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AN ELECTRICALLY CONDUCTING FIRST WALL
FOR THE FUSION ENGINEERING DEVICE-A (FED-A) TOKAMAK*

B. A. Cramer, Fusion Engineering Design Center/McDonnell Douglas Astronautics Company
Oak Ridge National Laboratory, P.O. Box Y, Oak Ridge, Tennessee 37830 (615) 576-5470
G. M. Fuller, J. R. Haines, V. D. Lee, McDonnell Douglas Astronautics Company/FEDC
F. W. Wiffen, Oak Ridge National Laboratory/FEDC
Y. Gohar, Argonne National Laboratory, FEDC

ABSTRACT

The first wall of the FED-A tokamak device must satisfy two conflicting requirements. These are long eddy-current-decay time (low electrical resistance) and high neutron transparency. The trade-off between these requirements results in a baseline copper alloy shell design that satisfies the requirements for FED-A: a minimum eddy-current-decay time of 0.55 and a tritium-breeding ratio of 1.2. Aluminum alloys come close to meeting the requirements and would probably work. Stainless steel will not work in this application because shells thin enough to satisfy temperature and stress limits are not thick enough to permit long eddy-current-decay time and avoid disruption-induced melting. The baseline first-wall design is a rib-stiffened, double-wall construction. The total wall thickness is 1.5 cm, including a water-coolant channel of 0.5 cm. The first wall is divided into twelve 30° sectors. Flange rings at the ends of each sector are bolted together to form the torus. Structural support is provided at the top center of each sector.

INTRODUCTION

The objective of the Fusion Engineering Device-A (FED-A) study¹ was to quantify the improvement in cost-effectiveness of FED when aggressive physics assumptions are incorporated into the design. These assumptions result in plasma operating regimes where tokamak experiments have shown that many plasma burns end in plasma disruptions. However, calculations suggest that the addition of an electrically conducting shell of modest thickness (e.g., 0.5- to 1.0-cm-thick copper) close to the plasma surface should decrease the adverse effects of plasma disruptions. This is because the conducting shell lengthens the plasma eddy-current decay time to a significant

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fraction of the plasma internal sawtooth oscillation time. Calculations show that, as the decay time becomes long enough, disruptions should be eliminated. For FED-A, the suggested decay time is 0.5 s or greater.

Observations in some tokamak devices have shown the advantages of an electrically conducting first wall. In particular, the DIVA experiment² demonstrated plasma disruption-free operation with a 3-cm-thick copper shell located at a minor radius 20% greater than the plasma minor radius. Therefore, a major emphasis of the FED-A study was to incorporate a continuous, conducting first wall in the design and assess its effect on performance.

Baseline FED-A Design

An elevation view of the FED-A device is shown in Fig. 1. Both the shield and the first wall are located inside the vacuum vessel. Reference parameters for FED-A are given in Table 1.

First Wall Design Description

The first wall is a toroidal shell with an approximately elliptical cross section. The shell is fabricated in twelve 30° sectors. A typical sector is shown in Fig. 2. Each sector of the shell is removable through the cryostat window module between the TF coils. Each sector is supported from the shield by a linkage above the sector center of gravity.

The first wall is not a vacuum boundary; therefore, it is not necessary to have a vacuum seal between the shell sectors or at penetrations for heating and for the pumped limiter. Access doors are required in all sectors of the first wall shell that do not have large cutouts for major components. The effect of the cutouts in the first wall was not included from a structural or electrical standpoint.

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Fig. 1. FED-A device elevation view

ORNL-DWG 83-2307A FED

Table 1. Reference parameters for FED-A

Description	Unit	Value
Major radius, R	m	4.22
Plasma radius, a	m	0.92
Plasma elongation, κ	m	1.2
Aspect ratio, A		4.59
Scrape-off layer	m	0.15
Burn time, t_{burn}	s	100 to 1000
Fusion power, P_{DT}	MW	255
No. of full-field current pulses/lifetime		3×10^4
Avg. no. of burn pulses in each current pulse		10
Avg. neutron wall load at first wall	MW/m^2	1.2

Fig. 2. First wall shell sector

Cooling water flows in the poloidal direction through passages in the shell, as shown in Fig. 3. Inlet and outlet manifolds are attached to the shell above and below the limiter cutout, respectively. Coolant passages approaching cutouts merge with a single, larger coolant passage running around the periphery of the cutout.

Fig. 3. Water flow in FED-A shell

The shell is a double-wall construction, as shown in Fig. 4. Copper is the baseline material. Each skin is 0.5 cm thick. The coolant channel depth is also 0.5 cm, resulting in a total shell thickness of 1.5 cm. The average rib spacing is approximately 2.0 cm.

