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Design description and validation results for the IFMIF High Flux Test Module as outcome of the EVEDA phase

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ABSTRACT

During the Engineering Validation and Engineering Design Activities (EVEDA) phase (2007-2014) of the International Fusion Materials Irradiation Facility (IFMIF), an advanced engineering design of the High Flux Test Module (HFTM) has been developed with the objective to facilitate the controlled irradiation of steel samples in the high flux area directly behind the IFMIF neutron source. The development process addressed included manufacturing techniques, CAD, neutronic, thermal-hydraulic and mechanical analyses complemented by a series of validation activities. Validation included manufacturing of 1:1 parts and mockups, test of prototypes in the FLEX and HELOKA-LP helium loops of KIT for verification of the thermal and mechanical properties, and irradiation of specimen filled capsule prototypes in the BR2 test reactor. The prototyping activities were backed by several R&D studies addressing focused issues like handling of liquid NaK (as filling medium) and insertion of Small Specimen Test Technique (SSTT) specimens into the irradiation capsules. This paper provides an up-todate design description of the HFTM irradiation device, and reports on the achieved performance criteria related to the requirements. Results of the validation activities are accounted for and the most important issues for further development are identified.

1. Introduction

During the Engineering Validation and Engineering Design Activities (EVEDA) phase (2007–2014) of the International Fusion Materials Irradiation Facility (IFMIF) [1], two types of High Flux Test Module (HFTM) have been developed as dedicated devices to irradiate ferritic martensitic steel samples at blanket/first-wall relevant conditions. In this article, the so called “HFTM-V” (with vertical capsules and temperatures 250–550 °C) developed by KIT as part of the EU contribution to IFMIF/EVEDA is described. As shown in Fig. 1, the HFTM is the irradiation experiment in the region directly behind the neutron source with a neutron flux of up to $2 \cdot 10^{15}\,cm^{-2}\,s^{-1}$.

2. Functions, requirements and design paradigms

The functions and requirements of the HFTM are closely linked to the IFMIF mission, to generate materials irradiation test data for design, licensing, construction and safe operation of fusion demonstration reactors (DEMO) under a simulated fusion environment up to about full lifetime of anticipated service in DEMO. For this purpose a set of qualified specimens, of types to determine all necessary material data, in the application-relevant temperature and structural damage dose ranges, in sufficient quantity for statistics, must be irradiated and examined within a timeframe compatible with the fusion roadmaps. Quality requirements such as precise irradiation temperature control, limited spatial gradients of nuclear responses in the gauge volumes and understanding and containment of possible cross-influences (such as corrosion) apply. The following functions and requirements have guided the design during the IFMIF/EVEDA phase:

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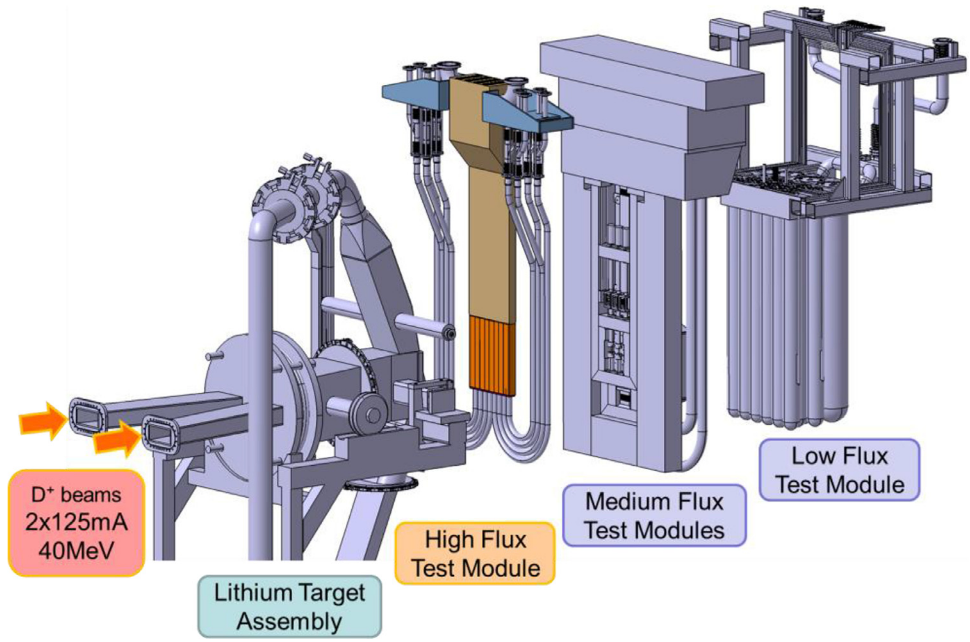

Fig. 1. Arrangement of the neutron source (Lithium target irradiated by 40 MeV deuterons) and the irradiation experiments (Test Modules) inside the IFMIF Test Cell. The HFTM occupies the first 58 mm (including a gap) behind the Lithium target backplate in the strongest neutron flux region.

