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DEVELOPMENT OF ITER DIVERTOR OUTER VERTICAL TARGET

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Abstract

A full-scale prototype of the ITER Divertor Outer Vertical Target (OVT) was successfully manufactured, and it was confirmed to meet all dimensional acceptance criteria. A highly sensitive Hot Helium Leak Test (HHeLT) facility was also developed, verifying that the OVT prototype exhibits excellent leak-tightness, $< 1 \times 10^{-10}$ Pa·m³/s. The High Heat Flux Test (HHFT) facility was upgraded to enhance testing efficiency for evaluating the heat removal capability during the series production of the OVT. With the successful completion of the prototyping phase, the series production of the OVT has now commenced.

1. INTRODUCTION

The ITER divertor consists of the cassette body and three Plasma-Facing Components (PFCs)—the outer vertical target, the inner vertical target, and the dome as shown in Fig.1[1]. National Institutes for Quantum Science and Technology (QST) as Japanese Domestic Agency (JADA) is responsible for the procurement of the OVT. The OVT is composed of two geometrically similar Half-OVTs, designated as the L-OVT and the R-OVT. Each half-OVTs consists of a Plasma-Facing Unit (PFU) and a Steel Support Structure (SSS). The OVT is designed to avoid leading edges during steady-state operation and to prevent melting under transient events, requiring stringent dimensional tolerances [2]. The plasma-facing unit (PFU) consists of a tungsten (W) monoblock with an oxygen-free copper (OFCu) interlayer, onto which an ITER-grade copper alloy tube (CuCrZr-IG) is brazed. In the target part, a swirl tape is inserted into the CuCrZr-IG tube to enhance heat removal capability. Both the PFU and SSS incorporate cooling channels and are actively water-cooled to withstand cyclic heat loads of up to 20 MW/m², necessitating a high level of leak-tightness and heat removal capability. Specifically, the leak-tightness requirement is that the leak rate shall be less than 1×10^{-10} Pa·m³/s at both room temperature and 250 °C. Regarding the heat removal performance, the target part of the PFU is required to withstand 5000 cycles at 10 MW/m² and 300 cycles at 20 MW/m². During the series production of OVT, leak testing (Hot Helium Leak Test, HHeLT) at both room temperature and 250 °C must be performed on all OVTs (100% inspection). In addition, High Heat Flux Test (HHFT), as the confirmation test of the quality of materials and heat removal capability, must be conducted on a sampling basis using test samples manufactured from the same batch as the PFUs. This paper reports the manufacturing of the full-scale OVT prototype and the development of two key test facilities, the HHeLT facility and the HHFT facility.

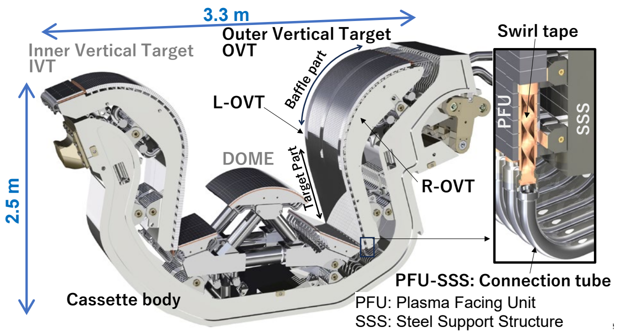

FIG. 1. The ITER divertor.

