Neutronics Analysis for the Stellarator Power Plant Study SPPS

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ABSTRACT

The neutronics activities for SPPS included the determination of the blanket dimensions that provide tritium self-sufficiency, radiation damage to the structural materials, lifetime of the in-vessel components, radiation level at the superconducting magnets, and shielding requirements for magnet protection. The neutron wall loading varies in both poloidal and toroidal directions. For an average wall loading of 1.3 MW/m^2, the distribution peaks at 2 MW/m^2. The 35 cm thick blanket will breed sufficient tritium to ensure the self-sustaining operation of the DT fueled stellarator. The blanket utilizes the liquid lithium as a coolant and breeder and the low activation vanadium alloy V5Cr5Ti as a structural material. The first wall and blanket will be replaced every 11 years due to radiation to the vanadium structure. The shield follows the blanket and is primarily used to protect the magnets against radiation. Since the dimensions of the shield directly affect the size and cost of the machine, an extensive analysis was performed for the shield including evaluation of candidate materials, variation of composition, and computation of radiation effects on magnets. The shield is 80 cm thick and is made of borated steel filler supported by V structure. A successful attempt was made to lower the cost of the shield while keeping the attractive safety features of the design.

I. INTRODUCTION

Stellarators offer some operational advantages as steady-state disruption-free power plants. The stellarator power plant study (SPPS) identified and assessed the main physics and engineering issues and showed that stellarators could be economically competitive with tokamaks [1]. The SPPS is a 1000 MWe modular Helias-like Heliac (MHH) design having a beta of 5%, major radius of 14 m, peak field at coil of 16 T, and 4 field periods generated by 32 modular nonplanar coils, as illustrated in Fig. 1. Fig. 2 shows four plasma shapes at the beginning (0 degree) and middle (45 degrees) of a field period and at two other locations (22.5 and 67.5 degrees). The inner surface represents the plasma boundary while the outer surface is the magnet centroid. The first wall follows the plasma contour. The reference design incorporates the inherent characteristics of stellarators, such as low power density, low recirculating power, and steady-state disruption-free operation. The design utilizes vanadium as the main structural material and lithium as coolant and breeder. Section II documents the details of the design requirements for tritium breeding, optimal blanket parameters, radiation damage to the V structure, and lifetime of the different components. The extensive analysis performed to optimize the shield composition and performance is covered in Section III. Finally, the conclusions to be drawn from this work are summarized in Section IV.

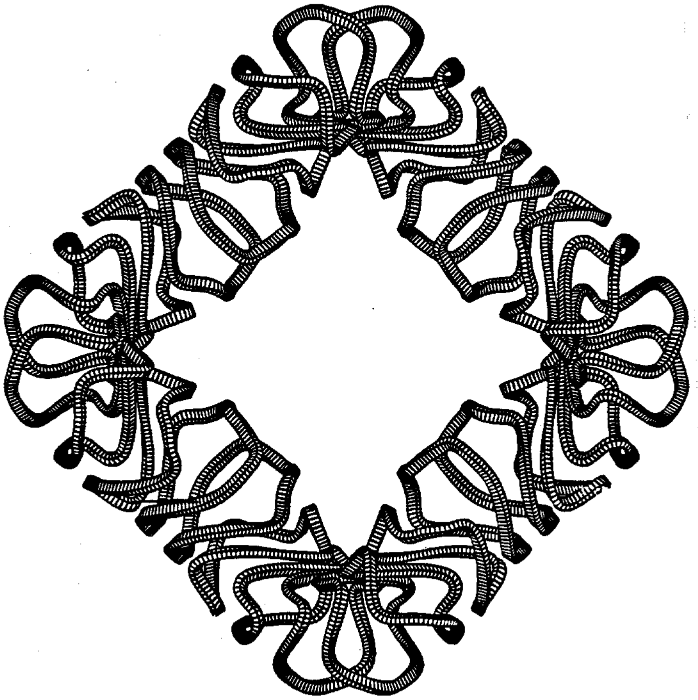

Fig. 1. SPPS reference coil set.

II. BLANKET NEUTRONICS

The primary goal of the blanket design is to breed sufficient tritium (T) that ensures the self-sustaining operation of the plant. SPPS will attain T self-sufficiency if the calculated TBR is equal to or exceeds 1.12. The actual achievable TBR from the blanket during operation will be ~1.02. The 10% margin accounts for the uncertainties in the design elements such as basic nuclear data and calculational models. It should be mentioned that the TBR is calculated for the reference design and the effects of the blanket coverage, Li burnup, penetrations, assembly gaps and side walls are all included in the computed TBR.

