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NEUTRONICS ANALYSIS FOR A HIGH WALL LOADING COMPACT TOKAMAK POWER REACTOR

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ABSTRACT

Neutronics analysis is presented for a compact high wall loading (HWL) tokamak reactor with a major radius of 2.6 m, an aspect ratio of 4.33 and a fusion power of 1025 MW. A normal bean coil is used to achieve a high β value of 20%. The peak and average wall loadings are 12 and 8.7 MW/m^2. No breeding blanket is used on the inboard side. The impact of using different materials on the overall TBR is assessed. Despite the limited breeding blanket coverage, an overall TBR > 1.05 is obtained when a 10 cm thick layer of a neutron multiplier is used on the inboard side above and below the bean coil. The total reactor thermal power is ~ 1300 MW.

INTRODUCTION

There has been a growing interest recently in not breeding on the inboard side of tokamaks. The impact on the overall tritium breeding ratio (TBR) has been investigated for different designs with emphasis on solid breeders.[1-3] There is a larger incentive for not breeding on the inboard side of a high wall loading tokamak. Achieving a high fusion power density requires large magnetic fields on axis. It is therefore essential to reduce the space between the plasma and the inboard leg of the TF coil. Since the breeding blanket is not an effective neutron shield, it is preferable to replace it with a more effective shield that reduces the space required for adequate magnet protection from the high neutron wall loading environment. Furthermore, the reactor compactness makes it difficult to maintain or replace an inboard blanket. Careful design of such a reactor is necessary to ensure tritium self-sufficiency.

In this work, we present the neutronics analysis for a high wall loading (HWL) tokamak design.[4] The reactor has major and minor plasma radii of 2.6 and 0.6 m, respectively and a high β value of 20%. The fusion power is 1025 MW. A normal conducting bean coil is used on the inboard side to establish an initial bean shaped plasma that allows operation in the second stability regime ,with the high β value. The very high surface heating necessitates using a 1 cm thick separately cooled first wall. The HWL blanket utilizes static $Li_{17}Pb_{83}$ contained in HT-9 cylinders 15 cm in diameter and cooled by helium gas. The blanket cylinders are oriented in the poloidal direction and grouped in twelve modules that cover the outboard, top and bottom sides. The high wall loading necessitates frequent blanket replacement. The modules are designed for removal between the TF coils implying that the space between modules is not available for tritium breeding. A single null bottom divertor is utilized. Figure 1 is a cross section of the reactor through the center of a TF coil.

The primary goal of this work is to determine whether an adequate overall TBR can be obtained in the HWL blanket design. The impact of the material used on the inboard side on tritium breeding in the outboard blanket is assessed. One-dimensional analysis has been performed to determine the local TBR and blanket energy multiplication (M). Because of the limited breeding blanket coverage dictated by the requirement that the LiPb in the blanket cylinders be drainable, a relatively thick blanket is used to maximize the local TBR. Detailed three-dimensional neutronics calculations have been performed to determine the overall TBR with different materials on the inboard side. An overall TBR $\gtrsim$ 1.05 is required in the three-dimensional calculations to allow for tritium losses and radioactive decay and supplying fuel for startup of other fusion reactors. The neutronics characteristics for the final HWL blanket design have been determined from the three-dimensional calculations.

NEUTRON WALL LOADING DISTRIBUTION

The neutron wall loading in a tokamak reactor has a poloidal variation that depends on the plasma shape, the neutron source distribution and the first wall shape. This poloidal distribution has an important impact on the reactor thermal-hydraulics design and magnet shield design. The NEWLIT code[5] was used to calculate the poloidal variation of the neutron wall loading in the HWL reactor. The results

