Acceptance tests of the industrial series manufacturing of WEST ITER-like tungsten actively cooled divertor

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Abstract

The activelly cooled plasma facing units (PFUs) constituting the WEST lower divertor must meet strict technical specifications before their installation into the WEST tokamak. The tests performed at CEA lead mainly: to provide information on the feasibility to attach mechanically PFUs on sectors, to ensure geometrical tolerances for the welding of PFUs to water manifolds, to check the PFU vacuum tightness and to confirm the PFUs heat exhaust capability. Using high heat flux (HHF) test facilities, such as HADES at CEA-Cadarache and GLADIS at IPP-Garching, ~5% of the PFU production was tested. Infrared thermography (IR) tests were also performed (~24% of the PFU production tested). We show that PFUs are with a quality in agreement to the requirements and that the assessement of the heat exhaust capability during the series production is needed. Based on statistical approaches, this work also provides information on the methods to assess the quality of tested components using statistic process control.

Keywords: acceptance tests, ITER-like divertor target, statistical approach, statistic process control

1 Introduction

The WEST lower divertor is composed of 456 actively-cooled plasma-facing components called PFUs (Plasma Facing Units) using ITER tungsten monoblock technology [1]. They are assembled onto 12 independent toroidal sectors through mechanical fixation and welding to a cooling system [2]. As for ITER vertical target, PFUs must sustain 10MW/m² in steady state and 20MW/m² in transient [3]. Based on the thermal-hydraulic conditions circulating in the ITER vertical targets [4] and on the WEST hydraulic cooling loop characteristics, the inlet pressure and coolant temperature are set in WEST at 2.5MPa and 70°C, respectively and the coolant velocity is ~10m/s.Before launching the PFUs series production, the qualification of the manufacturing technologies to achieve the expected heat exhaust capability were performed on mock-ups [5]. To be installed in the WEST tokamak, these PFUs must meet technical specifications (dimensions, material, heat exhaust capability …). This paper presents a description of the PFUs, the non-destructive tests performed during the series production to ensure their good conformity and the acceptance tests performed at CEA and IPP. Information on the criteria and statistic process control (SPC) strategy that can be used to assess the heat exhaust capability are detailed.

2 Plasma Facing Unit description, main manufacturing steps and tests performed by the manufacturer

The PFUs were manufactured by AT&M company (China) using hot isostatic pressing (HIP) for bonding W blocks to CuCrZr tube with an intermediate Cu ring. Involved materials comply with the ITER specification [6]. The geometry of the PFU is detailed in [7], a sketch is presented in Figure 1. A swirl (twist ratio = 2, thickness = 0.8 mm) is installed in the cooling channel (inner diameter = 12 mm) to enhance the cooling capability. The PFU have 1mm x 1mm chamfers on the poloidal edge located on the leading edge side and on both sides for the private heat flux region (Figure 1). As for ITER vertical target, toroidally beveled blocks [3] (1°) are present on the PFU (except for blocks on the private heat flux region). The orientation is dependent on the incident flux direction. The poloidal width of blocks varies from 26.3 mm to 31.8 mm to adapt to the WEST torus shape.

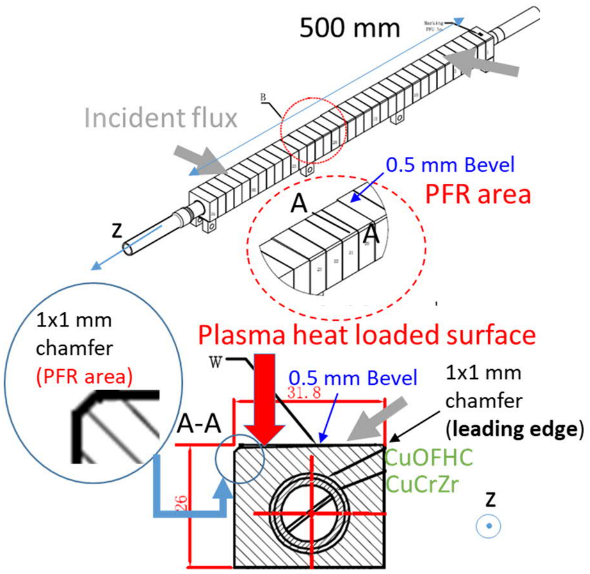

Figure 1: Schematic view of a WEST ITER like PFU

To produce the final PFU, the main manufacturing steps and reception tests are [8]:

(1) Manufacturing of CuCrZr, steel 316L and Inconel 625 tubes after which dimensional and eddy current tests are performed for CuCrZr tubes

(2) Manufacturing of W plates after which ultrasonic testing (UT) inspection and thermo-physical and hardness tests are performed. Then W blocks are machined into the W plates.

(3) Manufacturing of W/Cu monoblock by hot isostatic pressure (HIP) after which dimensional and UT inspection are performed

(4) Steel legs bonded by brazing on Cu interlayer after which dimensional and UT inspections are performed

(5) Assembly of W/Cu monoblock on CuCrZr tube by HIP after which dimensional and UT inspections are performed

(6) Fixing of the swirl, welding of Inconel and steel tubes: qualified after the results of X-ray inspection

(7) Final machining with electrical discharge machining, grinding and milling:followed by hot helium leak test

Imperfections at W to Cu and Cu to CuCrZr interfaces, are quantified by their position (θ / °), extension (Δθ / °) and axial length (Δx / mm) (Figure 2). The maximum acceptable axial length is set to fulfill acceptance criteria defined for the ITER inner vertical targets [9][10]. However, the WEST PFU acceptance criteria is more restrictive than the one related to he ITER inner vertical target. This was possible owing to the feedback provided by AT&M company on the achievable quality after manufacturing.

Among the 456 PFUs delivered to CEA, 83 acceptable imperfections are present within 64 different PFUs (14% of the delivered PFUs) (Figure 3). Imperfections are mainly located on the first (30%) and the last blocks (60%).

In total 456 PFUs were delivered within 9 "delivery batches" to CEA. For the assessment of the thermal solicitation handling capability, the quality of the PFUs is analyzed according to "HIP batch". This corresponds to a group of PFUs which undergone identical HIP cycle conditions (step 5 in the manufacturing process).

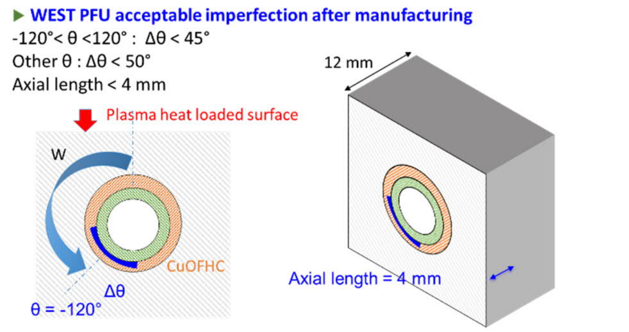

Figure 2: Sketch of imperfection positioned at the interface between W and CuOFHC and acceptance criteria for WEST PFUs

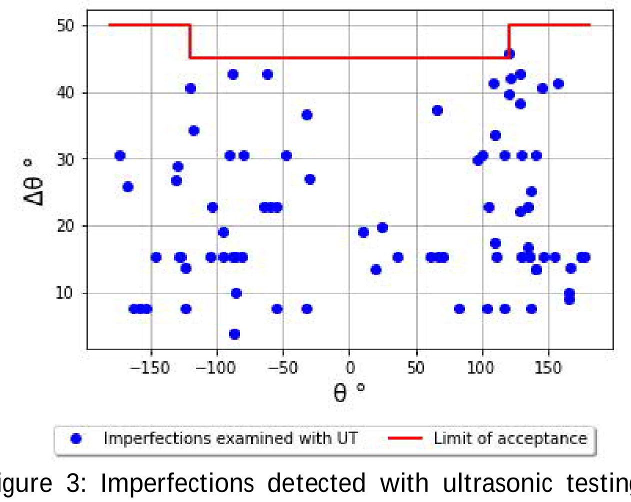

Figure 3: Imperfections detected with ultrasonic testing after the manufacturing step n°5