2. MANUFACTURING OF THE OVT PROTOTYPE

The OVT is among the most challenging components of the ITER in-vessel component to manufacture. Its fabrication demands advanced high-precision techniques in material processing, welding, and brazing as shown in Fig. 2. The PFU is manufactured by brazing a W monoblock with an OFCu interlayer to a CuCrZr-IG tube using a brazing filler metal (Nicuman-37). Strict dimensional tolerances are required: the inner diameter of the OFCu interlayer in the W monoblock is 15 mm +0.17/+0.15, and the outer diameter of the CuCrZr-IG tube is 15 mm $\pm$0.02. In the PFU target part, the gap between adjacent W monoblocks must be controlled to 0.4 mm $\pm$0.1. Furthermore, a swirl tape is inserted into the CuCrZr-IG tube in the target part to enhance heat removal capability. To prevent wall thinning due to fretting, the swirl tape is also subject to strict dimensional tolerances, with an outer diameter of 12 mm −0.05/−0.10. The support structure (SSS) is machined from forged austenitic stainless steel (XM-19, supplied by Daido Steel). The SSS is initially divided into seven segments for machining of the internal cooling channels, and subsequently joined into a single structure by thick-wall welding, requiring advanced welding and machining techniques. The PFU and SSS are joined by welding with SUS316L tubes, while mechanical fixation is achieved by inserting NiAlBronze pins through the PFU support legs and the SSS plugs. The SUS316L tubes have a wall thickness of 1.5 mm, demanding thin-wall welding technology.

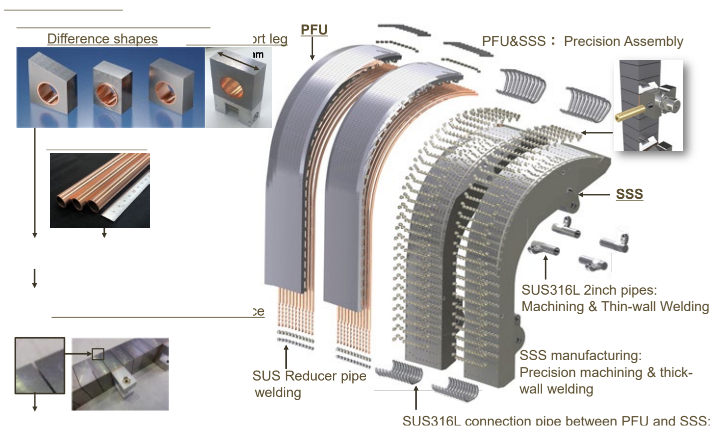

FIG. 2. Structure of the ITER divertor.

3. INSPECTION OF THE OVT PROTOTYPE

Dimensional inspection is conducted on all applicable components, while ultrasonic testing is performed at 100% coverage for thin-wall sections. Non-destructive testing methods—including PT, VT, and RT—are applied to all welds without exception. The water pressure test is carried out at 7.15 MPa for 30 minutes. Helium leak testing is performed under both cold and hot conditions, with a required leak rate of less than 1×10^{-10} Pa·m³/s in air. Visual inspection is conducted on each part, and cleanliness testing is also performed at 100% coverage. For the PFU, ultrasonic testing (UT) was performed on all brazing joints. This included 100% UT coverage of the brazed connections at both the support leg and the cooling tube. These inspections were conducted to ensure structural integrity and detect any internal defects within the joints. For the half-OVT, several functional and leak tests were carried out. A water flow test was conducted at three specified flow rates: 7.0 kg/s, 8.6 kg/s, and 10.0 kg/s. The flow rate distribution within the PFU was verified to remain within ±10% of the target values, confirming uniform coolant delivery across the component. Additionally, a Hot Helium leak test was performed under air atmosphere conditions. The acceptance criterion for this test was a leak rate of less than 1×10^{-10} Pa·m³/s, ensuring vacuum integrity and compliance with ultra-high vacuum standards. All inspections mentioned above were executed at 100% coverage, with no sampling or partial testing applied.

The combination dimensional test of OVT prototype demonstrated that the measured dimensions (e.g. the Gap and Step between adjacent PFUs of the OVT) were within acceptance range as shown in Fig. 3. All the aforementioned tests and inspections were conducted on the manufactured L- and R-OVT prototypes, and their conformity was successfully verified.

