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THREE-DIMENSIONAL NEUTRONICS ANALYSIS OF THE U.S. BLANKET DESIGN FOR ITER

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ABSTRACT

Detailed three-dimensional neutronics analysis has been performed for ITER with the U.S. solid breeder blanket utilizing sintered product materials for both the breeder and multiplier. The overall tritium breeding ratio is 0.81 with two outboard breeder zones and 0.89 for the three outboard breeder zone design option. The total reactor thermal power is 1150 MW in the technology phase.

INTRODUCTION

The blanket in the International Thermonuclear Experimental Reactor (ITER) is required to produce the necessary tritium required for the ITER operation while performing adequately and safely in the ITER nuclear environment. The U.S. solid-breeder water-cooled blanket design proposed for ITER utilizes Li_2O for breeding and beryllium for neutron multiplication and breeder temperature control. Different blanket concepts have been developed based on a multilayer configuration. The main difference between these concepts is in the fabricated form of the breeder and multiplier. In this paper, the neutronics analysis is given for the U.S. design utilizing sintered product materials for both the breeder and multiplier. The inboard blanket has a single Li_2O breeder zone embedded in a beryllium zone and the outboard blanket has two breeder zones. The poloidal variation of the neutron wall loading is accommodated by varying the beryllium thickness to maintain a constant minimum breeder temperature >450°C in the poloidal direction as required for tritium extraction.[1]

Several penetrations are used in ITER for blanket testing, plasma heating, startup, current drive, and vacuum pumping. This results in significant reduction in the space available for tritium breeding. The one-dimensional neutronics results have been coupled with the coverage fractions of the different reactor components to estimate the impact of these penetrations on the overall tritium breeding ratio (TBR). This approach was very useful in the early stages of the design where several design iterations were necessary. The detailed three-dimensional neutronics analysis performed for ITER with the U.S. blanket, utilizing sintered product materials, is presented here and the resulting overall TBR is compared to the one-dimensional estimate.

ESTIMATE OF OVERALL TRITIUM BREEDING RATIO BASED ON ONE-DIMENSIONAL ANALYSIS

Several one-dimensional toroidal cylindrical geometry calculations have been performed to determine tritium breeding in both the inboard and outboard blankets. In these calculations, the neutronics coupling (reflection and spectral effects) between the inboard and outboard blankets is taken into account. The calculations have been performed using the one-dimensional discrete ordinates code ONEDANT[2] with cross section data based on the ENDF/B-V evaluation. 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 in the plasma and represents the fraction of source neutrons going directly to this region. The NEWLIT code[3] was used to determine the coverage fractions for the different reactor regions taking into account the actual neutron source profile from the D-shaped plasma.

Coverage Fractions of Different Reactor Regions

The inboard blanket extends vertically from z = -3.4 m to z = 3.4 m. The outboard side blanket module extends from z = -4.8 m to z = 4.4 m. The outboard top central blanket module extends from z = 1.7 m to z = 4.1 m and the outboard bottom central blanket module extends from z = -4.8 m to z = -1.7 m. The coverage fractions for the inboard and outboard regions have been determined to be 16.4% and 68.1%, respectively. Sixteen penetrations are used in the outboard region at the midplane. All penetrations are 3.4 m high. It is assumed that eight 1.07 m wide ports will be utilized for blanket testing in ITER with 4.9% of the source neutrons going directly to them. Other penetrations include two 1.3 m wide maintenance ports, one 1.07 m wide EC startup port and two 1.07 m wide LH ports. The coverage fractions for these three types of ports are 1.5%, 0.6% and

1.2%, respectively. In addition, three NBI ducts are used in ITER. Each NBI duct is 0.8 m wide and tangent to a 6.2 m radius circle implying that the port is 1.2 m wide at the first wall. The coverage fraction for the three NBI ports is 2.1%. The total coverage fraction of the 16 ports in the outboard region is 10.3%. The actual coverage fraction of the outboard blanket should be modified by subtracting the coverage fraction of the penetrations. This leads to a coverage fraction of 57.8% for the outboard blanket.

