Assessment of the High Heat Flux Performance
of European DEMO Divertor Mock-ups

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Abstract

In the framework of the DEMO divertor project an extensive R&D program has been carried out to develop advanced design concepts for hot water cooled divertor targets. These plasma-facing components are made of W monoblocks as plasma facing material bonded on CuCrZr cooling tubes. They are designed to allow a reliable DEMO operation of two hour long pulses up to a 20 MW/m² maximum heat flux. Considering the current experiences of the qualification of ITER divertor components, the operation at significantly higher neutron fluence, the longer required lifetime, and the coolant temperature of 150 °C are challenges for design and manufacturing.

The aim of the performed HHF tests is to support the identification of the most promising design concepts for further development. Eight different types of monoblock mock-ups were designed and manufactured by the involved research groups. These mock-ups were assessed by HHF examination in the test facility GLADIS at IPP Garching. The HHF tests were focused on 20 MW/m² loading with 500 – 1000 cycles using hot water cooling to simulate slow thermal transients in DEMO. In screening tests heat fluxes up to 32 MW/m² were applied to study the performance of the components against single thermal events exceeding the expected heat flux limits.

This paper gives an overview of the main results obtained from the HHF tests of about 45 components. The microscopic examination after loading analyses recrystallization effects and investigates the W/ Cu interfaces in more detail.

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1. Introduction

The highly heat loaded divertor target plates are one of the most challenging components of a future demonstrational power plant (DEMO). In the EUROfusion DEMO divertor project (PPPT-WP-DIV) an extensive R&D program has been carried out to develop advanced design concepts for hot water cooled divertor targets [1][2]. These plasma-facing components (PFCs) made of W blocks as a plasma-facing material (PFM) bonded on CuCrZr cooling tubes should allow a reliable DEMO operation for 2 h long pulses at nominal 10 MW/m² and maximum heat flux excursions up to 20 MW/m² during 300 cycles of slow transient events shorter than 10 s [3]. Compared to ITER (~0.1 dpa after 4 years of nuclear operation [4], the significantly higher neutron dose of 4 dpa in W armour, 13 dpa in the divertor cooling tubes during two full power operation years [3], the longer required lifetime and the operation at higher coolant temperature of 150 °C, are challenges exceeding the current extent of experience of the world-wide development of W monoblock components for the ITER divertor [4]. The expected neutron embrittlement and reduction of thermal conductivity of W and Cu based materials requires the development of concepts for the specific operation in DEMO. The development of innovative target designs started on the basis of the ITER monoblock design as a reference. More details about the design and the thermal performance of the ITER monoblock concept can be found in references [5][6]. The R&D activities take into account advanced structural analysis, code based design, the implementation of new high-performance materials, as well as verification by high heat flux (HHF) tests.

In the first phase of WP-DIV (2014 -2018), 8 different concepts, including so-called flat tile design (bonding of a W tile on a heat sink), were developed and their HHF performance was assessed. Mock-ups with different block sizes and W/Cu interfaces were designed and fabricated by the EUROfusion members CCFE, CEA, ENEA, KIT and IPP (Garching). The variation of outer W block dimensions allows for the study of the influence of the monoblock size on the plastic fatigue and fracture behavior. The width ranged from 23 to28 mm and the axial length from 4 to12 mm, respectively. All W blocks were provided by A.L.M.T. (Japan) and AM&T (PR China). The cooling tubes of the mock-ups manufactured by ENEA were made of the Cu alloy CuCr1Zr "ELBRODUR®HF" provided by KME Germany GmbH. The mock-ups were manufactured by hot radial pressing performed by ENEA, or brazing and hot isostatic pressing performed by different European manufacturers.

To adapt the mismatch of thermal expansion between W and CuCrZr different approaches were applied to improve the W/Cu interface by variation of Cu interlayer thickness between 0.1 to 1 mm or the application of W/Cu graded interlayers. The thermal break concept reduces temperature and stress concentration at the cooling pipe and finally, the development of a W fibre reinforced Cu tube improves the thermo-mechanical properties of the cooling tube. Information in more detail about the design rationales, the material interfaces and the structure of the project are published elsewhere [3], [7]. Further details of the design, manufacturing and testing of 1st phase mock-ups are given in the literature, e.g. [8], [9], [10], [9], [11], [12]. Results of ultra-sonic inspection, which was performed before and after HHF loading, are published in reference [13].

