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SHIELD DESIGN FOR NEXT-GENERATION, LOW-NEUTRON-FLUENCE, SUPERCONDUCTING TOKAMAKS*

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ABSTRACT

A shield design using stainless steel (SST), water, boron carbide, lead, and concrete materials was developed for the next-generation tokamak device with superconducting toroidal field (TF) coils and low neutron fluence. A device such as the Tokamak Fusion Core Experiment (TFCX) is representative of the tokamak design which could use this shield design. The unique feature of this reference design is that a majority of the bulk steel in the shield is in the form of spherical balls with two small, flat spots. The balls are purchased from ball-bearing manufacturers and are added as bulk shielding to the void areas of built-up, structural steel shells which form the torus cavity of the plasma chamber. This paper describes the design configuration of the shielding components.

INTRODUCTION

In an effort to reduce the projected direct capital cost of the next-generation tokamak device, the trend in most present-day design studies is toward a very compact device. This trend has led to exhaustive examination of the cost basis for every centimeter of radial build. The bulk shielding components represent a significant portion of this radial build. Due to this compact nature, the total nuclear shielding of the plasma chamber is provided by the material makeup of "functional" components (vacuum vessel, TF coils, support structure), as well as "bulk shielding" components added strictly for shielding.

The approach to the bulk shield design in this reference design study was to use a higher performance shield in the inboard region (to minimize the overall size of the device) while using a lower performance shield on the outboard region where more shielding volume does not directly affect the size of major machine components.

The general configuration of this reference design is shown in Fig. 1. Table 1 contains a brief listing of significant machine parameters. The bulk shield components of the torus are the removable shield module and the shield post. The 16 removable shield modules are inserted in the window between the outboard legs of each TF coil. The modules come together in a radial, spoke-like fashion, with the inboard nose of each module adjacent to the next module. The removable shield module is shown in Fig. 2. The shield post is a C-shaped bulk shield component, forming the outboard TF shield in the plane of the TF coil. The shield post is shown in Fig. 3. The 16 shield modules and shield posts form the shielded toroidal plasma chamber.

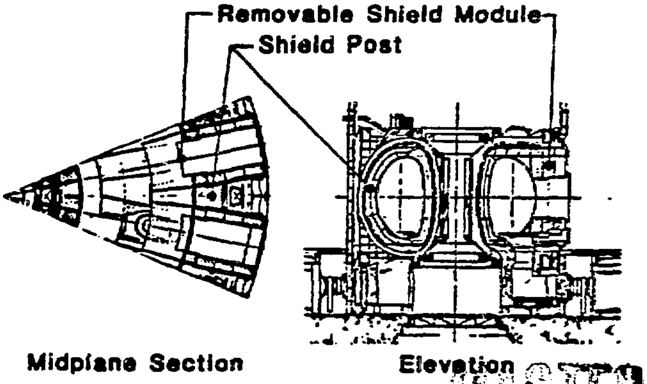

Fig. 1. Plasma chamber shield components.

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Table 1. Significant parameters of a reference superconducting tokamak design

Field Axis, B_t(T)	3.73
Maximum Field, B_{max} (T)	10.0
Plasma Current, I (MA)	11.2
Ignition Parameter	1.5
Safety Factor, q	2.4
Beta, %	5.5
Fusion Power, MW	264.0
Neutron Wall Loading, MW/m^2	0.65
Total D-T Burn Time, s	2×10^5

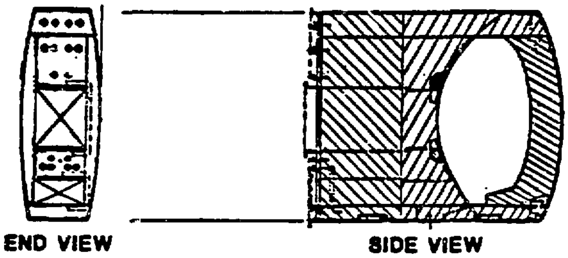

Fig. 2. Regions of bulk shielding and envelope dimensions.

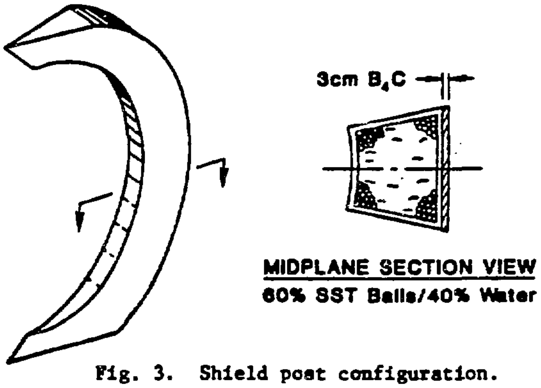

Fig. 3. Shield post configuration.

