Nuclear Analysis for the Inertially Confined Direct Drive Laser Fusion Power Reactor SIRIUS-P

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Abstract

The SIRIUS-P commercial reactor design produces 1000 MWe and is driven by 60 KrF laser beams. The chamber has an inner radius of 6.5 m and consists of a first wall fabricated from a carbon/carbon composite and a blanket made of SiC. The chamber is cooled by a flowing granular bed of solid ceramic material, TiO_2 for the first wall and Li_2O for the blanket. The overall tritium breeding ratio is 1.09 and the overall energy multiplication is 1.08. Adequate shielding is provided around the chamber to reduce the operational dose to acceptable levels. Grazing incidence metallic mirrors are utilized to enhance the lifetime of the dielectric coated final focusing mirrors.

1. Introduction

The SIRIUS-P conceptual design study is of a 1000 MWe KrF laser driven inertial confinement fusion power reactor utilizing near symmetric illumination of direct drive targets [1]. Sixty beams providing 3.4 MJ of energy are used at a repetition rate of 6.7 Hz and a target gain of 118. The chamber has an inner radius of 6.5 m and consists of a first wall (FW) fabricated from a carbon/carbon (c/c) composite and a blanket made of SiC. The chamber is cooled by a flowing granular bed of solid ceramic material, TiO_2 for the FW and Li_2O for the blanket. Figure 1 shows a cross section of the reactor building.

The main objective of the neutronics analysis is to optimize the blanket design to insure tritium self-sufficiency while maximizing the overall reactor energy multiplication. The solid angle fraction subtended by the 60 beam ports in the SIRIUS-P chamber is only 0.4% resulting in negligible loss of breeding. Hence, overall tritium self-sufficiency can be achieved with a modest local (1-D) tritium breeding ratio (TBR). This attractive feature of inertial confinement reactors allows for a simple blanket design in which no special neutron multipliers are needed. The FW is varying in thickness and is made of c/c composite and cooled by flowing granules. The FW coolant material and thickness affect the achievable TBR. TiO_2, BeO and Al_2O_3 have been considered to cool the FW. A scoping analysis that investigates the impact of FW coolant material and thickness on the TBR is presented. The neutronics performance parameters for the reference design will be determined.

The reactor chamber is housed within a cylindrical containment building with a radius of 42 m. The chamber is surrounded by an internal concrete wall at a radius of 10 m. This wall reduces the dose in the remainder of the building which contains the beam handling optics. The required shielding around the chamber will be determined.

SIRIUS-P utilizes grazing incidence metallic mirrors (GIMM) located at 25 m from the target in the direct line-of-sight of the source neutrons streaming through the beam ports. The use of GIMM was first proposed by Bieri and Guinan [2] in 1991 as a solution to the problem of protecting the final focusing (FF) mirrors from neutron damage. The dielectric coated FF

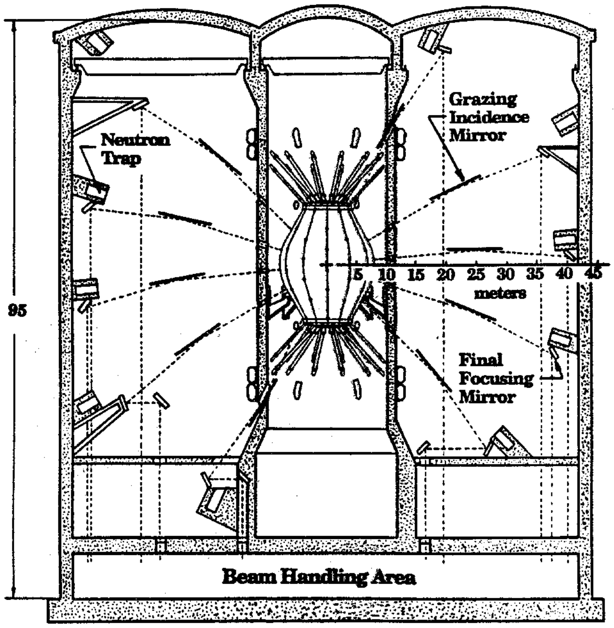

Fig. 1. Cross section of the SIRIUS-P reactor building.

mirrors are placed out of the direct line-of-sight of the source neutrons at 40 m from the target. However, secondary neutrons resulting from the interaction of the streaming source neutrons with the containment building can cause significant radiation damage to the coating. To reduce the secondary neutron flux and increase the lifetime of the mirrors, neutron traps are attached to the outer reactor containment building along the direct line-of-sight of streaming source neutrons. Two-dimensional (2-D) neutronics calculations have been performed to determine the neutron flux levels at the GIMM and dielectric coated final focusing mirrors and their predicted lifetime.

2. Calculational Model

Neutronics calculations for the SIRIUS-P chamber have been performed using one-dimensional (1-D) spherical geometry. The discrete ordinates code ONEDANT [3] was utilized along with cross section data based on the ENDF/B-V evaluation. The 6.5 m inner radius spherical chamber is modeled with a point isotropic source used at the center emitting neutrons and gamma photons. The LIBRA [4] target spectrum, that takes into account neutron multiplication, spectrum softening and gamma generation, is used. For each DT fusion reaction, 1.025 neutrons are emitted from the target with an average energy of 11.64 MeV. In addition, 0.013 gamma photons are emitted with 3.85 MeV average energy. 69.5% of the target yield (energy) is carried by neutrons and gamma photons which interact with the different regions surrounding the target and the rest of the target yield is carried by x-rays and debris which deposit their energy at the front surface of the blanket.

