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ITER First Wall Module 18 – The US Effort

R.E. Nygren, M.A. Ulrickson, T. J. Tanaka, D.L. Youchison, T.J. Lutz, J. Bullock[1], K.J. Hollis[2]

Sandia National Laboratories, P.O. Box 5800, Albuquerque, NM, USA 87185*
[1]Orion International Technologies
[2]Los Alamos National Laboratory, P.O. Box 1663, Los Alamos, NM, USA 87545

Abstract

The US will supply outboard module 18 for the International Thermonuclear Experimental Reactor. This module, radially thinner than other modules with a "nose" that curves radially outward to mate with the divertor, has the potential for high electromagnetic (EM) loads from vertical displacement events and high heat loads. The 316LN-IG shield block and first wall (FW) panels must be slotted to mitigate the EM loads and progress in developing the design is summarized. The FW has beryllium (Be) armor joined to a water-cooled CuCrZr heat sink with embedded 316LN-IG cooling channels. The US Team is considering possible fabrication methods as the design develops. Brief results of high heat flux experiments at Sandia on mockups with plasma-sprayed Be armor prepared at Los Alamos National Laboratory are noted.

Keywords: first wall materials, beryllium, joining, fabrication, eddy currents, plasma facing components

1. Introduction

The US will provide 36 ITER blanket module 18 (Mod18) units of the total 440 modules for the International Thermonuclear Experimental Reactor or ITER. Mod18 consists of first wall (FW) panels in front of a shield block of 316LN-IG stainless steel and water. ("IG" suffix refers to an ITER grade version of 316LN.) A module's trapezoidal shape is 400 mm thick (radially), 1225 mm in height and 1060-1208 mm wide. Each unit will weigh ~3 metric tons. Mod18 is the lowermost

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outboard blanket module. Fig. 1 shows a CAD drawing of a Mod18 unit in its place above the divertor.

Among the features that complicate the design of Mod18 are its curved and exposed "nose" just above the divertor and provisions for diagnostic ports at several locations that will require units of differing designs that depend on requirements for ports not yet fully specified. Each module hangs from four stub keys on the triangular support attached to the vacuum vessel wall.

The basic design must satisfy many requirements. The shield block must fit the prescribed mounting structure and coolant manifolds. The forces on these structures must be within acceptable limits, which implies slotting of the shield and segmentation of the FW to reduce loads from EM induced eddy currents. The shape of the FW must align with the edge of the plasma. The FW panels and shield blocks must have adequate cooling to control thermal stresses and distortions. The FW panels must be replaceable by remote cutting and rewelding in a hot cell. Mod18, with ~70% of the mid-plane neutron wall load, must attenuate neutron heating by a factor of ~50.

Much has been accomplished in the ITER Project, but only a few references [1-4] are given here due to space limitations. Much still remains to be done in detailed design and supporting R&D to permit efficient construction of ITER. For example, as US began active participation with the ITER Home Team during the last half of 2004, ITER drawings showed Mod18 only as a conical section with cutouts for the interfaces with the coolant manifolds and load pads; even this basic shape has changed over the last year. Some design details in other modules, such as coolant passages or the layout of FW panels, can serve as examples for the details in modules that are not yet designed. This paper describes ongoing work on design development for Mod18.

2. ITER Blanket Module 18 – Configuration and EM Loads

During the type of disruption of the plasma called a downward vertical displacement event, or DVDE, eddy currents that flow around the perimeter (top, sides and bottom) of the shield block will produce an EM-induced torque on the Mod18 shield block that will be reacted through the four key stubs. Two of the four M36 bolts will have pulling forces. Our first task is to design deep slots in the shield block that reduce eddy currents and force them inward from the perimeter to reduce the integrated mechanical moment (current crossed with field), so the load on any bolt is below 300 kN. We need to fix the size and locations of the slots before we can proceed with details of the cooling channels. Figure 2 shows an early US CAD model[1] of Mod 18 with the FW and cover plate removed from half the module.

As a DVDE proceeds, eddy currents generated in the passive stabilizers (triangular support and vacuum vessel wall) rotate the magnetic field from its initial direction parallel to the surface of Mod18 to one that intercepts this surface. In the first part of the DVDE, the change in field direction with time (changing direction of B-dot) drives the eddy currents in Mod18. Later, as the plasma moves onto Mod18 (and the divertor), the decreasing magnitude of the field in time dominates the B-dot.

The plasma changes both its position and its current distribution during a DVDE. The US Team is using the electromagnetics code OPERA, as it has for FIRE[5][2], to model the event and analyze its effect on Mod18. The model includes a self-consistent solution of the changing mutual inductances of Mod18 and the plasma. The global model includes the inner and outer vacuum vessels, triangular support, bulk structures of the divertor and Module 17, and details of Mod18, such as the slots and the openings for the FW support stalks. Figure 3 shows the configuration of the global model used in OPERA to calculate the EM-generated currents in the (passive stabilizers) vacuum vessel and triangular support. (The space here does not permit the figures necessary to show the actual results. They will be reported in the future.) The ITER Project [6] has used a different computational model in its analyses and results from the US and ITER analyses will be compared in the future.