SHIELD DESIGN METHODOLOGY

The materials for the shielding system were selected based upon tradeoff studies and the results from the previous designs.[1-3] Cost, resource availability, and performance were considered in the selection process. The main shielding materials are water, concrete, and steel plates or balls (Fe1422, Nitronic 33, or type 316 stainless steel). A small amount of boron carbide is used as a neutron absorber to reduce the activation and nuclear heating in the reactor components and structural materials. A density factor of 0.7 is considered for the boron carbide to avoid the fabrication cost required to obtain a high-density material. Also, a small layer of lead is used as a gamma ray attenuator at the outermost surfaces of the shield to reduce the biological dose in the reactor building and the gamma heating in the reactor components. The low concentration of nickel motivated the use of Fe1422 and Nitronic 33 steel alloys. Low-nickel concentration reduces the production of long-lived isotopes, the biological dose after shutdown in the reactor hall, and the steel cost.[4]

The use of steel balls as a bulk shield material was investigated primarily because of the projected ease with which an irregular volume could be filled with a relatively high percentage of steel (60%) at a low cost. The balls are procured from ball-bearing manufacturers who produce the balls by a mechanical stamping process from bulk rod shapes. This process produces an eclipse ball (spherical ball with two small, flat spots) which is machined to a spherical shape for ball bearings. The eclipse balls are acceptable as a bulk shielding material and may be procured at a cost of \$8.50/kg.[5] The comparable cost of steel plates machined to size and with coolant passages is \$17/kg. The cost of eclipse balls is independent of their size for the range of 0.375 to 0.75-in. diam. This reference design utilized a 1.27-cm-diam. ball.

The use of borated stainless steel balls was also investigated. The cost of adding boron to stainless steel depends on the percentage of boron, as shown in Fig. 4. The costs of the steel balls (borated and unborated) are based on quantities of 3.3×10^6 kg. Because of the significantly higher cost of borated steel balls, the reference design is based on unborated, stainless steel balls.

The transport calculations were performed using the discrete ordinate code ANISN[6] with S_8 symmetric angular quadrature set and P_3 legendre expansion for the scattering cross sections. A 67-multigroup, cross-section set (46 neutrons and 21 photons), collapsed from the CTR library,[7] was used for ANISN calculations. The MACKLIB[8] was employed to calculate the nuclear-response functions (nuclear heating, radiation damage, gas production, etc.). For radioactivity and dose equivalent after shutdown, the calculations follow the ANISN-RACC-ANISN[9] path. The ANISN code was first used to obtain the steady-state neutron fluxes in each interval of the geometry. These fluxes, after normalization for proper wall loading, were used by the RACC code to generate the decay gamma source distributions for various operating and decay times. Decay gamma transport was then performed with the ANISN code to obtain the dose equivalent for each operating and decay time.

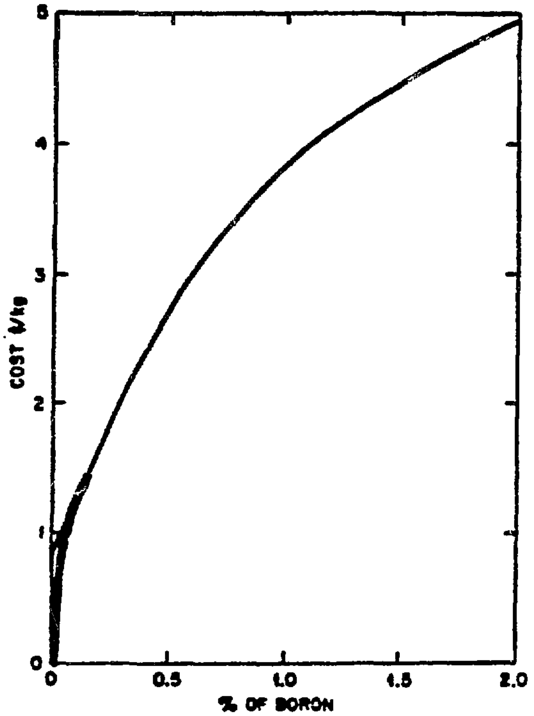

Fig. 4. Cost of adding natural boron.