The second project phase was focused on both, the improvement of manufacturing technologies and the reduction of design variations. A uniform W block geometry (23 mm width, 12 mm axial length and 8 mm armor thickness) was used for all mock-ups. All mock-ups were equipped with swirl tapes (twist ratio =2). In this paper we discuss the latest HHF test results from the 2nd phase which were focused on 20 MW/m² loading with 500 – 1000 cycles using hot water cooling to simulate fatigue due to slow thermal transients in DEMO. In screening tests, heat fluxes up to 32 MW/m²

were applied to study the performance of the components against single thermal events exceeding the predicted heat flux limits during operation.

2. Approach of HHF testing procedure

The aim of the HHF tests is the evaluation of the thermal performance of different target concepts, the experimental validation of numerical predicted thermo-mechanical behaviour under DEMO relevant heat load and cooling conditions and finally the selection of the most promising concepts for further development.

The two-step procedure according to reference [8] was complemented by additional screening up to 32 MW/m². The first step was performed for each component as an "initial quality assessment" of the delivered components,

- screening up to 25 MW/m², at cold water (20°C inlet, 1MPa static pressure, 12 m/s velocity),
- 100 cycles at 10 MW/m² as low cycle test.

After having passed this assessment without damage, the hot water, high pressure tests (130°C inlet, 4 MPa pressure, 16 m/s velocity) were performed as the second step:

- Screening from 6 to 20 MW/m², each component,
- 100 cycles at 20 MW/m², each component,
- 500 (1000) cycles at 20 MW/m² as low cycle fatigue, one component of each concept at least.

Since a number of concepts passed these tests with comparable good results, the heat load was increased up to the thermal limit of a safe heat transfer to the coolant. The aim was to study the integrity of the component after such single overloading events. To apply significant higher heat fluxes it was necessary to perform these tests at 20°C cold cooling water with 16 m/s velocity.

3. High heat flux loading

3.1. Heat transfer conditions and loading limits

The components should ensure a safe heat transfer in the regime of sub-cooled boiling for both, the cold water- and hot water cooling. The following heat flux limits were set in consideration of the geometry of the loaded components and the safety margin against the onset of critical heat flux (CHF), which was calculated according to TONG75-CEA [14]:

- 28 MW/m² for the 1st step cold water tests,

- 22 MW/m² for the 2nd step hot water tests (similar to the DEMO limits [9]) and

- 32 MW/m² for the cold water overload tests.

A more detailed view on the consequences of 20°C cold and 130°C hot water cooling related to the 150°C design water temperature of the DEMO divertor is given in reference [8].

3.2. Loading and surface temperature measurement

All mock-ups were installed and tested individually in GLADIS [15]. The mock-ups were installed in the horizontal direction, normal to the beam axis. This resulted in an 8 degree inclination of the loaded surface to the vertical plane. The actively water cooled mock-ups reached the thermal equilibrium after ~7 s loading, meaning a constant temperature and stress profile across the component. Therefore, all cyclic tests were performed with 10 s loading followed by 50 or 80 s cooling, respectively. The applied hydrogen neutral beam (Gaussian profile with 150 mm FWHM) ensures a simultaneous and homogeneous heating of all monoblocks of the mockups shown in Fig. 1. The calorimetrically measured absorbed power compared to the calculated incident power is in an agreement within ±5%. The surface temperature of the exposed mock-ups was measured with one- and two-colour pyrometers as well as monitored by an infrared camera Infratec VARIOCAM HD. The two-colour pyrometer (∅8mm focus, λ=1.4-1.75μm, temperature range 500-1700 °C) was used as reference for the emissivity (ε) determination of the one-colour pyrometer (∅22mm focus, λ=2.0 – 2.2 μm, temperature range 350 – 3500°C) and the IR camera. A crucial point of reliable surface temperature measurements of such W components is the surface modification during HHF cyclic loading (see Fig. 4) and the resulting change of emissivity during cyclic loading. The long term fluctuation of the beam power density distribution is in a range of ±5% as confirmed by cooling water calorimetry. A constant ε=0.3 was applied for all presented one-color pyrometer data. Only for measurements during screening are the obtained pyrometer data up to 3000 °C reliable within an accuracy of ±5%.

Fig. 1: Example of a HHF tested W monoblock mock-up. The mock-up is equipped with 23 x 12x 28 mm³ W blocks provided by A.L.M.T (JP) or AM&T (CN).

4. Results and discussion

4000 cycles at 10 MW/m² cold water cooling and 8000 cycles at 20 MW/m² hot water cooling have been applied on 45 components up to now. No unexpected serious defect occurred during cyclic testing of the various target concepts in total equipped with 252 monoblocks.

