Fusion Ignition Research Experiment Vacuum Vessel Design and Configuration*

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18th IEEE/NPSS Symposium on Fusion Engineering
October 25–29, 1999
Albuquerque, New Mexico

*Research sponsored by the Office of Fusion Energy Sciences, U.S. Department of Energy under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

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Abstract—The design status of the vacuum vessel for the Fusion Ignition Research Experiment (FIRE) is presented. The purpose and configuration of the various components of the vessel are described, along with the results of preliminary structural analysis. It appears that a vessel can be designed to meet the requirements within the rather restricted space constraints.

INTRODUCTION

The Fusion Ignition Research Experiment (FIRE) is proposed as a versatile, high field tokamak that will investigate near-ignition (Q > 10) deuterium-tritium (D-T) plasma operation for pulse lengths of at least 10 s. The vacuum vessel provides the vacuum environment for the plasma as well as the first confinement barrier for radioactive materials. The vessel also serves as the support structure for all in-vessel components, provides the first level of nuclear shielding, and helps provide for the passive stabilization of the plasma. The vessel system includes the torus, the ports and port extensions, the gravity supports, the supports for internal components, the passive stability plates, the internal control coils, and the integrated coolant/bakeout lines (Fig. 1).

VESSEL CONCEPT

The vessel torus is a double-wall sandwich structure consisting of 15-mm-thick inner and outer facesheets attached to poloidal ribs. The space between the facesheets, which varies from 20 mm on the inboard side to 540 mm on the outboard side, is filled with radiation shielding material and coolant. Water at 20–50°C and 1 MPa is used to remove nuclear heating during normal operation. The water temperature is raised to 150°C for heating the vessel and internals during bakeout. The shielding material can be single-sized stainless steel balls with a packing fraction of about 60% or stacked plates with a similar packing fraction. The vessel parameters are summarized in Table 1.

The primary advantages of the double-wall structure include higher bending stiffness (for a given total material thickness)

