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Damage evaluation under thermal fatigue of a vertical target full scale component for the ITER divertor

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Abstract

An extensive development programme has been carried out in the EU on high heat flux components within the ITER project. In this framework, a Full Scale Vertical Target (VTFS) prototype was manufactured with all the main features of the corresponding ITER divertor design. The fatigue cycling campaign on CFC and W armoured regions, proved the capability of such a component to meet the ITER requirements in terms of heat flux performances for the vertical target. This paper discusses thermographic examination and thermal fatigue testing results obtained on this component. The study includes thermal analysis, with a tentative proposal to evaluate with finite element approach the location/size of defects and the possible propagation during fatigue cycling.

1. Introduction

The extensive EU research and development effort on high heat flux components for the International Thermonuclear Experimental Reactor (ITER) aims in particular at the demonstration of Divertor component prototype manufacturing. These efforts culminated in the successful manufacturing and testing of a medium-scale vertical target prototype [1]. On the basis of this experience, the manufacturing of a full-scale prototype was launched. The aim was to qualify all the main features of the corresponding ITER component and to demonstrate the capability of the developed technologies to meet or to exceed the ITER requirements. A high heat flux (HHF) testing campaign dedicated to such issues, based on fatigue cycling and lifetime, was performed at the FE200 electron beam European facility located in Le Creusot (France) in the frame of an European Fusion Development Agreement (EFDA) contract. This paper summarises the main test results obtained on the Vertical Target Full-Scale (VTFS) mock-up of the ITER divertor and analyses the thermographic examination performed before and after the HHF loading. Considering the experimental surface

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temperature profile, a methodology based on the finite element (FE) approach was proposed in order to investigate the possible damage propagation during fatigue cycling.

2. Vertical target full-scale (VTFS) design

The VTFS prototype is 1000 mm long and represents the main features of the vertical target ITER divertor design (Fig. 1). Four units (A–D) having a full monoblock geometry, obtained by drilling a hole into each armour block, were assembled in parallel and actively cooled. The lower part of the prototype (blocks 1–32) has a carbon fibre reinforced carbon (CFC) armour, grade NB31, supplied by the French company *Snecma Propulsion Solide*. The upper part of the prototype (blocks 33–64) is armoured with tungsten. A commercial grade was used (WL10) which contains 1% La_2O_3. Active Metal Casting (AMC® registered by Plansee company [2]) process is used to join the OFHC Cu to the CFC armour. This assembling process is obtained by casting pure Cu onto a laser-textured CFC with a Titanium coating that aids wetting to improve the joint strength. The W/Cu joint was obtained by a conventional casting process [3]. The Cu/CuCrZr joint was accomplished using a 'low temperature' hot isostatic pressing technique. Pressurised water circulates through the component in the internal CuCrZr tube equipped with a twisted tape in the straight part of the mock-up. The back side of each monoblock is fastened to the stainless steel support structure via a set of pins.

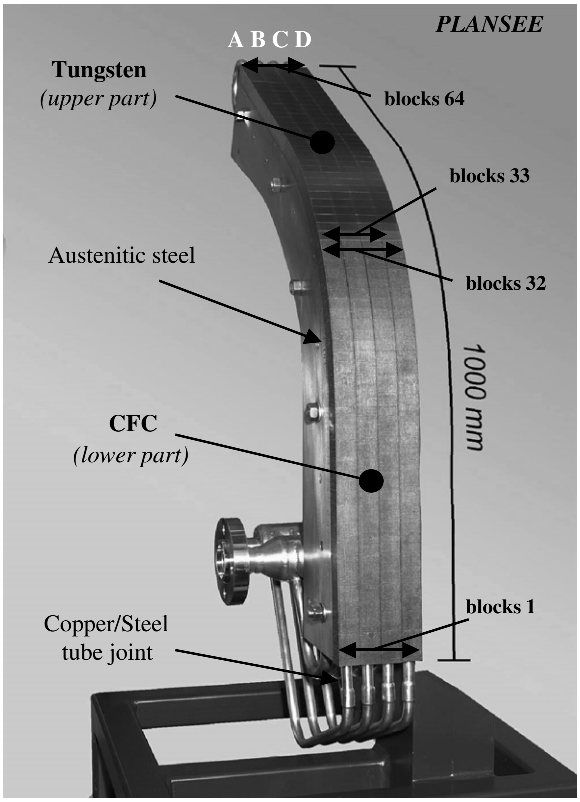

Fig. 1. Vertical target full-scale prototype manufactured by Plansee (high heat flux units) and Ansaldo Ricerche (support structure and integration).

