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# High heat flux performance assessment of ITER enhanced heat flux first wall technology after neutron irradiation

T. Hirai<sup>a,\*</sup>, L. Bao<sup>a</sup>, V. Barabash<sup>a</sup>, Ph. Chappuis<sup>a,f</sup>, R. Eaton<sup>a</sup>, F. Escourbiac<sup>a</sup>, M. Merola<sup>a</sup>, R. Mitteau<sup>a,f</sup>, R. Raffray<sup>a,f</sup>, J. Linke<sup>b,g</sup>, Th. Loewenhoff<sup>b</sup>, D. Dorow-Gerspach<sup>b</sup>, G. Pintsuk<sup>b</sup>, M. Wirtz<sup>b</sup>, D. Boomstra<sup>c</sup>, C.J. Klaassen<sup>c</sup>, A. Magielsen<sup>c</sup>, J. Chen<sup>d</sup>, P. Wang<sup>e</sup>

<sup>a</sup> ITER Organization, Route de Vinon-sur-Verdon, CS 90 046, 13067 St. Paul Lez Durançon Cedex

<sup>b</sup> Forschungszentrum Jülich GmbH, 52425 Jülich, Germany

<sup>c</sup> Nuclear Research and Consultancy Group, NL-1755, LE Petten, The Netherlands

<sup>d</sup> Southwestern Institute of Physics, Chengdu 610-225, China

<sup>e</sup> China International Nuclear Fusion Energy Program Execution Center (ITER China Domestic Agency), 15B Fuxing Rd., 100862 Beijing, China

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## ABSTRACT

Eight mock-ups imitating the ITER Enhanced Heat Flux First Wall panel were subjected to thermal fatigue test after neutron irradiation at two dose levels,  $\approx 0.1$  dpa and  $\approx 0.5$  dpa. All the mock-ups successfully withstood repeated thermal fatigue loads up to  $4.7 \text{ MW/m}^2$ . The test results confirmed the performance of mock-ups in the tested condition, specifically the design and manufacturing technologies of the suppliers of two domestic agencies in charge of the series production.

## 1. Introduction

The Blanket system consists of 440 Blanket Modules (BMs). The BM consists of two main components: a first wall (FW) panel and a Shield Block. The BMs are actively cooled by water supplied by the Tokamak Cooling Water System via the Blanket Manifolds (inlet temperature  $70^\circ\text{C}$  and inlet pressure 4 MPa). Two levels of design steady-state heat fluxes lead to the selection of two types of high heat flux (HHF) technology: a “normal heat flux” (NHF) technology ( $\leq 2 \text{ MW/m}^2$ ) and an “enhanced heat flux” (EHF) technology ( $\leq 4.7 \text{ MW/m}^2$ ). All these FW panels are clad with beryllium (Be) flat tiles. The NHF FW panels that correspond to 50% of the FW panels, are to be procured by the European Domestic Agency (EU DA) whereas the EHF FW panels that correspond to the remaining 50% of the FW panels, are to be procured by the Chinese DA (CN DA) and Russian DA (RF DA) [1–3].

During the fusion power operation phase of ITER, these EHF FW panels are bombarded by energetic neutrons, maximum 1.7 dpa in Be and 4 dpa in steel, during the whole ITER life time, as well as a high heat flux up to  $4.7 \text{ MW/m}^2$  [2]. It should be noted that the FW panels are

foreseen to be replaced once in the ITER life time. Therefore, it is essential to assess the thermal performance of neutron-irradiated FW panels.

There were three HHF test campaigns of neutron-irradiated Be armoured FW mock-ups in the past. In the first campaign, a geometry with Be flat tiles bonded onto precipitation hardened Cu alloy, CuCrZr blocks, was tested [4,5]. The geometry was similar to the NHF FW finger in ITER, although the Be tile size, manufacturing technology and hydraulic design were different. In the study, the actively cooled mock-ups were tested under HHF loads at JUDITH 1 facility, Jülich, Germany [6,7] after a neutron irradiation of  $\approx 0.35$  dpa (in Be) at  $350^\circ\text{C}$  in the fission reactor HFR, Petten, the Netherlands [8]. The mock-ups consisted of beryllium armour tiles (Be grade S65C, tile size  $15 \times 25 \times 8 \text{ mm}^3$ ; CuMnSnCe and InCuSil braze filler metals) brazed on a monolithic CuCrZr heat sink block with a coolant channel (hole diameter  $D = 8 \text{ mm}$ ; with a swirl tape). The successful HHF test results at  $\approx 8 \text{ MW/m}^2$  (1000 cycles, inlet coolant water  $P = 4 \text{ MPa}$ , room temperature, 12–15 m/s) confirmed the performance of the design and technology after neutron irradiation. The second campaign was the in-pile test, a thermal fatigue

\* Corresponding author.