3 Acceptance tests

The tests performed at CEA and related criteria are presented in Figure 4. The acceptance tests performed at CEA lead: to provide information on the feasibility to attach mechanically PFUs on sectors, to ensure geometrical tolerances for the welding of PFUs to water manifolds, to check the PFU vacuum tightness and to ensure PFU alignment in WEST vacuum chamber, this later avoiding leading edge during tokamak operation. To this aim dimensional, visual, hardness and tightness tests are performed.

Since the PFUs have to sustain 10MW/m² in steady state, CEA tests aim also to confirm the PFUs heat exhaust capability. The heat exhaust capability is attributed to the combination of several PFU characteristics such as: the quality of the PFU hydraulic cooling system, the quality of the PFU interfaces (W to Cu and Cu to CuCrZr), the relevancy of materials (W, Cu, CuCrZr) thermal properties. Heat exhaust is assessed using Infrared thermography (IR) [11][12] and high heat flux test (HHF) facilities [13][14]. In this paper, HHF tests are used as a non-destructive, integral quality assessment tests complementary to the NDE performed by the manufacturer.

A PFU is declared as accepted if all the requirements are fulfilled. If it is not the case, PFU is declared as derogated or rejected. In particular, if no solution for its adaptation on WEST sector is possible then the PFU is declared as rejected.

The percentage of tested PFUs and the number of rejected PFUs, according to the acceptance tests, are presented in Table 1.

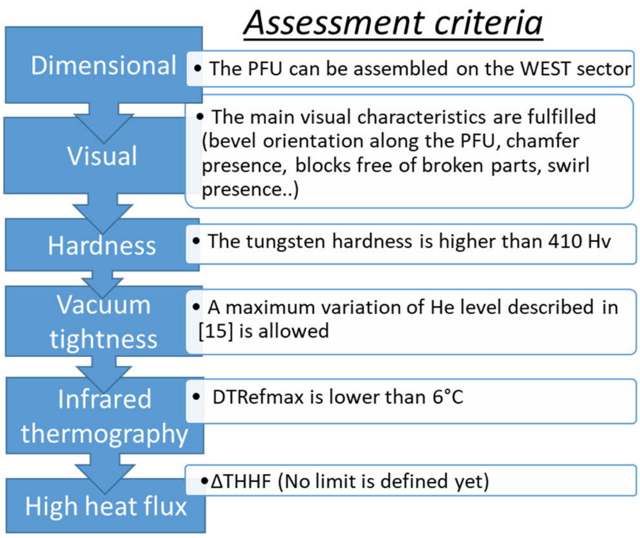

Figure 4: Assessment criteria and tests performed at CEA

	Visual	Dimensional	Tightness Cold He	Tightness Hot He	Hardness	Infrared thermography	High heat flux testing
Batch / HIP batch 1	100%	100%	100%	78%	21%	32%	12%
Batch / HIP batch > 1	100%	100%	100%	3%	20%	21%	3%
Rejected PFUs	0	0.2 %	0	0	0	1 PFU	-

Table 1: Percentage of tested PFUs and number of rejected

3.1 Dimensional, visual and hardness tests

As dimensional tests, a caliber is used to check the possibility to assemble the PFUs on the WEST sectors (Figure 5). Visual tests consists in checking the main visual characteristics of the PFUs described in section 2. The conformity of the tungsten hardness is checked using conventional Vickers hardness tests applying 30kg load during 15s. W is declared as conformed if Vickers hardness is higher than 410 Hv .