Halo currents closing through the vacuum vessel as the plasma crashes onto Mod18 during a downward VDE also will produce EM-induced loads. Such currents flowing along the lower portion

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[1] CAD modeling is being done by Jim Bullock under contract to Sandia with assistance from Mike Ulrickson, Tina Tanaka and Richard Nygren of Sandia.

[2] The ITER analysis is being performed by Mike Ulrickson (Sandia National Laboratories). A presentation of initial results was made to the ITER Project but the analyses continue and published results are not yet available. Ulrickson and Dennis Youchison (Sandia) performed EM analyses for FIRE, a US design for a burning plasma experiment.

of a FW finger (visible in Fig. 2) would try to bend the finger into or away from the shield block, depending on the direction of the current. We have not yet begun analyzing these halo currents.

3. ITER Module 18 First Wall

Fig 4 shows a concept for a generic ITER FW panel [1] made of six parallel heat sinks of CuCrZr with 316LN-IG liners in the water channels and armored on the plasma-facing surface with Be tiles. These parallel "fingers" are joined along shared (toroidal) manifolds that run across the center of the panel. Designers in the European Fusion Development Activity developed an alternative in which each FW finger is keyed to the shield block and individually bolted.[7]

We are proceeding with the former ITER baseline design. However, if the FW is to curve around the exposed "nose" on the bottom of Mod18, HIPping (Hot Iso-static Pressing) of a structure with a significant feature extending out of the dominant plane of the panel will entail significantly more risk than a flat panel. Also, during a disruption, torque from anti-parallel eddy currents in a finger would try to twist it so that the curved end of one finger would contact the adjacent finger. If a short occurred, the anti-parallel currents would separate into the two adjacent fingers with the opposing forces now each acting on a separate finger. Our initial solution is a flat, overhanging FW panel that "shadows" the nose of the shield block from some of the radiated power from the edge plasma in and above the divertor. The feasibility of this design will depend on the heat removal in the Be-armored portion of the shield and the flow redirection and heat removal at the exposed end of the FW panel. These details are still being developed

4. Mod18 Fabrication

The development of fabrication methods for ITER has been a continuing area of work, especially in Europe. In the 23rd Symposium on Fusion Technology, held in September 2004, most of the 30+ papers on ITER dealt with manufacturing and materials. Again only a few references are given here.

The rationale for fabrication of the 316LN-IG shield block in the current ITER design is to drill and cut quarters from four forgings of a size readily available from industry and then weld these together to make the full shield block for a module. To provide shielding and cooling, about 25% of the shield is water in radial holes and toroidal and poloidal connection passages. The flow within the modules is directed by a set of insert tubes that divide the water into fast flowing sections in the annulus between the tube and the bulk shield and slower flowing regions in the interior of these tubes.

Fabrication of the ITER FW will require several joining operations. The CuCrZr heat sink must be joined to 316LN-IG tubes that line the water channels, to the 316LN-IG backing plate, and also to Be armor. HIPping is a likely option for bonding of the CuCrZr and 316LN-IG subcomponents; however the fit of very thin stainless steel tubes with multiple bends would be a challenge. The options currently being considered by the ITER Project are described elsewhere.[7,8] Testing of European FW mockups with brazed Be tiles has shown that their design will withstand heat fluxes up to 2.5M W/m^2 for 1000 cycles or 0.7 MW/m^2 for 13,000 cycles.[7]

As our design development proceeds, in addition to the fabrication options currently specified for other ITER modules, we are considering (1) plasma spraying of Be armor on FW panels and the nose of the shield block, (2) precision casting of the shield block forms, and (3) roll bonding or explosion bonding for joining the FW panels. The US ITER Team in the late 1990's performed R&D in all of these areas for the ITER divertor cassette body, divertor target and Be FW.[9-11]

Significant effort will be needed to qualify plasma spraying as a method for applying Be armor for the ITER FW. There is potential for this as a less expensive fabrication method and also for cost-saving as a repair procedure, and some R&D has begun to assess this potential.

Sandia recently tested (single channel) water-cooled CuCrZr mockups armored with 5 or 10 mm of plasma-sprayed (PS) Be armor in our Plasma Materials Test Facility. The 22x58 mm surfaces of the heat sinks were castellated with 5x5-mm blocks protruding 2 mm. The PS Be was applied with the heat sink at 600-650° without any interlayer. Areas of porosity and weakness in the PS Be adjacent to and above the castellations create preferred locations for crack formation in directions that are not detrimental to the thermal performance of the FW.