One-Dimensional Neutronics Analysis

The radial build for the solid breeder blanket varies poloidally according to the poloidal neutron wall loading variation in order to maintain constant minimum breeder temperature in the poloidal direction.[3] The neutronics calculations have been performed for the blanket configurations at different poloidal locations. The thickness of the Be layer was assumed to vary linearly with the wall loading. The effect of the 0.5 cm thick copper stabilizer loops used at the top and bottom of the outboard blanket has been taken into account by performing the neutronics calculations with the Cu in the outboard region at distances more than 2.7 m vertically away from the reactor midplane. The results of the toroidal cylindrical geometry neutronics calculations are given in Table 1 for the U.S. blanket design option with a single Li_2O zone in the inboard blanket and two breeder zones in the outboard blanket. This design option utilizes sintered product material for both the beryllium multiplier and the solid breeder. The Li in the Li_2O breeder is enriched to 95% ^6Li. Taking into account the poloidal variation of the neutron wall loading and radial build, the poloidally averaged TBR was determined to be 0.21 for the inboard region and 1.003 for the outboard region.

Table 1. Results of Toroidal Cylindrical Geometry Calculations for the U.S. Blanket Design.

Region	Z (m)	Wall Loading (MW/m^2)	Cu Thickness (cm)	TBR
Inboard				
	0	0.884	0	0.206
	3.4	0.325	0	0.217
Outboard				
	0	1.204	0	0.948
	2.7	0.958	0	1.070
	2.7	0.958	0.5	0.991
	4.3	0.600	0.5	0.966

Estimate of Overall Tritium Breeding Ratio

In the one-dimensional toroidal cylindrical geometry model, 21.2% of the source neutrons go directly to the inboard region with the rest going to the outboard region. The results of the toroidal calculations have to be modified by the actual coverage of the inboard and outboard regions of ITER to determine the contribution to the net TBR. In addition, space taken by the assembly gaps and side walls amounting to 11% of the inboard region and 4.4% of the outboard region should be taken into account. Figure 1 illustrates the estimation of the overall TBR for the U.S. solid breeder blanket design utilizing sintered product materials. The overall TBR is estimated to be 0.84 with 0.14 contributed from the inboard blanket modules. The effect of the fabricated form of the breeder on the overall TBR has been investigated by performing the neutronics calculations for the U.S. blanket design with double size breeder pebbles instead of the sintered product. The overall TBR is estimated to be 0.81 as indicated in Figure 2.

An alternate blanket design that utilizes three breeder zones in the middle of the outboard blanket (-2.7 m < z < 2.7 m) has been considered. In this design, two breeder zones are used in the outboard blanket regions behind the Cu stabilizer shells. The impact on tritium breeding has been assessed. The poloidally averaged outboard TBR determined from the one-dimensional toroidal calculations for the U.S. design option with sintered product material used for both the breeder and multiplier is 1.113 and the overall TBR is 0.92. This implies that using three breeder zones instead of two in the middle of the outboard region results in a 9.6% enhancement in TBR. The impact of the Cu stabilizer shells used in the outboard region has been investigated by performing the calculations for the reference two breeder zone design without the copper. This resulted in an overall TBR of 0.87 for the U.S. design implying that the Cu stabilizer loops reduce the overall TBR by 3.4%. The overall TBR increases to 0.95 for the three breeder zone design if the Cu stabilizer loops are not used. It is therefore concluded that the overall TBR of the U.S. solid breeder blanket for the current ITER configuration is in the range between 0.81 and 0.95 depending on the fabricated form of the breeder, whether two or three breeder zones are used in the outboard blanket and whether Cu stabilizer loops are utilized.

