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NEUTRONICS AND THERMAL ANALYSES FOR THE BREEDING BLANKET OF THE ICF TRITIUM PRODUCTION REACTOR SIRIUS-T

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ABSTRACT

A breeding blanket design for the tritium production ICF reactor SIRIUS-T is presented. The blanket consists of alternating layers of beryllium multiplier and lithium breeder/coolant with vanadium alloy structure. A tritium breeding ratio of 1.9 can be achieved for the optimum layered configuration with lithium enriched to 90% ^{6}Li. An optimum coolant routing scheme is utilized to achieve adequate thermal hydraulics performance. The maximum structural material temperature is 650°C.

INTRODUCTION

SIRIUS-T is a conceptual design of a symmetrically illuminated inertial confinement fusion (ICF) tritium production facility.[1] The target is illuminated by 92 KrF laser beams symmetrically distributed around a 4-meter-radius spherical cavity filled with xenon gas. The target yields 100 MJ of fusion energy at a repetition rate of 10 Hz. A spherical structural frame supports 92 blanket modules, each with a beam port in the center. We have selected liquid lithium in vanadium structure as the primary breeding concept. This was the number one recommendation of the Blanket Comparison and Selection Study (BCSS).[2] In order to minimize the production cost of tritium, the neutronics analysis aimed at optimizing the blanket design to maximize the achievable tritium breeding ratio (TBR). This required using beryllium as a neutron multiplier. In this paper, the neutronics analysis leading to the reference blanket design is given. Several cooling schemes have been investigated to determine the optimum coolant routing. The nuclear heating calculated in the different components of the blanket has been used to perform the detailed two-dimensional thermal analysis reported here.

NEUTRONICS ANALYSIS

Calculational Model

The neutronics analysis performed for SIRIUS-T is aimed at optimizing the blanket design to maximize the TBR. A self-cooled liquid lithium blanket with the vanadium alloy V-3Ti-1Si structure and beryllium neutron multiplier is utilized in SIRIUS-T. The Be is assumed to have a 0.9 density factor. Each blanket module is composed of several layers of beryllium tiles shaped to conform to the structural frame and the central beam port. The lithium coolant is radially fed to five coolant layers between the Be layers. 1 cm thick graphite tiles, followed by 1 cm thick back structure that has 50% Li coolant, are used in front of the blanket. The blanket has a 1 cm thick front wall that is separated from the tile back structure by a 1 cm thick void region. The total tile and blanket thickness is 1 m. Based on the mechanical design and structural analysis for the blanket support frame, the webs of the frame and the blanket module side walls were determined to occupy 12.77% of the volume in the blanket region. In addition, the beam penetrations correspond to 1.97% of the blanket volume. The lithium in the radial tubes feeding the coolant layers amounts to 2.3% of the blanket volume.

The neutronics calculations have been performed using the one-dimensional discrete ordinates code ONEDANT[3] with cross section data based on the ENDF/B-V evaluation. The 4 m inner radius spherical chamber is modeled in spherical geometry with the target at the center emitting neutrons with energy distribution given by the SIRIUS target spectrum. As a result of neutron target interactions the source spectrum has only 78% of the neutrons at 14.1 MeV. Two approaches were considered to calculate the overall TBR. One approach is based on performing the neutronics calculations using the local blanket composition excluding the structural support webs and beam penetrations. The results are then modified to account for the reduced blanket coverage. The other approach uses a homogenized composition for each blanket layer taking into account the beam penetrations and structural frame. This yields conservative estimates for the overall TBR and is utilized here. In the neutronics calculations, each Li layer is considered to consist of 85.26% Li, 12.77% V, and 1.97% void. On the other hand, each Be layer has 82.96% Be, 2.3% Li, 12.77% V, and 1.97% void.

