Fabrication and Testing of the EU FW Qualification Mock-up

F.Zacchia[1], B.Bellin[1], P.Lorenzetto[1], Ph. Bucci[2], PE.Frayssines[2], JM Leibold[2], B. Oresic[2], C. Thomser[3], A. Schmidt[3], M. Roedig[3], J.M. Mcdonald[4], T.J. Lutz[4], D.L. Youchison[4], M.A. Ulrickson[4], O. Zlamal[5], T. Klabik[5], V. Masarik[5].

[1)] F4E, Barcelona, Spain
[2)] CEA Grenoble, France
[3)] Forschungszentrum Juelich, Germany
[4)] Sandia NL, USA
[5)] NRI Rèz, plc, Czech Republic

Author's e-mail: Francesco.zacchia@f4e.europa.eu

Phase 1 of the qualification campaign for the ITER FW consisted of the fabrication and testing of 2 small-scale mock-ups (SSMU) - 80 x 240 mm - to demonstrate the ability of the selected fabrication technology to resist to the expected thermal loads. This paper first describes the activities performed in Europe to manufacture the EU FW SSMU. In particular, the EU-DA has manufactured and tested 2 SSMU's produced by Hot Isostatic Pressing (HIP) to bond both stainless steel to CuCrZr and then CuCrZr to Be. Manufacturing has taken place at CEA, in Grenoble. Then, this paper reports on the SSMU successfully passing the required 12000 cycles at both 0,88 and 0,625 MW/m^2 fatigue tests and the 1000 cycles of the MARFE tests at 1,75 MW/m^2, and additional tests up to 2.75 MW/m^2, fully validating HIP as a robust bonding technology for the considered FW materials. The testing campaign took place at 3 locations: the Nuclear Research Institute (NRI Rèz, plc) in the Czech Republic, the Forschungszentrum Juelich (FZJ) in Germany and Sandia N.L. in the USA.

1. Introduction

As stated in the Final Report of Negotiations on ITER Joint Implementation of 1st April 2006, a prequalification will be needed for the critical procurement packages shared by multi-Parties such as the Blanket FW. Well in advance of the assumed start of the procurement, each DA shall first demonstrate its technical capability to carry out the procurement with the required quality, and in an efficient and timely manner. For the Blanket FW system, this is achieved via a two-stage qualification process: a mock-up qualification stage and a semi-prototype qualification stage. Each stage is also split into two phases: a manufacturing acceptance phase and a High Heat Flux (HHF) testing acceptance phase.

A FW panel is an actively cooled structure constituted by a 316L(N) stainless steel, a CuCrZr copper alloy and beryllium. Different industrial processes exist to manufacture these components. Among all the available processes, the diffusion welding assisted by Hot Isostatic Pressing (HIP) has been chosen in Europe as the prime candidate solution for their manufacture following an extensive R&D programme over more than 10 years where the quality of the so obtained bonding between the FW materials was well demonstrated. In the following, fabrication and HHF testing of the mock-up finally selected by the EU is presented and results of the tests are summarised.

2. FW mock-up manufacturing

2.1. Status of bonding technology

The HIP technique presents several advantages to fabricate efficient and robust primary first wall panels. These advantages are:

- A perfect mechanical contact between the bounding materials over their whole surface in order to extract efficiently the heat produced by the plasma.
- Strong protection against water leakage during operations. Any welds required during the manufacture of the ITER PFW panels can be covered by similar material which, after being joined by HIP, offers a double containment to the water cooling circuit. In this way, no seal welds are directly in contact with the plasma.
- A small deformation of the materials when they fit well with each other. This point is particularly interesting in order to keep the position of the cooling circuit inside the materials as well as the size of the cooling pipes.
- The limitation of the reaction zone between dissimilar materials to obtain joints with good mechanical properties.