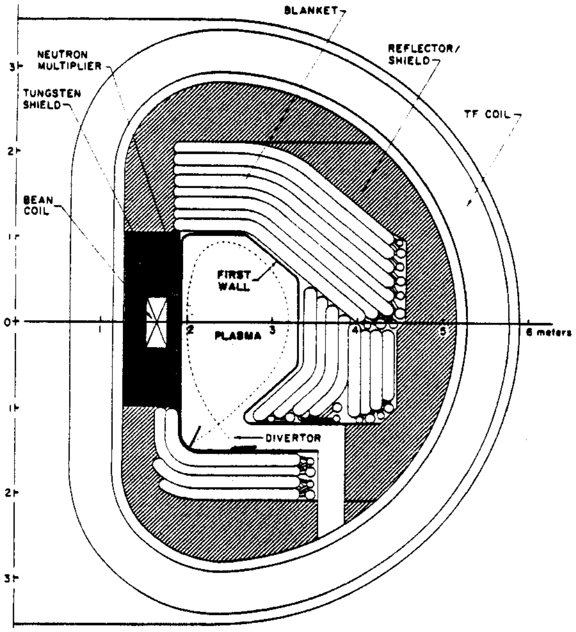

Fig. 1. Cross section of the HWL reactor.

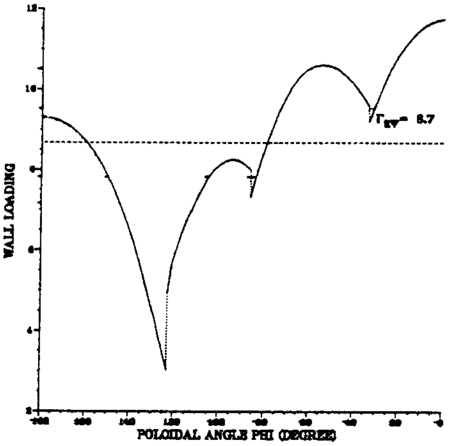

Fig. 2. Poloidal variation of the neutron wall loading in the HWL reactor.

are given in Fig. 2. The wall loading distribution in each segment of the first wall is indicated. The dashed line represents the average value of 8.7 MW/m^2. The peak reactor wall loading of 12 MW/m^2 occurs at the reactor midplane on the outboard side. The inboard peak wall loading occurs at the midplane indicating that the hot spot in the inboard leg of the TF coil is at the reactor midplane.

Table I. Impact of Inboard Material on TBR

Inboard Material	TBR (63% Coverage)/ TBR (Full Coverage) Outboard Li Blanket	Outboard $Li_{17}Pb_{83}$ Blanket	14 MeV Albedo
Be	0.840	0.733	1.77
Pb	0.830	0.719	1.60
C	0.726	0.636	0.69
SS	0.734	0.621	0.75
Cu	0.720	0.596	0.79
W	0.716	0.572	0.96
H_2O	0.653	0.550	0.39
TiH_2	0.626	0.494	0.40
B_4C	0.608	0.468	0.47

IMPACT OF INBOARD MATERIAL ON TRITIUM BREEDING

Proper choice of the material used on the inboard side is essential. Materials that provide large neutron reflection are required to enhance tritium breeding in the outboard breeding blanket. Calculations were performed to compare the ability of the different shielding materials and neutron multipliers to reflect neutrons. A composition that allows for structural material and cooling was used. The albedo, which measures the number of neutrons, regardless of their energy, reflected per 14.1 MeV incident neutron was calculated for 40 cm thick slabs and is given in Table I. Similar calculations were performed by Micklich and Jassby.[6] However, no allowance was made for the required structural material and coolant.

While the albedo values indicate the ability of the material to reflect the source neutrons, many secondary neutrons originating in the outboard blanket will be incident on the inboard material. Hence, the 14 MeV albedo is not an accurate measure of the impact of inboard material on TBR. This can be properly assessed by performing a neutron transport calculation in which both the inboard shield and outboard blanket are included.

We performed a one-dimensional toroidal cylindrical geometry calculation using the model shown in Fig. 3. Two outboard blanket designs were considered: a natural liquid lithium blanket and a $Li_{17}Pb_{83}$ blanket with 90% ^6Li enrichment. A 30 cm thick stainless steel reflector is included to properly account for the blanket boundary condition. The P_3S_8 calculations were performed using the discrete ordinates code ONEDANT[7] with cross section data based on ENDF/B-V. The breeding blanket coverage fraction in the model is only 63% since the top and bottom blankets are not included.