3. High heat flux fatigue testing

3.1. Experimental procedure

Three fatigue testing campaigns were performed between May 2003 and October 2005 in the FE200 electron beam European facility at Le Creusot in France.

The experimental campaigns were devoted to several steps of fatigue cycling on the CFC and W armoured regions, taking into account the ITER safety margin requirements in terms of thermal fatigue. Initial, intermediate and final screening tests were regularly done at 5 MW/m^2 absorbed heat flux between these cycling sequences. During such a screening, a non-uniform temperature distribution pattern was observed at steady-state and interpreted as an image of the thermal resistance from the surface to the cooling channel.

3.2. Fatigue testing results

The *CFC part* survived the first cycling tests (up to 10 MW/m^2) with a stable surface temperature. The destructive examination of one CFC monoblock characterized by a poor thermal response during the initial screening and thermally cycled up to 10 MW/m^2 showed minor distributed flaws. However, the stable surface temperature observed during the initial and intermediate screening indicates that these minor flaws are induced by the manufacture process but still withstand a level of flux close to the ITER design target in steady state with no evidence of progressive damage. Finally, CFC monoblocks were successfully tested up to 1000 cycles at 20 MW/m^2 followed by an additional 1000 cycles at 23 MW/m^2 without any indication of failure [4]. An increase of local surface temperature was observed between the initial and final screening which can be attributed to numerous effects such as variation in thermal conductivity, local differences in the surface emissivity or progressive damage at the joint interface. However, except for localised hot spots, a low apparent evolution of the surface temperature is observed during the HHF cycling.

The *W part* survived the cycling test at 5 MW/m^2 with a stable surface temperature, followed by an additional 1000 cycles at 10 MW/m^2 on the straight part (equipped with a twisted tape) without any indication of damage. After this first step, which demonstrated the capability of the W monoblock to withstand fluxes one order of magnitude higher than the ITER design target for the upper part of the vertical target, post-mortem analysis showed the formation of cracks in the CuCrZr tube due to fatigue in the areas exposed to higher heat fluxes. To continue the fatigue testing campaign to higher heat loads, transverse castellations were introduced in the W monoblocks to reduce the operating stress. Finally, the units A and D were successfully exposed to HHF cycling up to 15 MW/m^2 followed by 1000 cycles at 20 MW/m^2.

4. Non-destructive examination

4.1. Description

The thermographic examinations were performed Cadarache (France) in the SATIR (*S*tation d'*A*cquisition et de *T*raitement *I*nfra *R*ouge) experimental device [5]. This facility, mainly composed of hot (95 °C) and cold (5 °C) water circuits and an infrared camera, is used to detect plasma facing component internal defects. Detection is based on monitoring the surface temperature during a transient period. A slow surface temperature response is interpreted as a high thermal resistance, i.e., a bad joining between different layers of materials. For each block of the tested unit, the DTref parameter based on comparison with reference blocks is calculated. The DTref is the value of the difference

