



**Neutronics Performance Characteristics
of the High Power Density EVOLVE
First Wall/Blanket System**

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NEUTRONICS PERFORMANCE CHARACTERISTICS OF THE HIGH POWER DENSITY EVOLVE FIRST WALL/BLANKET SYSTEM

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ABSTRACT

The neutronics performance of the EVOLVE concept was analyzed using two-dimensional calculations. The vapor fraction in the boiling blanket has a small impact on the nuclear performance parameters. For the worst case condition with the highest predicted vapor fraction distribution, all nuclear performance parameters are acceptable with a comfortable margin. The EVOLVE boiling blanket is expected to perform adequately from the neutronics point of view for any of the boiling regimes considered. Analysis was performed also for a preliminary design of the transpiration blanket option indicating that it will also have adequate nuclear performance parameters.

I. INTRODUCTION

The EVOLVE (EVaporation Of Lithium and Vapor Extraction) concept was developed in the APEX project as an advanced concept capable of handling high power densities with high power conversion efficiency.^{1,2} It utilizes the extremely high heat of vaporization of lithium (about 10 times higher than water) to remove the entire heat deposited in the first wall (FW) and blanket. Boiling lithium at 1200°C, corresponding to the saturation pressure at 0.035 MPa, is contained in a structure made of refractory W-5Re alloys. In the EVOLVE concept, the FW and primary breeding zone are combined in one unit. Behind this unit, there is a high temperature shield in the inboard (IB) side and a secondary breeding blanket in the outboard (OB) region. The OB secondary breeding blanket is followed by a high temperature shield.

Figure 1 shows the configuration of the EVOLVE FW/blanket concept. The FW consists of a tube bank arranged in the toroidal direction. Within each tube is another tube that supplies the liquid lithium to the FW. Capillary forces in a wick structure, attached to the backside of the FW, are employed to transport the liquid lithium to the entire surface of the FW tube. The blanket consists of a number of trays, stacked poloidally, containing liquid lithium. Each tray contains a lithium pool with a height ranging from 19 cm at the front to 16 cm at the back, which is maintained by a system of overflow tubes. The radial thickness of the trays in the OB region is 50 cm while the thickness in the IB region is 40 cm. The lithium in the trays is allowed to boil and the

vapor is routed through the space between trays to a vertical vapor manifold. An alternate blanket design approach is an extension of the FW transpiration-cooling concept. There is no lithium boiling or bubble formation with this approach. The lithium is confined to thin slab zones surrounded by 0.5 mm thick walls with capillary openings. Lithium vapor flows in channels between the liquid lithium slabs.²

Since the lithium density in the FW and primary breeding blanket is low and the trays do not fully cover the FW area, a 40 cm thick secondary breeding blanket is utilized in the OB region to enhance tritium breeding and to improve neutron shielding. The neutron flux in the secondary breeding zone is considerably lower than at the front blanket, allowing the use of a variety of blanket concepts. However, a self-cooled lithium/tungsten blanket (90% Li, 10% W-5Re) concept has been selected in order to limit the number of materials used and to also allow high temperature operation in this zone. Both the IB and OB high temperature shields required for additional shielding of the VV and magnets are also made of W-5Re as structural material and cooled by flowing lithium. Tungsten carbide is used as a shielding material. The composition of shield is 20% Li, 10% W-5Re, and 70% WC. The OB and IB shield thicknesses are 50 and 60 cm, respectively. The VV thickness is 30 cm. It consists of two steel sheets each 5 cm thick sandwiching a 20 cm thick shielding zone made of 80% WC with 20% He coolant.

