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Preparation to manufacturing of ITER plasma facing components in Russia

I.V. Mazul[a,*], V.A. Belyakov[a], R.N. Giniatulin[a], A.A. Gervash[a], V.E. Kuznetsov[a], A.N. Makhankov[a], V.S. Sizenev[b]

[a] *Efremov Institute, St. Petersburg, 196641, Russia*
[b] *Corporation "Kompozit", Korolev, 141070, Russia*

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ABSTRACT

The preparation of the procurement activities for the ITER plasma-facing-components (PFC) is currently well underway. Three ITER procurement packages associated with PFCs are currently allocated to the Russian Federation (RF): delivery of the central assembly of the divertor (dome and reflector plates assemblies), delivery of 40% of the first-wall (FW) panels and high heat flux testing of divertor components during the qualification and subsequent manufacturing phases. The results of the qualification process for these tasks undertaken by RF industry are presented. Qualification mockups of the dome divertor structure were successfully manufactured in accordance with the ITER specifications and tested at heat fluxes exceeding operational ones. The maturity and reliability of the proposed design and manufacturing technologies, proposed by RF industry, was therefore demonstrated. To confirm the manufacturing readiness of technologies proposed for the fabrication of the ITER first wall, three qualification mockups were fabricated. Two were heat flux tested in two facilities abroad. In addition to launching the qualification process, the PFC team at Efremov Institute is preparing the industrial facilities for serial production of above mentioned components. A brief description of such facilities is presented in this paper, together with the manufacturing technologies to be used. Two electron beam facilities (Tsefey and IDTF) for various high heat flux testing of PFC components are also described.

1. Introduction

The ITER project has entered into the construction phase. This construction will be provided to a great extent via in-kind delivery of reactor components by countries, participating in the project. According to the project agreement, the Russian Federation (RF) in particular will be responsible for making the following contribution related to the ITER plasma-facing-components (PFC):

- Manufacturing and delivery of the divertor central assembly (dome and reflector plates).
- Manufacturing and delivery of 40% of the first-wall (FW) panels.
- High heat flux (HHF) testing of all divertor components (for all parties) during the qualification and series-production phases.

It was agreed that each country involved in the procurement of ITER PFCs, prior to signing a so-called procurement arrangement with the ITER Organization (IO) shall pass the qualification procedure in order to demonstrate its technical capability and readiness to perform the required works and meet the stringent quality specifications and the tight fabrication schedule.

The results of the preparation and qualification efforts undertaken, for ITER PFC construction, by RF industry during the years 2008–2010 are presented.

2. Description of plasma facing components

Designs of the ITER FW and divertor dome were subjected to significant changes during last two or three years [1].

Fig. 1 shows the last design version of the divertor dome, which is used as a basis in the Procurement Arrangement (PA) signed between the RF and the IO in June 2009. This divertor component consists of three plasma-facing elements (the umbrella/dome in the center of the assembly and two reflector targets/plates adjacent to inner and outer divertor separatrix zones) and the supporting/manifold structure. The plasma-facing elements are the multilayered structures consisting of tungsten armour tiles with a thin Cu–substrate, which are brazed to the CuCrZr–SS heat-sink rectangular elements with hypervapotron-type cooling channel. These elements are mechanically attached to a support structure by pins, and water connection is provided via bended tubes welded to box-like manifolds. Attachment of the dome to the divertor cassette

* Corresponding author. Tel.: +7 812 4645793; fax: +7 812 4644623.
E-mail address: mazuliv@niiefa.spb.su (I.V. Mazul).

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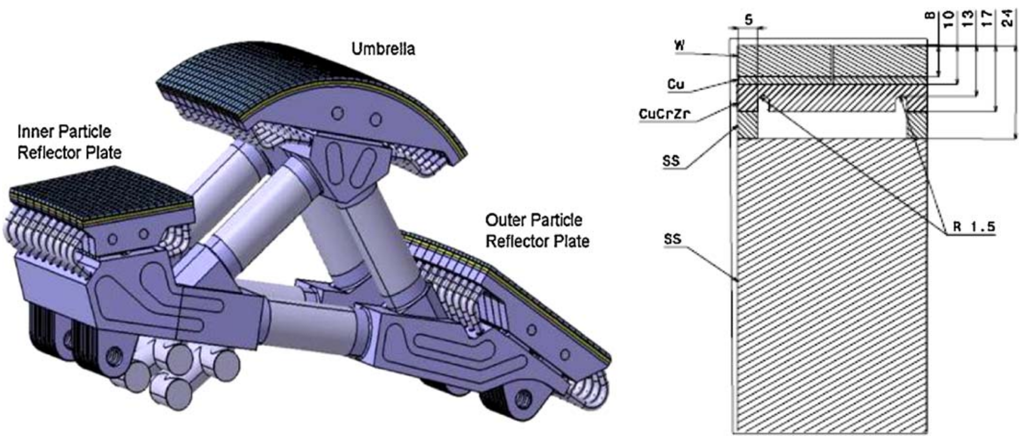

