The development and testing of the thermal break divertor monoblock target design delivering 20 MW/m^2 heat load capability

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Abstract. The design and development of a novel plasma facing component (for fusion power plants) is described. The component uses the existing "monoblock" construction which consists of a tungsten "block" joined via a copper interlayer to a through CuCrZr cooling pipe. In the new concept the interlayer stiffness and conductivity properties are tuned so that stress in the principal structural element of the component (the cooling pipe) is reduced. Following initial trials with off-the-shelf materials, the concept was realized by machined features in an otherwise solid copper interlayer. The shape and distribution of the features were tuned by Finite Element (FE) analyses subject to ITER Structural Design Criterion In-Vessel Components (SDC-IC) design rules. Proof of concept mock-ups were manufactured using a two stage brazing process verified by tomography and micrographic inspection. Full assemblies were inspected using ultrasound and thermographic (SATIR) test methods at ENEA and CEA respectively. High heat flux tests using IPP's GLADIS facility showed that 200 cycles at 20 MW/m^2 and five cycles at 25 MW/m^2 could be sustained without apparent component damage. Further testing and component development is planned.

Keywords: divertor target; high heat flux; thermal break; structured interlayer; brazing.

1. Introduction

The purpose of the divertor in fusion tokomaks is to remove plasma exhaust products and to extract useful heat for power generation. As such it experiences some of the highest plant heat loads. The divertor in the proposed European DEMO fusion power plant [1] , is required to withstand nominal heat load of 10 MW/m^2 during the expected 2 hour plasma pulses with and occasional overloads of 20 MW/m^2(estimated to last several seconds). The magnitude of the loads is similar to that in ITER but pulse durations are greater for DEMO (~ 2 hours) requiring components with a copper based heat sink to survive up to ~13 dpa neutron irradiation damage per full-power-years [2]. It is thus necessary that DEMO divertor components show increased robustness over those in ITER. The ITER divertor target is constructed from a tungsten armour block surrounding a CuCrZr cooling pipe with copper interlayer. This construction is termed a monoblock. The present work describes the development of a modified monoblock divertor target design for DEMO aiming to improve on the ITER monoblock performance. The design development is driven by analysis, and the principal method of performance improvement is achieved using a modified interlayer design.

The idea of modifying the interlayer properties to improve the monoblock performance was proposed by Li-Puma et al. [3] using the interlayer to create a thermal barrier for "heat flux repartition". This repartition (redistribution) encourages a more even distribution of flux around the circumference of the heat sink pipe, allowing higher total heat flux to be absorbed before the limiting local coolant heat transfer conditions (critical heat flux) are experienced. Barrett et al. [4] later showed that interlayer properties could be used to manipulate tungsten temperatures to reduce pipe stress caused by differential expansion. A contributing factor to this stress is the difference in the coefficient of thermal expansion (CTE) of armour and pipe materials. The ratio of tungsten and CuCrZr CTEs is typically approximately 1:4, depending on temperature. Figure 1 shows the calculated temperature distribution in a monoblock where thermal break methods are applied. It illustrates that by changing the thermal resistance of the interlayer, temperatures in areas of the tungsten can manipulated. This can be used to offset the CTE ratio effects, and so reduce differential expansion. In this example, to illustrate the effect, the ratio of peak surface temperature to pipe wall temperature (relative to ambient) has been arranged to be 4:1 (inverse of CTE ratio). In practice stress reduction is achieved from the integral of effects throughout the full component and so detailed FE methods are required to determine optimum temperature and thermal break conditions. Further studies showed that both interlayer conductivity and stiffness need to be modified to achieve optimum pipe stress reduction [4]. By raising the tungsten temperature generally, thermal break also has the advantage that brittleness in colder regions of the block is mitigated, but this has to be weighed against the disadvantage that the thickness of recrystalised layer generated under 20 MW/m^2 slow transient events will be increased.