Lithium tray boiling analysis is underway for the EVOLVE boiling blanket design to determine the vapor fraction distribution. This is expected to impact the nuclear performance parameters. In a previous work, the nuclear performance parameters were determined assuming a uniform vapor fraction of 17% in the trays.³ Initial results obtained using a standard drift-flux model and considering the churn-turbulent boiling regime that does not include MHD effects show a large vapor fraction of up to 65%.⁴ On the other hand, a flow pattern with triggered vapor channels is being analyzed. Preliminary results obtained by applying balances for forces, mass, and energy including static, dynamic, friction, and MHD pressure terms indicate that void fractions below 8% might be achievable.⁴ In this work, we will assess the impact of the lithium vapor fraction in the trays on the nuclear performance parameters of the EVOLVE concept. The design analysis for the

transpiration blanket is progressing.² The preliminary radial build and material composition for that blanket option will be used to compare the expected nuclear parameters with those for the boiling blanket design.

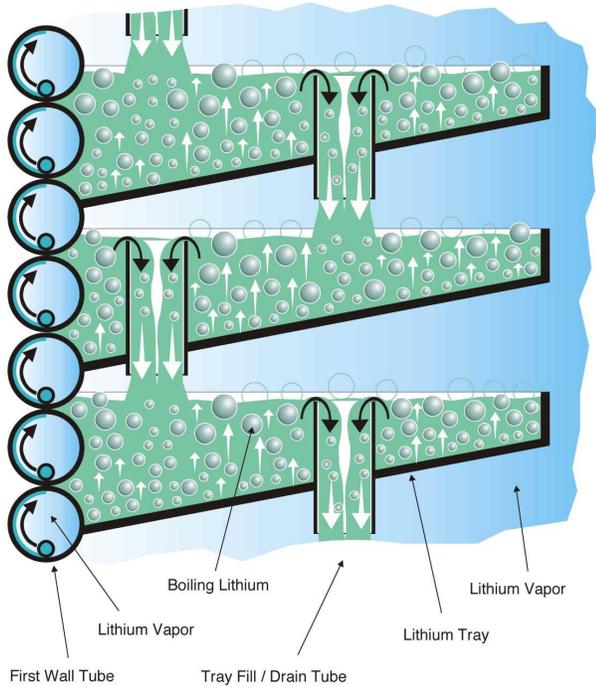


Fig. 1. Schematic of EVOLVE first wall and blanket.

II. NUCLEAR HEATING IN BOILING BLANKET

Two-dimensional (2-D) modeling of the front evaporation-cooled blanket of EVOLVE is needed to properly account for the poloidal heterogeneity and gaps between the trays. In addition, 2-D modeling is required to determine the detailed distribution of nuclear heat deposition in the boiling blanket which is an important input for the lithium boiling analysis. An R-Z geometrical 2-D model was used in the calculation.³ It includes the FW, trays with lithium vapor manifold, secondary breeding blanket, shield, VV, and magnet in both the IB and OB regions. Both the IB and OB regions are modeled simultaneously to account for the toroidal effects. Due to the limitations of 2-D modeling, the trays are assumed to have a uniform height of 17.5 cm. In addition, the detailed FW tube configuration is not modeled and the FW is represented by a 0.6 cm thick plate. These design details require 3-D modeling and are not expected to affect the neutronics results. The TWODANT module of the DANTSYS 3.0 discrete ordinates particle transport code system was utilized in the calculations.⁵

The nuclear heating calculation was iterated with the lithium tray boiling analysis to determine a nuclear heating distribution that is consistent with the vapor fraction distribution. The lithium pool was divided into 25 zones

(5 radial x 5 vertical). The tray bottom and back W plates are 0.5 cm thick. Results were normalized to an OB peak neutron wall loading of 10 MW/m². The distribution of nuclear heating in the OB tray was generated using an initial uniform vapor fraction of 17%. The results were used as input to the lithium boiling calculations with a drift-flux model to produce a new vapor fraction distribution. Subsequently this vapor fraction distribution was used to modify the lithium density distribution in the 2-D model. A new set of nuclear heating values was obtained from the neutronics calculations. The iteration process continued with results converging after 3 iterations yielding a consistent set of vapor fraction and nuclear heating distributions given in Figures 2 and 3. Starting from 17% uniform vapor fraction, the average vapor fraction values after the first, second, and third iterations are 52.4%, 55.6%, and 55.5%, respectively.

