# Nuclear Analysis for the Blanket and Shield of the KrF Laser Driven Inertial Fusion Reactor SOMBRERO

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# Nuclear Analysis for the Blanket and Shield of the KrF Laser Driven Inertial Fusion Reactor SOMBRERO

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## ABSTRACT

The SOMBRERO inertial fusion reactor conceptual design produces 1000 MWe utilizing near symmetric illumination of targets by KrF laser. The blanket design optimization results in achieving an overall tritium breeding ratio of 1.25 and an overall reactor energy multiplication of 1.08. The first wall is expected to have a 5 full power year (FPY) lifetime. The shield surrounding the reactor chamber has been designed to reduce the operational dose rate to an acceptable level and make it possible to perform hands-on maintenance on final optics and the intermediate heat exchanger (IHX) located outside the reactor chamber. The chamber is surrounded by a cylindrical concrete shield with 10 m inner radius and 1.7 m thickness. An outer containment building is used at 55 m from the target. Grazing incidence metallic mirrors are located at 30 m and dielectric coated final focusing mirrors at 50 m from the target. Source neutrons are directed into neutron traps attached to the containment building to enhance the lifetime of the final mirrors.

## I. INTRODUCTION

The 1000 MWe SOMBRERO inertial fusion reactor conceptual design study is KrF laser driven with near symmetric illumination. It utilizes a $Li_2O$ solid breeder moving bed in a blanket made entirely of low activation carbon/carbon composite material [1]. The $Li_2O$ particles flow through the various parts of the blanket under gravity, then are transported through an intermediate heat exchanger and around the loop in a fluidized state by helium gas at 0.2 MPa. There are 60 beams with laser energy of 3.4 MJ. The target gain is 118 and the rep-rate is 6.7 Hz. The first wall is at 6.5 m radius and is protected from x-rays and ions by 0.5 torr of Xe gas. Fig. 1 is a cross section of the reactor chamber. Grazing incidence metallic mirrors (GIMM) [2] are located at a distance of 30 m and dielectric final focusing (FF) mirrors at 50 m from the target. Source neutrons are directed into neutron traps located in line with the GIMM. The FF mirrors which are out of line-of-sight of source neutrons are subjected to low energy scattered neutrons only.

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 chamber is only 0.25% resulting in negligible loss of breeding. Hence, overall tritium self-sufficiency can be achieved with a modest local tritium breeding ratio (TBR). This allows for a simple blanket design in which no special neutron multiplier is needed. The local TBR for SOMBRERO is required to be at least 1.15 to achieve overall tritium self-sufficiency. In order to enhance the safety and environmental features of the design, low activation materials are used. Carbon/carbon composite structure and $Li_2O$ breeder are used in the blanket. The reference blanket design that satisfies the neutronics requirements is presented. The neutron induced damage in the blanket structure is calculated to determine the achievable lifetime. The lifetime of the final optics is also determined. In addition, an objective of this neutronics analysis is to provide adequate biological shielding to maintain an acceptable operational biological dose rate <2.5 mrem/hr everywhere outside the reactor building.

Neutronics calculations for SOMBRERO have been performed using one-dimensional (1-D) spherical geometry. The discrete ordinates code ONEDANT [3] was utilized along

