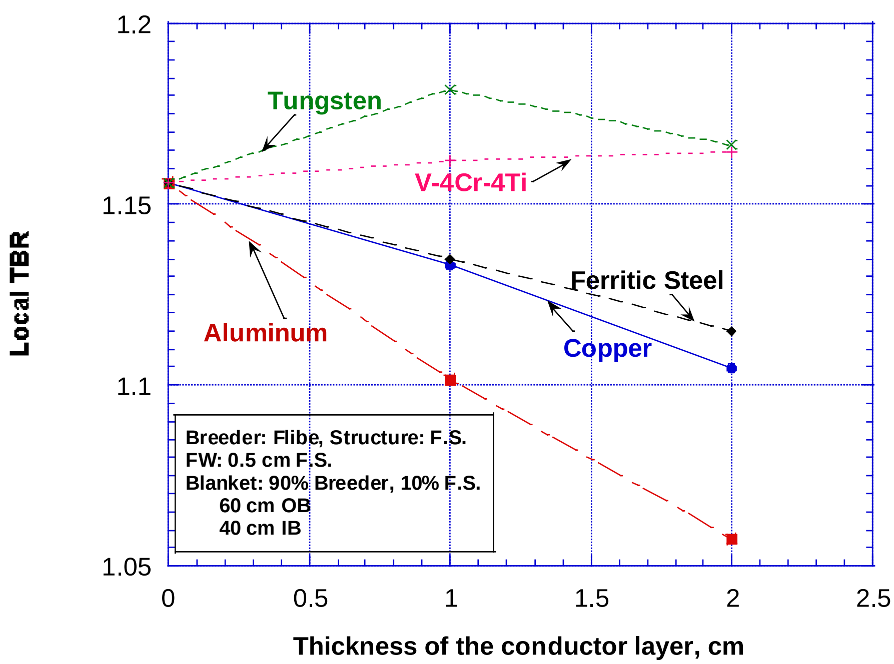
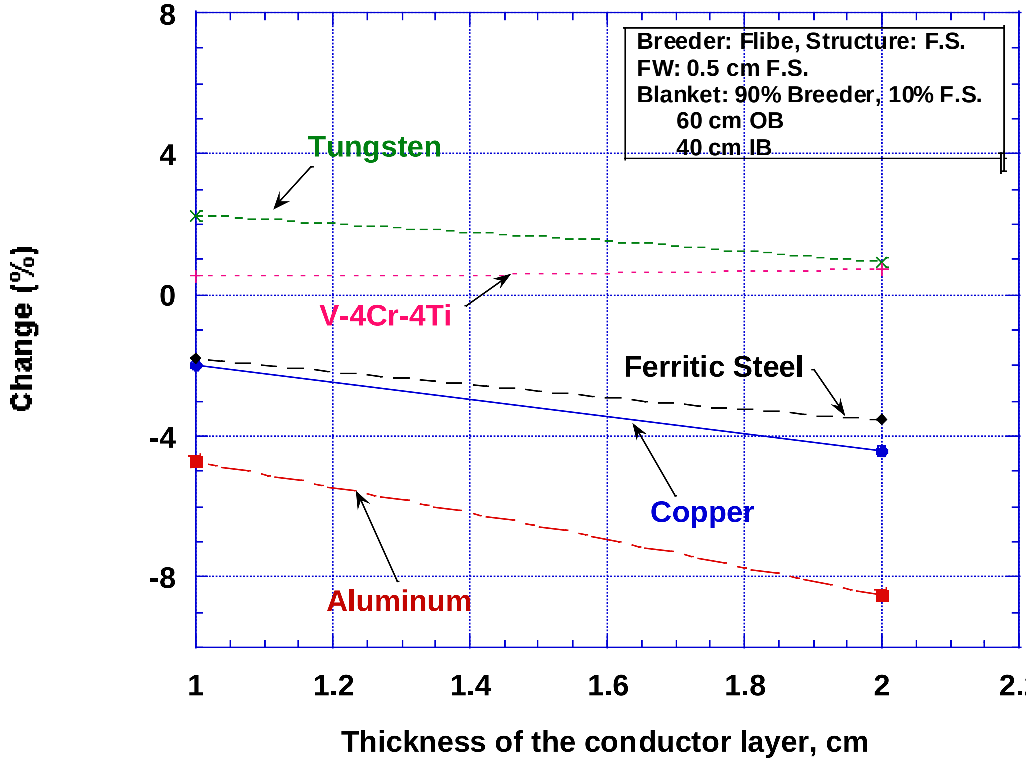


