He-cooled Divertor Development: Technological Studies and HHF Experiments for Design Verification

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Abstract. Within the framework of the power plant conceptual study, modular He-cooled divertor concepts have been investigated in detail at the Forschungszentrum Karlsruhe in cooperation with the Efremov Institute. The design goal is to resist a heat flux of at least 10 MW/m^2. The development covers the fields of design, analyses, material and fabrication technologies, and experiments. The helium-cooled modular jet concept (HEMJ) has been defined as reference solution which is based on jet impingement cooling. The 2005 divertor work programme (TW5-TRP-001) focused on construction and high-heat-flux tests of prototypical tungsten mock-ups to demonstrate their manufacturability and their performance. A helium loop was built to simulate the realistic thermohydraulics conditions close to those of DEMO (10 MPa He, 600°C). The first high-heat-flux tests using 1-finger mock-ups confirm the feasibility and the performance of the current divertor design.

1. Introduction

A helium-cooled divertor for future fusion power plants is presently being developed at the Forschungszentrum Karlsruhe [1] within the framework of the European Power Plant Conceptual Study (PPCS) [2]. The goal is to resist a heat flux of at least 10 MW/m^2. The development covers the fields of design, analyses, and experiments. Two concepts, HEMS (helium-cooled modular divertor with integrated slot array) and HEMJ (helium-cooled modular divertor with multiple jet cooling) (Fig. 1), have been pursued so far, of which HEMJ [3] has now been defined as reference solution. A series of technological breakthroughs will be necessary for obtaining a functioning design. For all critical points, the solutions have been found within the framework of cooperation with the Efremov Institute, St. Petersburg, Russia, in particular for the joining of W-W and/or W-steel components as well as for the fabrication of the W parts.

The 2005 divertor work programme (TW5-TRP-001) focused on construction and high-heat-flux (HHF) tests of prototypical tungsten mock-ups to demonstrate their manufacturability and performance. The first series of W 1-finger mock-ups were manufactured based on the knowledge gained from the technological studies mentioned above. The TSEFEY electron beam (EB) facility available at Efremov is used for HHF simulation. In addition, a helium loop was built there for these tests to simulate the realistic thermohydraulic conditions close to those of DEMO (10 MPa He, 600°C). The preparation and the results of the first HHF tests will be reported below.

2. The present design

Material aspects: the high resistance the armour material required against high heat flux (HHF) and sputtering led to the choice of tungsten [4] as the most promising divertor material. Tungsten offers advantages in terms of a high melting point, high thermal conductivity, low thermal expansion, and low activation. On the other hand, it has the disadvantages of a high hardness and brittleness, as a result of which fabrication of W components is difficult. Poor values of the ductile-brittle transition temperature (DBTT) and recrystallisation temperature (RCT) also lead to a limitation of the operational temperature window of the W structure. The oxide dispersion-strengthened (ODS) version of W by adding 1% lanthanum oxide (WL10) is regarded the most suitable option for the divertor structures, because it helps increase the ductility of pure W. The DBTT and RCT of WL10 under fusion neutron irradiation are estimated to be around 600°C and 1300°C, respectively. These values determine the "design window" range (Fig. 2), according to which the helium coolant temperature at the inlet must not be below 600°C.