Blanket Design Optimization

Preliminary blanket optimization based on treating the blanket as a single homogeneous region indicated that the TBR maximizes at a lithium enrichment of 20% ^{6}Li and a Li volume fraction of 13.5%. Starting from this optimum homogeneous composition, the Li and Be have been arranged in alternating layers with the overall Li volume fraction being preserved. The neutronics calculations have been performed for the layered configuration to maximize the TBR by varying the Li enrichment and the thicknesses of the alternating layers. Varying the Li enrichment for the layered configuration indicated that the TBR maximizes at a Li enrichment of 70% ^{6}Li. The thicknesses of the different Li and Be layers were then varied one at a time to determine the optimum configuration. In general, the results indicate that thinner Li layers and thicker Be layers yield higher values for the TBR. However, thermal hydraulics requirements constrained the Li coolant layers not to be thinner than 1 cm.

Varying the Li enrichment for the optimum layered configuration, the TBR was found to increase as the enrichment increases as shown in Figure 1. Although the TBR enhancement appears to be small, the cost impact will be significant since an enhancement of 0.001 in the TBR results in an additional 1.65 kg of tritium produced over the 30 FPY reactor life. At a tritium cost of \$10,000/g, this translates into \$16.5 M enhancement in the value of tritium produced. A simple cost tradeoff analysis has been performed to assess the economic impact of increasing the Li enrichment. The analysis indicates that using 90% ^{6}Li results in a net economic gain in spite of the increased Li cost. The effect of varying the total tile and blanket thickness is shown in Figure 2. The cost tradeoff analysis indicated that increasing the thickness to 1.1 m leads to a net economic loss with the increase in tritium produced for the thicker blanket being negated by the increased chamber cost as shown in Table 1. Furthermore, reducing the thickness to 0.9 m is not economically attractive with the reduced chamber cost being more than offset by the loss in the value of produced tritium. Therefore, a 1 m thick blanket is chosen for SIRIUS-T with the radial build given in Figure 3 and the Li enriched to 90% ^{6}Li. This yields an overall TBR of 1.9025.

Table 1. Cost impact of key blanket design parameters.

Thickness (m)	%^{6}Li	TBR	Increase in Tritium Value (M\$)	Chamber Cost Savings (M\$)	Net Gain (M\$)
1	90%	1.9025	0.0	0.0	0.0
1	80%	1.8991	-56	4	-52
1	70%	1.8938	-144	8	-136
1.1	90%	1.9031	12	-20	-8
0.9	90%	1.9008	-28	19	-9

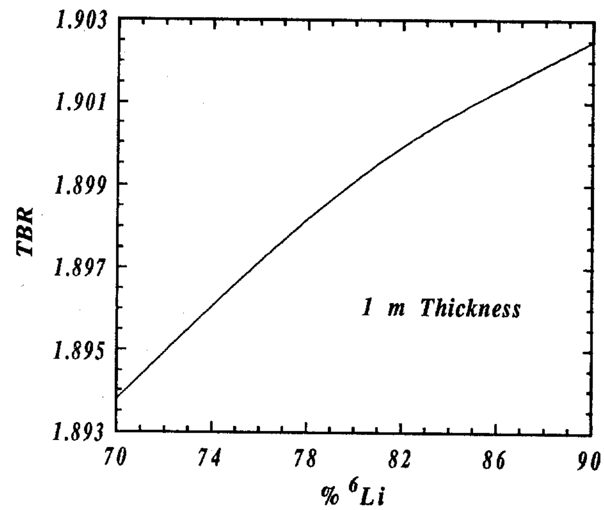

Figure 1. Effect of lithium enrichment on TBR.

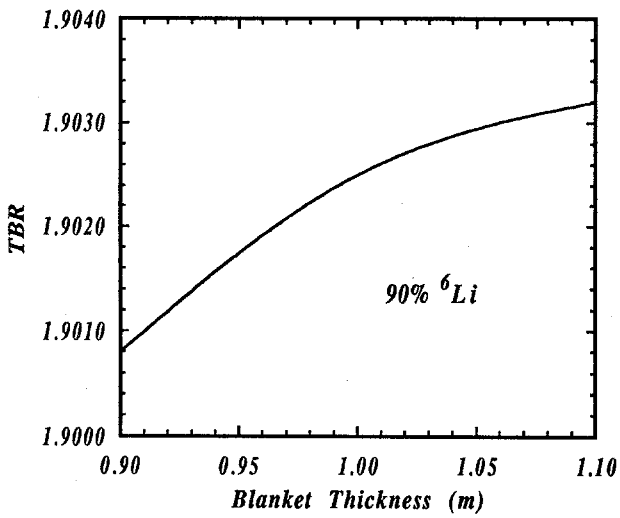

Figure 2. Effect of blanket thickness on TBR.