	65.2	64.2	63.6	63.1	63.4	
	64.6	63.4	62.8	62.1	62.5	
	63.6	62.4	61.6	60.8	61.0	
	62.1	60.6	59.5	58.5	58.5	
	30.5	29.7	29.1	28.5	28.4	

Fig. 2. Vapor fraction (%) distribution in OB tray.

104.4						
104.5	13.5	11.9	10.4	9.3	8.4	56.7
105.5	13.7	12.1	10.6	9.5	8.5	55.8
106.4	14.1	12.3	10.9	9.8	8.8	54.8
107.2	14.6	12.6	11.5	10.3	9.3	53.8
109.0	27.0	23.1	20.0	17.7	16.0	52.7
109.0	98.0	84.2	72.9	64.1	56.8	50.5
110.0						

Fig. 3. Nuclear heating (W/cm³) distribution in OB tray.

III. IMPACT OF VAPOR FRACTION IN BOILING BLANKET ON NUCLEAR PARAMETERS

The lithium tray boiling analysis using the drift-flux model without MHD effects indicates that high vapor fractions up to 65% might exist in the lithium pool. This is much higher than the 17% average value assumed in previous neutronics calculations. In these calculations, the overall tritium breeding ratio (TBR) was determined to be 1.37 at a lithium enrichment of 40% ⁶Li with no breeding assumed in the divertor region.³ The TBR maximizes at this enrichment due to the relatively high (n,2n) cross sections for W. Higher vapor fractions lead to lower densities in the tray resulting in lower TBR and reduced shielding effectiveness. In addition, the lithium pools with higher vapor fractions are more transparent for neutrons, resulting in a smaller fraction of nuclear heating carried as high-grade heat by the lithium vapor generated in the trays.

Several one-dimensional (1-D) scoping calculations were performed for poloidal sections going through the trays to assess the impact of the vapor fraction on the nuclear performance parameters. Figure 4 shows the impact of varying the vapor fraction in the lithium pool on the TBR. The drop in local TBR at poloidal locations where the trays are located is only ~4% when the vapor fraction is increased from 17% to 60%. More neutrons go through the front of the tray producing more breeding at the back of the tray, secondary blanket, and shield resulting in a relatively small drop in TBR. In other words, while the vapor fraction affects the radial distribution of tritium breeding, it has minimal effect on total TBR. Notice that if a vapor fraction <8% can be achieved with triggered vapor channels, the TBR will increase by <1% compared to the 17% vapor fraction case.

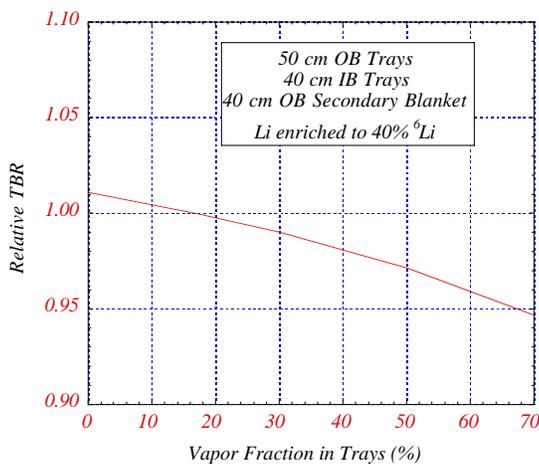


Fig. 4. Impact of void fraction on tritium breeding.

The results for sections through and between trays were combined to determine the fraction of energy carried by the vapor. With 60% vapor fraction in the lithium pool, ~54% of the total energy is carried by the Li vapor compared to 66% obtained using the same analysis with 17% vapor fraction. The impact on the power conversion efficiency remains to be determined. The peak damage (dpa and He production) in the structural material behind the trays is increased by a factor of 1.78. This is not a concern since enough margins existed for these parameters (peak dpa rate in back manifold plate was 7 dpa/FPY and peak end-of-life He in VV was 0.3 appm with 17% vapor fraction).³ The peak fast neutron fluence and insulator dose in the magnet increase by a factor of 1.77. To keep magnet radiation effects at the same level we need to increase the radial build of the shield by about 4 cm. However, this is not needed since magnet radiation effects are still much lower than the design limits. It is concluded that the higher vapor fraction in the lithium trays predicted with the conservative boiling analysis will have minimal impact on the nuclear performance parameters.