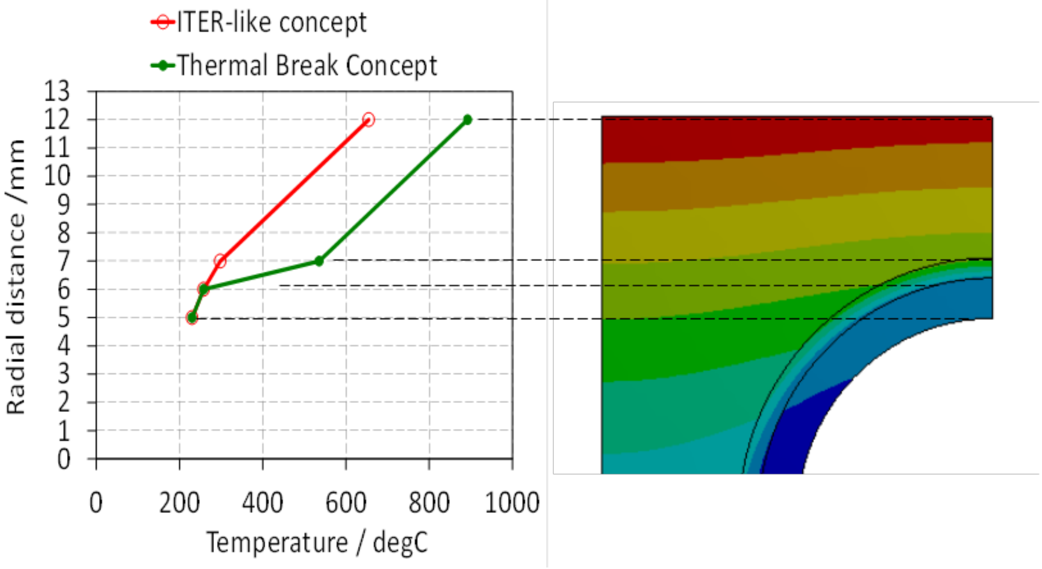

Figure 1 Showing how the modification to the interlayer thermal resistance of the thermal break concept (green line) over that of the ITER-like (red) can increase the tungsten temperature sufficiently to create (in this example) a 4:1 tungsten to pipe temperature ratio. This has a compensating effect for the 1:4 ratio of thermal expansion coefficients, leading to a reduction of differential expansion stress.

In the work described here, design merit was assessed using ITER's in-vessel components Structural Design Codes (SDC-IC) [5]. Of these, the rule guarding against progressive deformation, known as the "3Sm" rule was used. This rule in particular was used because it is based on the range of strain, which is thought to be independent of the (effectively unknown) residual stress effects (effects likely to be present particularly in monoblock structures). The rule is

$$P + \Delta Q < 3S_m, \qquad (1)$$

Where P = primary membrane +bending stress intensity, ΔQ is thermal (secondary) stress intensity range and $3S_m$ is approximately twice yield stress (~350Mpa at 300˚C for CuCrZr). Stress analysis of ITER-like designs indicate that the margin to failure on $3S_m$ is slim with a reserve factor close to 1.0 under 10 MW/m^2 heat flux [6], whereas a design with identical geometry but a thermal break / low stiffness interlayer has been shown theoretically to give an improved $3S_m$ reserve factor of 1.49 [7].

2. Design development

2.1. Use of readily available materials

Initial efforts to achieve a practical design realising previous theoretical proposals focused on using readily available materials for the thermal break interlayer. Two materials thought to have potentially the correct properties were feltmetal (a copper felt used on MAST-U as a compliant conductor) and copper foam (a filter material); see Figure 2a,b. The initial selection was largely subjective since structural property data for the materials was scant, and had to be determined by test and analysis as described below.

The proposed method of monoblock construction using these materials involved wrapping the interlayer material around the pipe and then encasing pipe and interlayer with a tungsten block formed in two halves (see Figure 2c). A rigid fix between the tungsten and the pipe is achieved using a "fixing block" on the back face of the component. The construction leads to a split in the plasma facing surface, but this was seen as beneficial, both for stress relief and as a feature that "anticipates" the deep cracking failures seen in existing ITER high heat flux tests [8].