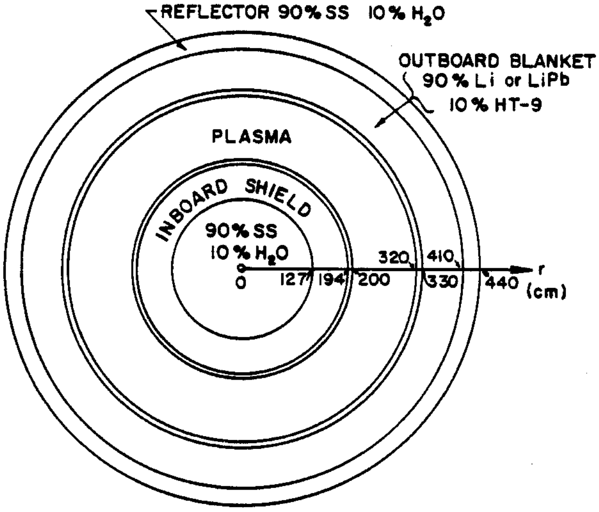

Fig. 3. The one-dimensional toroidal cylindrical model used to investigate the impact of inboard material on TBR.

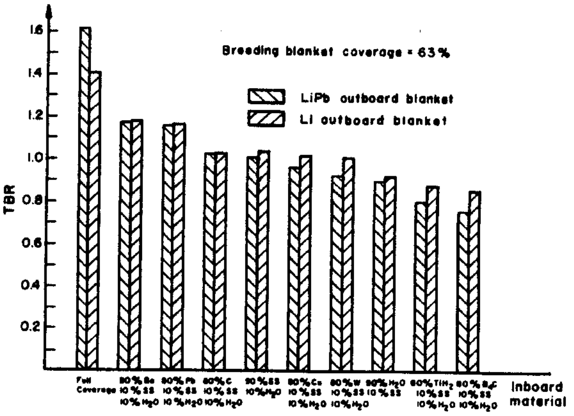

Fig. 4. The overall TBR using different inboard materials for Li and LiPb outboard blankets.

Table I gives the ratio of TBR obtained with different inboard materials to that obtained with full breeding blanket coverage. A ratio > 0.63 implies that replacing the inboard breeder by the given material yields more tritium breeding in the outboard blanket. More inboard materials enhance outboard breeding when they replace Li than LiPb. The reason is that Li is a strong neutron absorber while LiPb is a good neutron multiplier in addition to being a strong neutron absorber in the low energy region.

Table I demonstrates the inadequacy of the 14 MeV albedo for predicting the impact of inboard material choice on TBR. For example, while tungsten has the largest 14 MeV albedo among non-multiplier inboard shields, it yields a TBR lower than that obtained using most of the other materials. This is due to its large neutron absorption in the resonance and lower energy ranges. The neutron multipliers (Be and Pb) used on the inboard side give the best overall TBR. Graphite and steel are the best non-multiplier materials.

Fig. 4 is a bar chart that shows the overall TBR obtained using different inboard materials. While the overall TBR with full breeding blanket coverage is larger for LiPb than for Li, the overall TBR is more sensitive to the breeding blanket coverage fraction and inboard material choice when LiPb is used. This is attributed to the large neutron multiplication in the LiPb outboard blanket that results in larger reflection into the inboard shield. The 14 MeV albedo values for the Li and LiPb blankets were calculated to be 0.85 and 1.14, respectively.

ONE-DIMENSIONAL ANALYSIS

The one-dimensional calculations for the HWL blanket were performed using ONEDANT with 30 neutron-12 gamma energy group cross section data based on ENDF/B-V. A poloidal cylindrical geometry model was used. Therefore, the results are indicative of the local neutronics parameters. The blanket cylinders are made of HT-9 and contain a stationary $Li_{17}Pb_{83}$ breeder enriched to 90% ^6Li and cooled by helium gas. The first wall is 1 cm thick and is made of HT-9 and cooled by helium gas. The structure content in the first wall is 30%.

The geometrical model used in the calculations is shown schematically in Fig. 5. A 10 cm scrapeoff zone is considered. The 6 cm space between the first wall and the blanket is considered to allow for accommodating the first wall coolant manifolds. A 60 cm thick water cooled Fe 1422 reflector/shield is used behind the blanket. The volume fractions of the constituents of the different cylinders were determined from a thermal-hydraulics analysis. The structure content as well as the He coolant content decrease as one moves away from the plasma deep in the blanket due to the degradation in nuclear heating.