- Allow the irradiation of Reduced Activation Ferritic Martensitic (RAFM) steel specimens in the irradiation area directly behind the IFMIF neutron source, in the projection of the beam-footprint (20 cm width × 5 cm height), where 20–50 dpa/fpy prevail.
- Control the specimen temperature at defined levels between 250 and 550 °C. The temperature spread within the specimen stack of one irradiation capsule shall be limited to ±3% relative to the absolute (Kelvin) temperature (in 80% of the available volume – cold corners without specimen loading can be accepted). Temporal stability, also during beam trips, must be achieved.
- Transmit the incident neutron flux effectively to the specimens, avoiding as much as possible flux attenuation and undesired alterations of the spectrum.
- Reasonably low gradients of nuclear responses (structural damage, gas production) and low temperature spread inside the specimen gauge volume.
- Enable instrumentation that allows ascertaining with sufficient precision the irradiation conditions such as temperature, neutron fluence and spectrum experienced by the specimens.
- Integrate with specific facility requirements: Lifetime up to 1 year, and structural damage up to 50 dpa (displacements per atom, NRT model).
- Specimen payload in the order of 24 batches of each 40 specimens.
- A design which enables assembly/disassembly under remote handling conditions.

3. Design description

The overall structure of the HFTM is illustrated in Fig. 2(left). The space for irradiation is behind the 20 cm width x 5 cm height beam footprint. In this region, the outside structure is a thin walled (2 mm) container, which is subdivided by stiffening plates into 8 slots called “compartments” into which each 3 irradiation rigs can be inserted (see Fig. 2, right). The rigs and the container are cooled by a low pressure (0.3 MPa abs., 50 °C at inlet) high speed helium gas flow, which is fed by 8 feed pipes to the bottom of the container. The helium flow through each compartment can be controlled individually (6–24 g/s) and is scaled so that the exit temperature from each compartment is the same. The container is connected by the so called attachment adapter to the upper support trusses (for fixation in the test environment). The attachment adapter also serves as return duct for the cooling helium (at about 0.2 MPa abs. and 100–120 °C). The feed pipes, container and attachment adapter together form the hermetic pressure boundary of the HFTM assembly and are a TIG welded construction of X2 CrNiMo 17-12-2 (AISI 316 L) austenitic steel, for which a maximum allowable irradiation of 53 dpa (at 20 °C < T < 375 °C) is defined in the RCC-MRx [2] code. The container provides fixtures for holding the rigs in place while allowing their thermal elongation. Cables of thermocouples and electric heaters are run inside the attachment adapter and exit the hermetic enclosure through feedthroughs on the top. Feedthroughs, flanges (with metal gaskets) and elastic bellows are installed only at the top of the assembly in a region of reduced neutron flux.

As shown in Fig. 3, the specimens are enclosed in hermetical capsules, which also provide electrical heating. The capsules are installed in thin walled envelopes called irradiation rigs. These rigs implement a thermal insulation gap (stagnant helium, gap width defined by a knobbed pattern on the outside capsule surface) around the capsules, as well as solid metal upper and lower neutron reflectors. The outside surfaces of adjacent rigs together with the compartment walls form an array of parallel mini channels (gap width 0.6–1.0 mm) through which the cooling helium flow is guided (see Fig. 3, right). Each capsule contains 86 specimens. Voids in the specimen stack, which would disturb the heat conduction are as far as possible reduced by using steel filler pieces and specimen cages. Remaining gaps are filled up by NaK-78 eutectic liquid metal, which has a thermal conductivity similar to RAFM steels and a low neutron absorption cross section. Three heater coils are brazed in the capsule wall. The heater powers are guided by thermocouples, and thus allow to compensate the axial nuclear heating profile, the heat-up of the external cooling gas flow, fluctuations of the beam power and cooling conditions, as well as partly manufacturing tolerances (insulation/cooling gap widths). The thermocouples are installed along the capsule

