Neutronics Features of a High Power Density First Wall/Blanket with Lithium Evaporation Cooling

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Abstract

Two-dimensional neutronics analysis has been performed for the EVOLVE (EVaporation Of Lithium and Vapor Extraction) FW/blanket concept. The concept utilizes a refractory alloy (W-5Re) structure. The overall tritium breeding ratio is 1.37 at a lithium enrichment of 40% ^{6}Li. The amount of nuclear heat deposited in the different regions was determined. About 76% of the total thermal energy is carried by the Li vapor to the heat exchanger. Since this heat is extracted at a temperature of 1200°C, a power conversion efficiency >60% can be achieved. No significant poloidal peaking is observed in the nuclear heating and damage profiles. Shielding requirements for the vacuum vessel and magnet are satisfied.

1. Introduction

Economically attractive fusion power plants require high power density, high thermal efficiency, and high availability in order to compensate for the high capital costs. The Advanced Power Extraction (APEX) project [1] was initiated to evaluate design ideas for the first wall (FW) and blanket that have potential for enhancing the attractiveness of fusion power systems and to explore the limits of such concepts. As minimum requirements, neutron wall loads >10 MW/m^2 and surface heat fluxes >2 MW/m^2 have been defined, combined with a thermal efficiency >40% in the power conversion system.

The EVOLVE (EVaporation Of Lithium and Vapor Extraction) concept [2] was developed in the APEX project. It utilizes the extremely high heat of evaporation of lithium (about 10 times higher than water) to remove the entire heat deposited in the first wall and blanket. Boiling lithium at 1200°C, corresponding to the saturation pressure at 0.035 MPa, is contained in a structure made of refractory alloys. Both tungsten and tantalum alloys were considered. Figure 1 shows the configuration of the EVOLVE FW/blanket concept. The FW consists of an array of tubes with each having an inner tube with slits that allow the liquid lithium to spray into the annulus of the outer tube and vaporize. The outer tube is 0.3 cm thick and has an inner diameter of 5 cm. The size of the 0.1 cm thick inner tube varies toroidally and an average inner diameter of 1 cm is used in the analysis. Flat trays are attached to the FW and are filled with lithium from the top by a system of overflow pipes. Each tray contains a lithium pool with a height ranging from 18 cm at the front to 14 cm at the back. The lithium flow rate is approximately a factor of ten slower than that required for self-cooled FW/blanket. The low velocity means that an insulator coating is not required to avoid an excessive MHD pressure drop. The radial thickness of the trays in the outboard (OB) region is 50 cm while the thickness in the inboard (IB) region is 40 cm. A vapor manifold back plate with a thickness of 1 cm is used. Since the lithium density in the FW and trays is low and the trays cover only 70% of the FW area, a secondary breeding blanket is utilized in the OB region to enhance tritium breeding and to improve neutron shielding. High temperature shields are utilized in the IB and OB regions to meet the shielding requirements of the vacuum vessel (VV) and magnets. The same coolant (lithium) and structural material is used in all FW, breeding, and shielding zones. The two chamber coolant streams (Li vapor and liquid Li) are fed to two heat exchangers to transfer the thermal energy to a helium loop.

Neutronics and shielding calculations have been performed for the EVOLVE concept. The calculations were carried out in two stages. One-dimensional (1-D) scoping calculations were performed to optimize the blanket design in order to achieve attractive nuclear performance. These calculations were used also to determine the radial build required to provide adequate shielding for the vacuum vessel (VV) and magnet. These calculations were followed by two-dimensional (2-D) calculations to evaluate the nuclear performance parameters for the reference design.