Neutronics Performance of the Reference SIRIUS-T Blanket

The radial variation of dpa and helium production rates in the vanadium alloy structure is shown in Figure 4. The results indicate that the peak dpa and helium production rates in the V back structure of the tiles are 30 dpa/FPY and 94 appm/FPY, respectively. The peak dpa rate in the front wall of the blanket module is 24 dpa/FPY and the helium production rate is 70 appm/FPY. Detailed lifetime analysis for the V-3Ti-1Si alloy that takes into account swelling and radiation embrittlement indicated that the vanadium alloy lifetime in the SIRIUS-T blanket is expected to be ~4 FPY. The peak dpa rate in the graphite tiles is 18 dpa/FPY. The lifetime of graphite is determined by the damage level at which the graphite passes through the shrinkage phase and crosses the zero dimensional

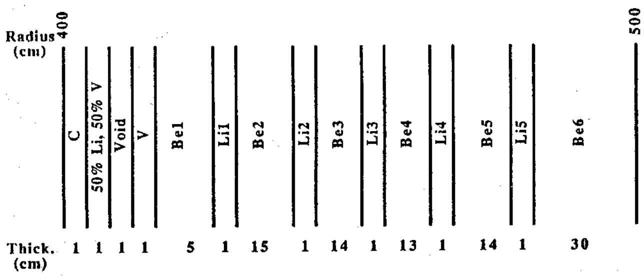

Figure 3. Reference radial build of SIRIUS-T blanket.

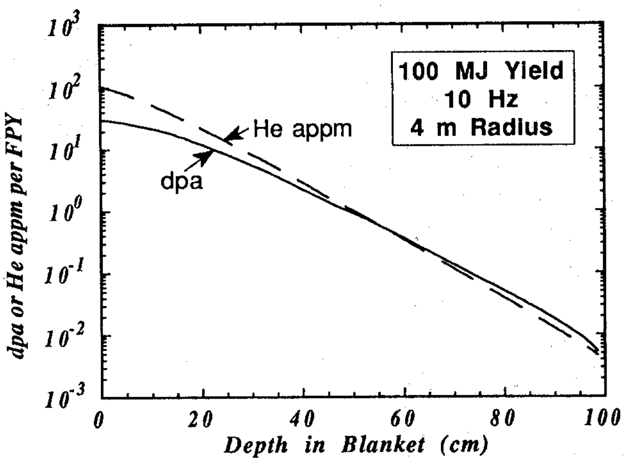

Figure 4. Helium and dpa production rates in V structure.

change axis on the way to runaway swelling. Data on irradiation of several forms of graphite show that the useful life in SIRIUS-T is 2 FPY.[4]

Neutron irradiation of beryllium in fusion reactors results in the production of tritium. The tritium inventory in the Be depends on the rate of tritium production and the retention and transport characteristics of tritium in Be. The limited data available on tritium retention in Be show that the retention rate drops as the temperature increases.[5] The tritium production rate determined from the neutronics calculations along with the calculated temperature distribution have been used to determine the tritium inventory in the different Be layers of the blanket at the end of the blanket lifetime. The results given in Figure 5 assume that the Be is annealed to 650°C every 2 months. At this temperature only 2% of the tritium produced is retained in the Be. The total tritium inventory in the Be used in the SIRIUS-T blanket is 19 g.

Table 2 gives the major neutronics parameters for the reference SIRIUS-T blanket.