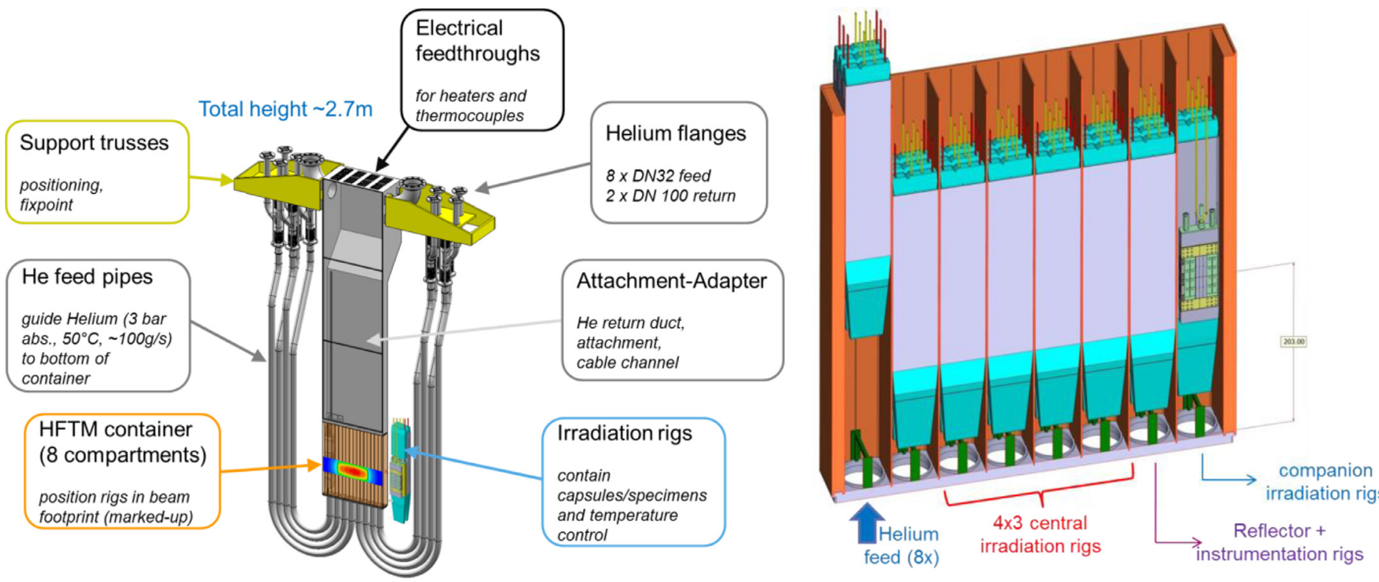

Fig. 2. Left: overall structure of the HFTM, with color mark-up of the neutron beam footprint. Right: cut-open container showing the 8 internal compartments with each 3 rigs. The rightmost rig is dissected to show the position of the specimen stack.

