Provisional Procurement Activity and R&D's on Divertor HHF Components in JADA

K. Ezato 1), S. Suzuki 1), Y. Seki 1), K. Yokoyama 1), M. Enoeda 1), M. Akiba 1), S. Mori 1), S. Satoh 2), M. Merola 3), M. Pick 3)

1) Japan Atomic Energy Agency (JAEA), Ibaraki, Japan
2) Kawasaki Plant Systems, Ltd., Tokyo, Japan
3) ITER organization, Cadarache Centre, Saint Paul lez Durance, France

Abstract Japan domestic agency (JADA) will procure the ITER divertor components in the cooperation with ITER organization (IO) and other DAs in EU and RF after qualification processes. In the qualification processes that started in 2007, JADA need to demonstrate our technical capability of the divertor procurement through a specific divertor mock-up, called a qualification prototype (QP), which includes most of the technical specifications of the ITER divertor and a quality assurance system of material and fabrication process is applied to it. JADA is now carrying out further provisional activity on the divertor procurement under close collaboration with IO, especially joining plasma-facing materials to heat-sink material in order to simplify the fabrication process that is more suitable for the series production of the ITER divertor components compared with the past mock-ups. The mock-up fabricated by using a new joining process shows its durability against the repetitive heat load of more than 20MW/m^2.

1. Introduction

Procurement of ITER divertor is shared with three domestic agencies, EU-, RF- and JA-DAs. Each DA will deliver its fabricated divertor high heat flux components (HHFCs) to the ITER site, Cadarache in France where the components are being integrated into 54 cassette bodies. There are three major HHFCs in the ITER divertor cassette as shown in FIG 1; the first is inner vertical target, the second is outer vertical target, and the third is dome. JADA is assigned to procure all of the outer vertical target (OVT). The OVT is designed to withstand the repetitive high heat flux up to 20MW/m^2 of 300 cycles and 10MW/m^2 of 1000 cycles. The lower and upper parts of the OVT are covered by armor tiles made of Carbon-Fiber-reinforced-Carbon Composite (CFC) and pure tungsten with a monoblock geometry pierced with the cooling tube made of Cu-alloy, CuCrZr. The high heat load region of the divertor, which corresponds to the lower part of the vertical target, is covered with the CFC, because the CFC has high sublimation temperature and high thermal conductivity more than that of pure copper. The other part is covered with tungsten which has high melting temperature and low sputtering yield. These armor materials are metallurgically bonded to the cooling tube

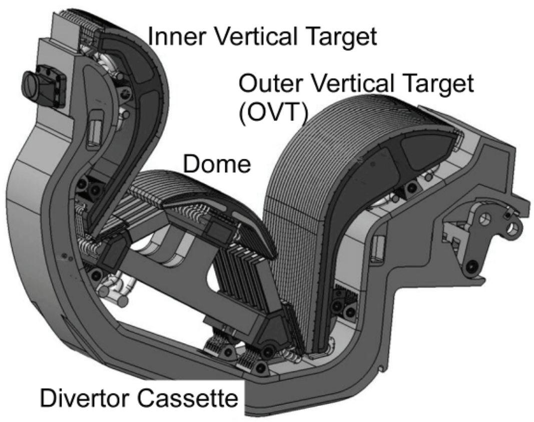

FIG. 1. ITER divertor cassette

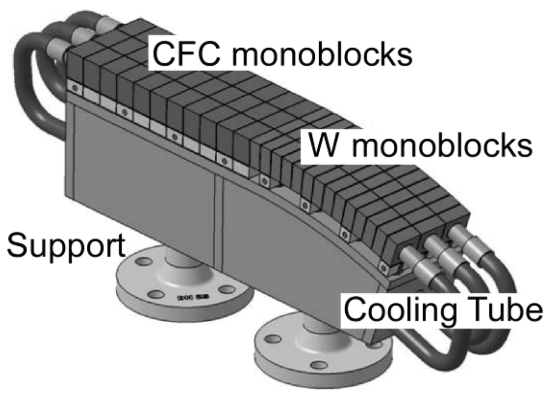

FIG 2: Qualification Prototype of vertical target with monoblock geometry

with soft copper interlayer to mitigate the interfacial stress at the bonded interface due to mismatching of the thermal expansion between the armor materials and the tube materials. The soundness of the ITER divertor components strongly depends on the quality of these bonded interfaces. A swirl tape is inserted into the tube to enhance its heat transfer capability.

