Consequences of Fatigue on Heat Flux Removal Capabilities of W Actively Cooled Plasma Facing Components

M. Missirlian[1], M. Richou[1], Th. Loarer[1], S. Constans[2]

(1) CEA, IRFM, F-13108 Saint-Paul-Lez-Durance, France
(2) AREVA-NP, Le Creusot, France
E-mail: marc.missirlian@cea.fr

Abstract
High heat flux tests have been performed to assess the thermal fatigue life-time in steady-state conditions of different small/medium-scale mock-ups including most recent developments related to actively cooled W-armoured plasma-facing components. In particular, the behaviour of these mock-ups manufactured by European companies with all the main features of the ITER divertor design, was investigated for thermal cycling under heat fluxes higher than 10 MW/m^2, to explore the capability for a full W divertor system to meet the present ITER requirement in terms of heat flux performances and operational compatibility. Critical heat flux (CHF) experiments were also carried out on the components which survived the above thermal fatigue.
Main results showed promising behaviour with respect to heat flux removal capability up to 15 MW/m^2 and after a limited number of cycles at 20 MW/m^2. Beyond, the bonding to cooled structure and the embrittlement of W armour materials are still considered unfavourable regarding high temperature deformation and cyclic thermal fatigue. The results of CHF experiments were also rather satisfying and in line with safety margins required for ITER operation, since the tested components sustained heat fluxes in the range of 30 MW/m^2 in steady-state conditions.

1. Introduction

Extensive R&D programs have been performed in Europe to develop reliable actively cooled plasma facing components (PFCs) for existing machines (e.g. Tore Supra, W7X) and future fusion experiments such as ITER. These activities focus on the development and fabrication of relevant plasma facing materials and components compatible with plasma scenarios and associated plasma wall interaction. Due to its capability to withstand cyclic high heat load, the use of carbon in the divertor within the strike-point region and tungsten (W) on moderate loaded baffle area for the initial “non-active” phase of ITER was chosen. While the carbon material is considered to be adapted for the ‘exploratory’ stage of operation in H and He, the deployment of an all-tungsten divertor in ITER is foreseen for the following deuterium-tritium (D-T) phase. Therefore high heat flux (HHF) tests on actively cooled W armoured PFCs, relevant at ITER strike-point conditions, have been performed to assess the fatigue life-time of bonding techniques and to validate different design concepts.
In this paper, main results in Europe in terms of heat flux removal capability and thermal fatigue performances at high heat flux for various types of actively cooled W armoured prototypes, including most recent developments are presented and discussed. In particular, the behaviour of different mock-ups with all the main features of the ITER divertor design was investigated for thermal cycling under heat loads above 10 MW/m^2, to explore the heat flux performances and operational compatibility of a full W ITER divertor system.

2. HHF thermal fatigue testing of PFCs under steady state loads

2.1. Main previous results

2.1.1. Medium/Small-scale mock-ups

Mainly, two high power electron beam European facilities have been used to assess the “fitness for purpose” of the developed technologies for W armoured components.

- the 60 kW JUDITH-I with a hot cell of 0.4 m^3 at Forschungszentrum Jülich, Germany, for smaller mock-ups.

- the 200 kW FE200 with a vacuum chamber of 8 m^3 at AREVA in Le Creusot, France, for larger mock-ups and prototypes.

The major relevant results of high heat flux tests obtained with representative mock-ups over the last few years by the European community on W armoured actively cooled high heat flux component are summarized in **Table 1.** They show that bonding techniques such as casting/HIP, brazing/HIP, casting/HRP of the W/Cu joints provide relevant high heat flux durability performance. In addition, these results show that technical solutions for the baffle region expected on vertical targets of ITER Divertor were feasible (5 MW/m^2 x 3000 pulses in steady state) and even exceed the HHF requirement for ITER during the "exploratory" stage of operation **[1]**.

Year	Supplier	Geometry *(LxWxH)*	Tube *(ID/OD)*	W grade (armour)	Cu-Alloy (heat sink)	W/Cu joining technique	Cu/Cu joining technique	TESTING CONDITIONS Flux (MW/m^2)	Number of cycles	Facility	Ref.	Results
1999	CEA	W-Flat tile	(10/12)	W	DS-Cu	Brazing	HIP at HT (900℃)	6	700	FE200	[13]	FJ
1999	Plansee	W-Macrobrush	(10/12)	W	DS-Cu	Cast	EBW	9	1000	FE200	[13]	WF
								16	1000			OH + FJ
2001	ENEA	W-Monoblock	(10/12)	WLa_2O_3	CuCrZr	Cast	HIP at HT (700℃)	12	200	JUDITH	[15]	WL
		(monolith 4x23x25 mm3)						14.5	1000			WF
2002	Plansee	W-Macrobrush	(10/12)	WLa_2O_3	CuCrZr	Cast	EBW	13.7	1000	JUDITH	[14]	WF
2002	CEA	W-Monoblock	(10/12)	WLa_2O_3	CuCrZr	HIP-Ni interlayer	HIP at LT (550℃)	18	1000	JUDIT H	[14]	WF
		(monolith 4x23x25 mm3)										
2002	Plansee	W-Monoblock	(10/12)	W Sheet	CuCrZr	Cast	HIP at LT (550℃)	14.4	1000	JUDITH	[14]	WF
		(thin lamellae)										
2005	Ansaldo	W-Monoblock	(12/15)	W	CuCrZr	Cast	HTB	10	1000	FE200	-	WF
		(monolith 12x27x30)						20	1000			OH + FA
2005	Plansee	W-Flat tile	-	W	CuCrZr	Cast	HIP at HT	10	1000	FE200	-	WF
		(hypervapotron)						20	766			OH + FJ
2006	Ansaldo	W-Flat tile	-	W	CuCrZr	Cast	HTB	10	1000	FE200	-	WF
		(hypervapotron)						20	766			OH + FJ
2006	ENEA	W-Monoblock	(10/12)	WLa_2O_3	CuCrZr	Cast	HRP	10	3000	FE200	[6]	WF
		(monolith 10x24x23 mm3)						15	2000			WF
2007-2008	Plansee	W-Monoblock	(12/15)	W	CuCrZr	Cast	HIP at HT	10	3000	FE200	[5]	WF
		(monolith 12x28x36 mm3)						20	500			WF
2007-2008	Plansee	W-Flat tile	(12/15)	W	CuCrZr	Cast	HIP at HT	5	3000	FE200	[5]	OH
		(4 tiles)						10	500			OH + FJ
2007-2008	Ansaldo	W-Monoblock	(12/15)	W	CuCrZr	Cast	HRP	10	3000	FE200	[5]	WF
		(monolith 12x28x36 mm3)						20	500			OH
2007-2008	Ansaldo	W-Flat tile	(12/15)	W	CuCrZr	Cast	HRP	5	3000	FE200	[5]	WF
		(4 tiles)						10	500			OH + FJ

