Potential Coatings for Li/V System: Nuclear Performance and Design Issues

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Abstract

Many oxide and nitride coatings are under consideration worldwide for vanadium (V) structure to mitigate the magnetohydrodynamic (MHD) pumping power losses for the self-cooled lithium (Li) blanket system. To date, researchers have focused on the MHD resistance, compatibility, adherence, thermodynamic, and interface issues, paying little attention to the nuclear concerns. This assessment examines the nuclear-related issues for the leading coatings proposed for the self-healing approach in particular. Specifically, we assessed the impact of the coating additives to Li on the breeding potential of a typical Li/V system. An important outcome of this study has been to identify the coatings that compromise the breeding and rank the remaining candidates based on their nuclear behavior using the ARIES-RS operating conditions. It appears likely that the nuclear requirements will have an important impact on the choice of the coating material and on the maximum coating concentration in Li. Potential solutions that mitigate the effect of coatings and compensate for the breeding losses are discussed in the paper. However, these solutions introduce additional requirements and concerns that must be considered in future studies.

1. Introduction and background

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 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 inhibits the flow of the lithium and leads to a significant 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.

Several requirements must be considered for coatings. They must be thin (1-10 µm) and exhibit high electrical resistivity, high corrosion resistance, good thermal expansion match with V, and high stability during thermal cycling. Additional requirements include compatibility of coatings with Li at high temperatures (~700^{o}C), high radiation damage resistance, acceptable degradation to breeding, and attractive safety and environmental features.

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 [1-5]. Very few coatings are sufficiently stable at high temperature, but the most promising candidates are AlN, Y_2O_3, and Er_2O_3 [6]. Coatings are fabricated by a variety of techniques. The most practical scenarios include the self-healing and multilayer approaches. Our research aimed at understanding and assessing the nuclear-related issues for the self-healing approach in particular as coating elements dissolved in Li are expected to have a more profound impact on breeding. Specifically, we examined the impact of Ca, Y, Er, N, Al, Zr, and Mg dissolved in Li on the breeding potential of a typical Li/V blanket.

1.1. In-situ self-healing approach

This approach offers the advantage of self-healing the defects and cracks during plant operation as repairing or replacing a V component would be difficult and costly. Adding coating elements to the Li flow has been judged necessary for self-healing of microcracks developed in the micron-thick coatings. It is recognized that coatings must be applied in-situ after blanket assembly since joining and welding may affect the integrity of the coatings. The coating application method must have the potential for covering large, complex coolant channels and manifolds.

During the decade of the 1990s, the US effort focused on both CaO and AlN for the self-healing approach because of the high Ca and N solubility in Li [1,2]. The primary mechanism of coating formation involves reactions of oxygen (or aluminum) from the vanadium surface with calcium (or nitrogen) dissolved in the lithium (refer to

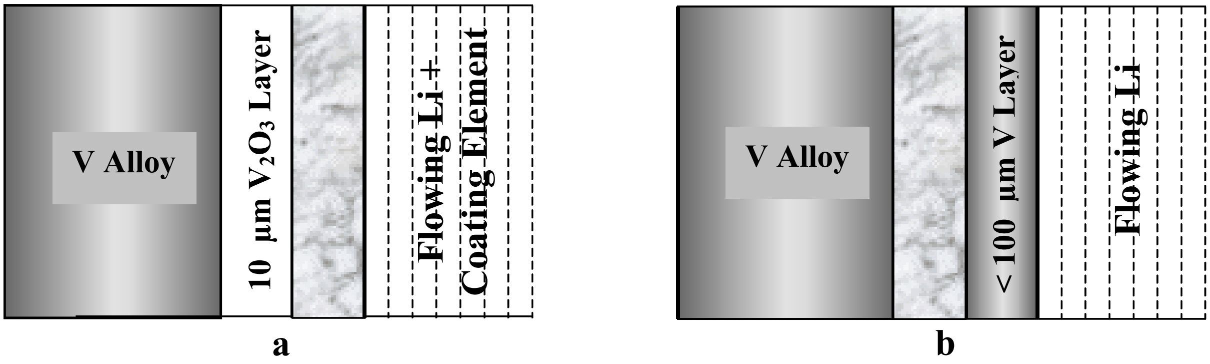

Figure 1. Schematic of coating, V structure, and flowing Li arrangement for the self-healing (a) and multilayer (b) approaches.