Two design options are considered for SIRIUS-P depending on the thermal conversion cycle used [1]. These designs are SIRIUS-PB, utilizing the Brayton cycle, and SIRIUS-PR, utilizing the Rankine cycle. In order to achieve a net electric power of 1000 MWe from SIRIUS-P, different target yields are used for the two designs to compensate for the difference in thermal cycle efficiency. The SIRIUS-PB design has a target fusion yield of 365 MJ and a repetition rate of 6.7 Hz corresponding to a fusion power of 2444 MW. The fusion power for the SIRIUS-PR design is 2688 MW implying that the nuclear heating and radiation damage will be 10% higher than that for the SIRIUS-PB design. The neutron wall loading values for SIRIUS-PB and SIRIUS-PR are 3.12 and 3.43 MW/m^2, respectively. The results presented here are for the SIRIUS-PB design.

3. Chamber Design Scoping Analysis

Granules of different materials have been considered as coolant for the c/c composite FW. The FW thickness increases as one moves away from the reactor midplane. The FW coolant material and thickness will have significant impact on the TBR achievable from the SiC/Li_2O breeding blanket. Several neutronics calculations have been performed to assess the impact of the FW coolant and thickness on TBR.

In this scoping analysis, a front zone representing the FW is considered with thicknesses ranging from 5 to 50 cm and followed by a 1 m thick breeding zone. A 20 cm thick SiC reflector and a 3 m thick concrete shield are used at the back of the breeding zone to properly account for

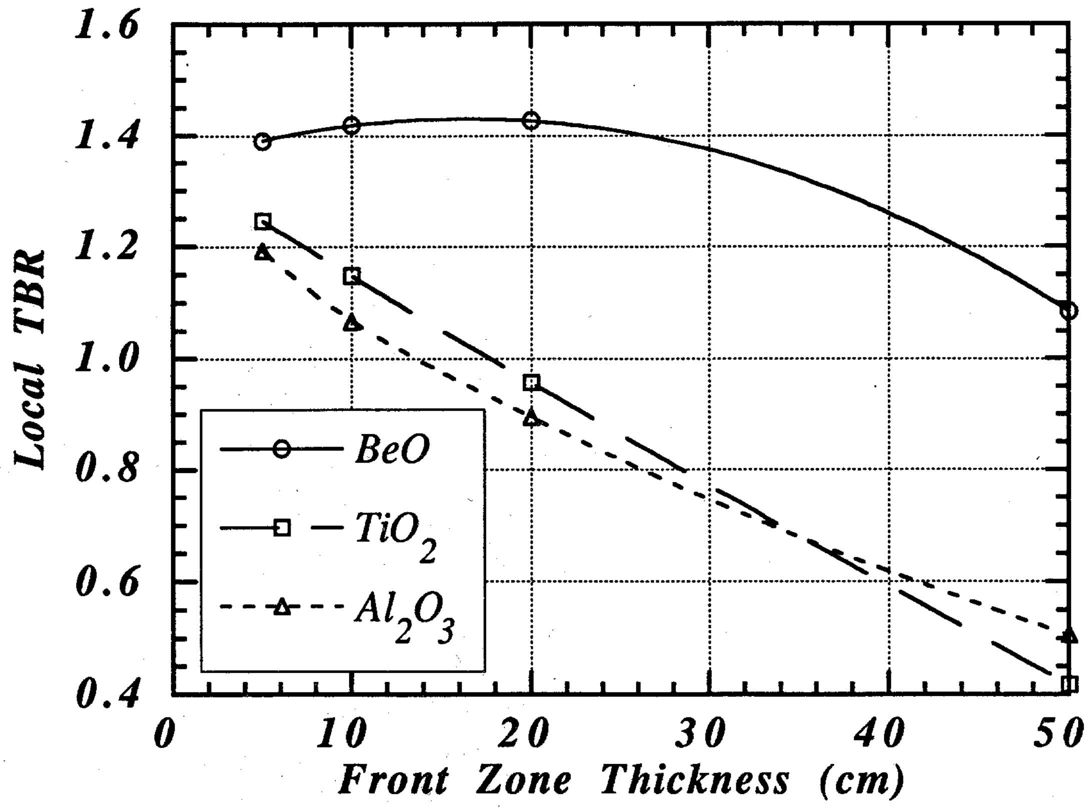

Fig. 2. Effect of front zone thickness on local TBR for the three candidate FW coolant materials.

neutron reflection. Preliminary calculations with different lithium enrichments indicated that there is no incentive for enriching the Li with the added cost penalty. Hence, a Li_2O breeder with the natural ^6Li content is used. Three different materials have been considered to cool the first wall. Calculations have been performed using TiO_2, BeO and Al_2O_3 in the front zone at a packing fraction of 60%.

Figure 2 shows the variation of the local TBR with the front zone thickness for the three candidate materials. Using BeO yields the largest TBR due to neutron multiplication in the beryllium. The local TBR drops below unity for the cases with TiO_2 and Al_2O_3 when the front zone thickness exceeds ~15 cm. The total nuclear heating increases as the thickness of the front zone increases. BeO yields the highest energy multiplication followed by TiO_2. An estimate of the impact of FW coolant material on the overall TBR in SIRIUS-P has been determined taking into account the variation in FW thickness. The overall TBR is estimated to be 1.34 for BeO, 1.13 for TiO_2, and 1.08 for Al_2O_3. Based on these results, using TiO_2 granules as coolant for the FW is expected to yield adequate overall TBR and is chosen for the reference SIRIUS-P design. Although BeO yields a higher breeding margin, the added cost, limited Be resources, and safety concerns related to Be toxicity were strong incentives for not choosing it for the reference design.

4. Neutronics Parameters for the Reference Chamber Design

The reference SIRIUS-P chamber design utilizes a FW consisting of banks of elliptical tubes made of c/c composite and cooled by TiO_2 granules. The FW thickness and composition vary as one moves around the target. The FW thickness is smallest at the reactor midplane and largest at the top and bottom of the chamber. The variation in FW thickness and composition has been determined from thermal hydraulics and mechanical design considerations [1]. The FW is followed by a breeding blanket consisting of SiC structure and Li_2O granules for cooling and breeding. While a constant blanket thickness is used, the structure content in the blanket increases as one moves from the chamber midplane towards the top and bottom of the chamber. A Li_2O granule packing fraction of 60% is considered in the blanket. The blanket is followed by a 10 cm thick SiC reflector and a concrete biological shield.