Designation

HIP: Hot Isostatic Pressing
HTB: Hot Temperature Brazing
HRP: Hot Radial Pressing
HT: Hot Temperature
LT: Low Temperature
EBW: Electron Beam Welding

WF: Without Failure
WL: Water Leakage
FJ: Failure in Joint
FA: Failure in Armour
FH: Failure in Heat sink
OH: OverHeating

Table I: Main survey of HHF tested W armoured mock-ups

2.1.2. Full-scale prototypical mock-ups

During the ITER EDA (Engineering Design Activity) and CTA (Co-ordinated Technical Activities) phases, experience of European industry on W armour joining has proved that the most reliable process for W/Cu joints was the casting of a pure Cu layer on a CuCrZr heat sink tube. A full scale prototype **(Fig. 1)** produced by Plansee SE and assembled by low temperature hipping, has been tested in the high heat flux FE200 electron beam facility at Le Creusot in France between 2003 and 2006. The lower part of this component was a Carbon Fibre reinforced Carbon (CFC) armour, grade NB31, supplied by the French company *Snecma Propulsion Solide*. The upper part of the prototype was armoured with tungsten alloyed (WL10).

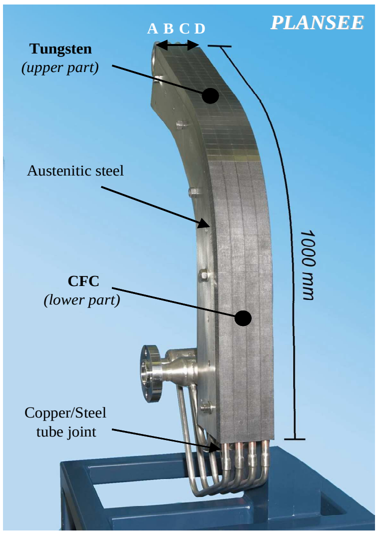

FIG 1 Vertical target near full-scale prototype

The W monoblock section endured up to 1000 cycles at 10 MW/m^2 of absorbed heat flux. To pursue the fatigue testing campaign at higher heat fluxes, transversal slots ("castellation") in the W tiles were necessary to alleviate the operating stress. Finally, the W monoblock was successfully exposed to high heat flux cycling up to 1500 cycles at 15 MW/m^2 followed by an additional 1500 cycles at 20 MW/m^2 **[2, 3]**.

Additional investigations (metallographic studies) after thermal fatigue testing showed a brittleness of W armour surface areas thermally loaded above 10 MW/m^2. This embrittlement of a W-alloy appeared mainly by micro-cracks oriented perpendicularly to the loaded surface, but had not induced critical overheating in testing conditions. However, some micro-cracks oriented parallel to the surface were found inside W armour or close to the transition area between W and copper interlayer (OFHC Cu) in areas thermally loaded beyond 10 MW/m^2 before the introduction of transversal slots **[4]**.

Results of this intensive thermal fatigue tests have confirmed previous works, that possible measures to overcome component failure due to thermo-mechanical stresses at high heat fluxes, was to reduce the size of W armour tile to a subcritical value and that this procedure was suitable and even mandatory to sustain successful higher heat flux (up to 20 MW/m^2).

2.2. Recent results

The on-going effort of the European R&D program is now focused in optimizing the existing technologies to improve their quality and reliability. Possible repairing methods to maximize the acceptance rate of the divertor high heat flux components during the unprecedented series production for ITER are also investigated to reduce the fabrication costs. Having demonstrated very promising results, the Hot Radial Pressing (HRP) process **[5]** and the optimized Hot Isostatic Pressing (HIP) techniques **[6]** were consolidated and adopted respectively by Ansaldo Ricerche and Plansee SE (i.e. the two “potential” European companies appointed to participate at the prequalification phase) as final bonding techniques to join the heat sink cooling tube to the W armour structure.

2.2.1. Main features of the tested elements

A total of eight (small-scale) W components (so-called W mock-ups) and three (medium-scale) Vertical Target Prototypical components (so-called VTP component) were manufactured by Ansaldo Ricerche by Hot Radial Pressing (four W mock-ups s, one VTP component) and Plansee SE by Hot Isostatic Pressing (four W components, two VTP components). All PFCs, armoured with pure W monoblock tiles, are constituted of monoblocks having a total height of 25 mm ; separated by gaps, with a width and an axial length of 28 and 12 mm, respectively.

The W components **(Fig. 2a)** and the W part of the VTP components **(Fig. 2b)** have a curved shape with a radius of curvature of 511 mm along the tube axis. To reduce the joint interface stress, a pure Cu interlayer (1 mm thick) was provided between the armour and the CuCrZr tube. The cooling tube (12/15 mm Inner/Outer diameter) is made of CuCrZr. A twisted tape, 0.8 mm thick, with a twist ratio of 2, was also inserted into the cooling tube as turbulence promoter to enhance heat transfer and to increase the critical heat flux margins.