2. One-dimensional scoping analysis

One-dimensional calculations were performed at different poloidal locations through and between the trays. The ONEDANT module of the DANTSYS 3.0 [3] discrete ordinates particle transport code system was used along with nuclear data based on the FENDL [4] evaluation. The results were coupled with the appropriate coverage fractions to estimate the overall nuclear parameters. Both the IB and OB regions were modeled simultaneously to account for the toroidal effects. The results were normalized to OB and IB wall loadings of 10 and 7 MW/m^2, respectively. The Li density in trays and

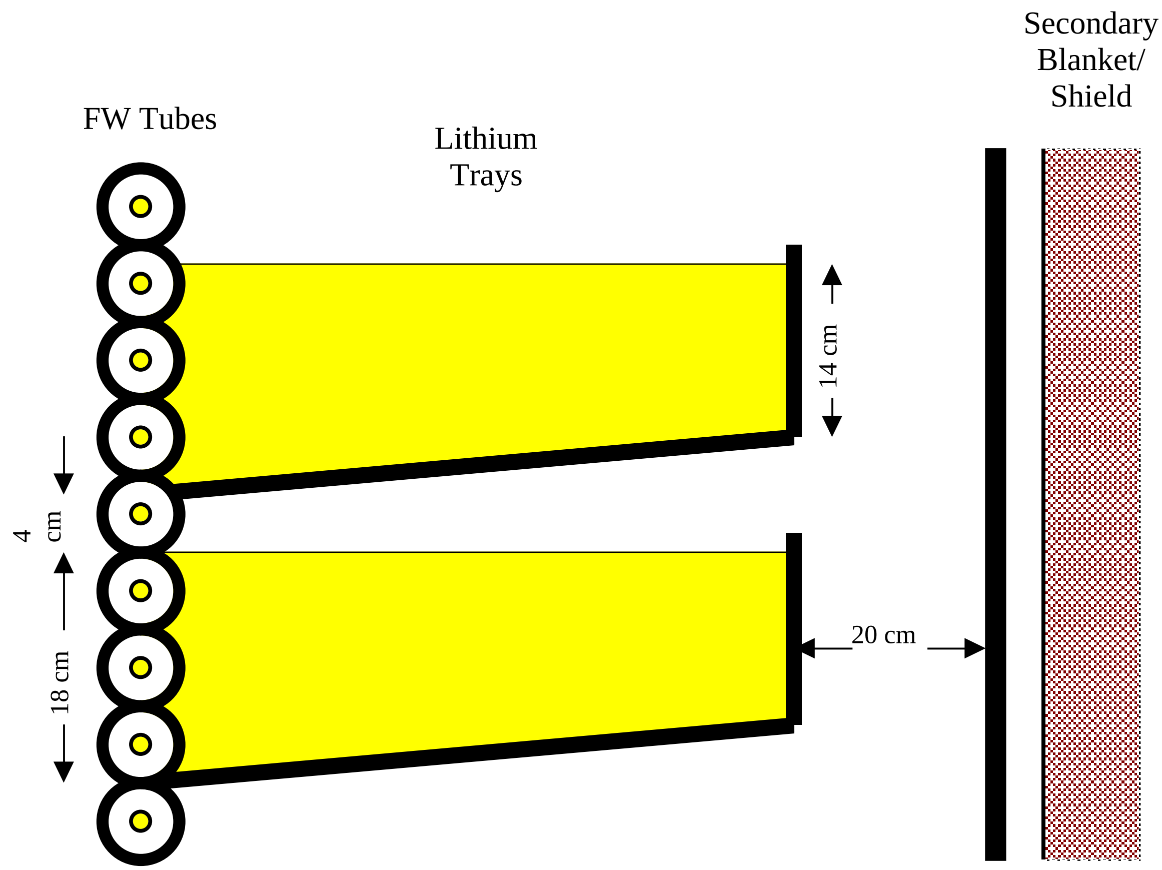

Fig. 1. Configuration of the EVOLVE FW/blanket concept.

FW is taken to be 0.35 g/cm^3 based on the density at saturation temperature and assuming 17% average vapor fraction.

2.1 Tritium breeding

The local tritium breeding ratio (TBR) was determined in the OB and IB trays for the two candidate refractory alloys. Figure 2 compares the OB local TBR with W and Ta alloys. Using W alloy results in ~10% higher TBR compared to the case with Ta alloy. In addition, W has better strength, higher thermal conductivity, and better compatibility with Li while Ta has the edge in the area of fabrication and welding. W-5Re alloy is used in the reference design. The local TBR values for the trays were modified by the trays' coverage fraction (72.7%) to determine the local OB and IB TBR values. The overall TBR depends on the neutron coverage fractions (NCF) of the regions surrounding the plasma. The relative NCF for the IB and OB regions varies significantly with the aspect ratio. In APEX, neutron coverage fractions of 75%, 15%, and 10% for the OB, IB, and divertor regions, respectively, were assumed corresponding to an aspect ratio of 2.5. The resulting overall TBR values are significantly below unity. Therefore, a 40 cm thick secondary breeding blanket is utilized in the OB side to enhance the overall TBR. The neutron flux in the secondary breeding zone is considerably lower than at the front, allowing the use of a variety of blanket concepts. For simplicity reasons, however, a self-cooled lithium/tungsten blanket concept has been selected as the reference solution. Using W structure in the secondary blanket reduces the number of materials used and allows use of