Modular design and accompanying analyses: for the reduction of thermal stresses, a modular design is preferred. Two promising modular concepts are illustrated in Fig. 1. The HEMS design at the bottom is based on the use of a flow promoter in the form of a slot array. The HEMJ design (top right) is based on the use of multiple-jet cooling. This design has been chosen as reference because of its simpler design and cheaper production. Both concepts use small hexagonal W tiles (18 mm width over flat) as a thermal shield and sacrificial layer (5 mm thickness). They are brazed to a thimble (Ø15 x 1 mm) made of WL10, thus forming a cooling finger which is connected to the supporting structure made of ODS steel (e.g. an advanced ODS EUROFER or a ferrite version of it). To compensate the large mismatch in the thermal expansion coefficients of W and steel, a transition piece is needed. The current transition piece design is based on Cu casting with a conical interlock. For HEMJ, a steel cartridge carrying the jet holes is placed concentrically inside the thimble. The number, size (D), and arrangement of the jet holes as well as the jet-to-wall distance H are important parameters (Table 1). The results of the CFD parametric study [5] of HEMJ show that the jet-to-wall distance (within the design range of 0.6 – 1.2 mm) has no excessive influence on the divertor performance. On the other hand, the jet hole diameter has a substantially larger influence on the divertor performance and the pressure losses. With the help of the CFD analyses, the following geometry (J1c) was found suitable: 24 holes Ø 0.6 mm and 1 centre hole Ø 1 mm, jet-to-wall spacing 0.9 mm. For the J1c geometry under 10 MW/m^2 and 6.8 g/s mass flow rate, the results yield a maximum tile temperature of 1700°C which is well below the design limit of 2500°C (Fig. 2). The maximum thimble temperature amounts to 1157°C which is below the permissible value of 1300°C. The calculated pressure loss (Δp) of 0.13 MPa seems to be overestimated compared to the measured values of about 0.10 MPa obtained from the earlier gas puffing experiments [6] at Efremov, which are based on the reversed heat flux principle. A maximum divertor performance of up to 12 MW/m^2 was found in these experiments for the HEMJ-J1a (similar to J1c) at a nominal mass flow rate of 6.8 g/s.

3. Preparations for high-heat-flux tests

Work carried out in 2005 was aimed at technically investigating and manufacturing 1-finger divertor mock-ups for the high-heat-flux experiments at the Efremov Institute. These experiments are performed at the new test facility which consists of the TSEFEY electron-beam testing machine and the He-loop facility. This combined device provides for a steady-state surface-loading heat flux (with a total power of up to 60 kW at 27 keV beam energy) and a He coolant at a pressure of ~ 10 MPa, an inlet temperature of ≤ 600°C, and a mass flow rate of ≤ 50 g/s.

Preliminary technical investigation: Technological studies related to the high-temperature brazing of W and W components at Efremov [7] revealed the best results for the filler materials STEMET® 1311 (Ni-based) and 71KHCP (Co-based). The brazed curved joint withstood 100 thermal cycles at about 14 MW/m^2. For the transition joint between the WL10 thimble and

Eurofer steel structure, functioning of a joint with Cu filling and conical lock was demonstrated successfully in the preliminary tests.

Definition and Fabrication of the W 1-finger mock-up: Based on the knowledge gained from the above investigation, the reference W mock-up was defined for the high-heat-flux tests. The HEMJ version J1c (Table 1) was chosen as reference. The definition of the 1-finger mock-up is given in Table 2. The HEMJ jet cartridge and the holding structure of the mock-ups are made of Eurofer which differs from the designated ODS Eurofer material. Besides this basic definition, the 71KHCP (Co-based) filler metal was applied to certain mock-ups. Castellated and non-castellated W tiles were investigated. In the first test campaign six 1-finger mock-ups (Fig. 3), five of HEMJ and one of HEMS type, were fabricated. The manufacturing sequence was as follows:

- Machining of external surface of the W thimble (from WL10)
- Machining of cylindrical ring from Eurofer
- Machining of internal surface of the tile (manufactured from pure W)
- Brazing of W thimble to cylindrical ring (filler metal 71KHCP, T_{br} = 1100°C)
- Brazing of W thimble to W tile (filler metal STEMET® 1311, T_{br} = 1100°C)
- Machining of the internal surface of the W thimble
- Machining of the tile to the shape required

As an alternative to the W/Eurofer joint by cast copper, a brazed W/Eurofer joint using Co-based filler metal was considered for mock-up manufacture (mock-ups #5/HEMJ and #6/HEMS).
For HHF testing of the mock-ups manufactured at the TSEFEY facility, a special target device was designed and manufactured. This target device consists of two main parts, the manifold device and the water-cooled shielded mask. This mask (Fig. 4) has a hexagon-shaped frame made of molybdenum.

