Impact of CaO Coating on Breeding Potential of ARIES-RS Li/V Blanket System

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UNIVERSITY OF WISCONSIN

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L. El-Guebaly and the ARIES Team

Fusion Technology Institute
University of Wisconsin
1500 Engineering Drive
Madison, WI 53706

http://fti.neep.wisc.edu
(608) 263-1623
elguebaly@engr.wisc.edu

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ABSTRACT

A number of studies have proposed several electrically insulating coatings for the vanadium structure to mitigate the magneto-hydrodynamic (MHD) pumping power losses for the self-cooled lithium blanket system. The most practical scenario for power plant designs is to add the coating material to the liquid lithium breeder to help the in-situ self-healing process of the microcracking developed during operation to the microns-thick coatings. To date, the coating research has focused on the MHD resistance, compatibility, adherence, thermodynamic, and interface issues, paying little attention to the nuclear issues. Among many coatings, the U.S. researchers have identified CaO as the leading candidate based on overall but non-nuclear criteria. The emphasis of this assessment relates to the impact of the CaO coating on the tritium breeding ratio (TBR) of ARIES-RS (1), a typical Li/V power plant. Our results indicate up to 10% drop in the overall TBR, depending on the Ca concentration in Li. The nuclear requirements could have an important impact on the choice of coating materials and on the maximum coating concentration in Li. Potential solutions that mitigate the effect of the coating and satisfy the design requirements are discussed.

I. INTRODUCTION

The MHD force and its influence on the pressure drop is a major concern for self-cooled lithium-vanadium systems. If the electrically conductive Li flows across the magnetic field lines, a potential difference across the V walls is induced in the Li, causing an electric current to flow perpendicular to the magnetic field. This results in a mechanical force that leads to MHD pressure drop. An electric insulator coating on the V surface decouples the Li and V structure and prevents the MHD-generated current, mitigating the influence of the magnetic field on the Li flow. The coating must be thin, electrically resistive, durable, radiation resistant, and compatible with Li at temperature up to 700^{o}C. Many oxide (CaO, Y_2O_3, Er_2O_3, $CaZrO_3$, Sc_2O_3, $YScO_3$, BeO, MgO, and $MgAl_2O_4$) and nitride (AlN, Si_3N_4, and BN) coatings are under consideration worldwide. During the past decade, the U.S. effort has focused on CaO and AlN for V alloys because of their solubility in Li, meaning it is possible to have a self-healing coating (2). In the mid-1990s, the AlN coating was ruled out due to a potential reaction between Ti in the preferred V-4Cr-4Ti alloy and the nitride coating. Thus, based on thermodynamic stability in Li systems, CaO has been recognized as the leading candidate for the Li/V blanket (3-6).

This report examines the nuclear-related issues for the CaO coating, specifically the impact of the Ca additive to the Li on the breeding potential of the ARIES-RS blanket. Developed in the mid-1990s by the national ARIES team, ARIES-RS (1,7) is a 1000 MW_e power plant employing Li as the coolant/breeder and V-4Cr-4Ti alloy as the main structure. The 20 cm thick inboard and 50 cm thick outboard blankets supply the needed tritium for plasma operation. Figure 1 shows a vertical cut through ARIES-RS while Figs. 2 and 3 display the internal components of the fusion power core. An overall TBR of 1.13 seems attainable in the absence of coatings. At this early stage of coating development, the precise concentration of Ca in Li and the thickness of the CaO coating on V structure are unknown. So, a wide range of 1-10 atom% Ca dissolved in the Li breeder of ARIES-RS and 1 μm CaO layer bonded to the V structure have been considered in this analysis. The changes in Li properties due to the Ca additive need to be examined for Li systems.

