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In-pile testing of ITER first wall mock-ups at relevant thermal loading conditions

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ABSTRACT

The paper describes the experimental technique and preliminary results of thermal fatigue testing of ITER first wall (FW) water-cooled mock-ups inside the core of the RBT-6 experimental fission reactor (RIAR, Dimitrovgrad, Russia). This experiment has provided simultaneous effect of neutron fluence and thermal cycling damages on the mock-ups. A PC-controlled high-temperature graphite ohmic heater was applied to provide cyclic thermal load onto the mock-ups surface. This experiment lasted for 309 effective irradiation days with a final damage level (CuCrZr) of 1 dpa in the mock-ups. About 3700 thermal cycles with a heat flux of 0.4–0.5 MW/m^2 onto the mock-ups were realized before the heater fails. Then, irradiation was continued in a non-cycling mode.

1. Introduction

The paper presents the fourth-in-run experiment on the in-pile thermocycling tests organized and carried out in Russia by the Efremov Institute of Electrophysical Apparatus jointly with the Research Institute of Atomic Reactors. The purpose of all these experiments [1–3] was to simulate the integral and synchronous influence of neutron irradiation and thermal cycling factors of a fusion reactor on the plasma facing components. At the same time, the fourth experiment differs considerably from the previous three, which were adapted for small in size ($\sim 50 \times 22 \times 20$ mm^3) divertor mock-ups and performed in the SM high-flux reactor with radiation-driven high-*Z* heaters. The purpose of the experiment described was to test rather large and massive objects, which are the ITER FW mock-ups, making the proven and earlier applied experimental technique impractical.

2. Search for a new approach

The ITER first wall has a low level of armor segmentation because it is subjected to comparatively low heat fluxes. It means that its elementary part, taken as a testing mock-up, shall be larger. When this experiment was developed (2002), the size of one FW armor tile was assumed as $56 \times 56 \times 10$(h) mm^3. So, the experimental mock-ups were designed with a cross-section of 56×56 mm^2, about 114 mm long and were armored with two full-size beryllium tiles each (Fig. 1). These mock-ups were much larger and more massive than the previously irradiated mock-ups of divertor. Since a larger mass involves a higher bulk heat release, the FW mock-ups in a high-flux reactor would be inadequately hot. As a result, the RBT-6 (Reactor of Basin Type) low-flux mixed-spectrum reactor was chosen for this experiment. This reactor has the energy distribution similar to the SM but 15 times lower neutron density (5.6×10^{13} cm^{-2} s, $E \geqslant 0.1$ MeV). For example, irradiation of steel or copper samples for 0.1 dpa in the RBT-6 takes about 40 effective days. The proved method of reciprocally moving (into/out of the core) mock-ups with high-*Z* heaters could not be realized in this low-power reactor because of an expected insecure core reactivity.

3. Scheme and parameters of the experiment

Thus, only an electrical heater could provide the required cycling heat load. Such a heater provides for a motionless fixation of the in-pile assembly inside the core and allows for free regulation of heat flux onto the mock-ups. Heat transfer from heater to mock-ups surface could be provided by superposition of irradiative and conductive (via a thin helium gap) heat exchange. The cross-sectional view in Fig. 2 illustrates this experimental concept.

The general scheme of the experiment is given in Fig. 3. The heater is operated by a PC-controlled thyristor regulator providing the desired parameters of thermal cycling. Environment of high-purity (99.9999) helium protects the heater against oxidation and reduces its thermal erosion. Necessary water flow in cooling channels of the mock-ups is supported by an additional water pump.

The main parameters of the FW in-pile thermocycling experiment are given in Table 1 in comparison with the ITER corresponding ratings. It is seen that this experiment reproduces more or less

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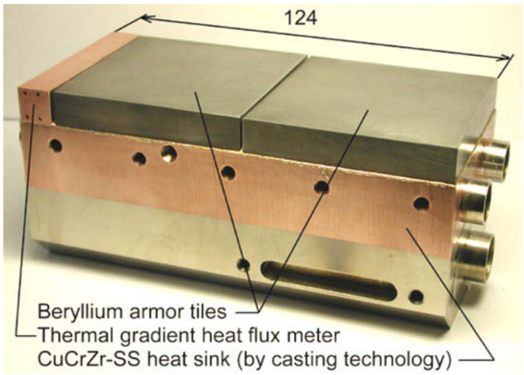


Fig. 1. One of the tested mock-ups.

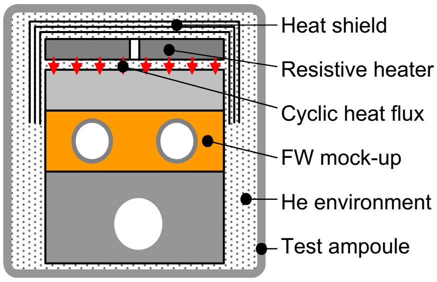


Fig. 2. The experimental concept.

adequately the main ITER factors with some deviations in the reference temperatures of the mock-ups and number of applied thermal pulses. If the first disagreement is a consequence of a lower temperature of cooling water (taken directly from the reactor basin), the number of performed cycles was non-predictably constrained by a heater failure. The final damage level of 1 dpa is certainly much less than that expected for the ITER first wall, but, on the other hand, such level corresponds to its operation years.