Neutronics calculations have been performed for four zones with different radial builds corresponding to the average thicknesses and compositions over each zone. The impact of the breeding blanket thicknesses on the overall TBR and energy multiplication has been assessed. Figure 3 shows the radial build used for the four zones. The zone boundaries are defined by the polar angles measured from the top or bottom of the chamber. The polar angle ranges are 0°-15°, 15°-30°, 30°-45°, and 45°-90°, for zones I, II, III, and IV, respectively. The coverage fractions for the zones which represent the solid angle fraction subtended by each zone are 3.4%, 10%, 15.9%, and 70.7%, respectively.

Figure 4 shows the effect of blanket thickness on the overall TBR and energy multiplication. It is clear that the TBR enhancement is insignificant when the blanket thickness

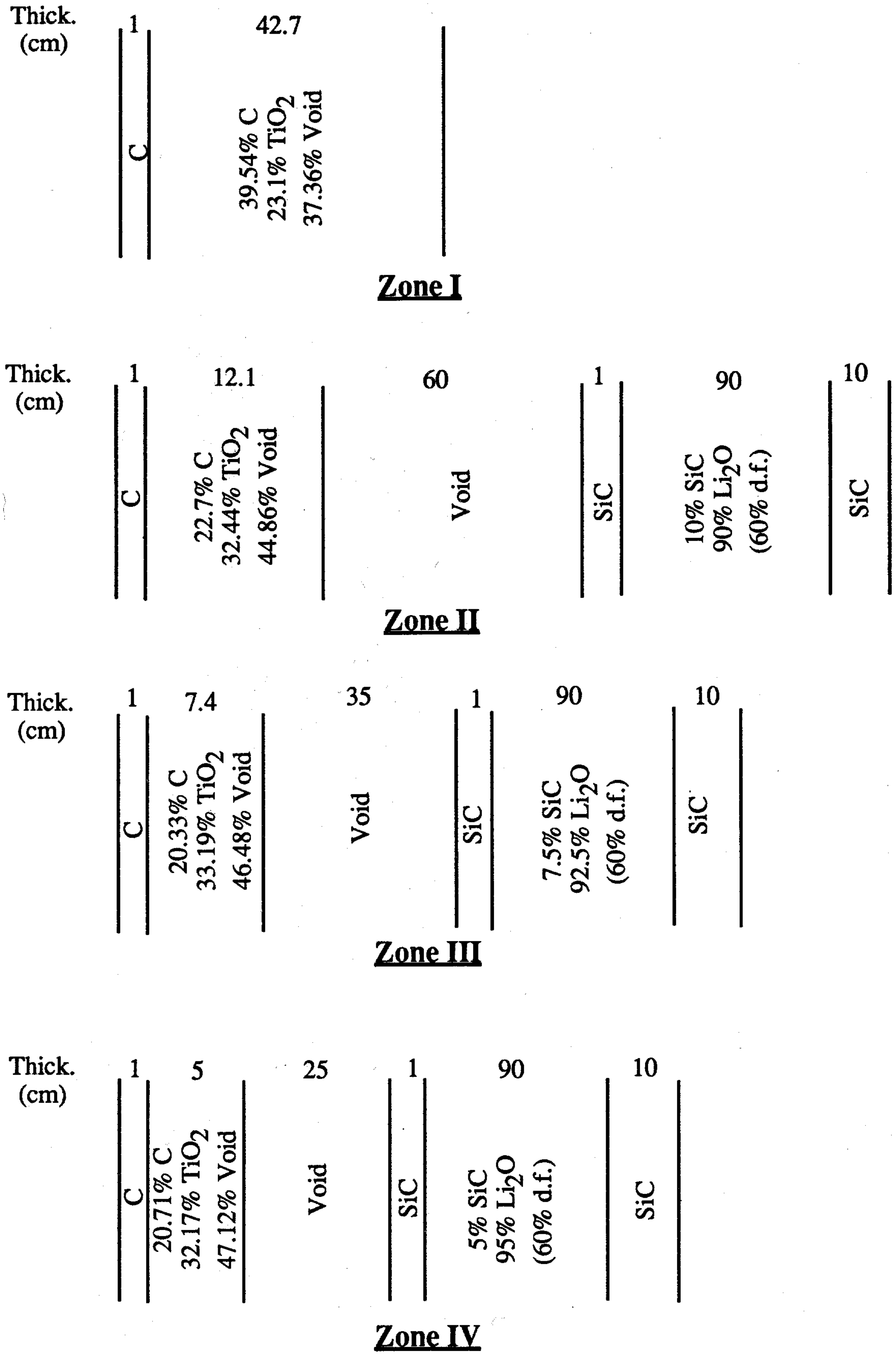

Fig. 3. Radial build for the four chamber zones.