Fig. 1. Divertor dome: general view (left), cross-section of plasma facing element (right).

will be made via a pair of special links located under the divertor dome and made of steel XM-19.

Fig. 2 shows instead the cross-section of the new design option of the FW panel. It consists of a central SS beam, which serves as a support and the water manifold for a number of plasma facing elements (fingers) attached (mechanically or by welding/HIP) to this beam. Each finger is armoured on the plasma side with beryllium tiles and has two options of CuCrZr–SS cooling support. For the areas of the FW expected to be exposed to moderate heat flux loads ($\leq$2 MW/m^2) each finger has two thin-wall (1 mm) cooling SS-tubes embedded in a CuCrZr heat-sink body. For the areas of the FW expected to operate at a higher heat flux (up to 5 MW/m^2) cooling is provided by means of rectangular channels (hypervapotron-type) with a CuCrZr wall from the plasma side.

3. Manufacturing technologies and industry preparation

Because of it's long standing experience in the development and manufacturing of different fusion devices

The Efremov Institute is currently considered as the main contractor candidate for the procurement of the ITER PFC in the RF [2]. Our main strategy for industry preparation assumes:

- Organization of a complete manufacturing cycle in one place (i.e. at the Efremov Institute).
- Selection and preparation of each type of manufacturing and testing equipment by the end of 2010 to start their systematic application for the qualification phase and afterwards for the series production.

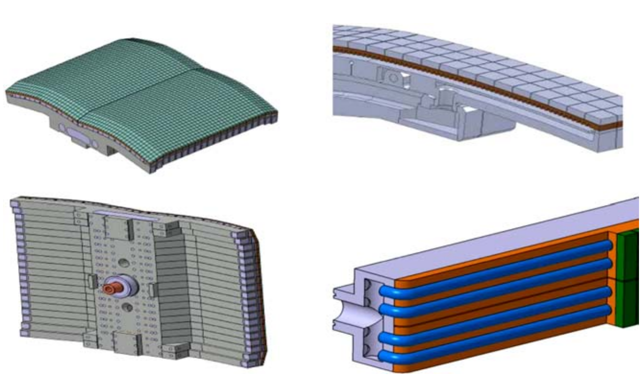

Fig. 2. New first wall design: top/bottom views of FW panel (left), two options of plasma facing finger composition (right).

- Optimization of the manufacturing cycle (reliable operation, quality control, testing procedures, operational time and cost, etc.) during manufacturing of the qualification mock-ups and full-scale prototypes.
- Multiplication/upgrading of industrial equipment (if necessary, depending on the final procurement schedule and achieved product ability of equipment) for series production, which will be started in 2013.
- Implementation of modern quality insurance system during qualification stages before serial production will be started.

For manufacturing of the PFC the following main groups of operations are necessary:

- Procurement of structural materials;
- procurement of armour materials and tiles manufacturing;
- machining of heat-sink and support structures;
- joining of different parts of components;
- staged testing of manufacturing quality and final acceptance tests.

The production of the structural (SS-316 LN-IG, CuCrZr, etc.) and the armour (W, Be) materials as well as the bimetallic SS–CuCrZr semi products will be performed outside the Efremov Institute. The fabrication of bimetallic SS–CuCrZr sheets used for heat-sink structure manufacturing will be made by explosion welding or by hipping. The fabrication of the Be-tiles (typical dimensions of rectangular tiles: 25–50 mm × 25–50 mm × 6–10 mm) will be performed in a special Be-compatible bay by an electro-discharge machine cutting from blanks of larger dimensions.