THERMAL-HYDRAULICS ANALYSIS

The configuration and parameters of the coolant system must be optimized simultaneously with the

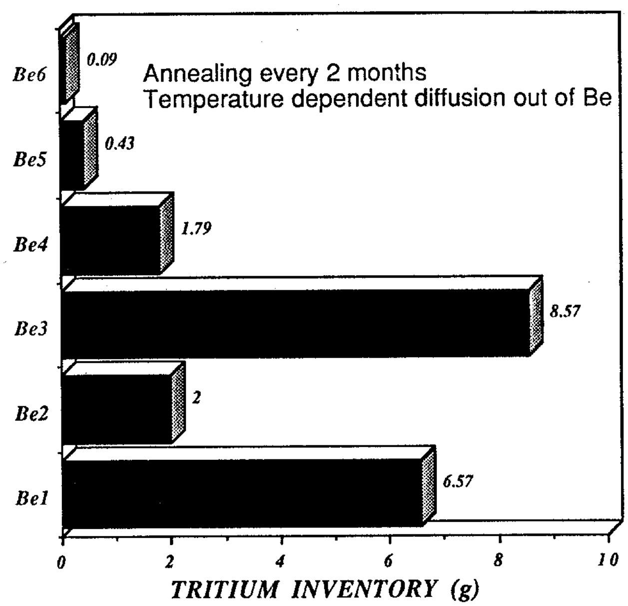

Figure 5. Tritium inventory in the different Be zones.

Table 2. Neutronics parameters for the reference SIRIUS-T blanket design.

Tritium breeding ratio:	T6	1.8993
	T7	0.0032
	Total	1.9025
Nuclear heating (MeV/fusion):	Neutron	16.88
	Gamma	3.44
	Total	20.32
Nuclear energy multiplication		1.55
Overall energy multiplication		1.41
Peak dpa rate in graphite tiles		18 dpa/FPY
Peak He production rate in graphite		4420 appm/FPY
Peak dpa rate in V alloy		30 dpa/FPY
Peak He production rate in V alloy		94 appm/FPY
Total tritium inventory in Be		19 g

neutronics and thermal stresses calculations to achieve the maximum possible TBR, while satisfying the engineering constraints imposed on the design. Iterations are needed to determine the optimum configuration of Li coolant and Be multiplier in the SIRIUS-T blanket. The neutronics results have been used in the blanket thermal-hydraulics analysis. The SIRIUS-T cavity is spherical and has 92 beams symmetrically distributed around it. Each beam is located in the center of a blanket module of which there are 80 hexagonally and 12 pentagonally shaped. All modules are fitted into the structural support frame[1]. Each blanket module consists of a 1 cm thick vanadium topless box with a hexagonal/pentagonal cross section. The box contains several layers of beryllium multiplier tiles stacked

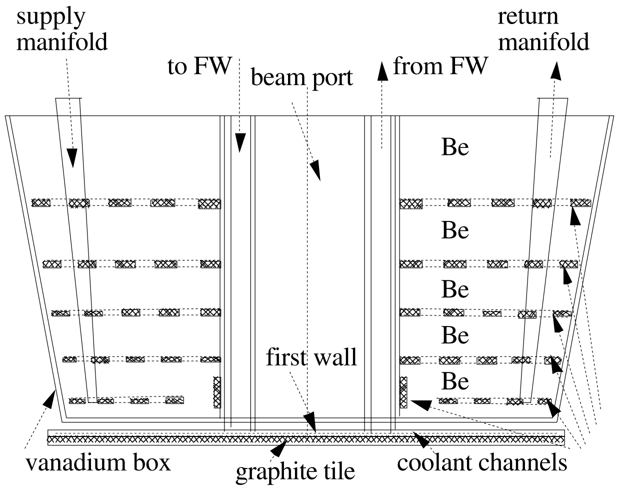

Figure 6. Detailed cross section of a hexagonal blanket module with FW.