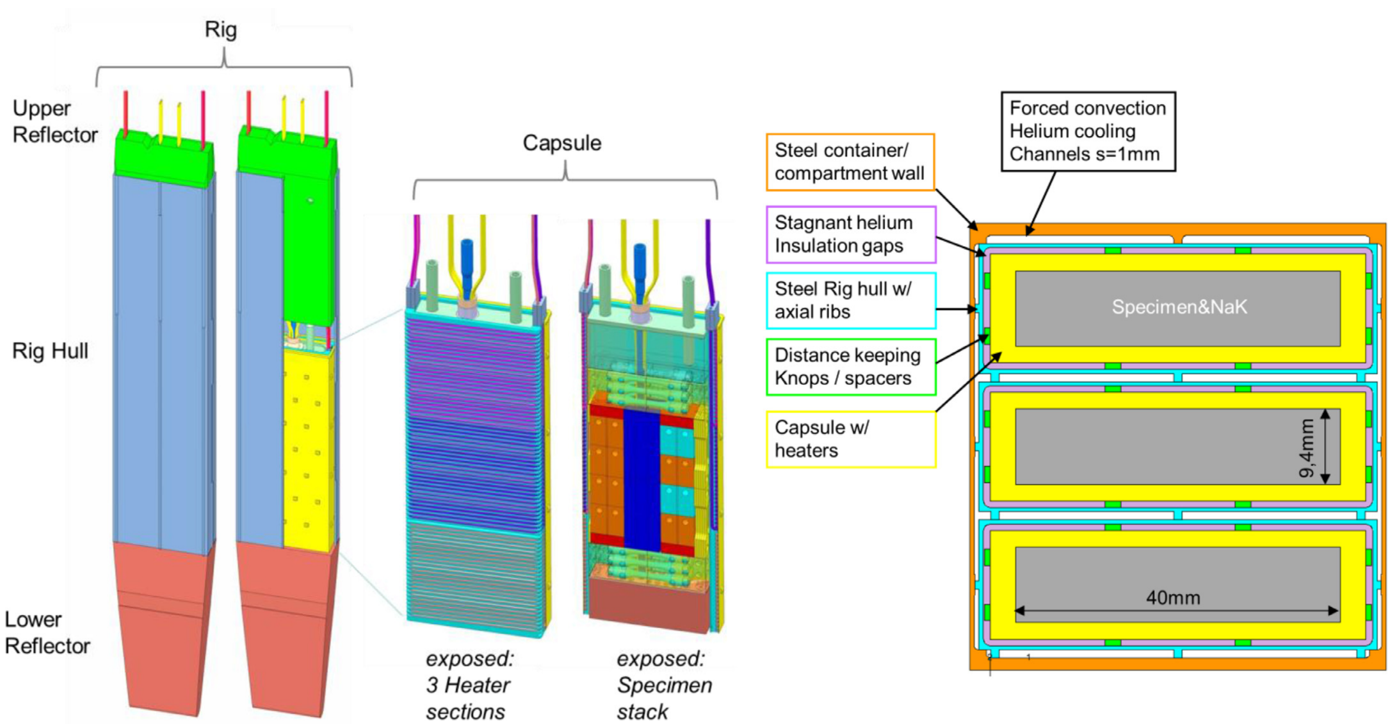

Fig. 3. Left: design of rig and capsule. Right: cross section through a (single) compartment of the HFTM containing three rigs, showing the insulation gaps and the array of helium cooling (mini) channels.

center axis in the middle of each heater section. The capsule is also equipped with tubes for filling/draining the NaK liquid metal.

4. Design analyses

Neutronic, thermal-hydraulic and mechanical analyses have been iteratively performed for several design stages of the HFTM. Special care has been taken to select applicable data and simulation models. For the neutronics, the Monte Carlo code McDeLicious [3] which is custom developed to implement the Deuteron–Lithium source term for neutrons has been operated with cross section data from FENDL3 (Energies up to 150 MeV) [4]. For the thermal-hydraulic analyses performed with the CFX [5] fluid dynamics code, dedicated experiments were performed to select and validate turbulence modeling approaches suitable for the laminar-turbulent transitional helium flows in the HFTM mini channels [6–8].

4.1. Neutronic analyses

Results of the neutronic analyses [9,10] provide data for the (i) material responses relevant for material testing like