E-mail address: [takeshi.hirai@iter.org](mailto:takeshi.hirai@iter.org) (T. Hirai).

<sup>f</sup> contributed while affiliated at a.

<sup>g</sup> contributed while affiliated at b.

test during neutron irradiation, of actively cooled mock-ups [9]. In this study, the mock-ups were irradiated up to 0.15 dpa (in Be) in the SM-2 reactor, Dimitrovgrad, Russia. The mock-ups consisted of beryllium armour tiles (Be grade TGP-56, tile size  $10 \times 20 \times 5 \text{ mm}^3$ ; STEMET 1108 braze filler metal) and a monolithic CuCrZr heat sink block with smooth coolant channel (hole diameter  $D = 10 \text{ mm}$ ). It was a similar heat sink geometry to the NHF FW panel in ITER although the Be tile size, manufacturing technology and hydraulic design were different. It was reported that the mock-ups withstood thermal fatigue at  $7.5\text{--}8 \text{ MW/m}^2$  over 1000 cycles (inlet coolant water  $P = 5.2 \text{ MPa}$ ,  $\approx 70 \text{ }^\circ\text{C}$ ,  $\approx 8 \text{ m/s}$ ). More recently, mock-ups with beryllium flat tiles bonded by hot isostatic pressing (HIP) onto a CuCrZr heat sink block were tested in the JUDITH 1 facility after neutron irradiation of  $\approx 0.75 \text{ dpa}$  (in Be) at  $60 \text{ }^\circ\text{C}$  in the RBT-6 fission reactor in Dimitrovgrad, Russia [10]. The components consisted of HIPped beryllium armour tiles (Be grade of S65C, tile size  $56 \times 56 \times 9 \text{ mm}^3$ ), a monolithic CuCrZr heat sink with stainless steel pipes (smooth coolant channel; pipe diameters, ID/OD = 10/12 mm). These mock-ups imitated the NHF FW panel design in ITER, same key dimensions, manufacturing technology and material selection. The HNF test results confirmed the performance of this design and technology after neutron irradiation and HNF testing at  $2.4 \text{ MW/m}^2$  for 500 cycles (inlet coolant water  $P = \approx 0.4 \text{ MPa}$ , room temperature,  $\approx 2.8 \text{ m/s}$ ).

In this current study, performance of irradiated mock-ups, that imitated the EHF FW panel under thermal fatigue loads, is reported. The neutron irradiation and high heat flux testing was implemented by the ITER Organization (IO) to demonstrate the performance of ITER EHF FW panel design, manufacturing technology, material selection, after irradiation. These mock-ups were manufactured by two suppliers (SWIP, China and Efremov Institute, Russia) of two DAs which are in charge of the series production of EHF FW panels. The design contained beryllium tiles of either  $16 \times 16 \times 6 \text{ mm}^3$  bonded by brazing (RF) or  $12 \times 12 \times 6 \text{ mm}^3$  bonded by HIP (CN) a hypervapotron cooling channel structure and a bimetallic (CuCrZr and 316L steel) heat sink [11]. The detailed geometry (see Fig. 1(b)) and manufacturing routes of mock-ups were reported elsewhere [12]. After pre-irradiation thermal screening test in the electron beam test facility JUDITH 1 facility, the mock-ups were irradiated in the fission reactor HFR, at two different dose levels (four mock-ups at each dose level). The high dose level was selected at the level of  $\approx 0.7 \text{ dpa}$  in Be. This dpa level is close to the half of dpa level in

whole ITER life. Assuming the replacement of FW panels, the dpa level for Be was considered to be relevant. Furthermore, the radiation effects on mechanical properties of 316L(N)-IG and CuCrZr tend to saturate after 0.5-0.7 dpa [13,14]. Therefore, the dpa level was considered to be relevant for the assessment. These mock-ups were finally subjected to thermal fatigue loads in the JUDITH 1 facility.

