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Development of a Full-Size Divertor Cassette Prototype For ITER

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Abstract

Production of a full-size divertor cassette involves eight major components. All of the components are mounted on the cassette body. Inner divertor channel components for both the vertical target and the gas box design are being provided by the Japan Home Team. Outer divertor channel components for the vertical target design are being provided by the European and United States Home Teams. Gas box liners are being provided by the Russian Home Team. The full-size components manufactured by the four parties will be shipped to the US Home Team for assembly into a full size divertor cassette. The techniques for assembly and maintenance of the cassette will be demonstrated during this process. The assembled cassette will be tested for proper flow distribution and proof of the filling and draining procedures. The testing will include vacuum leak tightness at full temperature and pressure, cyclic heating to 150°C, verification of dimensional accuracy of the assembled components, and application of thermal gradients to measure dimensional stability. The development of the divertor for the International Thermonuclear Experimental Reactor (ITER) depends on successful R&D efforts on materials, joining, and plasma materials interactions. Results of the development program are presented. The scale-up of the processes developed in the basic research and development tasks is accomplished by producing and high-heat-flux testing medium and full-scale mock-ups. The design of these mock-ups is discussed.

1. Introduction

The divertor is one of the critical heat removal systems in the ITER machine. Steady-state high heat flux in a neutron environment coupled with erosion and very large transients due to plasma current disruptions create a very challenging environment. The divertor is composed of modules (cassettes) which permit easy maintenance (see Figure 1). Beryllium, carbon-fiber composite, and tungsten are being considered for the plasma facing materials (PFM). The heat removal structures are being designed with copper alloys while the structural supports are 316 stainless steel.

The divertor task will develop, test and demonstrate the fabrication technology for the divertor and its high heat flux and plasma facing components (PFC), with particular attention to the achievement of tolerances, reliability, and maintainability. The lifetime due to disruptions and realistic estimates of tritium retention and permeation will also be established within the scope of this project. A full-size divertor cassette, including support structure (body) and PFC, is to be developed and tested in the main design task (see Figure 1). Non-destructive examination (NDE) techniques suitable for full-size components will be developed. Development of PFM and techniques for attaching the PFM to a water-cooled copper-alloy heat sink for full-size PFCs is essential for demonstrating the ability of the divertor to meet ITER heat loads. Erosion of the PFM due to normal operation or disruptions will determine the lifetime of the PFCs. The lifetime can be extended if the PFM can be repaired without removing the PFC. Development of plasma spray offers a method for such repair.

2. Design Requirements and Organization of the Work

The divertor components are to be designed for operation with 4 MPa water cooling at 140°C and a maximum flow rate of 4 m^3/s. The peak heat flux is 5 MW/m^2 on the vertical target with a peak off-normal flux of 20 MW/m^2[1]. The other components have a peak heat flux of between 2 and 6 MW/m^2. The peak neutron heating is 7 MW/m^3 in the dome. A total of 10,000 pulses of 1000 s duration are planned for the basic performance phase of operation. The divertor must be designed for halo currents and eddy currents due to disruptions. The forces exerted on the components are equivalent to about 5 MPa of pressure. Electrical connections between the vacuum vessel and the first wall shield components must be established.

The development of the divertor cassette is being shared among teams from the United States (US), Japan (JA), the European Union (EU), and the Russian Federation (RF). Each party has responsibility for one of the major high heat flux components. The EU will supply one half of the outer vertical target and one wing assembly. JA will supply one half of the inner vertical target, two inner wings, and one set of dump targets for the gas box option. The RF will supply five gas box liners to be joined to the wings and the JA gas box option. The US will supply the cassette body, one outer wing, and one half of the outer vertical target. The US has the additional responsibility for determination of the tolerances, interface control, assembly of the completed cassette, and final testing. The final