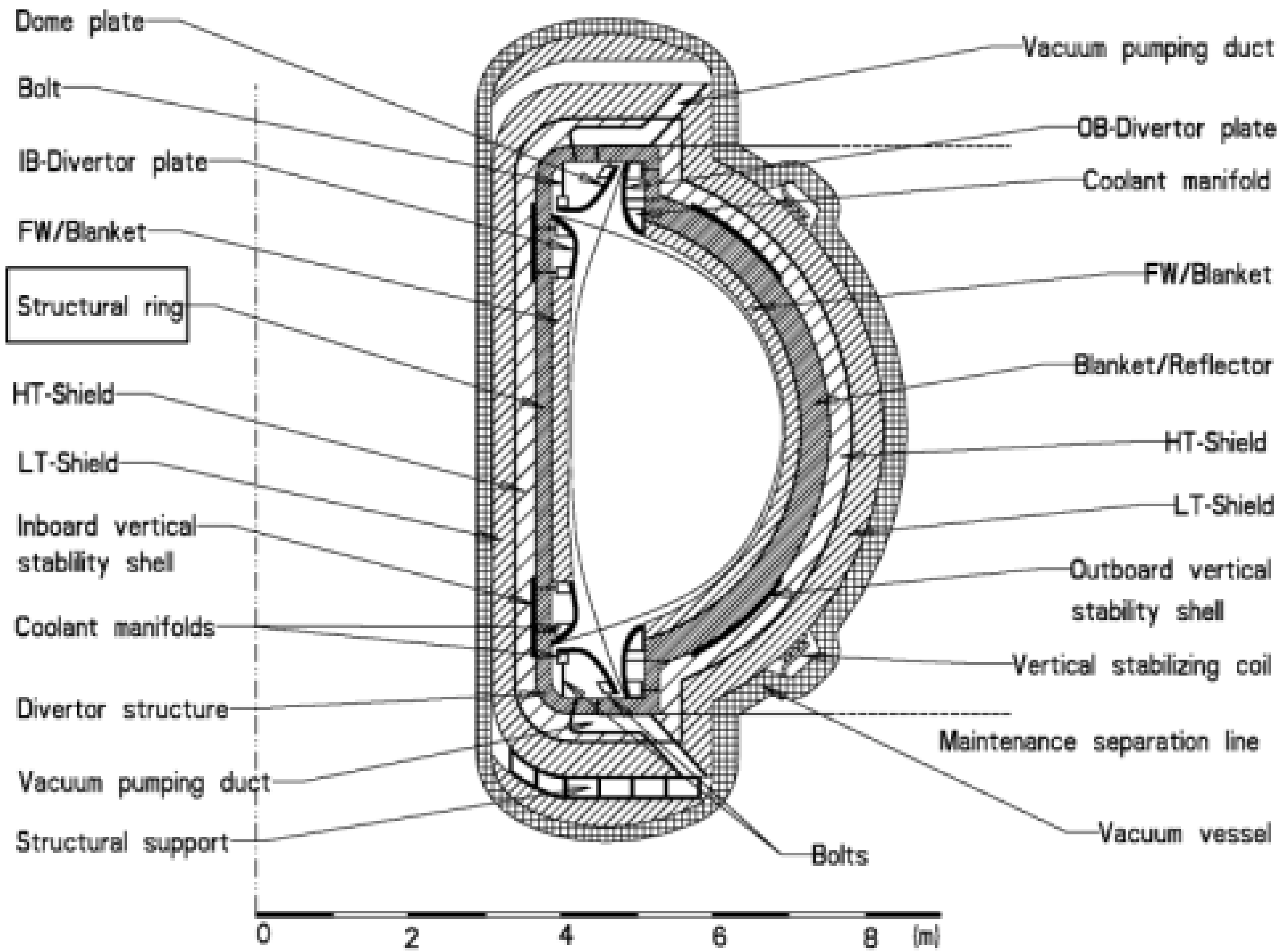

Figure 1. Vertical cross section of ARIES-RS.