$\approx 0.5 \text{ dpa}$  (in Be), 250-260  $^\circ\text{C}$  at CuCrZr part ~ Be/CuCrZr joint  
 $\approx 0.1 \text{ dpa}$  (in Be), 240-260  $^\circ\text{C}$  at CuCrZr part ~ Be/CuCrZr joint

This paper reports the neutron irradiation campaign and results of thermal fatigue testing of the neutron-irradiated mock-ups.

## 2. Pre-irradiation thermal screening tests

The 14 EHF FW mock-ups representing the key features of EHF FW panel geometry were delivered from the two suppliers. Four of the 14 mock-ups are shown in Fig. 1(a).

All the mock-ups were inspected at different manufacturing stages by non-destructive tests such as visual test, ultrasonic test for armour-heat sink joints and bimetallic joints, radiographic and/or ultrasonic test for the laser weld beads. Their leak tightness was checked by He leak test after a proof test (hydraulic pressure test at 7.15 MPa). The dimension inspection was performed during and after the manufacturing at the supplier sites to verify the required tolerances (Fig. 1(b)) as well as on receipt at the European laboratories. The Be mock-ups were transported from the supplier sites to the HNF test site, and between the HNF test site and the neutron irradiation site. The mock-ups were not delivered to the ITER site. The beryllium contamination test requirements (maximum allowable surface contamination:  $< 100 \mu\text{g/m}^2$  on the mock-up surface,  $< 10 \mu\text{g/m}^2$  on the outer packaging surface) were strictly observed. This was particularly important in view of the occupational safety.

Pre-irradiation thermal screening tests were performed up to  $4 \text{ MW/m}^2$  in JUDITH 1. Prior to the thermal screening tests, proof of flatness of heat flux profile within  $\pm 5 \%$  variation [15], proof of power density within  $\pm 5 \%$  variation by water calorimeter and temperature calibration were executed as required. The hydraulic parameters were: inlet pressure of  $1.8 \pm 0.13 \text{ MPa}$ , inlet temperature of  $22 \pm 2.5 \text{ }^\circ\text{C}$ . The mass flow rate of coolant was  $52 \pm 3.6 \text{ l/minute}$ , which corresponds to an average

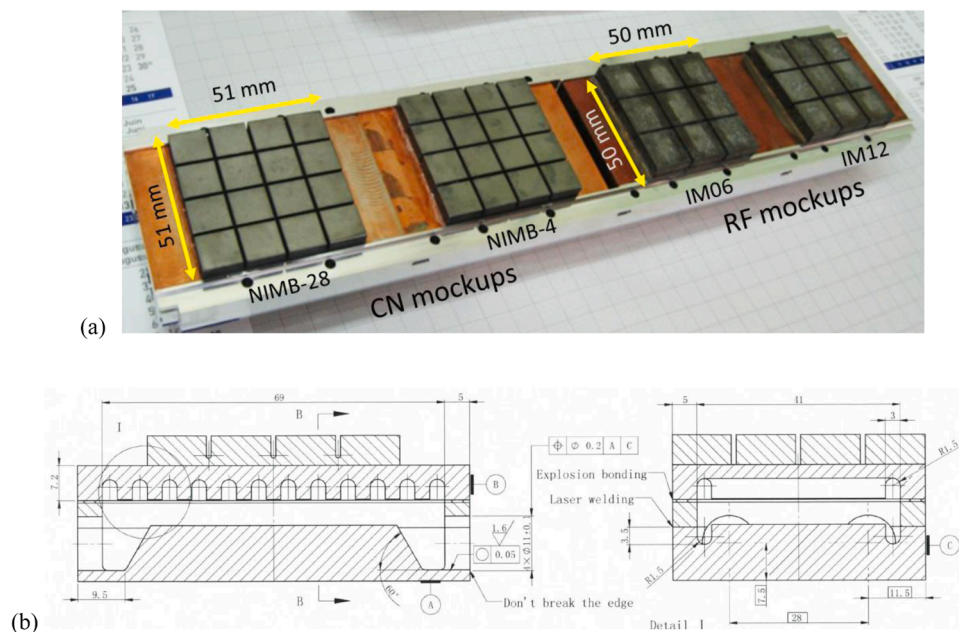


Fig. 1. (a) Photo of 4 mock-ups before irradiation. 2 CN mock-ups and 2 RF mock-ups are mounted in the aluminium blocks. (b) Drawing of an irradiation mock-up (only drawing of CN mock-up is shown).