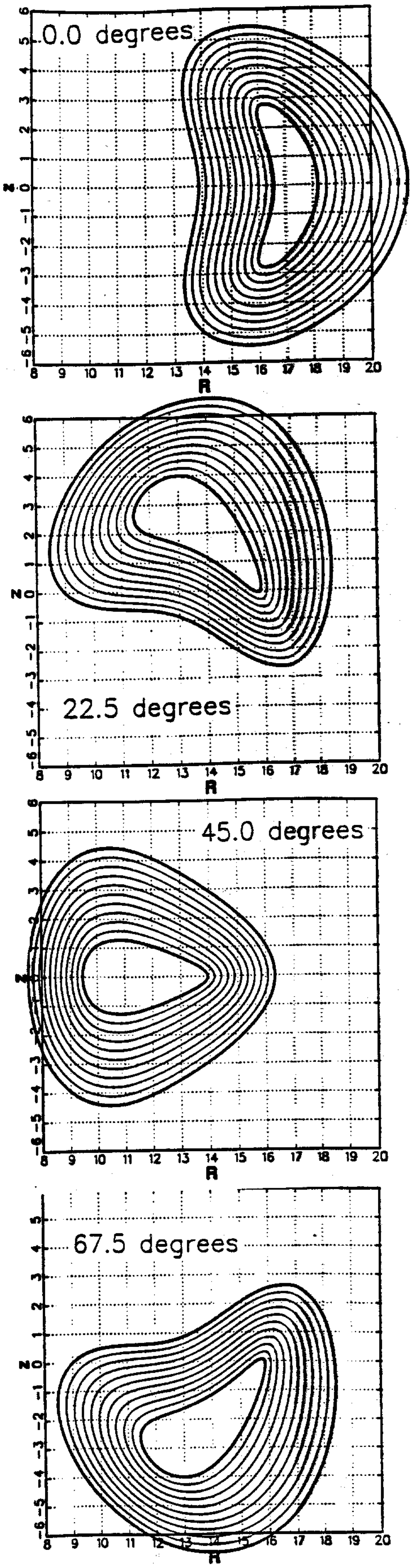

Fig. 2. Plasma cross sections at four toroidal locations of a field period.

The configuration of the MHH stellarator dictates that a simple one-dimensional (1-D) model is capable of handling the MHH geometry due to the fact that each of the 4 field periods extends toroidally for ~22 m. Therefore, a poloidal cylindrical model along the plasma axis can reasonably predict the neutronics parameters within a few percent. Provisions were made in the tritium breeding requirements for such uncertainties in the results. The blanket (90% Li and 10% V) surrounds the entire plasma except for the area occupied by a few penetrations needed for plasma fueling, heating, and control. These penetrations cover approximately 2% of the first wall (FW) area. Other components that degrade the breeding are the divertor plates/baffles (DP/B) and their support structures. They are ~5 cm thick, cover 15% of the FW area, and consist of 50% V structure, 20% Li coolant, and 30% void. Taking into account the penetrations and divertor effect, the neutronics analysis indicates that a 35 cm thick Li/V blanket will provide an overall TBR of 1.12. The T bred in the Li cooled shield amounts to less than 3%.

The neutron energy multiplication (M) accounts for the nuclear energy deposited in both blanket and shield. The shield design will be covered in detail later in Section III. However, some changes made to the conventional shield design are discussed here along with their impact on M and the rationale for these changes. The economic analysis of a recent tokamak design [2] employing a Li/V system has indicated that the shield is one of the most expensive components of the machine. The shield contains 15% V structure which comprises more than half of the shield cost. The potential of using less costly materials in the shield while maintaining the safety features of the design was investigated for the MHH stellarator. If the V structure (300 $/kg) is replaced by a cheaper steel structure (35 $/kg), the savings in the shield cost will be significant. This certainly will come at a cost in the power balance since V can operate at a higher temperature (700°C) compared to steel (550°C). An attractive solution is to divide the shield into two parts: the inner part following the blanket operates at a high temperature while the outer part operates at a relatively lower temperature (~300°C). The high temperature (HT) shield along with the FW and blanket employs V structure whereas the low temperature (LT) shield utilizes SS as the main structural material. As the nuclear energy deposited in the low temperature shield will not be recovered, the dividing boundary between the two shields will depend on how much power could be dumped as low grade heat without affecting the power balance much (e.g., 1-5%). It was decided to define the HT-LT shield boundary such that 1% of the total nuclear heating be deposited in the LT shield. The results indicated that the 1.4 cm FW, 35 cm blanket, and 45 cm thick shield contain 99% of the nuclear heating and the rest of the shield contains 1% of the heating. The overall energy multiplication is estimated to be 1.4, excluding the 1% heating in the LT shield.