The results of the monoblock concepts tested in GLADIS as shown in Table 1 are now discussed.

Design concept	Design by, Reference	Cycles at 20 MW/m² hot water cooling	32 MW/m², 5 cycles cold water cooling

ITER like, 1 mm Cu interlayer [1]	ENEA [9]	500, no visible failure	no visible failure [5]
500 µm FGM	CEA [10]	500, no visible failure	No component available
300 µm Cu interlayer	ENEA [7]	500, no visible failure	no visible failure [5]
100 µm Cu interlayer	ENEA [7]	500, no visible failure [2]	no visible failure [5]
20 µm Cu-HIP	CEA [10]	300 [3]	Not performed
20 µm FGM	CEA [10]	300 [4]	Not performed
Thermal break	CCFE [11]	500, no visible failure	Surface melting [6]
W_f Cu composite tube	IPP [12]	1000, no visible failure	no visible failure [5]

Table 1: Summary of investigated monoblock concepts of 2nd phase. The term "no visible failure" means that the surface temperature is stable during HHF loading and no indication of debonding is visible.

[1]   Two different W material delivered by A.L.M.T. and AT&M

[2]   cooling down of one block delayed

[3]   debonding of two blocks started after 132 cycles

[4]   debonding of two blocks started after 122 cycles

[5]   additionally loaded with 100 cycles at 25 MW/m²

[6]   one pulse, melting was expected from FEM prediction

For the seven different monoblock components the equilibrium surface temperatures during cyclic fatigue tests at 20 MW/m² and 130 °C water temperature are shown in Fig.2. Despite the various W/Cu interface designs, ranging from CCFE thermal break to 1mm thick pure Cu applied for "ENEA ITER like" and up to 100 µm Cu for "ENEA 100 µm Cu", the surface temperature variation is in the range of only ±5 % related to FEM calculated temperature of an ITER like geometry. The results of the seven tested mockups subjected to 20 MW/m² cyclic loads with hot water cooling illustrate the high thermal performance and the robustness of the individual designs.
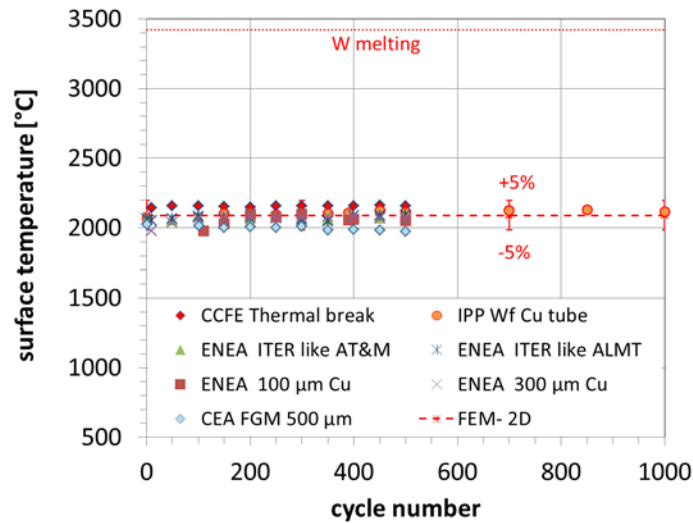
Fig. 2. Surface temperature of selected concepts depending on the cycle number for 20 MW/m² heat flux at 130 °C, 4 MPa, 16 m/s cooling water. The presented temperatures were pyrometrically measured in the centre of mock-ups.

The limits of the concept against thermal overloading can be concluded from overload tests up to 32 MW/m². We applied five 10 s pulses at each loading step. Fig.3. summarizes the measured surface temperatures of these tests. As mentioned above the temperatures were measured with the one-colour pyrometer at constant ε=0.3. The accuracy of the measurement at high temperature is reduced due to the strong temperature dependence of the emissivity. As seen in Fig. 3, the temperatures above 3000 °C were measured too low. Tungsten surface melting was reached at 32 MW/m² heat flux on the thermal break mock-up as predicted from the FEM calculation. To reduce the risk of loss of stable cooling conditions this test was only performed for the CCFE thermal break where the highest surface temperatures and the lowest heat flux peaking at the cooling tube were expected.