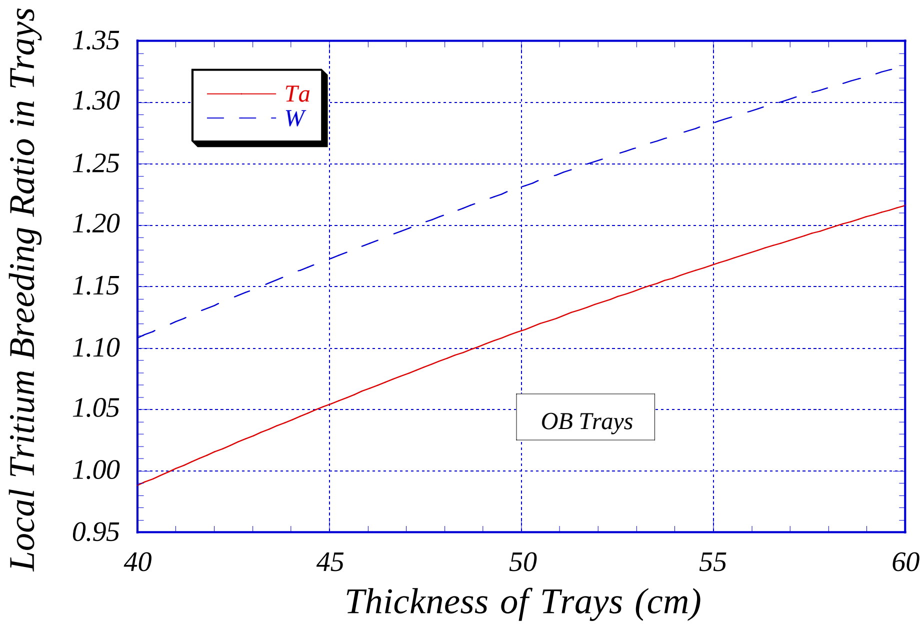

Fig. 2. Impact of structural material on local TBR.

high Li temperature for efficient power conversion. In addition, using W structure results in a lower damage rate compared to steel (factors of ~3 lower dpa and ~50 lower He production). The secondary blanket was assumed to consist of 90% Li and 10% W. 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 considered to be 20% Li, 10% W-5Re, and 70% WC.

The effect of enriching the lithium on the TBR was assessed. Modest Li enrichment (30-50% ^{6}Li) enhances the TBR. The TBR enhancement with enrichment is lower in the trays, with less structure, than in the secondary blanket and shield. Less than 1% of tritium breeding takes place in the FW. In this work, we made the conservative assumption of no breeding in the divertor region. Figure 3 gives the overall TBR as a function of Li enrichment. The TBR maximizes at 40% ^{6}Li with a value of 1.336. This is ~22% higher than the value for natural Li. Lithium enriched to 40% ^{6}Li is considered in the reference design. Tritium breeding has a comfortable margin that gives the flexibility to reduce the thickness of the breeding zones, allow for higher vapor content in the front zone, increase thickness of the structure, or include more shielding material in the secondary breeding blanket.

2.2 Nuclear heating and radiation damage

Nuclear heating in the blanket and shield components were calculated at locations through and between the trays. Most of the nuclear heating (~60%) is deposited in the front blanket. Adding the surface heat deposited in the FW implies that ~66% of the total energy is deposited as high-grade heat in the front evaporation-cooled zone and carried to the heat exchanger by the Li vapor.

