Definition Of Workable Acceptance Criteria For The ITER Divertor Plasma Facing Components Through Systematic Experimental Analysis

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Abstract. Experience has shown that the most critical part of a high heat flux (HHF) plasma facing component (PFC) is the armour to heat sink joint. An experimental study was launched in order to define acceptance criteria with regards to thermomechanical fatigue of the ITER Divertor PFCs. This study, which includes the manufacturing of samples with calibrated artificial defects relevant with the Divertor design, is reported in this paper. In particular, it was concluded that defects detectable with non-destructive examination (NDE) techniques appeared to be below the threshold of propagation during high heat flux experiments relevant with heat fluxes expected in ITER Divertor. On the basis of these results, a set of acceptance criteria was proposed and applied to the European vertical target medium-size qualification prototypes. It appeared that the ultrasonic and the SATIR NDE techniques allow to be confident in the capability of commissioning respectively W and CFC components reaching the required design values of the ITER Divertor PFCs: 98% of the inspected CFC monoblocks and 100% of W monoblock and flat tiles elements were declared acceptable.

1. Introduction

The ITER divertor system [1] is aimed at exhausting the alpha particles and reducing the impurity content of the plasma. It consists essentially of two parts: the plasma facing components (PFCs) and a massive support structure called cassette body. The PFCs are actively cooled thermal shields devoted to sustain the heat fluxes– in the range 5-20 MW/m²- and particle fluxes in steady-state and transient conditions. The cassette body is aimed at supporting the PFCs, routing the water coolant and providing neutron shielding. In the PFCs, the failure of the heat sink to armour joints would compromise the performance of the divertor and potentially results in its failure and the shut down of the ITER machine. There are tens of thousands of such joints in the divertor assembly, either carbon fibre composite (CFC) or tungsten (W) to copper alloy (CuCrZr) joints. After extensive R&D effort, PFC prototype manufacturing is now mastered in industry [2], however, the need to ensure the same quality and performance throughout the manufacturing of the about 4000 plasma-facing units of the ITER divertor poses additional challenge [3].

As a consequence, thermal performance evaluation is required at the end of manufacturing in order to detect and quantify potential imperfections. As commonly developed for any industrial field, for each type of imperfection, criteria should allow for each component to decide for its acceptance and must consequently be defined in advance of the series reception.

Experience shows that the most critical part of a PFC is the armour to heat sink joint [4], therefore, maximum dimensions and location of an acceptable defect at the interfaces of bonding appeared to be relevant criteria with regards to thermomechanical fatigue. By definition, an acceptable imperfection is one, if detectable by Non Destructive Examination (NDE) techniques will remain stable during High Heat Flux (HHF) testing. The NDE SATIR technique is considered as well adapted to assess the final quality of the joints between the CFC armoured monoblocks (see §2 for details of the design) and the cooling tube [5] whereas

ultrasonic detection technique is selected for metallic interfaces inspections and may be complementary with SATIR technique in case of CFC inspection [6].
In the first part of this study, the NDE and the related HHF testing of samples with calibrated artificial defects at the bonding interfaces are reported.
In the second part, this paper analyzes the SATIR inspections results performed on the Vertical Target Divertor Qualification Prototypes (VTQP) manufactured by European industry. Experimental results obtained on CFC samples with calibrated artificial defects are extended to the VTQP and it is proposed a decision on the acceptance of these prototypes with reference to the acceptance criteria defined by ITER Organization on the basis of the first part of the study.

2- Description of samples with calibrated artificial defects

108 samples were procured via industry for the study. Two sets were manufactured, each set consisted of: 26 CFC NB31 (SAFRAN trademark) monoblocks, 14 W monoblocks and 14 W flat tiles. The CFC monoblock design option is planned to be used in the lower part of the Divertor Vertical Target subject to the highest heat flux whereas W monoblock and W flat tile design options are planned to be used at the upper part of the target [1].
For the 3 design options (Fig.1), an interlayer of pure Copper (Cu) was used as compliant layer between the armour material and the CuCrZr heat sink (12 mm inner diameter, 15 mm outer).
The first set was manufactured by PLANSEE SE company, the technologies of joining selected were Active Metal Casting (AMC®) for CFC/Cu joint and Hot Isostatic Pressure technique (HIP) for Cu/CuCrZr joint in case of the CFC NB31 monoblock design option; copper casting and HIP for the W monoblock and for the W flat tile options.
The second set was manufactured by ANSALDO Ricerche company, the technologies of joining selected for this study were : Pre-Brazed Casting (PBC) for CFC/Cu joint and Hot Radial Pressing technique (HRP) for Cu/CuCrZr joint in case of the CFC NB31 monoblock design option; copper casting and HRP for the W monoblock and brazing for the W flat tile options.
Each sample was made of one unique monoblock or one flat tile, with reduced armour thickness for HHF testing (4.5 mm for CFC , 5.5 mm for W). Along the axis of the 150 mm CuCrZr tube, the CFC monoblock, W monoblock and W flat tile samples were respectively 20, 12 and 25 mm length.