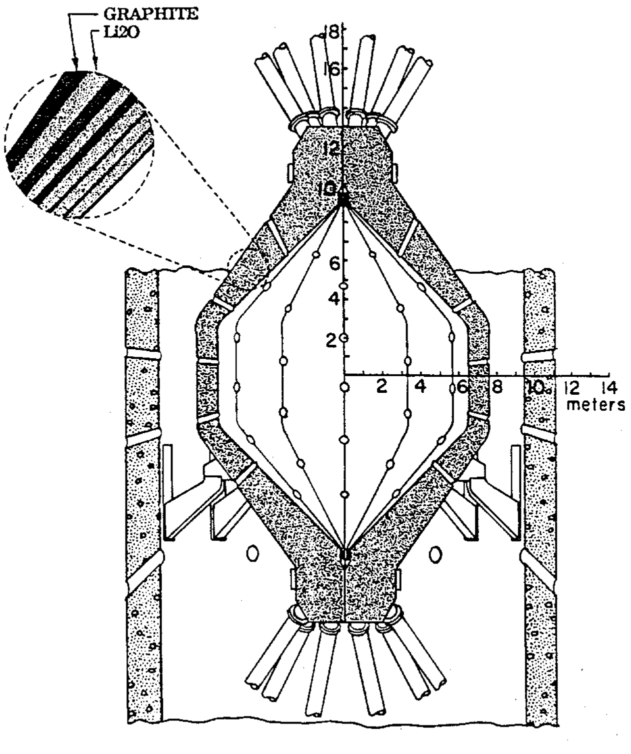

Fig. 1. Cross section of SOMBRERO reactor.

with cross section data based on the ENDF/B-V evaluation. A point isotropic source is used at the center of the chamber emitting neutrons and gamma photons with energy spectra corresponding to the target spectra.

## II. BLANKET PARAMETRIC ANALYSIS

Several neutronics calculations have been performed to determine the nuclear performance of the blanket. In these calculations, the lithium enrichment, blanket thickness, and structure content have been varied. In addition, the impact of using a metallic reflector was assessed. The nuclear performance parameters considered in this analysis are the TBR and the overall energy multiplication ($M_o$) which is defined as the ratio of the total thermal power deposited in the blanket both as surface and volumetric heat to the DT fusion power. In the calculations, a 1-cm-thick carbon/carbon first wall is located at 6.5 m from the target. A $Li_2O$ solid breeder moving bed is used in the blanket at a packing fraction of 0.6. The density factor of the $Li_2O$ used is taken to be 90%. In the preliminary analysis, the carbon/carbon (C/C) composite structural material is considered to occupy 5% of the blanket volume. For a 0.5 m thick blanket, the TBR increases by only 0.4% as lithium is enriched from natural to 10% $^6Li$. Increasing the enrichment beyond 10% reduces the TBR significantly. In addition, enriching the lithium results in a small (<3%) enhancement in $M_o$. Based on these results, natural lithium is used in the $Li_2O$ breeder. Using a 0.5 m thick metallic reflector (90% ferritic steel and 10% He coolant) increases the TBR by only 1.3% and $M_o$ by 3.5% for a 0.7 m thick blanket. Since the enhancement of TBR and $M_o$ is not significant, it was decided not to use a metallic reflector to avoid design complexity and steel activation.

In order to increase neutron utilization in the blanket, the use of a carbon reflector is considered. Table I lists the nuclear performance parameters for different design options. In option 1, no reflector is used and the carbon structure content is 5% in the blanket. In option 2, a 0.5 m thick carbon reflector with 10% He coolant is used behind the 0.7 m thick blanket. The TBR and $M_o$ values increased to 1.275 and 1.069, respectively. Notice that nuclear heating in the reflector amounts to only 2% of the total nuclear heating and is not included in the calculated energy multiplication. In options 3, 4, and 5, instead of using a separate carbon reflector, a relatively thicker blanket is used with the volumetric content of the carbon structure increasing towards the back. The blanket is divided into three zones with different structure contents. In these options, the total blanket and reflector thickness is reduced compared to the case with a separate reflector. The values for neutron leakage at the back of the blanket are 0.017, 0.016, and 0.009 neutrons per fusion in options 3, 4, and 5, respectively, compared to 0.124 without a reflector. Comparing the results for options 3, 4 and 5, it is clear that TBR and $M_o$ are not sensitive to the thickness and structure content of the back layer of blanket. Therefore, design option 3 is chosen for the reference SOMBRERO blanket design.