Fig. 2
% Change in Local TBR as a Function of the Thickness of the Conductor Layer Placed in Front of the FW



<u>(B) CliFF design with Flibe/SiC structure (No beryllium multiplying zone)</u>

In this non-optimized 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 Flibe/Ferritic Steel combination gives larger TBR at all Li-6 enrichment than Flibe/SiC combination. Local TBR in the case of Flibe/F.S. peaks around 25% Li-6 enrichment whereas it always decreases with Li-6 enrichment in the case of Flibe/SiC breeder/structure combination. Since SiC is chosen as the structural material in APEX this year (Task III), 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 and 5 show the impact on TBR upon including the conducting shell in front of the FW. Tungsten has the worse impact. Table 1 summarizes the change in TBR.

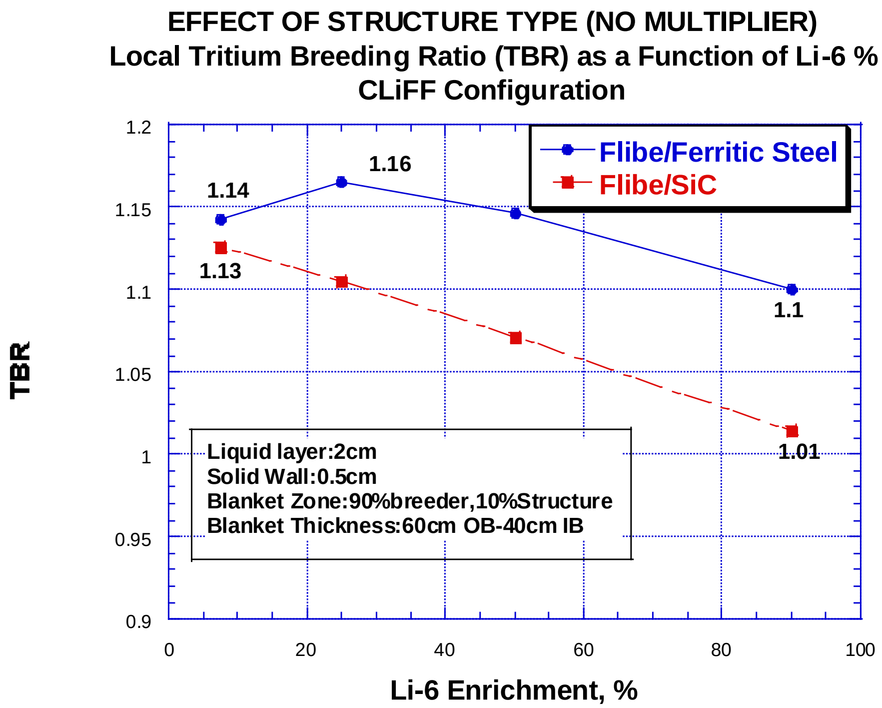


Figure 3: Effect of replacing Ferritic Steel Structure with SiC- No Be multiplying zone