Figure 5: PFU caliber used for the dimensional tests

3.2 Vacuum tightness tests

Cold helium leak test aims at verifying the mechanical integrity of the multi-material junctions (CuCrZr to SS tubes via Inconel ring) of components at 20°C [15]. For the WEST PFUs, the same procedure and acceptance He level as the one described in [15] are used. Picture of PFUs during cold helium leak is presented in Figure 6 left.

Hot helium leak test aims at verifying the mechanical integrity of the multi-material junctions of PFUs under WEST operational conditions: baking up to 200°C and pressurization of the hydraulic network up to 4.5MPa (20°C) (Figure 7). For the WEST PFUs, the acceptance He level during testing are described in [15]. A special tooling was developed to test 40 PFUs in parallel (Figure 6 Right). The number of PFUs tested at the same time was set in accordance to the tank volume dedicated to the hot helium leak test and to the number of PFUs constituting the delivery batches. The test duration (mouting and dismounting included) is approximatively three weeks.

Figure 6: (Left) PFU during cold helium leak test (Right) tool enabling the hot helium leak testing of 40 PFUs in parallel

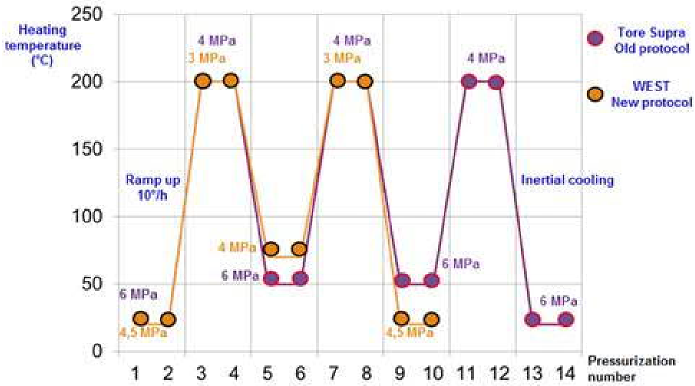

Figure 7: Cycles for hot helium leak tests performed for WEST PFUs– As comparison, the cycles performed for Tore Supra plasma facing components [15] are enclosed

3.3 Thermal solicitation handling capability

The thermal solicitation handling capability is checked using IR [11][12] and HHF testing [13][14].

For IR, the thermal solicitation is an abrupt variation of temperature in the cooling channel from 110°C to 10°C. For HHF tests, the thermal solicitation consists in applying heat flux in the range of 10MW/m² in steady state for 10s.

Quality assessment criterion are defined for both tests. For IR it is "DTRefmax", estimated as the maximum of difference, between the measured temperature on the tested PFU and on the PFU numerical reference, during imposed thermal solicitation [16]. Based on the relation between DTRefmax and the thermal behavior of the PFUs under HHF test, a maximum value of 6°C (called later "Max") has been set to declare the quality of the component as questionable [16]. For PFUs with DTRefmax higher than "Max", further investigations on the PFUs are performed, such as HHF tests.

For HHF tests, the difference of surface temperatures, estimated at given positions and number of cycles (ΔTHHF), is defined as assessment criteria [13]. For the moment, no maximum limit has been set to declare the quality of the component as questionable.

3.4 Measurement concepts in statistical quality control

In our study, statistical analysis is used to determine whether the measurements and manufacturing process (MP) functions properly or not (an adequate function fulfills the defined requirements on the acceptable quality of PFUs). Capabilities of IR measurements and of the production process are checked [13] [14]. MP is characterized by mean (m) and standard deviation values (s) of the DTRefmax and ΔTHHF distributions. For the different batches, MP is assessed. Anderson – Darling statistical test is performed to evaluate the hypothesis of rejecting the hypothesis of normal distribution on measured data [19].

Reproducibility measurements of DTRefmax are performed to assess the DTRefmax intrinsic variance. Measurements of ΔTHHF are difficult because the change of W emmissivity during HHF cycling influences this evaluation criterion. However, this effect should be minimized according to the method described in [13].