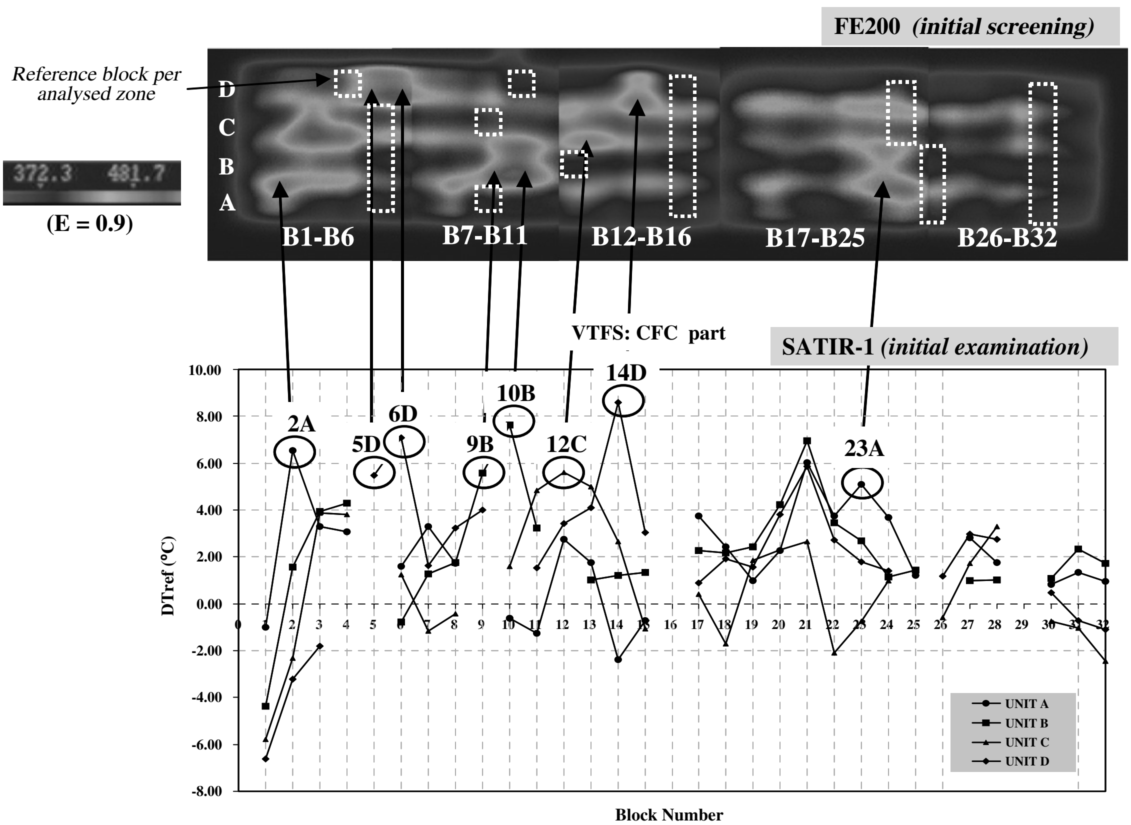

Fig. 2. *CFC* component infrared examination before the fatigue testing campaign.