Helium loop construction: This He loop enables mock-up testing at a nominal helium inlet temperature of 600°C, an internal pressure of 10 MPa, and a pressure loss in the mock-up of up to 0.5 MPa. The flowchart of the loop is shown in Fig. 5 (left). Since the He loop is designed for operation together with the TSEFEY facility with its own water-cooled target system, all of its main units are placed on a vehicle moveable on railways (Fig. 5, right). In the first stage of the helium loop a stationary helium mass flow rate of 24 g/s was achieved by means of an oil-free membrane compressor. The combined testing facility (TSEFEY EB device and moveable He loop) is illustrated in Fig. 6.

4. HHF experimental results

The first test campaign covered six mock-ups, the tiles of which were made of Russian tungsten. The mock-ups were tested within an HHF range of 5–13 MW/m^2. The heat flux is determined via the heat power absorbed in the helium. The helium cooling parameters are 10 MPa inlet pressure, ~ 500–600°C inlet temperature, and a varying mass flow rate in the range of ~ 5–15 g/s. The thermocyclic loading was simulated by means of switching the beam on and off (e.g. 60s/60s).

The experiments started with the mock-up #4 with a non-castellated W tile. Heat flux loading was applied to the mock-up surface at a constant mass flow rate (MFR) of ~ 13 g/s. The mock-up survived stepwise heat loads from 4 up to 11 MW/m^2 each with 10 temperature cycles (60s/60s) without any damage. A maximum tile surface temperature of ~ 1500°C was measured by means of an IR camera at q = 11.6 MW/m^2, MFR ~ 13.5 g/s, Tin, He ~ 540°C. For comparison, the value predicted in [5] was about 1750°C at MFR = 6.8 g/s and $T_{in,\ He}$ ~ 634°C. The pressure loss of 0.32 MPa was measured at 13.7 g/s MFR. An extrapolation of the pressure loss leads to an equivalent value of 0.085 MPa at 6.8 g/s nominal MFR, which is slightly below the value of 0.10 MPa measured in the GPF experiments [6]. For comparison, the values calculated by the CFD codes Flotran [6] and Fluent [5] of 0.14 MPa and 0.13 MPa, respectively, seem to be more pessimistic. The mock-up was then further tested at higher heat fluxes to find out the maximum heat load performance. After 6 cycles at 13 MW/m^2 (last power step), an overheating of the mock-up surface was observed, which led to tile surface melting (Fig. 7). Cracks appeared in the middle of each of the tile's flat sides. The long cooling-down period after this shot indicates that the tungsten tile and thimble were partially detached. No gas leakage was detected, i.e. the pressure-carrying thimble and the loop remain absolutely intact.

The following mock-up #2 with a castellated W tile outstandingly survived up to 11.5 MW/m^2 at MFR ~ 13.5 g/s; $T_{in,\ He}$ ~ 550°C (Fig. 8). The tile temperature measured was ~ 1600°C, the measured pressure loss ~ 0.38 MPa. This pressure loss is equivalent to about 0.08 MPa at the nominal mass flow rate of 6.8 g/s and regarded optimistic compared to the value calculated above. At a higher load of 12.5 MW/m^2, cracks in the tile and thimble and gas leakage were detected. The gas leakage was found to come from the top area of tile slots, the cracks occurred at the tile side and penetrated the thimble wall between the tile and the steel ring. Crack propagation in the thimble came from the inside. Two tile castellation segments were molten when gas leakage occurred, probably because of the increased heat flux density caused by beam focusing in the last shot. Gas leakage through the side of the tile indicates that the crack can propagate through the brazing.

Mock-up #5 (non-castellated): this mock-up was the one with the Co-brazed joint which is much harder than the Cu filler. Thermomechanical (TM) screening tests were performed with a step-by-step increase of the applied heat flux q in the range of 4–9 MW/m^2 at a constant He mass flow rate MFR ~ 13.5 g/s. At q = 9 MW/m^2 and MFR ~ 13.5 g/s, the mock-up successfully survived 100 cycles (15 s/15 s). A surface tile temperature of ~ 1490°C was measured, whereas the calculated value was ~ 1400°C. The measured pressure loss was 0.29 MPa. At a reduced mass flow rate of g ~ 7 g/s, a crack in the thimble close to the joint and gas leakage were detected after 24 cycles. During the last thermal load shot, the tile surface melted probably due to an increase of the heat flux density caused by e-beam focusing. The W grain size in the central part of the tile was found to be large, an effect due to tile melting in the last shot.