The peak W structure nuclear heating and damage in the blanket and shield components have been calculated at locations through and between the trays. The peaking in the manifold backplate,

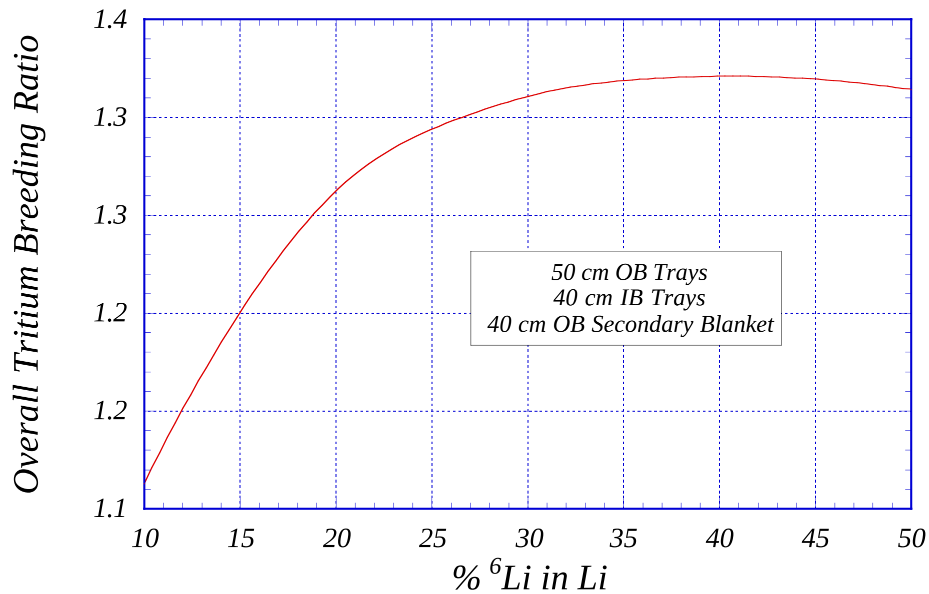

Fig. 3. Effect of Li enrichment on overall TBR.

secondary blanket, and shield resulting from streaming between the trays is a factor of ~3-5 for nuclear heating and dpa and ~8-11 for He production. The values between the trays are based on 1-D calculations and are very conservative estimates since the space between the FW and secondary blanket is assumed to be completely empty.

2.3 Shielding requirements

The VV is located behind the shield. It consists of two steel sheets each 5 cm thick sandwiching a 30 cm thick shielding zone made of 80% WC and 20% He. For the VV to be reweldable, the cumulative helium production in the structure should not exceed 1 He appm. The shield thickness needed to reduce the peak end-of-life helium production in the VV to less than 1 He appm was determined. The plant lifetime is assumed to be 30 full power years (FPY). The calculations were performed using the 1-D model for the section between the trays where VV damage is expected to be the highest. Figure 4 shows the effect of shield thickness on the peak end-of-life helium production in the VV. Based on these results, the reference design uses a 50 cm thick OB shield and a 60 cm thick IB shield.

Adequate shielding must be provided for the superconducting magnets such that their performance is not degraded by neutron and gamma radiation. The component most sensitive to radiation is the organic insulator because of possible degradation in mechanical strength. Radiation damage could also affect the critical properties of the superconductor and the resistivity of the copper stabilizer. In addition, magnet nuclear heating that is removed by cryogenic liquid helium should be limited. We will assume that the magnet radiation limits are similar to those adopted in the ITER design [5]. These are end-of-life fast neutron fluence of 10^{19} n/cm^2, end-of-life dose to the insulator of 10^9 Rads, 6×10^{-3} end-of-life dpa to Cu stabilizer, and 1 mW/cm^3 peak nuclear heating. The results indicated that all magnet radiation limits are satisfied.