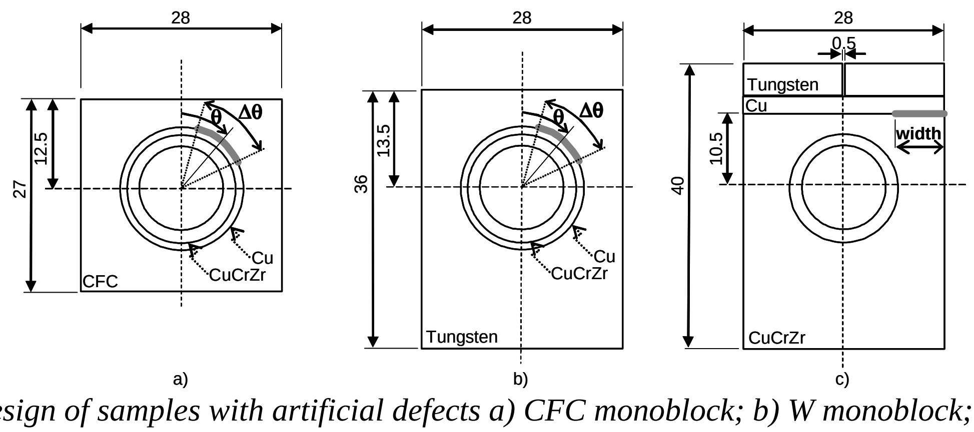


Fig.1 : Design of samples with artificial defects a) CFC monoblock; b) W monoblock; c) W flat tile

The artificial defects on PLANSEE samples were implemented by Electro Discharge Machining (EDM) with a wire of 0.3 mm diameter. In case of ANSALDO, the artificial defects on monoblock samples were implemented by preventing the wetting of CFC surface by local lack of pre-brazed casting alloy and by a stop-off coating for defects at W/Cu and Cu/CuCrZr interfaces. For W flat tile geometry the defects at W/Cu and Cu/CuCrZr interfaces were provided by EDM and stop off technique, respectively. During previous studies [4], it was calculated that the defects to be implemented into the CFC samples must follow the following rules of design : do not degrade margin to Critical Heat Flux occurrence below 1.4; do not increase CFC surface temperature higher than 2000°C (to limit erosion) or copper temperature higher than 550°C during normal operation (to avoid crack formation). These studies allowed to conclude that the calculated maximum acceptable defect in case of CFC monoblock geometry was an extension of 60° angle ($\Delta\theta_{2D}$) at a 30° position (θ) at the CFC/Cu interface (see Fig.1 for defects definition). In order to study the fatigue behaviour of such range of defects and extending these results to W monoblock geometry and W flat tile geometry, it was decided to manufacture the 108 samples with defects extensions and positions as detailed in Table 1. All the implemented defects has the same axial length L than the monoblock or the tile length[1].

Interface	CFC monoblock	W monoblock	W flat tile
Armour / Cu	θ=0° : Δθ= 20, 35, 50, 65° θ=45° : Δθ= 20, 35, 50, 65°	θ=0° : Δθ= 15, 30, 45°	2, 4, 6 mm (edge)
Cu / CuCrZr	θ=0° : Δθ= 40° θ=45° : Δθ= 20, 40, 60°	θ=0° : Δθ= 15, 30, 45°	2, 4, 6 mm (edge)

Table 1: Specified artificial defects interface, dimensions and locations

3- Non Destructive Examination

3.1 Ultra Sound (US) technique

NDE by US technique was found reliable in case of W/Cu or Cu/CuCrZr interfaces. For these metallic materials, it can be stated that a defect lower than 2mm width in case of flat tile geometry or 20° extension in case of monoblock geometry can reliably be detected [6].