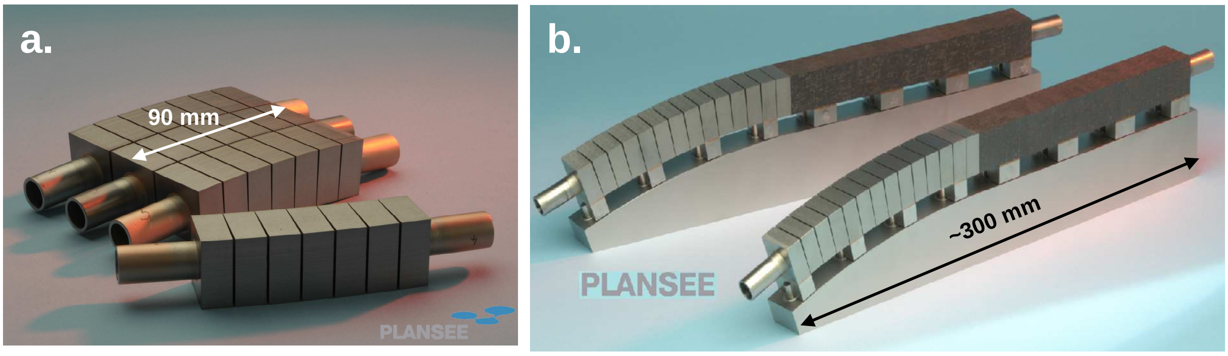

FIG. 2 Small-scale W components (a) and Medium-scale Vertical Target Prototypical components (b)

The VTP components consist of a HHF unit including a steel supporting structure. The monoblocks are mounted onto the steel plate via a number of pads fixed onto the supporting structure. The attachment system allows sliding of the monoblock caused by thermal expansion of the heat sink tube during operation.

For each manufacturer, two W components included one repaired monoblock tile preferably localized in the centre. For the VTP components, Ansaldo Ricerche unit is provided with two repaired monoblocks in both the CFC and W parts and the two Plansee SE units are provided with two repaired monoblocks, one in the CFC part, the other one in the W part. Apart from the repairing process, all the components have a final identical geometry.

Based on previous in-depth analysis of various possible repairing modes **[7]**, the mode characterized by two vertical half monoblocks with no gap, having proved to be the best one in terms of residual stresses after manufacturing, was adopted by each manufacturer as repairing process for monoblock geometry. Moreover, this mode presents the huge advantage to avoid the loss of a monoblock tile in case of a complete heat sink bonding failure.

Hence, this repairing process consists in cutting away the monoblock from the the CuCrZr tube. This cutting is performed in the middle of monoblock tile **(Fig. 3a)**. The monoblock is then removed in two parts. The joining of two half virgin monoblocks with the copper cast layer is then performed on the CuCrZr unit tube **(Fig. 3b**) by a second HIP cycle for Plansee SE and by HRP for Ansaldo Ricerche.

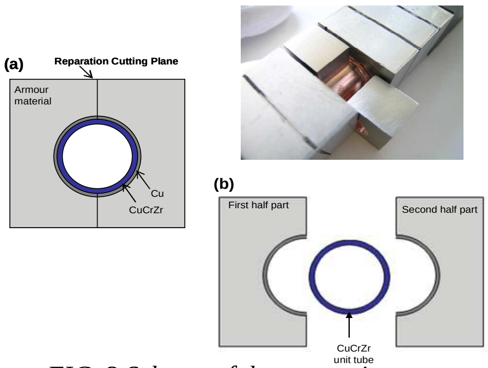

FIG. 3 Scheme of the reparation process

2.2.2. Testing procedure

Fatigue testing campaign was performed in the high heat flux AREVA FE200 electron beam facility at Le Creusot in France. The monitoring of the shots was provided by means of a CCD camera, two optical pyrometers, a pyro-reflectometer and an Infrared camera. The absorbed heat flux is obtained by global calorimetry from the measurement of two thermocouples installed at the inlet and at the outlet of tested components. The experimental campaign was devoted to several steps of fatigue cycle tests consisting for (small-scale) W components in 1000 cycles at 10 MW/m² and in either 1000 cycles (for the no-repaired components) or 500 cycles (for the repaired ones) at 20 MW/m². Taking into account the first results, and in order to investigate the behavior of the components under reduced heat flux, the following testing plan of the (medium-scale) VTP components W parts was then modified to 1000 cycles at 10 MW/m², 1000 cycles at 15 MW/m² and 300 cycles at 20 MW/m². The thermal cycle was 10s power on (provided by electron beam sweeping), then 10s dwell time. Initial, intermediate and final screenings (thermal mapping) were performed at 5 MW/m² between the cycling sequences. The hydraulic conditions were set at nominal ITER conditions, namely at a pressure of 33 bar, an inlet temperature of 120°C and a water velocity inside the tube of 12 m/s.

2.2.3. Experimental results

a. Performance assessment of consolidated technologies for divertor strike point conditions

Main experimental HHF results were recently reported **[8]** and pointed out that all tested components with *'not-repaired'* monoblocks endured correctly the cycling at 10 MW/m^2 without any visible damage **(Fig. 4a)**. This first step of thermal cycling did not show hot spots or steadily evolution of surface temperature, and confirmed the promising behavior already observed in the past. While no water leakage or degradation of thermal behavior in terms of heat flux removal capabilities occurred during the thermal fatigue tests above 10 MW/m^2, visual surface damage was observed **(Fig. 4b)** after the following thermal cycling conditions in steady-state:

- Presence of longitudinal primary millimeter-length cracks oriented perpendicular to the loaded surface after 1000 cycles at 15 MW/m^2 on some monoblocks. This embrittlement tends to spread on a majority of monoblocks after a few hundreds of cycles at 20 MW/m^2. These cracks did not modify the thermal behaviour of the components in terms of heat flux removal capabilities.
- Presence of dense network of secondary micro-cracks after a few tens of cycles at 20 MW/m^2 inducing a slight overall alteration of the surface in addition of primary cracks.
- Presence of melted W droplets at the surface of altered monoblocks by secondary micro-cracks after several hundreds of cycles (typically more than 500 cycles) at 20 MW/m^2. During the cycling, no significant increase of surface temperature was detected by pyrometers or pyro-reflectometer measurements, but the IR diagnostic showed clear drop of emissivity when local melting occurs.