Thermal fatigue tests performed on bi-metallic joints fabricated by HIP have led to good results [1]. CuCrZr/316LN joints tested under e-beam facility withstood 1000 cycles under 5MW/m² and then respectively 267 and 76 cycles at 7MW/m2. Be/CuCrZr joints withstood 20 000 and 30 000 cycles under 0.6MW/m² without indication of failure. These results confirm that the HIP is the reference process route for the fabrication of the FW panel.

2.2. Mock-up fabrication

Material properties: The qualification mock-ups have been manufactured by using the following materials: a stainless steel ITER grade material, a CuCrZr copper alloy and beryllium S65C grade in the form of tiles. The chemical composition and mechanical properties were according to the ITER material specifications.

Fabrication of the CuCrZr/316LN support structure: The fabrication of the CuCrZr/316LN support structure begins by the machining of the CuCrZr and 316LN pieces. The geometrical size of each piece is controlled and a test assembly is performed. Then, the metallic pieces are cleaned and assembled inside the canister which is hermetically closed by TIG welding. Evacuation of the canister and leak testing is performed before the HIP cycle. The 316LN stainless steel plates, the CuCrZr alloy plates and the 316LN stainless steel cooling pipes are joined together with one single HIP cycle at 1040°C and 140MPa for 2 h. As the cooling rate inside the HIP vessel is two small, a post HIP treatment is performed on the CuCrZr/316LN structure. The solutionning heat treatment is performed by Bodycote at 980°C during 1 hour. The cooling parameters (pressure and mass flow of the gas) are selected to cool the mock-ups at a rate higher than 60°C/min (measured between 980°C and 450°C).

Fabrication of the CuCrZr/Be joint: Beryllium and the 316LN/CuCrZr structure are thoroughly cleaned before assembly. Be tiles are degreased and etched by chemical solutions. The beryllium tiles are HIPed on the CuCrZr at 580°C under 140MPa during 2 hours. After the HIP cycle, the mock-ups are machined and the water boxes are TIG welded on their cooling circuits. Figure 1 shows a qualification mock-up after the machining operations.

2.3. Mock-up in-factory acceptance testing

After the fabrication process, ITER qualification mock-ups are helium leak and pressure tested to demonstrate the integrity of the components. A second helium leak test was performed after completion of hydraulic tests. Pressure has been kept constant at 0.55MPa during 30min without indication of a leak. Ultrasonic examinations were performed with two ultrasonic transducer working at 10MHz and 20MHz show no default of the Be/CuCrZr and CuCrZr/316LN pipes joints. The minimum defect size that could be detected was 1 mm.

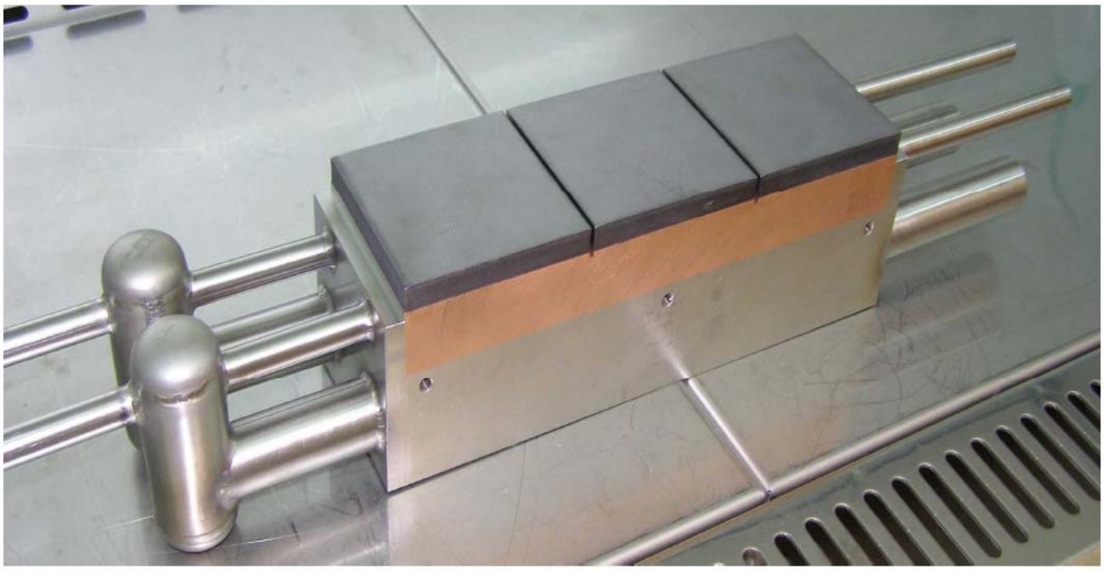

Fig.1: EU qualification mock-up after manufacturing.