Fig. 1a). More recently, two self-healing coatings have been investigated based on Y_2O_3 from Li-Y and Er_2O_3 from Li-Er [4-6].

1.2. Multilayer approach

Because of the likelihood of through-thickness cracks and the high mass losses of coatings at elevated temperature (inherent to the self-healing approach), researchers [6] have investigated the multilayer (or dual) coating approach as a more durable system where the coating is sandwiched between the main V structure and a thin (< 100 μm) V layer facing the flowing Li (see Fig. 1b). This innovative approach solves the compatibility, coating dissolution, and Li wetting issues facing the self-healing approach. However, the fabrication of the multilayer V structure and the integrity of the thin V layer during plant operation are certainly design concerns that need further development and assessment.

2. Assumptions and description of neutronics model

An overall tritium breeding ratio (TBR) ≥ 1.1 assures tritium self-sufficiency for fusion power plants. Reference 7 provides a detailed breakdown of the breeding margin. For instance, a 10% breeding margin could account 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%).

A simple cylindrical model has been developed to estimate the degradation in breeding due to coating additives. The model includes a 42 cm thick blanket (10% V and 90% Li, by volume) closely followed by a thick shield to

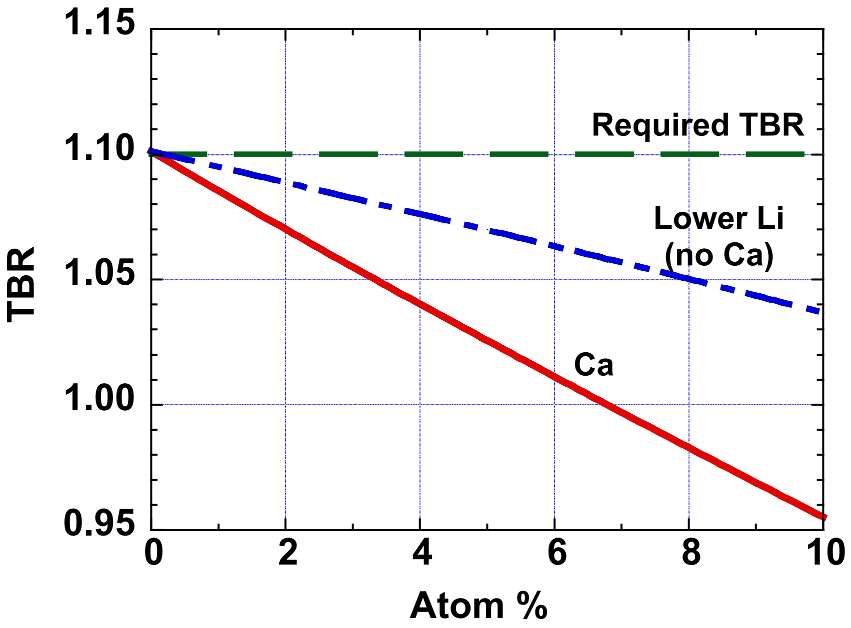

Figure 2. Sensitivity of TBR to Ca added to Li. The "Lower Li" curve reflects the drop in breeding for 1-10 atom% less Li content in the absence of Ca.

account for the proper neutron reflection. Using the DANTSYS [8] discrete ordinates transport code and the FENDL-2 175 neutron 42-gamma group coupled cross section library [9], the model predicts a TBR of 1.1 for a blanket without coating elements. Since yttrium and erbium cross-section data are missing from the FENDL library, we used the MCNP Monte Carlo code [10] and its data library [11,12] for these materials. Ten thousand histories were used to keep the statistical error below 1%. Benchmarking the Ca results showed an excellent agreement between the two codes.