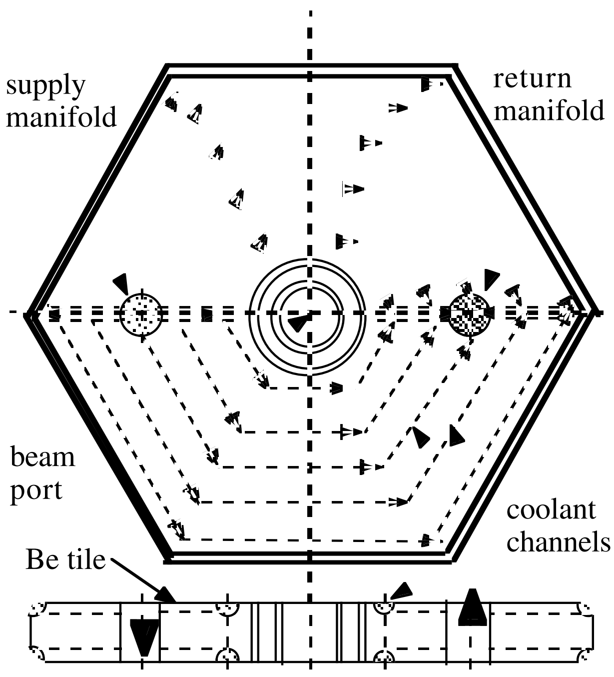

Figure 7. A schematic of the coolant channels at one of the coolant layers.

on top of each other. The tiles are shaped to conform to the interior of the vanadium container at their perimeters and the beam port tube at their centers. Coolant channels are engraved in the beryllium tiles at 5 different levels. At each level 5 concentric coolant paths are utilized. The positions of these levels have been optimized to insure maximum TBR. The liquid lithium, coolant and breeder, enters each module from a single supply manifold at the top down a radially tapered hole in the Be tiles to feed the coolant at the different cooling levels. Figure 6 shows a detailed cross section of a hexagonal blanket module. The

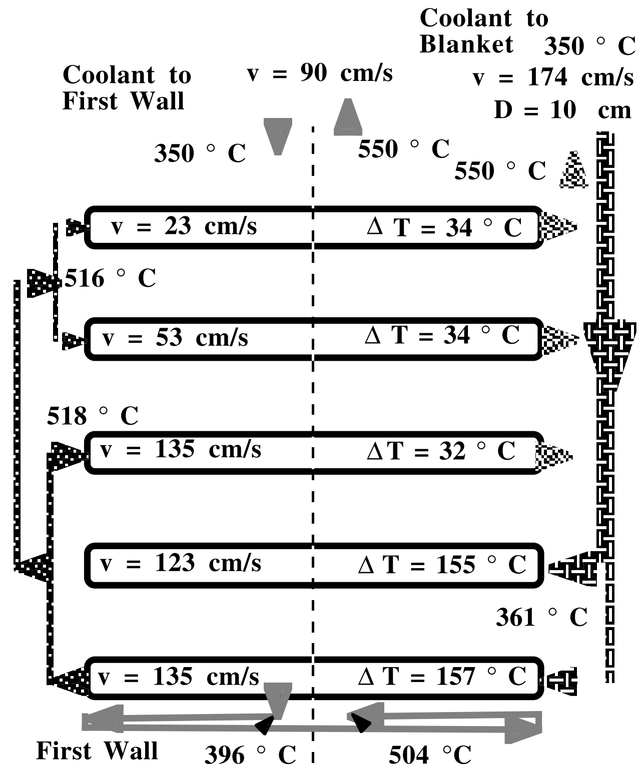

Figure 8. The reference coolant layout to the blanket and FW.

coolant traverses each channel to the other side where it finds its way up and out through the return manifold. Figure 7 is a schematic of the coolant channels at one of the coolant layers. The first wall is composed of graphite tile on Li cooled vanadium structure. Cooling the first wall is achieved by feeding the coolant down an annulus around the beam port to the coolant channels which have the same geometrical configuration as the blanket coolant channels. The annulus is divided into two separate channels, one for supply and the other for return.