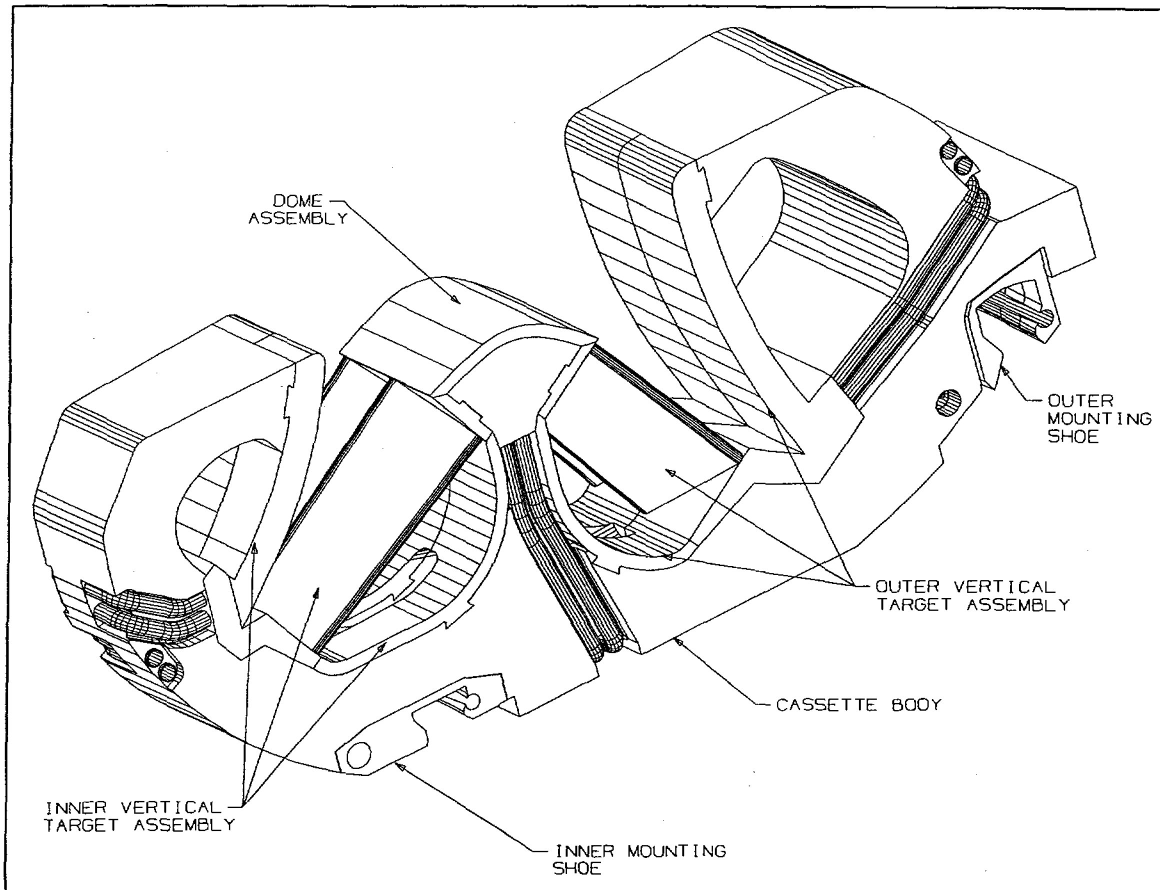

Figure 1. The ITER divertor cassette showing the subelements of the assembly, the shoes for mounting the cassette in the vacuum vessel, and some of the cooling lines.

testing will include flow testing, leak testing, verification of assembly techniques and tolerances, and proof-of-principle for remote handling. The development of the cassette is closely tied to the research tasks in the parties. The results from the research tasks are scaled to the size of the cassette in order to complete the cassette manufacturing.

3. Results of the Research and Development

3.1 European Union Home Team Results

Extensive thermohydraulics testing was performed by CEA Cadarache (FE-200) on five different heat sink schemes [2]. The results are summarized in Figure 2 for the selected ITER coolant conditions (10 m/s and 100°C subcooling). For 10mm swirl tubes (ST) with a 2mm thick swirl tape, a good agreement was found with the existing CEA database for uniform heating and incident critical heat fluxes (ICHF) of 26 and 42 MW/m^2 for uniform (100 mm heated length) and peaked heat flux (100mm heated length with a full-width at half-maximum of 45mm, about one-half of the ITER peaked profile width), respectively. For hypervapotrons (HV), a 30% higher incident-critical heat flux was found compared with the ST, but the maximum critical heat flux may be limited by the copper operating temperature or stresses. The 16mm annular flow (AF) design had performance similar to the ST. We conclude that peak transient heat fluxes up to 30 MW/m^2 could be tolerated with a 50% margin to critical heat fluxes for divertor-like peaked profiles.