Before the start of series production of HHFCs, each DA need to demonstrate its capability of fabricate HHFCs through the fabrication of a specific mock-up including most of the technical specifications, material testing and non-destructive examinations (NDEs) indispensable in the ITER divertor procurement which is called "Qualification Prototype" (QP). The specifications of QP including not only its geometry but also the grades of the materials such as chemical composition and thermo-mechanical properties has been determined after discussion between IO, material supplier and JADA and approved by IO. Especially, the grade of CFC is strictly specified regarding the fiber direction and its density. QP is designed to be examined at the same test facility and the same heat load conditions with the witnessing of IO. This test campaign will start in autumn 2008 at Efremov Institute in RF. Figure 2 shows a drawing of QPs of the inner and outer vertical targets. JADA has finalized the joining technology and process between the monoblocks and the cooling tube, which are described in the following section, to fabricate QPs. During the fabrication of QPs, two kinds of examination are indispensable as a quality assurance system. First is mechanical and metallurgical testing for all of the materials used in QPs to confirm that the materials meet the ITER specification. Second is NDE including ultrasonic and thermographic examinations to reject the HHF elements with joining defect larger than a specified size. Development of a thermographic examination system is presented in Sec. 3.

After the qualification phase, each DA finally fabricates one full-scale prototype followed by the series production of the real components. All of the series production will be checked with thermographic examination and the first several tens percents of them will be subjected to high heat load testing to confirm its heat removable capability and production yield.

2. Finalization of the joining technology

As a final demonstration of the joining technology for the fabrication of the divertor outer vertical target, divertor mockups with the same dimension of the CFC-armored straight and W-armored curved parts of QPs have been developed in JADA under close collaboration with IO and Kawasaki Plant Systems, Ltd. These mockups have been fabricated to determine the applicable joining method for the fabrication of QPs.

Figure 3 shows the overall view of the mockup with the CFC monoblocks and its dimensions. Specific feature of these mock-ups are summarized in Tab.1. The CFC material is CX2002U supplied by Toyo Tanso Co., ltd. In the QP mock-ups, the density of CFC is strictly mandated to be more than 1.65 g/cm^3 as the average value with the scatter band of ± 5% as the specifications of other thermo-mechanical properties of CFC are strictly defined. These CFC armor tiles were brazed to the soft copper interlayer collar by using the Ni-Cu-Mn braze filler with Ti-Cu metallization on their bonded surface of the CFC tiles. This Ti-Cu metallization, which has 5-10% Ti content, works not only for the improvements of the wettability at the braze interface, but also enables precise gap control between the CFC armor and the soft copper collar. The actual accuracy of the gap size was successfully kept within a range of ±5 microns to the target value even if the CFC has porous surface. Therefore it was not necessary for these mockups to be made "gauging fit" during the assembly process, which means that the manufacturing process of the outer vertical targets can significantly be simplified and be more suitable for the series production than the past [1]. The soft copper interlayer collar was also brazed to the CuCrZr cooling tube with Ni-Cu-Mn (NiCuMn37) braze filler. These braze processes were simultaneously made in vacuum environment at 980 ^{o}C followed by Ar gas quench and aging heat treatment at 480 ^{o}C for 2 hr to sustain sufficient mechanical strength of the CuCrZr cooling tube.