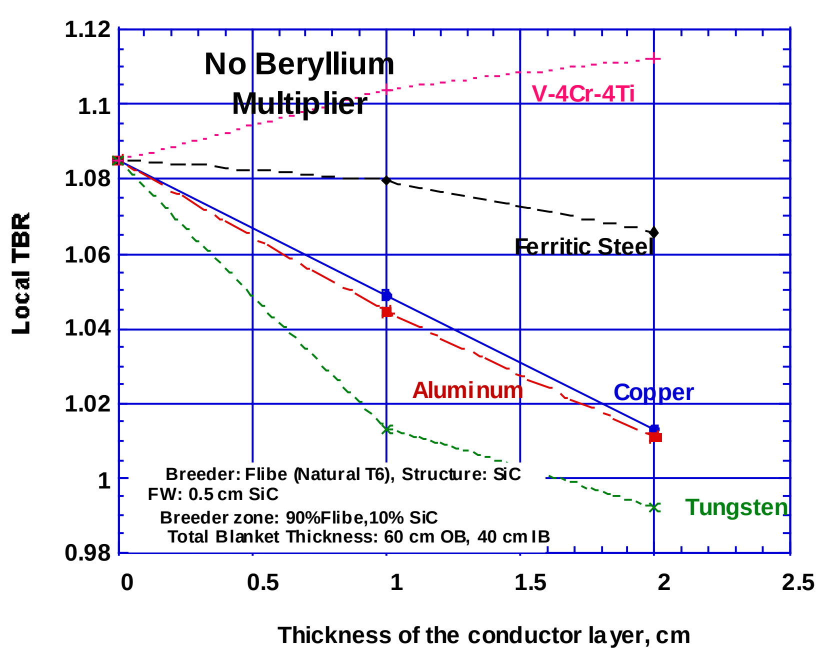


Fig 4: Local TBR as a Function of the Thickness of the Conducting Shell (CliFF Configuration: Flibe/SiC-No Beryllium)

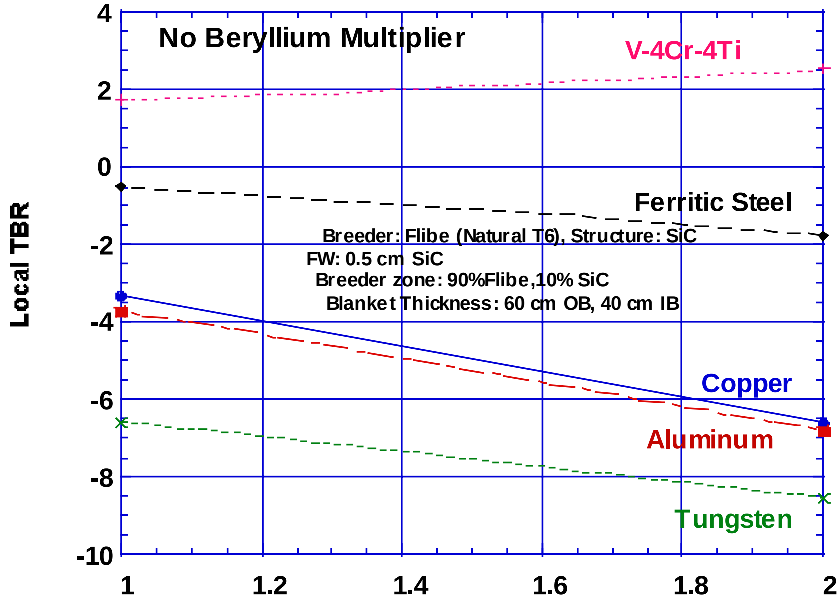


Fig 5: % Change in Local TBR as a Function of the Thickness of the Conducting Shell (CliFF Configuration: Flibe/SiC-No Beryllium)

Table 1: The % change in TBR upon including a conducting shell of thickness d (Flibe with natural 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%

In this system, tungsten has the worse impact on TBR. TBR drop 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'a)t reactions. Note in particular that the absolute value for the TBR 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.

Dr. Sawan (UW) performed Independent calculations in a similar system. His e-mail communication is included in Appendix 1. Table 2: gives % drops in TBR in his system:

Table 2: The % change in TBR upon including a conducting shell of thickness d (Flibe with natural Li/SiC structure- no Be multiplying zone) Independent Calculation in a similar system (See Appendix I)

Material of Conducting shell	d=2 cm
Cu	-10%
Al	-8.7%
Ferritic Steel	-8.4%
W	-10.3%
V	-1.6%

Except for FS and V, the % drop in TBR is comparable. The difference for the FS and V cases could be attributed to the fact that a 0.5 cm-thick SiC FW is included in the model shown in Fig.0-a and 0-b in all cases while it is not considered in the results shown in Table 2. Again, tungsten has the worse impact in this system with natural Li. The situation could be reversed if lithium 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. This also was confirmed by the independent calculations given in Appendix I.

