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9700 South Cass Avenue
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ENERGY DEPOSITION IN STARFIRE REACTOR COMPONENTS

by

Y. Gohar and J. N. Brooks

Fusion Power Program

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Y. Gohar and J. N. Brooks

ABSTRACT

The energy deposition in the STARFIRE commercial tokamak reactor was calculated based on detailed models for the different reactor components. The heat deposition and the 14 MeV neutron flux poloidal distributions in the first wall were obtained. The poloidal surface heat load distribution in the first wall was calculated from the plasma radiation. The Monte Carlo method was used for the calculation to allow an accurate modeling for the reactor geometry.

1.0 INTRODUCTION

The energy deposition in the STARFIRE commercial tokamak reactor was calculated based on detailed models of the reactor geometry, neutron source distribution, and plasma radiation. The neutron source distribution was determined from the fusion power density as a function of (r,z) . The Monte Carlo method was employed to carry out the calculations in three dimensional geometry. The track length estimator technique was used to calculate the energy deposition in the different reactor components; first wall, neutron multiplier, tritium breeder, reflector, blanket jacket, rf-system, limiter, shield jacket, and shielding materials.

The volumetric heat load, the 14 MeV neutron flux and the surface heat flux in the first wall were calculated as a function of the poloidal angle. The surface heating is a result of bremsstrahlung, line, and recombination radiations mainly from the presence of iodine injected into the plasma.

2. CALCULATIONAL MODEL

The STARFIRE blanket employs a solid tritium breeder which minimizes the stored chemical energy compared to other blanket options.⁽¹⁾ A neutron multiplier is used with the solid breeder to achieve an adequate tritium

breeding ratio.⁽²⁾ An α -LiAlO₂ solid breeder with Zr₅Pb₃ neutron multiplier is the choice for STARFIRE blanket. The water coolant is used with the austenitic stainless steel (PCA, prime candidate alloy) structural material for the blanket.

The blanket configuration and dimensions are based on an optimization study given in Refs. (1-3). The blanket parameters are listed in Table 1, while the blanket and shield arrangements are shown in Fig. 1. The first wall is a water cooled corrugated panel which has the plasma on one side and the neutron multiplier material on the other. The LiAlO₂ tritium breeder is separated from the neutron multiplier by another water cooled corrugated panel (the second wall). Both walls are used to remove the nuclear heat from the neutron multiplier material. In addition, the first wall removes the surface heat load from the plasma.

Table 1. Blanket Parameters for STARFIRE Blanket

Zone Description	Zone Thickness cm	Zone Composition Percentage by Volume
First wall	1	50% PCA steel structure 27% H ₂ O coolant
Neutron multiplier	5	100% Zr ₅ Pb ₃
Second wall	1	35% PCA steel structure 17% H ₂ O coolant
Tritium breeder	30	80% LiAlO ₂ ^a tritium breeder 10% PCA steel structure 5% H ₂ O coolant 5% He purge stream
Reflector	15	90% C reflector 5% PCA steel structure 5% H ₂ O coolant

^a A 60% lithium-6 enrichment.

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The combinatorial geometry was used to model the reactor geometry in this analysis. The geometrical model developed for the calculations is shown in Fig. 2. The toroidal geometry of the reactor, the actual dimensions of the individual zones (first wall, neutron multiplier, second wall, tritium breeder, reflector, and shield), the limiter system, the rf system, and the geometrical change in the poloidal direction are explicitly represented in the geometrical model. The inner blanket and shield thickness is limited to a 101-cm due to economic considerations.⁽¹⁾ The inner blanket has a thickness of 28 cm (including 0.6 density factor for the tritium breeding material) without reflector material which is necessary to achieve the required tritium breeding ratio. A tantalum alloy (Ta-5W) is used for the limiter system.

The neutron source distribution for the calculation was determined from the fusion power density as a function of (r,z) . Figure 3 shows the neutron source distribution used in the analysis. It should be noted that the neutron source peak is shifted a 79-cm from the geometrical center of the reactor chamber towards the outer blanket.

STARFIRE was designed to operate in an "enhanced radiation mode" whereby a high-Z impurity is intentionally added to the plasma in order to increase radiation. This was done for two reasons: (1) to radiate as much of the α -particle energy to the first wall, thereby minimizing the transport power to the limiter/vacuum impurity control system, and (2) to establish the basic plasma thermal equilibrium. Iodine has been selected as the reference high-Z material based on plasma physics and chemical considerations, though other materials particularly Xenon and krypton are also candidates. By using an iodine density equal to about 0.1% of the DT fuel density, about 90% of the ~ 700 MW alpha particle and RF heating power to the STARFIRE plasma can be radiated. This leaves only about 100 MW of energy to be transported to the limiter. One purpose of these calculations therefore is to see how the enhanced radiation concept impacts the first wall heat load.