A two-dimensional finite-element thermal model has been generated for use with the ANSYS code,[6] to examine the thermal performance of the proposed configuration utilizing the nuclear heating results obtained from the neutronics analysis. It is assumed that the liquid lithium enters at a temperature of 350°C and exits at 550°C. The temperature of the vanadium structure should be in the range between 350°C and 650°C. The lower limit is needed to eliminate any concern about DBTT and the upper limit is required to avoid helium induced degradation in ductility. In the mean time, the temperature of the beryllium should be kept as high as possible to allow tritium to diffuse out of it and hence reduce the tritium inventory.[5] Several approaches for blanket and FW coolant routing have been examined. Figure 8 gives the reference coolant routing for the blanket and FW. Included also in the figure are the parameters of the coolant as it traverses the coolant channels in the blanket and FW.

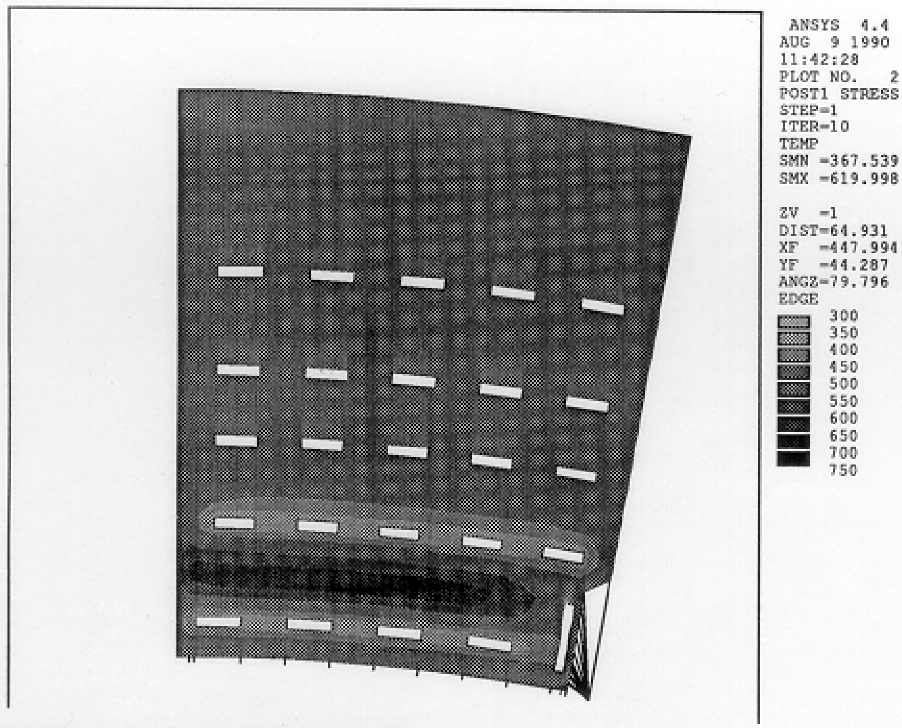

Figure 9. Temperature distribution for the right side.

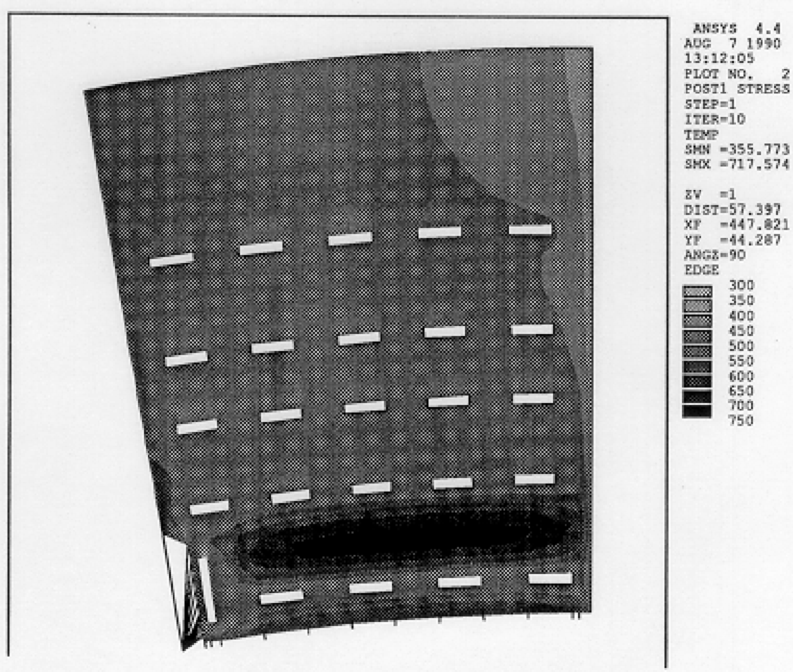

Figure 10. Temperature distribution for the left side.