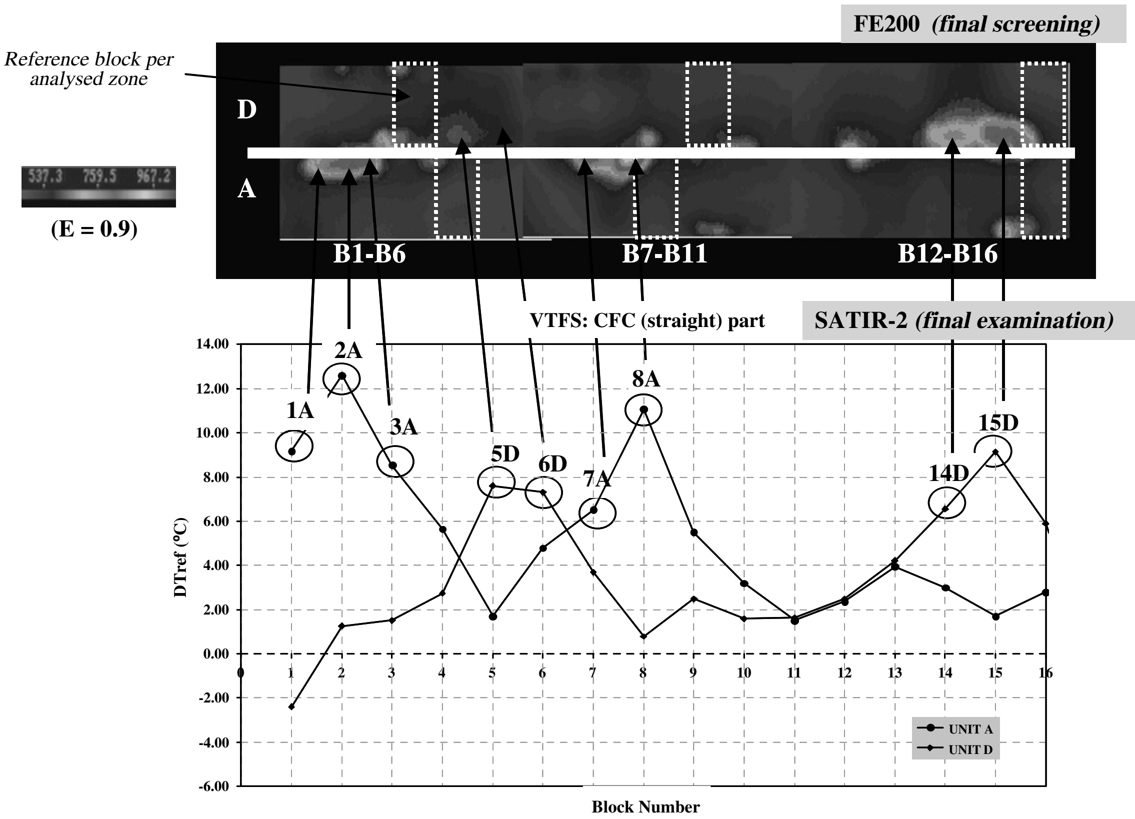

Fig. 3. *CFC* component infrared examination after the fatigue testing campaign.

between maximum temperature of the measured block and a reference block during the transient.

4.2. Non-destructive examination before and after high heat flux testing

Before and after fatigue testing, non-destructive examination was performed with SATIR, then, compared with the surface temperature fields obtained during the FE200 initial and final screening.

The measurement of the surface temperature of the tungsten part was quite uncertain, mainly due to the low emissivity. However, the preliminary SATIR thermographic examinations did not indicate poor bonding. This result is consistent with the non-destructive testing using ultrasounds, carried out by Framatome-ANP prior to the fatigue testing, as well as with the post-mortem analysis conducted by Plansee after the first step of the experimental campaign on the areas not exposed to high heat fluxes.

On the other hand, the SATIR thermographic examination of the CFC straight part showed a quite good correlation with the FE200 screening. These comparisons are shown in Fig. 2, before fatigue testing of all units, and Fig. 3, after fatigue testing of units A and D.

The SATIR facility is based on comparison with a reference mock-up. If a reference mock-up is not available – which is the situation with VTFS – a healthy neighbour block (with a fast and homogeneous thermal response) is chosen as reference. Consequently, the estimation of DTref is only indicative (qualitative observations) except in case of high values. On the other hand, each FE200 screening, mainly using infrared monitoring, gives an image of thermal resistance from the surface to the cooling channel: a significant modification of the temperature distribution with an increase of T^{max} (maximum surface temperature at steady state) and DT^{max} (difference between maximum and minimum surface temperature at steady state) between these screenings can be interpreted as progressing damage to the element. Therefore, the observation of poor thermal contact on some blocks were correlated with FE analysis to evaluate the localisation/size of possible defects.

