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A NEUTRON-TRANSPARENT FIRST WALL FOR MODULE TESTING*

G. M. Fuller, Fusion Engineering Design Center/McDonnell Douglas Astronautics Company
FEDC Building, Oak Ridge National Laboratory
P.O. Box Y, Oak Ridge, Tennessee 37830
(615) 576-5463

B. A. Cramer, J. R. Haines, and J. Kirchner, FEDC/McDonnell Douglas Astronautics Company
B. A. Engholm, General Atomic Technologies, San Diego, California
M. Seki, Japan Atomic Energy Research Institute, Japan

ABSTRACT

Major design goals for FED-R are the achievement of (1) a high level of neutron exposure of the test modules and (2) a capability for rapid changeout of test modules. A major factor in rapid changeout is perceived to be the location of the vacuum boundary. In FED-R this boundary was set at the first wall so that module changeout did not require the plasma chamber to be brought up to atmosphere. Efforts to realize these goals in the design resulted in a neutronically thin outboard wall for the vacuum vessel constructed of 316 stainless steel (SS) with helium as a coolant. A normalized 14-MeV neutron transmission of 0.82 is expected, with an inlet pressure of 2 MPa and a pumping power requirement of 8.7 MW. Other options considered in the study were aluminum as a wall material and water and sodium potassium (NaK) as coolants.

INTRODUCTION

The FED-R, Fig. 1, is one of a series of tokamak fusion reactor studies performed at the Fusion Engineering Design Center (FEDC). The FED-R concept differs from the other studies in the use of all-copper toroidal field (TF) coils. Another unique feature is the vacuum vessel, which has a double function: It maintains the plasma vacuum conditions and serves as the first wall. Test modules are located outside the vacuum vessel, so they can be replaced without bringing the plasma chamber up to atmosphere. The vacuum vessel is divided into six 60° segments for ease of manufacturing and erection. Each segment has independent cooling loops. The bottom, inboard, and top walls are water cooled; the outboard wall is helium cooled for greater neutron transparency. The design of the outboard wall and the coolant selection rationale for the outboard wall are described in this paper.

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Fig. 1. Major features of the FED-R

OBJECTIVE

The objective of this study is to define a vacuum wall that permits maximum transmission of 14-MeV neutrons in the outboard region. Quantitatively, the goal for normalized 14-MeV neutron transmission was set at 0.80, which corresponds to a wall with a thickness equivalent to 1.0 cm of solid stainless steel.

APPROACH

Achievement of maximum 14-MeV neutron transmission through the outboard wall is related to the choice of structural material, the coolant material, and the thicknesses. Minimum thickness requirements exist for structural reasons. These equate to skin thicknesses and to panel depths. Coolant passage requirements relate to coolant flow conditions required to maintain material temperatures within specified limits. These limits are 400°C for 316 SS and 200°C for 5083 aluminum.

MASTER

It is clear that satisfactory thermo-dynamic and structural responses exist over a range of skin thicknesses and panel depths. Hence, once a satisfactory operating domain is established, it is relatively simple to select the maximum neutron transmission condition, limited by coolant pumping power.

Configuration and Loads

The outboard wall and the region where the test modules are located are indicated in Fig. 1. The outboard wall, isolated from the other components of the device, is shown in Fig. 2. Shown in Fig. 2(a) are the features of the wall that were varied in order to establish relationships between structural behavior, thermal hydraulic performance, and neutron transmissibility. These include the option of adding vertical stiffeners; the rib spacing, S ; the skin thickness, t ; and the coolant passage depth, w .

Fig. 2. Outboard wall of the vacuum vessel

Shown in Fig. 2(b) are the loading conditions for the wall. The external pressure load (1 atm) and heat and neutron loads are fixed in the study, but the coolant pressure is allowed to be determined by the thermal-hydraulic and structural requirements.

In addition to these configurational and loading variables, two structural material options and three coolant options were

identified. These are 316 SS and 5083 aluminum for the structural materials and ordinary water, gaseous helium, and NaK as the coolants. Typical properties assumed for these options are shown in Table 1.