The V structure will require frequent replacement during the 40 y planned operation of the MHH stellarator. The V5Cr5Ti alloy is the candidate structural material for the stellarator design. This alloy seems to possess high radiation resistance to fusion neutron damage. The lifetime of V is determined by the dpa level attainable during operation. The criterion adopted in this study is that no more than 200 dpa is desirable. For a peak wall loading of 2 MW/m^2 and a system availability of 76%, the 200 dpa limit implies that the FW/B should be replaced every 11 y and the corresponding end-of-life (EOL) fluence is 16.4 MWy/m^2. The blanket provides lifetime protection for the shield. At the end of the plant life (40 y), the atomic displacement at the V structure of the shield is 170 dpa which is below the 200 dpa limit. On this basis, the shield is considered a lifetime component and does not need replacement due to radiation damage.

III. SHIELD DESIGN

The main function of the shield is to protect the superconducting magnets and keep the radiation level below the allowable limits. In fact, these limits have a strong impact on the characteristics of the shield, in terms of thickness and composition. In order to reduce the radial standoff of the MHH stellarator, it was essential to optimize the shield in order to reduce the overall dimensions of the machine. As such, a serious effort was made to optimize the shield and the impact of the shield performance on the design was assessed with a view to cost, complexity, and safety.

Sufficient shield should be placed between the blanket and magnet to keep the radiation effects below certain limits. These limits are set by the magnet designers to insure the proper performance of the TF coils. For instance, at the end of 30 full power years (FPY) of operation, the fast neutron fluence ($E_n > 0.1$ MeV) should not exceed 10^{19} n/cm^2 to avoid degradation of the critical properties of the Nb_3Sn superconductor material. It is undesirable to subject the magnets to a total nuclear heating above 50 kW to avoid excessively high cryogenic load to the cryoplant. A limit of 2 mW/cm^3 is imposed on the peak nuclear heating in the winding pack. The end-of-life dose to the glass-fiber-filled (GFF) polyimide is limited to 10^{11} rads to ascertain the mechanical and electrical integrity of the insulator. The neutron-induced atomic displacement in the Cu stabilizer should not exceed 6×10^{-3} dpa to avoid high increase in the Cu electric resistivity. It should be mentioned that the fluence and dose limits are at least a factor of 2-3 lower than the experimental values at which degradation of properties was observed. Our neutronics calculations indicate that the predominant magnet radiation limits are the EOL fast neutron fluence and the nuclear heat load to the magnets. Hence, the shield is optimized to primarily minimize these effects.

An extensive optimization analysis was performed to design a cost-effective high performance shield to protect the magnet against radiation. The optimization study included the selection of the shielding materials, assessment of the shielding capability of the various candidate materials, optimization of the composition of the shield, and determination of the thickness of the shield required to keep the radiation damage at the magnet below the permissible level. The analysis employed the 1-D transport code ONEDANT [3] with the P_3 Legendre expansion for the scattering cross section and the S_8 angular quadrature set. The associated 46 neutron and 21 gamma group cross section library was derived from the ENDF/B-V evaluation. The different components of the blanket, shield, and magnet were modeled in poloidal cylindrical geometry around the plasma axis. All the in-vessel components are Li cooled. The vacuum vessel is located outside the magnets which are enclosed in a common cryostat. The 75.5 cm winding pack of the magnet includes Incoloy structure, Nb_3Sn superconductor and conduit, Cu stabilizer, GFF polyimide insulator, and liquid He coolant at 25, 15, 20, 25, and 15 vol.%, respectively. The cryostat is 15 cm thick, the scrapeoff layer (SOL) is 15 cm, the circularized plasma radius is 1.6 m, and the neutron source strength is normalized to the 2 MW/m^2 peak wall loading.

A variety of shield options was examined and the ability of various materials to protect the magnets was assessed. Besides V and steel, many materials have the potential to protect the magnets. Each material has some merits and drawbacks. The behavior of the shielding material in radiation fields may limit its use in the shield, particularly in the high radiation zones. As mentioned in Section II, the 35 cm thick blanket is followed by a 45 cm thick HT shield and then a LT shield. All shielding components contain 5% Li coolant and 15% V structure, by volume. The option of using steel filler was investigated. At the present time, there is no structural role envisioned for the filler materials in the shield and, therefore, a substantial cost reduction will result from the use of such low cost fillers. There are a few low activation steels that are readily available for use in fusion plants. Tenelon has the best performance as it results in the lowest magnet damage and the highest neutron energy multiplication which have a positive economic impact on the overall design. It should be mentioned that Tenelon has a slightly higher decay heat compared to other steels, but this does not seem to present a problem even in the event of a loss of coolant accident.