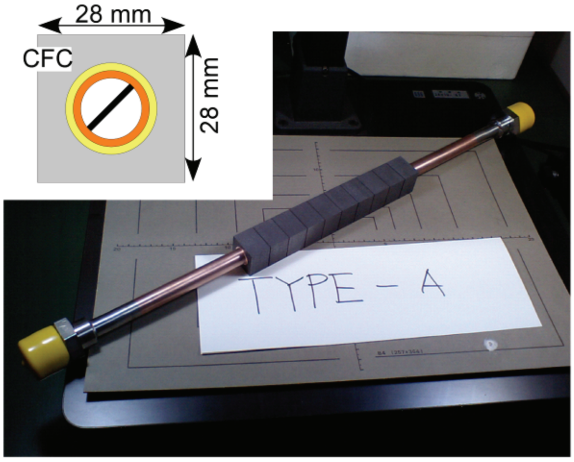

FIG. 3. Overall view of the divertor mockup with CFC monoblocks

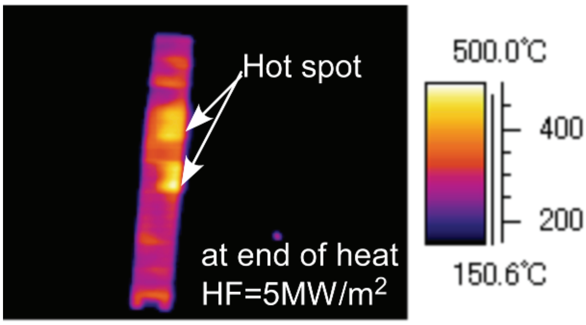

FIG. 4. Infrared image of the TYPE A mock-up with CFC monoblocks at 5MW/m^2.

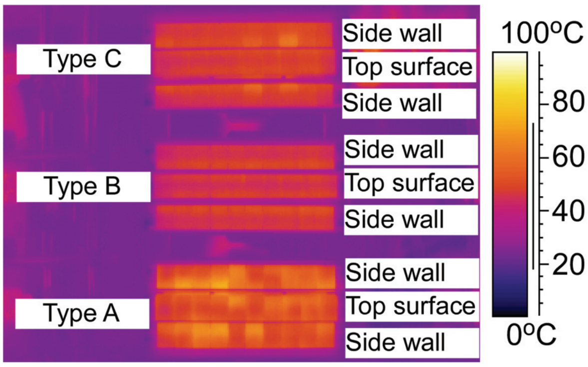

FIG. 5. Infrared image of the NDE test based on the transient thermal responses from 95^{o}C to 5^{o}C

High heat flux tests to demonstrate the thermal performance and durability of these mockups have been performed at the heat flux up to 20 MW/m^2 and more, which is equivalent to the maximum design value of the heat flux onto the CFC part of the ITER OVT, by using an electron beam test facility, JEBIS, in JAEA. The pulse duration of the electron beam is 10 s to simulate the transient heat flux injection to the ITER divertor. In the experiments, one of the mock-up (TYPE A)showed hot spots in several CFC armor tiles at even low heat flux level (= 5MW/m^2), as shown in FIG. 4. This is attributable to the initial defect at the braze interface. On the other hand, the rest two mock-ups (Type B and C) showed no hot spots in the experiment at a heat flux of 20 MW/m^2. In prior to the high heat flux experiment, a non-destructive examination (NDE) using infrared thermography method was made [2, 3]. In this NDE test, these mock-ups were kept 95 ^{o}C by using hot water flow. And then the hot water flow is switched to the cold water (5 ^{o}C) flow to observe their transient thermal response. Details of its set-ups are described in Sec. 3. Figure 5 shows the infrared image taken just after the coolant switching. Some of the CFC armor tiles of the Type A mock-up showed higher temperature than those of the Type B and C, which indicates that the Type A mock-up has initial defects at the braze interface. According to these results, more than 7.5% titanium content metallization layer is essential to obtain sound braze joint in this braze process using Nicuman37. This braze procedure is reflected to the manufacturing process of the ITER divertor qualification prototypes.