Table 1. Candidate material properties

Property	Materials				Sodium potassium (Ref. 22/78)
	316 SS	5083 Al	Water	Helium gas	
Thermal conductivity, k (W/m 2)	16.6	167.8	0.67	0.17	25
Specific heat, C_p (kJ/kg $^{\circ}$ C)	0.46	0.90	4.20	5.20	0.92
Density, ρ (kg/m 3)	7900	2700	1000	1.18×10^{-3} (800 $^{\circ}$ C, 0.1 MPa)	850
Viscosity, μ (kg/m 2 s)	N.A.	N.A.	3.5×10^{-4} (800 $^{\circ}$ C)	2.5×10^{-5} (800 $^{\circ}$ C)	N.A.
Electrical conductivity, σ (1/cm 2 s)	N.A.	N.A.	N.A.	N.A.	2.15
Elastic modulus, E (GPa)	179	69	..	..	..
Tensile strength, F_{TS} (MPa)	207	131	..	..	..
Coefficient of thermal expansion α (1/ $^{\circ}$ C)	17×10^{-6}	24×10^{-6}	..	..	..
Allowable stress (S_{all}) (MPa)	154	95	..	..	..

^aThermal conductivity value, actual temperature-dependent properties were used in analysis
N.A. = not applicable

Neutron Transmission Characteristics

The neutronic input to this trade study consisted of the 14-MeV transmission characteristics of several possible first-wall structural materials and coolants, including 316 SS, aluminum, water, NaK, and helium. The Los Alamos MCNP Monte Carlo code⁴ was used for these calculations, in order to take advantage of the pointwise cross-section treatment available with this code.

Individual MCNP cases were run by locating a D-T surface source on one side of a slab of structure or coolant. This source had a Gaussian fusion spectrum ($E = 14.1$ MeV) and a cosine angular distribution directed into the slab. The slabs were treated as infinite by surrounding the lateral boundary with a reflective surface. Neutrons scattered back from the source side of the slab were killed.

The RMCSS pointwise cross-section set, which is based on ENDF/B-IV, was used. Transmitted neutrons (neutrons crossing the outside surface of the slab) were tallied in 29 energy bins. Transmitted 14-MeV neutrons are defined as neutrons remaining in the 13.5- to 16-MeV energy group, though there are a few in-group scattering events. Each case was run with 5000 histories, sufficient to provide $\sim 1\%$ uncertainty in the transmitted 14-MeV component.

Results of the neutronics study are summarized in Fig. 3, which shows 14-MeV neutron transmission (current out/current in) for various materials as a function of thickness. Gaseous helium is assumed to have 100% transmission. It is interesting that Al and H₂O provide essentially the same transmission, while NaK is markedly more transparent; 316 SS (as are other steel alloys) is much less transparent. The 14-MeV e-folding distance in steel is about 4.5 cm, according to these calculations.

Fig. 3. 14-MeV neutron transmission

If total neutron transmission (which includes down-scattered neutrons) is considered, a different set of curves is obtained, shown in Fig. 4. The 316 SS total neutron e-folding distance is 11.9 cm for this case.

Fig. 4. Total neutron transmission

Thermodynamic Performance

Normal operating heat loads for the outboard first wall are summarized in Table 2. The surface heat flux of 0.6 MW/m² and neutron wall loading of 1.3 MW/m² were used for thermal analyses of both 316 SS and aluminum outboard first walls. The coolant materials considered for these analyses were water, helium gas, and NaK.

Table 2. Operating heat loads for the first wall

Heat load from plasma* - W/cm ²	25
Heat radiated to outboard first wall from 5-cm-thick inboard tiles - W/cm ²	35
Nuclear heating - W/cm ³	
• Graphite	8.4
• 316 SS	14.4
• Aluminum (optional wall material)	8.0
Neutron wall load - MW/m ²	1.3

*Includes radiation, charged particles, and neutral atom bombardment and takes into account divertor effectiveness.

The configuration of the coolant flow passages in the outboard first wall coolant is shown in Fig. 2. Skin thickness (t) limits were determined based on maximum operating temperature limits of 400°C for 316 SS and 200°C for aluminum. Assumptions used for the outboard first-wall coolant flow analyses are an inlet temperature of 60°C and a rib spacing (S) of 3.0 cm. An inlet temperature of 60°C for the primary coolant loop represents a reasonable outlet temperature from a heat exchanger connected to a secondary loop that exchanges heat with the environment.

