Received by OCT

JAN 23 1991

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September 1990

MASTER

* Work supported by the Office of Fusion Energy, U.S. Department of Energy under Contract Number W-31-109-Eng-38.

Paper to be presented at the 9th Topical Meeting on The Technology of Fusion Energy, Oak Brook, IL, October 7-11, 1990.

NEUTRONICS AND THERMAL DESIGN ANALYSES OF U.S. SOLID BREEDER BLANKET FOR ITER*

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ABSTRACT

The U.S. Solid Breeder Blanket is designed to produce the necessary tritium required for the ITER operation and to operate at power reactor conditions as much as possible. Safety, low tritium inventory, reliability, flexibility cost, and minimum R&D requirements are the other design criteria. To satisfy these criteria, the produced tritium is recovered continuously during operation and the blanket coolant operates at low pressure. Beryllium multiplier material is used to control the solid-breeder temperature. Neutronics and thermal design analyses were performed in an integrated manner to define the blanket configuration. The reference parameters of ITER including the operating scenarios, the neutron wall loading distribution and the copper stabilizer are included in the design analyses. Several analyses were performed to study the impact of the reactor parameters, blanket dimensions, material characteristics, and heat transfer coefficient at the material interfaces on the blanket performance. The design analyses and the results from the different studies are summarized.

1. INTRODUCTION

The blanket is designed with a tritium breeding ratio as close to unity and to operate at power reactor conditions as much as possible. Also, the reliability and the safety aspects of the blanket are enhanced by using low-pressure water coolant and the separation of the tritium purge flow from the coolant system by several barriers. The other criteria used to guide the design process are mechanical simplicity, predictability, performance, cost, and minimum R&D requirements. Lithium oxide (Li_2O) and lithium zirconate (Li_2ZrO_3) are the primary and the backup breeder materials, respectively. Austenitic steel (Type 316 solution annealed) was selected as the reference structural material on the bases of an extensive data base and ease

of fabrication. Low pressure (0.5 to 1.0 MPa), low temperature (60 to 100°C) water is used as the coolant. The desire to achieve a high local tritium breeding ratio (TBR) requires the use of beryllium as a neutron multiplier. This is due to the limited inboard blanket thickness because of inboard shielding requirements and the limited first wall coverage on the outboard section because of testing requirements and plasma systems. The multilayer blanket concept^{1,2} is used to satisfy the design criteria mentioned above. The beryllium zones are used to provide the required breeder temperature control for the tritium recovery. This design approach increases the confidence in the blanket performance because it does not make use of an adjustable thermal conductivity or helium gaps to adjust the solid breeder temperature. A high lithium-6 enrichment is used for the breeder material to maximize the tritium breeding ratio. The use of high lithium-6 enrichment reduces the solid breeder volume required in the blanket and consequently the total tritium inventory in the solid breeder material. Also, it increases the blanket capability to accommodate a wide range of neutron wall loading.

The inboard blanket has a single breeder zone embedded in a beryllium zone. The poloidal coolant of the first wall (FW) and the shield behind the blanket are used to cool the inboard blanket by conducting the nuclear heating to these coolant zones. This results in a simple blanket design. The outboard blanket, shown in Fig. 1, has two breeder zones with toroidal coolant flow. The first wall, blanket, and shield are integrated into a single unit.

Several analyses were performed to study the impact of the reactor parameters, blanket dimensions, material characteristics, and heat transfer coefficient at the material interfaces on the blanket performance. The design analyses and the results from the different parametric studies are summarized.

* Work supported by Office of Fusion Energy, U.S. Department of Energy under Contract No. W-31-109-Eng-38.

Figure 1. Isometric of blanket internals.

II. OPERATING CONDITIONS & DESIGN GUIDELINES

The blanket is designed to accommodate the change in the power levels between the two operating phases and significant variations in fusion power within each phase. Also, the blanket accommodates the poloidal changes of the neutron wall loading. The twin loop copper stabilizer and the sixteen ports are integrated in the outboard blanket. Operating temperature windows are defined for each material to satisfy the different design criteria. The minimum temperature limits for breeder materials are based on tritium recovery issues while the maximum temperature limits are based on mass transfer and material sintering considerations. A summary of the main operating conditions and the design guidelines is listed in Table 1.