Mock-up #3 (non-castellated): cyclic thermal loading was performed by a step-by-step increase of the applied heat flux from ~ 5–9 MW/m^2 at a constant MFR of ~ 7 g/s, a value which corresponds to the nominal MFR in the DEMO design [1]. The mock-up survived 10 thermal cycles at 5.2 and 6.5 MW/m^2, but only 5 cycles at q = 9 MW/m^2. Then, a crack at the tile side and gas leakage through the tile/thimble interface were detected. A maximum tile temperature of 1530°C and a pressure loss of 0.1 MPa were measured at an MFR of 7 g/s and $T_{in,\ He}$ of about 590°C.

Mock-up #1 (castellated): screening tests were performed with a step-by-step increase of the applied heat flux from 5 to 9.7 MW/m^2 at a constant MFR of ~ 9 g/s. An early gas leakage was detected, starting after 5 TM cycles at q = 7.9 MW/m^2 ($T_{max,\ tile}$ ~ 1340°C measured at $T_{in,\ He}$ ~ 600°C). The tests were continued up to 10 cycles under the same heat load. They were terminated after 2 TM cycles at 9.7 MW/m^2 ($T_{max,\ tile}$ ~ 1550°C and Δp ~ 0.17 MPa measured at $T_{in,\ He}$ ~ 600°C). After the last shot, gas leakage was detected to occur through the thimble near the steel ring.

Mock-up #6 (HEMS, Co-brazed thimble/steel joint): the HHF tests were performed with a step-by-step increase of the applied heat flux from 4.5 to 9.5 MW/m^2 (60 s/ 60 s) at a constant MFR of ~ 10 g/s. No visible damage and gas leak were detected. Then, the mock-up survived 100 TM cycles performed with a shorter load frequency (30 s beam on and 30 s beam off) at the same MFR as well as another 100 TM cycles of the same kind, but at an MFR reduced to ~ 8 g/s. After a further decrease of the MFR down to 6 g/s at a lowered $T_{in,\ He}$ of ~ 500°C, the mock-up survived 70 thermal cycles at a power level of 8–10 MW/m^2, giving a total number of 300 TM cycles applied to this mock-up. A pressure loss of 0.5 MPa was measured at an MFR of 10 g/s and $T_{in,\ He}$ of about 600°C ($T_{max,\ tile}$ ~ 1800°C) which is about a factor of five larger than the values of the HEMJ mock-ups. After the last shot, cracks were detected at the top and side of the tile together with a gas leak and penetration of brazing alloy at the surface.

These six mock-ups tested in the first testing campaign were subjected to destructive post-examinations. It turned out that W parts of some mock-ups, in particular the thimble, were pre-damaged, presumably by micro cracks initiated during the fabrication processes. There never was a suddenly and/or completely broken mock-up, i.e. no brittle failure. Nor was a recrystallisation of the thimble observed in any mock-up. Altogether, it can be said that the performance of the He-cooled divertor concepts (HEMJ and HEMS) of 10 MW/m^2 was confirmed by the first experiment series.

5. Conclusions and outlook

The current phase of the divertor development is aimed at the construction and high-heat-flux tests of prototypical tungsten mock-ups to demonstrate their manufacturability and their performance. In cooperation with the Efremov Institute, comprehensive technological studies were performed on W/W and W/steel joints of the divertor parts. Based on these results, first series of W mock-ups were fabricated for high-heat-flux testing in a test facility, consisting of the Tsefey EB and a helium loop (10 MPa He, 600°C) built for this purpose to simulate the thermohydraulics conditions close to those of DEMO. The first HHF test campaign of six mock-ups was performed successfully. The results confirmed the feasibility of the design. The divertor performance of 10 MW/m^2 required was demonstrated for both designs, HEMJ and HEMS.

Prior to the next series of tests on 1-finger mock-ups, which is planned to start in the beginning of 2007, further improvement of the mock-ups has to be done as regards the design of the finger elements to reduce the thermal stresses at the joint interfaces as well as the manufacturing technique for the tile and thimble production. The rules for the manufacturing process are to be specified as a basis for the production of the following 9-finger module. The future steps will focus on the completion of the 9-finger mock-ups and their tests in the second stage of the helium loop construction, which shall provide for a sufficient mass flow rate for such tests.