**Table I**
**Nuclear Performance for the Different Design Options**

| Option | Zone Thickness (cm) | %C in Blanket | Blanket/* Reflector Thickness (m) | TBR | $M_o$ |
|---|---|---|---|---|---|
| 1 | 69 | 5 | 0.7/0 | 1.174 | 1.039 |
| 2 | 69 | 5 | 0.7/0.5 | 1.275 | 1.069 |
| 3 | 19/40/40 | 3/20/50 | 1.0/0 | 1.251 | 1.080 |
| 4 | 19/40/40 | 3/20/60 | 1.0/0 | 1.251 | 1.080 |
| 5 | 19/40/50 | 3/20/50 | 1.1/0 | 1.259 | 1.083 |

*Includes 1 cm thick C/C first wall

## III. NEUTRONICS PARAMETERS FOR THE REFERENCE DESIGN

The radial build of the reference blanket design is given in Fig. 2. The 1-D local TBR for the reference blanket is 1.25. The overall TBR value is expected to be close to the 1-D value since the solid angle fraction subtended by the 60 beam penetrations is less than 0.3%. The overall reactor energy multiplication is 1.08. For the DT fusion power of 2688 MW, the total thermal power is 2903 MW with 803 MW deposited at the surface of the first wall by x-rays and debris and 2100 MW deposited volumetrically in the blanket by neutrons and gamma photons. The peak first wall power density is 10.9 W/cm$^3$. The power density in the blanket varies from 12.6 W/cm$^3$ at the front to 0.1 W/cm$^3$ at the back.

Fig. 3 gives the radial variation of damage rate in the C/C composite structural material. The peak dpa rate is 15.3 dpa/FPY which occurs in the first wall (FW) at the reactor midplane. The dpa rate drops to 0.05 dpa/FPY at the back of the blanket. The peak helium production rate in the structure is 3770 He appm/FPY at the first wall. The main problem for the C/C composite is the dimensional stability after operating at high temperature in a neutron environment for long periods of time. During high temperature irradiation, the graphite first shrinks and then expands at a very rapid rate. A useful lifetime is usually determined when the dimensional change reverses and crosses the zero swelling line. Birch and Brocklehurst [4] reported data on three forms of graphite which show that AXZ-5Q1 graphite will reach the zero swelling point at a fluence of 35 dpa at 1300°C. We assume

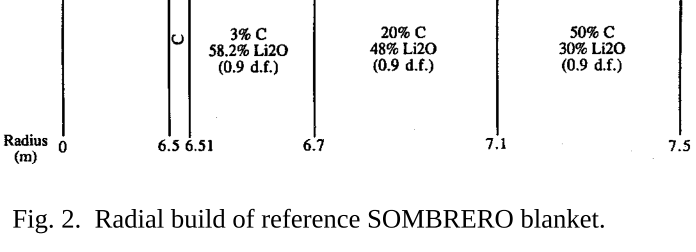

Fig. 2. Radial build of reference SOMBRERO blanket.

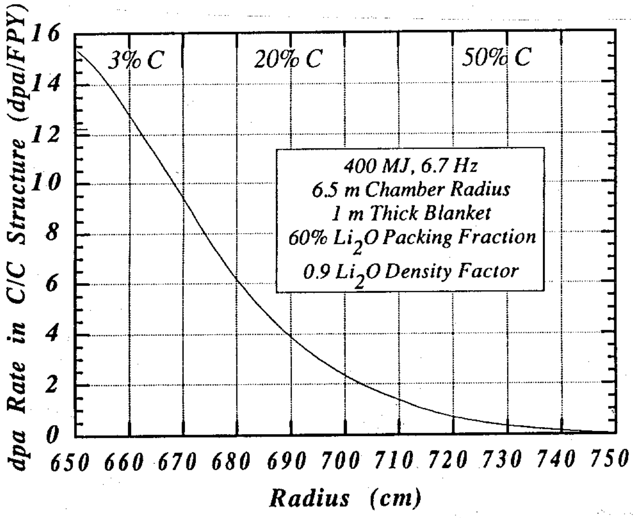

**Fig. 3. Radial variation of structure damage rate in blanket.**

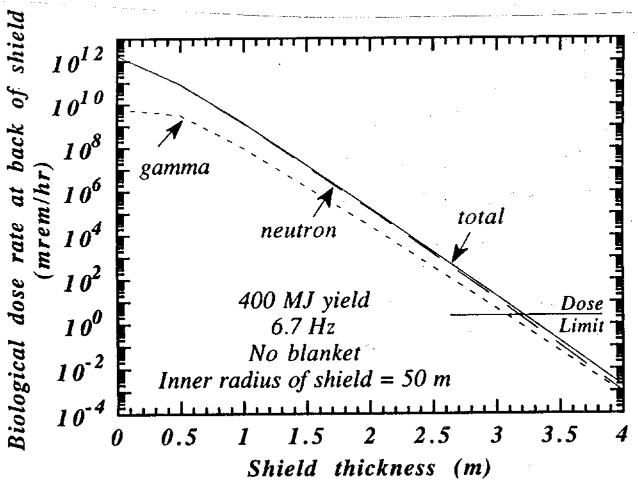

Fig. 4. Operational biological dose rate as a function of shield thickness without blanket.