Table 1 Specific features of the divertor mock-ups with CFC monoblocks

	No. of CFC tiles	Soft Cu interlayer	CuCrZr tube	Metalization layer on CFC
Type A	10	O.D. = 18 mm I.D. =15 mm	O.D. = 15 mm I.D. = 12 mm	5%Ti-95%Cu
Type B				7.5%Ti-95%Cu
Type C				10%Ti-95%Cu

The curved mock-ups with the W monoblocks have also been fabricated and tested. The grade of W is the sintered and rolled and the orientation of its crystal grain is perpendicular to the plasma-facing surface. The overview of the mock-up with the W monoblock is shown in FIG 6. In these mock-ups, the W monoblocks are brazed with soft copper interlayer to a CuCrZr tube with the constant curvature equal to that of the QP design. The repetitive electron beam exposure to these mockups was carried out under the heat load condition at 5 MW/m^2 for 10s. In the thermal cycles test using Type 1 mock-up, in which the W monoblocks were brazed by Ni-Cu-Mn alloy, the maximum surface temperature of the tiles with the Cu interlayer with the thickness of 1.2mm was kept 560-600 ^{o}C throughout 1000 cycles, although the other tiles that has no interlayer and the interlayer with 0.8mm thickness were overheated because of the initial defect as shown in FIG 7. On the contrary this, in the Type 2 mock-up with W monoblocks brazed by the Bni-6 filler and plated Ni, the W tiles with 0.8-mm-thickness interlayer showed uniform surface temperature during the thermal cycles, although the other tiles showed overheated. From the viewpoint of simultaneous brazing process with the CFC tiles to the CuCrZr tube, the application of Ni-Cu-Mn brazing filler and the Cu interlayer with the thickness of 1.2 mm is suitable for joining the W tiles to the CuCrZr tube in JADA's QP. To demonstrate at the higher heat flux level, further thermal cycles test on the Type 1 mockup is planned to perform at $10MW/m^2$.

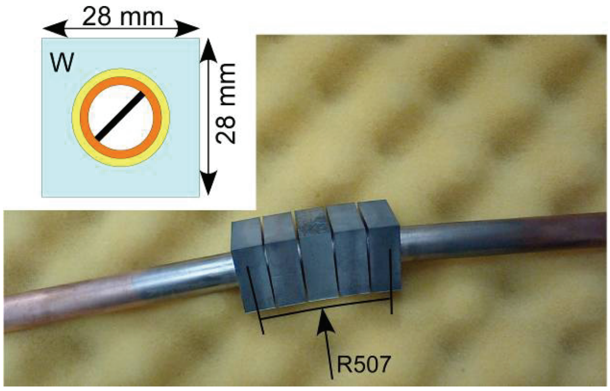

FIG 6. Overall view of the curved divertor mockup with W monoblocks.

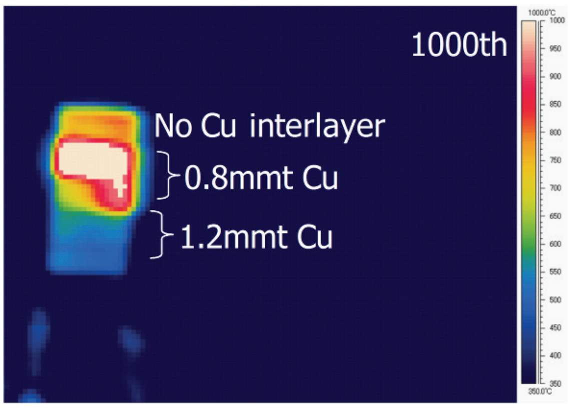

FIG. 7. Infrared image of the TYPE 1 mock-up with W monoblocks at $5MW/m^2$.

Table 2 Specific features of the divertor mock-ups with W monoblocks

Tile No.		#1	# 2	# 3	# 4	#5
Type 1	Brazing filler	NiCuMn37	NiCuMn37	NiCuMn37	NiCuMn37	NiCuMn37
	Cu interlayer	No	0.8mmt	0.8mmt	1.2mmt	1.2mmt
Type 2	Brazing filler	Bni-6	Bni-6	Bni-6	Ni-plating	Ni-plating
	Cu interlayer	No	0.8mmt	0.8mmt	1.2mmt	1.2mmt