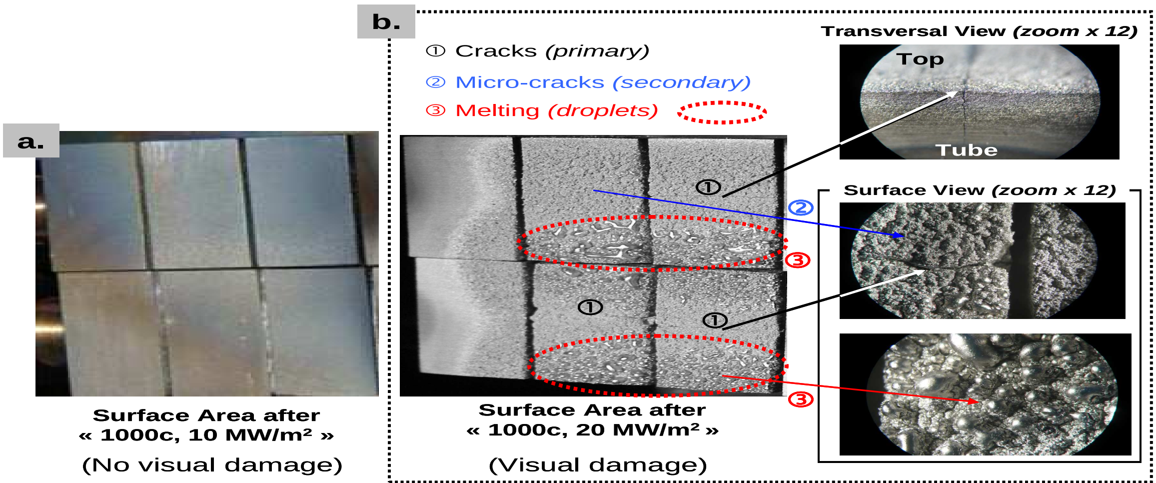

FIG. 4 CCD pictures: Visual surface damage after thermal fatigue at10 MW/m^2 (a), then 20 MW/m^2 (b) Longitudinal primary cracks (①); network of secondary micro-cracks (②); melted W droplets (③)

In addition, the complete melting of two monoblocks (i.e. 4% of tested monoblocks) occurred during the cycling at 20 MW/m^2 (namely, after 450 and 520 cycles respectively), probably due to the propagation of a defect at the W/Cu interface combined with a creep deformation of the pure copper interlayer. This factual event was detected by the IR diagnostic, with a sudden increase of the surface temperature, followed by a decrease due the change of surface emissivity **(Fig. 5)**. However, the thermal cycling pursued until 1000 cycles as planned in the testing plan without occurrence of a water leak.

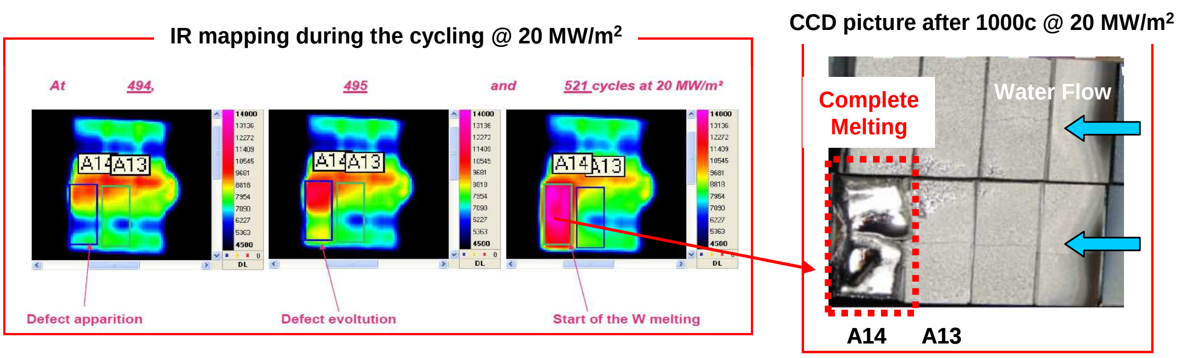

FIG. 5 Complete surface melting after 1000 cycles at 20 MW/m^2 of W components (IR (left) and CCD (right) pictures)

b. Performance assessment of repairing methods for W monoblock geometry

Main experimental HHF results were recently reported **[9]** and pointed out that all tested components with *'repaired'* monoblocks endured correctly the cycling at 10 MW/m^2 without any visible damage. This value of flux is well beyond the ITER design target qualification for the upper part of the vertical target with W armoured PFC for the 'exploratory' stage of ITER operation validating the repairing process for both European industrials.

Above 10 MW/m^2, no degradation of thermal behavior in terms of heat flux removal capabilities was noticed after 1000 cycles at 15 MW/m^2, but again a surface alteration (i.e. high roughening, brittle failure) was visually observed on W armour. These cracks initiated at the loaded surfaces did not impair the heat transfer capability. This demonstrates the good quality of materials and repairing process proposed by each manufacturer for W monoblock geometry. Thereafter, during the cycling at 20 MW/m^2, continuous increasing of surface temperature, due to a debonding at the repaired W/Cu tile interface is observed. In addition melting events for W components and VTP components manufactured by Ansaldo Ricerche with a repairing process based on HRP technology are observed. Melting events appears after a few hundreds of cycles at 20 MW/m^2 (namely, 300 and 360 respectively). Before rupture of the repaired assembly plan occurred, a surface collapse around the gap area was observed; this is caused during debonding propagation creating a thermal barrier. CCD pictures of repaired monoblocks after fatigue testing campaigns are shown in **Fig. 6**.