3. Results

At this early stage of coating development, the precise concentration of the coating elements in Li is unknown for most elements. So, a wide range of concentrations (1-10 atom%) has been considered in this analysis. An assumption is made that the coating element atoms replace the Li atoms so that the total number of Li and coating atoms in the blanket remains fixed. To sort out the effect of the lower Li atoms and the addition of coating elements, an initial run involved a gradual reduction of the Li atoms from 1 to 10% with no coatings added to the blanket. Figure 2 shows the sensitivity of TBR to both Li reduction and Ca addition. The TBR ranges from a baseline value of 1.1 to a low value of 0.96 for 10 atom% Ca in Li, representing ~13% drop in breeding. The

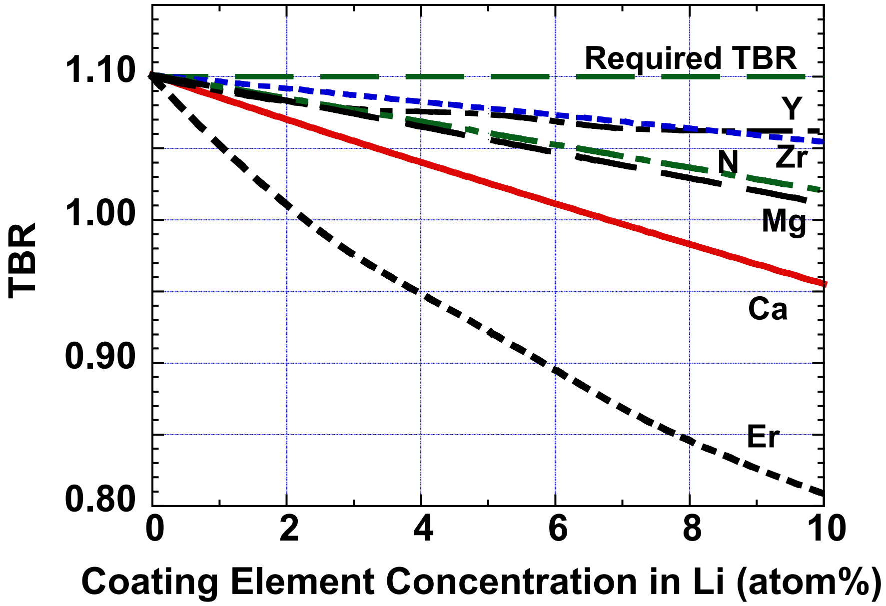

Figure 3. Relative effect of coating materials on breeding of Li/V system.

difference between the two curves reflects the effect of Ca on the neutron balance. Note that Ca exhibits a higher total cross section than Li for fast neutrons (E > 0.1 MeV) and thus competes with Li in neutron absorption.

The sensitivity of TBR to all candidate coatings is displayed in Fig. 3. The results must be regarded as indicative of the relative effect of coating elements. Yttrium and zirconium have a superior nuclear performance compared to other coatings. Apparently, the Y and Zr (n,2n) reactions help compensate for the breeding losses. Magnesium and aluminum (not shown in the figure) behave similarly to nitrogen. Because of the strong absorption for thermal neutrons, erbium results in a dramatic reduction in breeding (27% for 10 atom% Er).

We have incorporated the coatings in the blanket of ARIES-RS [7] to identify potential solutions that could mitigate the breeding losses and satisfy the design requirements. Developed in the mid-1990s by the national ARIES team, ARIES-RS is a 1000 MW_e power plant employing Li as the coolant/breeder and V-4Cr-4Ti alloy as the main structure. There is only one 20 cm thick blanket segment on the inboard (IB) side, whereas on the outboard (OB) side there are two segments, 20 and 30 cm thick. The rationale for the blanket design is given in Reference 7. The nuclear model included the essential components that influence the breeding, namely the first wall, blanket, and shield. An overall TBR of 1.13 seemed attainable in ARIES-RS. This 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.

