THE ITER DIVERTOR CASSETTE PROJECT

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Abstract

The divertor "Large Project" was conceived with the aim of demonstrating the feasibility of meeting the lifetime requirements by employing the candidate armor materials of beryllium, tungsten (W) and carbon-fiber-composite (CFC). At the start, there existed only limited experience with constructing water-cooled high heat flux armored components for tokamaks. To this was added the complication posed by the need to use a silver-free joining technique that avoids the transmutation of n-irradiated silver to cadmium. The research project involving the four Home Teams (HTs) has focused on the design, development, manufacture and testing of full-scale Plasma Facing Components (PFCs) suitable for ITER. The task addressed all the issues facing ITER divertor design, such as providing adequate armor erosion lifetime, meeting the required armor-heat sink joint lifetime and heat sink fatigue life, sustaining thermal-hydraulic and electromechanical loads, and seeking to identify the most cost-effective manufacturing options. This paper will report the results of the divertor large project.

1. INTRODUCTION

The ITER divertor is an assembly of 60 separate modules or "cassettes". Segmentation facilitates the rapid exchange of the divertor. A cassette is based on a stainless steel body that performs several functions: neutron shielding, helium pumping ducts, mechanically supports and feeds coolant to the plasma facing components (PFCs). The entire cassette assembly must be capable of withstanding the thermal loads from the plasma and from the neutron flux, and the loads generated by electromagnetic forces. The divertor design that meets these requirements is described in other recent papers [1,2]. The results of the research program conducted by the four HTs (European Union (EU), Japan (JA), Russian Federation (RF) and United States (US) to demonstrate the capability to meet the requirements are summarized in this paper.

2. MATERIALS SELECTION

For the strike point regions of the PFCs, CFC is selected because it provides adequate erosion lifetime and since it sublimates it is tolerant to disruptions. W is selected for the other plasma facing surfaces where the low sputter yield of W makes it suitable in regions where erosion is dominated by sputtering by charge exchange neutrals. 3-D CFC materials are preferred to 1-D and 2-D, because of their more isotropic properties, higher thermal shock resistance, better neutron irradiation resistance and their suitability to be used in a monoblock configuration. The reference grades are SEP NB31 (EU) and NIC-01 (JA). Both grades demonstrated excellent thermal performance [3]. The baseline choice of W is powder metallurgy tungsten (pure and W-1% La_2O_3). Other grades (CVD-W, W-13I, PS W and single crystal W) are back-up. The materials program has reduced the candidate Cu alloys for the heat sink to the precipitation hardened CuCrZr and the dispersion strengthened Cu (DS-Cu) The CuCrZr alloy composition has been optimized by narrowing the Cr content and the limitation of oxygen and other impurities. The commercial DS-Cu of Glidcop Al25® has been modified CuAl25-IG (ITER Grade), to provide a better ductility at high temperature. CuCrZr is the first choice alloy because of its significantly higher fracture toughness and only if the mechanical strength of the

CuCrZr manufactured component is too low, or if the operating temperature too high, is CuAl25-IG recommended.

3. SMALL-SCALE TESTS ON CFC-CU JOINTS

More than fifteen unirradiated, small-scale mock-ups have been tested by the EU and JA using three basic geometries: flat tile, monoblock and saddleblock [3,4]. The best results were obtained with a thin pure Cu compliant layer that mitigates the effect of the large difference in coefficient of thermal expansion of the Cu heat sink and CFC armor. Testing of the small-scale mock-ups has demonstrated the feasibility of both approaches to provide a silver-free joining of CFC-Cu heat sink. However, based on all the high heat flux test results available (summarized in Figure 1), the CFC monoblock joined to a Cu alloy tube using the EU developed Active Metal Casting technique (AMC) and Ti brazing appears to be the most robust option [5,7,8] and has been selected as the reference. In addition, no failures occurred in >10 small scale mock-ups n-irradiated at 350°C to 0.3 dpa and subsequently heat flux tested in the EU at 15 MW/m^2 for up to 1000 cycles [9].