The chosen joining method was vacuum brazing, which consequentially requires that interlayer materials must withstand thermal mismatch strains caused by a (circa) 1000˚C temperature change. The expected strain created by this process was approximately 25% across a 1mm interlayer (at a point farthest away from the "fixing block" centre of expansion). Tensile tests (Figure 2d) revealed that the felt was unable to sustain this strain without degradation. Further, thermal measurements using the apparatus described in Ref. [9] exposed problems with thermal conductivity levels. For one foam type trialled, the range of densities of commercially available materials were limited. Pore sizes were larger than desirable, and conductivity levels were low such that at 20 MW/m^2 surface heat load it was calculated that the foam would melt. As small poor higher density variant was also trialled, but this was manufactured using a different process and proved to be very brittle. These findings suggested therefore that neither material in there currently available form had all the required properties necessary for the envisaged thermal break component.

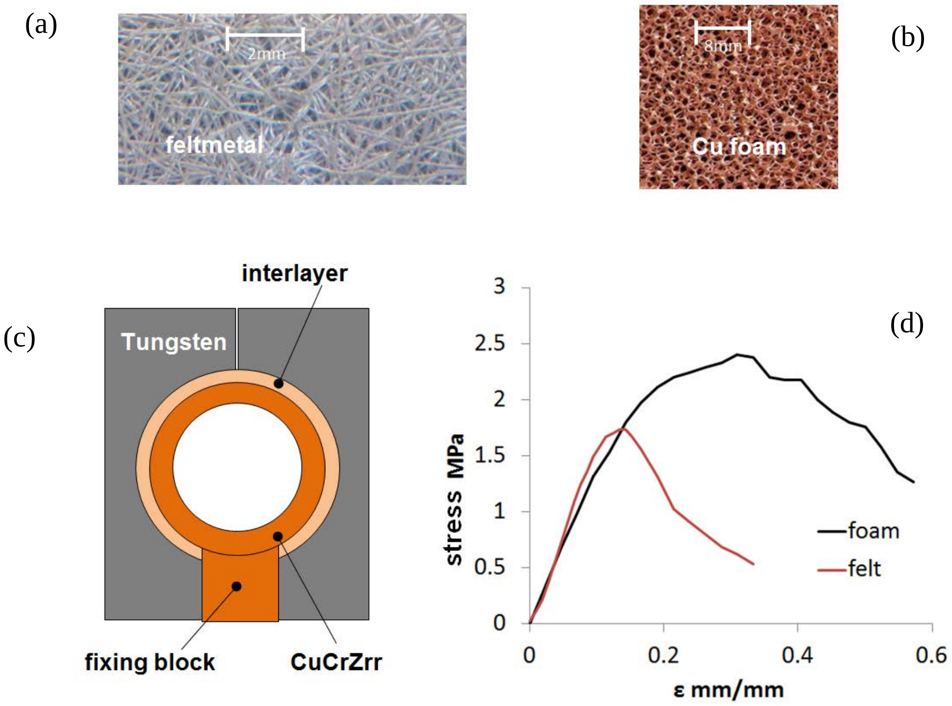

Figure 2 Showing two potential commercially available thermal break interlayer materials (a) felt metal and (b); copper foam). To ensure the tungsten is rigidly attached to the pipe, a construction method is proposed (c), consisting of a split tungsten block brought together around pre-assembled pipe and thermal break interlayer material, and joined to the pipe via a CuCrZr fixing block. The stress strain characteristics of the thermal break materials (d) were found to be insufficient for the needs of manufacturing.

2.2. Structured interlayer

An alternative method proposed for achieving the desired compliance and thermal break effect was by interlayer shape design, and in particular the use of features cut into an otherwise solid interlayer to reduce its stiffness and conductance. This method was termed a “structured” interlayer. An initial design incorporating radial inclined “spokes” connecting tungsten and pipe showed promising results (Figure 3). The $3S_m$ reserve factor for this design was 2.6.

Further extensive FE analysis was then carried out to optimise the shape and distribution of these spokes. Figure 4 shows the range of designs considered, and the resulting performance in terms of pipe $3S_m$ reserve factor. The figure summarises the observations made that:

a) the use of curved spokes over straight was not deemed significantly beneficial;
b) the use of a rigid connection between block and pipe (deemed necessary) did reduce performance, but an explicit block could be avoided by simply retaining a section of solid interlayer;
c) machined features achieved by simple drill or milling operations did reduce reserve factor still further, but these were still significantly better than those of the original ITER-like design; and
d) only a small number of spokes were required to achieve the desired effect.