The blanket performance during the off-normal conditions (plasma disruption, loss of coolant, or loss of coolant flow) is another key factor in the blanket design process. The design philosophy is to accommodate such conditions with passive methods. Therefore, the blanket is segmented, as indicated in Table 1 to accommodate the electromagnetic forces during the plasma disruption. In addition, internal reinforcement ribs are used for the outboard blanket.

III. NEUTRONICS ANALYSIS

The nuclear data base and the calculational methodology for the design analyses are briefly discussed. The studies carried out to define the blanket design parameters are presented.

A. Calculational Methodology and Nuclear Data Base

The first step in the analysis is to define a blanket configuration that maximizes the tritium breeding ratio and satisfies the temperatures limits for the different

Table 1.
Summary of Operating Conditions
and Design Guidelines

Reactor Power	Physics Phase	Technology Phase
Fusion power, MW	1100	860
Neutron wall loading, MW/m ²		
Inboard (min/max)	0.42/1.13	0.33/0.88
Outboard (min/max)	0.77/1.54	0.60/1.20
DT flat burn time, s	400	2290
Minimum dwell time, s	200	200
DT fluence goal, MWa/m ²	0.05	3
Water Coolant		
Temperature (inlet/outlet), °C		60/100
Pressure, MPa		< 1.5
Number of Blanket Segments		
Outboard - One sector per TF coil, three poloidal segments per sector, central segments have lower and upper segments to accommodate central ports, a total of 64 segments.		
Inboard - Two segments per TF coil, each is divided into three subsegments which are electrically insulated a total of 96 subsegments.		
Integrated First Wall, Blanket, and Shield		
Twin loop copper stabilizers are integrated with the blanket.		
Coolant manifolds at the top except the lower central segments use bottom manifolds.		
Key Temperature Limits		
Maximum load structural temperature during normal operation for annealed Type 316 SS.		400°C
Maximum load structural temperature during off-normal conditions for annealed Type 316 SS.		800°C
Operating temperature window for Li ₂ O solid breeder.		320-1000°C
Operating temperature for Li ₂ ZrO ₃ solid breeder.		320-1000°C

materials. The first wall/blanket/shield design and optimization system (BSDOS)³ was used to carry out the neutronics and thermal-hydraulics analyses in an integrated manner. BSDOS use the one/two-dimensional discrete

ordinates code ONE/TWODANT to carry out the transport calculations. The analyses use a P_3 approximation for the scattering cross sections and an S_8 angular quadrature set. A 67-coupled group nuclear data library (46 neutron and 21 gamma) based on ENDF/B-V is used for all the one-dimensional calculations. This library is based on VITAMIN-E⁴ for the transport cross sections and KAOS/LIB⁵ for the nuclear responses.

The calculational model uses a poloidal cross section with the plasma minor radius. The radial build of the blanket is defined at six locations to insure the accommodation of the poloidal distribution of the neutron wall loading. The radial build is defined at the midplane and the blanket extremities for the inboard and the outboard sections. The other two locations are at the starting point of the copper stabilizer in the poloidal direction.

B. Radial Blanket Build

The blanket radial build is defined based on neutronics and thermal considerations. In the inboard section, the beryllium material is used with a 0.65 density factor to reduce the thermal conductivity of the sintered blocks. This reduces the beryllium thickness required to get the temperature distribution of the solid breeder material within the temperature window. On the contrary, the beryllium material of the first outboard breeder zone has a density factor of 0.85 to get high thermal conductivity. This permits the use of a thick beryllium zone in the front section of the blanket where it is needed from the neutronics point of view. The beryllium material of the second breeder zone has a 0.65 density factor to reduce the required beryllium thickness similar to the inboard section. The range of the beryllium density factor of 0.65 to 0.85 is defined based on material considerations including swelling and mechanical properties.

The calculated radial build of the outboard and inboard blankets at the different locations are given in Table 2. The change in the beryllium material thickness in the poloidal direction is similar to the poloidal change of the neutron wall loading on the first wall. The local tritium breeding ratio varies from 1.375 at $Z = 0.0$ to 1.461 at $Z = 2.7$ where the copper stabilizer starts. The loss in the local tritium breeding ratio due to the copper stabilizer is 7.7% at $Z = 2.7$ m. At the end of the blanket, the local tritium breeding ratio is 1.310. The blanket thickness varies from 26.5 cm at the midplane to 58.5 cm at the end. The local tritium breeding ratio of the inboard blanket changes from 0.755 at $Z = 0$ to 0.895 at the end of the blanket. The corresponding blanket thicknesses are 10.7 and 18.3 cm, respectively.