Acknowledgements

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Table 1: HEMJ design parameters.

	Jet hole diameter D (mm)	Jet-to-wall distance H (mm)
J1a	0.6	1.2
J1b	0.6	0.6
J1c	0.6	0.9
J1d	0.7	0.9
J1e	0.85	0.9

Table 2: Material and joining techniques defined for 1-finger mock-up manufacturing.

Materials	
W tile	PM pure tungsten
Thimble	WL10
Supported tube structure	Eurofer
Joining methods	
W tile/thimble	Brazing (STEMET® 1311) T_{br} = 1100°C
Thimble/supported tube structure of Eurofer	Conic lock filled with cast copper

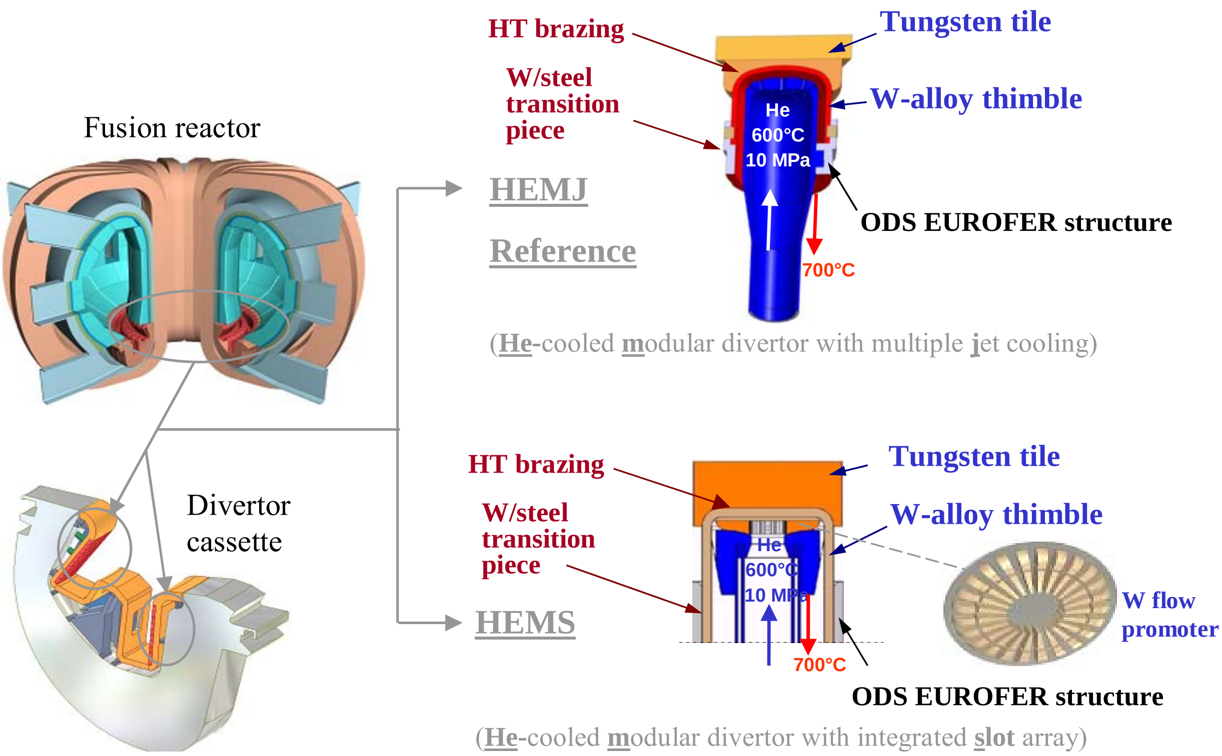


Fig. 1: Design principle of the He-cooled divertor with multiple-jet cooling.