The industrial development of 3D-carbon fiber composites (CFC) with and without Si doping has been completed. Characterization is in progress. For the CFC with 10% Si [3], a high thermal conductivity of 320 and 150 W/m K at room temperature and at 800°C has been measured. These materials are thermally stabile when

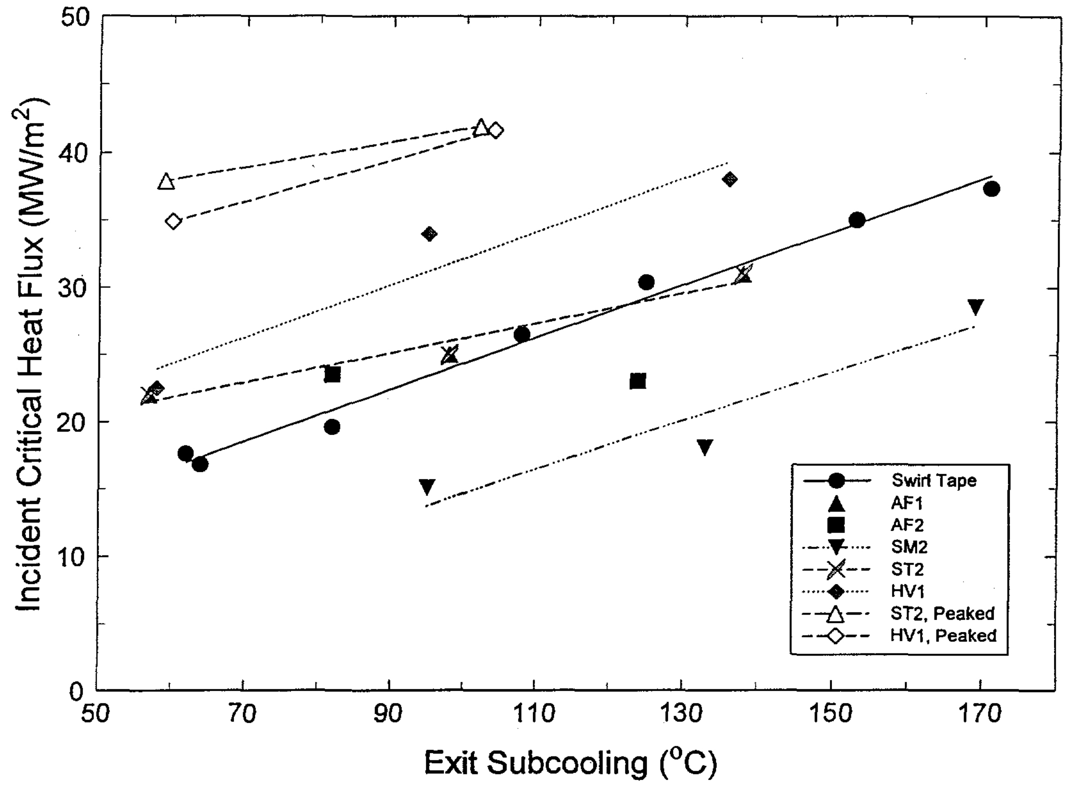

Figure 2. Results of measurements of incident critical heat flux as a function of exit subcooling (see [2]) for a variety of coolant channel designs. All the samples were 27mm wide and heated from one side with 100 mm of heated length except for the peaked profile with 23 mm. The flow velocity was 10 m/s. The samples are: (a) swirl tape is two 10mm dia. tubes with twist ratio 2; (b) AF1 annular flow channel OD=16mm, ID=11mm with twist ratio 2; (c) AF2 annular flow channel OD=22mm, ID=18.6mm with twist ratio 2; (d) SM2 is two 10mm dia. smooth tubes; (e) HV1 is a hypervapotron with a 4mm fin height and 5mm between the fin and the back of the channel and a 21mm width of fin.

heated to 1600°C for one hour. The Si containing CFC showed a reduction of chemical erosion by a factor two to three at 500°C and an order of magnitude reduction of tritium retention, outgassing, and water/air reactivity compared with CFC without Si.