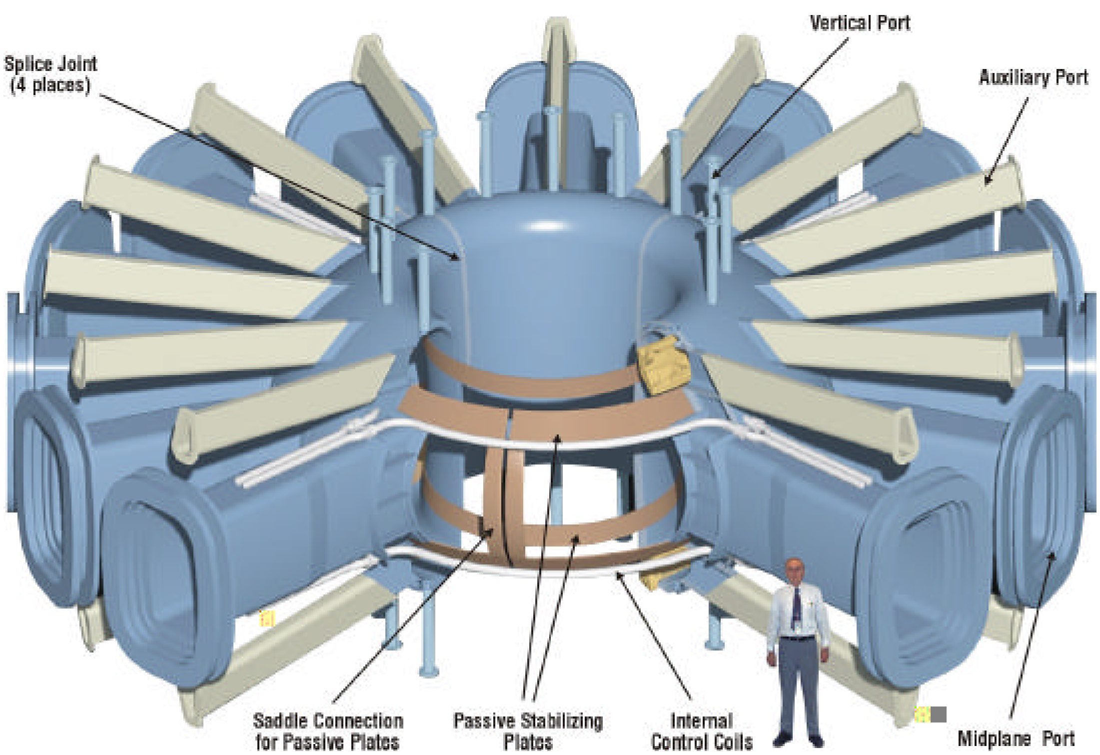

Fig. 1. Cutaway view of vacuum vessel with port extensions.

* Work supported by U.S. Department of Energy under Contract DE-AC05-96OR22464

Table 1. Vacuum vessel parameters

Dimensions and weights	
Volume of torus interior	35 m^3
Surface area of torus interior	89 m^2
Facesheet thickness	15 mm
Rib thickness	15 mm
Weight of structure, including ports	50 tonnes
Weight of torus shielding	80 tonnes
Power	
Direct neutron heating	~200 MW
Indirect first wall load	< 40 MW
Cooling	
Coolant	Water
Pressure	~ 1 MPa
Normal operating temperature, bakeout temperature	< 100°C ~ 150°C
Materials	
Torus, ports, and structure	316L ss
Shielding	304L ss (tentative)

and better integration of cooling and shielding. Most vacuum vessel designs in use [Joint European Torus (JET), JT60, DIII-D] and most designs on the drawing board [International Thermonuclear Experimental Reactor (ITER) and KSTAR] use full or partial double-wall vacuum vessels. Figure 2 shows an elevation section of the vessel and selected dimensions.

There are 16 sets of access ports around the torus, which are used for radio frequency (RF) heating, remote maintenance, diagnostics, and internal cooling. There are large 1.4- by 0.7-m midplane ports, upper and lower trapezoidal ports ~0.1 by 0.5 m, and upper and lower round vertical ports ~0.1 m in diameter. The sets of port openings are identical at each toroidal location to provide structural and design symmetry, but the port extensions may be varied to match their specific purpose. The port extensions are required to extend the vacuum boundary past the toroidal field (TF) coil legs and through the thermal shield region.

VESSEL LOADING AND ANALYSIS

The vessel is subjected to large gravity, seismic, and electromagnetic (EM) loads, as summarized in Table 2. The total vertical load is estimated to be about 20 MN, while the net lateral load is about 7 MN. To react these loads, the vessel is supported near the midplane on the outboard side via vertical and lateral links to the TF coil structure. The vertical links are attached to the radial ribs to spread the applied loads vertically into the vessel. This minimizes the local bending stresses in the vessel and provides a means for adjusting the vessel location globally relative to the TF coils. Lateral links are located near the vertical links and are tied to the top (and/or bottom) of the midplane ports.

The vessel must support all internal components, including the divertor assemblies, the passive stability structure, the poloidal limiters, and the first wall tiles. The outboard divertor modules are actively cooled via pipes at each of the upper and lower auxiliary ports. The two poloidal limiters are also actively cooled via piping located in the midplane ports. The first wall, inboard divertor, and passive stability structures are cooled by conduction to the vacuum vessel. All components must have robust supports to react the EM loads from a plasma disruption.