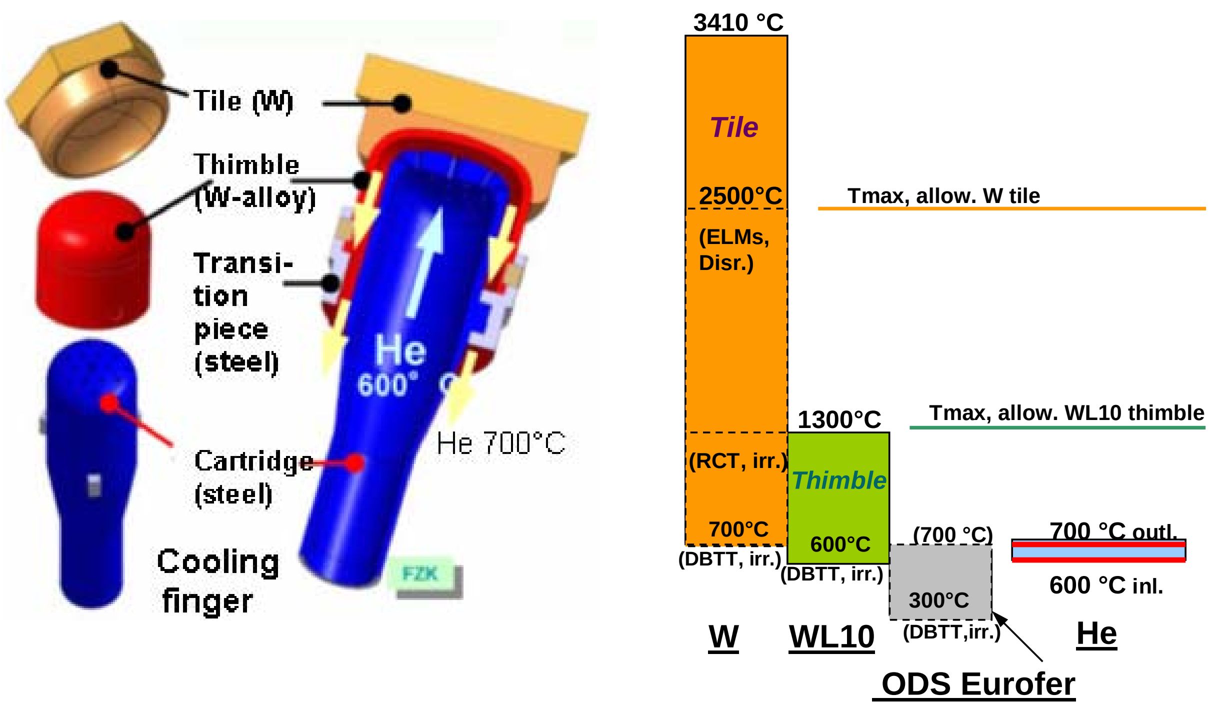


Fig. 2: Temperature windows.

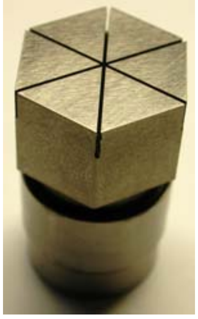
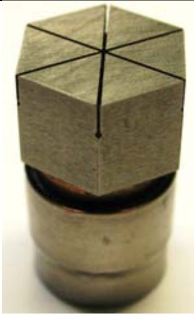
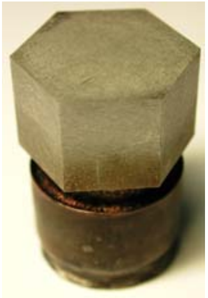
Mock-up #1 Exp. No. 5	#2 Exp. No. 2	#3 Exp. No. 4	#4 Exp. No. 1	#5 Exp. No. 3	#6 Exp. No. 6
					
HEMJ					HEMS

Fig. 3: First series of W 1-finger mock-ups manufactured: Five HEMJ (four – with Cu cast in thimble-steel conical lock, one - with Co brazing in thimble-steel conical lock); One HEMS with Co brazing in thimble-steel conical lock.