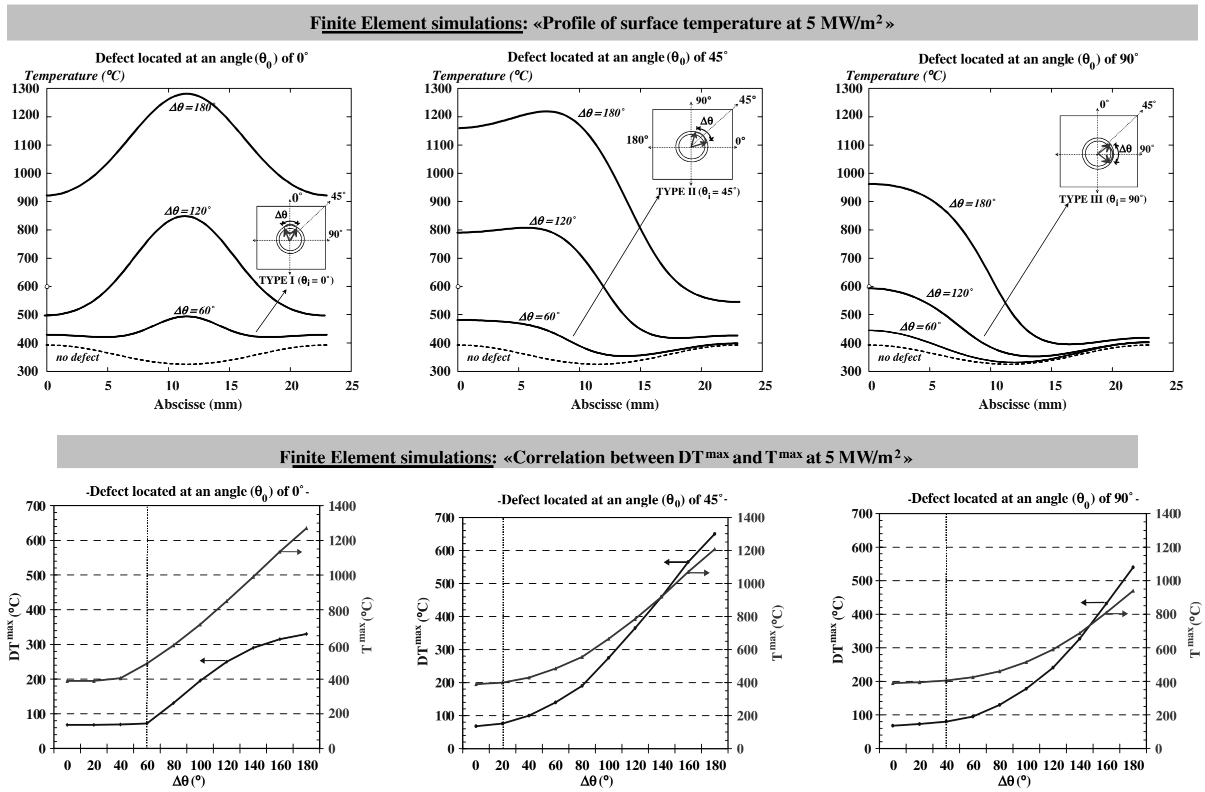

Fig. 4. Calculated profiles obtained from finite element simulations (CAST-3M) – T^{max} profiles and correlation DT^{max}/T^{max} versus the location/size of defects.

5. Analysis and discussions

First, the quality of the CuCrZr/Cu joint was inspected by ultrasounds and revealed an overall quite good quality of bonding. Second, FE calculations were done using the CAST-3M code to evaluate the location and size of defects observed for both SATIR and FE200 screening. The analysis of experimental data[1], compared to a set of calculated transverse profiles (Fig. 4) obtained from 2D simulations (hypothesis of traverse defects, corresponding to the experimental evidence) allowed the determination of possible defect location (θ_0) from the T^{max} profile, and size ($\Delta\theta$), considering the T^{max} and DT^{max} amplitudes (cross check between these two parameters).

The main observations obtained by IR examination before fatigue cycling and after the HHF loading are given in Fig. 5. The analysis of blocks characterized by poor thermal contact showed that a few manufacturing defects at the Cu/CFC joint (11 blocks among 64) preferably appeared at an angle of 45° or 90° along the tube (with 0° corresponding to the top of the monoblock, i.e., parallel to the plasma facing surface) and are minor with an extension ranging not exceeding 60° (i.e., ~5 mm size) (Fig. 5a). The SATIR testing showed that the detected defects are preferentially located at an angle of 45° along the tube. The detection of minor defects located at an angle of 90° would have required an examination of lateral surfaces (not possible with this parallel assembly).

After the fatigue testing campaign (three series of 1000 cycles at 10, 20, 23 MW/m^2), a generally increasing DT^{max} and T^{max} is observed during the FE200 final screening, mainly on the blocks already identified with a poor thermal contact during the initial screening. This does not show any critical defect propagation. The systematic analysis of experimental profiles correlated with calculated

[1] The analysis of experimental data includes the normalisation of fluxes as well as a correction to take into account the variation of optical transmittance and change of surface emissivity.