IV. TWO-DIMENSIONAL NEUTRONICS WITH DETAILED VAPOR FRACTION DISTRIBUTION

The analysis given in the previous section is based on 1-D calculations at poloidal locations through the trays with uniform vapor fractions. The iterated process between the 2-D neutronics calculations and the lithium tray boiling analysis with the drift-flux model resulted in a detailed vapor fraction profile in the boiling lithium blanket. 2-D calculations have been performed using this vapor fraction profile to determine the nuclear performance parameters and compare them to those obtained from the previous 2-D calculations with 17% vapor fraction.³

The overall TBR is 1.33 without breeding in the divertor region. 61.5% of tritium breeding occurs in the FW and primary breeding blanket (54.9% OB and 15.6% IB). The OB secondary blanket contributes 35.2% of the total overall TBR. The contribution of the shield is only 3.3% (1.2% OB and 2.1% IB). It is clear that tritium breeding has a comfortable margin that allows for design flexibility. Comparing these results to the results of the previous 2-D calculations with 17% vapor fraction, one notices that while the overall TBR is lower by only 3%, more breeding is contributed by the secondary blanket and shield due to the lower attenuation of neutrons in the lithium pool.

Nuclear heating in the blanket and shield components was calculated using the 2-D model. The nuclear energy multiplication, M_n , defined as the amount of nuclear heating per unit neutron energy incident on the FW, is 1.195. This is only 0.3% lower than that with 17% vapor fraction. Nuclear heating partitioning indicates that 65.3% of the nuclear heating is deposited in the evaporation cooled primary blanket. Adding the surface heat deposited in the FW implies that ~70% of the total IB and OB energy is deposited as high-grade heat in the front evaporation cooled zone and is carried by the lithium vapor to the heat exchanger. This is slightly lower than the 76% fraction calculated for the 17% vapor fraction case.

The peak dpa and helium production rates have been determined in the structure using the 2-D model. Figure 5 shows the poloidal variation of the dpa rate around an OB tray. The results are given for the FW, front of secondary blanket, and front of shield. No significant poloidal peaking is observed. Since the source is volumetrically distributed and the poloidal gap between trays is only 1 cm (5% of FW area), the FW and trays intercept most of the source neutrons. The secondary neutrons which give large contributions to radiation damage tend to give nearly poloidally uniform profiles. The peak damage rate in the OB secondary blanket and IB shield is about a factor of ~5 lower than in the FW and, hence, they are expected to have a factor of 5 longer lifetime than the FW and trays. The lifetime of the OB shield is about an order of magnitude longer than for the OB secondary blanket and the IB shield, making it a lifetime component.

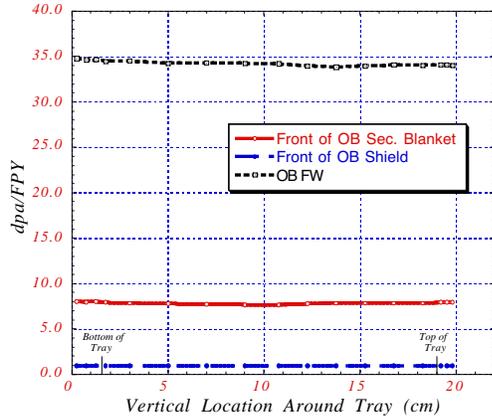


Fig. 5. Poloidal variation of structure damage around tray.

The peak end-of-life He production values in the VV after 30 FPY of plant operation are 0.44 and 0.27 appm on the IB and OB sides, respectively. These values are less than the 1 appm required for reweldability.⁶ Table 1 gives the peak nuclear parameters in the magnet. In this study we adopted the magnet radiation limits used in ARIES-RS.⁷ It is clear that all magnet radiation limits are satisfied with a large margin.