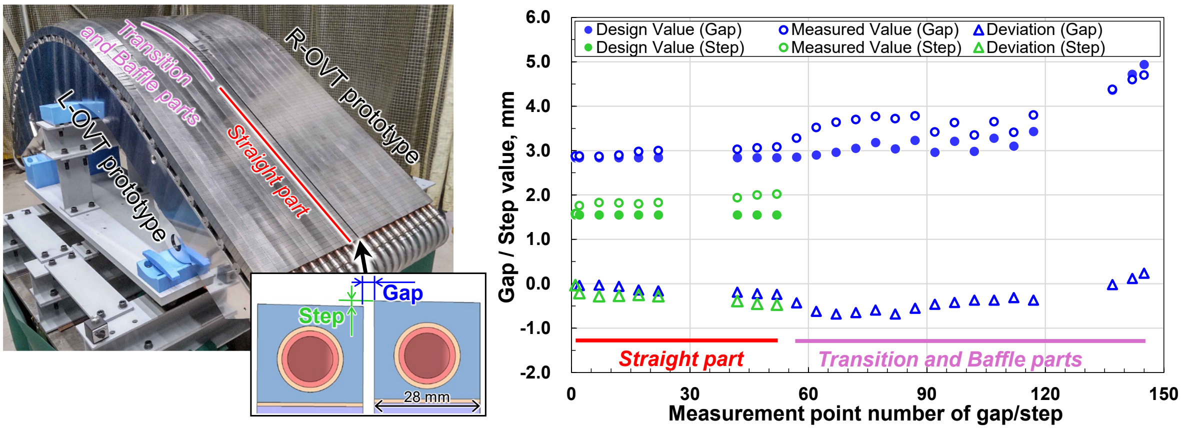

FIG. 3. The measurement result of gaps and steps between L- and R-OVT prototypes.

4. HOT HELIUM LEAK TEST FACILITY

As shown in Fig. 4, the HHeLT facility primarily consists of a vacuum chamber, vacuum pumping system, pressurization system, and heating units for temperature elevation. After installing the heating panels around the Half-OVT, as illustrated in Fig. 4, the Half-OVT is inserted into the vacuum chamber. To ensure uniform heating of the Half-OVT ($\Delta T \leq 50$ °C), the system is equipped with 30 independently controllable heaters. Nineteen thermocouples are mounted on the surface of the Half-OVT, enabling temperature monitoring at multiple locations and allowing for precise adjustment of heater output. The test procedure for HHeLT is illustrated in the Fig. 5. The test sequence comprises three leak tests. Following an initial leak test at room temperature, the Half-OVT is heated and subjected to a leak test at 250 ± 20 °C. After cooling, a final leak test is conducted again at ≤ 80 ºC. In each leak test, the Half-OVT is pressurized twice, and the presence of leakage is assessed during the second pressurization. The applied pressure is 5.0 ± 0.2 MPa at room temperature and 4.2 ± 0.2 MPa at 250 °C.

The Fig. 6 presents the temperature profile and temperature differential (maximum – minimum) during the heating of the R-OVT prototype. The target temperature differential ($\Delta T < 50$ °C) was successfully maintained throughout the heating process up to 250 °C, the leak test at 250 °C, and the subsequent cooling phase. The results of the leak tests conducted at 250 °C and after cooling are also shown in the Fig. 7. No variation in leak rate was observed even when pressurized to the specified levels, confirming the absence of leakage from the R-OVT prototype. In addition to the R-OVT prototype, the L-OVT prototype was also confirmed to exhibit a leak rate of less than 1×10^{-10} Pa·m/s at both room temperature and 250 °C.