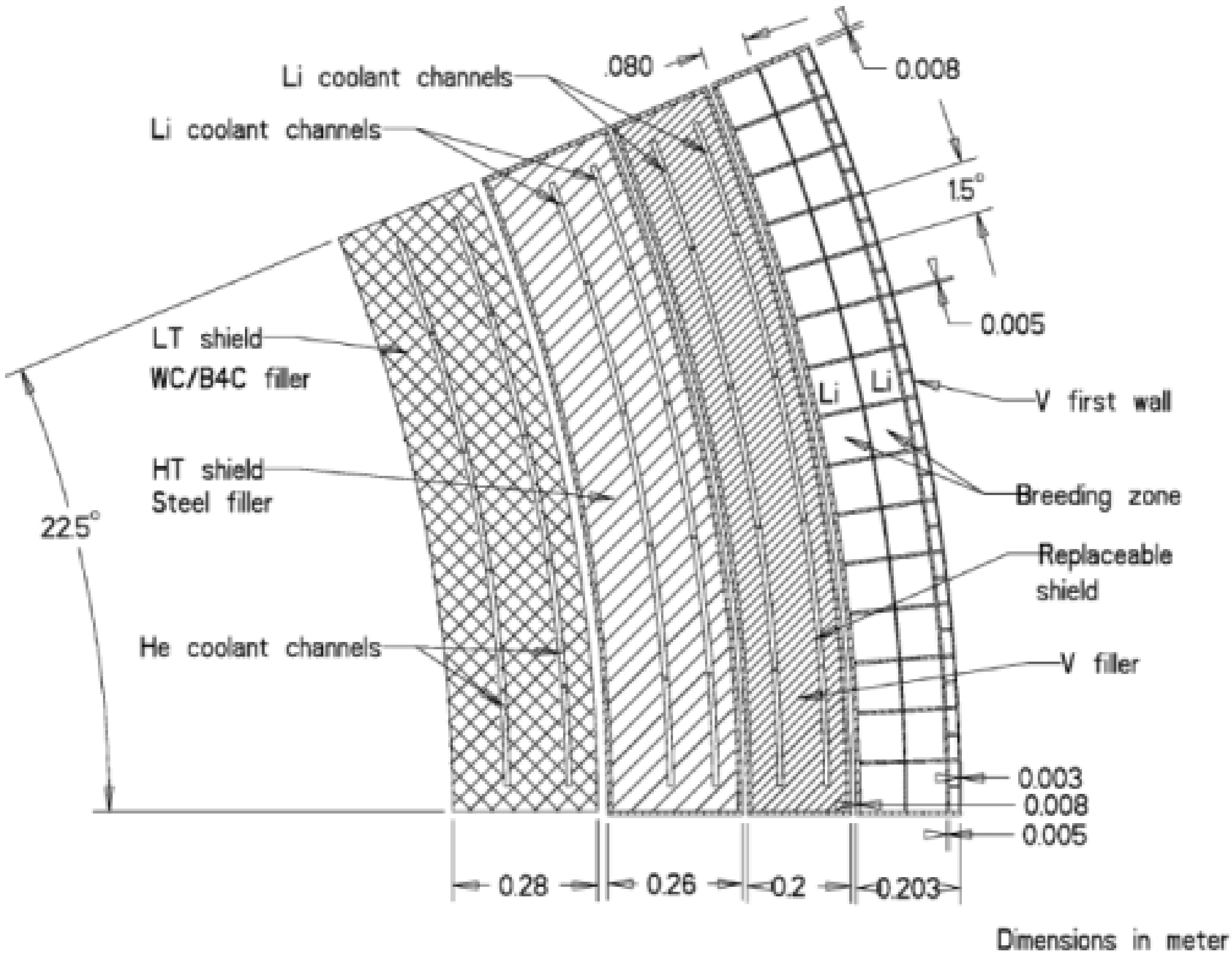

Figure 2. Radial build of ARIES-RS inboard blanket and shield.