Table 1. Peak Magnet Neutronics Parameters

	IB	OB	Design Limit
Peak Nuclear Heating (mW/cm ³)	0.15	0.10	2
Peak end-of-life Fast Neutron Fluence (n/cm ²)	4x10 ¹⁸	2.7x10 ¹⁸	10 ¹⁹
Peak end-of-life Dose to Polyimide Insulator (Rads)	4.3x10 ⁹	2.7x10 ⁹	10 ¹¹
Peak end-of-life dpa to Cu Stabilizer	1.9x10 ⁻⁷	1.2x10 ⁻³	6x10 ⁻³

Figure 6 shows the nuclear parameters relative to the values obtained using 17% vapor fraction. It is clear that the impact of the high void fraction is small. Notice that even though the 2-D neutronics calculations presented here are for the worst case conditions, all nuclear performance parameters are acceptable with a comfortable margin. Therefore, the EVOLVE boiling blanket is expected to perform adequately from the neutronics point of view for any of the boiling regimes considered.

V. COMPARISON BETWEEN NUCLEAR PARAMETERS FOR TRANSPARATION AND BOILING BLANKETS

The preliminary radial build and material composition for the transpiration blanket was used to compare the nuclear parameters for the EVOLVE boiling and transpiration design options. One should keep in mind that the relative results depend on the assumptions made for material composition. The overall material fractions used in the FW/primary blanket are given in Table 2. It is clear that with these assumptions, the boiling blanket is more transparent for neutrons and gamma photons.

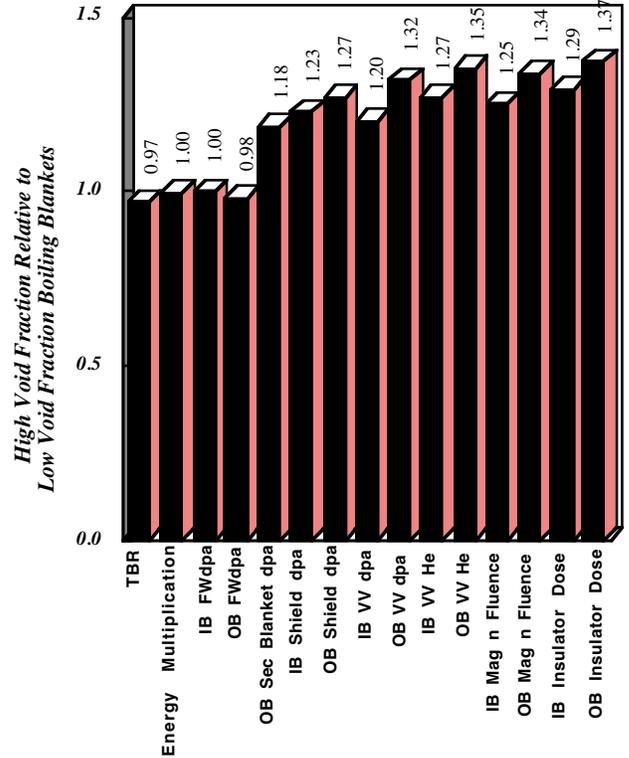


Fig. 6. Nuclear parameters compared to the 17% vapor fraction case.

Figure 7 shows the nuclear parameters for the transpiration blanket relative to those obtained with the boiling blanket. The dimensions and composition of shield, VV, and magnet are kept the same. Slightly higher TBR and energy multiplication result from using the transpiration blanket due to the lower vapor fraction and larger content of Li and W. Neutron multiplication in the larger amount of W contributes also to the larger TBR. A larger fraction of thermal power of ~80% is removed as high-grade heat by the Li vapor in the transpiration design. More neutrons and gamma photons penetrating the more transparent boiling blanket result in generating more nuclear heating in the liquid Li-cooled secondary blanket and shield.