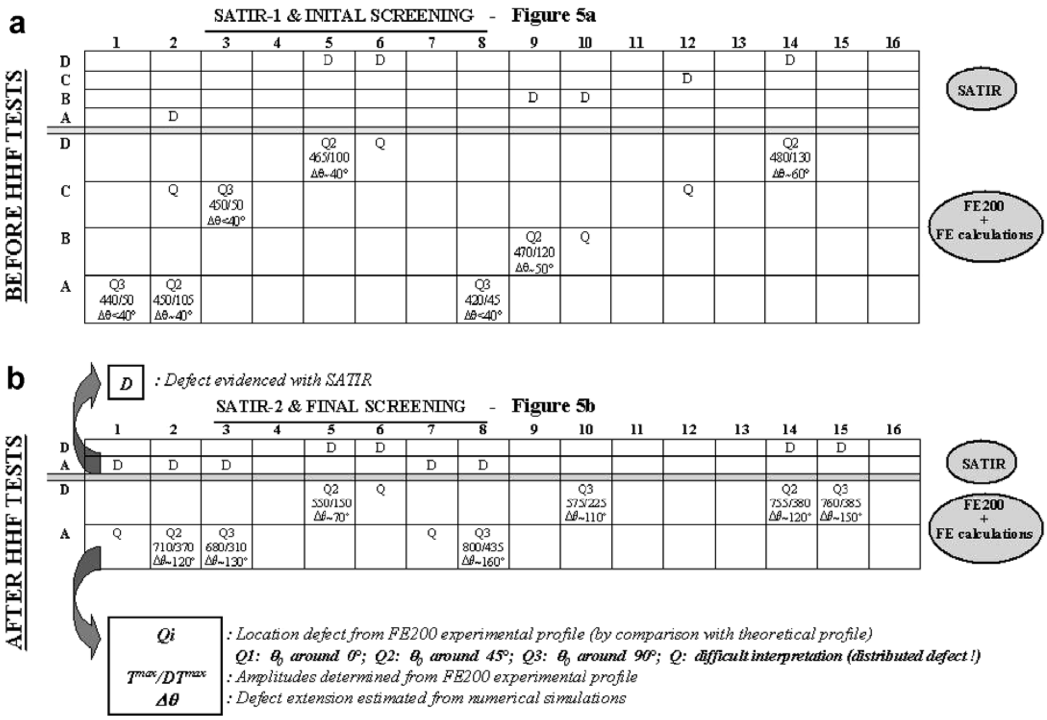

Fig. 5. Global sketch based on IR examination (SATIR/FE200-screening) before and after HHF loading.

profiles, allowed an estimation of flaws location and propagation during HHF testing (Fig. 5b), leading to these main findings:

– The AMC bond defects identified at an angle of 90° are more sensitive to damage propagation under high heat flux cycling than those located at an angle of 45°.
– The transient infrared thermographic (SATIR) control[2], including the uncertainties due to background noise, is especially sensitive to the detection of defects located near the examination surface. The detectable minimum defect was identified close to ~40° circumferential (i.e., ~4 mm size) in the CFC–Cu joint for the VTFS geometry (5 mm thickness of CFC). To obtain comprehensive information on internal bond quality of the monoblock component, this type of inspection requires control of all outside surfaces (top and lateral sides).
– AMC bond defects, identified initially by thermographic examination with an extension not exceeding ~60° (i.e., ~5 mm size), remain relatively stable up to 10 MW/m^2. At higher heat flux, some defects slowly propagate during fatigue testing, reducing the thermal lifetime of the component. However, the results obtained during this experimental campaign with heat fluxes higher than required for normal operation, demonstrates the impressive high defect tolerance of the monoblock technology, confirming results obtained elsewhere [6].

Finally, a post-test destructive analysis campaign is planned on these two units (units A and D) to allow better damage evaluation.

6. Summary and conclusions

A full-scale vertical target prototype, manufactured with all the main features of the corresponding ITER divertor design, was intensively tested in the HHF FE200 facility. The prototype consisted of four units having full monoblock geometry. The lower part (CFC armour) and the upper part (W armour) of each monoblock were joined to the

[2] An upgrade of the SATIR test device is planned in view of the definition of acceptance criteria of the ITER divertor PFCs. These modifications (water flow rate, pressure, temperature) will improve the detection sensitivity.

solution annealed, quenched and cold worked CuCrZr tube by HIPping techniques. The *CFC monoblock* was successfully tested up to 23 MW/m^2 during 1000 cycles without any indication of failure. This value is well beyond the ITER design target of 300 cycles at 20 MW/m^2. Furthermore, a thermal analysis coupled to FE calculations allowed a flaw location and damage estimation. This analysis showed that possible minor AMC defects produced during the manufacturing process (with an extension not exceeding $\sim 60°$), can be identified by IR thermographic examination but remain relatively stable for a heat flux up to 10 MW/m^2. The *W monoblock* endured 1000 cycles at 10 MW/m^2. This heat flux is one order of magnitude higher than the ITER design level for the upper part of the vertical target. To pursue the fatigue testing campaign to higher heat fluxes, transverse castellations were necessary to reduce the operating stress. With this modification, the W monoblock was successfully exposed to 20 MW/m^2 during 1000 cycles.

The VTFS experimental campaign, taking into account ITER safety margin requirements in terms of thermal fatigue, demonstrated that the EU has developed the technology to manufacture the vertical target component for the ITER divertor, including both W and CFC options.

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