It should be noted that the results of these cold water tests cannot be applied directly to the operation conditions in DEMO. As mentioned in section 3.1, the expected onset of CHF is much earlier for 150°C DEMO cooling water conditions in comparison to the cold water tests performed in this study. Therefore, for heat fluxes exceeding 25 MW/m² a collapse of heat transfer and a sudden melting of cooling tube is expected. Such a loss of coolant event should be strictly avoided.
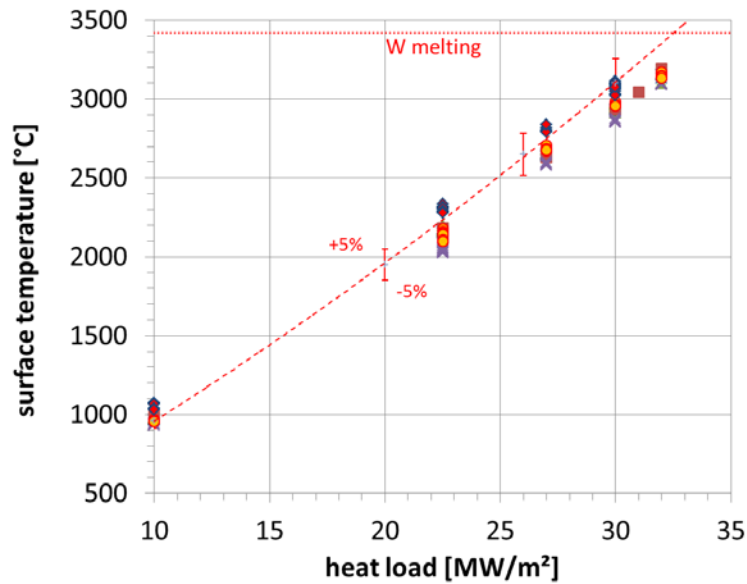
Fig. 3. Surface temperature of selected concepts depending on heat flux at 20°C, 1 MPa, 16 m/s cooling water velocity. The temperatures were pyrometrically measured in the centre of mock-ups. The applied constant emissivity causes deviations at temperatures above 3000 °C. The symbols of the data are the same as in Fig. 2.

4.1. W surface investigation after 500 cycles at 20 MW/m²

No cracks in the W armour occurred during the cyclic tests of all components as shown in Fig. 4. The surface temperature of ~ 2050 °C applied for 25 min total equilibrium time resulted in a strong change of surface morphology due to recrystallization and thermo-mechanical effects. Compared to 28 mm wide W blocks, the change of the block geometry to a barrel-like shape due to accumulation of plastic deformation is suppressed for all tested 23 mm wide blocks. The observed geometry change could mostly be interpreted as a cyclic accumulation of creep strain and creep-plasticity interaction as described in reference [16]. We attribute the observed suppression to the smaller W block width of 23 mm compared to results of HHF testing of 28 mm wide ITER small scale mock-ups. The occurrence of deep W cracks and so-called "self-castellation" effects for higher cycle numbers at 20 MW/m² loading have been published in a number of references for 28 mm wide W blocks [17], [18], [19].

The quantitative assessment of such size effects is of importance for the divertor component design. A computational study about the thermal and structural impact of monoblock size on the plastic fatigue and fracture behavior of an ITER-type tungsten divertor target is published in reference [16]. The authors show that the trend of J-integral assessment for the larger monoblock dimensions implies that a monoblock geometry with the width of 28 mm will likely be subjected to high risk of armor cracking, resulting in deep cracks up to the W/Cu interface. For 23 mm wide W blocks there is a significantly lower risk of deep cracking in the armor and plastic fatigue in the copper interlayer.
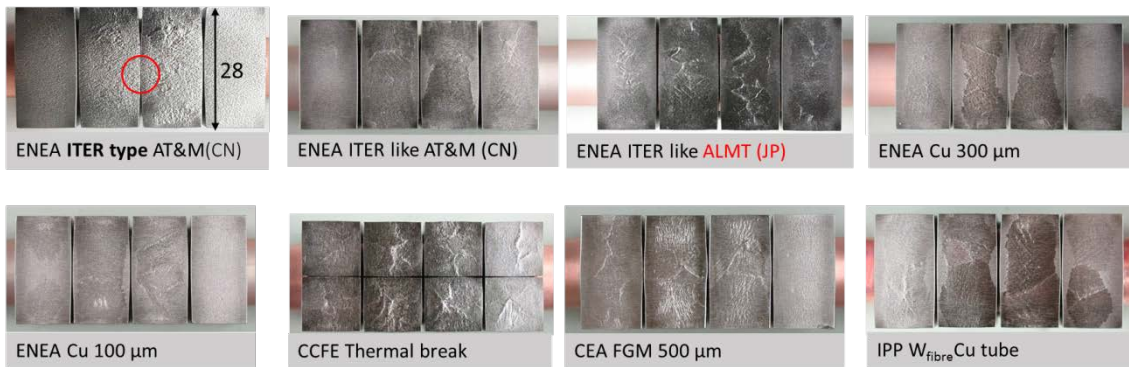
Fig 4 . View on loaded surface of the components after 500 cycles 20 MW/m² at hot water cooling. The circle marks the closed 0.5 mm manufacturing gap of the 28 mm wide ENEA ITER like equipped with W made by AT&M.