The radiation power to the first wall consists of x-rays from bremsstrahlung, line and recombination radiation. The iodine increases the bremsstrahlung by increasing the Z_{eff} of the plasma, and also increases the line and recombination radiation because of radiation from partially stripped ionic states. For our calculations, the line and recombination radiation is given by:

Fig. 2. STARFIRE geometrical model used in the calculations.

Fig. 3. STARFIRE neutron source distribution used in the calculation.

$$P_{LR} = N_e N_i S(T_e) \quad (1)$$

where P_{LR} is the radiated power density due to line and recombination radiation from iodine, N_e is the plasma electron density, N_i is the iodine density and T_e is the electron temperature. The function $S(T_e)$ is taken from the coronal equilibrium results of Ref. (10) where the Xenon data are used since iodine is not listed. The reference density and the temperature profiles for the STARFIRE design are used in the above equation. These are given as:

$$\begin{aligned} T_e(\hat{\psi}) &= 22.5 \hat{\psi}^{0.3}, \text{ keV} \\ N_e(\hat{\psi}) &= 2.5 \times 10^{20} \hat{\psi}^{1.1}, \text{ m}^{-3} \\ N_i(\hat{\psi}) &= 2.5 \times 10^{17} \hat{\psi}^{1.1}, \text{ m}^{-3} \end{aligned} \quad (2)$$

where $\hat{\psi}$ is the normalized flux function defined as

$$\hat{\psi} = \frac{\psi_L - \psi}{\psi_L - \psi_m} \quad (3)$$

where ψ_L and ψ_m are the values of ψ at the limiter and magnetic axis, respectively. The flux function ψ is shown as a function of (r, z) in Fig. 4. By using this flux function, together with the reference profiles and the bremsstrahlung radiation power the radiation source is defined for the Monte Carlo calculation. The bremsstrahlung radiation is computed in an analogous manner using the above mentioned plasma profiles.

The Monte Carlo MORSE-CG code⁽⁴⁾ was used for all the calculations. A neutron and photon transport calculation with track length estimator was carried out to get accurate nuclear responses in each reactor component. A 67-multigroup cross section set (46 neutrons and 21 photons) collapsed from the CTR library⁽⁵⁾ with the P_3 approximation was used for the calculations. The MACKLIB-IV⁽⁶⁾ nuclear response library was employed to calculate the nuclear heating. All the nuclear data used in the analyses are based on ENDF/B-IV data files.

Fig. 4. Flux surfaces of STARFIRE equilibrium.

3. RESULTS AND DISCUSSIONS

The Monte Carlo neutronics analysis with the track length estimator was performed to accurately determine the nuclear energy deposition per fusion neutron in the reactor. Table 2 gives the nuclear energy deposition in the different reactor components. The fractional standard deviation (FSD) is less than 6% for any reactor component, however the main blanket components have less than 1% FSD as shown in Table 2. Also, the results from a one-dimensional calculation at the midplane of the reactor which does not account for the limiter or the rf system are listed in Table 2. The results in Table 2 show that the one dimensional analysis overestimates the energy deposition in the main reactor components. For example, the Monte Carlo analysis shows a 3.29 MeV per fusion neutron deposited in the neutron multiplier zone where the corresponding value from the one dimensional analysis is 21% higher. On the contrary, the Monte Carlo result for the energy deposition in the reflector zone is higher than the one-dimensional value by 44% which is caused by the

Table 2. Energy Deposition in STARFIRE Reactor Components

Blanket Component	Three-dimensional Analysis		One-Dimensional Analysis ^a Energy Per Fusion Neutron (MeV)
	Energy per Fusion Neutron (MeV)	Fractional Standard Deviation	
First wall	1.19	0.007	1.30
Neutron multiplier	3.29	0.009	3.98
Second wall	0.41	0.009	0.44
Tritium breeding zone	11.01	0.006	11.18
Reflector	0.16	0.043	0.09
Blanket jacket	0.08	0.034	--
Limiter system	0.82	0.040	--
RF system	0.15	0.046	--
Inner shield	0.12	0.061	--
Outer shield	0.22	0.057	--

^a One dimensional analysis using ANISN code.

presence of the plenum region behind the reflector zone and the neutron streaming through the limiter duct. The energy deposition in the shielding material is 0.33 MeV per fusion neutron where a 35% of this energy is deposited in the inner shield.