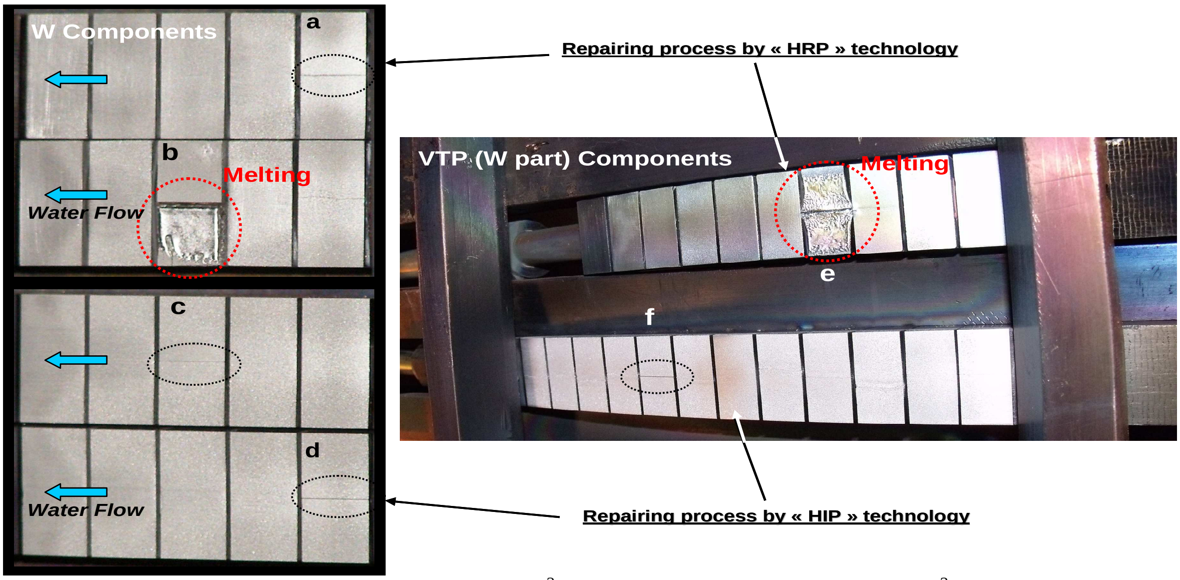

FIG. 6 CCD pictures after 1000cycles x 10MW/m^2, followed by 500 cycles x 20 MW/m^2 on W components (right); and 1000cycles x 10MW/m^2, followed by 1000 cycles x 15 MW/m^2, then 300 cycles x 20 MW/m^2 on VTP components (left)

2.2.4. Analysis and discussion

a. Pre and Post-examinations (SATIR)

Before fatigue testing, preliminary IR thermographic examinations were performed in Cadarache (France) with the SATIR (Station d'Acquisition et de Traitement Infra Rouge), **[10]** experimental device. Aim of this facility, mainly composed of two water circuits at different temperature levels and an infrared camera is to detect plasma facing components internal defects. Detection is based on the monitoring of the surface temperatures of inspected elements and of defect free one during a transient period. The maximum surface temperature difference during the thermal transient sequence (so-called DTrefmax) is stored and the presence of a faulty behaviour (i.e. a higher thermal resistance due to a bad joining between the different layers of materials) is detected by a slower surface temperature response.

SATIR testing did not reveal any poor bonding quality with regard to each monoblock tested (namely, a total of 80 W monoblocks) after manufacturing phase. DTrefmax values measured by SATIR method are quite homogeneous from monoblock to monoblock **(Fig. 7a)**.

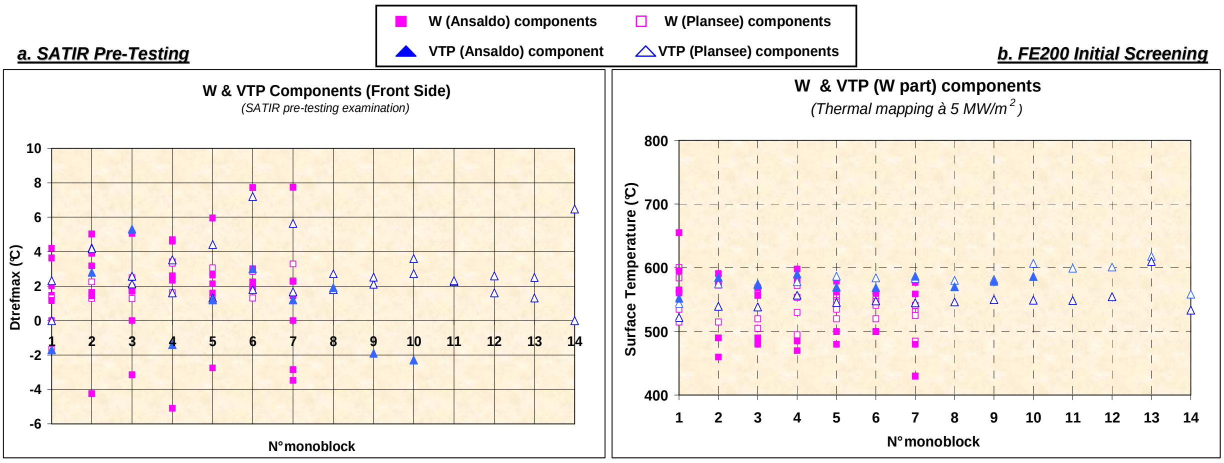

FIG. 7 SATIR pre-examination (a) and FE200 Initial Screening (b) for each monoblock of each component

This result is also confirmed by the initial screening (thermal mapping) performed before HHF fatigue testing in the FE200 facility **(Fig. 7b)** with an average IR surface temperature of about 550°C, within a measurement accuracy of ± 50°C in agreement with FE evaluation which provides a maximum surface temperature of 540°C located in the edge and a minimum surface temperature of 470°C located in the center for an healthy monoblock.

After fatigue testing, final thermographic examinations (SATIR post-testing examination) show no clear evidence of heat transfer degradation of tested monoblocks, except for monoblocks which completely melted during the HHF fatigue testing. DTref max measured by SATIR method before and after the thermal fatigue testing is rather constant **(Fig. 8)**, within the accuracy of the test bed (± 5°C). This result tends to confirm that:

- the armour material embrittlement leading to the crack formation near the heat loaded surface during the fatigue testing, does not impair the heat transfer capability between the surface and the coolant;
- the high surface temperature leading to the surface melting cannot be explained neither by a global deterioration of heat transfer between the surface and the coolant nor by the propagation of defects at the W/Cu interface. Therefore, it appears that the surface melting described here above mainly depends on the material structure rather than on the manufacturing technique.