3. Mock-up thermal-hydraulic simulation

Thermal hydraulic analysis of the First Wall Qualification mock-up was performed using the SC-Tetra code [2]. This was essential for the proof of the uniformity of the absorbed power because the surface temperature is not uniform with uniform heat flux. The spacing between the cooling tubes in the copper layer and the stainless steel tube lining the cooling channels both cause higher temperature in the center of the mock-up than at the edges. In addition the temperature of the cooling water increases as it passes through the mock-up. This causes the entrance end to be cooler than the exit end. Since the heat flux calibration was carried out with long pulses to assure steady state in the coolant, we performed steady state analysis in SC-Tetra. The coolant conditions were 0.3 l/s, 3 MPa, and 100 ºC inlet. Correlations were used to evaluate the heat transfer coefficients in the tubes in the copper and steel layers. The thermal properties of each of the materials (Be, CuCrZr, and 316LN SS) were fully temperature dependent. The predicted temperature rise in the water was used to adjust the power from the electron gun to achieve the desired heat flux. Figure 2 shows the predicted temperature profile on the surface of the beryllium tiles (left side) compared to the observed profile along the length of the mock-up (right side). It can be seen that the agreement between the prediction and the calculated profile is excellent. The standard deviation of the temperature on a single tile was used to set the threshold for determining if a part of a tile had de-bonded. The standard deviation in the temperature was monitored by three separate measurement area in the IR camera. If the deviation on any tile exceeded the predicted value the beam pulse would be stopped. This was to avoid losing a whole tile and to avoid excessive surface temperatures that would coat the windows due to beryllium evaporation.

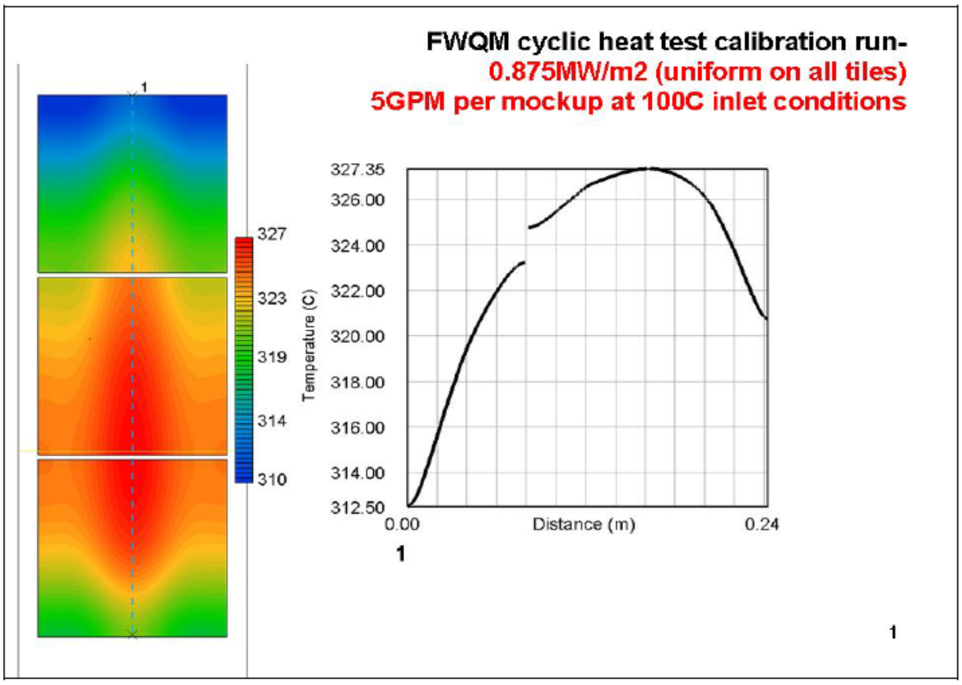

Figure 2. A comparison of calculated surface temperature distribution (left side) with measured temperature along the length of the mock-up (right side) during heat flux and uniformity calibration