More than 50 small-scale mock-ups of high heat flux components have been manufactured with CFC, Be and W-armor, CuCrZr and DS-Cu heat sinks, and several bonding techniques, primarily without silver. Brazing was mainly used for Be armor, where a monoblock mock-up survived ~150 cycles at about 10 MW/m^2 in the Joint European Torus (JET) neutral beam test facility and a flat tile mock-up survived 500 cycles at about 5 MW/m^2 in the 60 kW electron beam facility JUDITH at Kernforschungsanlage (KFA) [4, 5]. One of joining technique for the CFC tiles to the copper heat sink materials was already developed and tested on scale one prototypes for TORE-SUPRA. These elements survived several thousand cycles of heat flux testing at 15 MW/m^2 on FE-200 [6]. "Active metal casting" of a Cu interlayer was applied to CFC and W armor with subsequent brazing or electron beam welding of the armor tiles to the Cu heat sink. Several CFC monoblock mock-ups survived 1000 cycles at 20 MW/m^2 without damage in JUDITH [7]. Two mock-ups with CFC and W flat tiles are being tested in FE 200 [8]. Hot isostatic pressing (HIP) and diffusion bonding is used for all armor materials. The testing of these small scale mock-ups at up to 20 MW/m^2 is expected by October 1996 to provide the basis for the selection of the manufacturing technique and reference design for the divertor target plate prototypes. A neutron irradiation program has been carried out at High Flux Reactor (HFR) Petten[9]. Irradiation at 0.5 dpa at 350 and 700°C was completed for several different CFCs, Be and W-alloys as well as small mock-ups to be tested in JUDITH [10].

The European design of the vertical target features CFC-monoblocks in the high heat flux region for maximum lifetime and W-flat tiles on the remainder of the target. A 10mm swirl tube in DS-Cu is chosen as the heat sink in the CFC-monoblock region (ST2, see Figure 2). The target is made as an assembly of plate like modules consisting of plasma facing armor, heat sink and a thick stainless steel support.

3.2 Japanese Home Team Results

The Japanese Home Team has developed a saddle-shaped divertor mock-up with parallel cooling channels, and tested it in the Japan Atomic Energy Research Institute (JAERI). The armor tile was unidirectional CFCs and the cooling tube was made of OFHC Cu. The mock-up successfully withstood both a heat load of 5 MW/m^2 at 15 s for more than 10,000 cycles, and a heat load of 15 MW/m^2 at 15 s for more than 1000 cycles, which corresponded to heat load requirements for the normal operation and the slow transient condition of ITER, respectively [11]. Neither degradation of thermal response nor failure of the armor was found. In parallel, development of the bonding technique for 3-D CFCs brazed on a DS Cu swirl tube with a nonsilver braze has also been continued for this configuration to enhance thermal fatigue performance. Based on this encouraging result, a 1/4-width mock-up of the vertical target has been fabricated as shown in Figure 3.

Small CVD-tungsten-coated divertor mock-ups were fabricated and tested in an ion beam test facility in JAERI. The mock-up endured a heat load of 15 MW/m^2 at 0.3 s for more than 1000 thermal cycles without failure, which gives an equivalent thermal stress at the bonding interface under a steady-state heat load of 5 MW/m^2[12].

For the short dump target, the Japanese Home Team proposes to use a saddle-shaped configuration or a new configuration based on the thermal bond layer(TBL) concept proposed by the ITER Joint Central Team (JCT). A small mock-up was fabricated with a Pb-0.1Cu filler as the thermal bond layer. The mock-up endured up to 15 MW/m^2 for several cycles without degradation of thermal response[13].

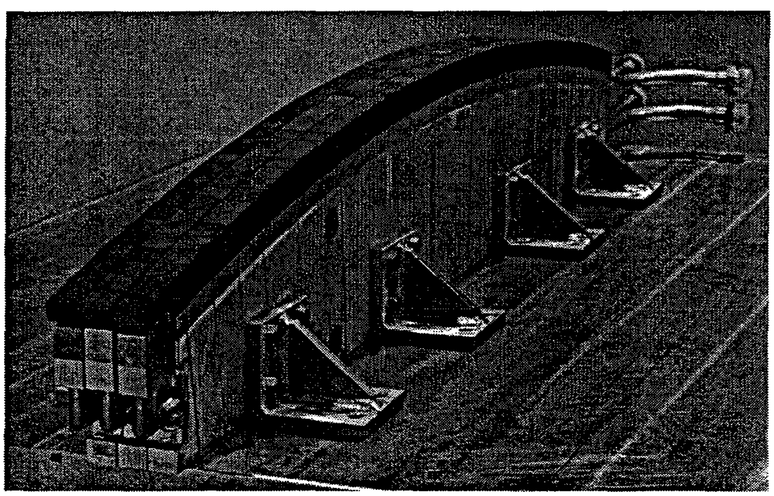

Figure 3. One-quarter-width mock-up of the vertical target. The length is 1.3 m, and the width is about 10 cm. The armor tile is unidirectional CFCs brazed on an OFHC Cu heat sink with a silver braze. The cooling tube is an OFHC Cu swirl tube.