The internal rib spacing (S) must be as large as possible to minimize the attenuation of the 14-MeV neutrons. However, if rib spacing is too large, then the skin thickness required to maintain an acceptable bending stress becomes large, and a large fraction of the 14-MeV neutrons are excessively attenuated by the wall. A rib spacing of 3.0 cm is a reasonable compromise between attenuation and skin thickness.

Skin thicknesses (t in Fig. 2) of 0.20 cm for 316 SS and 0.26 cm for aluminum at a pressure of 0.7 MPa (100 psi) were used for these analyses. The skin thickness is proportional to the square root of the coolant pressure (for a constant rib spacing).

Therefore, the thickness (t) was increased according to this relationship as the coolant pressure was increased above 0.7 MPa (100 psi).

The skin spacing (flow passage depth, w) required for structural stability (discussed in the structural performance section) was varied as a function of skin thickness. For all three coolant materials, the optimum coolant passage depth from a thermal-hydraulic viewpoint was smaller than that required for structural stability.

A convection heat transfer coefficient of $1.0 \text{ W/cm}^2\text{K}$ was required for the water coolant flow system to inhibit subcooled boiling at a pressure of 0.7 MPa (100 psi). The resulting pressure drop and pumping power for cooling the outboard wall are 0.07 MPa (0.1 psi) and 0.2 MW. The pressure drop and pumping power with water coolant were found to be relatively insensitive to inlet pressure.

To maintain the structure below its upper temperature limit with water coolant, the thickness must be less than 0.66 cm for 316 SS and 0.85 cm for aluminum. Thermal stress limits are discussed in the structural performance section.

The sensitivity of the helium coolant system pumping power to inlet pressure is shown in Fig. 5. The helium coolant system is sized to maintain the 316 SS temperature below 400°C and the aluminum temperature below 200°C .

At high pressures, the good transport properties of helium make the required coolant velocity small, resulting in low pumping power. However, the skin must be thick at high pressures, resulting in a low coolant-side structural temperature (for the heated surface temperature held constant) and thus requiring high coolant velocity and large pumping power. These competing influences result in a minimum pumping power at an intermediate pressure. The pressure at which this maximum pumping power occurs is very sensitive to the thermal conductivity of the wall.

For a stainless steel wall, a minimum helium pumping power of 6.5 MW is achieved at an inlet pressure of about 4 MPa (600 psi). The required 316 SS wall thickness at this pressure is 0.48 cm.

For helium coolant pressures less than about 6 MPa (900 psi), the 316 SS wall

requires less pumping power than the aluminum wall. The minimum helium pumping power for an aluminum wall occurs at a pressure greater than 20 MPa (3000 psi), which is an impractically high operating pressure. Since aluminum has a high thermal conductivity compared to 316 SS (about a factor of 10 higher), the effect of the temperature drop through the wall thickness on pumping power is insignificant until pressures are high. Therefore, at high pressures (greater than 6 MPa), the pumping power for an aluminum wall is less than that for a stainless steel wall.

Fig. 5. Impact of first wall structural material on coolant pumping power

In addition to these thermal-hydraulic considerations, the effect of operating pressure on wall thickness and the resulting 14-MeV neutron transmission must also be considered. The trade-off between helium pumping power and neutron transmission is discussed in later paragraphs.

For NaK Coolant, the pressure drop at the minimum pumping power (60 MW) is 10.6 MPa (1540 psi). This pumping power is about the same as the total thermal power incident on the outboard first wall. The large pressure drop and pumping power are caused by the MHD effects of a liquid metal flowing across a magnetic field. This condition cannot be avoided since the flow must cross either the poloidal field of 0.9 T at the outboard wall (vertical flow direction) or the toroidal field of about 8 T (horizontal flow direction). Either flow direction also crosses the radial field of 0.4 T. The vertical flow direction was assumed for these analyses. In addition to the poor thermal-hydraulic performance of this coolant, there are also safety and maintenance concerns associated with using NaK, which is also inferior to helium as a neutron transmission medium.