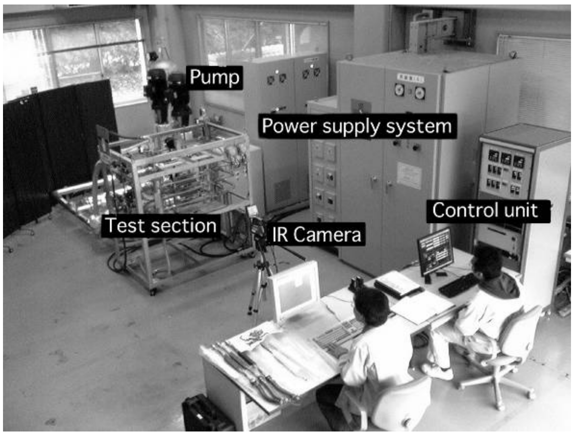

FIG 8. Overview of an infrared thermographic NDE facility

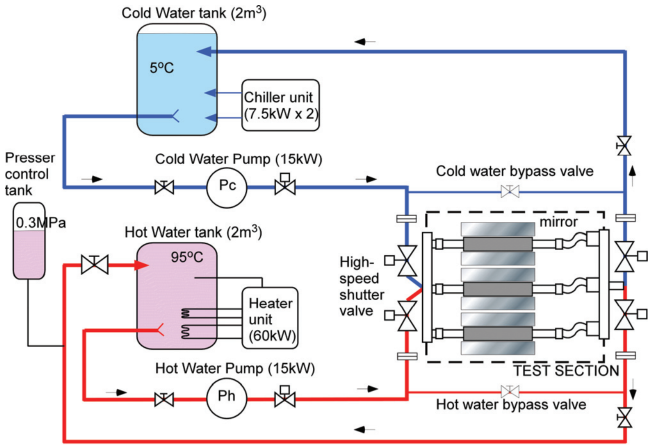

FIG 9. Diagram of Overview of an infrared thermographic NDE facility

3. Non-destructive examination (NDE)

One of the key points of the procurement of QP and OVT is a quality assurance at the joint interface especially the armor tiles. In the divertor manufacturing process, two examination methods are mainly applied; one is the infrared thermography method and the other is ultrasonic wave method.

For the application of the infrared thermography method to the divertor high heat flux components, a facility called "Facility for Infrared Non-destructive examination of Divetor" has been built in JAEA as shown in FIG 8. In this system, tested samples with the CFC armor tiles are set and keep their temperature at 95 ^{o}C to circulate hot water. The hot water circulation is switched to the cold water at 5 ^{o}C within a short time. Transient thermal responses at the surface of the tested surface is measured with an infrared camera and stored digitally. Hot and cold waters are fed by individual pump from each tank with the volume of 2 m^3. Switching from the hot water to cold water is realized by controlling of high-speed shutter valves with the operation time below 1s. Before this switching, hot water remained in the test samples are purged by air blowing in order to prevent mixing of hot and cold water during the cooling phase and to make the surface temperature responses of the test samples quick. In addition, two mirror made of stainless steel are installed in both sides of each test sample to measure three faces of the test sample at once. This makes the examination process efficient.

At the joint interfaces between metals like the soft copper interlayer and the CuCrZr cooling tube and the W armor tile and the soft copper interlayer are going to be checked by an ultrasonic wave examination method. The apparatus of the ultrasonic wave examination is prepared in Kawasaki Plant Systems, Ltd.

In the QP mock-ups, the acceptance criteria for the joint defect have been developed to ensure that the surface temperature of the tiles and the heat flux at the cooling wall would not exceed the limit values [4] with discussion between IO and JADA.

4. Concluding Remarks

JADA is now carrying out final provisional activity on the divertor procurement under close collaboration with the IO, especially joining plasma-facing materials (CFC and W monoblocks) to heat-sink material in order to simplify the fabrication process that is more suitable for the series production of the ITER divertor components. The mock-up fabricated by using a new joining process of the CFC and W monoblocks to the cooling tubes shows its durability against the repetitive heat load of more than $20MW/m^2$ for 1000 cycles in the CFC part and $5MW/m^2$ for 1000 cycles in the W part, respectively. These heat load conditions are relevant to the ITER divertor design value. Based on these promising results, JADA is now fabricating the Qualification Prototype of ITER divertor vertical target.

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