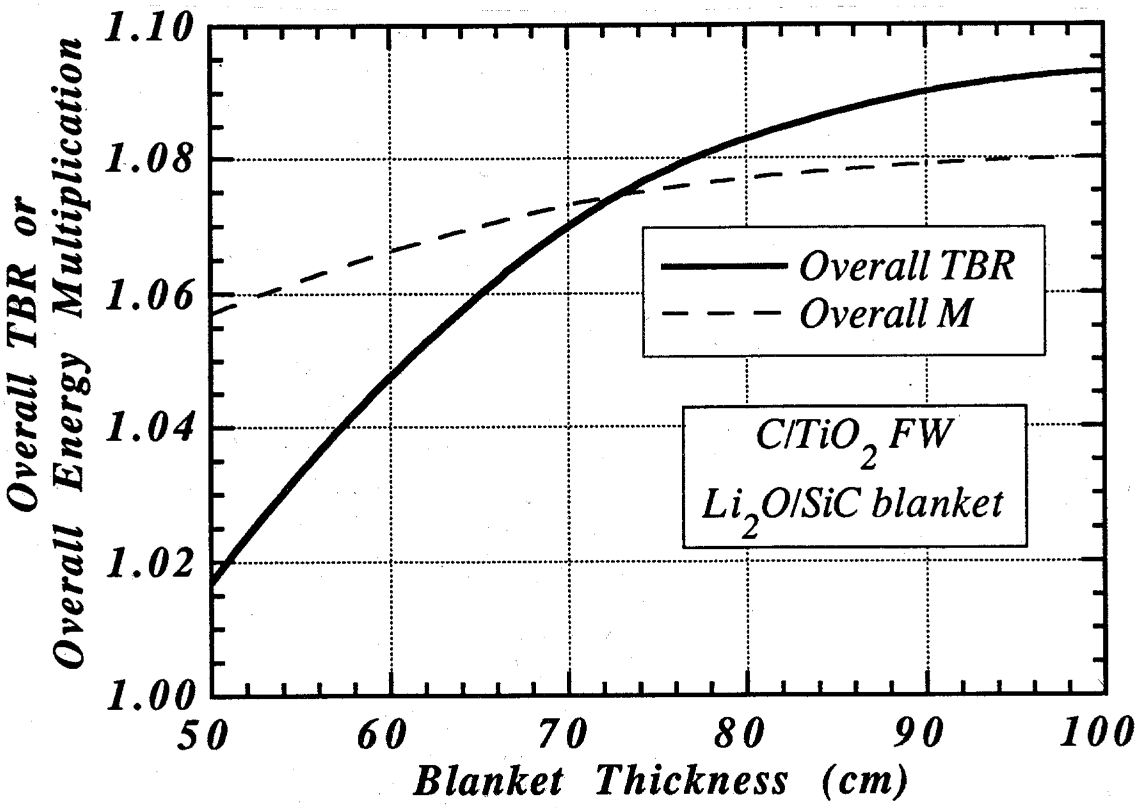

Fig. 4. Effect of blanket thickness on overall TBR and energy multiplication.

is increased beyond ~90 cm. The breeding blanket thickness is taken to be 90 cm in the reference SIRIUS-P chamber design. The overall TBR for the reference SIRIUS-P design is 1.09 which is adequate to assure tritium self-sufficiency. The corresponding overall energy multiplication factor M_o is 1.08. M_o is defined as the ratio of the total thermal power deposited in the blanket both as surface (x-rays and ion debris) and volumetric (neutrons and gamma photons) heat to the DT fusion power. For the SIRIUS-PB design, the total thermal power amounts to 2640 MW with 730 MW deposited at the front surface of the first wall and 1910 MW deposited volumetrically in the chamber by neutrons and gamma photons.

The peak power densities in the FW and blanket are 11.54 and 12.05 W/cm^3, respectively. As one moves towards the midplane, the peak power density in the FW decreases while the peak power density in the blanket increases as a result of FW thinning. The peak dpa rate values in

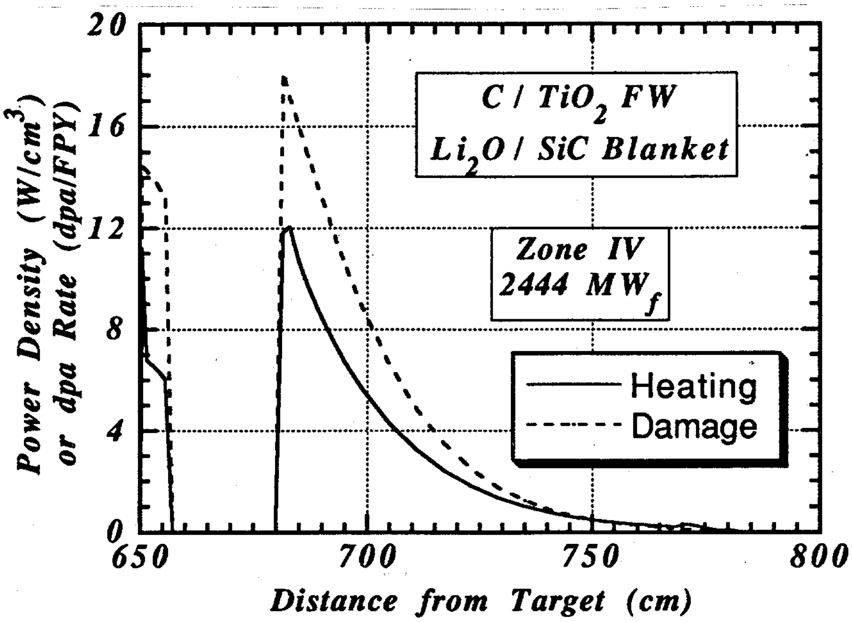

Fig. 5. Radial variation of nuclear heating and damage rate in the FW and blanket at the midplane.

the FW and blanket are 14.76 and 18.12 dpa per full power year (FPY), respectively. The peak structure damage decreases slightly in the FW and increases in the blanket as one moves toward the midplane where the FW is the thinnest. Peak damage in the blanket at the midplane is 30% higher than that at the top and bottom of the blanket. Figure 5 shows the radial variation of nuclear heating and damage rate in the FW and blanket at the midplane (zone IV). The peak helium production rate in the FW is 3635 appm/FPY. Helium production at the front of the FW is nearly the same for all zones. On the other hand, the helium production rate at the front surface of the blanket strongly depends on the FW thickness. At the midplane it is 2512 appm/FPY and drops to 1610 appm/FPY at the top and bottom. Helium production drops by about three orders of magnitude as one moves from the front to the back of the blanket.