Several one-dimensional calculations have been performed using different numbers of cylinder rows. Both the local TBR and M were calculated. The results are shown simultaneously in the T-M plot in Fig. 6. Increasing the blanket thickness increases T while M decreases. The primary goal here is to maximize the local TBR because of the limited breeding blanket coverage

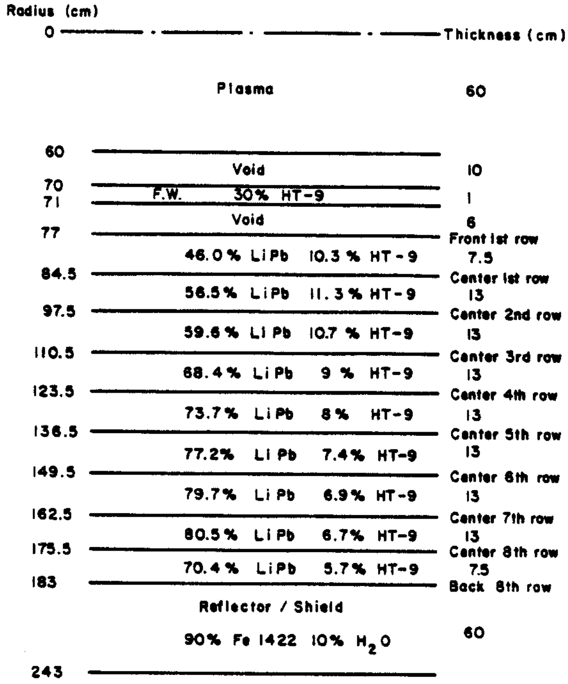

Fig. 5. The one-dimensional model.

fraction. A local TBR of 1.5 is obtained using a 106 cm thick blanket consisting of eight rows of cylinders. Adding another row of cylinders will insignificantly increase the local TBR while increasing the reactor direct cost as larger TF coils are required to provide enough space between the outboard legs of the coils that allows for removing the blanket modules. Based on a peak neutron wall loading of 12 MW/m^2, a peak power density of 72 W/cm^3 is obtained in the first wall. The peak power density in the blanket structure is 64 W/cm^3 and the peak power density in LiPb is 93 W/cm^3.

The results of Table I were utilized together with the one-dimensional local TBR results to give a preliminary estimate for the overall TBR in the HWL reactor when different numbers of breeding blanket cylinder rows are used in the different segments and different materials are used in the non-breeding zones. In order not to jeopardize the magnet shielding, the optimum shield composition, determined from the magnet shield optimization[8], was used in the bean coil zone where the peak radiation effects occur in the superconducting TF coil. A tungsten shield is used between the bean coil and the first wall in this zone. Because of its lesser impact on reducing the TBR, stainless steel is used behind the first wall in the other non-breeding zones. The possibility of enhancing the overall TBR by using a layer of a neutron multiplier behind the first wall in the upper and lower inboard zones was considered.

Table II summarizes the overall TBR estimate for the different options. According to this one-dimensional estimate, Case 4 gives an overall TBR greater than 1 by a very small margin. Case 5 shows that the overall TBR can be made greater than the required value of 1.05 by using a layer of a neutron multiplier (80% Be, 10% Fe 1422 and 10% H_2O) behind the first wall in the upper and lower inboard zones. Using lead instead of beryllium yields a slightly lower TBR as given for Case 6. Cases 4, 5 and 6 are considered further in this study. The final design given in Fig. 1 indicates that L-shaped cylinders are used in the bottom blanket zone with four rows in the horizontal section and only two rows in the vertical section as required for adequate magnet protection. This design is properly represented in Cases 4, 5 and 6 where three rows of cylinders are assumed to be used in the bottom blanket zone. Using a front neutron multiplier layer in the upper and lower inboard zones, the radiation effects in the TF coil were found not to exceed the design limits.[8]

THREE-DIMENSIONAL ANALYSIS

Because of the approximations used in estimating the overall TBR given in Table II, detailed three-dimensional neutronics calculations for Cases 4, 5 and 6 were performed. The continuous energy coupled neutron-gamma Monte Carlo code MCNP[9] and cross section data based on ENDF/B-V were used. Because of symmetry only 1/24 of the reactor was modeled with two reflecting surfaces surrounding it. The model