<u>(C) CliFF design with Flibe/SiC structure (With beryllium multiplying zone)</u>

Including a front beryllium multiplying zone (60%Be, 30%Flibe natural, 10%SiC) is a must to improve TBR and ensure tritium self-sufficiency condition. Figure 6 shows how TBR improves as the thickness of this multiplying zone increases up to the total blanket thickness (60 cm OB, 40 cm IB). Figure 6 shows this improvement. Local TBR increases drastically and the effect is more pronounced in the Flibe/SiC combination than in the Flibe/F.S. case. Local TBR can be larger in with Flibe/SiC than with Flibe/F.S. (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 as loge as SiC is used as the structural material. (See correspondence for Task III, memo to Dai-Kai, Feb. 4, 2000, http://www.fusion.ucla.edu/APEX). Since this configuration is most likely to be adopted and tuned for better performance in Task III of APEX study, the effect of including a conducting shell on TBR should be considered here if further investigation on improving the plasma performance with a liquid conducting shell is intended by Mike Kotschenreuther. 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.

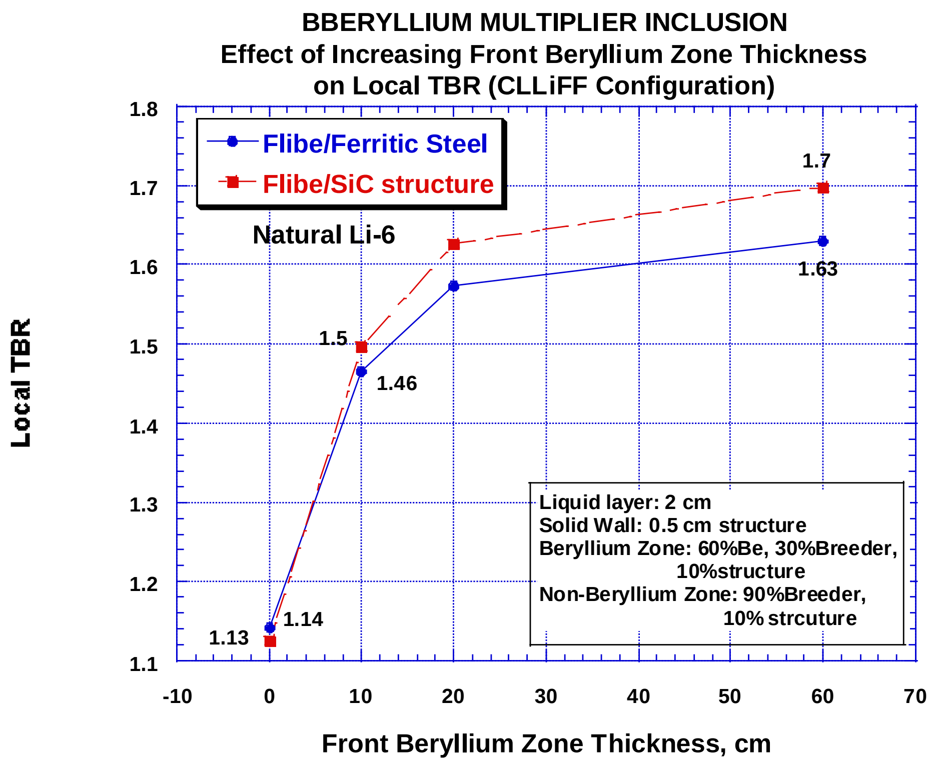


Figure 6: Effect of including a front beryllium-multiplying zone on TBR- natural lithium is used

The reason for the increase in TBR in 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. 7 and 8. And is summarized in Table 3.

Table 3: The % change in TBR upon including a conducting shell of thickness d (Flibe with natural 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%
V	-6.9%	-11.9%