Manufacturing of W-tiles with a Cu interlayer is carried out at several stages [3]:

- W strips (dimensions: 20–25 mm × 100–150 mm × 8 mm-tile thickness) are cut with proper orientation from large rolled/forged W-sheets.
- Then a thin (2 mm thick) layer of pure Cu is casted in vacuum on one side of these strips.
- Finally bimetallic W–Cu tiles of necessary dimensions (20–25 mm × 20–25 mm × 8 mm W + 2 mm Cu) are cut from above strips by the electro-discharge machine.

Machining of heat-sink and support structure elements will be performed on modern conventional equipment at the Efremov Institute existing pilot plant.

The fabrication of hermetic box-like structures of the plasma-facing heat-sink elements and the water manifolds will be made by laser or TIG welding of SS walls with thickness varying in the

a - Electro-discharge machine b – 15 kW laser for welding c - vacuum brazing facility

Fig. 3. Some examples of technological industrial equipment selected for PFC manufacturing at the Efremov Institute: (a) electro-discharge cutting machine, (b) welding facility with ytterbium fiber laser, (c) vacuum brazing facility with fast gas quenching.

range of 5–12 mm. Welding of cooling tubes will be performed by the automatic orbital welding machine "Orbimatic".

Joining of armour tiles to a CuCrZr wall of the heat-sink structure will be made by brazing using Cu-based amorphous brazing alloys of MIFI-AMETO company (STEMET 1101 and/or 1108).

For joining of W–Cu tiles brazing is performed at ~970 °C, then brazing assembly is fast cooled in a furnace by gas quenching at cooling rate above 100 °C/s [3]. Thus, necessary strength of CuCrZr may be provided after an additional aging cycle (450 °C, 1 h) in the same furnace.

In order to prevent growth of fragile Be–Cu intermetallics when joining Be-tiles, brazing is performed at lower temperature (~780 °C) and the heating cycle in the range of 450–780–450 °C is limited to ~12 min (fast brazing). Such short brazing cycle can be provided by the above mentioned furnace or by a special furnace with direct ohmic heating of the brazing assembly [4].

Quality of welded joints is controlled by the X-ray detector while quality of brazed joints by ultrasonic inspection in a special bath with automatic scanning.

Leak tightness of the PFC is controlled by water pressure and vacuum helium leak testing. Dimensional control of assemblies is performed by the 3-D manipulator with a computer link.

Some examples of the industrial technological equipment for PFC manufacturing at the Efremov Institute are presented in Fig. 3.

4. Qualification testing of the PFC mock-ups

There are several stages of qualification testing that need to be satisfied to qualify potential candidate manufacturers. During the first stage (before signing of the PA) the adequacy and quality of manufacturing technologies proposed by each contributing Party must be demonstrated on small- and medium-scale mock-ups. During the second stage, a full-scale prototype must be fabricated after selecting the manufacturing company and only after passing the acceptance testing of this prototype the Party is permitted to start the serial production.

Following this procedure, two medium size divertor dome qualification mock-ups were manufactured at the Efremov Institute (see Fig. 4) and successfully tested in accordance with the testing specifications imposed by the IO that included:

- Inlet water temperature – 120 °C, inlet pressure – 33 atm., flow velocity – ~5 m/s:
- Absorbed surface heat flux – 3 MW/m^2, number of cycles – 1000.
- Absorbed surface heat flux – 5 MW/m^2, number of cycles – 1000.

Additionally mock-ups were subjected to extra heat loads at 10 MW/m^2 and successfully survived these loads at least for 800 thermal cycles.

As no damage of the mock-ups was detected the procurement contract on divertor dome delivery was signed. Before the end of 2011 the RF Party shall produce and test the full-scale divertor dome prototype.

As far as the FW is concerned, three qualification mock-ups were manufactured at the Efremov Institute in order to demonstrate required quality of Be–CuCrZr and SS–CuCrZr joints. Two of them were tested at two facilities in the USA (Sandia NL) and in the Czech Republic (NRI Rez) by thermocyclic thermal load according to the IO specifications.

The testing conditions were as follows:Testing at SNL (Albuquerque, USA):

- 12000 "normal" cycles (48 s/48 s) at 0.875 MW/m^2.
- 1000 MARFE cycles (20 s/20 s) at 1.4 MW/m^2

Testing at NRI (Rez, the Czech Republic):

- 12000 "normal" cycles (30 s up/120 s hold/30 s down/60 s off) at 0.625 MW/m^2

Testing at JUDITH (Juelich, Germany).