The overall TBR has been estimated by coupling the one-dimensional results with the coverage fractions of the different blanket regions. The coverage fraction corresponds to the solid angle fraction subtended by the particular region as seen by the source neutrons going directly to this region. The overall TBR is estimated to be 0.84 with 0.14 contributed from the inboard blanket segments.

Three-dimensional neutronics calculations⁶ have been performed to determine the overall tritium breeding ratio as well as tritium breeding and nuclear heating in the different components of the blanket. The net overall TBR is 0.81 based on this three-dimensional calculation compared to 0.84 estimated from the one-dimensional analysis.

IV. THERMAL ANALYSES

A. Introduction

The thermal analysis is always performed for each blanket configuration after the neutronics analysis to insure the appropriate temperature profiles of the different materials. The zone dimensions and material density factors are defined to get a minimum temperature of 450°C for the solid breeder material during normal operation in the technology phase. This choice results in a satisfactory tritium inventory for the physics and the technology phases. Also, it limits the maximum temperature at the steel clad beryllium interface to <430°C. This results in a steel reaction layer of <0.1 mm at the end-of-life of 3.8 full power years.

The thermal calculational procedure and the results are presented. Steady state and transient analyses were performed in detail, which are required for the tritium inventory analyses. Analyses were performed to show the blanket capability to accommodate changes in the neutron wall loading. The change in the blanket performance as a function of the different blanket parameters is analysed in detail. The analyses include gap conductance, breeder zone thickness, breeder clad thickness, lithium-6 enrichment, and beryllium density factor.

B. Calculational Methodology

The BSDOS system gets the zone dimensions and the radial distribution of the nuclear heating over a fine mesh from the neutronics analysis. The three-dimensional mesh generator modeling nonlinear systems, INGRID, uses these data to model the blanket geometry. Geometrical data, coolant conditions, and gap conductance model are included in the modeling process. INGRID generates a three-dimensional finite element model for the blanket segment. The three-dimensional finite element heat

transfer code TOPAZ3D calculates the temperature distribution profiles and the change in the coolant conditions. The physical properties of the different materials are evaluated at each node as a function of the temperature and the material density factor.

The coolant inlet temperature is 60°C and the water pressure is 10 atm. The coolant flow direction is included in the model. In the transient analyses, the fusion power during the start up and the shut down for the pulse is assumed linear. Also, the coolant is flowing continuously during the dwell time.

C.Steady State and Transient Thermal Analyses

The neutronics and the thermal calculations are usually iterated. The purpose of this iteration is to get the minimum temperature of the solid breeder at 450°C for the technology phase. The results from these analyses give the radial build and the temperature distribution of the blanket. The extreme temperatures of the blanket zones at each poloidal location are given in Table 3. The minimum solid breeder temperatures for the different radial builds are $450 \pm 5^\circ\text{C}$ except for the outboard blanket at $z = \pm 2.7$ m. The minimum solid breeder temperatures at this location are 484 and 476°C for the first and second breeder zones, respectively. At this location the copper stabilizer replaces a 0.5 cm of the beryllium material behind the first wall. The minimum solid breeder temperatures with the copper stabilizer are 455 and 452°C for the first and second breeder zones, respectively. At this poloidal point, the calculations assume no material change in the poloidal direction for the zone materials. However, copper will be contacting beryllium in the poloidal direction. This results in minimum solid breeder temperatures in the range of 455-484°C and 449-465°C for the first and second breeder zones, respectively. The lithium breeder uses only about 90°C of the 600°C temperature window (400 to 1000°C).

In the physics phase, the reactor fusion power is 1100 instead of 860 MW for the technology phase, and the carbon tiles are used for first wall protection. Also, the DT burn time is relatively short. It is 400 s instead of 2290 s for the technology phase. Figure 2 gives a sample of the temperature history of the first solid breeder zone of the outboard blanket. At the midplane section, the solid breeder temperatures reach very close to saturation during the second pulse, while the end of the blanket requires more than 3 pulses to reach saturation values.