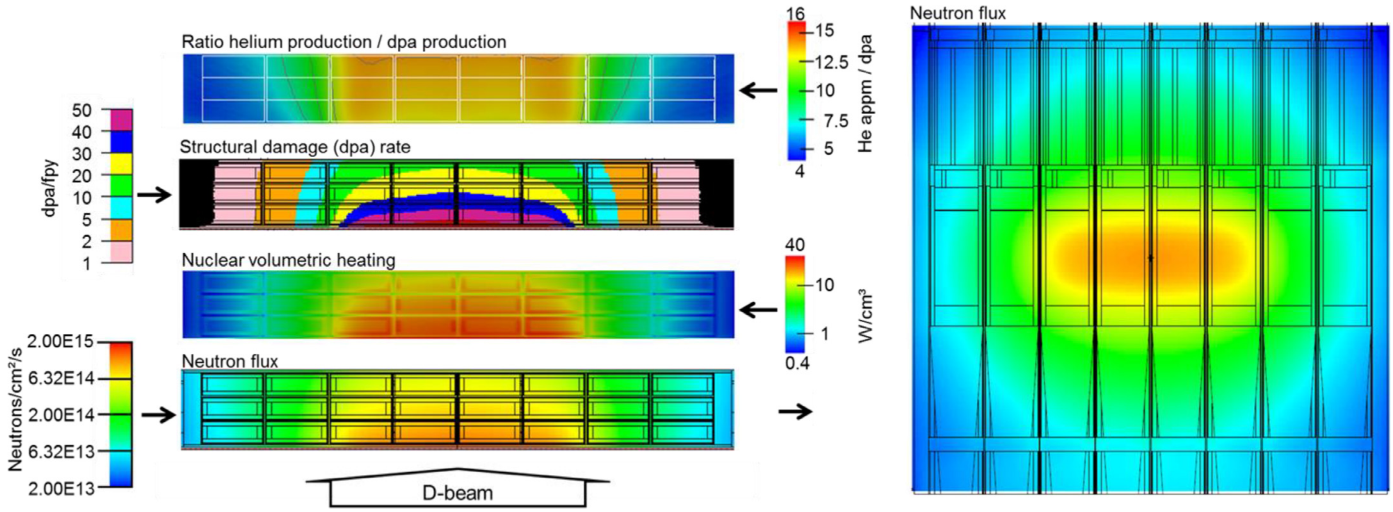

Fig. 4. Cross-section maps of the most important neutronic responses in the HFTM.

structural damage (dpa), gas production (H, He) and transmutation, (ii) design relevant parameters such as volumetric nuclear heating during irradiation and decay heat production, and (iii) facility relevant quantities such as activation (produced radio isotopes) and shielding requirements. As shown in Fig. 4, damage rates of 10–50 dpa/fpy (displacements per atom per full power year) are reached in the central 4 compartments (volume available for specimens 337 cm^3), with He/dpa production rates of typically 12–14 appm(He)/dpa, representative for the DEMO First Wall [11]. The capsules receiving the highest neutron flux have an average (86 specimens) dpa rate of 33 dpa/fpy.

Activation analyses performed with FISPACT-2007 [12] and the EAF-2007 [13] activation cross sections data, yielded nuclide inventory, activity, contact dose rate, required shielding and decay heat production resolved on component level and dependent on time after irradiation shutdown. Immediately after 345 days of irradiation, the total decay heat of the HFTM is 545 W, and activity is 3.55 $\cdot$ 10^{15} Bq. The decay heat drops below 50% of the initial value after about two days.

4.2. Thermal-hydraulic analyses

The complete HFTM receives about 19.3 kW of nuclear heating and additionally 13.7 kW through the electrical capsule heaters during normal irradiation. The CFD calculation takes into account the detailed geometry of the HFTM and the 3D nuclear heating distribution. Besides the forced convection of the helium flow, also radiation, contact heat resistances and heat transfer to the surrounding Test Cell atmosphere were considered in the model [14,15]. In some runs, even the individual specimens were geometrically resolved inside the capsules. Exemplary results are shown in Fig. 5. The container temperature is limited to below 160 °C. The flow velocities in the mini channels obtain more than 400 m/s and vary strongly between the compartments. It was also shown, that for the criteria for the temperature spread of less than +/−3% is met in over 97% of the volume (compared to the 80% according to requirements). If the specimen stack is simulated with NaK replaced by stagnant helium, the temperature spread increases by 10 K. Transient calculations indicate that the time constant for temperature control is in the range of 10 s, and the grace time in a loss of cooling scenario is several hours before critical temperatures are reached.

5. Prototyping and validation experiments

The HFTM design validation process included a series of prototypes leading from single capsules and rigs up to a 1:1 length scale prototype with 2 compartments (6 rigs). Single rig tests in a helium loop (ITHEX) delivered early feedback about thermal-hydraulic characteristics of the rigs [8,16] and possible fabrication issues. The double compartment prototype was tested in the HELOKA-LP helium loop [17] at 1:1 cooling conditions (with surrogate nuclear heating by additional electric heaters) over the full range of temperatures and heating powers. A set of 3 full-featured capsules were fabricated and irradiated 3 cycles in the BR2 reactor.

5.1. Manufacturing of prototype components

Manufacturing tests were performed for all parts necessary to build the HFTM. Fig. 6 shows a selection of such prototype items, like the specimens, capsule, rig and HFTM double compartment prototype. All parts were produced fit for function. The tightly toleranced container and rig hull are manufactured by wire-cut spark erosion. Here, an effective stress relief before manufacturing and single-clamping machining (achievable by an optimized cutting pattern) were essential for manufacturing success. The attachment adapter was machined from two parts and cover plates. The welding of this long and slender but tick walled structure requires special attention to reduction of welding distortions. The brazing of the heater to the capsule is done with a Ni-105 braze for nuclear applications. By cutting of test pieces and by non-destructive testing by infrared imaging, it was assured that the brazing produces good thermal contact in every capsule. The filling of NaK was performed in a Glovebox using a custom metal syringe to deliver a predetermined amount of NaK. The capsule is kept at temperatures >300 °C during the filling (which is delivered in several steps) and is vibrated to ensure the distribution of NaK into the cavities.