4. Mock-up fatigue testing in Sandia NL

4.1. Test conditions and facility

Stage 1 consisted of tests on two mockups, one from the European Union and one from the United States placed side by side in the 1.2 MW electron beam facility at Sandia National Laboratories, see Figure 3. The heat flux cycle was based on an expected heat flux of 0.5 MW/m^2 for 100 s. Calculations on the stresses at the Be/CuCrZr interface were used to determine test conditions and a heat flux of 0.7 MW/m^2 was determined for a 48 s on/48 s off cycle.[2] The coolant conditions were 100 C water with 1 m/s flow in each tube of the mockup. The heat flux was then increased by a factor of 1.25 as a safety margin to 0.875 MW/m^2 as required by the IO. The MARFE condition was 10 s of 1.75 MW/m^2 for 1000 cycles. The equivalent cycling with equal on and off times was found to be 20 s on/20 s off with 1.4 MW/m^2. The final test conditions were up to 2.7 MW/m^2 for cycles of 20 s on/20 s off. The coolant flow was increased 4 m/s. Surface temperatures were limited to 650 °C to prevent excessive beryllium evaporation.

4.2. Diagnostics

Two FLIR SC4000 IR cameras are the primary diagnostics for this test. They measure the surface temperatures of the beryllium tiles on the mockups. Data from each camera was transferred to both IR Control and High Speed Data Recording. IR Control was set up to be able to turn off the electron gun in the case that the tiles get too hot (over 400° C) or the variance of the tile temperature is too high. Two Land Pyrometers view spots at the middle tiles. These pyrometers were also be used to trip the gun off if temperatures are too high. Three type K thermocouples were placed at the center of each tile near the beryllium to CuCrZr interface. The thermocouples were used for emissivity calibration.