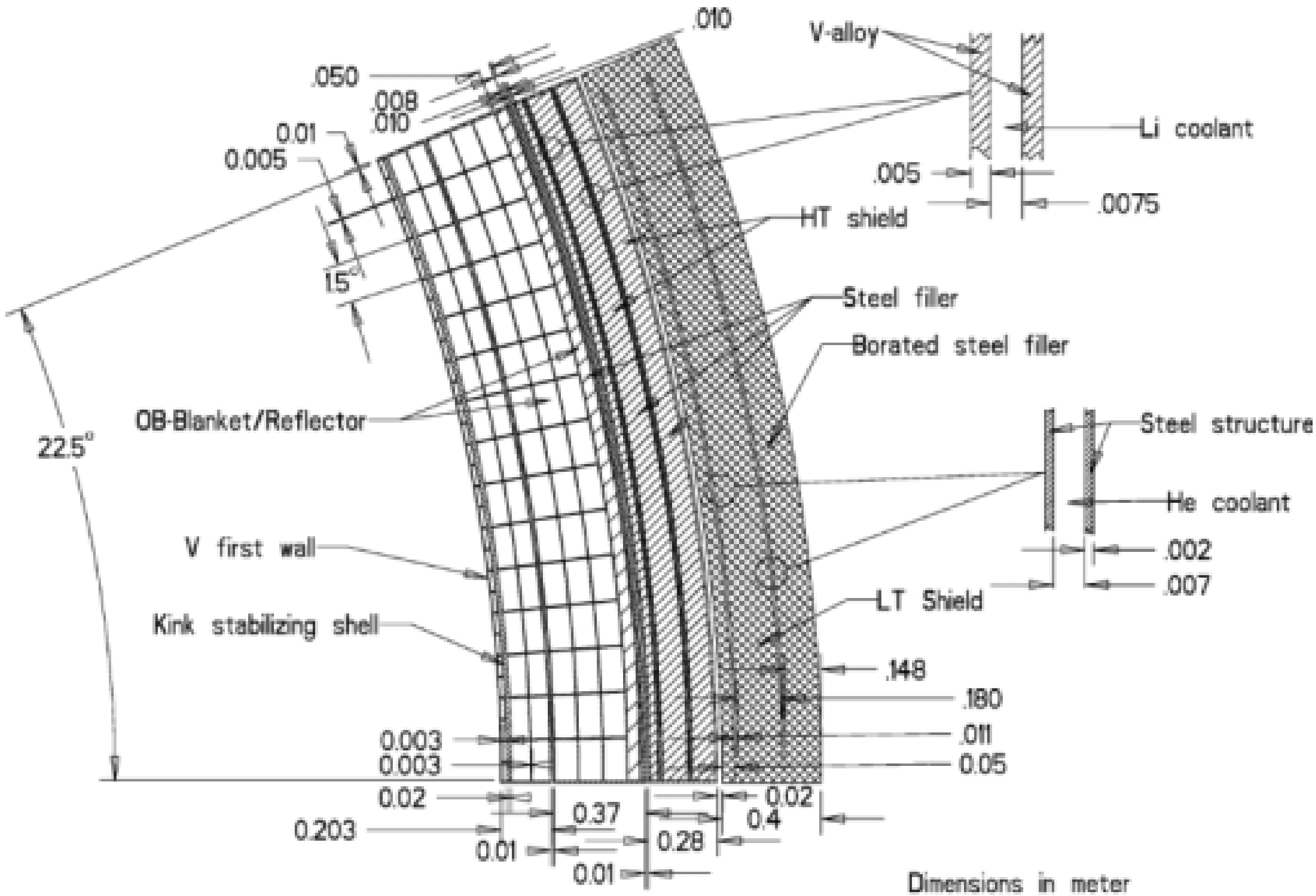

Figure 3. Radial build of ARIES-RS outboard blanket and shield.