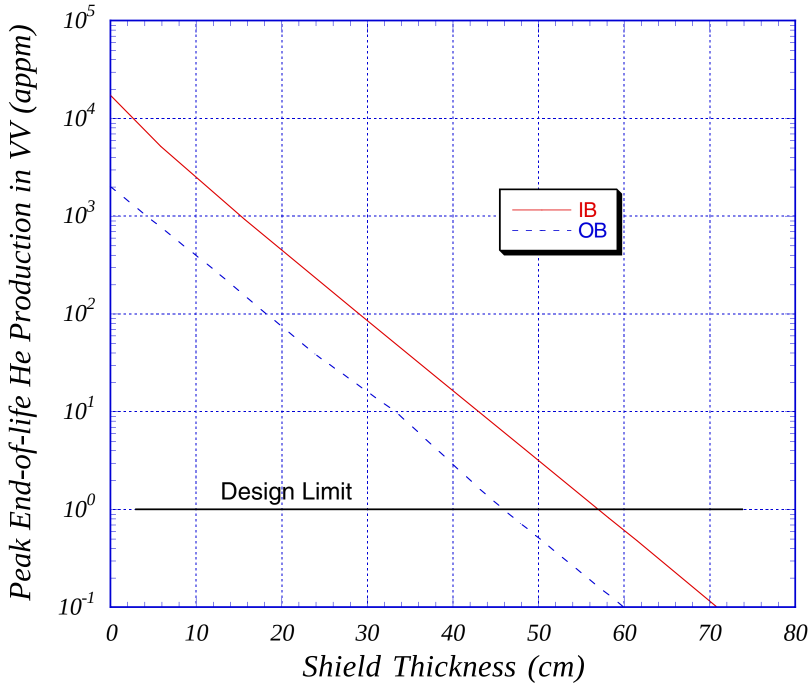

Fig. 4. Effect of shield thickness on peak end-of-life helium production in the VV.

2.4 Recommended radial build for the reference design

The radial build that satisfies requirements for VV reweldability and superconductor magnet shielding was determined for both the IB and OB regions. The total IB radial build between the FW and magnet is 165.5 cm. In the OB region, the total radial build is 212.5 cm. Table 1 gives the breakdown of the radial build in both the IB and OB regions. Based on the 1-D scoping analysis, this configuration allows for tritium self-sufficiency with an estimated overall TBR of 1.34. In addition, it leads to about two thirds of the thermal power being carried by the high temperature Li vapor.

3. Two-dimensional calculational model

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. The nuclear heating and damage hot spots at the parts of the OB secondary blanket and IB shield between trays, estimated from the 1-D calculations, are conservatively high. The R-Z geometrical 2-D model used in the calculation is shown in Fig. 5. It includes the FW, trays with Li 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 16 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.

Table 1. Recommended radial build for the reference design.

	IB	OB
FW	5 cm	5 cm
Li tray	40 cm	50 cm
Back wall of tray	0.5 cm	0.5 cm
Li vapor manifold	15 cm	20 cm
Manifold backplate	1 cm	1 cm
Clearance	2 cm	2 cm
Secondary blanket	0 cm	40 cm
Clearance	0 cm	2 cm
Shield	60 cm	50 cm
Clearance	2 cm	2 cm
VV front sheet	5 cm	5 cm
VV shielding zone	30 cm	30 cm
VV rear sheet	5 cm	5 cm
Total	165.5 cm	212.5 cm

Table 2. Nuclear energy multiplication in IB and OB components

	IB	OB
Front Blanket	0.883	0.856
Back Blanket	NA	0.304
Shield	0.310	0.041
Total	1.193	1.201

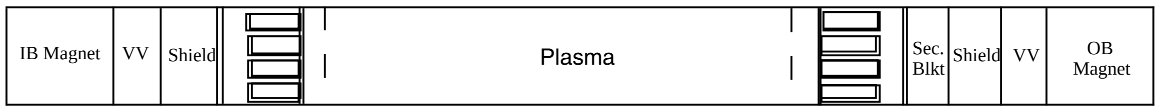

Fig. 5. R-Z two-dimensional model for EVOLVE.