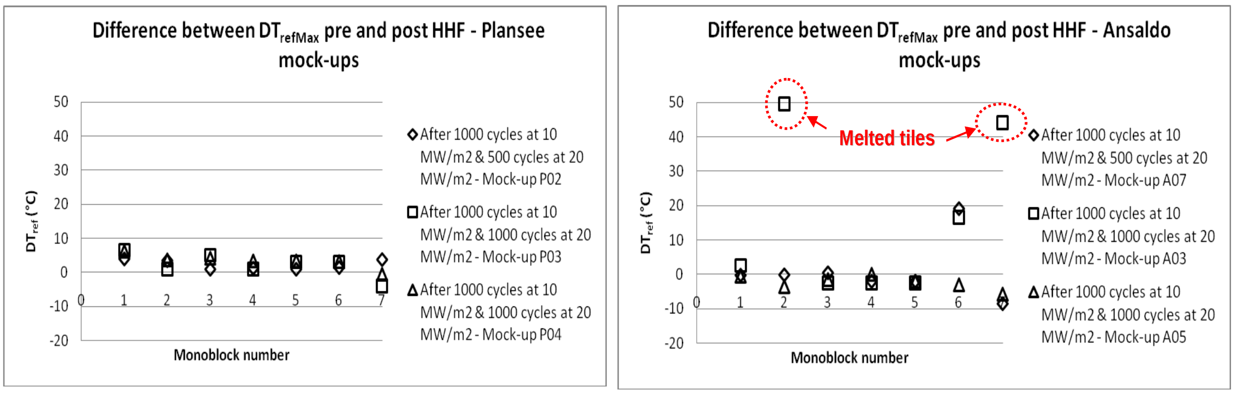

FIG. 8 Comparaison of DTrefmax before and after HHF thermal fatigue testing of (small-scale) W components manufactured by Plansee SE (leftt) and by Ansaldo (right)

Those interpretations are preliminary conclusions which will have to be confirmed in the near future by the metallographic examination of the monoblocks.

b. Finite Element Method (FEM) simulations

In order to evaluate the effects of surface and interface temperature rise during thermal loading, thermal analyses were performed simulating the experimental conditions.

For an absorbed heat flux of 10 MW/m^2 in steady-state, the highest computed temperature on the heated surface reaches 1100°C and the maximum temperature close to the W/Cu interface is about 300°C.

For an absorbed heat flux of 15 MW/m^2 (resp. 20 MW/m^2) corresponding values are 1400°C (resp. 1900°C) on the W surface and 400°C (resp. 500°C) close to the interface (**Fig. 9**).

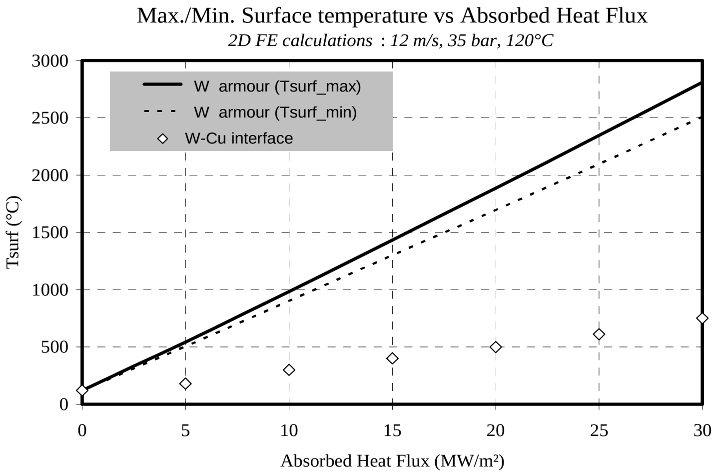

FIG. 9 Computed surface and interface temperatures vs. Absorbed heat flux

These results are in agreement with the experimental temperatures measurements observed on FE200 facility which are comprised between 1750°C and 2100°C at 20 MW/m^2. This also underlines the possible re-crystallization phenomenon ($T^{W}_{recrys.}$~1200-1500°C) which can explain the presence of micro-cracks experimentally observed near the loaded surface from 15 MW/m^2.

Furthermore, thermomechanical stresses assessed by FEM simulations highlight areas close to the top of the cooling tube and the surface with high stresses **(Fig. 10)**. These stresses are close to the ultimate tensile strength for heat flux deposits of 15 MW/m^2 and exceed it for higher heat fluxes. Hence, this result points out that there is a high probability for generating structural defects such as cracks in these areas. Moreover, this probability increases with the degradation of mechanical properties of W in the vicinity of the heat loaded surface regarding recrystallization phenomenon due to high temperature usage.

All these results are consistent with the visual experimental observations, namely a primary longitudinal cracks occurred during the HHF fatigue testing at 15 MW/m^2 or after a few hundreds of cycles at 20 MW/m^2 for the not-repaired monoblocks and a tendency to collapse on surface for the repaired monoblocks around the reparation zone when a melting event is occurred.