flow velocity of 3.5 m/s in the test configuration. These hydraulic parameters were selected in the HHF tests because of technical constraints related to the cooling loop of JUDITH 1. In fact, the ITER EHF FW panels are cooled with an average flow speed of  $\approx 2$  m/s at a coolant temperature of 70°C [2]. In order to investigate the impact of mass flow rate on temperature, a dedicated flow variation test was done on one of the non-irradiated mock-ups. It revealed that the measured surface temperature under a heat load of 4.7 MW/m<sup>2</sup> was  $\approx 540$  °C and  $\approx 490$  °C at 30 l/min ( $\approx 2$  m/s) and 52 l/min ( $\approx 3.5$  m/s), respectively [16]. According to FEM modelling, benchmarked with the flow variation tests, the temperatures at the Be-CuCrZr and CuCrZr-steel joints were  $\approx 54$ °C lower in the HHF test conditions than they would be under the relevant hydraulic parameters at 4.7 MW/m<sup>2</sup>. The temperature achieved at the joints during the HHF tests is comparable to the one at a heat load of 3.4 MW/m<sup>2</sup> if the relevant cooling conditions would have been used [16]. HHF tests under these relevant cooling conditions would be desirable, however currently no HHF facility with the relevant cooling conditions was available for the neutron irradiated components.

The thermal screening test is to examine the thermal response of each tile at a fixed power density to compare with other screenings. This test is performed at every step, e.g. before and after neutron irradiation, before and after thermal fatigue. The surface temperature evolution under step-wise increase of the heat load was monitored by infrared (IR) camera (Fig. 2). Degradation can be detected as higher surface temperature (overheating) and longer cool down time of tiles after loading. At this test, the strength of joints under thermal stress induced by surface heat flux would be examined.

In the pre-irradiation thermal screening test, no notable joint imperfection was found. These results confirmed the inspection results of the armour-heat sink joints at the supplier sites. All the mock-ups were acceptable for neutron irradiation. Eight mock-ups (4 mock-ups from the CN supplier and 4 mock-ups from the RF supplier; see mock-up ID in the Table 1) were selected to be irradiated in the HFR. Importantly, the leak tightness of mock-ups to coolant connection of JUDITH 1 facility was verified during the pre-irradiation thermal screening tests. Furthermore, the minimum duration to reach thermal steady state both during heating and cooling phases was found to be  $\approx 25$  s. Based on that the duration for a cycle in the thermal fatigue test was decided to be 60 s (30 s heating and 30 s cooling).

### 3. Thermal fatigue test for non-irradiated mock-ups

Thermal fatigue test is to examine the fatigue performance of the joints under repeated surface heat loads. In this test, the surface temperature is monitored to detect evolution of thermal response during cyclic loads.

To confirm the thermal fatigue performance of the as-manufactured state, two non-irradiated mock-ups from each supplier (the mock-up IDs: NIM31 and IM01) were subjected to thermal fatigue loads (30 s on/ 30 s off) in the JUDITH 2 facility [17] with exactly same cooling parameters (see Section 2). Both mock-ups withstood the thermal fatigue loads at 4.7 MW/m<sup>2</sup> for 2500 cycles without indication of degradation. This result verified the performance of the design and manufacturing technology at the non-irradiated state.

## 4. Neutron irradiation in fission reactor

### 4.1. Preparation of neutron irradiation

Neutron irradiation was executed in the fission reactor HFR in Petten. The fission neutron irradiation were considered to be relevant in terms of radiation damage in dpa despite the difference between fusion and fission neutron energy spectra. As shown in Fig. 1, one irradiation capsule contained 4 mock-ups. The 4 mock-ups were mounted in the aluminium blocks which filled the space in the capsule and accommodated the mock-ups and instrumentations in the capsule. Additionally

nine beryllium tiles ( $16 \times 16 \times 6$  mm<sup>3</sup>) were included in the capsule (not shown in Fig. 1). These tiles were placed on the CuCrZr parts between Be armoured parts of two mock-ups and imitated continuous beryllium tiles in the capsule. This contributed to homogenizing the material distribution in the capsule in view of neutron transport. The aluminium blocks (upper and lower halves) were pre-loaded by bolting for a good surface contact with the mock-ups in order to dissipate the nuclear heat to the surrounding spaces filled with gas, eventually to the reactor primary coolant water at 40-50 °C. For this reason, tight geometrical tolerances were required for the mock-ups [12] and aluminium blocks.