V. BLANKET PERFORMANCE ANALYSES

Several studies were carried out to improve the blanket performance including the

tritium breeding ratio and the power variation accommodation. The other objective is to determine the blanket performance as a function of the different design parameters. The key parameters for these studies are the number of the breeder zones, the breeder clad thickness. The lithium-6 enrichment, the carbon tile thickness, the thickness of the first wall materials, the fabrication tolerance in the beryllium density, and the gap conductance. The results from these studies were used to define the blanket configuration.

Figure 2. Lowest temperature history of the first breeder zone during five physics pulses at the outboard midplane section.

For example, the blanket configuration given in Table 2 is reconfigured with three breeder zones and the same constraint on the minimum breeder temperature of 450°C. The local poloidal tritium breeding ratio at the midplane for the new configuration is 1.634 compared to 1.375 for the blanket with two breeder zones, which is a 19% increase. However, the blanket thickness is increased from 26.5 to 45.1 cm. The estimated net tritium breeding ratio from this blanket is 0.92 compared to 0.84 for the blanket with two breeder zones. It should be noted that the third breeder zone is only used for the outboard blanket between $z = -2.7$ to 2.7 m. The minimum temperature of the three breeder zones are 452, 454, and 459°C. Similar to the blanket configuration with two breeder zones, the solid breeder uses only 84°C of the temperature window.

Another example of the performance analysis is the power variation accommodation. Figure 3 shows the extreme temperatures of the

Table 2. Radial Build of the Blanket

ZONE	MATERIAL (DF)	THICKNESS (cm)					
		Outboard			Inboard		
		1.2 MW/m ² Z = 0	0.958 MW/m ² Z = ±2.7 m	0.6 MW/m ² Z = ±4.3 m	0.884 MW/m ² Z = 0	0.325 MW/m ² Z = ±3.4 m	
First Wall Layers							
Tile ^(a)	C	2.0	2.0	2.0	2.0	2.0	2.0
First wall	steel	0.5	0.5	0.5	0.5	0.5	0.5
Coolant	H ₂ O	0.4	0.4	0.4	0.4	0.4	0.4
Back wall	steel	0.5	0.5	0.5	0.5	0.5	0.5
Stabilizer	Cu			0.5	0.5		
Blanket							
Multiplier	Be	3.4 ^(a)	4.8 ^(a)	4.3 ^(a)	7.2 ^(a)	3.3 ^(b)	9.0 ^(b)
Clad	steel	0.1	0.1	0.1	0.1	0.1	0.1
Breeder	Li ₂ O (0.80)	0.8	0.8	0.8	0.8	1.0	1.0
Clad	steel	0.1	0.1	0.1	0.1	0.1	0.1
Multiplier	Be	5.9 ^(a)	7.9 ^(a)	7.9 ^(a)	12.7 ^(a)	4.6 ^(b)	6.5 ^(b)
Coolant channel	steel	0.2	0.2	0.2	0.2	0.2	2.8 ^(c)
Coolant	H ₂ O	0.2	0.2	0.2	0.2	0.2	0.2
Coolant channel	steel	0.2	0.2	0.2	0.2		
Multiplier	Be (0.65)	5.7	8.4	8.4	19.0		
Clad	steel	0.1	0.1	0.1	0.1		
Breeder	Li ₂ O (0.80)	0.8	0.8	0.8	0.8		
Clad	steel	0.1	0.1	0.1	0.1		
Multiplier	Be (0.65)	7.1	11.6	11.6	15.2		
Coolant channel	steel	0.2	0.2	0.2	7.2 ^(d)		
Coolant	H ₂ O	0.2	0.2	0.2	0.2		
<hr/>							
Total first wall/blanket thickness		26.5	37.1	37.1	58.5	10.9	18.5
Local tritium breeding ratio		1.375	1.461	1.356	1.310	0.755	0.895

a- A 0.85 density factor.

b- A 0.65 density factor.

c- 2.6 cm of the steel in this zone is part of the bulk shield and it is not included in the total first wall/blanket thickness.

d- 7.0 cm of the steel in this zone is a part of the bulk shield and it is not included in the total first wall/blanket thickness.