- 1000 MARFE cycles (10 s on/off period sufficient to allow the mock-up to return to initial temperature after each cycle) at 1.75 MW/m^2.

Both RF mock-ups have survived thermal cycling without any damage.

However, due to significant changes that have occurred with the FW design additional qualification tests are needed before signing the procurement contract and are being planned. In according

Fig. 4. Medium size qualification prototype of divertor dome.

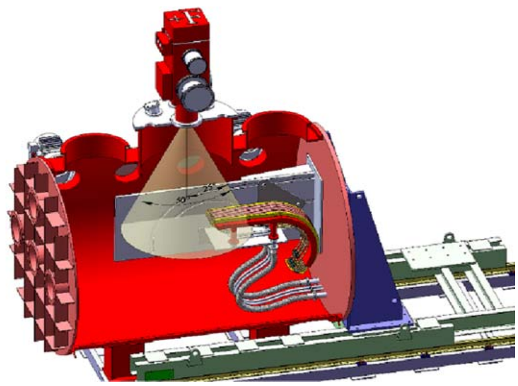

Fig. 5. IDTF testing facility: scheme of divertor target loading.

with this new qualification program RF team during 2011 has to demonstrate reliable manufacturing technology for Be–Cu mock-ups which are able to withstand thousands of thermal cycles at heat flux of 5 MW/m^2. Intention of RF team to manufacture the most loaded part of FW is based on R&D results achieved at Efremov Institute at earlier stage of ITER project. On small size mockups it was demonstrated that Be–CuCrZr compositions made by fast brazing techniques are able to withstand thousands of thermal cycles at heat fluxes exceeding 5 MW/m^2 level [5,6]. At final stage of qualification a large-scale FW semi-prototype shell be manufactured and tested by each candidate Party before the end of 2012. Then after contract signature, a full-scale prototype must be fabricated prior to start serial production.

5. Qualification and preparation of HHF testing facilities

HHF testing of representative mock-ups, prototypes and full-scale components for serial production is considered to be one of the most reliable methods to check the adequacy of the design solution and the proposed manufacturing technologies, and quality of the manufactured components (especially the joints between the armour and the heat sink). The Efremov Institute was preliminary selected on the basis of its extensive experience on this type of tests, for testing divertor components (for all parties) during the qualification and series-production manufacturing phases.

Tsefey e-beam facility at Efremov Institute is widely used for such purposes since 1994. Several internationally proved tests of PFC component mockups were performed on this facility [7]. After several upgrades currently facility has a beam power of 200 kW, maximum allowable target length of 1.0 m, hot water loop. It is compatible with Be materials/mockups.

In 2008, qualification testing of the HHF facility Tsefey was undertaken by the IO. In few months, 7 qualification divertor mock-ups coming from the RF, Japan and the EU were tested at heat loads in the range of 3–20 MW/m^2 at cooling water parameters relevant to meet ITER testing requirements. In total, more than 50,000 thermocycles were made, for a total achieved beam operation time of 450 h, showing reliability of testing equipment and satisfactory quality of testing parameters diagnostics.

In order to perform HHF testing of various divertor components at the stage of serial production another facility with a higher total power and larger test chamber is required. Such facility IDTF (see Fig. 5.) is under construction at the Efremov Institute. This facility has 800 kW electron beam (scanning frequency 10 kHz), 3 m long target chamber with inner diameter of 2.2 m, modern cooling loop with water chemistry control. The first operation of the facility is planned in March 2011.

While IDTF facility is allocated for testing of ITER divertor components, Tsefey facility is planned to be used for testing of ITER FW components (FW fingers).

6. Conclusions

Manufacturing of a significant part of the ITER PFC is planned in Russia and particularly at the Efremov Institute. During an extensive and comprehensive qualification testing phase that was conducted in 2008–2009 the following key results were demonstrated:

- The divertor dome qualification mock-ups were successfully manufactured and tested under specified heat loads testing specifications;
- the FW phase 1 qualification mock-ups were manufactured and successfully withstood thermal cyclic tests simulating ITER operational conditions for first wall area with moderate (<1.5 MW/m^2) heat loads;
- the Tsefey e-beam facility showed necessary testing regimes and operational reliability to be considered along with its personnel as base for PFC regular testing at the serial production stage;
- organization of the complete manufacturing cycle for the ITER PFC is under way at the Efremov Institute.

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