The main problem for c/c composite is the dimensional stability after operating at high temperature in a neutron environment for long time. During high temperature irradiation, the graphite first shrinks and then expands at a very rapid rate. Birch and Brocklehurst [5] reported data on several forms of graphite with some showing that at a fluence of 35 dpa at 1300°C, they return to the zero swelling line. These graphites have not been optimized and improvements of 30-50% are reasonable to assume for materials used in commercial fusion reactors. A c/c lifetime fluence of 50 dpa is used in SIRIUS-P. This implies a FW lifetime of ~3 FPY in SIRIUS-P. On the basis of not letting the thermal conductivity of SiC drop below 1 W/mK and not allowing the fracture strength to fall by more than a factor of ~6, the useful SiC lifetime has been chosen to be 60 dpa at 600-900°C [6]. This will be consistent with the 3 FPY for the c/c FW and corresponds to the burnup of ~1% of the SiC molecules.

5. Biological shielding

The reactor shield is designed such that the occupational biological dose rate outside the shield does not exceed 0.5 mrem/hr during reactor operation. The biological shield consists of 70 vol.% concrete, 20 vol.% carbon steel C1020 and 10 vol.% He coolant. Several 1-D calculations have been performed to determine the required shield thickness. Figure 6 shows the effect of shield thickness on the biological dose rate. The inner surface of the shield is at a distance of 40 m from the target with no material used in the region between them. This is representative of the areas of the reactor building exposed to the direct source neutrons streaming through the beam ports. The results indicate that a wall thickness of 3.3 m is required in these zones. Calculations for a concrete shield located at 10 m from the target with the FW, blanket and reflector included indicate that a total shield thickness of 2.7 m is required behind the blanket.

The chamber is surrounded by a cylindrical concrete shield with an inner radius of 10 m. The IHX and steam generators are located in the space between this inner shield and the outer containment building. The thickness of the inner shield is determined such that hands-on maintenance can be performed on these components following shutdown. The dose rate resulting from the decay gammas emitted from the activated material should not exceed 0.5 mrem/hr one day after shutdown. Based on activation analysis [1], a 1.5 m thick inner shield is needed. The results of the 2-D neutronics calculations performed for the SIRIUS-P final

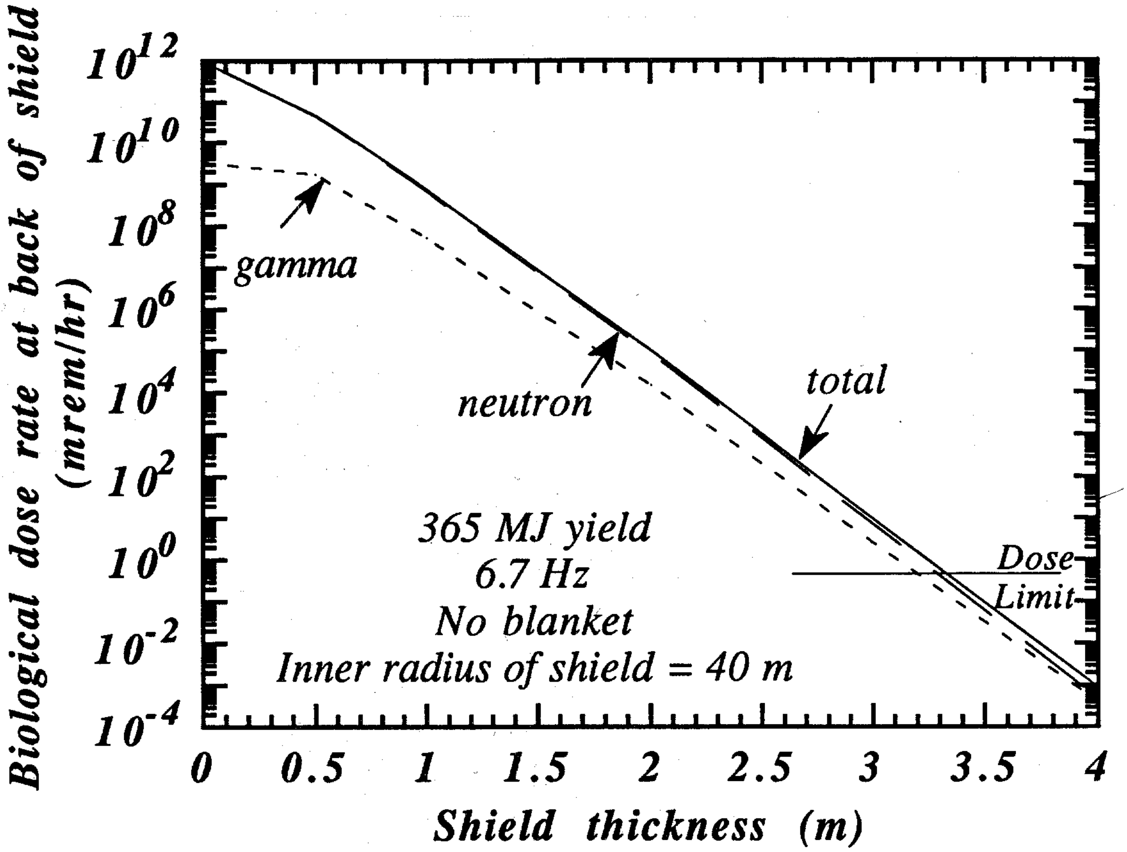

Fig. 6. Effect of shield thickness on biological dose during operation.

focusing mirrors indicated that, if the beamlines are not surrounded with shielding material, the secondary neutrons resulting from interaction of streaming neutrons with the outer containment building result in a neutron flux at the back of the 1.5 m thick inner shield that is ~4 orders of magnitude higher than that predicted by the 1-D model without penetrations. Hence, areas behind the 1.5 m thick inner shield where hands-on maintenance should be performed must be separated from the beamlines by at least 1 m thick walls. While the 1-D analysis without penetrations indicated that only a 1.2 m thick outer shield is needed away from the direct neutron traps, the higher neutron flux at the inner surface of the outer shield resulting from neutron streaming implies that a thicker outer shield should be utilized. The 2-D analysis indicated that a 2.5 m thick outer shield should be used. In summary, the inner shield should be 1.5 m thick and