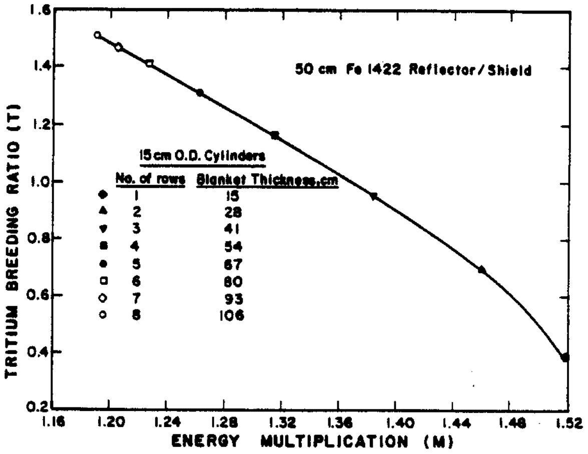

Fig. 6. The T-M plot for the HWL blanket with the effect of number of cylinder rows.

Table II. Overall TBR Estimate Based on One-Dimensional Results

	Upper Inboard Segment	Bean Coil Zone	Lower Inboard Segment	Top Blanket	Bottom Blanket	Outboard Blanket	Space Between Modules	Overall TBR
Case 1	SS	W	SS	7 rows	SS	7 rows	SS	0.901
Case 2	SS	W	SS	7 rows	1 row	7 rows	SS	0.939
Case 3	SS	W	SS	7 rows	2 rows	7 rows	SS	0.974
Case 4	SS	W	SS	7 rows	3 rows	7 rows	SS	1.002
Case 5	Be	W	Be	7 rows	3 rows	7 rows	SS	1.129
Case 6	Pb	W	Pb	7 rows	3 rows	7 rows	SS	1.089

includes one-half of one of the twelve blanket modules. The vertical cross section and a horizontal cross section at the reactor midplane are given in Figs. 7 and 8. The inboard shield consists of 80% W (0.95 density factor), 10% Fe 1422 and 10% H_2O. The normal bean coil is assumed to have 63% Cu, 25% MgO and 12% H_2O. The reflector/shield used behind the breeding blanket consists of 90% Fe 1422 and 10% H_2O. Three different materials are considered in the 10 cm thick layer behind the first wall in the upper and lower inboard zones. In the first option, the same composition as the reflector/ shield is used. In the second option, 80% Be, 10% Fe 1422, and 10% H_2O is used. In the third option the beryllium is replaced by lead.

The neutron source was sampled from a D-shaped plasma zone with elongation and triangularity of 1.6 and 0.3, respectively. The magnetic shift used to determine the spatial source distribution is 10 cm. At the midplane the scrapeoff zones are 6 cm and 10 cm thick on the inboard and outboard sides, respectively.

Five thousand histories were used in the calculations yielding statistical uncertainties less than 1% in the calculated overall TBR and M. The overall TBR and M for the three design options are given in Table III. It is interesting to note that the results for the TBR agree to within ~ 4% with the preliminary estimate based on the one-dimensional analysis. The first design option does not meet the requirement of a TBR > 1.05 and a neutron multiplier should be used on the inboard side above and below the bean coil.

The results indicate that about 19% of the tritium breeding occurs in the bottom blanket. Almost all the tritium is produced in the $^6Li(n,\alpha)t$ reaction. About 55% of the total nuclear heating comes from gamma heating. This is a direct consequence of using a metallic reflector. Based on a reactor fusion power of 1025 MW, we calculated the thermal power resulting from nuclear heating in the different reactor zones. The results are given in Table IV for the two design options. About 33% of the