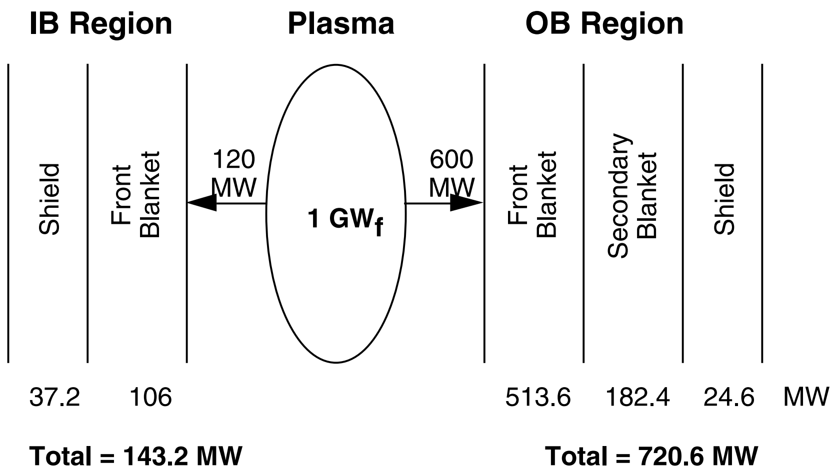

Fig. 6. Nuclear heating partitioning in the reference EVOLVE design.

The TWODANT module of the DANTSYS 3.0 [3] discrete ordinates particle transport code system was utilized along with the FENDL data [4]. An inherent problem associated with multi-dimensional discrete ordinates calculations is referred to as the "ray effect". It is related to the fact that the angular flux is given only in certain discrete directions which could lead to underestimating neutron streaming. This effect is mitigated by using the ray tracing first collision source option in TWODANT [3].

4. Tritium breeding ratio

The overall TBR calculated for the reference design using the 2-D model is 1.37. It is based on the conservative assumption of no breeding in the divertor region. 69.8% of tritium breeding occurs in the trays (57.3% OB and 12.5% IB). The OB secondary blanket contributes 27.7% of the total overall TBR (20.2% behind trays and 7.5% between trays). The contribution of the shield is only 2.5% (1% OB and 1.5% IB). Tritium breeding has a comfortable margin that allows for design flexibility. The overall TBR determined from the 2-D calculation is slightly higher than that estimated from the 1-D calculations coupled with coverage fractions (1.37 vs. 1.336). The contribution to TBR from the trays is much larger than that estimated from the 1-D calculations (69.8% vs. 57%) due to the larger chance of intercepting the neutrons in the trays before reaching the secondary blanket and shield.

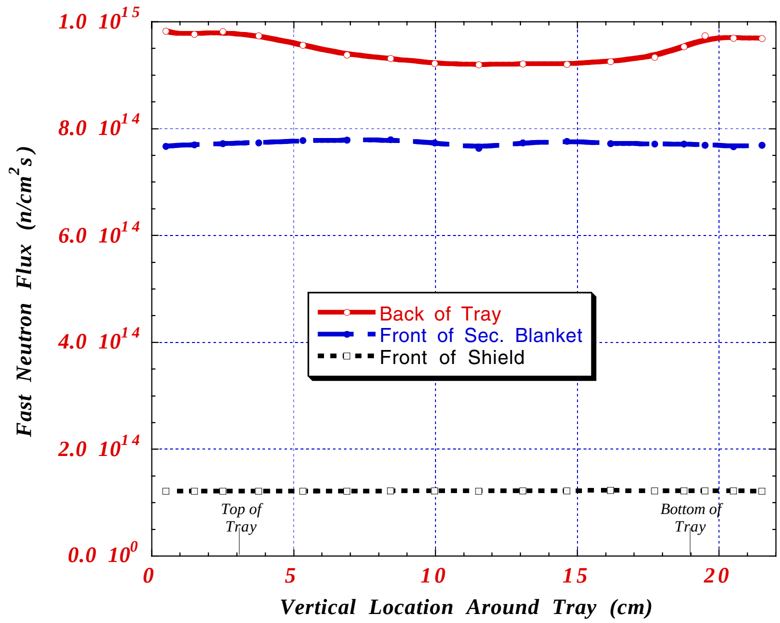

Fig. 7. Poloidal variation of fast neutron flux.

5. Nuclear heating distribution

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 given in Table 2 for both the IB and OB components. The nuclear heating in the FW and trays is ~20% higher than estimated from the 1-D calculations. Nuclear heating in the secondary breeding blanket and shield is ~30% lower than estimated from the 1-D results due to the larger chance of intercepting the neutrons in the trays before reaching the secondary blanket and shield. For a nominal fusion power of 1 GW, Fig. 6 shows the nuclear heating partitioning in the EVOLVE components. Most of the nuclear heating (~72%) is deposited in the evaporation cooled front blanket. Adding the surface heat deposited in the FW implies that ~76% of the total IB and OB energy is deposited as high grade heat in the front evaporation cooled zone (FW and trays) and carried by the Li vapor to the heat exchanger.

