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An operational non-destructive examination technique for ITER Divertor plasma facing components

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ABSTRACT

Within the framework of the Tore Supra Tokamak upgrade, a pioneering activity around the non-destructive infrared thermography techniques has been developed at the CEA to evaluate the capability of the plasma facing components to be efficiently cooled. In 1996 an active infrared thermography test bed based on the heat transient method was developed and was used as an inspection tool in order to guarantee the actively cooled plasma facing components performances. This paper deals with the improvements carried out on this infrared thermography test bed to obtain an accurate and reliable examination of the ITER Divertor, and highlights that infrared thermography facility is now an operational test bed for the commissioning of the full-scale ITER Divertor components.

1. Introduction

The high technology components used in plasma fusion devices, especially high heat flux Plasma Facing Components (PFC), require an efficient power exhaust capability. This characteristic can be only guaranteed by a very high level of quality control through a rigorous inspection method. Among all Non-Destructive Examinations (NDE), active infrared thermography is recognised as a functional inspection technique available today for testing the cooling performance of many structures involved in heat transfer. The plasma facing tiles on the loaded part of the ITER Divertor are made of Carbon Fibre Composite (CFC) with a high thermal conductivity. The cooling structure is made of Copper Chromium zirconium alloy (CuCrZr). The most critical part is the manufacture of the joint between CFC tiles and CuCrZr. The introduction of a compliant metallic joint accommodates the large mismatch in the thermal expansion coefficient between carbon and copper. As heat exhaust capability and lifetime of PFCs during in-situ operation are linked to the manufacturing quality, it is an absolute requirement to develop a reliable non-destructive inspection technique. An original technique named SATIR – French acronym of *Station Acquisition et Traitement InfraRouge* – was developed by CEA in order to evaluate the manufacturing process quality of PFC and has proved to be very efficient in terms of defect detection [1]. Notable SATIR test bed results were obtained on various actively cooled plasma facing components and allowing confidence in this method [2]. Consequently the technical requirements for the supply of International Thermonuclear Experimental Reactor (ITER) divertor targets stated that all copper cast layers on CFC armour should be subjected to 100% infrared thermographic examination, such as the CEA developed SATIR test [3].

2. Principle of satir test

The principle of SATIR test is based on the detection of a time delay in the surface temperature evolution produced through an abrupt variation of the water temperature flowing in the cooling tube. This delay is measured in comparison to the thermal behaviour of a 'defect-free' reference target. This is made by an alternate flow of cold (5 °C) and hot (95 °C) water into the cooling channels. The PFCs are tested in parallel to the reference and a DTref_max criterion (Maximum of the transient temperature difference) was stated as maximum mismatch with respect to this reference. The connection between this mismatch and defect size was established both by means of finite element modelling, taking into account material physical properties variation, thickness effect and the background noise of the facility, and tests on samples with calibrated defects. The detailed principle of SATIR facility and DTref_max value were the subject of many papers [1,2].

3. Background

Within the framework of the acceptance criteria definition [4,5] which is being carried out by Europe and the ITER Organisation, the SATIR diagnostic has been identified as the basis test to decide upon the final acceptance of the series Divertor components. However, the ITER Divertor targets pose new challenges for several

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reasons. The armour thickness is two or three times higher than any existing component manufactured. Therefore, the sensitivity of the SATIR diagnostic, which also depends on the armour thickness, is lowered. In addition, the number of units to be tested is three or four times higher than any existing, or under construction, fusion machine and the inspected surface dimensions are about one order of magnitude higher. Consequently the total time required to test all the units increases accordingly. In order to increase the defect detection limit of the SATIR test bed, several possibilities have been assessed.

The installation in 2003 of a cooled digital infrared camera instead of a scanning infrared camera allowed to develop new infrared data processing, which led to a significant improvement of detection performance. The emissivity correction of the measured surface took an important part in this improvement, a pixel normalization algorithm has been developed which allowed the detection threshold to be reduced. In parallel, the spatial resolution was increased up to 4 pixel/mm^2.