II. SPECIFIC REQUIREMENTS FOR COATINGS

Many coating requirements must be considered for fusion applications. Coatings must exhibit high electrical resistivity, good compatibility with Li, high corrosion resistance, good thermal expansion match with V, and high stability during thermal cycling. Additional nuclear-related requirements include high radiation damage resistance, acceptable degradation to the tritium breeding ratio, and attractive safety and environmental features. The coating application method must have the potential for covering large, complex coolant channels and manifolds. Coatings must be applied in-situ after blanket assembly since joining and welding may affect the integrity of the coatings. The potential of the self-healing process of defects is a major requirement as repairing a defect or replacing a component would be difficult and costly. The primary mechanism of in-situ coating formation involves reactions of oxygen from the V alloy with Ca dissolved in Li. Graded coatings typically provide improved bonding to the V structure. Compatibility of coatings with Li at high temperatures (700-800^{o}C) is also a strong requirement. Specific electrical requirements include the product of the electrical resistivity times the coating thickness. This parameter should exceed a nominal value of 100 $\Omega\cdot cm^2$, meaning a minimum resistivity of 10^6 $\Omega\cdot$cm for a 1 μm thick coating or a resistivity of 10^5 $\Omega\cdot$cm for a 10 μm thick coating. Over the temperature range of interest, BN offers the highest resistivity, followed by CaO. Based on the resitivity of all candidate coatings, a 1 μm thick coating or less would be adequate, providing that the change in resistivity during operation is not severe.

III. ASSUMPTIONS AND DESCRIPTION OF NEUTRONICS MODEL

A tritium-breeding ratio (TBR) of 1.1 assures tritium self-sufficiency for ARIES-RS. The 10% breeding margin accounts for the uncertainties in the cross section data (~7%), approximations in geometric model (~2%), holdups and losses during T reprocessing (~1%), and T supply for future power plants (~1%). Reference 7 provides a more detailed breakdown of the breeding margin. Using the DANTSYS (8) discrete ordinates transport code and the FENDL-2 175 neutron 42-gamma group coupled cross section library (9), the nuclear model for TBR included the essential components that influence the analysis, namely the first wall, blanket, and shield. The overall TBR has been estimated by coupling the 1-D results with the 20% and 68% neutron coverage fractions for the IB and OB blankets, respectively.

There is only one 20 cm thick blanket segment on the inboard (IB) side, whereas on the outboard (OB) side there are two segments, as shown in Figs. 2 and 3. The 30 cm thick outer segment is being designed as a lifetime component. The segmentation helps reduce the cumulative OB blanket waste and replacement cost. The blanket contains 10% V structure by volume and the 0.3 cm thick V first wall helps remove the surface heat flux. An overall TBR of 1.13 seemed attainable in ARIES-RS. The OB blanket supplies ~70% of the tritium, the IB blanket provides ~18%, and the Li-cooled divertor and shielding systems supply the balance. The rationale for the blanket and shield designs and the details of the in-vessel components are given in Reference 7.

IV. RESULTS

In the absence of firm data on the allowable Ca concentration in the Li breeder, we parameterized this parameter over a wide range of interest, 1-10 atom% Ca. Figure 4 shows the sensitivity of the overall TBR to the Ca concentration. The TBR ranges from a baseline value of 1.13 to a low value of 1.01 for a 10 atom% Ca in Li. Note that Ca exhibits a higher total cross section than Li for fast neutrons (E > 0.1 MeV) and competes with Li in neutron absorption. The reference ARIES-RS blanket design could tolerate up to 2 atom% Ca, satisfying the breeding requirement without design modifications. To explore the design space beyond the reference point, the OB blanket has been allowed to expand from 50 to 90 cm, covering a Ca concentration span of 5-10 atom%. Figure 5 illustrates a few important points. First, 10 atom% Ca cannot be accommodated in an ARIES-RS-type design as such a high Ca concentration compromises the breeding. Next, a 60 cm OB blanket could accommodate 5 atom% Ca with an adequate breeding margin. Finally, a slightly higher Ca concentration (6-8 atom%) places the breeding margin at risk and calls for more dramatic and costly design changes such as:

- Thickening the OB blanket to more than 60 cm
- Enriching the lithium to 10-20%
- Adding beryllium or Be_2C neutron multiplier to the Li/V blanket.