The peak W structure nuclear heating in the blanket and shield components obtained from the 2-D calculation is given in Table 3. No significant poloidal peaking is observed in the nuclear heating profiles. Since the source is volumetrically distributed, the FW and trays intercept most source neutrons. The secondary neutrons and gamma rays which give large contributions to nuclear heating tend to give nearly poloidally uniform profiles.

6. Radiation damage in the structural material

The peak dpa and helium production rates have been determined in the W-5Re structure using the 2-D model. Table 4 gives the results. No significant poloidal peaking is observed. The peak dpa rate in the manifold backplate, secondary blanket, and shield is a factor of ~3-5 lower than predicted from the 1-D calculations while He production is a factor of ~6-10 lower. This confirms that the peaking

Table 3. Peak structure nuclear heating (W/cm^3) in blanket and shield components.

	IB	OB
FW	85.0	105.8
Manifold Backplate	33.3	31.3
Secondary Blanket	NA	26.2
Shield	20.1	4.3

Table 4. Peak dpa and He production rates in the W-5Re structure.

	dpa/FPY		He appm/FPY	
	IB	OB	IB	OB
FW	25.7	34.8	14.0	20.2
Manifold Backplate	7.0	7.0	2.0	2.0
Secondary Blanket	NA	6.1	NA	1.8
Shield	4.3	0.74	1.3	0.12

Table 5. Peak VV neutronics parameters.

	IB	OB
Peak Nuclear Heating (mW/cm^3)	2.8	2.0
Peak end-of-life dpa	0.08	0.05
Peak end-of-life He appm	0.30	0.21

Table 6. Peak magnet neutronics parameters.

	IB	OB	Design Limit
Peak Nuclear Heating (mW/cm^3)	0.039	0.023	1
Peak end-of-life Fast Neutron Fluence (n/cm^2)	8.4×10^{17}	5.4×10^{17}	10^{19}
Peak end-of-life Dose to Epoxy Insulator (Rads)	1.0×10^{9}	6.4×10^{8}	10^{9}
Peak end-of-life dpa to Cu Stabilizer	4.8×10^{-4}	2.7×10^{-4}	6×10^{-3}

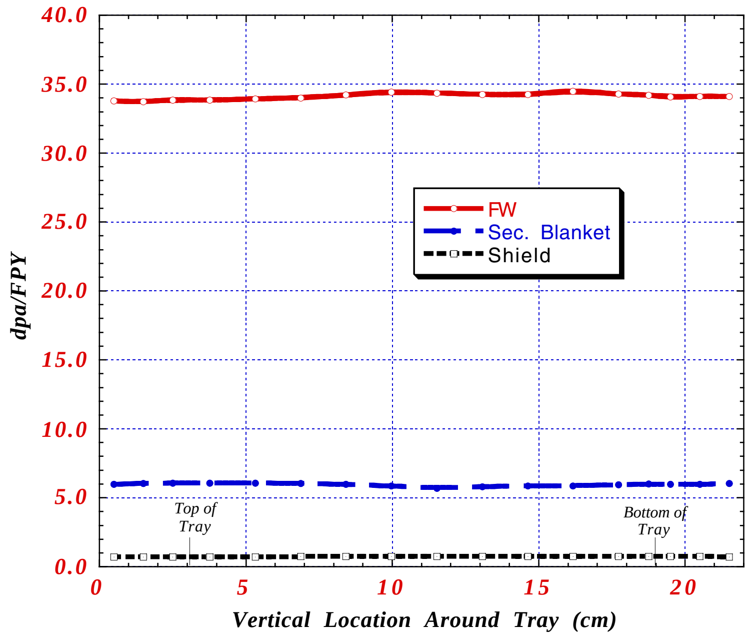

Fig. 8. Poloidal variation of damage rate around an OB tray.