THREE-DIMENSIONAL NEUTRONICS ANALYSIS

Calculational Model

Three-dimensional neutronics calculations have been performed for the U.S. solid-breeder water-cooled blanket design to determine the overall tritium breeding ratio as well as tritium breeding and nuclear heating in the different components of the blanket. The continuous energy coupled neutron-gamma Monte Carlo code MCNP, version 3B,[4] has been used with cross section data based

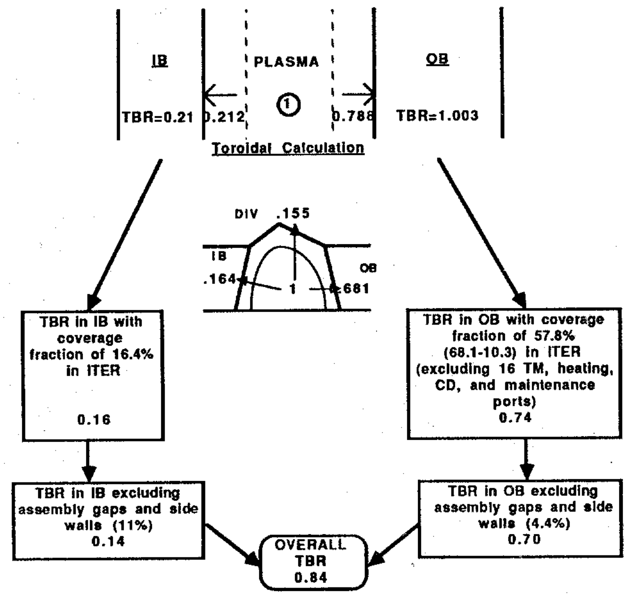

Figure 1. Estimation of overall TBR for the U.S. blanket design with two OB sintered product breeder zones.

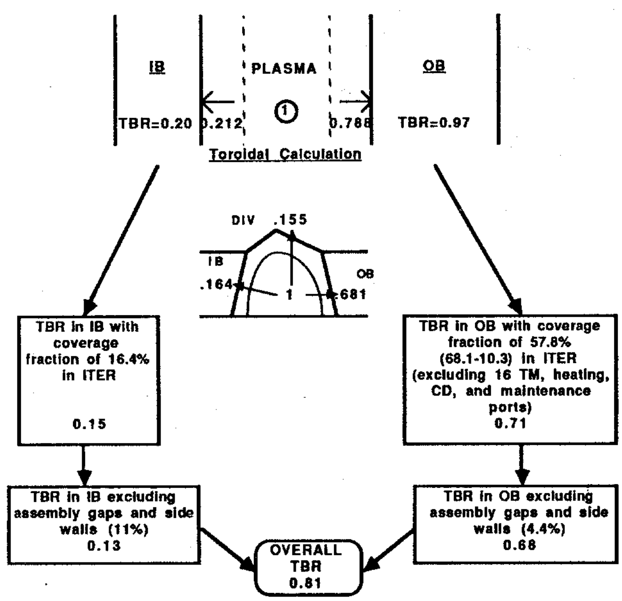

Figure 2. Estimation of overall TBR for the U.S. blanket design with two OB pebble bed breeder zones.

on the ENDF/B-V evaluation. The outboard blanket is divided into equally wide 48 modules. Three modules fit between adjacent TF coil center lines. Of the three, the central module is split into top and bottom modules by the 1.07 m × 3.4 m radial ports. The inboard blanket is divided into 32 identical modules with each module being divided into three electrically insulated segments. Because of symmetry, only 1/32 of the reactor was modeled with two vertical reflecting surfaces at azimuthal angles of 0° and 11.25°. The model includes one inboard blanket module, one outboard side blanket module, one-half of an outboard top central blanket module and one-half of an outboard bottom central blanket module.