From this study, it was concluded that only a small number of machined spokes was sufficient to demonstrate the desired effect considering factors of robustness and ease of manufacture.

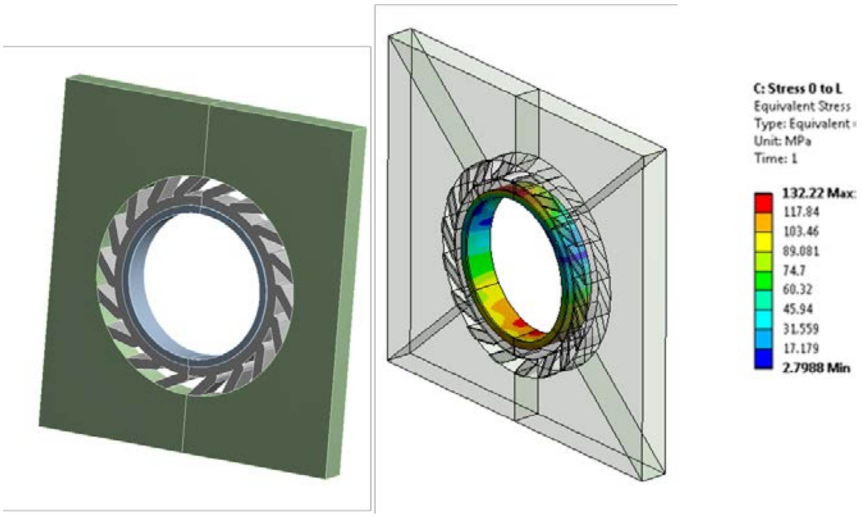

Figure 3 The initial structured interlayer design and analysis result indicating that pipe stresses can be reduced to 132MPa giving a reserve factor of 2.6 on the 3Sm design code limit of ~350MPa (at 300˚C)