The first wall heat load consists of two components, viz., volumetric and surface heat load. The volumetric heat load due to the fusion neutron is shown in Fig. 5 as a function of the poloidal angle where the fractional standard deviation is less than 10% for this calculation. The surface heat load is a result of the radiation from the plasma. The plasma radiation discussed in the previous section was used with the same calculational procedure to get the poloidal surface heat load distribution in Fig. 6. The fractional standard deviation for the surface heat load is less than 1%. The average surface heat load is 90.45 W/cm^2 , with a maximum and minimum of 117.57 and 62.70 W/cm^2 . It can be noted that the surface and volumetric heat loads in the first wall are effected by (1) the spatial distribution of the source strength within the reactor chamber, (2) the magnetic axis shift from the geometrical center of the chamber towards the outer blanket, (3) the aspect ratio, and (4) the shape of the poloidal cross section geometry of the first wall with respect to the plasma boundary.

The poloidal change of the volumetric heat load is smoother than the poloidal change of the surface heat load. This is due to the difference in the source for each heat load. The neutron source for the volumetric heat load is peaked sharply at the magnetic axis while the radiation source for the surface heat load is a smoother function over the reactor chamber. This means that the surface heat load is more sensitive to the first wall shape than the volumetric heat load as shown in Figs. 5 and 6.

Figure 7 shows the 14 MeV neutron flux (13.5 to 14.9 MeV) poloidal distribution in the first wall. The 14 MeV neutron flux shows a peak at $\sim 55^\circ$ poloidal angle measured from the outer blanket midplane where similar results were observed for different fusion reactors.⁽⁷⁻⁹⁾ Again, it should be noted that the volumetric heat load and 14 MeV neutron flux have the same shape, both peaked at $\sim 55^\circ$ poloidal angle as shown in Figs. 5 and 7.

Fig. 5. STARFIRE poloidal volumetric heat load distribution in the first wall.

Fig. 6. STARFIRE poloidal surface heat load distribution in the first wall.

Fig. 7. STARFIRE 14 MeV neutron flux poloidal distribution in the first wall.

4. CONCLUSIONS

The analysis of the energy deposition in the STARFIRE tokamak reactor based on the actual simulation for the geometry and the source distributions leads to the following conclusions:

- (1) The poloidal surface heat load distribution is more sensitive to the geometry of the first wall in the poloidal cross section relative to the volumetric heat load. A smoother variation in the surface heat load can be obtained if the first wall shape follows the plasma boundary.
- (2) The energy deposition in a tokamak reactor with divertor for plasma control does not influence the shape of the first wall in the poloidal cross section based on the previous conclusion.
- (3) The one-dimensional analysis overestimates the energy deposition in the blanket; first wall, neutron multiplier, second wall and tritium breeding zone.
- (4) The enhanced radiation mode of operation results in a somewhat non-uniform surface heat load on the first wall. In general, however, this is believed to be a much simpler problem than to try and take the full α -heating power on a limiter system. Other high-Z materials and/or other types of profiles, e.g., a broader temperature profile and narrower density profile are possible, and may result in different wall loadings. These need to be investigated.

REFERENCES

1. C. C. Baker, et al., "STARFIRE - A Commercial Tokamak Fusion Power Plant Study," ANL/FPP-80-1, (September 1980).
2. Y. Gohar, "An Assessment of Neutral Multipliers for DT Solid Breeder Fusion Reactors," Trans. Am. Nucl. Soc. 34, 52 (1980).
3. Y. Gohar and M. A. Abdou, "Neutronic Optimization of Solid Breeder Blankets for STARFIRE Design," Fourth ANS Topical Meeting on the Technology of Controlled Nuclear Fusion, King of Prussia, Pennsylvania, (October 14-17, 1980).
4. M. B. Emmett, "The MORSE Monte Carlo Radiation Transport Code System," Oak Ridge National Laboratory, ORNL-4972 (1975).
5. R. W. Roussin, et al., "The CTR Processed Multigroup Cross Section Library for Neutronics Studies," Oak Ridge National Laboratory, ORNL/RSIC-37.
6. Y. Gohar and M. A. Abdou, "MACKLIB-IV, A Library of Nuclear Response Functions Generated with MACK-IV Computer Program from ENDF/B-IV," Argonne National Laboratory ANL/FPP/TM-106 (1978).
7. Y. Seki and H. Iida, "Monte Carlo Calculation of First Wall Neutron Flux in Tokamak Fusion Reactor," Journal of Nuclear Science and Technology 17(4), pp. 301-304 (April 1980).
8. Y. Gohar, C. W. Maynard, and E. T. Cheng, "Neutronic and Photonic Analysis of UWMAK-III Blanket and Shield in Non-Circular Toroidal Geometry," Proc. of the Second Topical Meeting on the Technology of Controlled Nuclear Fusion, Vol. III, p. 833 (1976).
9. W. M. Stacey, Jr., et al., "Tokamak Experimental Power Reactor Conceptual Design, Volume I, IX-15, ANL/CTR-76-3, (1978).
10. D. E. Post, et al., "Steady State Radiative Cooling Rates for Low Density, High Temperature Plasma," PPPL-1352, Princeton Plasma Physics Laboratory (1977).

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