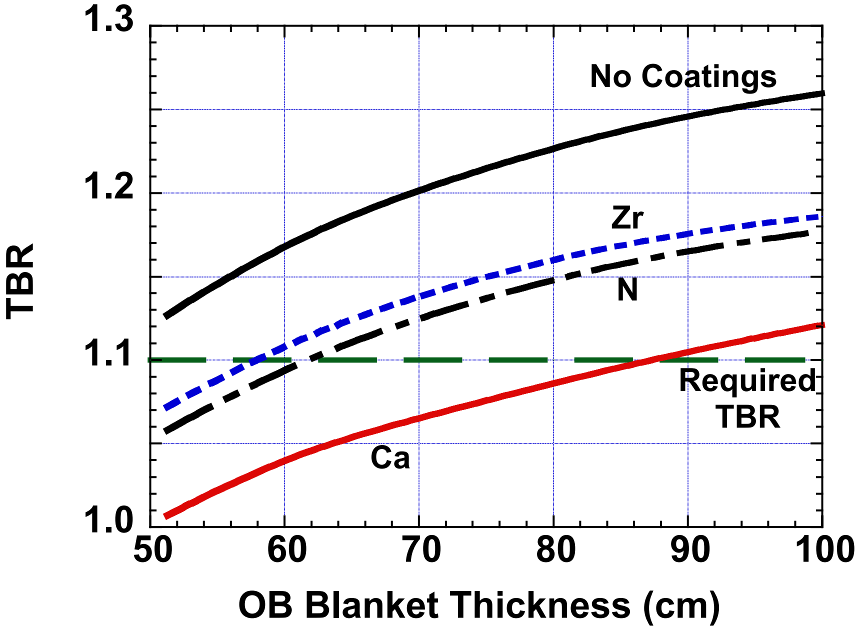

Figure 4. Variation of TBR with ARIES-RS-type OB blanket thickness.

A practical means to compensate for the anticipated breeding losses due to the addition of coating elements to Li involves a thicker OB blanket. To explore the design space beyond the reference ARIES-RS point design, the OB blanket thickness has been allowed to expand from 50 cm to 100 cm mainly to examine two extreme cases: (a) baseline design without coating and (b) 10 atom% coating additives to Li of both IB and OB blankets. Results for 1-9 atom% coating could be interpolated between the two cases. Figure 4 displays the results and illustrates a few important points:

- The reference blanket could accommodate up to 2 atom% Ca, 4 atom% N (or Mg and Al), or 5 atom% Zr (or Y) without any design change and still meet the breeding requirement of 1.1 TBR.
- To accommodate a higher fraction of 10 atom%, the OB blanket thickness should increase from 50 cm to 60-90 cm, depending on the coating materials.

Scaling from the erbium results of Fig. 3, it appears unlikely that the ARIES-RS reference design can tolerate more than 0.5 atom% Er. Even a small concentration of Er (3-4 atom%) will require major design changes such as doubling the OB blanket dimension and/or adding beryllium neutron multiplier to the Li/V blanket. Because of its low solubility, only 0.15 wt% dissolved Er (< 0.01 atom%) is necessary to form Er_2O_3 coating on the V-4Cr-4Ti alloy at 600°C [4]. Admittedly, there is no breeding concern for such a low concentration. However, undissolved Er or excess doping of Er into Li to keep enough Er saturation must be avoided.

4. Conclusions

We investigated, for the first time, the ability of the candidate coatings for the in-situ self-healing approach to degrade the breeding of ARIES-RS, a typical Li/V design. Although the coating requirements have been fairly well defined in the literature, the coating concentration in Li for the self-healing process is not yet known for most elements. In the absence of firm data, we parameterized the coating concentration in Li over a wide range of interest, 1-10 atom%.

Unlike the multilayer scenario, the self-healing approach poses unique breeding challenges. While some coatings exhibit a moderate effect on breeding, the blanket must be substantially modified to accommodate other coatings and compensate for the notable breeding losses. From the breeding perspective, Y and Zr are the best coatings, followed by N, Al, Mg, and Ca. Erbium causes far more degradation to the breeding to the extent that an ARIES-RS like tokamak cannot tolerate more than 0.5 atom% Er without major design changes. Potential solutions that mitigate the effect of coatings and satisfy the breeding requirement include doubling the blanket thickness and/or adding beryllium multiplier to the Li/V blanket. Even though these changes have been proposed on the basis of the breeding requirement, the economic and safety implications of such major modifications must be evaluated for the ARIES-RS design and the like.

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