SHIELD DESIGN CRITERIA

The main function of the shield during reactor operation is to reduce the neutron and photon leakage intensities from the shield to an acceptable level. This reduction ensures that (a) the different reactor components are protected from radiation damage and excessive nuclear heating, (b) the neutron reaction rates in the reactor components outside the shield system are reduced to avoid high-biological dose in the reactor hall after shutdown, and (c) the worker and the public are protected from radiation exposure. Another shield function is to attenuate the decay gamma rays so that personnel are permitted access to the reactor hall within one day after shutdown with all shields in place.

TFCX is designed to operate for 2×10^5 s, with 0.65-MW/m^2 D-T neutron wall loading. Under such operating conditions, the nuclear heating is the main driver for the shield design from the TF coils' point of view. The radiation-damage parameters in the TF coil components and the thermal-insulator layers are much lower than any design limits as discussed in ref. 10. The nuclear heating impacts the refrigeration power required since about 500 W of electrical power is consumed to remove 1 W from the TF coils at 4°K. This removal efficiency calls for minimizing the nuclear energy deposition in the coils. Therefore, the maximum nuclear heating is limited to 1 MW/m^3 to assure low-refrigeration power, simple TF coil design, and cryogenic stability during operation.

In general, the effect of radiation on the superconductor coils tends to lower their performance. For NbTi superconductor material, irradiation experiments[11-15] show that the critical current density is decreased by ~10% at 4×10^{18} n/cm^2 ($E > 0.1$ MeV) neutron fluence while the critical temperature is unchanged. The maximum atomic displacement rate in the copper stabilizer was limited to 4×10^{-4} dpa, which is corresponding to the 5×10^{-8} $\Omega \cdot$cm increase in the electrical resistivity.

The most sensitivie component in the coil is the insulator materials because the radiation damage in them is irreversible and limits the operating life of the coil. G-10, G-11, or polyimide materials are used in the superconductor coils for thermal and electrical insulation. Irradiation work at 4°K[16-17] suggests that polyimide can be used up to 10^{10} rads and retains 75% to 80% of its mechanical strength. G-10 and G-11 show serious degradation at ~2×10^9 rads. Therefore, dose limits to the polyimide thermal insulation were limited to 5×10^9 rads, while the limit to the TF coil conductor insulation was held to 2.5×10^8 rads.

The personnel access to the reactor hall within one day after shutdown requires the satisfaction of regulations pertaining to occupational exposure. Federal regulations[18] limit the occupational dose to 5 rem/y, with a maximum of 3 rem/quarter. Occupational exposure based on working 8 h per day and 40 h per week is 2.5 mrem/h. However, the current practice in the nuclear industry, the exposure policy of the Department of Energy (DOE), and the national laboratories' regulations is to reduce radiation exposures as low as reasonably achievable (ALARA). Specficially for facilities being designed, DOE-5480.1 states the following:

> "Exposure rates in work areas should be reduced as low as reasonably achievable by proper facility design and equipment layout. Design factors to consider are: occupancy time, source terms, spacing, processes, equipment, and shielding. Onsite personnel exposure levels less than one-fifth of the permissible dose equivalent limits prescribed in this chapter should be used as a design objective."

This policy limits onsite workers to less than 1 rem/y (0.5 mrem/h), which is the design goal for this study.

INBOARD SHIELD

The inboard shield parameters used in the neutronic analysis are shown in Table 2. The total shield thickness is 60 cm, with a basic composition of 80% type 316 steel, 20% H_2O with 2 cm of boron carbide with a density factor of 0.7. This concept is based on optimization studies from previous designs.[2,10,19-21] Although these studies used the type 316 steel in the neutronic analyses, Fe1422 or Nitronic 33 steel are the preferable reference materials, due to the lower nickel content. The bulk shield material is in the form of layered plates with machined coolant passages.