In 2005, to increase the defect detection threshold, a new design study and finite element modelling were performed. Finite element calculations, performed on the ITER CFC monoblock, showed that the water velocity increase inside the PFC would significantly improve the sensitivity of the SATIR diagnostic: 47% of DTref improvement with a water velocity of 12 m/s in each element, corresponding to 10 m^3/h of global flow rate. These calculations also point out the interest of checking the elements on both top and lateral surface in order to locate more accurately the defect position. As regards minimization of requested test time, it was found that detection sensitivity was better during cooling cycle. Consequently, an advanced SATIR facility, able to check ITER Divertor targets, was built at the beginning of 2007.

4. Description of satir test bed

The test bed consists on two pressurized independent injection lines (Fig. 1), a hot and a cold one, synchronized by an industrial programmable logic controller. This improvement protects the pumps against the repetitive thermal shocks, which might degrade their lifetime. The test bed is based on two continuously operated pressurized stages where each water injection stage is designed to be operated all day under pressure. The thermographic analysis is done on unique thermal transient, which allows reduction of both the size of infrared films and requested tests time. The capacity of the heating source (1.2 m^3) was designed for successive tests on ITER Divertor targets, taking into account that re-heating is done on line between two SATIR tests within time duration of 15 min. The water heating power is 12KW for each tank for a maximum temperature of 100 °C. The test bed has to be freed from the pressure fluctuations induced by the external open loop water network. In order to avoid a depressurisation of the water sources and a boiling phase in the hot water tanks, a safety device was installed. These feeding pumps have the role of rebuilding and maintaining a constant pressure of 5 bars in the water network at the inlet of the water source tanks. The hot water injection line allows the prompt achievement of a working steady state of 95 °C. In order to obtain the steepest controlled thermal shock for the cooling cycle to 5 °C, a more controlled powerful pump was implemented on the cold water line. An industrial cooling unit using a tubular thermal exchanger was implemented on the test bed, improving the detection sensitivity by about 10% (calculated).

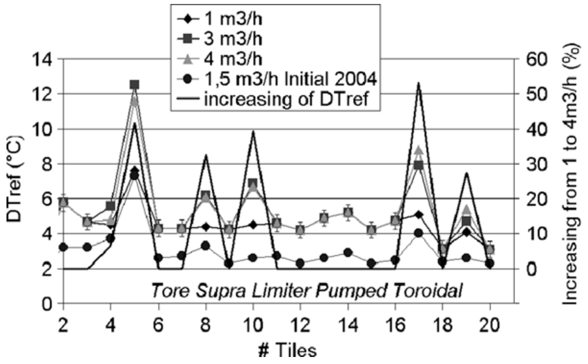

Fig. 2. Comparative SATIR results for the Tore Supra element, following various version of test bed.

5. Test bed validation

The approach used within the validation stage consisted of a preliminary study on a Tore Supra limiter component with calibrated defects located at different interfaces (CFC/Cu and Cu/CuCrZr). This element was tested for three water flow rates: 1, 3 and 4 m^3/h. The increase of water flow rate induces an improvement in the defect detection for the two interfaces CFC/Cu and Cu/CuCrZr. A deeper analysis of the flow rate effect was carried out on the DTref_max criterion. The comparative SATIR results, corresponding to the initial test bed (non-pressurized version) for the same element, were plotted on the same graph (Fig. 2). A significant gain in performance has been measured with a reproducible thermal signal.

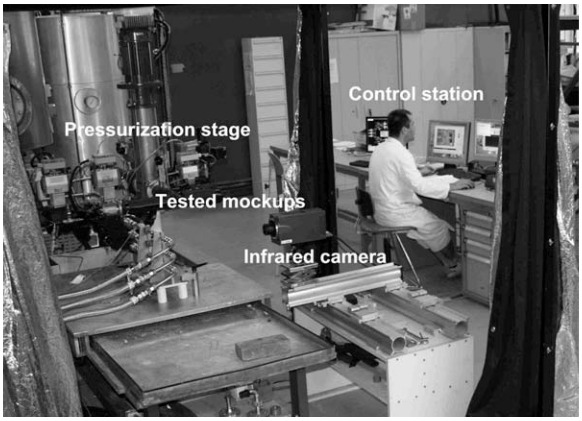

Fig. 1. View of SATIR test bed (mock-ups and infrared camera).