FIG. 4. HHeLT facility and installation of heater panel

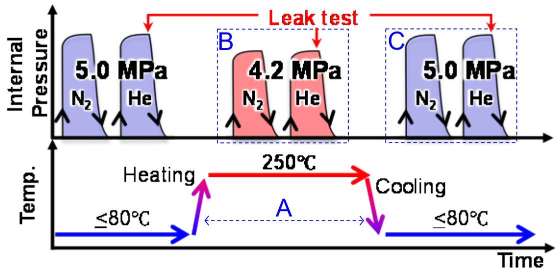

FIG. 5. HHeLT procedure

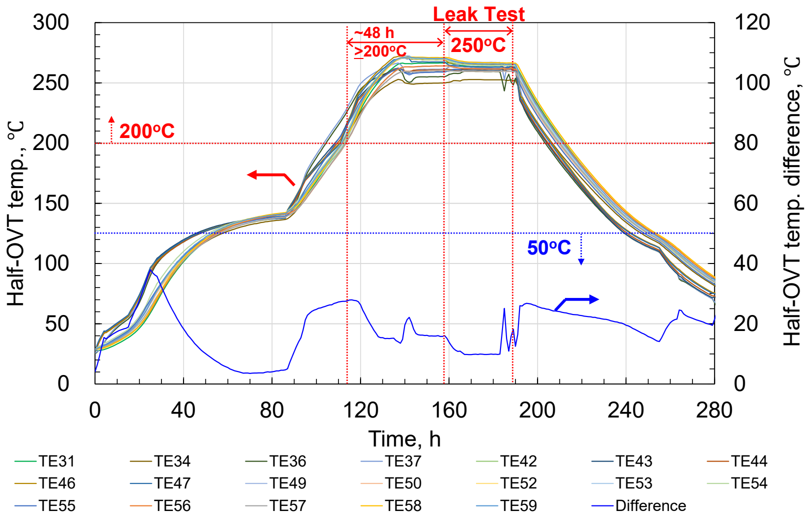

FIG. 6. Temperature history during HHeLT

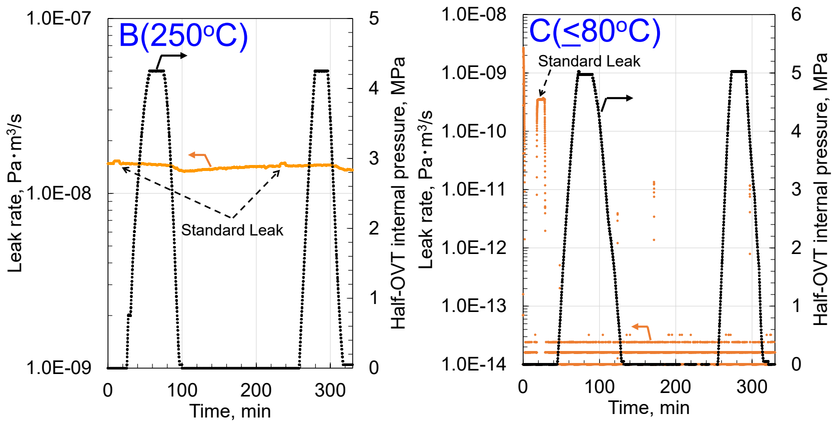

FIG. 7. Result of He leak test at 250 °C and <80 °C

5. HIGH HEAT FLUX TEST FACILITY

A cross-sectional view of the HHFT is shown in the Fig. 7. The electron gun is mounted at an oblique angle of 45 degrees. The test sample is positioned at the center of the lower part of the vacuum chamber, and the electron beam is directed onto the specimen using a 2D deflection system integrated into the electron gun and a 1D deflection system installed within the vacuum chamber. The test sample can be cooled with water at room temperature under a pressure of 2 MPa. The Fig. 8 illustrates the heat flux distribution before and after the upgrade of the electron beam gun. Previously, the heat flux tended to peak at the center of the irradiated surface. When an average heat flux of 20 MW/m² was applied across the entire surface of sample, the central region exceeded 22 MW/m², while the peripheral regions dropped to approximately 18 MW/m². Furthermore, the irradiated area was limited to around five W monoblocks (~28 × 62 mm). To conduct verification tests during the series production of OVT with both precision and efficiency, it was necessary to expand the irradiated area and achieve a more uniform heat flux distribution. Following the upgrade, the combination of the enhanced 2D deflection system and improved electron beam gun efficiency successfully flattened the heat flux distribution and doubled the irradiable area compared to the previous configuration. Regarding surface temperature measurement during HHFT, conventional methods relied on IR cameras. However, repeated heat loading altered the surface condition, leading to changes in emissivity and reduced accuracy in temperature measurement. Additionally, manual control made it difficult to perform temperature measurements for each cycle. To address these issues, a two-color thermometer system—which does not require emissivity correction—was introduced. A centralized control and data acquisition system was also developed to manage the operation of various measurement instruments and enable data collection for each cycle. These improvements have enabled high-precision and high-frequency acquisition of test data.