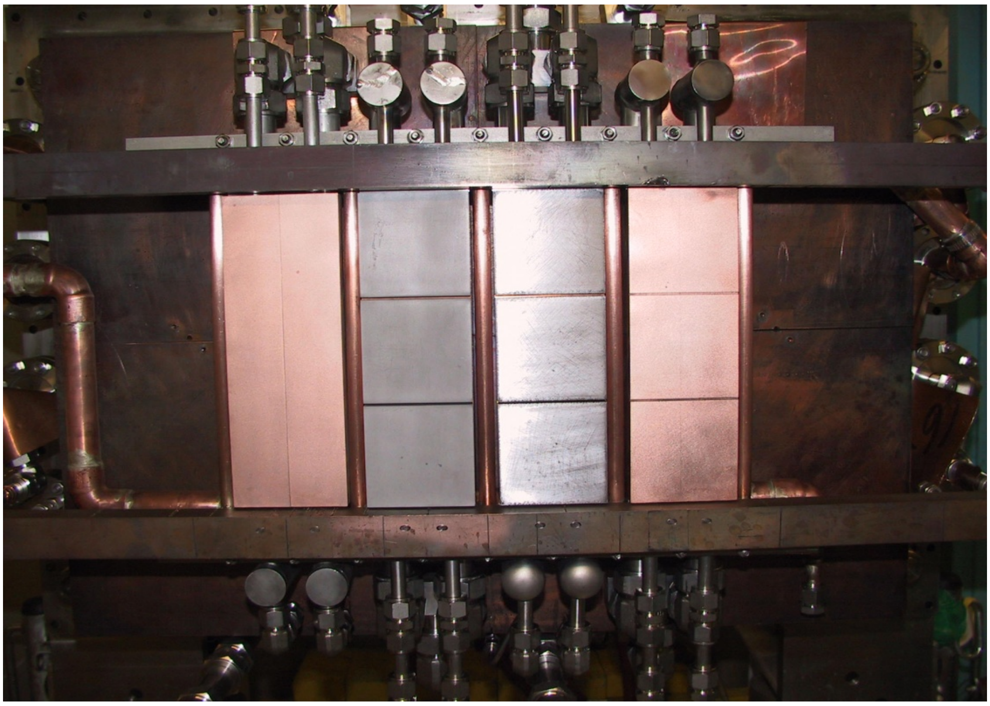

Figure 3. FW qualification mock-ups inside the US test facility, from left, copper blank, US mockup, EU mockup and copper blank.

4.3. Calibration

An emissivity map was generated to correct for the emissivity of the beryllium tiles in the IR Control software. Two images are used to correct the emissivity, one that is taken around 200-250 °C to get a baseline, and a second to create the map. The observed emissivity values were between 0.05 (polished areas) and 0.45 (discoloured areas). The map has been usually taken in the range of 300-317 °C. The mockup is heated without any coolant so that the thermocouples embedded in the beryllium tiles are the same temperature as the surface of the beryllium. A large pattern that covers both mockups is used to heat them very slowly. The combination of resistive temperature devices (RTD) and flow meters form the primary diagnostic for absorbed power calibration.

4.4. Test Results

Any significant hot spots or systematic temperature increase at constant power was noticed on the mock-ups, and the average temperatures of the tiles were less than 400 deg C throughout the normal and MARFE heating cycles. No unexpected behavior was observed during the additional high heat flux testing.

5. Mock-up fatigue testing at NRI

5.1. BESTH (Beryllium Sample Thermal) device

The BESTH device is able to provide cyclic heat flux up to 0.625 MW/m^2 by means of graphite panels and measurement of temperatures on the joint between Beryllium tiles and the CuCrZr heat sink. It consists of two cooling circuits, a heating furnace, a power supply unit, a glove box and a control desk. It is operated in a Beryllium laboratory equipped with air ventilation system with HEPA filters. The cooling is provided by a small cooling tower, located outside of testing laboratory, hence the thermal power is released to surrounding environment. Inside BESTH, two mock-ups are accommodated in the heating furnace, facing Beryllium sides. In between of them, the heating graphite panel is inserted and connected to the power supply source. The heating furnace is sealed and filled with cover gas (Helium) which assures low deterioration of graphite and high resistivity between mock-ups and heating panel. Heating cycles are generated by graphite panel; cooling of the mock-ups is supplied by cooling pipes appropriately designed to feed the mock-ups.

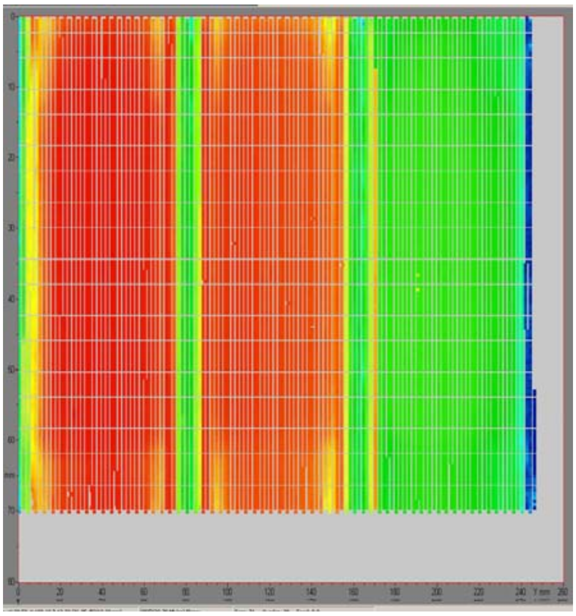

Figure 4. C-scan of the EU FW mock-up before testing in the BESTH device

Figure 5.C-scan of the EU FW mock-up after testing in the BESTH device

5.2. Mock-up testing campaign

Before testing in the BESTH device, the EU mock-up underwent non-destructive ultrasonic testing. Then, thermal fatigue testing was launched with the following parameters:

- Beryllium surface heat flux: 0.625 MW/m^2
- Cycle duration: 300 seconds
- Inlet water coolant temperature: ~100°C
- Water coolant pressure: 0.5 MPa
- Water coolant flow rate: ~1.5 m/s
- Cover gas pressure: 80 kPa

Both mock-ups were requested to reach 12 000 cycles; with 300 seconds per cycle, total testing time was estimated to 42 days. After reaching 12 000 cycles, BESTH device automatically turned off and was disassembled next day. According to the requirements stated in [2], all mock-ups must undergo two ultrasonic tests: one prior testing in BESTH device and other one after the testing in BESTH device. No significant changes were observed between first and second ultrasonic test hence the EU mock-up successfully passed the thermal fatigue test.

5.3. Test results

The heat flux was computed from water flow rate and inlet and outlet water temperature, with respective heat losses. Each beryllium tile was equipped with one thermocouple giving three measuring points on each mock-up. Both records of beryllium tile temperatures and ultrasonic inspection showed no beryllium detachment on the EU mock-up PH/S-75Qb, see figures 4 and 5, which document the Be/CuCrZr interface before and after 12 000 cycles in the BESTH device. The increase and rapid decrease of beryllium tile temperatures was caused by slow deterioration of Beryllium surface and its cleaning after the heating panel replacement. No rapid changes were observed in beryllium tile temperature behaviour.

6. Mock-up MARFE testing in FZJ

6.1. Description of test facility

The electron beam facility JUDITH-2 is placed in a hot materials laboratory in the restricted area of FZJ. The facility consists of an electron beam gun, a process chamber with vacuum system and cooling circuits and is equipped with a Electron Beam (EB) generator with a maximum beam power of 200 kW. A system of two magnetic lenses is used to focus the beam to a diameter of not smaller than 4 mm. The maximum heated area is 500 x 500 mm^2. Active cooling of mock-ups is carried out with water of 100°C, inlet water pressure of 3 MPa and a flow rate of 4m/s. The following diagnostics were installed for the tests: a) Digital infrared camera (IR camera FLIR SC6000), b) Two-colour pyrometer and c) Three thermocouples inside the three beryllium tiles of the mock-up. The following parameters were recorded electronically: Temperatures of thermocouples and pyrometer, cooling water conditions (water flow rate, inlet/outlet temperature, pressure) and IR images. The IR images were taken at the end of each heating cycle (at maximum temperature). The vacuum pressure was registered manually.

6.2. Test programme and preparation

The heat flux tests in the JUDITH 2 facility were performed in two steps, with loading conditions as follows: The surface heat load was 1.75 MW/m^2 (incident power density including effect of electron reflection effects) with a heating period of 10 s and a cool-down time of 90 s (this duration is necessary to achieve acceptable cool-down of the mock-up). 1000 cycles were performed with inlet cooling water temperature of 100°C and inlet water pressure of 3 MPa +/- 5% and a flow rate of 4 m/s +/- 5%. In order to check all systems of JUDITH 2, four heating up cycles with increased power densities at 0.5 MW/m^2, 1.0 MW/m^2, 1.5 MW/m^2 and 1.75 MW/m^2 (10 s heating period, 60 s cooling time) were performed.

6.3. Test results

The behavior of the mock-up was documented by temperature measurements and optical inspections before and after testing. The evolution of temperatures measured by the thermocamera on the surface of the three beryllium tiles and three thermocouples during the 1000 cycles of the MARFE tests is shown in Figure 6. The temperatures stayed constant during the MARFE test. After finishing the MARFE tests, additional tests at higher absorbed power density, namely 100 cycles at 2.25 MW/m^2 plus 100 cycles at 2.75 MW/m^2 were done.

After the completion of the tests at higher power densities the mock-ups were inspected again without showing any indication of failure.