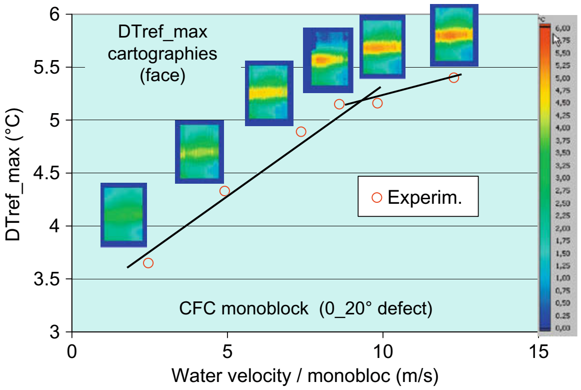

Fig. 3. Water velocity effect on the SATIR detection sensitivity (defect: 0° position and 20° extension).

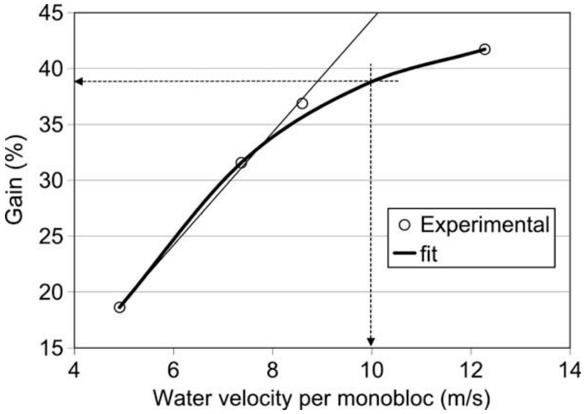

Fig. 4. Cumulated gain of detection performances (~38% for 10 m/s).

A similar study was carried out on one ITER CFC monoblock including a small calibrated defect (position 0°–extension 20°). This CFC sample was tested with six water flow rates: 1, 2, 3, 3.5, 4, 5 m3/h. Fig. 3 clearly shows a positive water velocity effect on the detection sensitivity for a calibrated defect of 0_20°. A non-linear phenomenon, at elevated flow rates, is observed, due to the pressure limit of the cooling line pump during the transient phase (<12 bar). Nevertheless, Fig. 4 presents a gain of detection performances of ~38% for 10 m/s (4 m^3/h each component) corresponding to the ITER requirements.

The full-scale hydraulic validation was done on two tubes – Divertor plasma-facing-unit-like (internal diameter 12 mm; tube of length 1500 mm) – installed in parallel on the SATIR_ITER test bed to assess the maximum value of the water flow rate. The maximum water flow rate has reached 5.5 m^3/h for each tube, corresponding to 13.5 m/s. The workable test conditions of SATIR diagnostic, in order to keep a reasonable reliability of the test bed, were estimated to be 4m^3/h for each tube, corresponding to the ITER requirements of 10 m/s.

6. Conclusion

Actively cooled plasma facing components of current plasma fusion devices require an increase in performance that has to be ensured by keeping a high inspection quality level. The major risk associated is that the heat loads can induce a partial or entire bond failure between the refractory tile and the heat sink if any large cracks remain. Consequently, a functional non-destructive examination – the SATIR test bed – based on a heat transfer method, was developed for the qualification of ITER Divertor plasma facing components. In order to increase the defect detection capability of the SATIR test bed, several possibilities have been considered and some of them implemented. In 2007, the increase of water velocity inside the tested component involving an increase of the convective heat transfer coefficient, improved significantly the sensitivity of the SATIR diagnostic. The SATIR test bed is now a mature NDE technique and entirely meets with the ITER requirements for the Divertor commissioning phase. During the ITER procurement phase, CEA will continue the R&D within the NDE field to still improve defect detection capability of SATIR and particularly utilizing signal processing methods [6].

Acknowledgments

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