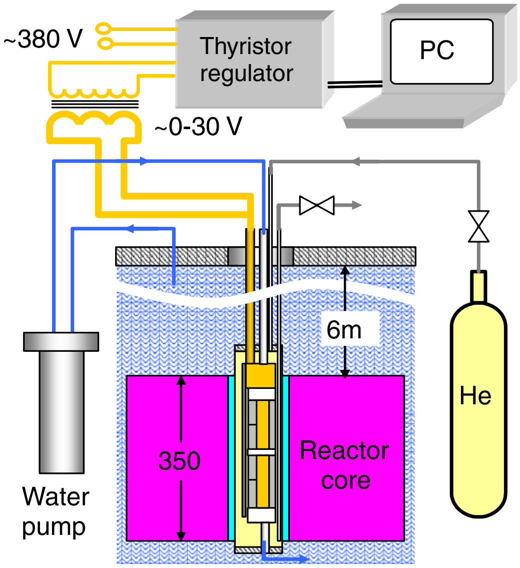


Fig. 3. General scheme of the experiment.

Table 1
Test parameters in comparison to ITER.

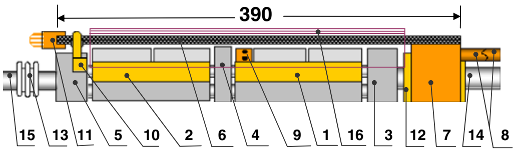
Parameter	ITER	In-pile experiment
Surface heat flux, MW/m^2	0.25/0.5	0.5
Bulk heat in steel, MW/m^3	6.5	7.2
Cooling water parameters		
P inlet, MPa	3	0.27
G, kg/s	1.2	1.3
T inlet, °C	100	40
Number of cycles	30000	20000 (planned) 3700 (in fact)
Cycle duration, s	400	320
Time in irradiation, h	3300	4800
Neutron damage (SS), dpa	2.7	1
Typical temperatures, °C		
Max. in the bulk	230	240
Surface of Be	220	140
Be/CuCrZr joint	190	110

4. In-pile assembly

Although the concept of the experiment looks quite simple, many efforts have been made to develop and manufacture the functional in-pile assembly. The severe operation regime, i.e. radiation, vibration, high-temperatures and ionized medium complicated by the cyclic duty of operation and a narrow (78 × 78 mm) in-ampoule space, required high-level reasoning of its design. On the whole, the in-pile assembly consists of 16 units (Fig. 4), each being in fact a smaller rank assembly. All these units are grouped into four major structures – 'water channel', unit of current ducts, heater unit and heat screens.

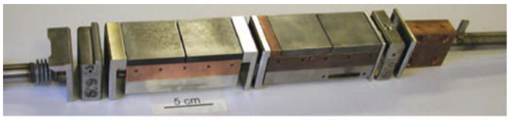
The tested FW mock-ups were manufactured by different technologies approved by ITER. One mock-up was produced at the Efremov Institute by CuCrZr/SS casting [4] of the heat sink followed by fast brazing of Be armor [5], the other by the EU Team by the HIP technology. These mock-ups welded in line with water collectors and inlet/outlet water pipes form the water channel. The inlet water pipe is provided with a cast-joined bronze block, which serves as a cooler of power contacts. The high-current electric buses are fixed on this cooler via ceramic insulation with 'papex' inserts improving the thermal contact.

The resistive heater is the most complex and important unit of the in-pile rig. After a number of out-of-pile tests of possible variants, a 7-mm-thick U-shaped graphite heater was chosen for generation of cyclic thermal load onto the mock-ups surface. The heater consists of two separate beams rigidly connected to the power supply poles and with a sliding positioning in the opposite end, where the beams are electrically connected in series by a flexible connector. The heater is positioned along the loaded surface with a nominal gap of 2.5 mm. The heater has 0-24V AC operating voltage, maximal current of 500 A, and is heated up to 1500 °C in



1- mock-up #1 (by RF team); **2**- mock-up #2 (by EU team); **3, 4, 5**- water collectors; **6**- resistive heater, **7**- bipolar power supply assembly; **8**- high-current electric buses; **9** –copper thermal gradient heat flux meter; **10**-heater support; **11**- flexible connection of the heater beams; **12** –power contacts cooler; **13**- bend/elongation compensator; **14** –water inlet; **15**- water outlet; **16**- triple heat screen

Fig. 4. Design and units of the in-pile assembly.



a. Mock-ups and water collectors before welding

b. After installation of the graphite heater

c. Fully assembled rig after out-of-pile pre-test

Fig. 5. Photographs of the assembly.