4.2. Microscopic examination after 20 MW/m² cycling

The microscopic examination of all mock-ups loaded with 500 cycles at 20 MW/m² hot water cooling did not reveal any W cracks or delaminations of the W/Cu interlayer. Fig. 5 a -b show as examples metallographic cross-sections of the loaded and unloaded part of block 3 of the ENEA ITER like mock-up made with W provided by A.L.M.T. Fig. 5 c shows a corresponding cross-section of an ENEA ITER like mock-up equipped with W blocks made by AT&M. The effects of recrystallization and grain growth are very similar for both W materials provided by A.L.M.T. and AT&M, respectively. Recrystallization started at 1200 ±50 °C according to the FEM predicted temperature distribution. This temperature is in good agreement with data published in the literature. From optical microscopy, it appears that the loaded surface is dominated by the formation of extremely large grains in contrast to the deeper laying recrystallized layers. However, from electron backscatter diffraction (EBSD) analysis, it is observed that this region actually consists of smaller grains (typical size between 50 to 100 μm) with nearly the same orientation. Therefore, the colour in the optical micrograph is identical in a large area. The grain size distribution is similar in the recrystallized part and the colder or unloaded part, respectively. However, the texture of the material due to the manufacturing disappears.

The Cu interlayer in the loaded part of the component was subjected to peak temperatures of about 450 – 500 °C during the cyclic tests. Strong grain growth is observed compared to the lower unloaded part of the component as shown in Fig 5. The grain size and orientation of the CuCrZr cooling tube seem unaffected from the performed HHF tests.
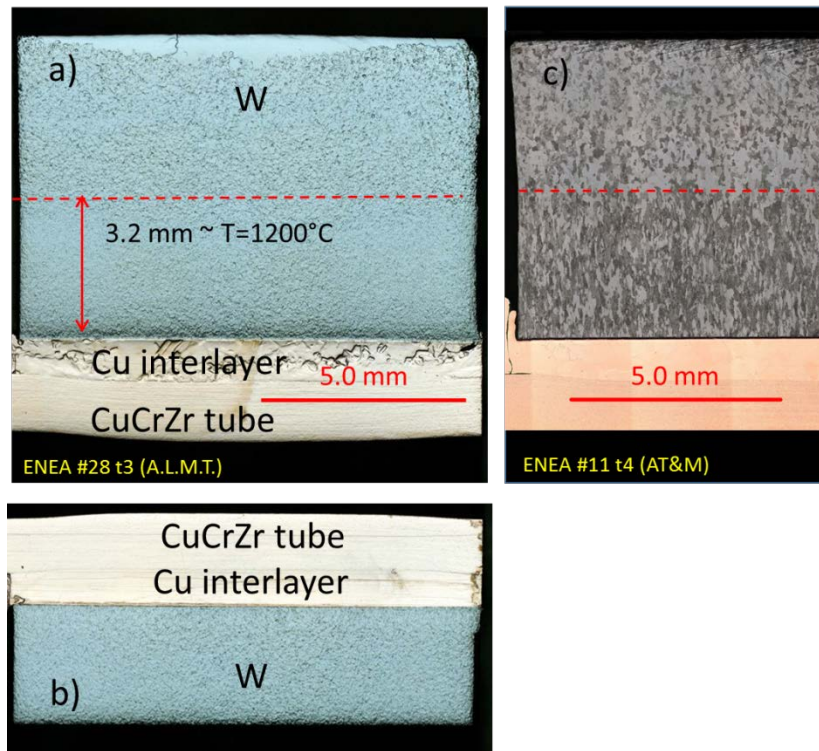
Fig. 5. Cross-sections of two mock-ups after 500 cycles 20 MW/m² loading at hot water cooling. The dashed line in a) and c) marked the beginning of recrystallized material. Image a) shows the upper half and the loaded surface on top of a W block provided by A.L.M.T. The lower unloaded part is shown in b). Image c) shows the loaded upper part of a W block made by AT&M.