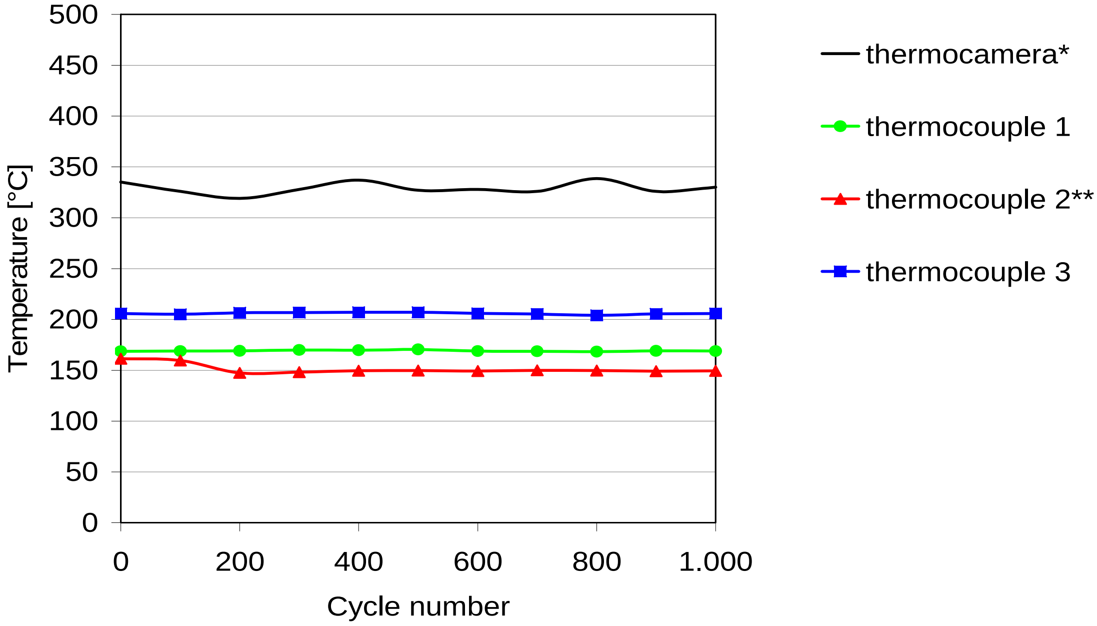

Figure 6. *Temperature development during the 1000 cycles of the MARFE tests, *average value at centre of middle Be tile with constant emissivity of 0.25, measured in calibration range of IR camera 150°C - 350°C. **thermocouple 2 seems to be not correctly connected during the MARFE tests.*

7. Conclusions

The EU-DA has been successful with Stage 1 of the ITER FW qualification programme by passing fabrication acceptance tests and subsequent high heat flux acceptance tests on the two required FW qualification mock-ups. Both were fabricated by HIP, the selected fabrication technology in the EU, and were tested up to 2.75 MW/m^2, i.e. well above the original ITER FW requirements of 0.5 MW/m^2. This shows the robustness of the proposed fabrication route, which is the achievement of an extensive R&D programme performed in the EU over more than 10 years. Discussions are on-going with the IO for the preparation of Stage 2 of this FW qualification programme which consists in manufacturing and testing larger scale FW panel semi-prototypes. The successful achievement of this Stage 2 by a DA is the prerequisite to be eligible for the procurement of the ITER FW.

Disclaimer

The views expressed in this publication are the sole responsibility of the authors and do not necessarily reflect the views of Fusion for Energy. Neither Fusion for Energy nor any person acting on behalf of Fusion for Energy is responsible for the use which might be made of the information in this publication

References

[1] P. Lorenzetto and al. “Status of the EU R&D programme on the blanket-shield modules for ITER”, Fusion Engineering and Design 83 (2008) 1015–1019
[2] Sc/Tetra code available from Software Cradle Co., Ltd., www.cradle-cfd.com
[3] Specification for manufacturing of First Wall qualification mock-ups, ITER_D_24KTBS, v2.0.