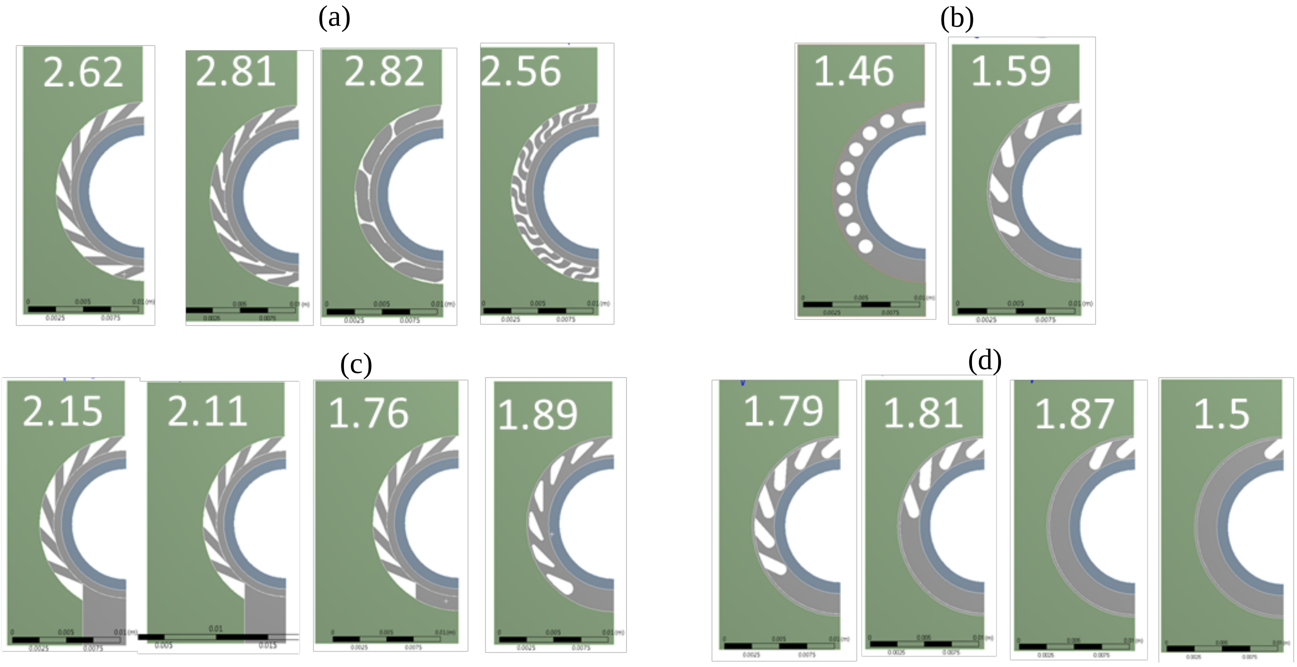

Figure 4 Showing styles of interlayer designs considered in order to gain an understanding of the factors within the proposed structured interlayer concept which contribute to reduced pipe stress including (a) spoke shape change, (b) method of pipe to tungsten fixing, (c) milling/drilling machining (i.e., avoiding potentially more expensive/complex EDM) and (d) number of compliant structural elements (spokes).

2.3. Interlayer assessment

Normally the interlayer is not considered a structural component and is not required to pass SDC-IC assessment rules; nonetheless analysis did show that the above increases in pipe stress reserve factors achieved using a structured interlayer were gained partially at the expense of an increase (~70%) in interlayer strain. This strain could be reduced by using radial spokes of the type shown in Figure 5a,c,d. However, attempts to confirm adequate interlayer fatigue life proved problematic because the proposed manufactured method resulted in analysis singularities at sharp corners, and so uncertainty in fatigue life calculation. Figure 5a shows an example analysis at 10 MW/m^2 load showing a peak strain range ($\Delta\varepsilon_p$) of 1.8% in the singularity, but more typically localised strains($\Delta\varepsilon_t$) of 0.8%. These values translate to cycles to “failure” in the range from several hundreds to several thousands of cycles as shown in the copper strain life curve in Figure 5b [10]. Similar range of strains are calculated for 20MW/m^2 heat load ($\Delta\varepsilon_p$ =6.0% $\Delta\varepsilon_t$ ~1.6%) with associated range in expected fatigue life as shown also in fig 5b. A number of additional factors contribute to uncertainty in life estimation: that analysed geometry is only an idealised representation of manufacture state (as illustrated in Figure 5d); that fatigue life curves represent only the time to crack initiation (which for this strain limited conditions can be considerably over-conservative); and that no fatigue life data exists at high temperatures >500˚C (at which the interlayer would be operating). It was concluded that further information could only be obtained by testing of physical mock-ups. The final spoke geometry selected for manufacture was that illustrated in Figure 5d, which gave a reasonable compromise between interlayer strain and pipe stress 3Sm reserve factor (in this case at 1.42).