Table 2. Overall Material Fractions in FW and Primary Blanket

	Inboard		Outboard	
	Boiling	Transpiration	Boiling	Transpiration
Thick. (cm)	42.6	42.85	52.6	60.3
% Li	43.4	80.5	43.6	83
% W	2.6	6.7	2.1	6.7
% Vapor	54	12.8	54.3	10.3

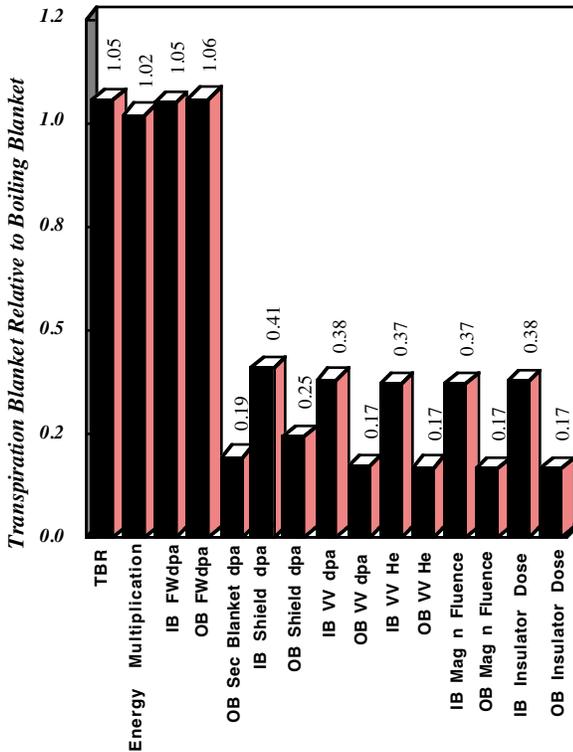


Fig. 7. Nuclear parameters with transpiration blanket relative to boiling blanket.

Higher nuclear heating and damage occur in the FW of the transpiration design due to the larger reflection from the more dense transpiration blanket. On the other hand, the nuclear heating and damage values in the OB components behind the transpiration blanket are a factor of 4-6 lower than for the boiling design due to the thicker and more dense transpiration blanket. Nuclear heating and damage values in the IB components behind the transpiration blanket are a factor of 2-3 lower than for the boiling design due to the more dense transpiration blanket. Neutronics results for the boiling blanket with widely varying vapor fractions (Fig. 6) imply that the shielding impact of void fraction is much smaller than the differences between the transpiration and boiling blankets given in Fig. 7. It is therefore concluded that the larger difference in shielding effectiveness between the transpiration and boiling blankets is attributed primarily to the larger structure content used in the transpiration blanket. Based on these results, the shield radial build in the transpiration design can be reduced by ~10 cm in the OB side and ~5 cm in the IB region compared to the boiling blanket design.

One needs to emphasize that these differences between nuclear parameters for the two blanket concepts are not inherent to the designs but are caused by composition assumptions which need to be verified by more analysis and experiments. The nuclear performance parameters for both designs are acceptable with a large margin implying that the choice between these two options should not be driven by differences in the nuclear performance.

VI. SUMMARY

The neutronics performance of the EVOLVE concept was analyzed using 2-D calculations. Lithium tray boiling analysis is underway for the EVOLVE boiling blanket design to determine the vapor fraction distribution. Preliminary results indicate that vapor fractions as high as 65% might be obtained. 2-D neutronics calculations showed that the higher vapor fraction in the Li trays has a minimal impact on the nuclear performance parameters. Based on the 2-D neutronics calculations for the worst case conditions with the highest predicted vapor fraction distribution, all nuclear performance parameters are acceptable with a comfortable margin. Therefore, the EVOLVE boiling blanket is expected to perform adequately from the neutronics point of view for any of the boiling regimes considered. The neutronics parameters for the preliminary design of the transpiration blanket option were compared to those obtained for the boiling blanket with the largest predicted vapor fractions. The results indicate that with these assumptions, the transpiration blanket has larger Li and structure content resulting in slightly higher TBR and a factor of 2-5 better shielding performance. The nuclear performance parameters for both designs are acceptable with a large margin implying that the choice between these two options should not be driven by differences in nuclear performance.

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