Statistic Process Control (SPC) methods are used to assess the quality of the MP functions. In other terms SPC methods are used to give a signal when the MP has moved away from the target. The target DTRefmax is characterized by a normal distribution (mean value (m_0), standard deviation (s_0)). If the MP mean value m deviates more than a quantity of δ (Eq 1), with regard to m_0, the MP has moved away from the target.

As statistical analyses are used to assess the potential deviation of the MP, the number of PFUs tested to evaluate the quality has to be taken with care. The number of tested PFUs is directly linked to the risk to decide to adjust the MP while it does not need to (α) and the risk to decide not to adjust the process while it needs to (β). Usually α is 0.27 % and β is 20 %. Moreover, in our case, the goal is to assess the stability and the capability of the MP to have DTRefmax below 6°C (Max), to control these points Shewhart charts are used in this study [17].

<u>Eq 1:</u> $\delta = \frac{Max - 3s_0 - m_0}{s_0}$

4 Summary of the acceptance tests

4.1 Visual, dimensional, hardness and tightness tests

100 % of the PFUS were tested visually, dimensionally and with cold helium leak tests. 2.6% of the PFUs have visual non-conformities (edges of blocks broken…) which imply to position them at a minimum of heat flux on the WEST sectors.

Applying dimensional tests, one PFU was rejected. This PFU has poloidal lengths out of the specifications, also emphasized by the manufacturer.

Vickers hardness tests were applied on W blocks of ~20 % of the delivered PFUs (Figure 8). All tested PFUs are conformed. A broad hardness distribution, due to tungsten specification, is obtained.

80% of the first batch was tested under hot helium leak test. All PFUs are conformed, it was consequently decided to reduce the number of tested PFUs (3%) for the remaining delivered PFUs. Conformity of all tested PFUs is obtained.

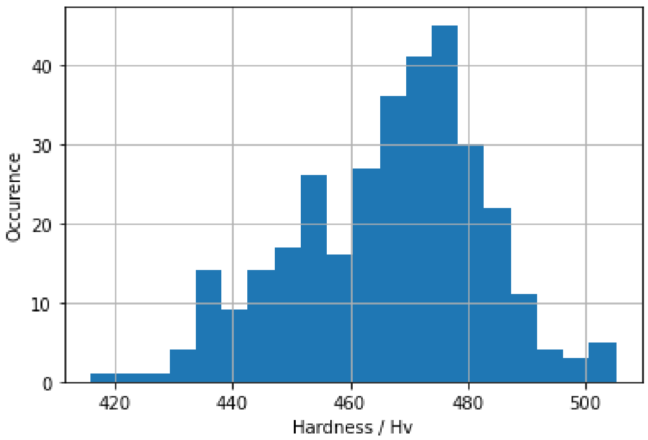

Figure 8: Histogram of measured tungsten hardness for the 89 PFUs (~300 tungsten blocks)

4.2 Infrared thermography

Based on 5 identical measurements performed on three different PFUs, intrinsic variance is estimated (0.6°C). Capability of IR is then calculated as 5.51%. As it is below 15% [17], IR can be considered as a good way to measure the required quality (i.e. DTRefmax lower than 6°C). It means that the use of IR test, applying the maximum DTRefmax allowable limit, will not lead to decide to adjust the MP while it does not need it. Capability of MP is estimated to 1.64, which is considered as medium [17] but very close to the limit of 1.67 for a good capability. In total 108 PFUs were tested (24%). For the first HIP batch, 32% of the PFUS were tested. DTRefmax distribution for this batch is plotted in Figure 9a. Normal distribution is fitted and not rejected by the Anderson darling statistical test. A mean value (m_0) of 0.87°C and a standard deviation (s_0) of 1.12°C are estimated. Based on Eq 1, the production deviates if a difference between mean values related to consecutive HIP batches is higher than 1.58°C. Normal distribution, tested and not rejected with Anderson – Darling statistical test, of all HIP batches are plotted in Figure 9b. A maximum deviation on mean m of 0.69°C is deduced, one can conclude that the MP is stable. Based on the quality of the MP and the DTRefmax which is necessary to detect (6°C), a sampling of 6 PFUs would have been sufficient to control according to the risks expressed in 3.4.