3.2 SATIR technique

The principle of SATIR technique [7] is based on the detection of a delay of the surface temperature evolution measured by infrared thermography during a fast decreasing of the water temperature flowing in the cooling tube. An imperfection at one of the joints or into a material may create a thermal resistance so that the delay increases during the transient thermal regime. This delay is measured by comparison with the thermal behaviour of a "defect-free" reference component. The maximum value of this delay – called DTref_max (°C) - is calculated for each pixel on the infrared images. SATIR is a functional technique which can be used both for W and CFC materials. In this study, the technique was applied to CFC monoblock samples.

[1] In the second part of the study, some "natural" defects will be detected with a length L shorter than the CFC monoblock length. In that case, the extension of the defect will be noted ($\Delta\theta_{3D}$) to underlines the fact that the thermal situation becomes three-dimensional (3D).

Testing protocol

A cartography of DT_ref_max was obtained in front side, then the samples were +90° turned for a second examination (right side) and finally turned of -180° (left side) for a third and last examination. A three-dimensional reconstruction can be done as proposed Fig.2.

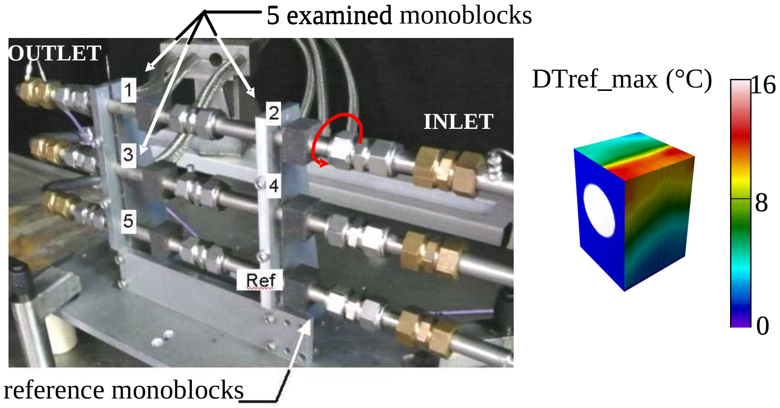


Fig.2 : 6 CFC monoblock samples connected to SATIR facility – 3D reconstruction of DTref_max by pixel for one sample

Results

The maximum value of the DT_ref_max was extracted from the cartography of each block and plotted as a function of defect extension for a given interface and position. Measurements were obtained on the front side of CFC monoblocks with defects located at 0° and 45°, CFC interface (Fig.3). Measurements were found reproducible with errors bars of +/- 1.5°C. The horizontal line represents the threshold below which the measure is considered in the noise from the SATIR facility and from the scattering of the CFC thermal properties (set at 5% for CFC NB31). The threshold of detection in terms of defect extension is approximately 20°. In parallel with the experimental activities, a bi-dimensional (2D) non-linear ANSYS model was developed to simulate the SATIR inspection thermal process, the results – 3 curves are proposed for min. average and max. values of CFC conductivities - are plotted and compare satisfactory with experiments.

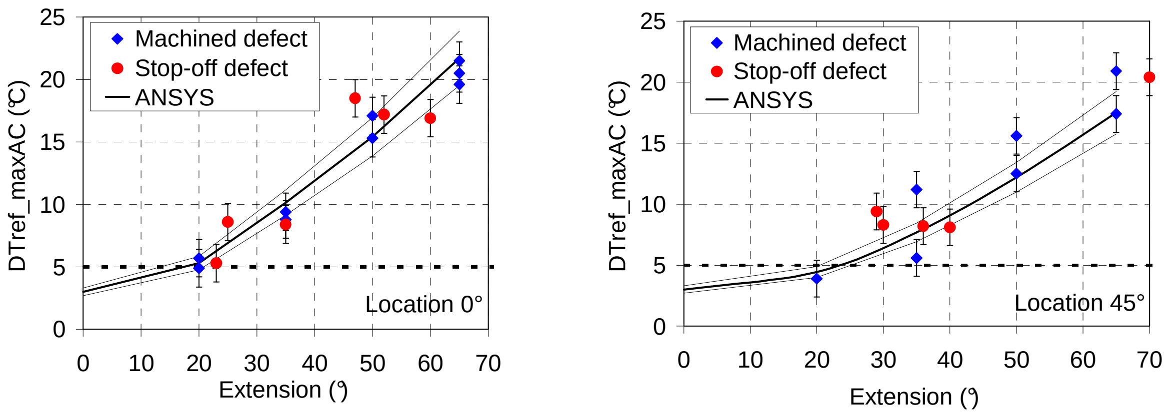


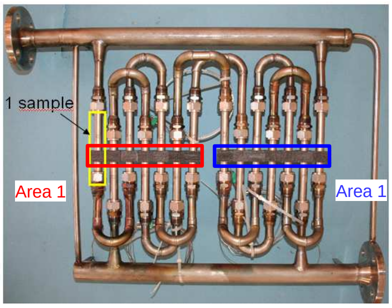
Fig.3 : DTref_max vs defect extension at CFC/Copper interface