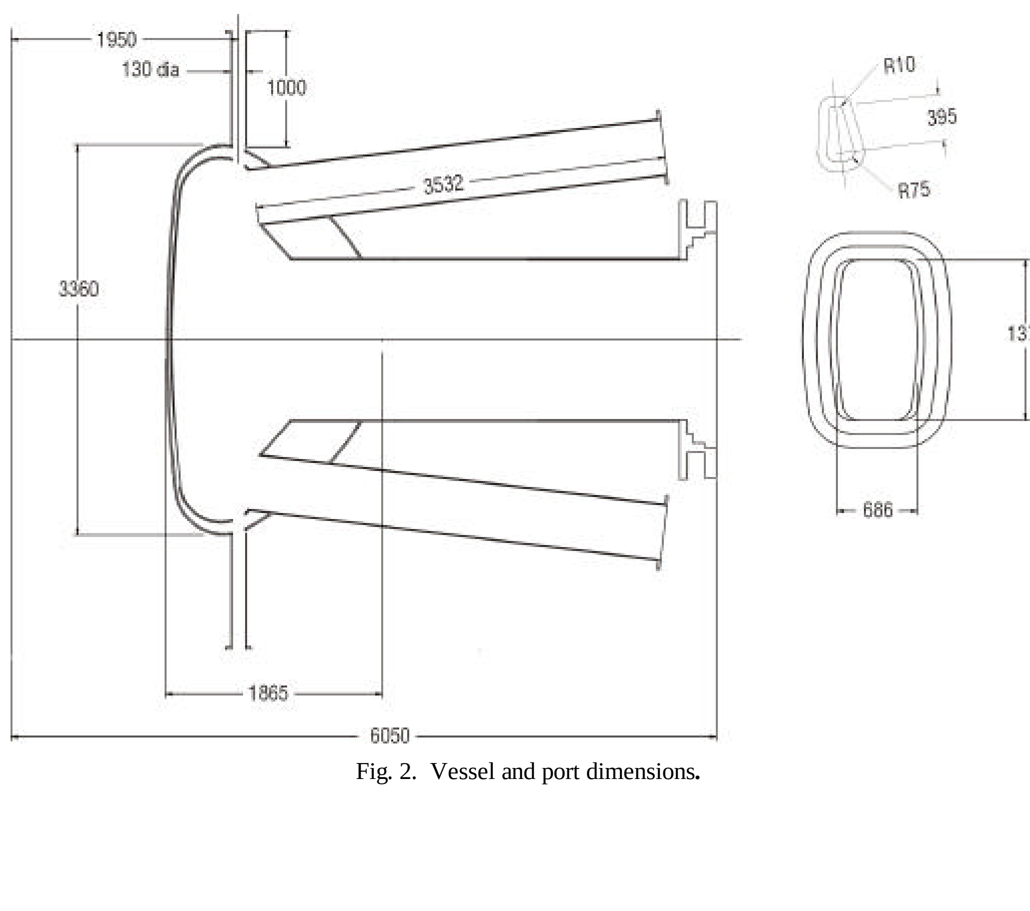

Fig. 2. Vessel and port dimensions.

Table 2. Vacuum vessel loading conditions

Load	Value
Gravity load	~3 MN
Vertical displacement event (VDE) load	
Vertical	20 MN
Lateral, net	7 MN
Seismic load (assumed)	
Vertical acceleration	0.2 g
Lateral acceleration	0.2 g
Maximum total vertical load	~27 MN
Maximum total lateral load	~9 MN
Maximum local EM load	
Local pressure on vacuum vessel from internal components	~4 MPa
EM load from TF ramp	~0.3 MPa
Coolant pressure	
Normal operation	<10 atm
Bakeout	<10 atm

Preliminary structural analysis of the vessel indicates that the present dimensions are about right to support the various loads. A finite-element model was developed for an earlier version of the vessel geometry, and the stresses and deflections obtained are summarized in Table 3. As seen in the table, there are some peak stresses around the port openings and at the top of the vessel that must be mitigated with additional structure. These reinforcements have already been incorporated in the vessel design, but the analysis has not been completed. Details of the stress and deflection analysis are contained in Appendix D of Ref. 1.