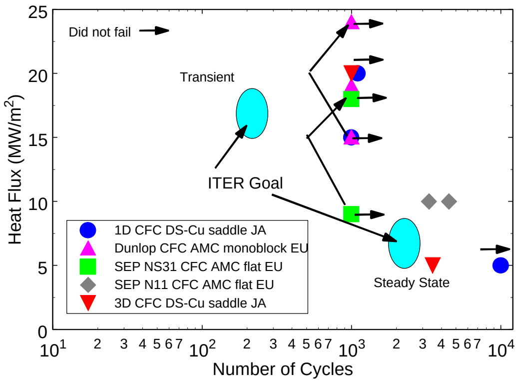

Figure 1. Results of HHF tests of the CFC-Cu actively cooled mock-ups.

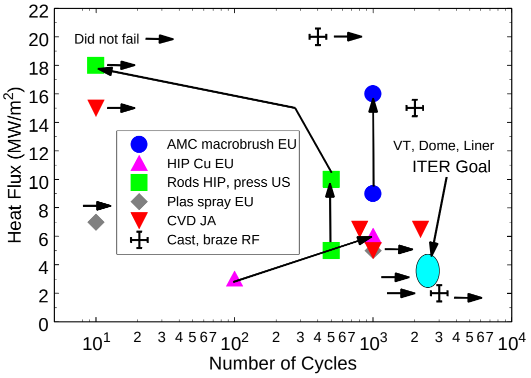

Figure 2. Results of HHF tests of the W-Cu mockups.

4. SMALL-SCALE TESTS ON W-CU JOINTS

Because of the large difference in the coefficient of thermal expansion between tungsten and Cu, new development was required for W-Cu joints for ITER. One of the more successful approaches from the EU is the use of a pure copper layer on a square tungsten brush-like structure [5]. A similar approach by the RF has had success using lamellae held in a pure Cu matrix [10]. In the US, two mock-ups with cylindrical tungsten brush armor have been built and HHF tested [11]. The JA have built and thermal fatigue tested mock-ups with 5 mm of chemical vapor deposited W (CVD-W) on both Cu and W-Cu (30%) substrates [12]. In the EU a 4.5mm thick layer of W plasma sprayed on a cylinder [13]. The achievement of HTs with the W-Cu mock-ups is summarized in Figure 2. The macrobrush has been selected as the reference tungsten armor for ITER for the upper vertical target and dome, and future R&D will focus on reducing the manufacturing costs of the brush structure.

5. CRITICAL HEAT FLUX (CHF) TESTS ON CU MOCK-UPS

The results of an extensive campaign of testing performed by the EU, supported by the US and JA, on unarmored Cu mock-ups employing typical ITER coolant parameters, show that for the maximum specified heat flux, 20 MW/m^2, a margin on the CHF limit of 1.4 is achievable by taking into account the peaked heating profile (see Table 1) [14,15,16,17,18]. In fact several of the turbulence promoters meet the requirement, however, the EU swirl tube design was adopted as the reference as it is readily adapted to the CFC monoblock.

6. MEDIUM-SCALE MOCK-UPS

An EU 0.5 m long CFC monoblock mock-up, using AMC armor joining, survived 1000 cycles at 20 MW/m^2. A vertical target mock-up being built by the EU is based on the reference materials and joining technologies based on the work described above, and will give input relevant to the manufacture of the full-scale mock-ups [19]. JA HT has fabricated several mock-ups; a mock-up with 3-D CFC joined with CuMn braze, mock-ups with both CVD-W and 1-D CFC armors joined with Ag-based braze, and 2-D CFC monoblocks bonded with Cu-Ti braze on DSCu swirl tubes. The latter mockup was tested at 5MW/m^2 for 3500 cycles and 20MW/m^2 for 1000 cycles without failure.