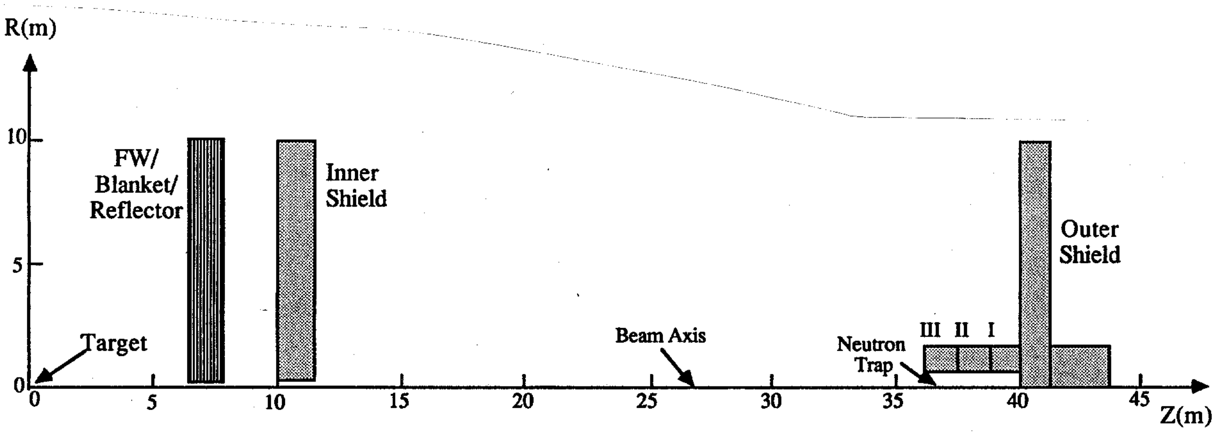

Fig. 7. Two-dimensional model for region around a beamline.

the outer shield should be 2.5 m thick everywhere except at the direct neutron traps where a thickness of 3.3 m should be used.

6. Lifetime of final optics

The lifetime of the final focusing mirrors depends on the neutron fluence limit for the dielectric coated or metallic mirrors, the solid angle fraction subtended by the beam ports, damage recovery with annealing and the location of the mirror relative to the target. 2-D neutronics calculations have been performed to determine the neutron flux levels at the GIMM and dielectric coated FF mirrors. The discrete ordinates code TWODANT [7] was utilized along with cross section data based on the ENDF/B-V evaluation. The region around a beam penetration was modeled in r-z geometry with the target represented by an isotropic point source on the z-axis as shown in Fig. 7. The detailed radial build of the FW, blanket and reflector is included in the model. The penetration in the chamber wall has a radius of 15 cm in order to allow for the transport of the laser beam with final optics f# of 32. The 1.5 m thick inner shield has a penetration with 18 cm radius. The outer shield located at 40 m from the target is 1.2 m thick except along the direct line-of-sight of streaming neutrons where the thickness is increased to 3.3 m. Calculations have been performed to assess the impact of using neutron traps along the direct line-of-sight of streaming neutrons. The cases without traps and with traps having aspect ratios (depth to diameter ratio) of 1, 2, and 3 were considered. The cylindrical trap has an inner radius of 65 cm and is 1 m thick. The model is surrounded by a reflecting cylindrical boundary at a radius of 3 m to account for contributions from other penetrations.

An inherent problem associated with multi-dimensional discrete ordinates calculations with localized sources is referred to as the "ray effect." It is related to the fact that the angular flux is given only in certain discrete directions. It is, therefore, not possible to exactly represent the component in the normal direction ($\mu = 1$) along the beam penetration which can lead to underestimating neutron streaming. We have fully mitigated the ray effect by using the first collision method [8]. In this method, the uncollided flux is determined analytically and the volumetrically distributed first collision source is used in the calculations.

Figure 8 shows the fast neutron flux ($E_n > 0.1$ MeV) in the space between the inner and outer shields for a neutron trap having an aspect ratio of 3. The variation of flux with distance from the beam axis is given at the outer surface of the inner shield, location of GIMM, front of trap, and the inner surface of the outer shield. The flux along the beam axis is dominated by the direct source neutrons and is not affected by the neutron trap. The trap reduces the flux away from the direct line-of-sight of source neutrons by about an order of magnitude. The fast neutron flux level at the GIMM located in the direct line-of-sight of the source neutrons at 25 m from the target has been determined to be 1.14×10^{13} n/cm^{2}s. Figure 9 gives the lifetime for these mirrors as a function of the fast neutron fluence limit and the recovery fraction with annealing. A minimum time of one month between anneals is assumed. It can be seen that, for a limit of 10^{21} n/cm^2, the GIMM can have a lifetime of 14 FPY assuming 80% recovery and 28 FPY for 90% recovery. If the limit is 10^{22} n/cm^2, it can have a lifetime of 28 FPY with no annealing. It is clear that the lifetime of the GIMM is very sensitive to the neutron fluence limit and damage recovery by annealing. Experimental data on radiation damage to metallic mirrors are essential to allow for a more accurate prediction of the GIMM lifetime.