V. STATUS OF CaO DEVELOPMENT

For coating evaluations, the figure-of-merit is the change in coating resistivity at high temperatures (~700^{o}C) after exposure to Li. Several experiments have been conducted at Argonne National Laboratory (ANL) and Oak Ridge National Laboratory (ORNL) to examine the in-situ fabrication of CaO coating on V, reaction of an oxygen-rich V surface with Ca dissolved in Li, and in-situ electrical resistance measurements of CaO as a function of time and temperature. The ANL experimental results showed that the CaO coating has been fabricated in-situ in a Li-Ca environment, but the coating was nonuniform with many bare V spots, the CaO thickness was much less than desired (<< 1 μm), and the CaO electrical resistivity was adequate at temperatures up to 350^{o}C but dropped substantially at higher temperatures (3). The study concluded that a significant additional effort is needed to develop CaO as a viable coating for Li/V blankets. A more recent ANL testing on the 40 μm thick CaO coating prepared by metal-organic chemical vapor deposition on V alloy showed no crack after several thermal cycles ranging from 25 to 715^{o}C and the coating resistance dropped 100 times at 600^{o}C but still remains high enough for fusion applications (10).

On the contrary, recent experimental work at ORNL has proven that CaO cannot perform adequately at 600-800^{o}C in static Li tests (11-14). The CaO mass losses in Li at these temperatures were unacceptably high for a thin coating. The ORNL results suggest that other oxides with a low solubility in Li will likely have better compatibility. For instance, Y_2O_3, AlN, and Er_2O_3 have shown promise in static Li tests at 800^{o}C with only limited dissolution. There is a need to test these oxides in flowing Li to determine if any of these candidates has sufficient Li compatibility.

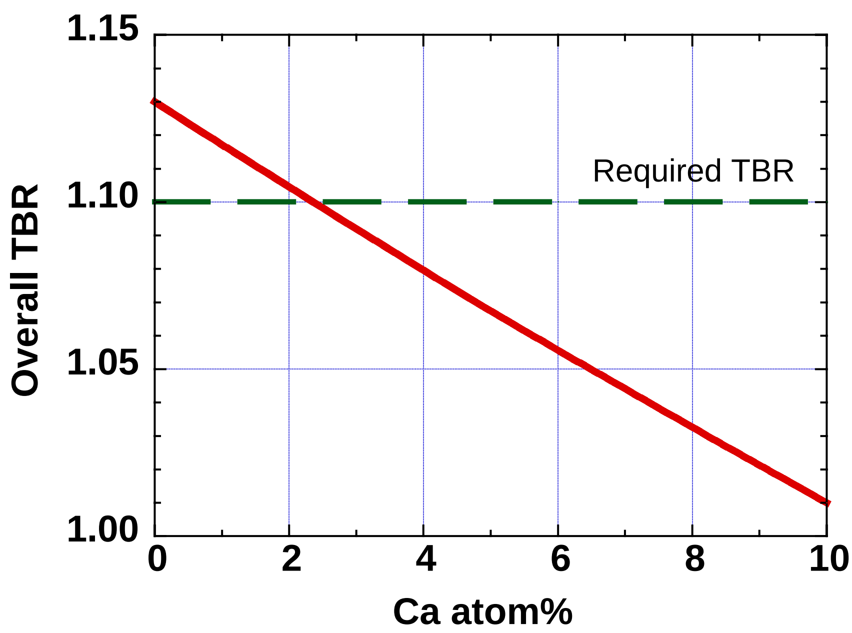

Figure 4. Sensitivity of overall TBR to Ca concentration in Li.