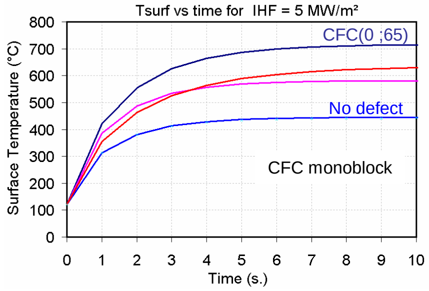
In case of defects implemented by preventing the wetting of CFC surface with local lack of pre-brazed casting or by EDM or stop-off coating for defects at W/Cu and Cu/CuCrZr brazed interfaces, it appeared that the defects extensions were not perfectly controlled. In this latter case W/Cu and Cu/CuCrZr interfaces defects extensions and positions were estimated by US NDE technique.

4 - High Heat Flux testing

4.1 Testing protocol

8 mock-ups were prepared for high heat flux (HHF) testing at FE200 facility [5] with a maximum of 14 samples per mock-up (maximum possible with regards to water loop pressure drop and available flow rate) (Fig. 4a). Alternative heating was done by the electron beam sweeping: 10 sec on Area 1, 10 sec in Area 2. Typically, the thermal steady-state was reached after a few seconds (Fig.4b).





a) b)

Fig.4 : a) Mock-up prepared for HHF testing ; b) thermal behaviour of samples

Selected heat loads on the 8 mock-ups were –from fatigue point of view - relevant with ITER Divertor design values [1]: a first cycling step of 3000 cycles at 10 MW/m² then a second cycling step of 500 cycles at 20 MW/m² on CFC and W monoblocks (resp. 5 and 10 MW/m² on W flat tile), a thermal mapping at 5 MW/m² being performed initially and between each cycling step. The second cycling step performed on the two W designs was aimed at investigate the possibility to use these designs on the lower part of the Divertor vertical target, for a full-tungsten divertor option.

4.3 Results

Surface temperature was measured by infrared thermography in order to estimate the thermal impact of a defect presence and potential propagation. During the study it was decided to use the following criteria to propose the rejection of a sample : rejection if Max(Tsurf-Twater) increasing is higher than 30% (unity : °C) at steady-state from a thermal mapping to the following one.
As example of results obtained during an HHF testing campaign, infrared measurements of first, intermediate and final thermal mapping are reported Fig.5 (respectively square, circle and triangle marks). A non-linear ANSYS model is also reported (line). Defects positions and extensions are indicated in transparency at the bottom of the graph for each sample marked M1-M14. Samples rejected are indicated with red circles. In this example, the defects implemented on the CFC monoblocks showed temperature initially consistent with the modelling taking account of CFC thermal properties variability. As variation of surface temperature is weak (~less than 100°C) from initial to second thermal mapping, it was stated that the implemented defects did not propagate during the first step of cycling at 10 MW/m². Afterwards, a majority of the defects at the interface CFC/Copper with an extension 50-65° propagated during the second step of cycling at 20 MW/m².

This result demonstrates that CFC monoblock design is suitable for heat fluxes expected at the lower part of the Divertor vertical target with reasonable tolerance to imperfections of manufacturing. For W flat tile and W monoblocks, the HHF experiments demonstrated that these options are suitable for heat fluxes up to 10 MW/m² at steady-state but need more development for higher values, which means for use at the lower part of the vertical target.