In the as-deposited coatings, "mounding" above the castellations was more pronounced on the 5-mm mockup, but there were also overall variations in the thickness of PS Be. It varied from 4.7 to 5.1 mm over the area of the thinner Be coating and from 9.4 to 10.0 mm on the other mockup.

The mockup with 5-mm armor survived 1000 cycles at 1 MW/m^2 and over 400 cycles, but with a rising surface temperature, at $2MW/m^2$. The mockup with 10-mm PS Be armor continued through 856 cycles at 1 MW/m^2, after which the test was terminated to prevent overheating of a small piece of Be that had become dislodged at one end of the mockup.

Fig. 5 shows the mockup with 5-mm Be armor. Evident in this figure are some areas of melting on the surface and also a significant transverse crack that did not impair the thermal performance of this mockup. Details will be reported in the future.

5. Concluding Remarks

The US design of ITER FW/blanket Module 18 has begun. Analyses of possible eddy currents from downward VDEs is the first major task because the configuration of the slots in the FW and shield necessary to manage the EM loads will affect the pattern of the cooling channels. A review of the conceptual design of the Mod18 FW and shield will take place before the end of 2004, and a more detailed design of the FW and shield and supporting analyses will be completed for the review.

For the US and perhaps other parties, the near term need to specify a component design, evaluate its cost and negotiate as the ITER Project evolves are strong drivers that tend to eliminate alternatives. But that breadth may be important in developing design options that take advantage of the US capabilities, such as those in plasma-spraying of Be and in precision casting. A first wall with PS Be armor, if developed, might have more resistance against cracking and allow repair rather than replacement of eroded FW panels. Near-net-shape casting of the shield might reduce machining and enable a simpler design of the cooling channels than an intersecting pattern of drilled holes. The choices to narrow scope and alternatives for Mod18 will be some of many difficult decisions as we proceed.

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Figures

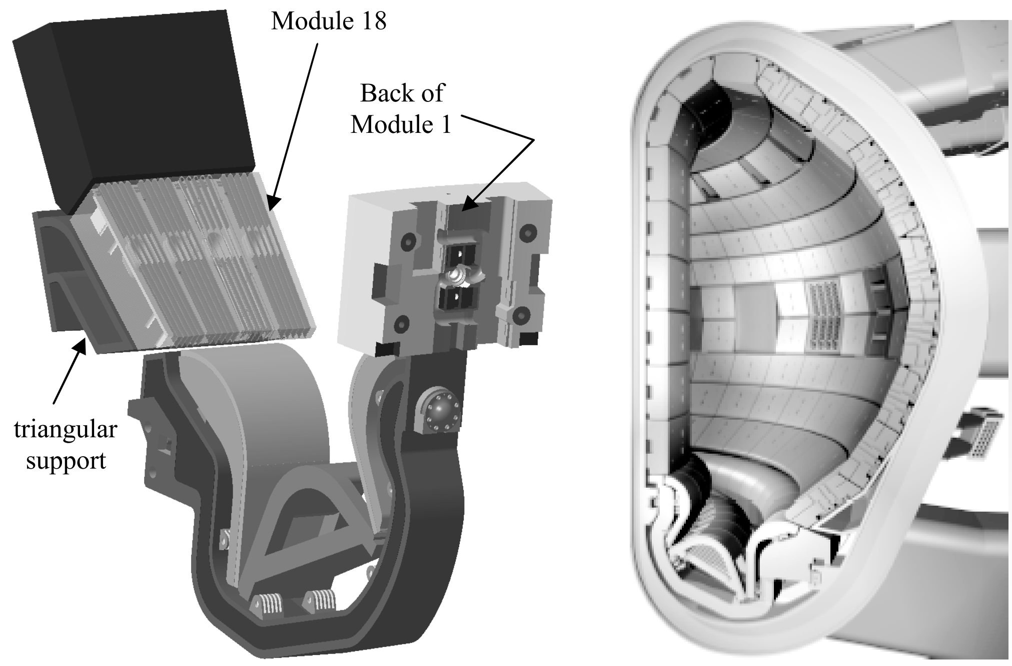

Fig. 1 CAD model of Module 18 in position above the ITER divertor segment; view is looking toward outboard face from inside.