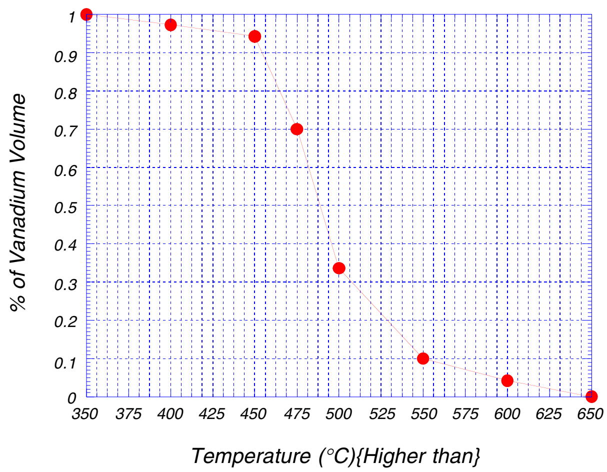

Figure 11. Percent volume-temperature relationship for the vanadium.

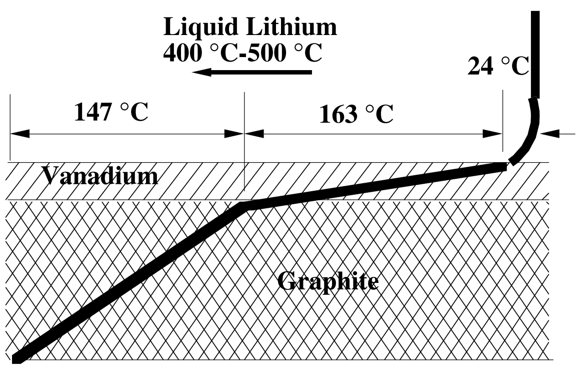

Figure 12. Temperature distribution in the first wall.

The two-dimensional thermal model uses the temperature dependent thermal properties for the different materials used. Moreover, it allows heat to be radiated between the blanket and FW. The two sides of the model have been modeled separately. Different boundary conditions are imposed on each side during the calculations since the thermal model handles each module side separately. Each side is thermally independent since the two sides are separated with the laser beam port. The resulting temperature distributions are shown for both the right and the left sides in Figures 9 and 10. One can see that the maximum Be temperature is 718°C in the middle of the first Be layer while the maximum vanadium temperature is 650°C at the front surface of the module. Figure 11 shows the volume fraction of structural material with temperatures below a given temperature. The steady state temperature distribution in the first wall has been calculated. The maximum temperature of the graphite tile surface, which is needed for stress analysis calculations, has been determined to be 834°C. Figure 12 shows the temperature distribution in the first wall.

SUMMARY

Neutronics calculations have been performed to determine the optimum SIRIUS-T blanket design that maximizes the TBR. The optimum blanket is 1 m thick with alternating layers of Be and Li. The Li is enriched to 90% ^{6}Li. The overall TBR achievable in SIRIUS-T is 1.9 and the thermal power is 1390 MW. The peak dpa rates in the graphite tile and vanadium structure are 18 and 30 dpa/FPY, respectively. The nuclear heating profile determined from the neutronics calculations has been used to perform a detailed two-dimensional thermal analysis. Different options for coolant routing have been investigated. The coolant inlet temperature is 350°C and the outlet temperature is 550°C. The maximum Be temperature is 718°C and the peak vanadium structure temperature is 650°C.

ACKNOWLEDGEMENT

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