PASSIVE PLATES AND INTERNAL COILS

As discussed in the physics section of Ref. 1, a set of highly conducting passive plates and a set of internal control coils must be incorporated into the vacuum vessel. The geometry of the passive plate system is shown in Fig. 1. The passive plates consist of 20-mm-thick copper sheets bonded directly to the surface of the vacuum vessel. A direct connection is considered to be the most straightforward approach because cooling and structural support can be provided directly by the vessel. The method of bonding has not been decided, but explosive bonding is one possibility. At one toroidal location on the outboard side there will be a saddle connection from the upper to the lower ring. The saddle will also consist of 20 mm of copper bonded to the surface of the vessel.

A pair of control coils is also shown in Fig. 1. They are located between the outboard walls of the vessel above and below the midplane ports. Multiple turns of conductors are run in a permanent conduit that is routed directly through the outboard wall. The conductor will receive a moderately high radiation dose (>10^9 rad) and will be insulated with either MgO or a polyimide insulation system. Redundant turns are being considered to mitigate one of the failure modes.

FABRICATION AND ASSEMBLY

The vessel is fabricated in quadrants, as shown in Fig. 3. Each quadrant consists of the torus, associated gravity and internal supports, and short reinforcing stubs around the major port openings. At assembly, the vessel quadrants are rotated into the bore of a TF coil quadrant. These are positioned with the mating joints located at radial planes between TF coils, through the center of the ports. Once all the quadrants are in place, they are welded together from the plasma side of the torus. The field joint for the double-wall structure uses splice plates to provide a means for accommodating assembly tolerances and for accessing the coil-side facesheet from the plasma side of the torus. This type of joint has undergone significant, full-scale testing using remote welding equipment as part of the ITER research and development (R&D) program [2]. The control coil conduit is routed around the joint and exits the torus at the ends of each quadrant such that each quadrant can be independently connected. Once the torus is

Table 3. Preliminary Von Mises stress estimates for vacuum vessel

Load condition	Torus		Ports (unreinforced values)	
	General stress[a] (allowable stress = 195 MPa)	Peak local stress[a] (allowable stress = 390 MPa)	General stress (allowable stress = 195 MPa)	Peak local stress[a] (allowable stress = 260 MPa)
Vacuum load	<60	~170	<100	~170
Coolant pressure[b] (1 MPa)	<150	~500	<250	~500
VDE[c]	<400	~480	<50	~400
Thermal stress from nuclear heating[d]	<150	~340	<150	~340
TF ramp-up[e]	<15	TBD	TBD	TBD

[a]Estimated demarcation between general and peak local stress, peak primary + secondary = 3 × Sm.
[b]Stress values reduced from Ref. 1 calculations by ratio of applied pressure (1.0/2.7).
[c]VDE loads applied in simplified manner as described in Ref. 1, supports on outside. Latest design has 50% thicker section at top/bottom; stress reduction should be factor of >2.
[d]Temperature gradient of ~60°C based on 10-s full-power pulse, preliminary geometry Allowable secondary stress = 390 MPa.
[e]Stress estimate based on hand calculation of hoop stress in inboard facesheets.