Table 2. Inboard shield parameters used in the analysis for the superconductor design

Zone Description	Radius (cm) From	Radius (cm) To		Width (cm)	Composition Volume Percentage
TF case	121	126		5	100% type 316 steel
TF coil	126	191		65	5% NbTi, 23% Cu, 65% type 316 steel, 8% insulator
TF case	191	196		5	100% type 316 steel
Thermal insulator	196	203		7	1% insulator
Vacuum vessel	203	213		10	100% type 316 steel
Gap	213	216		3	Vacuum
Shield jacket	216	218	60	2	100% type 316 steel
Boron carbide shield	218	220		2	100% B_4C (0.7 factor)
Steel shield	220	274		54	80% type 316 steel, 20% H_2O
First wall	274	276		2	50% type 316 steel, 50% H_2O
Graphite armor	276	281		5	100% C
Scrape-off	281	294		13	Vacuum
Plasma	294	506		212	Vacuum
Scrape-off	506	513		7	Vacuum
First wall	513	515		2	50% H_2O, 50% type 316 steel
Outboard shield	515	645		130	80% type 316 steel, 10% H_2O, 10% B_4C (0.7)

A trade study was conducted to evaluate the utilization of steel balls as the bulk shield material, which would have resulted in a 60% steel/40% H_2O inboard shield. The resulting shield would have been 70-cm thick, increasing the overall size of the device and negating the cost benefit of the steel balls. Therefore, the layered plate concept was selected as the reference design.

Table 3 shows a comparison of the design criteria limits to the inboard shield performance.

Table 3. Inboard shield limits vs performance

Requirement	Limit	Performance
Nuclear Heating at TF Coil Winding, mW/cm^3	1.0	0.58
Neutron Fluence to TF Coil Winding, n/cm^2	4×10^{18}	6.5×10^{15}
Dose to TF Coil Insulation,[a] rads	2×10^9-10^{10}	7.6×10^6
Dose to Thermal Insulation,[a] rads	2×10^9-10^{10}	1.3×10^7
Displacement Damage to Copper Stabilizer, dpa	4×10^{-4}	3.2×10^{-6}

[a] 2×10^{10} for G10 or G11 and 10^{10} for polyimide.

OUTBOARD SHIELD

The outboard shield design must prevent the radiation responses in the outboard leg of the TF coil from exceeding the design criteria limits. The shield must also provide a protective radiation shield for maintenance personnel at the outer face of the shield.

Since the location of the outboard TF coil leg is generally determined by ripple requirements, a thicker shield with a lower volume percentage of steel bulk shield material can be accommodated without affecting the overall size of the machine components. Therefore, a trade study[10] was conducted to evaluate the use of lower cost materials that require a thicker shield to compensate for the difference in attenuation characteristics. The shield design is divided into two zones. The first zone is designed to protect the TF coils from radiation damage and excessive nuclear heating. The second zone is located between the outboard legs of the TF coils and must combine with the inner zone to satisfy the dose criterion.

The steel balls concept is used in the inner zone. The evaluations of the inboard shield have shown that a 70-cm shield of steel balls (60% SST/40% H_2O) would protect the TF coil systems. Therefore, the inner-zone reference design is 70-cm thick, with the steel balls as the bulk shield material.

For the second, or outer zone of the outboard shield, three options were evaluated: (a) 106 cm of water in steel tanks (95% H_2O, 5% type 316 steel, (b) 124 cm of concrete, and (c) an additional 71-cm zone of steel balls (60% type 316, 40% H_2O). All three options met the 0.5-mrem/h-after-24-h dose limit. Option (a) was chosen for the reference design due to the cost and handling advantages. Therefore, the geometry and composition of the outboard shield design are shown in Table 4.

Table 4. Geometry and composition for the outboard shield

Zone description	Thickness, cm	Composition percentage volume
First wall	2	50% H_2O, 50% type 316 steel
Steel balls shield	60	40% H_2O, 60% type 316 steel
Boron carbide shield	3	100% B_4C (0.7 DF)
Lead shield	5	100% Pb
Biological shield	106	95% H_2O, 5% type 316 steel
Boron carbide shield	3	100% B_4C (0.7 DF)
Lead shield	5	100% Pb
TOTAL	184 cm	

CONCLUSION

A shield design was developed for a reference configuration of the next-generation tokamak device with superconducting TF coils and low D-T neutron fluence. The shield design uses a high-volume percentage of bulk-shield material (80% layered steel plates) in the inboard design while using a lower volume percentage of bulk-shield material (60% steel balls) in the outboard design. Use of the high-volume, moderate-cost, steel-plate material on the inboard shield reduces the radial build by 10 cm. Use of the low-volume, low-cost, steel-ball material on the outboard shield design significantly reduces the cost of the shield system. The shield-system cost was 4% of the total direct cost of the facility.[17]

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