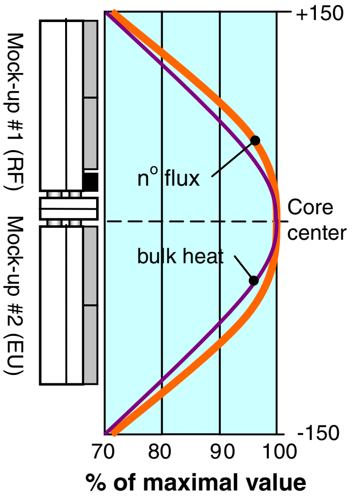


Fig. 6. Position of the mock-ups in the reactor core.

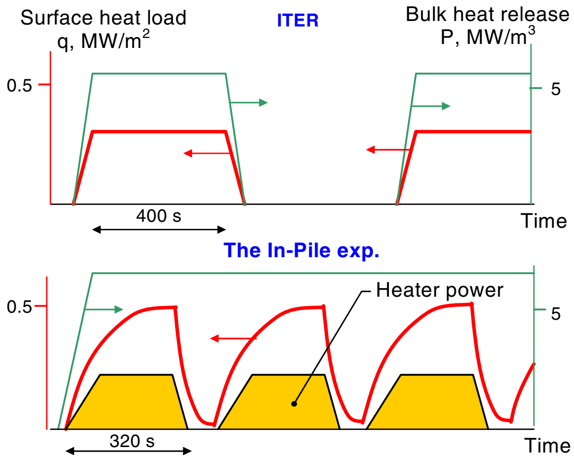


Fig. 7. Adequacy of loading conditions.

the cycle peak. The rear (faced to the ampoule wall) side of the heater is covered by a triple molybdenum heat screen.

Photographs of the in-pile assembly are given in Fig. 5. Before installation in the testing ampoule the assembly was instrumented with twelve thermocouples installed in the mock-ups, heater, meter of a heat flux and inlet/outlet water collectors. Then, the testing ampoule equipped with communication piping was sealed (welded) and placed into the reactor core channel.

5. Irradiation

Vertical positioning of the irradiated mock-ups in the reactor core is given in Fig. 6. The neutron flux and bulk heat along the assembly are not uniform, because the core is only 35 cm in height. But, in contrast to the radiation-driven heaters, the electric heater efficiency is independent of this factor, and a cyclic heat flux of 0.5 MW/m^2 was applied to the entire surface of the mock-ups. Integrated irradiation and thermal cycling loading diagrams of the test are presented in Fig. 7 in comparison with the ITER parameters.

The mock-ups were irradiated in the cycling regime 10–12 h a day on the average. At the rest (‘night’) time the heater operated in a continuous but reduced mode with a thermal load of about 0.4 MW/m^2 onto the mock-ups. Fig. 8 shows the typical temperature curves from the most important thermocouples installed in the irradiated assembly in the thermocycling mode.

Due to an open-circuit failure the heater provided 3700 thermal cycles only as against 10000–20000 planned for the experiment. The heater could not be replaced or repaired, because the operational access was hindered by the activation level of the assembly. The damage level attained by the mock-ups by this time amounted to about 0.15 dpa (CuCrZr). Therefore, the mock-ups continued to be irradiated in a steady-state non-cycling regime up to a damage level of 0.76 dpa in the Be armor (1 dpa in the CuCrZr/SS heat sink structure, respectively). Average irradiation temperatures are given in Table 2.

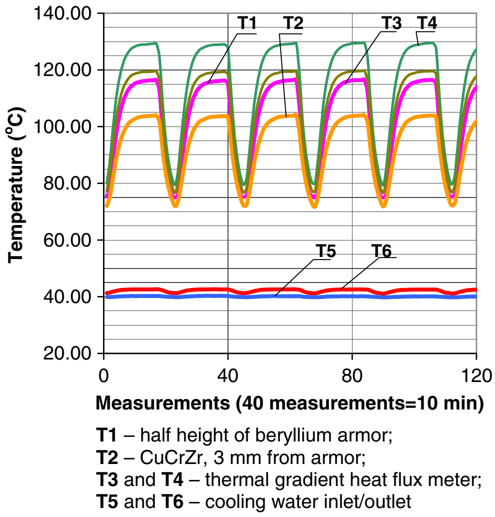


Fig. 8. Temperature graphs during in-pile cycling.

Table 2
Temperature regime in non-cycling irradiation.

Thermocouple location	Average temperature, °C
T1. Beryllium armor	68
T2. CuCrZr heat sink	67
T5. Water inlet	43
T6. Water outlet	44.5

6. Conclusions

Post-mortem inspection of the in-pile assembly has revealed a cause of the heater failure, which is an open transversal crack in one of its beams. At the same time, erosion of the heater was negligible and all the rest parts of the assembly remained intact. It may be concluded that the use of a heater made of carbon composite (CFC) might provide much better results. Softening of the cycling diagram (elongation of pulse edges and cycle duration) is likely to play a certain role, too.

General impression is that the result of this first trial on in-pile thermocycling of large-size mock-ups is positive, such experimental method can work. With this method further developed, it might be an efficient and widely accepted technique for testing of in-vessel fusion components.

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