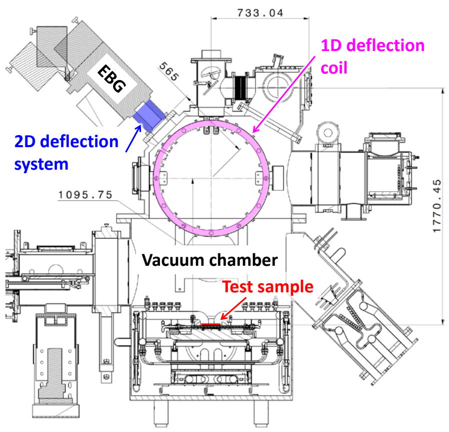

FIG. 8. Cross-section view of HHFT facility

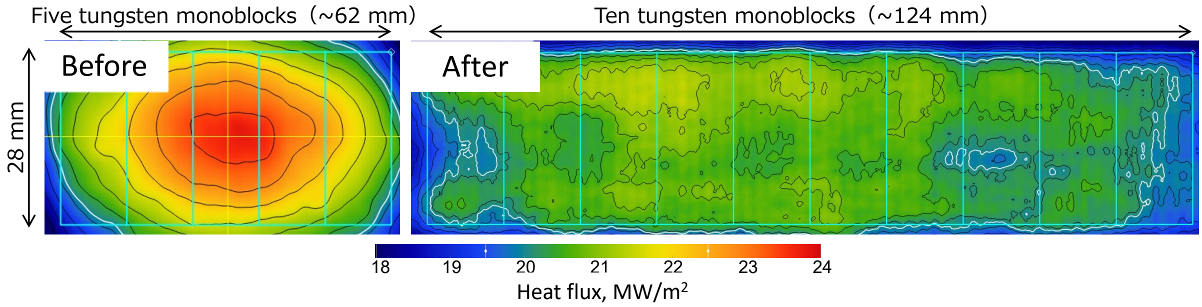

FIG. 9. Heat flux profile before and after upgrade

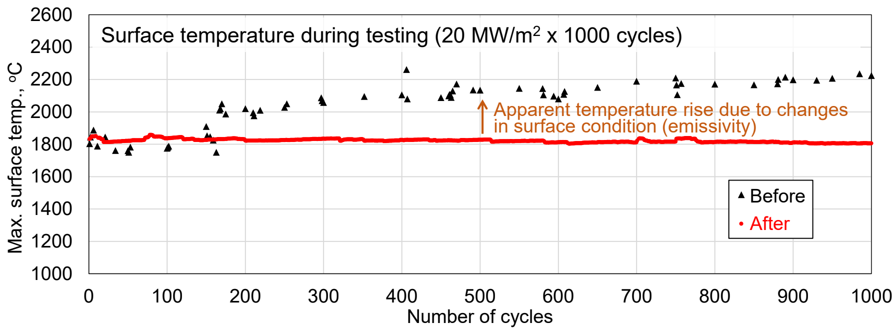

FIG. 10. Result of surface temperature measurement during HHFT (1000 cycles at 20 MW/m^2)

6. CONCLUSION

QST has successfully fulfilled all stringent dimensional tolerance and leak rate requirements specified for the OVT. In addition, the fabrication of the HHeLT and HHFT facilities—designed to evaluate the performance of the OVT—has been completed. Preparations for the seamless transition to full-scale series production of the OVT, which is currently in progress, have also been finalized.

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