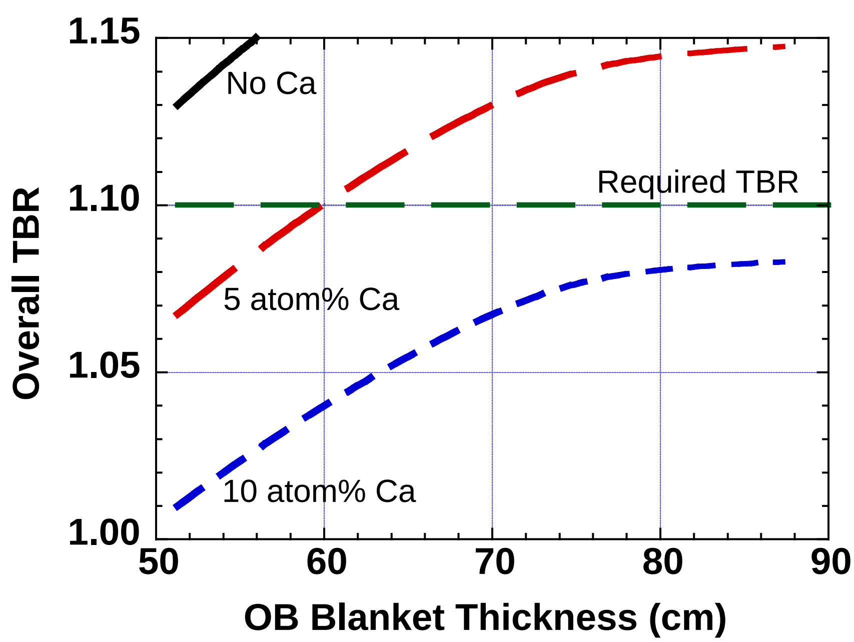

Figure 5. Variation of TBR with OB blanket thickness for 5 and 10 atom% Ca concentrations.

VI. CONCLUSIONS

We examined the sensitivity of the tritium breeding ratio to the Ca concentration in the Li breeder of ARIES-RS, a typical Li/V design. The CaO coating requirements have been fairly well defined in the literature and in-situ self-healing of coating micro-cracks is considered necessary for adequate reliability. However, the concentration of Ca dissolved in Li for the self-healing process is not yet known. We demonstrated that the nuclear requirements could have an important impact on the maximum Ca concentration in Li. The reference ARIES-RS design can tolerate up to 2 atom% Ca in Li without design changes. If the coating requirements call for more than 2 atom% Ca in Li, one or more design changes are necessary to compensate for the breeding losses. Potential solutions that mitigate the effect of the higher Ca concentration (> 2 atom%) and satisfy the breeding requirements include thickening the blanket, enriching the lithium, and/or adding beryllium multiplier to the blanket. Even though these changes have been proposed on the basis of the breeding requirement, the economics and safety implications of such changes must be evaluated for the ARIES-RS design and the like.

Because of its poor high temperature compatibility, the CaO coating development program in the U.S. has been recently concluded (10). Development of other coatings is progressing in the U.S. and worldwide, but no coatings have been tested yet in flowing Li or under irradiation. Our near-term plan is to examine the sensitivity of the tritium breeding to the addition of elements (other than Ca) to Li in order to help the in-situ self-healing process. Future neutronics analyses would examine the nuclear performance of the most recent candidate coatings recommended by ORNL (13) (Y_2O_3, AlN, and Er_2O_3) as well as other potential coatings ($CaZrO_3$, Sc_2O_3, $YScO_3$, BeO, MgO, $MgAl_2O_4$, Si_3N_4, and BN) proposed for Li/V fusion applications. An important outcome of this study would be to exclude some coatings for compromising the breeding of the Li/V system and rank the remaining candidates based on their nuclear performance using the ARIES-RS design operating conditions.

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