The blanket modules were modeled in detail with the poloidally varying radial builds required for breeder temperature control. The sidewalls and detailed layered configuration of the FW and blanket are included in the model. The sidewalls are 1.4 cm thick in the outboard modules and 1 cm thick in the inboard modules. The vertical extents of the inboard and outboard blankets are -3.4 to 3.4 m and -4.8 to 4.3 m, respectively. The total inboard FW and blanket thickness increases from 11.6 cm at the midplane to 21.5 cm at the top. The total outboard FW and blanket thickness varies from 26.5 cm at the midplane to 69.2 cm at the top. The calculations have been performed for the reference U.S. design that utilizes a single Li_2O breeder zone in the inboard blanket and two breeder zones in the outboard blanket. The lithium in the Li_2O breeder is enriched to 95% ^6Li and the beryllium density factor ranges from 0.65 to 0.85.

The 2-cm-thick assembly gaps between blanket modules were included in the model. The copper stabilizer loops used in the outboard region were modeled. The thickness of the Cu shell is 0.5 cm and covers both sides of each outboard blanket module as well as the front of the blanket at the top and bottom with vertical distances beyond 2.7 m from the reactor midplane. The FW configuration in the inboard, outboard, and divertor regions was modeled in detail. The divertor plates and vacuum pumping ducts in the lower divertor region were included in the model. The reference ITER divertor plate design consisting of tungsten, niobium, and water, was used. Sixteen standard 1.07 m × 3.4 m radial ports were used at the middle of the outboard region. These ports are utilized for testing, plasma heating, startup and maintenance. A typical Li/V blanket was used in the ports to represent a blanket test module. The test section used in the model is surrounded by a 25 cm thick steel buffer zone.

Figures 3 and 4 show vertical cross sections of the geometrical model used through central and side outboard blanket modules, respectively. A horizontal cross section at the reactor midplane is given in Figure 5 with cross sections showing the details of the inboard, outboard side, and outboard central blanket modules given in Figures 6, 7, and 8. The neutron source was sampled from the D-shaped toroidal plasma zone whose boundary was determined from the reference ITER plasma parameters. The plasma has a 6 m major radius, 2.15 m minor radius, 1.98 elongation, 0.383 triangularity, and 0.255 m magnetic axis shift. The location of the neutron source in the plasma zone was determined by sampling from the reference ITER source profile. The results were

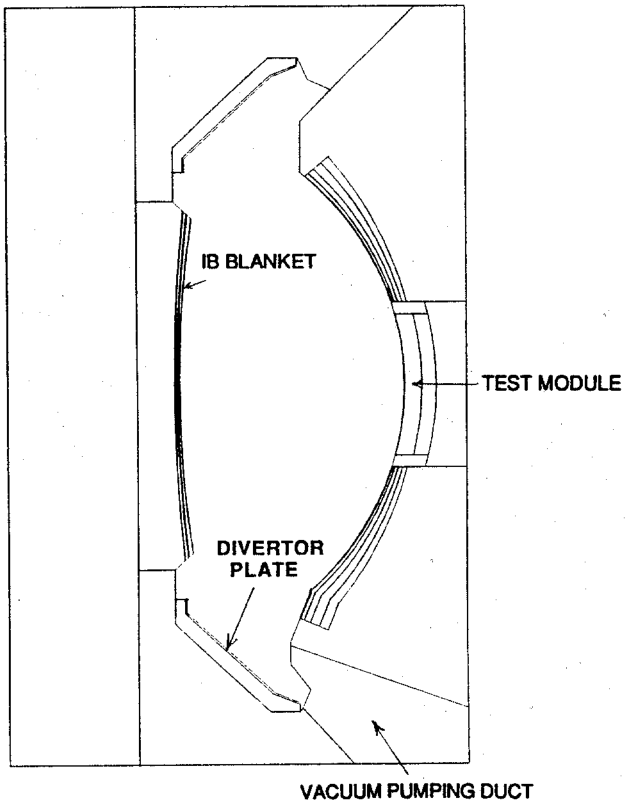

Figure 3. Vertical cross section through a central module.