The two main parameters, irradiation temperature and neutron fluence, were monitored by thermocouples (type K) and neutron fluence detectors, respectively. The capsule was equipped with 24 thermocouples (two thermocouples per mock-up in the CuCrZr part of the mock-up and the rest for temperature measurements of the aluminium blocks and capsule itself) and six neutron fluence detectors (one neutron fluence detector per mock-up at the beryllium armour side; additionally two neutron fluence detectors at the steel side of two mock-ups). The capsule had two layers of containment volumes to separate the mock-ups and aluminium blocks assembly from the reactor primary coolant water. This volume was filled with helium and/or neon gas of adjustable mixture ratio to vary the heat dissipation rate (thermal conductivity) for control of the mock-up temperatures.

During assembly of the capsule, rigorous visual and dimensional inspections were performed to ensure the correct fitting to the position-guide in the reactor. The leak tightness test of the capsule containments was verified after pneumatic pressure test at 1 MPa (maximum pressure in operation, 0.4 MPa). A functional test of all the actuators, gas lines and thermocouples was performed before installation in the reactor.

### 4.2. Neutron irradiation and post-irradiation activity

The capsules were exposed to 3 reactor cycles for high dose irradiation and 1 reactor cycle for low dose irradiation at an identical location in the HFR. Once a capsule was installed in the reactor, temperature control of the capsule was done by controlling the ratio of helium and neon filled into the containment volumes in the capsule to adjust the heat dissipation rate. Furthermore, the vertical position of the capsule was controlled with respect to neutron flux bucking profile to moderate neutron flux, i.e. nuclear heating. The reactor was operated at  $\sim 45$  MW for typically 31 days for a cycle in 2016-17.

Finally, the irradiation temperature was calculated as the average of two measurement points over the reactor cycle(s) during the steady-state reactor operation. The neutron fluence was estimated by nuclear analysis of various metallic strips such as iron and titanium, in the neutron fluence detectors after the neutron irradiation assuming the neutron energy spectrum in the reactor. Table 1 shows the reported irradiation temperature and neutron dose in dpa in Be.

After neutron irradiation, the capsule was extracted from the reactor core and disassembled by manipulator operation after months of cooling periods in the cooling pool. Visual inspection through a hot cell window confirmed soundness of mock-ups after disassembly (Fig. 3). Discoloration at beryllium and CuCrZr surfaces was observed. The origin of this discoloration was not understood because no suitable analysis method was available for the highly radioactive samples to determine the chemical composition of the discoloration. The discoloration was considered to be a surface modification without impact on the bulk and joints. However, it did have an impact on surface temperature measurement by optical diagnostics during HHF test. The irradiated mock-ups and beryllium tiles were packed in the type A certified containers and transported from the HFR site back to the HHF testing site.

## 5. Post-irradiation thermal fatigue test

Thermal fatigue tests (30 s on/ 30 s off) were performed in the JUDITH 1 facility. The hydraulic parameters were the same as in the

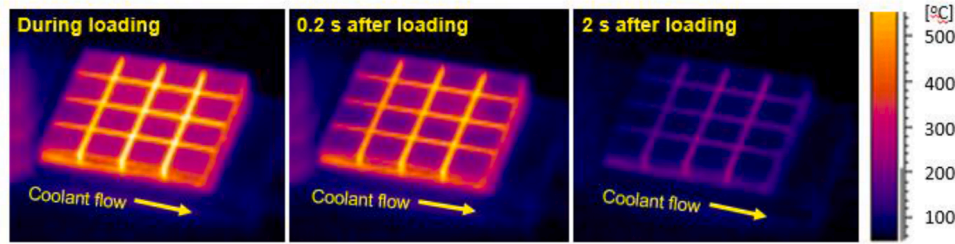


Fig. 2. IR image of mock-up (NIM-31) during thermal loading at 4 MW/m<sup>2</sup> (left) and 0.2 s (centre) and 2 s (right) after the end of thermal loading.

Table 1

Reported neutron doses and irradiation temperatures of EHF FW mock-ups in the neutron irradiation campaigns.