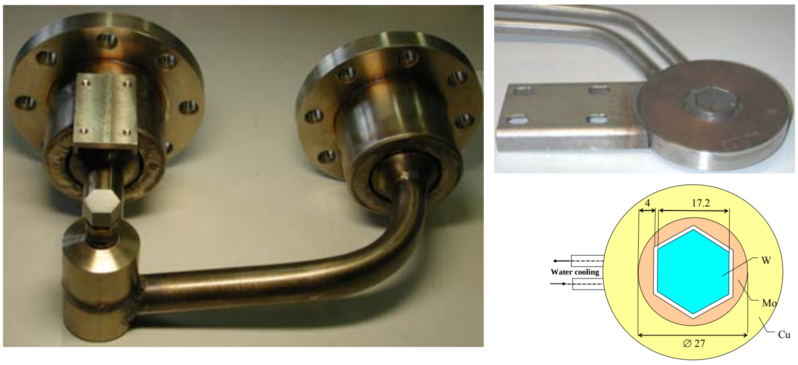


Fig. 4: Target device with mock-up holder and water-cooled shielded mask.

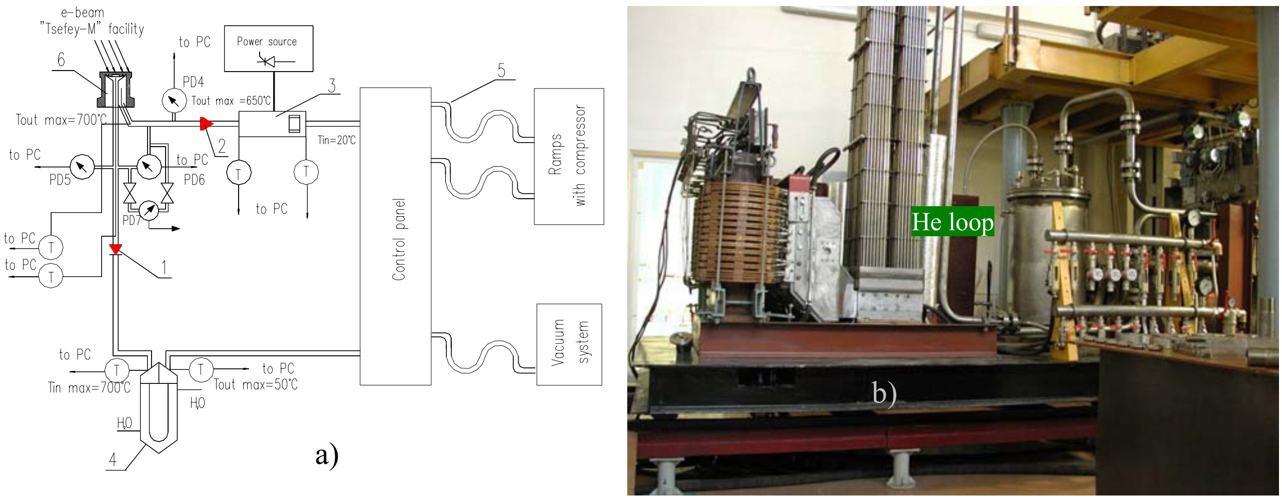
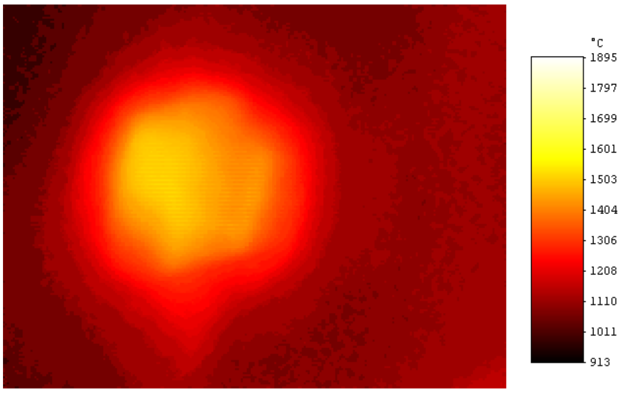