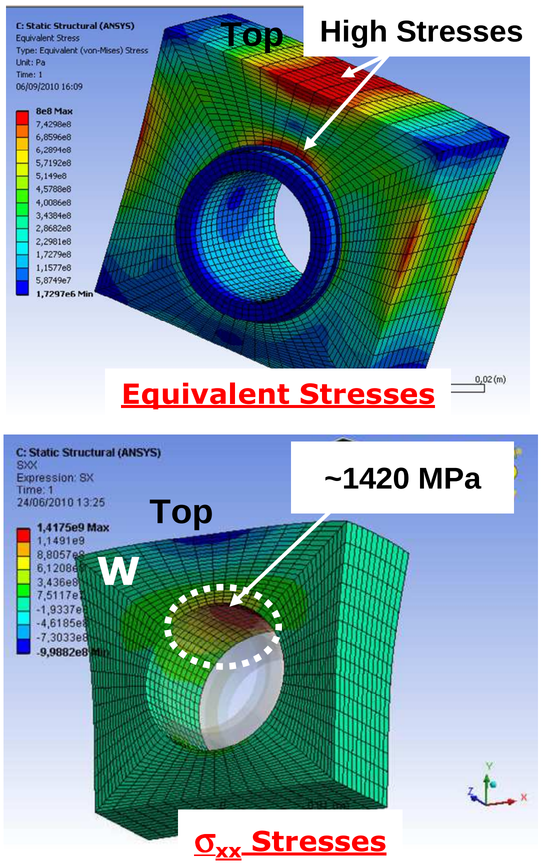

FIG. 10 FEM computed stresses at 20 MW/m2 (Equivalent Von-Mises and Tensile stresses in W armour)

3. Critical Heat Flux experiments

An extensive database on critical heat flux tests has been established over the last 15 years in EU on different cooling schemes (smooth tube, swirl tube, annular flow, hypervapotron) using mainly square shaped metallic heat sink structures (all-Cu mock-ups) **[11-12**] such as:

- '*hypervapotron'*, which however requires flat armour tiles;
- *'swirl tube'*, which can also be applied to a tubular heat sink inside a monoblock armour tile.

As far as the heat removal capability of a full W divertor is concerned, recently a critical heat flux test campaign was carried out in EU to extend the database for tube shaped heat sink structures as used by the ITER monoblock divertor concept (width 28mm, length 12mm, inner diameter 12mm) including for the first time a relevant thickness of W armour (typically 6-8 mm). The critical heat flux tests were performed with the reference range of ITER hydraulic conditions for the coolant: 3 MPa inner pressure, 120°C inlet water temperature, ~12 m/s flow velocity on mock-ups manufactured by European industrial (namely, Plansee SE and Ansaldo Ricerche companies) using available and consolidated technologies for W actively cooled PFCs, including a twisted tape insert (thickness 0.8, twist ratio 2).
The tests were performed at FE200 Facility electron beam at Le Creusot in France on two W components (see §2.2.1.) which sustained already 10 MW/m^2 x 1000 cycles followed by 20 MW/m^2 x 500 cycles in steady-state. After this cycling test, the mock-ups have not shown any indication of damage in terms of heat flux removal capability, and were able to sustain the final CHF testing. The power was progressively increased for 30s periods (30s beam on the component, 30s deflexion on bumper elements) up to observing at:

- 27 MW/m^2 of absorbed heat flux, a temperature increase at the surface of Ansaldo Ricerche component **(Fig. 11, left)**. Suggesting a precursor of a burn-out event, the test was stopped manually by the operator at the doubling of this event in order to preserve the testing program schedule.
- 37 MW/m^2 of absorbed heat flux, a water leakage due to a burn-out failure occurred on the heated area of Plansee SE component. **(Fig. 11, right)**. A sudden loss of vacuum was observed and the gun power was stopped immediately. Water leak and W melting were noticed by IR camera.

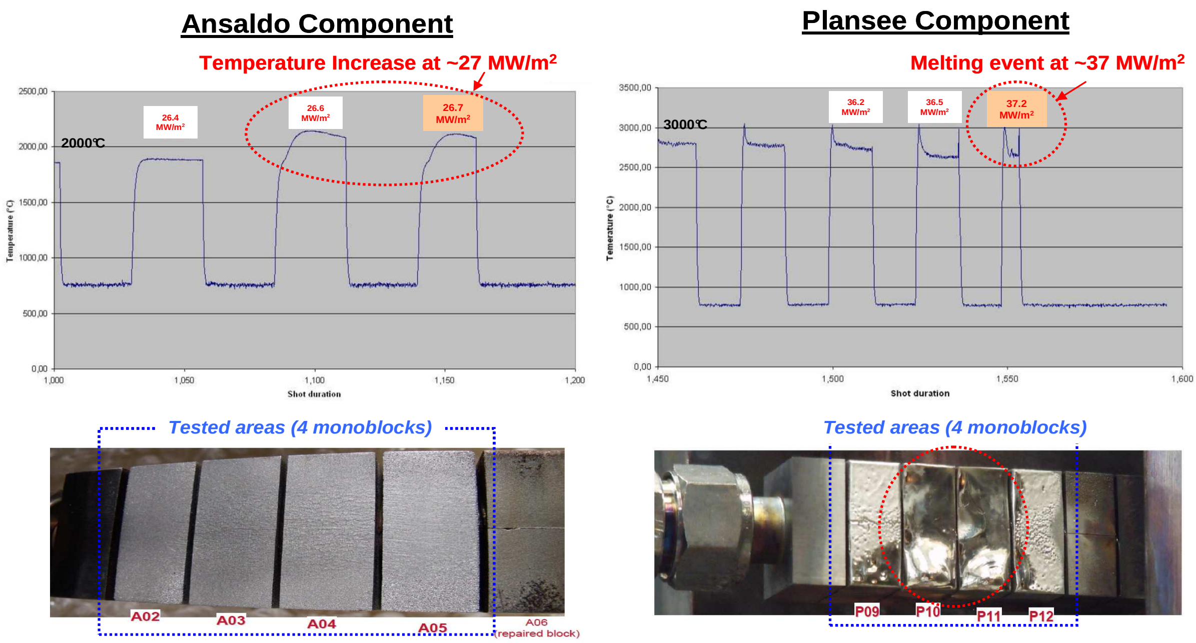

FIG. 11 Flux Increase during the CHF testing for Ansaldo (left) and Plansee SE (right) components

The surface temperatures during the test were monitored by one pyroreflectometer reaching a monoblock temperature incursion value close to 2200°C for the Ansaldo Ricerche component while on the Plansee SE component a temperature above 3000°C (saturated measurement) has been measured at the CHF event. This is in agreement with finite element (FE) simulation **(Fig. 12).**
These measured temperatures are also coherent with the CCD pictures after CHF testing where a large melting is observed on the heated area of Plansee SE component **(Fig. 11, right**.