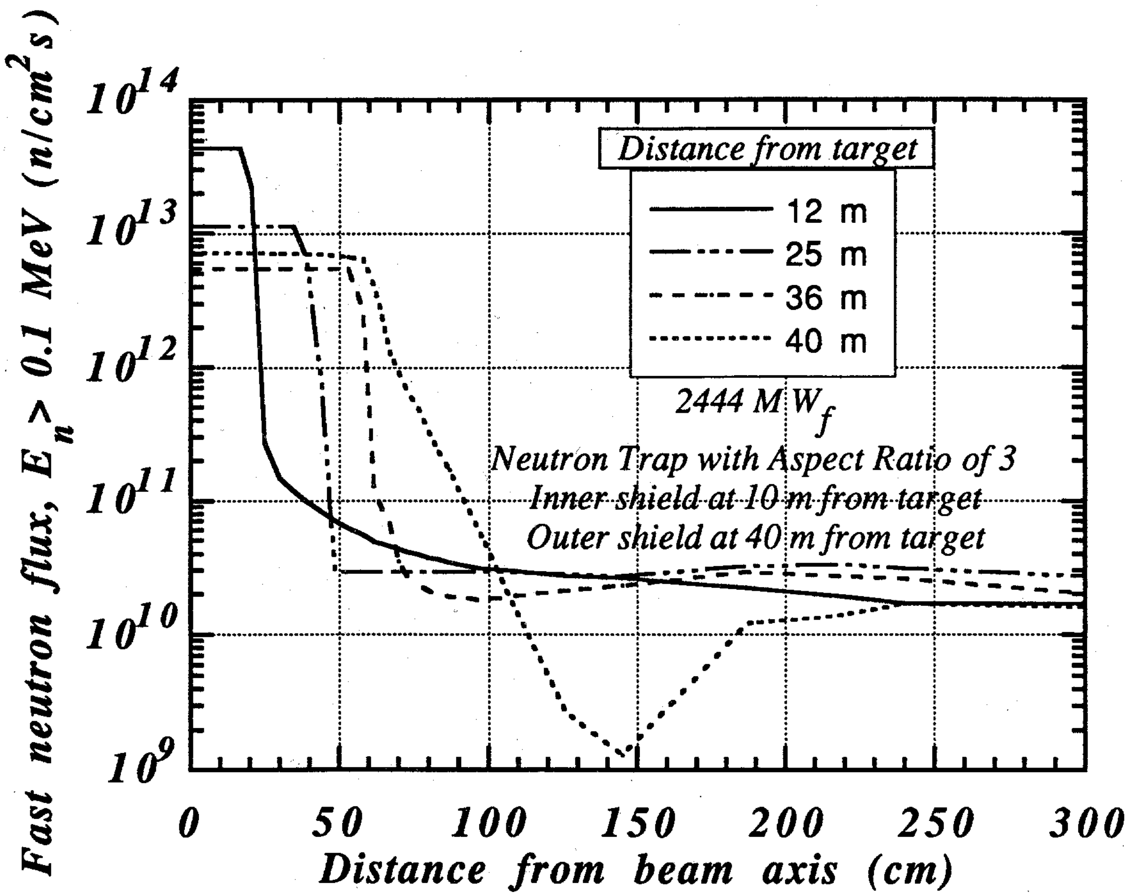

Fig. 8. Fast neutron flux in space between inner and outer shields with neutron traps having an aspect ratio of 3.

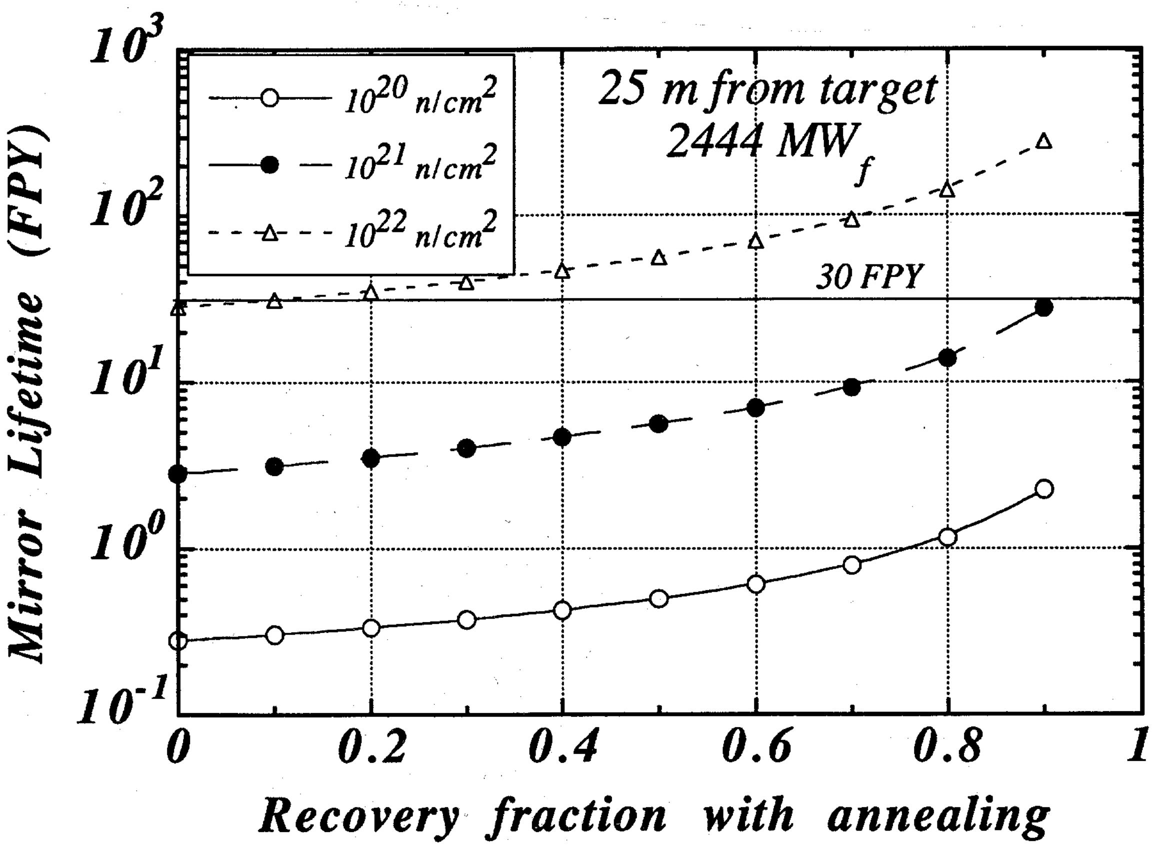

Fig. 9. Lifetime of the GIMM as a function of annealing recovery and fluence limit.