3.3 Russian Federation Home Team Results

The gas box liners receive power from photon and particle flux that passes through the wing structures. The maximum heat load is about 1 MW/m^2. Since there are large holes in the gas box liners for the pumping ducts, they must be constructed to allow simple diversion of the coolant flow around the cutouts. The Russian Home Team is proposing the use of a structure composed of a SS backing plate covered by array of Cu-Cr-Zr rectangular beams with circular cooling channels. These beams are armored by Be-Cu or W-Cu bimetallic tiles. The coolant is routed around the cutouts by adding a duct to the edge of the panel at the cutout. Interface to wing foot is a stainless steel welded joint. Small and medium scale mock-ups will be tested to prove and optimize the choice of joining technology for Cu-Cr-Zr to Cu, Be to Cu and W to Cu.

Coating a smooth tube with a porous coating has been found to increase the critical heat flux [14]. Medium-scale mock-ups (about 1m long) are being produced with porous coatings. One sample has ribbed channels running the long direction in the heat sink with porous coating on the ribs. The second sample has two tubes with porous coating applied to the inside of the tubes. Both samples will be high heat flux tested. Samples of beryllium joined to copper have been high heat flux tested, and some samples survived for nearly 7000 cycles at 5 MW/m^2[15].

3.4 United States Home Team Results

The US has proposed that the cassette body, including the internal cooling channels, be fabricated using a cast and HIP process. Two prototype castings (475 kg each) have been fabricated using stainless steel 316LN-IG material[16]. No porosity was detected in the castings. The strength of the material was about 7% less than that of wrought 316 stainless steel (155 MPa vs. 166 MPa). The uniform elongation of the cast material is higher than wrought material (48% vs. 30%). Weld development for joints up to 100 mm thick is in progress. The next prototype will be approximately 2000 kg and contain internal coolant channels. The results thus far are very encouraging for this inexpensive method for fabricating the cassette body.

The joining of beryllium to copper alloys is particularly complicated because beryllium forms brittle berylides with most elements (including copper)[17]. Our studies have indicated the formation of copper berylides (BeCu and Be_2Cu) at temperatures as low as 350°C for times as short as 100 hrs. The use of diffusion barriers between the Be and Cu is being investigated[18]. Aluminum is one of the elements that does not form berylides. Aluminum that is explosion bonded to copper alloys and then joined to Be using an AlSi braze (including HIP) has produced very strong joints (>100 MPa) which are being tested at high heat flux. Graded layers of Al and Be are in development. They have the advantage of about three times the strength and a better thermal expansion match. High thermal conductivity and high density (>98%) beryllium coatings on copper have been made using the plasma spray method[19]. These coatings will be high heat flux tested in late 1996. The relative thermal fatigue resistance of several grades of beryllium has been measured[20].

Tungsten and copper have very different thermal expansions. Thin tapes (0.5 mm) containing 20, 40, 60, and 80% W in a soft copper matrix have been produced using either HIP or liquid-phase sintering. These tapes have been joined to each other and to W and Cu alloys using HIP at 450°C and 100 MPa. High-quality joints were found in micrographs made of the joints. Mechanical testing and high heat flux testing are in progress. Tungsten infiltrated with either Mg or Li has been proposed as an alternative to CFC in the areas likely to be hit by disruptions[21]. Samples of Li-infiltrated W are awaiting testing.

An analysis of the tolerance buildup for assembly of the divertor cassette has been completed. The dome assembly was found to have the most critical tolerances because of the need to maintain the relationship between the dome and the wing structures. The design of the cassette was modified (by widening the interface between the dome and the body) to reduce the requirements. An overall tolerance of ±1.5 mm has been adopted for the fabrication of the cassette. This keeps the heat flux peaking factor to less than 1.5.

4. Conclusions

The four parties and the JCT are cooperating effectively on the design and development of the divertor for ITER. The preliminary design phase is nearing completion. Fabrication of the full-size components will begin in 1997. The supporting research is also progressing well. The development of joints between plasma facing materials (C, Be, or W) and the copper alloy heat sink is showing that joints suitable for ITER conditions can be produced, although the reliability of these joints under cyclic loading is not yet fully demonstrated. Irradiation effects on the joints are just beginning to be studied. The scale-up of the fabrication techniques to the full ITER size is just starting. While the schedule for producing the full-size divertor cassette is very ambitious, all of the parties still believe that the goal can be achieved during the Engineering Design Activity (by July 1998). Successful completion of this project will demonstrate that the four parties can cooperate on the construction of a very complex component for ITER. Such success will provide assurance that the machine can actually be built as an international project.

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