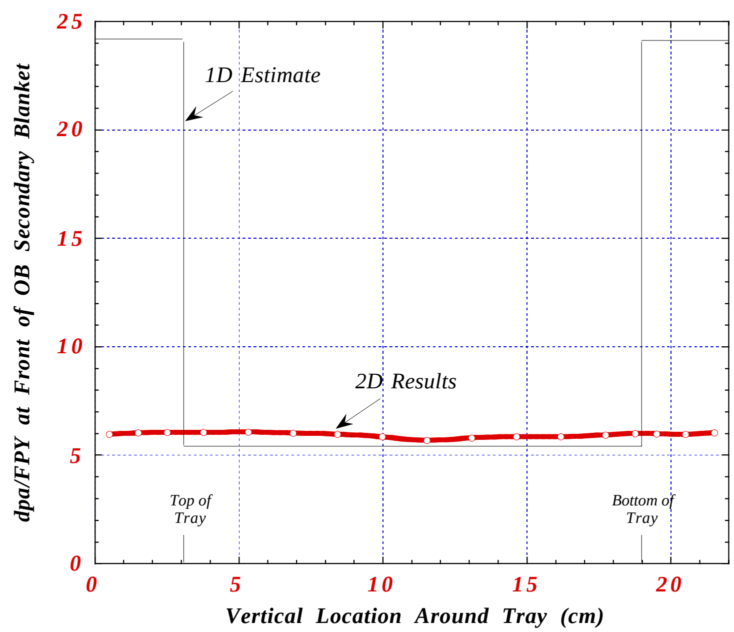

Fig. 9. Poloidal distribution of dpa rate at front of OB secondary blanket.

from the 1-D calculations was very conservative. The peak damage rate in the OB secondary blanket and IB shield is about a factor of ~6 lower than in the FW and, hence, they are expected to have a factor of 6 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.

Neutron streaming through the gaps between trays results in the largest poloidal flux peaking at the back surface of the trays. This flux peaking decreases rapidly as one moves away from the trays towards the secondary blanket and shield as evidenced from the results in Fig. 7. Figure 8 shows the poloidal variation of the dpa rate around an OB tray. Slight damage peaking occurs in the FW in front of the trays due to increased neutron reflection. Damage is nearly poloidally uniform in the secondary blanket and shield. Figure 9 compares the 1-D and 2-D predictions for poloidal variation of damage rate at the front of the OB secondary blanket. It is clear that the 1-D calculations significantly overestimate the peak damage rate in the secondary blanket.

7. Peak vacuum vessel and magnet nuclear parameters

The radial build required for VV reweldability and superconductor magnet shielding (Table 1) was used in the 2-D model. Table 5 gives the peak neutronics parameters for the VV. The peak end-of-life He production in the VV is less than the 1 appm required for reweldability. In addition, all magnet radiation limits are satisfied as shown in Table 6.

8. Summary and conclusions

The neutronics performance of the EVOLVE concept was analyzed using two-dimensional calculations. Using tungsten alloys yields ~10% higher TBR than with tantalum and is used in the reference design. The overall TBR with tray zones having a radial thickness of 50 cm in the OB region and 40 cm in the IB region is 1.37 at a lithium enrichment of 40% ^{6}Li. This value assumes 75% outboard blanket coverage, 15% inboard blanket coverage, and no breeding in the divertor region. Tritium breeding has a comfortable margin that allows for design flexibility. The amount of nuclear heat deposited in the different regions was determined. Most of nuclear heating (~72%) is deposited in the high temperature front blanket. Adding the surface heat deposited in the FW implies that ~76% of the total IB and OB energy is deposited as high-grade heat in the front evaporation-cooled zone (FW and trays) and carried by the Li vapor to the heat exchanger. Since this heat is extracted at a temperature of 1200°C, a thermal efficiency >60% in the power conversion system can be achieved by employing a closed cycle helium turbine system.

Nuclear heating and radiation damage profiles were calculated. No significant poloidal peaking is observed. The peak damage rate in the OB secondary blanket and IB shield is about a factor of ~6 lower than in the FW for which a damage rate of ~35 dpa/year has been calculated. This implies that they are expected to have a factor of 6 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. The radial build required for VV reweldability and magnet shielding was determined.

Acknowledgement

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