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INLET TEMPERATURE (°C)	60
OUTLET TEMPERATURE (°C)	115
INLET PRESSURE (MPa)	0.69
PRESSURE DROP (kPa)	4.2
MASS FLOW RATE (kg/s)	360
PUMPING POWER (kW)	1.6

Fig. 4. Shell cross-section geometry and coolant parameters

The sectors are mechanically joined to form a continuous shell. Both bolting and clamping of shell ring flanges were considered. Bolting was selected. A minimum face pressure of 0.7 MPa (100 psi) at the ring joint is needed to assure a current path across the joint with a resistance sufficiently low ($<1 \mu\Omega/\text{joint}$) to prevent arc welding. For a bolt spacing of 15 cm, fifty-two 12.7-mm bolts torqued to 17 N·m are required for each joint to provide adequate face pressure.

First-Wall Material Selection

The first wall of the FED-A tokamak device was designed to satisfy two conflicting requirements. These are long eddy current decay time and high neutron transmission ability.

A thick wall satisfies the first requirement because it results in low electrical resistance, which increases eddy-current decay time. A thickness that provides a 0.5-s or greater toroidal eddy current decay time was established for the FED-A. A thin wall satisfies the second requirement because it maximizes the transmission of neutrons. The neutronic transmission was characterized as a design goal of achieving a tritium breeding ratio of at least 1.20 for a Li_2O blanket module, without a neutron multiplier.

Austenitic stainless steel (type 316), a copper alloy (AMAX-MZC), and an aluminum alloy (5083) were candidate materials. Properties used for thermal and structural analyses are listed in Table 2.

Table 2. Material properties of alloys considered for conducting first wall

Property	316 SS (MPa°C)	5083 Al (MPa°C)	AMAX-MZC Cu (MPa°C)
Density (g/cm^3)	7.9	2.7	8.9
Thermal conductivity ($\text{W}/\text{m}\cdot\text{K}$)	17.8	210	380
Specific heat ($\text{J}/\text{kg}\cdot\text{K}$)	460	900	400
Thermal expansion coefficient ($10^{-6}/\text{K}$)	17×10^{-6}	24×10^{-6}	18×10^{-6}
Electrical resistivity ($\mu\Omega\cdot\text{cm}$)	69	6.3	6.3
Electric modulus (GPa)	130	66	120
Yield strength (MPa)	140	120	97 (300°)
Ultimate strength (MPa)	420	270	200 (300°)
Aluminum design stress (MPa)	99	97	99

^aSee Ref. 1 for material properties.
^bSee material and specification.

The neutron wall loading of FED-A is approximately 1.2 MW/m^2 . The goal service life of the device is $1.2 \text{ MW}\cdot\text{y/m}^2$. Most of the physical properties of metal alloys are relatively unaffected by this irradiation environment at temperatures in the range of interest for FED-A. Changes in the electrical resistivity and the thermal conductivity resulting from irradiation at $>60^\circ\text{C}$ are in the range of 1 to 10%. The mechanical properties of these alloys will also be affected by irradiation. Data for 316 stainless steel and for aluminum alloys similar to 5083 indicate that the FED-A environment would increase both yield and ultimate tensile strength. Similar strengthening should be expected in the AMAX-M2C copper alloy, although supporting data are not available. Changes in mechanical properties are not expected to have an adverse effect and were not included in the analyses.

Analysis was performed to determine the effect of thickness and composition of the first wall on neutronic performance of a representative tritium breeding blanket module behind the first wall. Shown in Fig. 5 is the tritium breeding ratio in Li_2O as a function of the total first wall thickness for the three materials. All three materials perform similarly in the thickness range of interest (near 1 cm).

The toroidal electrical resistance (R_t) of the first wall for the three candidate materials is shown in Fig. 6 as a function of wall thickness. The resistances include the contributions from contact resistance at the interfaces between shell segments.

Fig. 5. Breeding ratio of tritium breeding blanket behind first wall

The toroidal electrical resistance (R_t) of the first wall for the three candidate materials is shown in Fig. 6 as a function of wall thickness. The resistances include the contributions from contact resistance at the interfaces between shell segments.

Fig. 6. First wall toroidal electrical resistance

The maximum allowable wall thicknesses are defined by thermal and structural limits. One structural limit is the thickness at which the temperature allowable gradient through the wall causes excessive thermal stresses. The temperature gradient was assumed to be 100°C for copper, 75°C for aluminum, and 140°C for stainless steel. Another limit, the maximum allowable structural temperature for the material, was assumed to be 350°C for copper, 200°C for aluminum, and 400°C for stainless steel. The allowable thermal gradient places an upper limit on the wall thickness for copper and steel; the maximum allowable structural temperature places an upper limit on the wall thickness for aluminum.

The minimum wall thicknesses are defined by the electrical resistance required to achieve an eddy-current decay time of longer than 0.5 s. Achieving this 0.5-s eddy-current decay time corresponds to achieving a $12\text{-M}\Omega$ electrical resistance, as shown in Fig. 6. It can be seen that stainless steel will not work in this application. Its low electrical conductivity requires thick walls to meet electrical requirements. The relatively low heat transfer capability of stainless steel results in excessive thermal stresses in the thick walls.