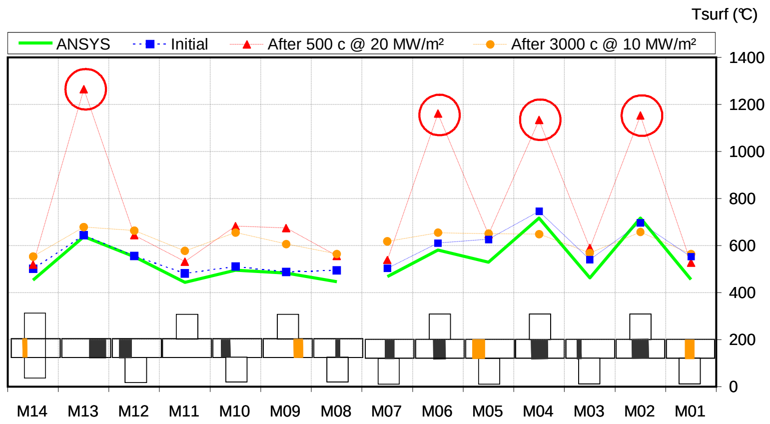


Fig 5 : Thermal mapping of 14 CFC monoblocks – defects are symbolized in black (*resp.* orange) for CFC/Copper (resp. Copper/CuCrZr) interface

5- Proposal of acceptance criteria

The above experimental results obtained on the 108 samples (detailed in [8]) showed that defects detectable with NDE techniques appeared to be below the threshold of propagation during HHF experiments. On this basis, a proposal of acceptance criteria was set in agreement with ITER Org : $\Delta\theta_{2D}^{lim}$.(° angle) and w_{2D}^{lim} (mm) are the maximum acceptable extension of defects for respectively monoblock and flat tile designs options. For one poloidal unit of the divertor, if one of the blocks or the tiles does not meet the following criteria (Table 2), the unit is rejected.

CFC monoblock		W monoblock	W flat tile
CFC/Cu	Cu/CuCrZr	W/Cu/CuCrZr	W/Cu/CuCrZr
$\Delta\theta_{2D}^{lim}$	$\Delta\theta_{2D}^{lim}$	$\Delta\theta_{2D}^{lim}$	w_{2D}^{lim}
60° (50° in top part (-45 ;+45°)	40°	50°	4 mm

Table 2 : proposal of acceptance criteria with regards to fatigue

6- SATIR inspection of Vertical Target Qualification Prototypes (VTQP)

6.1 Description of VTQP

Basically, one VTQP includes 3 HHF units. Three batches of HHF units manufactured by PLANSEE SE Company and ANSALDO Ricerche were received at CEA Cadarache. The CFC monoblock part of HHF units were straight and consisted of eleven CFC tiles with the same geometry of the previous samples except CFC thickness and grade (7 mm of NB41 to be compared with 4.5 mm of NB31). The SATIR inspection was performed on the CFC part of the HHF units prior to the insertion of the twisted tape and prior to the assembly of the components onto a steel support structure to assemble the VTQP. The curved part of each HHF unit was made of either W monoblocks (Fig.6) or W flat tile. Metallic joints of the HHF units including the Cu to CuCrZr in case of CFC monoblocks were controlled by the manufacturer without evidence of defect.

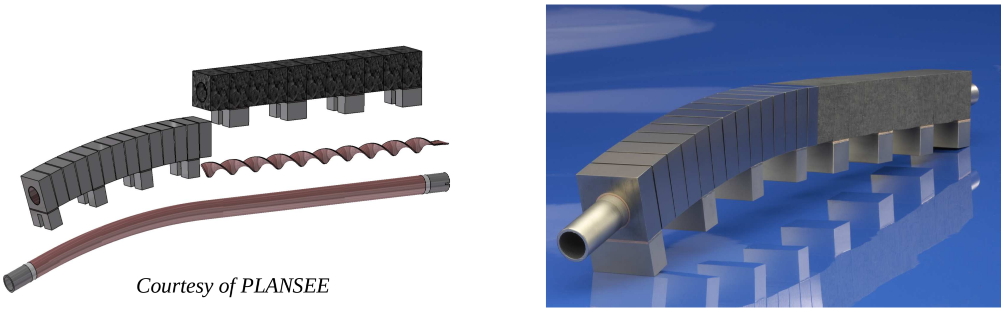


Fig 6 : HHF unit design (full-monoblock option)

6.2 SATIR image processing

The testing protocol described in 3.2.1 was applied to the CFC parts of the HHF units, then infrared images of DTref_max by pixel were processed.

Determination of the defect position θ and length L

Estimation of the position θ and of the length (L, in mm) of a defect are given by the geometric projection [9] of the defect at the CFC/Cu interface, taking into account of the orthotropy ratio of the CFC thermal properties (Fig. 7). The error margin on the estimation of the defect position is evaluated at ± 5° angle, ± 2 pixels (~2mm) on the length estimation.