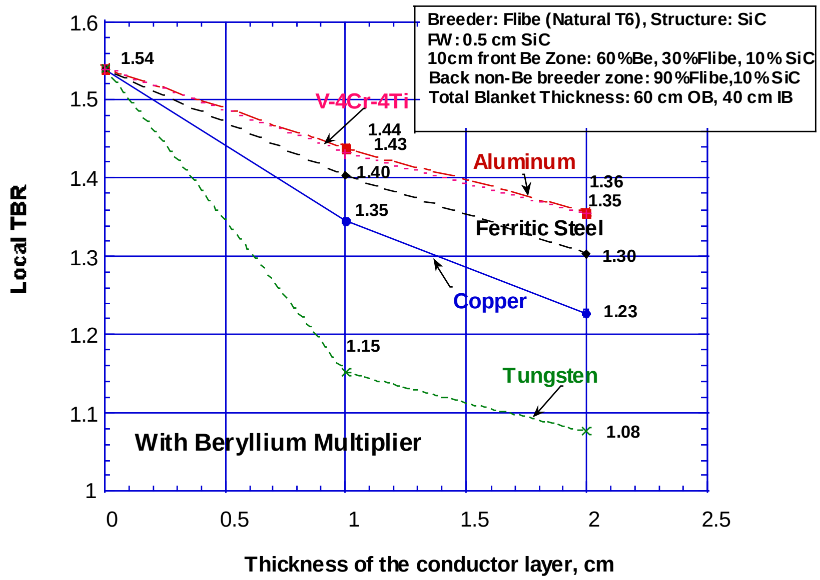


Fig 7: Local TBR as a Function of the Thickness of the Conducting Shell (CliFF Configuration: Flibe/SiC-No Beryllium)

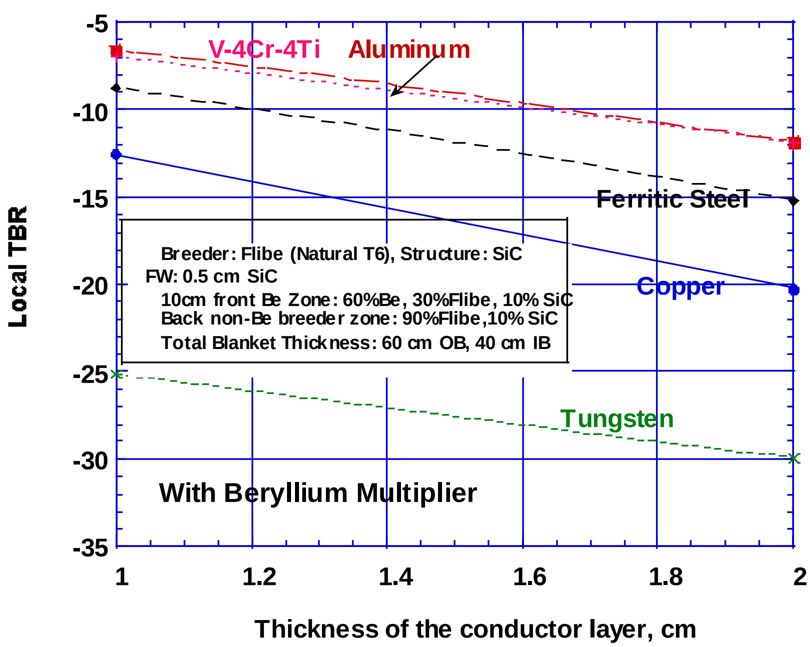


Fig 8: Change in Local TBR as a Function of the Thickness of the Conducting Shell (CliFF Configuration: Flibe/SiC-No Beryllium)

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).

Summary

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. It is obvious that placing the conducting shell deeper in the blanket will have marginal adverse effect on TBR.

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 (optimized design is now in progress in APEX Task III). 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 have 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).

Appendix I

Date: Mon, 28 Feb 2000 16:24:02 -0500
To: Mahmoud Youssef <youssef@fusion.ucla.edu>
From: Mohamed Sawan <sawan@engr.wisc.edu>
Subject: Shell effect
Content-Type: text/plain; charset="us-ascii" ; format="flowed"

Dear Mahmoud,
Here are some of the results that Laila had for ARIES-AT.
Effect of FW/stabilizing shell on local TBR. Blanket is LiPb(90%)/SiC at volume fractions 90/10. The values for the % drop in TBR using 2 cm of each of these materials are as follows
V 8%
W 8%
Al 11%
Cu 12.5%
FS 12.5%
I replaced the LiPb in the design by Flibe with nat enrichment which is representative of the reference for APEX. The volume fraction of SiC in blanket is still 10%. At 2 cm FW/Stabilizing shell, I got the following drops in TBR
V 1.6%
FS 8.4%
Al 8.7%
Cu 10%
W 10.3%
W here has the worst effect. You indicated in your calculations you used 25% Li6 in Flibe and FS structure. You showed improvement in TBR with W. Since (n,2n) is large for W the improvement will be pronounced for enriched cases. To check this, I did the same calculation for W but with the Flibe enriched to 50% Li6. Indeed that was the case and TBR increased as follows:
1 cm W 7.0% increase
2 cm W 7.7% increase
It is clear that the TBR effect of shell material and thickness depends on breeder material, enrichment and structural material.

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