CN mock-up ID	NIMB-4	NIM-28	NIBM-3	NIMB-1
Irradiation temperature [°C]	249-256	241-249	247	240
Neutron dose on beryllium [dpa]	0.474	0.426	0.111	0.100
RF mock-up ID	IM06	IM12	IM04	IM08
Irradiation temperature [°C]	255-258	249-253	250	254
Neutron dose on beryllium [dpa]	0.482	0.450	0.113	0.107

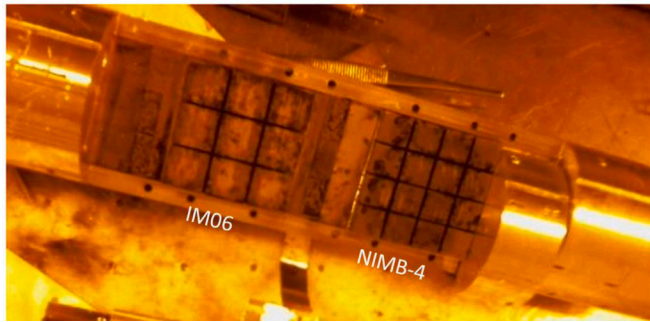


Fig. 3. Photo of the mock-ups (IM06 & NIMB-4) after neutron irradiation of ≈0.5 dpa at 250-260 °C.

thermal fatigue tests of non-irradiated mock-ups.

The thermal fatigue tests of the eight irradiated mock-ups (see Table 1) were performed at 2 MW/m<sup>2</sup>, 3 MW/m<sup>2</sup>, 4 MW/m<sup>2</sup> and then finally at 4.7 MW/m<sup>2</sup> 400 cycles [16]. The results from mock-ups irradiated at high dose are particularly important. One mock-up (IM6 manufactured by the RF supplier; ≈0.5 dpa) was loaded further up to 1216 cycles<sup>1</sup> at 4.7 MW/m<sup>2</sup>. Fig. 4 shows the thermal screening test before and after thermal fatigue test. The hot spots within tiles in these images were considered to be surface effects rather than due to joint defects since the areas were too localized to be caused by defects at the joints. Fig. 5 shows the surface temperature evolution during thermal fatigue test. The surface temperatures of a Be tile at the downstream side were recorded as time average around the end of thermal fatigue cycle. It should be noted that the inhomogeneous surface appearance and discoloration (see section 3.2) have an impact on the measurement by the IR camera. For the surface temperature measurement, a constant emissivity of 0.5 was assumed.

The thermal screening test before and after the thermal fatigue test did not show noticeable changes in the thermal response, i.e. no hot spot caused by degradation of the joints (overheating of the Be tiles). There

<sup>1</sup> Note: After completion of the planned extended program for IM06, the IO and FZJ decided to continue cycling until either the mock-up or the cathode gave in. The cathode failed at the cycle 1216 and this was the last test ever done in JUDITH 1.

was not noticeable change in the cool down time after HHF loading before and after thermal fatigue test. A surface temperature difference before and after thermal cycling was not detectable considering the uncertainty of the measurement due to the unknown emissivity. The difference in the surface temperature between CN and RF mock-ups was considered to be associated mainly with the different emissivity due to manufacturing process since this difference was already present in the screening tests before neutron irradiation.

## 6. Summary and outlook

Irradiation mock-ups that mimic ITER Enhanced Heat Flux First Wall panels were manufactured and inspected by two suppliers (SWIP, China and Efremov Institute, Russia) of two DAs who in charge of series production. Eight mock-ups were irradiated at ≈0.1 dpa and ≈0.5 dpa at 240-260 °C in the fission reactor HFR. All the eight tested irradiated mock-ups withstood thermal fatigue loads up to 4.7 MW/m<sup>2</sup> for 400 cycles, one mock-up irradiated at ≈0.5 dpa withstood a thermal fatigue test up to 1216 cycles at 4.7 MW/m<sup>2</sup>. Noticeable degradation was not observed on any of the tested mock-ups. These results demonstrated robustness of the selected design, manufacturing technologies and materials under the test condition.

Post-mortem analysis of two non-irradiated and two irradiated mock-ups after HHF test will be carried out as the next step. Six irradiated mock-ups remain available for a possible HHF test campaign in the future.