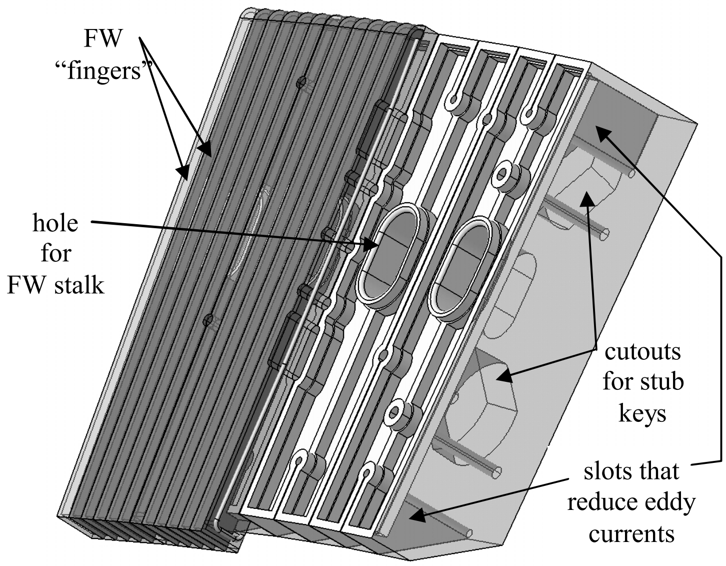

Fig. 2 Early version of Module 18 with the FW and cover plate removed over half the shield block. Semi-transparent view of shield reveals interior features.

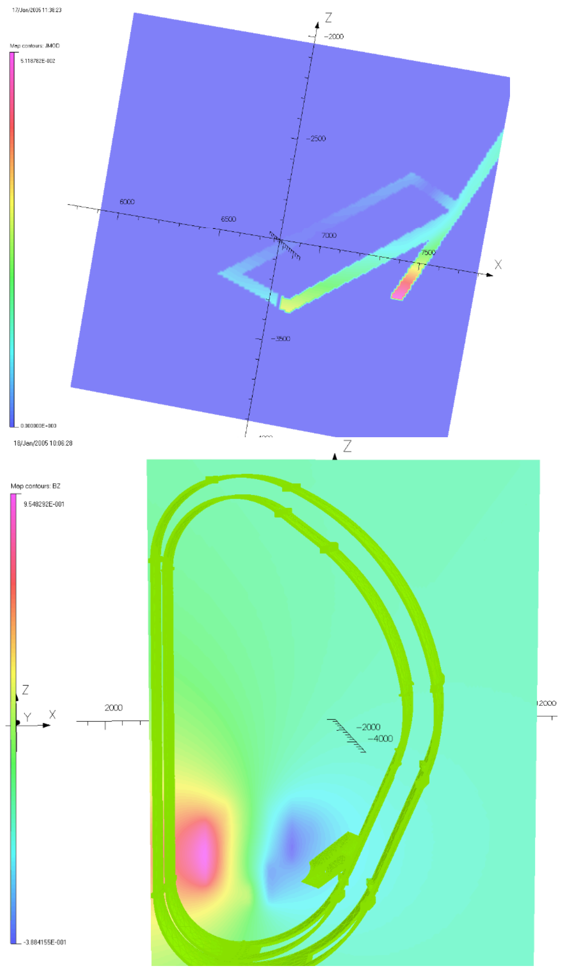

Fig. 3 OPERA model of the ITER vacuum vessel wall showing the current density in the triangular support and the Z component of the magnetic field intensity throughout the vessel.

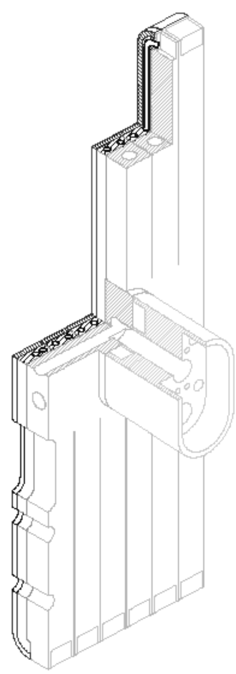

Fig. 4 Example of FW layout (for Module 11) showing cutaway view of coolant channels and stalk.

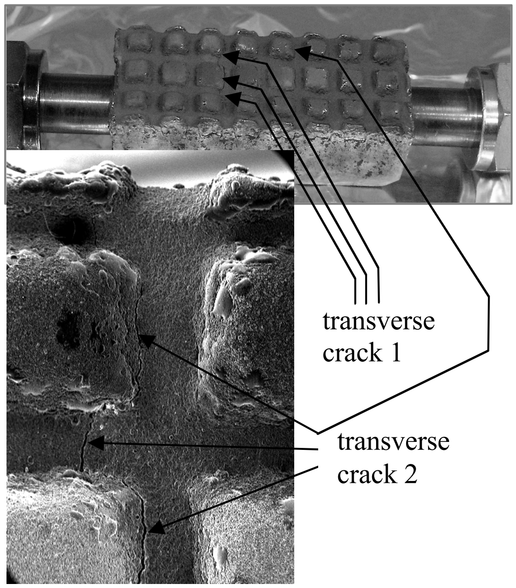

Fig 5. LANL Be-armored mockup after tests at Sandia with “beneficial” transverse cracking that relieves stress and mitigate lateral cracking within the armor and parallel to the surface of the heat sink.