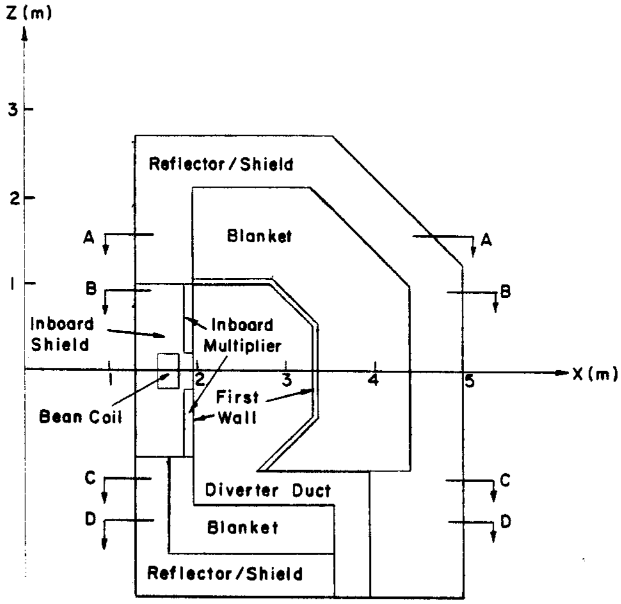

Fig. 7. Vertical cross section of the three-dimensional model.

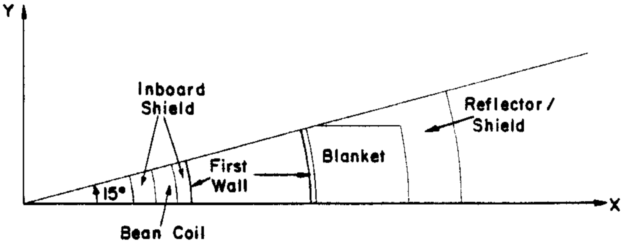

Fig. 8. Horizontal cross section at midplane.

Table III. Overall TBR and Energy Multiplication for the Three Design Options

Front Layer of Upper and Lower Inboard Zones	TBR	M
SS	1.012 (± 0.9%)	1.308 (± 0.6%)
Be	1.085 (± 0.9%)	1.336 (± 0.6%)
Pb	1.066 (± 0.9%)	1.307 (± 0.6%)

Table IV. Thermal Power (MW) Resulting from Nuclear Heating in the Different Zones

Front Layer of Upper and Lower Inboard Zones	Be	Pb
First wall	17.88	16.08
Blanket	718.43	706.02
Total in helium cooled zones	736.31	722.10
Reflector/Shield	356.37	346.29
Normal bean coil	4.25	4.48
Total in water cooled zones	360.62	350.77
Total System	1096.93	1072.87

total nuclear heating is deposited in the water cooled zones. Assuming that the energy carried by the α particles emitted in the fusion reaction will be recovered by the cooling systems of the divertor plates and first wall, the total reactor thermal power is 1300.76 MW for the Be case and 1276.71 MW for the Pb case. Assuming a 70% divertor efficiency and that the divertor is water cooled we determined that ~ 38% of the total reactor thermal power will be carried by the water coolant. This power can be used as a part of the power cycle.

SUMMARY

The poloidal variation of the neutron wall loading in the HWL design was determined. The average wall loading is 8.7 MW/m^2 and the peak value is 12 MW/m^2. The impact on the overall TBR of using different inboard materials was investigated. Using neutron multipliers gives the largest overall TBR. One-dimensional calculations were performed to determine the effect of the number of blanket cylinder rows on the local TBR and energy multiplication. A 1.06 m thick blanket consisting of eight rows of cylinders yields a local TBR of 1.5 and an energy multiplication of 1.19.

The peak power densities in the first wall and blanket are 72 and 87 W/cm^3, respectively. The average power densities in the front row of cylinders of the top and outboard blankets are 24 and 47 W/cm^3, respectively. The overall TBR in the HWL reactor was estimated based on the one-dimensional results using different inboard materials and different bottom blanket thicknesses. An overall TBR > 1.05 was obtained when a 10 cm layer of a neutron multiplier is used on the inboard side above and below the bean coil.

These results were confirmed by the detailed three-dimensional calculations where the overall TBR was found to be 1.085 and 1.066 for the beryllium and lead cases, respectively. The corresponding M values are 1.336 and 1.307, respectively. Based on a fusion power of 1025 MW, the total reactor thermal power was found to be ~ 1300 MW. In conclusion, we found that, despite the limited breeding blanket coverage and large structure content in the HWL reactor design, an adequate overall TBR can be obtained.

ACKNOWLEDGMENT

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