## Disclaimer

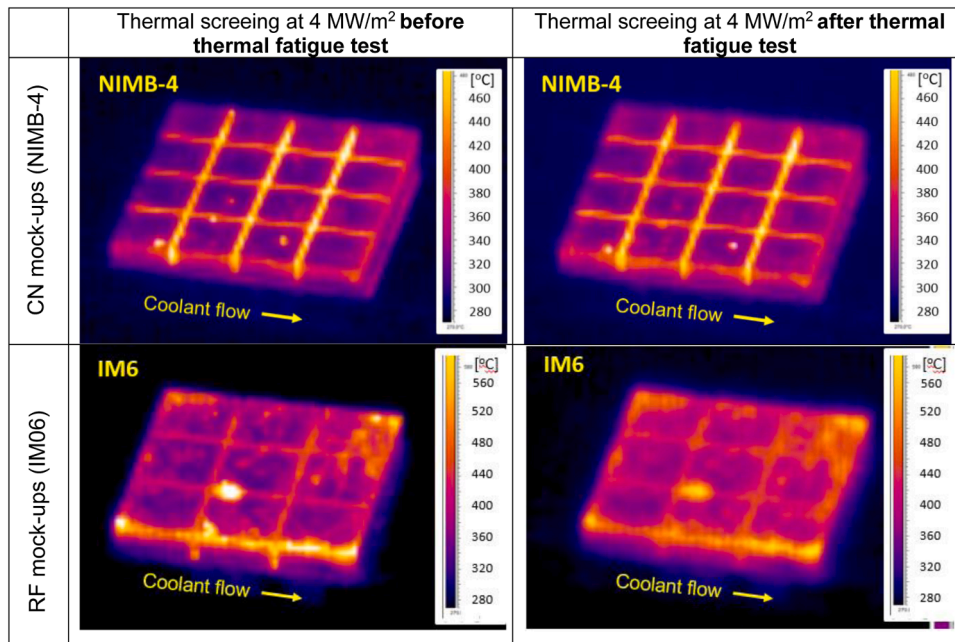
The views and opinions expressed herein do not necessarily reflect those of the ITER Organization.

## CRediT authorship contribution statement

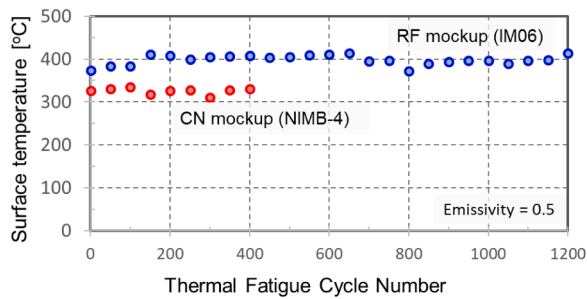
**T. Hirai:** Writing – original draft, Project administration. **L. Bao:** Writing – review & editing. **V. Barabash:** Writing – review & editing. **Ph. Chappuis:** Writing – review & editing. **R. Eaton:** Writing – review & editing. **F. Escourbiac:** Writing – review & editing, Funding acquisition. **M. Merola:** Writing – review & editing, Funding acquisition, Conceptualization. **R. Mitteau:** Writing – review & editing. **R. Raffray:** Writing – review & editing, Funding acquisition. **J. Linke:** Writing – review & editing. **Th. Loewenhoff:** Writing – review & editing, Investigation, Validation. **D. Dorow-Gerspach:** Writing – review & editing, Investigation. **G. Pintsuk:** Writing – review & editing. **M. Wirtz:** Writing – review & editing, Investigation. **D. Boomstra:** Writing – review & editing, Investigation. **C.J. Klaassen:** Writing – review & editing, Investigation. **A. Magielsen:** Writing – review & editing, Investigation. **J. Chen:** Writing – review & editing, Resources. **P. Wang:** Writing – review & editing, Resources.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence



**Fig. 4.** Thermal screening test at  $4 \text{ MW/m}^2$  before and after thermal fatigue test. CN mock-up (NIMB-4;  $0.47 \text{ dpa}$  at  $250\text{--}260 \text{ }^\circ\text{C}$ ) loaded at  $4.7 \text{ MW/m}^2$  for 400 cycles and RF mock-up (IM06;  $0.48 \text{ dpa}$  at  $250\text{--}260 \text{ }^\circ\text{C}$ ) loaded at  $4.7 \text{ MW/m}^2$  for 1216 cycles. The hot spots in these images were considered to be the surface effects since the areas were too localized to represent the defect at the joints.



**Fig. 5.** Surface temperature evolution during thermal fatigue test of CN mock-up (NIMB-4) and RF mock-up (IM06). The measured surface temperature showed no development, i.e. is constant within the experimental uncertainties.

the work reported in this paper.

#### Data availability

The authors are unable or have chosen not to specify which data has been used.

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