that the dpa limit can be increased to 75 dpa by optimizing the graphite for a fusion neutron environment in a materials development program. With a dpa limit of 75 dpa, the C/C composite first wall is expected to have ~5 FPY lifetime.

## IV. BIOLOGICAL SHIELDING

The concrete biological shield thickness required to achieve an operational dose rate of 2.5 mrem/hr depends on the location of shield and material between target and shield. Several 1-D calculations have been performed to determine the required shield thickness. The shield is composed of 70% concrete, 20% steel and 10% He coolant. It was found that 25 cm of the steel reinforced concrete shield will reduce the dose rate by an order of magnitude.

Fig. 4 shows the effect of shield thickness on the biological dose rate during operation at the back of the shield. The inner surface of the shield is at 50 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 3.2 m is required in these zones. Fig. 5 gives the effect of shield thickness on the operational dose rate for a concrete shield located at 10 m from the target with the 1-m-thick blanket included in the model. It is clear from the results that a total shield thickness of 2.7 m is required behind the blanket.

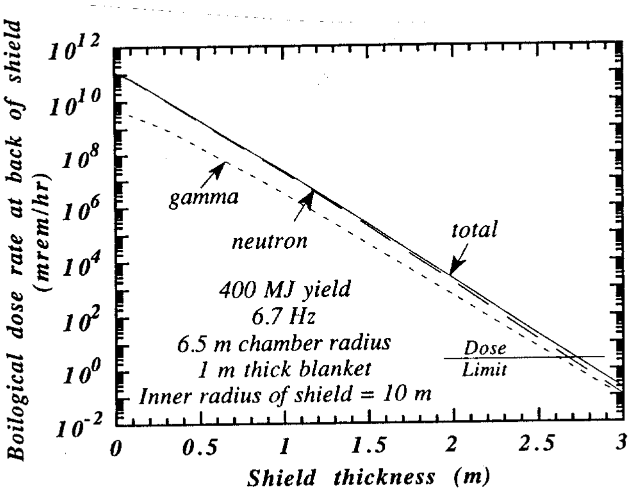

Fig. 5. Operational biological dose rate as a function of shield thickness behind the blanket.

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. Based on activation analysis [5], we determined that a 1.7 m thick shield wall surrounding the reactor at a radius of 10 m makes it possible to perform hands-on-maintenance in the space between it and the outer containment building. The outer building wall, therefore, needs only to be 1 m thick.

## V. LIFETIME OF FINAL OPTICS

The lifetime of the final optics depends on the neutron fluence limit for the dielectric coated or metallic mirror, the solid angle fraction subtended by the beam ports, damage recovery with annealing and the location of the mirror relative to the target. The solid angle fraction subtended by the 60 beam ports in SOMBRERO is only 0.25%. The fast neutron flux ($E_n > 0.1$ MeV) level at the GIMM located in the direct line-of-sight of the source neutrons at 30 m from the target has been determined to be $8.2 \times 10^{12}$ n/cm$^2$s and is due mostly to the direct source neutrons. Fig. 6 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 a

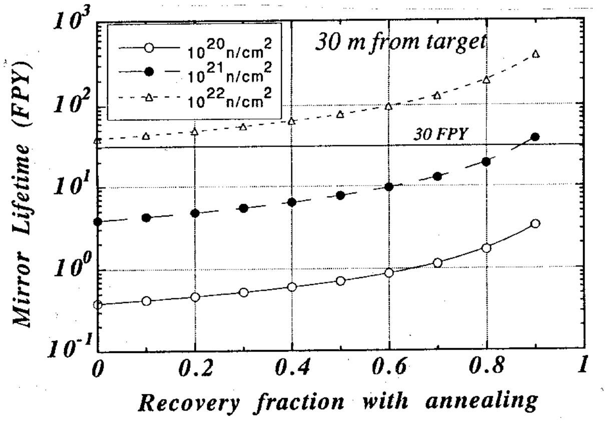

Fig. 6. Lifetime of metallic grazing incidence mirrors.