DTRefmax higher than "Max" are obtained on 8 PFUs (7% of the tested PFUs). 50% of these PFUs belongs to the first HIP batch. Based on the analysis of the first HIP batch, the proportion of block with defect detected by IR is 0.2 %. The probability to obtain one PFU with defect is 6.3%. Among the 8 PFUs with detected defects, 4 of them have imperfections only on the blocks located at extremity. Those PFUs are installed in WEST as blocks are located in a zone which is not heat loaded in WEST. For the 4 other PFUs, UT did not emphasize imperfection, those PFUs were or are about to be tested under HHF tests in HADES.

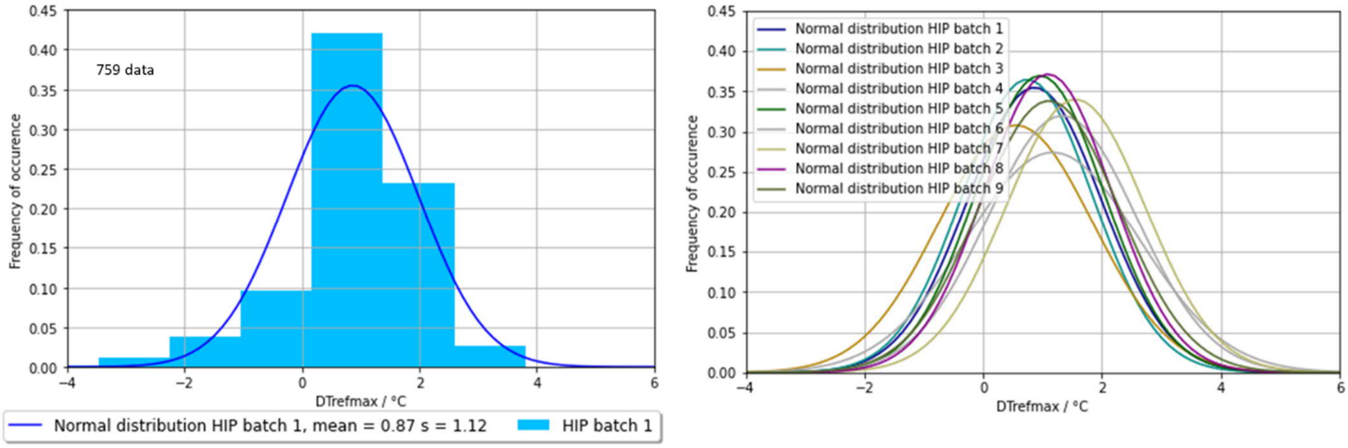

Figure 9: (Left) Histogram of Infrared thermography assessment criterion (DTRefmax) for the first HIP batch and related normal distribution (Right) normal distributions for delivered HIP batches

4.3 High heat flux tests

In total 23 PFUs were HHF tested (5%). An example of an assembly leading to test in parallel 6 PFUs in HADES (Inlet water cooling confitions : 10m/s, 2.5MPa, 70°C) is shown in Figure 10 .

For the HHF tests of the 12 PFUs which were performed in GLADIS [20], (Inlet water cooling confitions : 10m/s, 1MPa, 20°C) ΔTHHF distribution for all collected data and normal distribution, are plotted in Figure 11. No major deviation of the mean values along the HIP batches is noticed. The probability of defects in the remaining 433 untested PFUs was not assessed because the upper limit of ΔTHHF has not yet been defined.