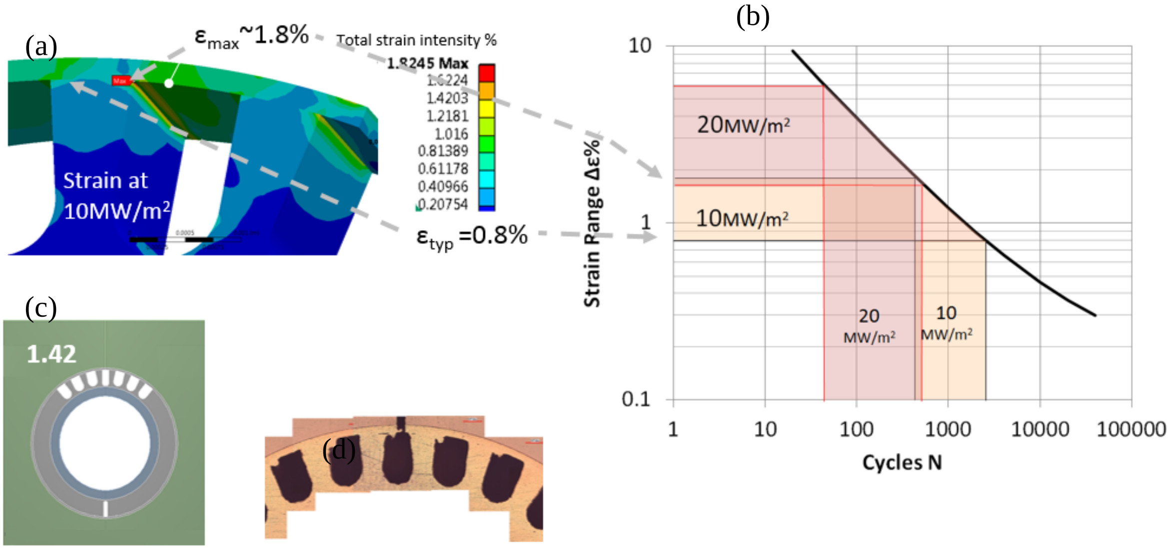

Figure 5 Showing (b) the range in the anticipated fatigue life expected (data extrapolated from [10]) for the proposed structured interlayer design with radial spokes with 1.42 3Sm reserve factor (c) based on FE strain range calculations (a). The FE calculations were imprecise because of strain singularities in the sharp corners of the idealised shape analysed (b) which compares only approximately to the real geometry of the manufactured part (d)

3. Manufacture

3.1. Fabrication process

Proof-of-concept mock-ups were fabricated using a two-stage vacuum braze process. Copper sleeves (for interlayer material) were first brazed to CuCrZr pipes and the structured interlayer geometry machined into the surface of the copper in the subsequent assembly. Tungsten monoblocks were cast with copper into the central bore. The copper was then machined out to leave a thin copper layer to facilitate the second Cu-to-Cu braze process where the W/Cu blocks are brazed (at 1000˚C) to the pipe/sleeve assembly to create the complete mock-up component. This final braze also including a precipitation hardening cycle (2hr at 475˚C).

3.2 Braze development

Initial brazing attempts used a commercially available nickel phosphor braze alloy. This has been shown to provide good joints provided gap thicknesses are well controlled. Joints from the first braze operation were inspected by computer tomography (at Rutherford Appleton Laboratory, UK) and by optical microscopy. These exposed the difficulty of achieving consistent braze clearance on cylindrical components, with inspection results showing cracked phosphor-rich zones in the over-thick braze areas. Tensile testing showed joints to be weak, failing by brittle fracture. Having already ascertained that significant level of strains occur in the interlayer joint area, a braze material having inherently ductile constituents of copper and gold was adopted. It was acknowledged that gold creates issues of transmutation to mercury, but deemed acceptable for proof of concept studies. Inspection of brazes using this material showed small thermal imperfections but no detrimental defects, and tensile tests indicated braze strength in excess of 100MPa. Using this braze material, six mock-ups were manufactured (Figure 6) for final inspection using NDT methods.

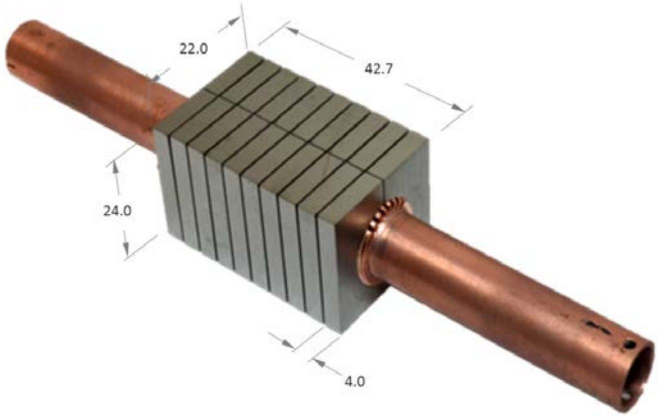

Figure 6 Showing an example of an assembled thermal break structured interlayer component prior to the insertion of swirl tubes in readiness for high heat flux testing.

4. Testing

4.1. Non-destructive testing (NDT) of complete assemblies

Two types of non-destructive testing were carried out. The first uses a thermal response method devised by CEA called SATIR [11]. This test applies alternating flows of hot and cold water through the coolant pipe and monitors (via infrared imaging) the resulting thermal response of the outer tungsten surfaces. The part showing the most uniform response, and having a block to block variation less than 5˚C, is selected as a reference. The response of other parts is then compared with the reference response and any anomalies found are used as an indication of potential defects. The test revealed no defects.

The second NDT test used the pulse echo ultrasound technique developed by ENEA [12]. This test uses a sensor placed inside the coolant pipe with water fill. The sensor can register echo signals at specified radial depth, and the subsequent result presented as a response map. Signal levels are calibrated with a reference component with known defect size. By this method the presence and location of defects can be found at each braze joint. In these tests one small defect was found on the outer braze joint, but this was at the back of the component and hence thought unlikely to significantly weaken the part.