The composition of the LT shield was optimized to further reduce the magnet damage. The Tenelon filler was traded for boron carbide, organic coolant (OC; a kerosene product commercially known as therminol 66 or HB-40), zirconium hydride, or tungsten carbide. The total HT and LT shield thickness was kept fixed. The results indicate that hydrides and WC are more effective than B_4C, borated Tenelon (B-SS; 3 wt% B) is more effective than Tenelon, and a 63-96 cm thick shield is needed to meet the magnet radiation limits, depending on the shield type.

Table I summarizes the required shield to protect the magnet for the various options. It should be noticed that the

Table I
Key Parameters for the Different Shield Options

Shield Type	SS	B-SS	B_4C	WC	OC	$ZrH_{1.7}$
Thicknesses (cm):						
FW	1.4	1.4	1.4	1.4	1.4	1.4
Blanket	35	35	35	35	35	35
HT SS/Li/V Shield	45	45	45	45	45	45
LT Shields:						
SS/Li	42	--	11	--	6.3	5
B-SS/Li	--	35	--	--	--	--
B_4C/SS/Li	--	--	15	--	--	--
WC/SS/Li	--	--	--	22	--	--
OC/SS	--	--	--	--	13.2	--
Pb/SS/OC	--	--	--	--	1.5	--
$ZrH_{1.7}$/SS/Li	--	--	--	--	--	13
Total*	123	116	107	103	102	99

*Excluding gaps.

HT shield contains only Tenelon filler while the use of other materials is limited to the LT shield where the radiation environment is less severe. Even though zirconium hydride and organic coolant are better shielding materials than WC and borides, the safety related issues associated with these materials limited their use in the MHH stellarator design. Although the shield temperature can be controlled during operation to remain below 500°C, the temperature in case of a loss of coolant accident will rise and certainly exceed 600°C causing dissociation of hydrogen and jeopardizing the integrity of the $ZrH_{1.7}$ and OC shields.

The optimization analysis has indicated that borated steel and tungsten carbide are the most promising shielding materials. A decision was made to employ the 80 cm thick borated steel to protect the magnets of the present design (R = 14 m). It was found that the minimum radial distance between the plasma and the magnet centroid is 196.2 cm and occurs at the inboard side of the middle of each field period. This space is actually more than what is needed for the SOL, blanket, shield, and magnet. The shield-magnet gap is, therefore, 8 cm wide for the reference B-SS shield. This gap gets wider as one moves in the toroidal and/or poloidal directions reaching 1.3 m at some locations. All magnet radiation limits are met and the reference B-SS shield results in the lowest heat load to the magnet. The 32 magnets of SPPS cover ~20% of the space. For an average wall loading of 1.3 MW/m^2, the nuclear heating deposited in the coil cases and winding packs amounts to 37 kW and will be removed at a cryoplant efficiency of 310 W/W. The cryoplant load is thus 11 MW. This corresponds to ~1% of the output power, which is acceptable.

A potential improvement to the present design is to employ a more efficient shield in order to reduce the radial standoff and thus the overall dimension of the machine. The most efficient shielding material is the tungsten carbide. However, WC is heavy and expensive (65 $/kg) and should be used only in the critical area where the space is constrained. There is a single critical area at the middle of each field period where the shielding space is limited. Utilizing WC in this region, which covers only 1% of the area, will allow the radial standoff to be reduced by 19 cm. The corresponding reduction in the major radius is estimated to be on the order of 1.5 m. It should be stressed that the WC used in the LT shield is subject to a relatively low radiation level implying that the afterheat generated by W is low and will not cause any problem in case of an accident.

IV. CONCLUSIONS

The 35 cm thick blanket will provide tritium self-sufficiency for the MHH stellarator design. An overall tritium breeding ratio of 1.12 seems adequate with provisions made for the presence of penetrations and divertor plates. The first wall and blanket should be replaced every 11 y due to radiation damage to the vanadium structure. Sufficient shield is placed behind the blanket to protect the magnets. For a peak neutron wall loading of 2 MW/m^2, the shield is 80 cm thick and is made of borated steel filler supported by V structure. A successful attempt was made to lower the cost of the shield while keeping the attractive safety feature of the design. A potential improvement to the present design is to employ the more efficient WC shield in the critical areas underneath the magnets in order to reduce the radial standoff and thus the overall dimensions of the machine.

ACKNOWLEDGMENT

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