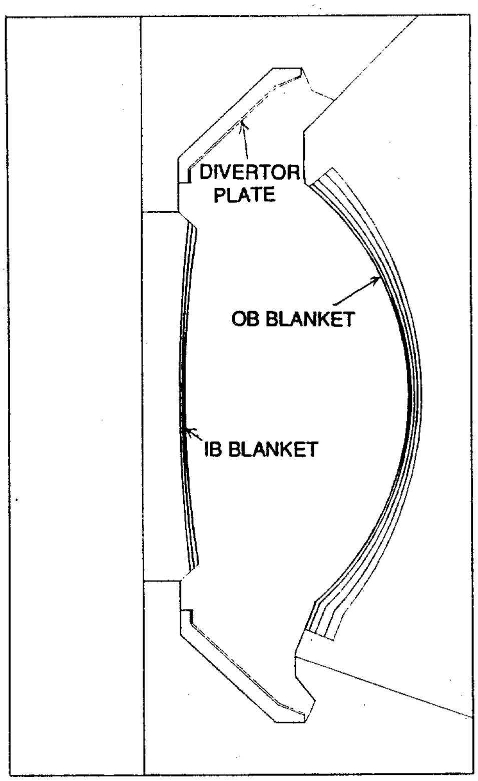

Figure 4. Vertical cross section through a side module.

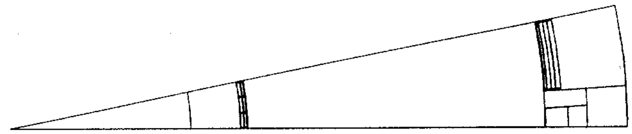

Figure 5. Horizontal cross section at midplane.

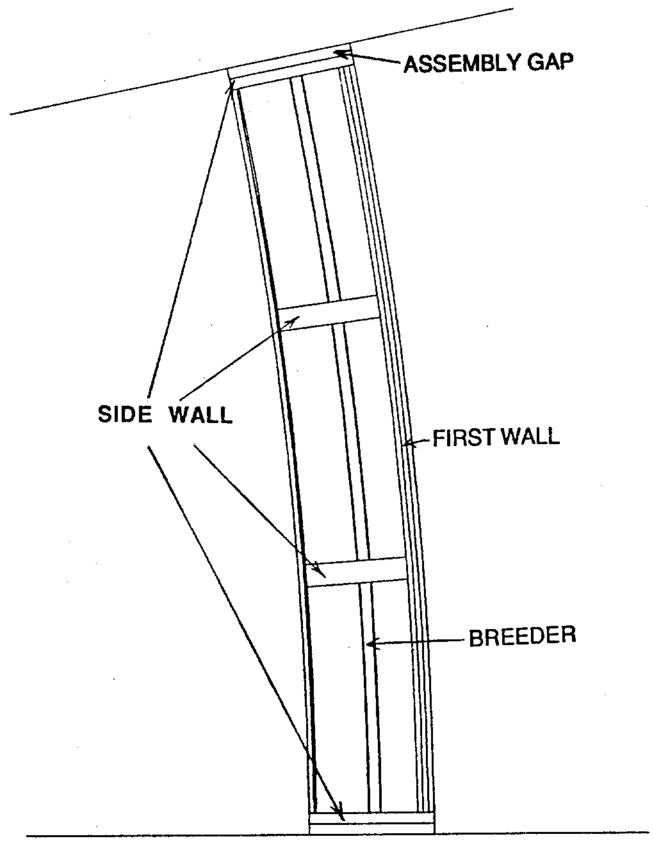

Figure 6. Horizontal cross section showing IB module details.

normalized to the technology phase fusion power of 860 MW. Several variance reduction techniques, including geometry splitting and weight cutoff with Russian roulette, were utilized to improve the accuracy of the calculations with a reasonable number of histories. Thirty thousand histories were used in the calculation yielding statistical uncertainties less than 0.8% in the calculated overall TBR and nuclear heating.