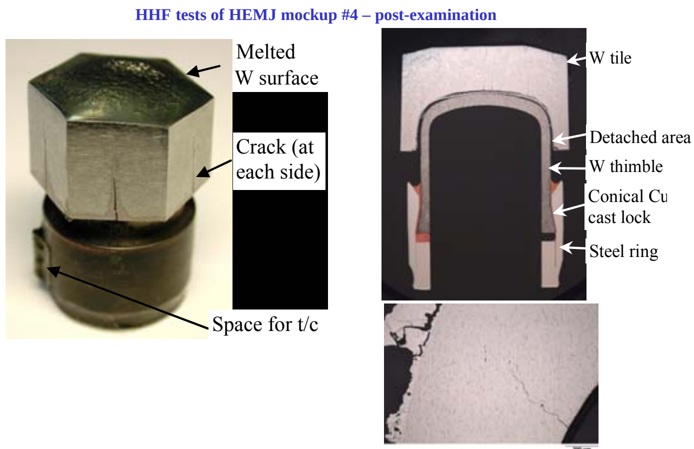
Fig. 5: Helium loop: a) flowchart (left): 1, 2 – hot valves, 3 – flowing helium heater, 4 – flowing helium cooler, 5 -flexible high-pressure line, b) assembled on vehicle (right).

Scheme a) b)

Fig. 6: The testing facility: a) TSEFEY, b) TSEFEY with He-loop integrated).

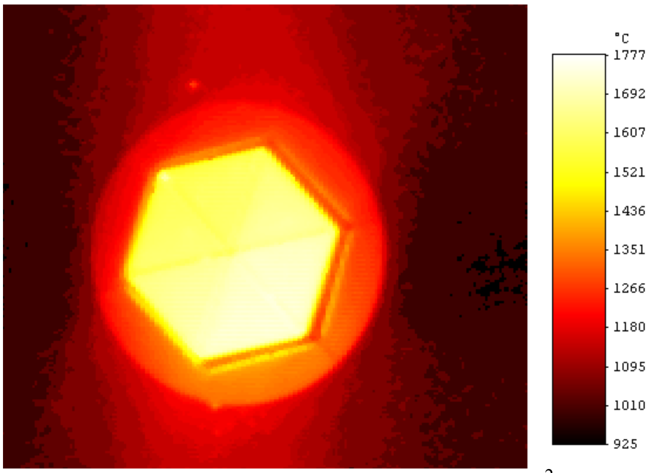


Mock-up #4: Temp. distribution at 11.6 MW/m^2, MFR ~ 13.5 g/s, $T_{in,He}$ ~ 540°C (T_{max} ~ 1500°C)

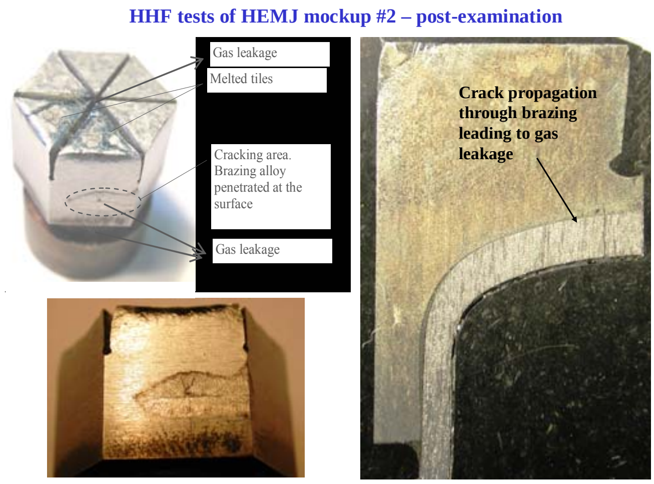


Crack in thimble, growing from inside

Fig. 7: HHF test of mock-up #4 (HEMJ, non-castellated): a) IR picture of temperature distribution (left), b) Post-examination (right) after the last power step (6 cycles at 13 MW/m^2).



Mock-up #2: Temp. distribution at 11.5 MW/m^2, MFR ~ 13.5 g/s; $T_{in,He}$ ~ 550°C (T_{max} ~ 1600°C)



Cracks at the side with brazing alloy penetration

Fig. 8: HHF test of mock-up #2 (HEMJ, castellated): a) IR picture of temperature distribution (left), b) Post-examination (right) after the last power steps (max. 13.5 MW/m^2).