Table 1. CHF Limits for bare Cu heat sinks

Geometry	Uniform Flux	Peaked Flux	Pressure Drop
	MW/m^2	MW/m^2	MPa/m
Smooth Tube 10 ID (EU)	17		0.20
Swirl Tube 10 ID, Y=2 (EU)	26	36	0.75
Hypervapotron-4x3x3 mm (EU)	35	43	0.56
Annular 16 OD, 11 ID (EU)	27		1.0
Porous Coating (RF)	20		0.20

NOTE: Inlet conditions: 100°C subcooling, 4MPa, 10 m/s

7. FULL-SCALE MOCK-UPS

The JA has fabricated several full-scale mock-ups; an Ag-free mock-up with 3-D CFC joined with CuMn braze, mock-ups with both CVD-W and 1-D CFC armors joined with Ag-based braze, and mock-ups with 2-D CFC monoblocks bonded this time with Cu-Ti braze. During cyclic HHF testing of the JA vertical target mock-up employing CVD-W armor (the flat 5 mm thick CVD tiles), and a vertical target saddleblock mock-up with 3-D CFC tiles bonded with Cu-Mn braze, survived up to 5 MW/m^2, though several tiles debonded between 6–8 MW/m^2. The wing mock-up with a monoblock configuration withstood 5 MW/m^2 for 3500 cycles and 20 MW/m^2 for 1000 cycles. The RF experimented with fast brazing using resistance heating by applying current through the mock-ups and with EB heating, where the tiles are heated with a rastered electron beam in order to melt the braze alloy. For the full-scale mock-ups they have settled on resistance heating, which is applicable to both the W and beryllium armors. The EU full-scale vertical target mock-up will be built and tested in 1999.

8. CASSETTE BODY

The cassette body design has been developed based on the cast/HIP approach which is estimated to be at least 20% lower cost than the other options (welded plate build-up, HIPing of solid plates, fabrication from hand forgings, powder HIPed structure) [20]. Based on evaluation of prototype full-scale castings it appears to be unnecessary to HIP the castings in order to remove voids. The elimination of HIP means that the entire cassette body could be cast as two symmetric castings and joined by welding along the midplane. Elimination of HIP lowers the reference fabrication costs by 20% because it eliminates the four segment welds. The original intention of the task was to manufacture an entire cassette body, but reductions in the USHT budget have reduced the deliverable to an inner/center section of one toroidal half of the cassette body. The chemical composition of the cast steel meets the specification of 316L(N)-IG with minor exceptions. Mechanical properties of the cast steel meet all ITER requirements for 316LN-IG except the strength allowables are about 30% lower than wrought material at 200°C [21]. The relatively low Sm (100 MPa) has been accommodated in the design by locally thickening of the cassette body beneath the inboard gas box liner. Racetrack shaped cover plates close the water channels machined into the side of the castings, and ~ 10 km of weld will be needed to close all the channels in a complete divertor system. Cover plate welding development has shown that a controlled-root-burn-through weld can be made up to 6 mm thick with the use of penetration enhancement compounds [22]. This development has reduced the number of fill passes from 10 to 3. A full-scale body segment has been cast and pre-machined prior to adding the coolant channels.

9. INTEGRATION OF PFCS ON CASSETTE BODY

Full-scale PFCs with dummy armor are being constructed by the HTs for installation on the cassette body. The US budget reductions will allow only the inboard vertical target and dump target, manufactured by JA, to be installed. Completion of the cassette installation is scheduled in the spring of 1999. However, within the scope of the project, the EU has agreed to manufacture an outer half cassette body using a welded box structure.

10. CONCLUSIONS

Because of the R&D program, the materials and configuration of the ITER divertor has been defined. Overall the project has been a success in identifying the technologies from which suitable Ag-free divertor components can be made. Undoped, 3-D CFC has been selected for the lower vertical target of ITER and either pure or lanthanated tungsten for the other armored surfaces. For the heat sink material, CuCrZr is preferred over DS-Cu. For the highest loaded heat flux surfaces of the divertor, a CFC monoblock has been identified as the reference design. The selected joining technique of CFC to Cu is by means of AMC and brazing or diffusion bonding. A swirl tape is incorporated inside the tube of the monoblock. For the tungsten armored regions, the use of a W brush-like structure set in a pure Cu layer followed by brazing or EB welding to the heat sink is selected. It is recommended that the cassette body be fabricated from 316L(N) castings without using a HIP cycle.

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