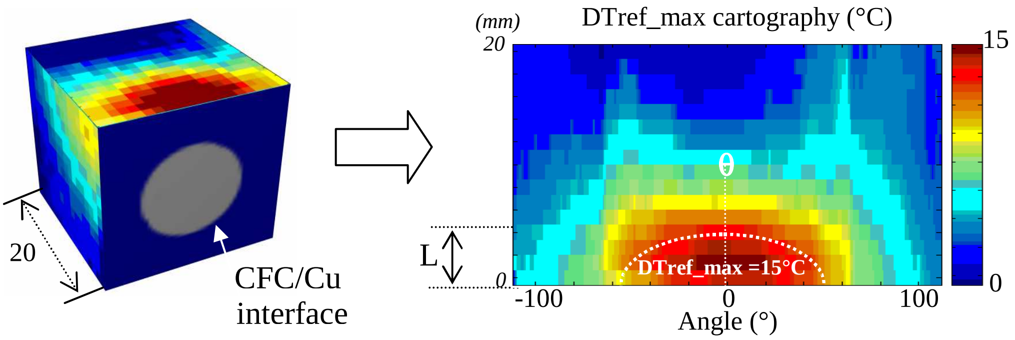


Fig 7 : Projection of DTref_max cartography on the developped interface for position θ and length estimation L

Determination of the extension $\Delta\theta_{2D}$ and $\Delta\theta_{3D}$

To estimate the defect extension $\Delta\theta_{3D}$ for a defect shorter than $L_{monoblock}$ from a DTref_Max measurement, a 3D approach is needed. The analysis was carried out in two steps. First the 2D model developed during the previous study was set up and used to calculate $\Delta\theta_{2D}$ assuming that $L = L_{monoblock}$. Then a corrective coefficient "k" was used to obtain $\Delta\theta_{3D}$ with the following definition : $\Delta\theta_{3D} = \Delta\theta_{2D} / k$. The coefficient k being obtained by a set of 3D calculations of SATIR inspection thermal process and given in a form of abacus. For instance, for θ = 0° and $\Delta\theta_{2D}$ = 57°, $L/L_{monoblock}$ = 1/5 then k = 0.3, we obtain a 3D extension of the defect $\Delta\theta_{3D}$ = 190°.

6.3 Results - Table of Acceptance for VTQP

Assuming that the fatigue behaviour of CFC monoblocks from samples and from HHF units are comparable, there is a need also to account for a length of the defect lower than the axial length of the monoblock. A method was proposed based on the use of an empirical Factor (F), F=1 if $L > L_{monoblock} / 3$ and $F=L_{monoblock} / 3L$ if $L \leq L_{monoblock} / 3$. Then, F is applied to $\Delta\theta_{2D}^{lim}$ to obtain $\Delta\theta_{3D}^{lim}$ by assuming $\Delta\theta_{3D}^{lim} = \Delta\theta_{2D}^{lim} \times F$.
A table of acceptance for each CFC monoblock was built in order to propose a status with regards to the acceptance criteria (Table 3), the component is declared accepted in case of successful inspection, questionable if not.
98% of the 165 inspected CFC monoblocks met both criteria and 100% of the W monoblocks and flat tiles met criteria C1. Due to the presence of 11 monoblocks per HHF unit, this led to 80% of the HHF units acceptance.

# CFC monoblock	*SATIR inspection results*			*3D processing*				*Acceptance*
	DTref_max (°C) *±1.5*	θ (°) *±5*	L *±1pixel*	k	$\Delta\theta_{3D}$ (°) *±8*	F	$\Delta\theta_{3D}^{lim}$ (°)	
1	14.8	0	$1/5L_{monoblock}$	0.28	190	5/3	83	Questionable
2	5.7	-45	$L_{monoblock}$	1	32	1	50	Accepted

Table 3 : Example of table of acceptance for 2 monoblocks

7. Conclusion

Experimental activity on HHF testing and NDE were performed on the 3 PFC design options CFC monoblock, W monoblock and W flat tile in view of their use for the ITER Divertor. This work provided the experimental basis to set up the acceptance criteria with regards to the thermomechanical fatigue of such PFCs. These criteria were applied to the European Vertical Target Qualification Prototypes, in particular with the SATIR NDE technique : 80 % of the inspected units were declared acceptable. Such results allow to be confident in the capability to procure components meeting ITER specification and design parameters. The next step of this qualification work will concern the high heat flux testing of units, which will allow the consolidation of the acceptance criteria defined in the frame of the EU procurement for the Inner Vertical target of the ITER Divertor.

8. Acknowledgments

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