4.2. High heat flux testing

High heat flux (HHF) tests were carried out at IPP using the test facility GLADIS [13]. The facility is equipped with two neutral beam heat sources and in-test diagnostics including cooling water calorimetry and IR & CCD cameras. Two coolant conditions were used: “cold” at 20˚C, 10 bar, 12 m/s; and “Hot” at 130˚C, 40 bar, 16 m/s. Tests at a number of heat loads and cycle counts have been completed at the time of writing. These include a screening test up to 5 cycles at 25 MW/m^2 and 100 cycles at 20 MW/m^2 in “cold” coolant condition plus a subsequent 100 cycles at 20 MW/m^2 in “hot” coolant condition. During the applied 10s pulse duration the mock-ups reached thermal equilibrium. Figure 7 shows the IR image taken at the first and 100th cycle (“cold” coolant condition). It can be seen that no degradation in the component response is discernible and that the tungsten surface temperature distributions remain relatively homogeneous throughout testing (end blocks show slightly higher temperatures). Close visual inspection revealed no apparent damage. The component was later tested for a further 100 cycles with “hot” coolant condition, again without apparent damage. Further testing up to 300-1000 cycles at 20 MW/m^2 is planned after which destructive metallographic inspection of the component will be completed, and correlation between HHF test and NDT testing will be assessed.

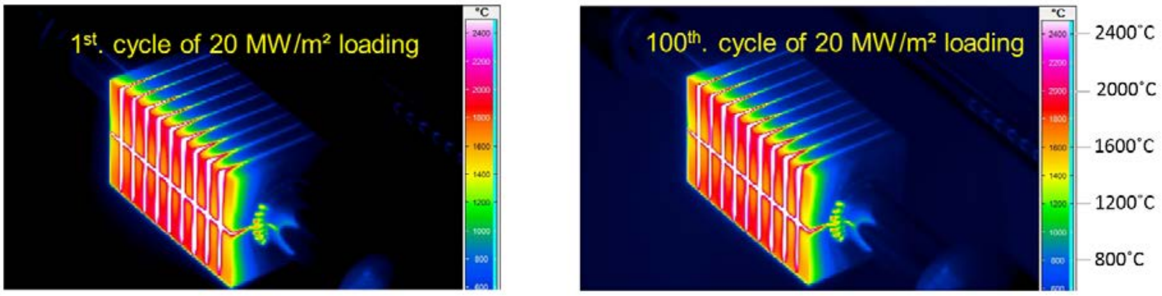

Figure 7 The infrared thermography results from a 20MW/m^2 heat load test shows that there is no detectable difference in the indicated temperatures of the first cycle (left) and the 100th cycle (right), suggesting that no mechanical deterioration has occurred.

5. Conclusions and further work

The potential for improving the structural integrity reserve factors of the monoblock target design using a structured thermal break/compliant interlayer has been demonstrated. It has also been shown that components realising the computationally optimised design can be manufactured by brazing using ductile braze fillers. The braze joints were shown to be almost entirely defect free by thermographic and ultrasonic NDT methods. Mock-ups tested at IPP GLADIS high heat flux facility were undamaged after 200 cycles at 20 MW/m^2 surface heat flux loading.

In the future, correlation of NDT to HHF testing will be performed to identify if small imperfections revealed with thermographic testing have an impact on the thermal heat exhaust capability. Metallographic examinations will also be performed in order to check the microstructure of mock-ups after HHF testing.

A second phase of development is also planned to provide the necessary confirmation of the initial performance delivered so far. This will include the development of a more practical assembly methodology, high temperature copper fatigue testing, continued optimisation studies, improved assessment interlayer strain at strain concentrations, and a change to key dimensions to increase robustness (such as armour thickness for plasma erosion resistance and pipe thickness for coolant erosion-corrosion resistance).

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Acknowledgements

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053 and from the RCUK Energy Programme [grant number EP/I501045]. To obtain further information on the data and models underlying this paper please contact PublicationsManager@ccfe.ac.uk*. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

The use of X-ray tomography equipment at Manchester X-ray Imaging Facility, Research Complex at Harwell is gratefully acknowledged.