For all the HHF tests, no overheating is noticed except for the PFUs for which DTRefmax is higher than the defined limit "Max" (6°C) [14]. Loaded at 6 MW/m², one PFU with a defect detected with IR testing, emphasizes a surface temperature ~50% higher than a PFU without defect. This last result emphasizes the consistency between IR and HHF results.

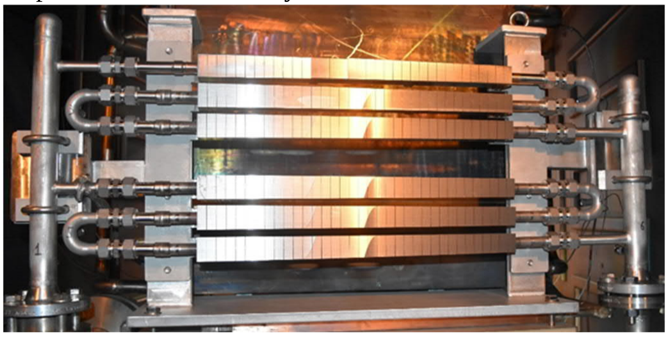

Figure 10: Assembly of 6 PFUs for HADES high heat flux testing

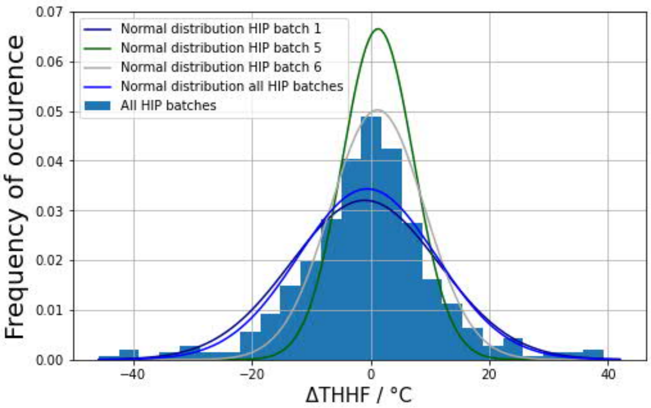

Figure 11: Histogram and normal distribution of HHF assessment criterion (**Δ**THHF) for all batches and normal distributions for the assessed HIP batches

5 Conclusions

To be operated in the WEST tokamak, plasma facing units constituting the lower divertor must meet strict technical specifications (dimensions, material …). To that end, non-destructive tests, such as visual and dimensional inspections, ultrasonic testing and leak testing, were performed on all PFUs during the series production to ensure their good conformity. After their reception at CEA, some acceptance tests are also performed. Practically, the tests performed at CEA lead: to provide information on the feasibility to attach mechanically PFUs on the sectors, to ensure the geometrical tolerances for the welding of PFUs to the water manifolds and to check the PFU vacuum tightness This study shows that all the PFUs are vacuum tight and that PFUs dimensions fit to the requirements.

Acceptance tests aim also to evaluate the PFUs heat exhaust capability, using high heat flux test facilities (~5% of the PFU production tested) such as HADES at CEA and GLADIS at IPP-Garching. Infrared thermography (IR) tests were also performed (~24% of the PFU production tested) before the HHF tests. These tests lead to the first conclusion that PFUs are with a quality fitting to the requirement. The imperfections detected with IR testing are in general consistent with the ones detected using ultrasonic testing, they are fully consistent with the ones obtained with HHF tests. The proportion of block with imperfection detected with IR testing is 0.2%. 7% of the tested PFUs are questionnable with regard to their hability to evacuate the heat. Half of these questionnable PFUs are installed in WEST since the blocks with defects are localised in a zone not heated in WEST. Based on statistical approach, IR can be considered as a good non-destructive examination to detect PFUs with a questionnable thermal sollicitation handling capability. The capability of the manufacturing process to produce PFU with the desired quality is closed to be declared as "good" and stable along the production.

Acknowledgements

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