Figure 10 gives the lifetime of the dielectric coated FF mirrors as a function of location along the outer surface of the trap for traps with different aspect ratios and a fast neutron fluence limit of 10^{18} n/cm^{2}. The lifetime is highest if the mirror is located as close as possible to the inner surface of the outer shield. For a trap with an aspect ratio of 3, the lifetime for the FF mirror located at 40 m from the target will be 2.8 FPY for a fluence limit of 10^{18} n/cm^{2}. The lifetime will reach 28 FPY if the fluence limit can be increased to 10^{19} n/cm^{2}. Increasing the trap aspect ratio beyond 3 leads to only a slight increase in mirror lifetime. Again, experimental data on the impact of radiation damage on the reflectivity of the dielectric coating of the FF mirrors are required.

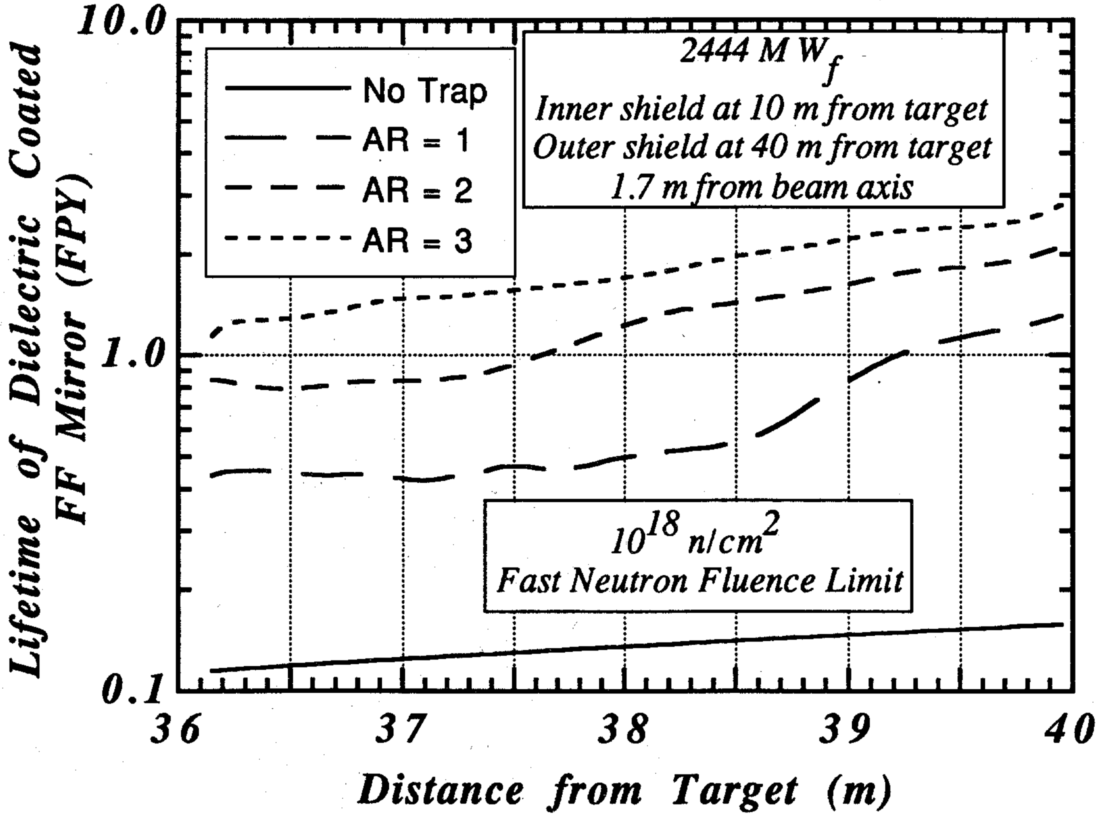

Fig. 10. Lifetime of dielectric coated FF mirrors for a fast neutron fluence limit of 10^{18} n/cm^2.

7. Summary

The overall TBR for the reference SIRIUS-P design is 1.09 which is adequate to assure tritium self-sufficiency. The overall energy multiplication factor is 1.08. The total thermal power amounts to 2640 MW. The peak FW power density and dpa rate are 11.54 W/cm^3 and 14.76 dpa/FPY, respectively. The FW and blanket are expected to have a lifetime of ~3 FPY.

A 1.5 m thick concrete shield surrounding the chamber allows for hands-on maintenance to be performed on the reactor components located between this inner shield and the outer containment building following shutdown. A two-dimensional analysis indicated that the limit on occupational dose rate during reactor operation can be satisfied with the outer containment building being 2.5 m thick everywhere except at the direct neutron traps where a thickness of 3.3 m should be used.

The lifetime of the dielectric coated final focusing mirrors is increased by an order of magnitude as a result of using grazing incidence metallic mirrors and high aspect ratio neutron traps attached to the outer reactor containment building along the direct line-of-sight of streaming source neutrons. The GIMM can have a lifetime of 14 FPY assuming 80% recovery with annealing for a fluence limit of 10^{21} n/cm^2. For a trap with an aspect ratio of 3, the lifetime for the dielectric coated mirror will be 2.8 FPY for a fluence limit of 10^{18} n/cm^2. The lifetimes of the GIMM and the dielectric coated mirrors are very sensitive to the neutron fluence limit and experimental data on radiation damage to these mirrors are essential.

Acknowledgment

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