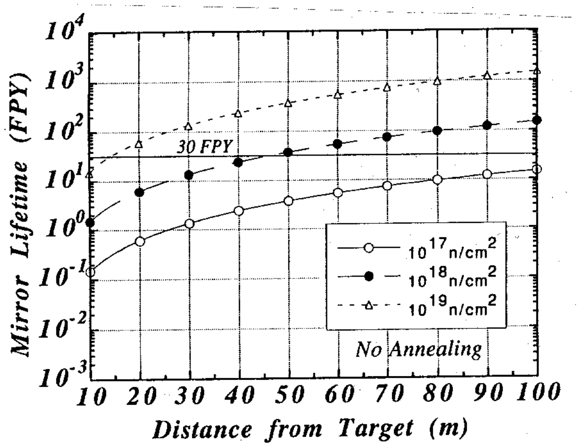

Fig. 7. Lifetime of dielectric coated FF mirrors.

GIMM at 30 m from the target, assuming an 80% annealing recovery, can have a lifetime of 17 FPY if the limit is $10^{21}$ n/cm$^2$. If the limit is $10^{22}$ n/cm$^2$, it can have a lifetime of 40 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.

Although the dielectric coated FF mirrors are placed out of the direct line-of-sight of the source neutrons, secondary neutrons resulting from the interaction of the streaming source neutrons with the GIMM and outer reactor building can cause significant radiation damage to the coating. To reduce the secondary neutron flux, the source neutrons are directed into high aspect ratio traps. Neutronic evaluations show that holes with aspect ratios ~2 will effectively trap most of the neutrons, allowing a negligible amount (<5%) of low energy neutrons to backscatter. As a result, the fast neutron flux (E > 0.1 MeV) at the dielectric coated mirrors located at 50 m from the target was determined to be $8.6 \times 10^8$ n/cm$^2$s. Fig. 7 gives the lifetime of the FF mirrors as a function of fluence limit and distance from the target. At a $10^{18}$ n/cm$^2$ fast neutron fluence limit, the SOMBRERO FF mirrors will be lifetime components with a lifetime of 37 FPY if they are located at 50 m from the target. Again, experimental data on the impact of radiation damage on the reflectivity of the dielectric coating of the FF mirrors are required.

## IV. SUMMARY

The overall tritium breeding ratio is 1.25 and the overall reactor energy multiplication is 1.08. For the DT power of 2688 MW, the total thermal power is 2903 MW, with 803 MW deposited at the FW surface by x-rays and ion debris, and the remainder deposited volumetrically by the neutrons and gamma photons. The peak FW power density is 10.9 W/cm$^3$ and the peak blanket power density is 12.6 W/cm$^3$, both occurring at midplane. Peak dpa and helium production rates in the graphite are 15.3 dpa/FPY and 3770 He appm/FPY, respectively. Based on this, the FW is expected to have a 5 FPY lifetime.

A 1.7 m thick shield wall surrounds the reactor at a radius of 10 m. Holes in this shield allow the laser beam to reach the target in the center of the chamber. Neutronic calculations show that this shield makes it possible to perform hands-on maintenance on the final optics as well as the IHX and steam generators in the space between it and the outer containment building wall following reactor shutdown. It has also been determined that the required wall thickness directly exposed to source neutrons must be 3.2 m, while the cumulative shield behind the blanket needs to be 2.73 m.

Grazing incidence metallic mirrors are used as the final optical components to remove the dielectric coated final focusing mirrors from the direct line-of-sight of high energy source neutrons. The dielectric mirrors are expected to be lifetime components.

## ACKNOWLEDGMENT

Support for this work was provided by the U.S. Department of Energy.

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