Structural Analysis

The shell configuration is shown in Fig. 2. The shell is a double-wall, rib-stiffened cylinder. Vertical stiffeners take vertical loads (pressure on top and bottom of the torus) and help stiffen the shell against a general instability failure.

Results of stability analysis for the 316 SS wall are shown in Fig. 6. The required effective structural shell thickness was determined from

$$\bar{t} = \sqrt[3]{\frac{p'(12)r^3(1-\nu^2)}{E(\pi^2/\alpha^2 - 1)}}$$

where

p' = critical external pressure for shell buckling, MPa (atmospheric pressure with factor of safety = 5.0),

$\bar{t}$ = effective thickness, cm,

r = shell radius, cm,

ν = Poisson's ratio (0.3),

α = toroidal angle between vertical stiffeners.

The effective thickness was then converted to required combinations of wall depth (h) and skin thickness (t). Values are plotted for cases with and without an intermediate vertical stiffener. Also shown are minimum skin thicknesses to provide the required strength for combined hoop compression (1 atm) and

local bending (1-MPa coolant pressure). Results show the decrease in wall depth that can be obtained with the addition of the intermediate stiffener.

Fig. 6. Addition of stiffeners significantly reduces wall depth

Thermal stresses for the 316 SS first wall shell with helium coolant, along with stresses for hoop compression and local bending, are shown in Fig. 7. The critical location for combined compressive stresses is on the skin surface facing toward the plasma at the rib joint.

Fig. 7. Limiting stress is compressive and on plasma side surface

The fatigue life of the first wall shell is a function of the cyclic nature of the stresses. For combinations of stresses at the design thickness, the following fatigue lives are predicted:

Thermal stress	40,000 pulses
Thermal stress + bending	14,000 pulses
Total stress	7,000 pulses

RESULTS

The results of the efforts to maximize neutron transmission through the outboard first wall are summarized in Fig. 8. The optimization parameters are pumping power and the normalized transmission of 14-MeV neutron flux. The coolant inlet pressure is also shown. The principal comparison is between 316 SS and aluminum structure using helium as a coolant.

Fig. 8. Selected design condition is for a 316 SS wall cooled with helium

For neutron transmissions above about 0.75, the 316 SS wall will result in the lowest pumping power requirements. The lowest pumping power is about 6.5 MW for inlet

pressures of about 4 MPa and a neutron transparency of about 0.78.

The results for water coolant are indicated by the note in the lower left corner. The best transmission for 316 SS with water was about 0.55.

The 316 SS exhibits a minimum value of pumping power in this figure for the following reasons: (1) to the right of the minimum point, the dominant effect is the reduction in the convective heat transfer properties of helium with decreasing inlet pressure, resulting in increased pumping power; (2) to the left of the minimum point, the pumping power goes up because of the dominant effect of increasing wall thickness with increasing pressure. The flow rate goes up, and pumping power goes up.

The aluminum data also exhibit a minimum, but it is at low values of neutron transmission and is therefore not shown in Fig. 8. The pressures for the same neutron transmission (or for constant pumping power) are higher for aluminum than for 316 SS because of the lower maximum wall temperature for aluminum.

The use of NaK as a coolant does not appear attractive. At an inlet pressure of 11 MPa (required to overcome magnetic-field-induced losses), the best neutron transmission obtained was 70% using an aluminum structure.

The selected reference design condition is the 316 SS wall with helium coolant operated at 2-MPa inlet pressure, giving a transmission of 0.82 and requiring a power of 8.7 MW.

CONCLUSIONS

The selection of materials for the vacuum wall structure and for the coolant in FED-R is very dependent on the specific wall loadings and on the requirements for neutron transparency. In the case of FED-R, superior neutron transmission (82%) is achieved with a 316 SS cooled by gaseous helium. The cost of cooling the outboard wall in this manner is 8.7 MW of pumping power.

REFERENCES

1. "MDNP - A General Purpose Monte Carlo Code for Neutron and Photon Transport," Los Alamos National Laboratory, April 13, 1981.

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