4.2. Microscopic examination after surface melting at 32 MW/m² loading

The aim of HHF loading up to surface melting was both, to study the effect of re-solidification of W and to investigate the integrity of the component after such single overloading events. Fig. 6 shows the homogenous surface melting which corresponds very well to the heat flux and the resulting temperature distribution. From the loading history, it can be assumed that the pronounced transition to recrystallized W occurred during 5 pulses at 30 MW/m² and the following single pulse at 32 MW/m². During this loading sequence the corresponding temperatures at the W/Cu bonding (~900°C) and a maximal temperature of about 470 °C at the CuCrZr tube did not lead to remarkable damage of these materials. With the exception of the change of shape of the W blocks due to loss of molten material and the formation of small re-solidification cracks, no structural damage of the component occurred.
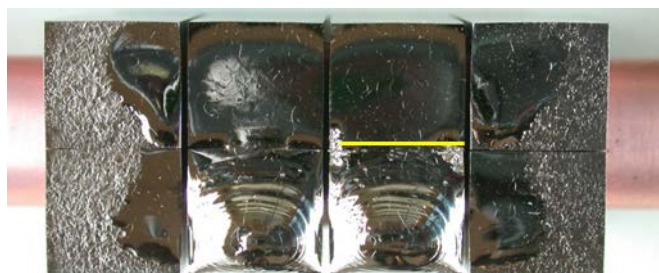
Fig 6. Surface melting of the CCFE Thermal break component occurred at a single 32 MW/m² 10 s heat pulse. The yellow line marks the position of cross-section shown in Fig. 7.
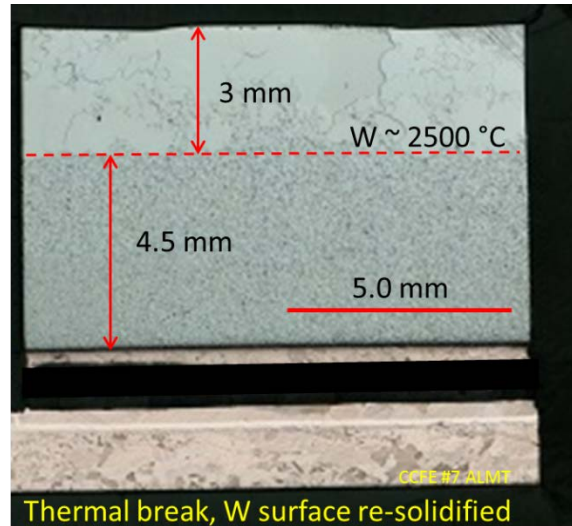

Fig 7. Cross-section of a W monoblock after 32 MW/m² 10 s heat pulse resulting in surface melting. A pronounced re-solidification and recrystallization of a 3 mm layer is visible. The cross-section cuts the interspace of the thermal break made of spokes. Therefore no Cu material is seen in this region.

5. Summary and conclusion

As mentioned in the introduction, this paper does not give a final assessment of all HHF tests performed in the frame of the WP-DIV project on water cooled DEMO divertor target concepts. In total 4000 cycles at 10 MW/m² cold water cooling and 8000 cycles at 20 MW/m² hot water cooling were applied on 45 mockups with the following results:

-   Five concepts, including three variations of "ITER like" have survived the cyclic testing procedure and loading up to 32 MW/m². Concepts with thin W/Cu interface are not robust against fatigue during cyclic loading.

-   No unexpected serious defect occurred during testing of the various W monoblock concepts.

-   No cracking occurred in W blocks delivered by both manufacturers, AT&M and A.L.M.T.

-   The recrystallization behavior of W provided by both manufactures is very similar, recrystallization started at 1200°C.

-   The HHF tests confirmed the FEM predictions concerning temperature distribution, accumulation of plastic deformation and creep

-   The hot radial pressing of the CuCrZr tubes is a reliable manufacturing technique.

Following this investigation, it can be concluded:

The tested concepts of DEMO water-cooled divertor targets are able to withstand a 20 MW/m² cyclic heat load. The WP-DIV program achieved an important R&D progress in the development of DEMO divertor targets made of W monoblock PFCs. The HHF tests have confirmed that the water-cooled W monoblock concept in general is close to thermal limits. The power load capability cannot be increased significantly, however, a reduction of stress is possible by the application of optimized designs. The HHF tests confirmed that the smaller 23 mm width W monoblocks are more resistant to cracking in comparison to larger monoblocks.

Acknowledgments

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