The results of the trade-off between tritium breeding ratio and toroidal eddy-current decay time are shown in Fig. 7. Wall thicknesses vary along each curve. Several values of wall thickness are shown in the figure. The thermal and structural limits discussed previously (Fig. 6) are shown.

Fig. 7. Electromagnetic and neutronic performance trade-off

The thickness at which melting occurs during plasma disruption establishes the lowest toroidal eddy-current decay time for each material. These limits are also shown in Fig. 7.

The desired eddy-current decay time and tritium breeding ratio severely limit the choice of material and thicknesses for the first wall. The desired operating range for FED-A is shown in Fig. 7. As thickness increases, the toroidal eddy-current decay time increases, but the breeding ratio decreases.

Copper was selected as the baseline material because the analysis indicates that it has a slightly better performance than aluminum. The design specifies a 1.5-cm-thick, double-wall shell, including 0.5 cm of cooling water. The toroidal eddy current decay time is 0.55 s, and the tritium breeding ratio is 1.22, both satisfying the FED-A requirements.

Baseline Shell Thermal and Structural Analysis

A bulk outlet water temperature of 100°C and a convection heat transfer coefficient of 1.0 W/cm²·K were assumed for the shell thermal analysis. A margin of 10°C was provided between the maximum water temperature and the saturation temperature at the calculated outlet pressure to prevent subcooled boiling. The reference water inlet temperature and pressure were 60°C and 0.7 MPa (100 psi), respectively. Resulting temperatures are shown in Fig. 8. The maximum temperature is 160°C, well below the

maximum attainable temperature of 350°C assumed for copper. The temperature gradient from plasma side to back side is only 40°C, far less than the allowable temperature gradient of 100°C.

Fig. 8. Copper first wall temperatures

A large coolant depth is desirable to minimize pumping power. However, a small depth is desirable for high neutron transmission. The reference water coolant passage depth of 0.5 cm represents a compromise between these conflicting performance parameters. For the baseline design of a 1.5-cm-thick shell, the reduction in the tritium breeding ratio caused by the presence of the 0.5-cm-thick coolant water is only 0.02 out of a total tritium breeding ratio of 1.22.

Reaction loads for the torus under dead-weight and a seismic disturbance are shown in Fig. 9. Each sector weighs 28,500 N (6,400 lb), and the total torus weighs 342,000 N (76,800 lb). It was assumed that seismic loads of 1 g in both the vertical and horizontal directions were acting simultaneously. The vertical load is taken equally by supports located at the top center of each of the 12 sectors. The horizontal load is reacted by horizontal (shear) loads at the supports. The supports carry only toroidal loads. They are designed to slide radially to accommodate thermal expansion of the torus and cannot carry loads in the radial direction.

Overturning due to the horizontal load is reacted above the center of gravity of the torus and carried by the 12 top center supports. The shell deadweight and seismic loads were assumed to be carried by the rings at the end of each shell sector (see Fig. 2). The rings are supported by a toroidal rib located at the top of each sector. The bending moment distribution in the highest loaded ring is shown in Fig. 10, and the rings were designed for this loading.

The toroidal rib was analyzed as a simply supported beam with a midspan load of 77,000 N (17,300 lb). A rectangular cross-section copper beam with a depth of 20 cm and a width of 7.5 cm is adequate to carry this load.

The maximum deflection, under deadweight, is 0.38 cm (vertically downward at the bottom of the shell). This deflection is not detrimental to performance. The radial thermal growth of the outboard shell surface during operation is 1.0 cm radially outward. The shell support system and attached components at ports have been designed to accommodate this growth.

Sector-to-Sector Attachment

Bolt loads in the bolted flange provide a positive approach to achieving sector-to-sector electrical contact. However, a wide range in bolt load can be expected for a given torque (e.g., function of bolt material) so the bolt torque must be high enough to provide adequate contact even under adverse tolerances. A bolt torque of 17 N·m (150 in·lb) for the 1.27-cm bolts spaced 15 cm apart represents a range in bolt stress from 55 MPa to 96 MPa per steel bolt.³ The minimum of these represents a sector-to-sector clamping pressure of 0.9 MPa. Thus, the required minimum clamping pressure of 0.7 MPa is obtained with very modest bolt stresses and torques.

Concluding Remarks

Selection of materials for first walls is sensitive to design requirements. Many conceptual designs have used stainless steel as the first-wall material, because it can generally be used to satisfy neutronic, thermal, and structural requirements. In the FED-A design, however, the additional requirement of low electrical resistance would not allow the use of stainless steel. This requirement dictated the use of a good electrical conductor such as copper.

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Fig. 9. Torus loads

Fig. 10. Ring bending moment distribution