Results

Table 2 gives the tritium breeding results in the different blanket zones. Numbers in parentheses represent the relative statistical error from the Monte Carlo calculation. The results indicate that the overall TBR is

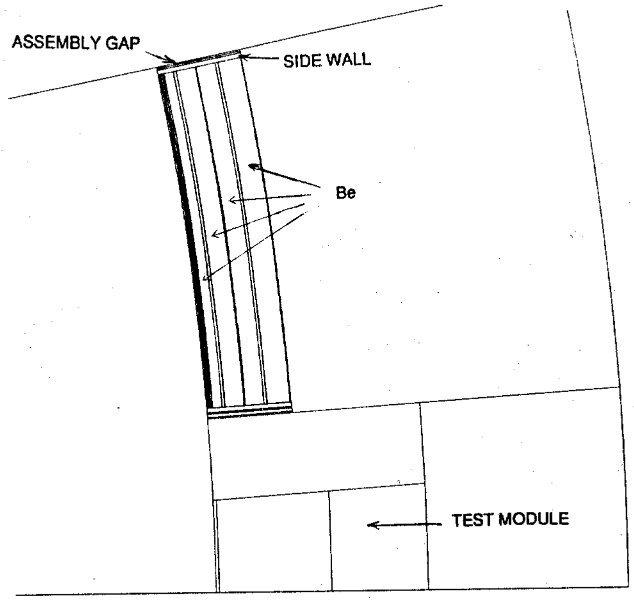

Figure 7. Horizontal cross section showing OB side module details.

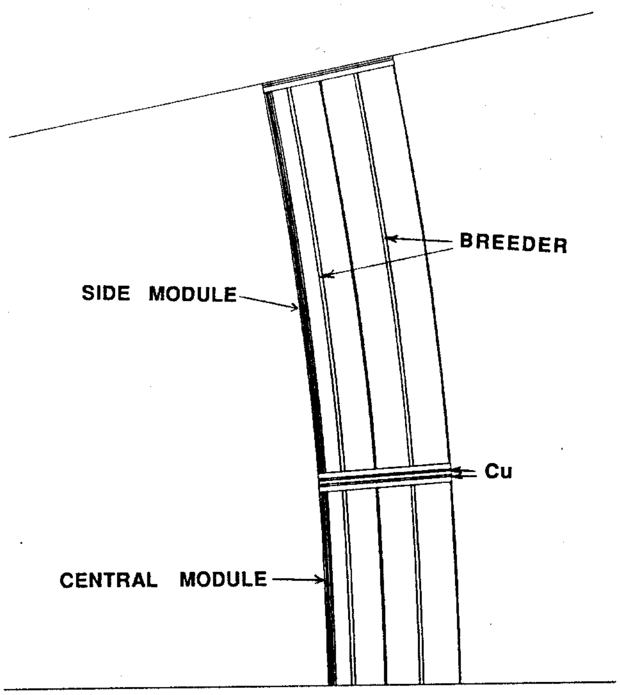

Figure 8. Horizontal cross section with OB side and central module details.

Table 2. Tritium Breeding (Tritons per DT Fusion) in the Different Breeder Zones of the U.S. Sintered-Product Solid Breeder Blanket.

Inboard Blanket	0.116 (0.021)*
Outboard Blanket	
Side Module:	
Front breeder zone	0.331 (0.012)
Back breeder zone	0.206 (0.017)
Total	0.537 (0.010)
Top Central Module:	
Front breeder zone	0.047 (0.032)
Back breeder zone	0.028 (0.046)
Total	0.075 (0.026)
Bottom Central Module:	
Front breeder zone	0.053 (0.031)
Back breeder zone	0.028 (0.044)
Total	0.081 (0.024)
Reactor Total	0.809 (0.008)