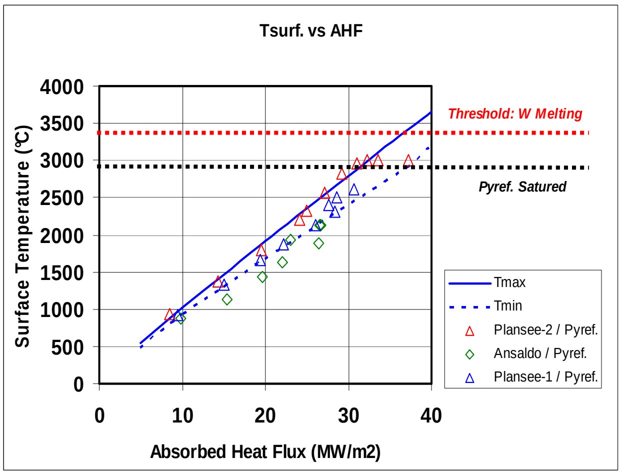

FIG. 12 Computed and measured temperatures during the CHF testing

Additional FE analysis showed that for a homogeneous incident heat flux of 37 MW/m^2, the surface temperature reaches 3400°C on the edge and exceeds locally 580°C at the wall-coolant interface. Considering acceptable potential bonding defect at the W/Cu interface, the surface temperature can drastically increase.
This is a satisfying result because the ICHF value obtained for the components with W armour gives a safety margin close to 1.8, with respect to the design heat flux of 20 MW/m^2 foreseen for ITER divertor strike-point region. This outcome is also in agreement with recent results obtained on CFC armoured monoblocks **[9]** and is above the prediction for square shaped heat sink structures.

4. Summary and Recommendations

R&D program has been launched to assess the performances in terms of thermal fatigue life-time of W-armoured actively cooled plasma-facing components under the conditions expected in the divertor strike-point region of ITER. For this purpose, W armoured mock-ups including most recent developments were manufactured by European companies (namely Ansaldo Ricerche and Plansee SE) and HHF tested in the AREVA electron beam FE200 facility (Le Creusot, France) up to 20 MW/m^2 in steady-state conditions.
All the mock-ups survived to the testing plan with no water leakage. No visible damage was observed up to 1000 cycles at 10 MW/m^2 of absorbed heat flux. This confirms that Europe masters with ITER margin requirements the suitable technologies (including repairing process) for the reliable manufacture of W-armoured plasma-facing components for series production of ITER divertor foreseen during the “exploratory” phase. Results showed also promising behaviour with respect to heat flux removal capability up to 15 MW/m^2 and after a limited number of cycles at 20 MW/m^2. Beyond, a systematic embrittlement of W armour near the loaded surfaces occurs (presence of longitudinal primary millimeter-length cracks, dense set of secondary micro-cracks, roughening aspect). This structural damage induces melted W droplets apparition at the altered surfaces after several hundreds of cycles (typically more than 500 cycles) at 20 MW/m^2. Despite of these visible damages, power handling capability seems to be well preserved with no significant increase of surface temperature during the thermal cycling, confirmed later with the SATIR thermography post-examination. This behaviour underlines hence that concerns regarding prolonged use above

recrystallization temperatures (high temperature usage) and below DBTT, impact preferably the material structure rather than the armour-heat sink bonding (i.e. manufacturing technique). Thus, the consequences of damage (like high roughening, brittle destruction and melting) on loaded surface for strike-point conditions on subsequent ITER operation in terms of plasma compatibility will have to be investigated in machines with ITER relevant W-armoured PFCs (e.g. metallic environment with actively cooled components). In particular, to explore the long pulse high heat flux exposition with repetitive high temperatures cycling as well as the effects of combined loads (e.g. short pulse loads to represent ELMs-like transient loads, thermal fatigue in steady-state conditions and neutron irradiation).
Finally, as far as the capability for a full W divertor is concerned, this extensive experimental campaign culminated with a remarkable CHF value beyond 30 MW/m^2 of absorbed heat flux at the thermal-hydraulic ITER conditions. This promising result for W-armoured actively cooled PFCs provides a safety margin greater than 1.5, with respect to the design heat flux of 20 MW/m^2 foreseen for ITER divertor strike-point region.

Acknowledgement
The author wishes to acknowledge the useful discussions with B. Riccardi, P. Gavila, F. Escourbiac and M. Lipa. This work, supported by the European Communities under the contract of association between F4E and CEA, was carried out within the framework of the contract F4E-2008-GRT-05 (MS-IV)-01. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

References

[1] R. Raffray *et al.*, Fusion Engineering and Design **85** (2010)
[2] M. Missirlian *et al.*, Fusion Engineering and Design **75-79** (2005)
[3] M. Missirlian *et al.*, Journal of Nuclear Materials **367-370** (2007)
[4] M. Missirlian *et al.*, 14th International Conference on Fusion Reactor Materials (2009)
[5] E. Visca *et al.*, Fusion Engineering and Design **84** (2009)
[6] F. Escourbiac *et al.*, 12th International Workshop on Plasma-Facing Materials and Components for Fusion (2009)
[7] J. Schlosser *et al.*, Nucl. Fusion **45** (2005)
[8] P. Gavila *et al.*, 26th Symposium On Fusion Technology (2010)
[9] M. Richou *et al.*, 26th Symposium On Fusion Technology (2010)
[10] A. Durocher *et al.*, Nuclear Fusion **47** (2007)
[11] J. Boscary *et al.*, Fusion Engineering and Design **43** (1998)
[12] J. Boscary *et al.*, International Journal of Heat and Mass Transfer **42** (1999)
[13] G. Vieder *et al.*, Fusion Engineering and Design **49-50** (2000)
[14] M. Roedig *et al.*, Fusion Engineering and Design **61-62** (2002)
[15] M. Merola *et al.*, Journal of Nucl. Materials **307-311** (2002)