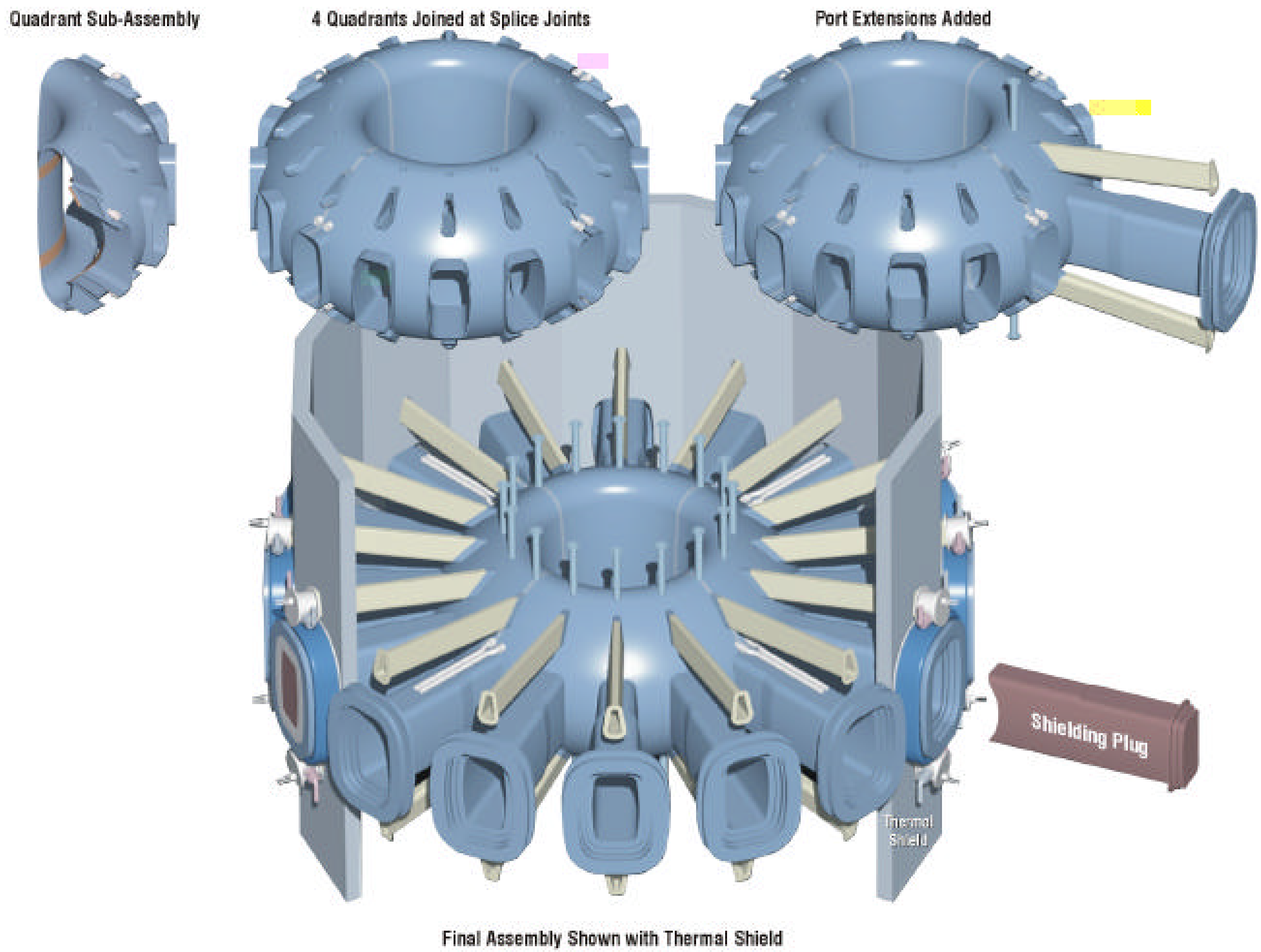

Fig. 3. Vacuum vessel assembly steps.

welded, the port extensions are fitted and welded to the port stubs.

CONCLUSION

The FIRE vacuum vessel serves multiple functions , including vacuum environment, safety barrier, nuclear shielding, and structural support for plasma facing components (PFCs). A double-wall configuration was chosen to provide the best mix of cooling and shielding and to simplify fabrication. The passive stabilizing plates and active control coils are integrated into the vessel structure, and large ports are provided for heating, diagnostic, and maintenance access. Preliminary structural analysis indicates that this concept is feasible.

ACKNOWLEDGEMENTS

Research sponsored by the Office of Fusion Energy Sciences, U.S. Department of Energy under contract DE-AC05-96OR22464 with Lockheed Martin Energy Research Corp.

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