*Relative error

0.81 with 15% of it contributed by the inboard blanket. The effect of using different materials in the radial ports on tritium breeding has been investigated by performing the 3-D calculation with 35% steel, 10% H_2O, 5% Cu, and 50% void in the outboard radial port. This is representative of a LH or RF port. The overall TBR calculated in this case is 0.802 implying that tritium breeding in the permanent breeding blanket is not sensitive to the material used in the ports. It is interesting to note that coupling the 1-D toroidal geometry results with coverage fractions of the different breeding zones, the overall TBR was estimated to be 0.84 which is only 3.7% different from the value obtained from the detailed 3-D calculation. In addition, the 1-D analysis for the blanket with double size breeder pebble beds resulted in 3.2% lower overall TBR compared to the sintered product design implying that the 3-D calculation for the blanket design with breeder pebble beds is expected to yield 0.78 for net TBR. Furthermore, the 1-D analysis indicated that the overall TBR increases by 9.6% if three breeder zones are utilized in the outboard blanket in the zone $-2.7 \text{ m} < z < 2.7 \text{ m}$. Therefore, the overall TBR from the 3-D calculations is expected to increase to 0.89 and 0.86 with three breeder zones for the sintered product and pebble bed breeders, respectively. Tritium breeding in each test module was determined to be 0.003 per DT fusion. Hence, if tritium bred in the 8 test modules is accounted for, the overall TBR will increase by 0.024. This value is expected to be higher for other types of blanket. Table 3 gives the breakdown of nuclear heating in the different reactor regions. The total nuclear heating in the reactor excluding test modules is 996 MW, for the technology phase implying that the overall energy multiplication is 1.45. Adding the surface heating in the different reactor regions excluding the ports implies that the total reactor thermal power is 1150 MW.

Table 3. Nuclear Heating in the Different Reactor Regions in the Technology Phase.

Region	Nuclear Heating (MeV/DT Fusion)	Nuclear Power (MW)
Divertor		
Divertor plates	0.425 (.03)*	21
Shield	3.201 (.02)	156
Total	3.626 (.02)	177
Inboard		
FW/Blanket	2.018 (.01)	99
Shield	1.642 (.03)	80
Total	3.660 (.01)	179
Outboard		
FW/Blanket	10.475 (.01)	512
Shield	2.617 (.02)	128
Total	13.092 (.02)	640
Reactor Total	20.378 (.007)	996

*Relative error

SUMMARY AND CONCLUSIONS

The overall TBR has been estimated by coupling the results of the one-dimensional toroidal cylindrical neutronics calculations with the coverage fractions of the different blanket regions in ITER. The overall TBR estimate is in the range between 0.81 and 0.95 depending on the fabricated form of the breeder, whether two or three breeder zones are used in the outboard blanket and whether Cu stabilizer layers are utilized. Using three breeder zones instead of two results in increasing the overall TBR by 9.6%. On the other hand, integrating the Cu stabilizer loops in the outboard blanket results in decreasing the overall TBR by 3.4%. The analysis has been performed for the U.S. solid breeder design option utilizing sintered product materials for both the Li_2O breeder and Be multiplier.

The ITER geometry has been modeled in detail for the three-dimensional neutronics calculations. The model includes the detailed reactor toroidal and poloidal geometrical variations with penetrations, assembly gaps, Cu stabilizer loops, divertor plates, test modules, as well as the detailed layered configuration of the blanket. The results indicate that the overall TBR is 0.81 with two outboard breeder zones and 0.89 for the design with three outboard breeder zones. From the tritium breeding point of view, the design with three outboard breeder zones is, therefore, recommended. The TBR values reported here do not include tritium bred in the eight blanket test modules which amounts to about 0.03 per DT fusion. The results of the detailed three-dimensional calculation and the estimate based on one-dimensional analysis agree to within ~4%. The total reactor thermal power has been determined to be 1150 MW, in the technology phase.

ACKNOWLEDGEMENT

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