Table 3. Steady State Extreme Temperatures of the Different Blanket Materials for the Technology Phase

ZONE	MATERIAL	OUTBOARD TEMPERATURES, °C				INBOARD TEMPERATURES, °C	
		1.2 MW/m ²	0.958 MW/m ²	0.6 MW/m ²		0.884 MW/m ²	0.325 MW/m ²
		Z = 0	Z = ±2.7 m	Z = ± 4.3 m		Z = 0	Z = ±3.4 m
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First Wall Layers ^(a)							
First wall	steel	77-191	74-168	74-168	69-132	92-174	65-98
Back wall	steel	82-225	81-222	82-228	79-203	94-187	69-131
Stabilizer	Cu			230-237	205-210		
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Blanket							
Multiplier	Be	280-401	277-440	285-412	252-418	224-413	155-427
Clad	steel	426-438	462-472	432-442	432-439	433-440	435-438
Breeder	Li ₂ O	453-537	484-559	455-522	448-492	452-526	442-472
Clad	steel	424-437	459-470	433-443	432-440	431-438	435-437
Multiplier	Be	192-401	180-437	174-413	143-418	162-415	288-427
Coolant channel	steel	77-138	75-131	75-127	71-109	91-126	67-275
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Coolant channel	steel	70-109	68-101	68-99	65-84		
Multiplier	Be	138-421	124-454	121-431	97-440		
Clad	steel	435-446	465-472	441-449	444-447		
Breeder	Li ₂ O	451-505	476-514	452-487	449-460		
Clad	steel	434-443	465-471	442-447	446-447		
Multiplier	Be	123-422	106-457	104-434	309-444		
Coolant channel	steel	68-99	66-88	66-86	63-303		
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Total first wall/blanket thickness		26.5	37.1	37.1	58.5	10.9	18.5
Local tritium breeding ratio		1.375	1.468	1.356	1.310	0.755	0.895

a- The surface heat flux is 25% the DT neutron wall load value.

lithium oxide material over a wide range for the neutron wall loading where the nominal value for this blanket configuration is 1.2 MW/m^2 . For continuous operation, the lithium oxide material in this blanket is designed to operate within the temperature range of 400 to 1000°C . The upper end of this range is reached at a 2.1 MW/m^2 neutron wall loading as shown in Fig 3. The low end of this temperature range insures a low tritium inventory. However, operating for a full power day at low temperature will result in a tritium inventory of less than 130 g. So from the solid breeder point of view, a continuous operation in the range of 0.94 to 2.1 MW/m^2 is acceptable during the technology phase and limited operation at lower power levels.

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19

Figure 3. Steady state extreme temperatures of the two breeder zones at the midplane as a function of the neutron wall loading during the technology phase.

The temperature limit of the steel clad is set based on the thickness of the reaction layer at the end-of-life. For example, the thickness of the reaction layer is 0.01 mm at the end of a full power day at 2.1 MW/m^2 relative to 0.1 mm expected at the end-of-life of 3.8 full power years. So, the steel clad does not restrict the blanket operation.

The beryllium temperature limit is set to avoid helium-induced swelling. During the physics phase the helium concentration in the beryllium material is very low, which allows the beryllium to operate at higher temperatures. As the beryllium accumulates neutron fluence, the temperature limit approaches the design limit of less than 700°C . This limit is corresponding to 1.88 MW/m^2 or 1350 MW of fusion power during the technology phase at the end-of-life. Also, the beryllium material in ITER is expected to show less swelling because of the low density factor (0.65 to 0.85) used for the design.

The blanket steel structure, the back wall of the first wall and the side walls are at less than the 400°C temperature limit because of the coolant conditions. These results show that the blanket can operate continuously over a wide range of neutron wall loading of 0.9 to 1.9 MW/m^2 . Also, a limited operation from 0 to 2.1 MW/m^2 is allowed from the blanket design point of view. It is expected that the other reactor components such as the divertor or the first wall will impose more restrictive limits on the upper end of the allowable range. Similar analyses were done for the physics phase where the same conclusion was reached.

VI. CONCLUSIONS

The neutronics and the thermal design analyses of the U.S. solid breeder blanket for ITER show that a net tritium breeding ratio close to unity is possible. Also, the blanket can tolerate transient conditions with passive methods and operates in the two phases of ITER.

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