5.2. Irradiation campaign in BR2

Three capsules containing different specimen sets have been fabricated and inserted into an irradiation rig of the BR2 test reactor at SCK-CEN:

- Capsule “K1” was irradiated at 1.8–2.1 W/g (lower rig position) at a temperature of 250 °C. This capsule contained no NaK between the specimens

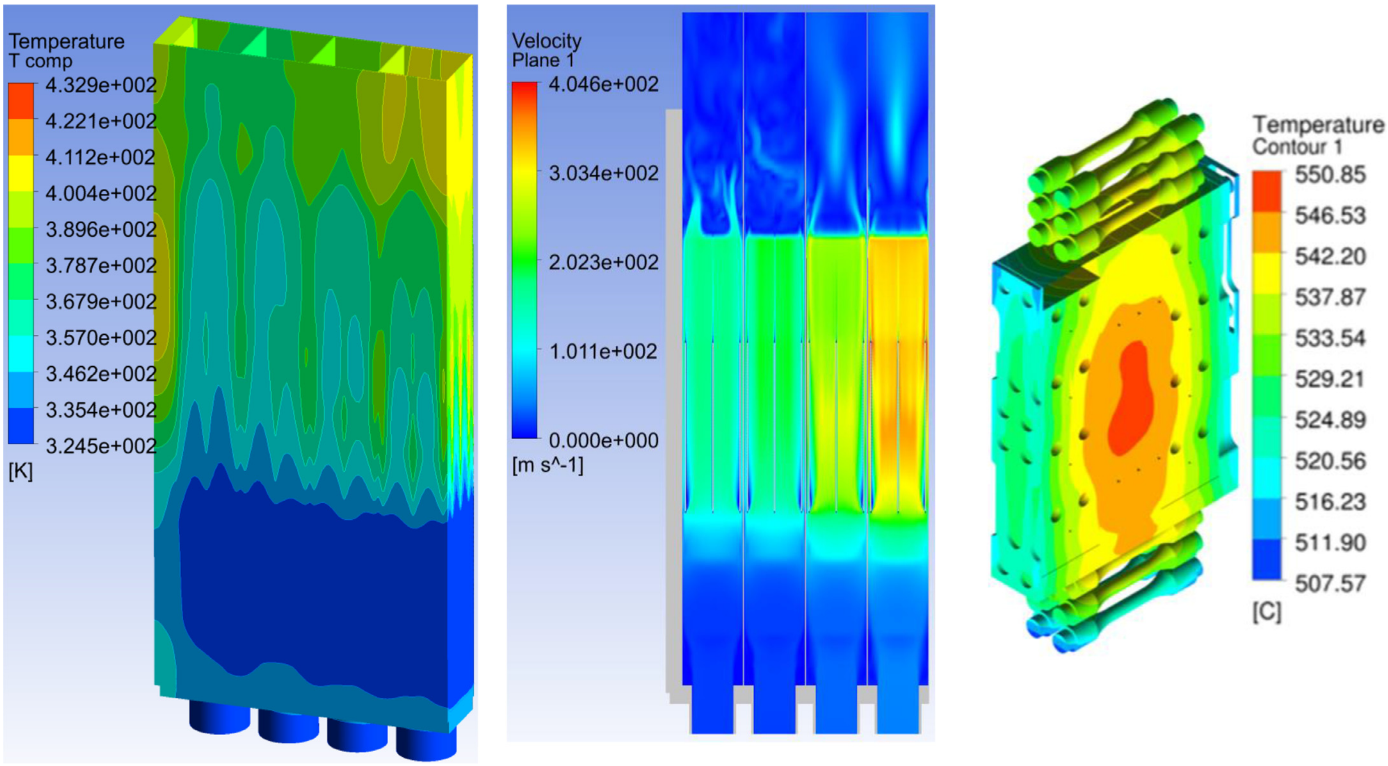

Fig. 5. Results from CFD simulations. Left: container temperature. Middle: gas velocity in the mini channels. Right: temperature distribution in the specimen stack with individual resolved specimens.

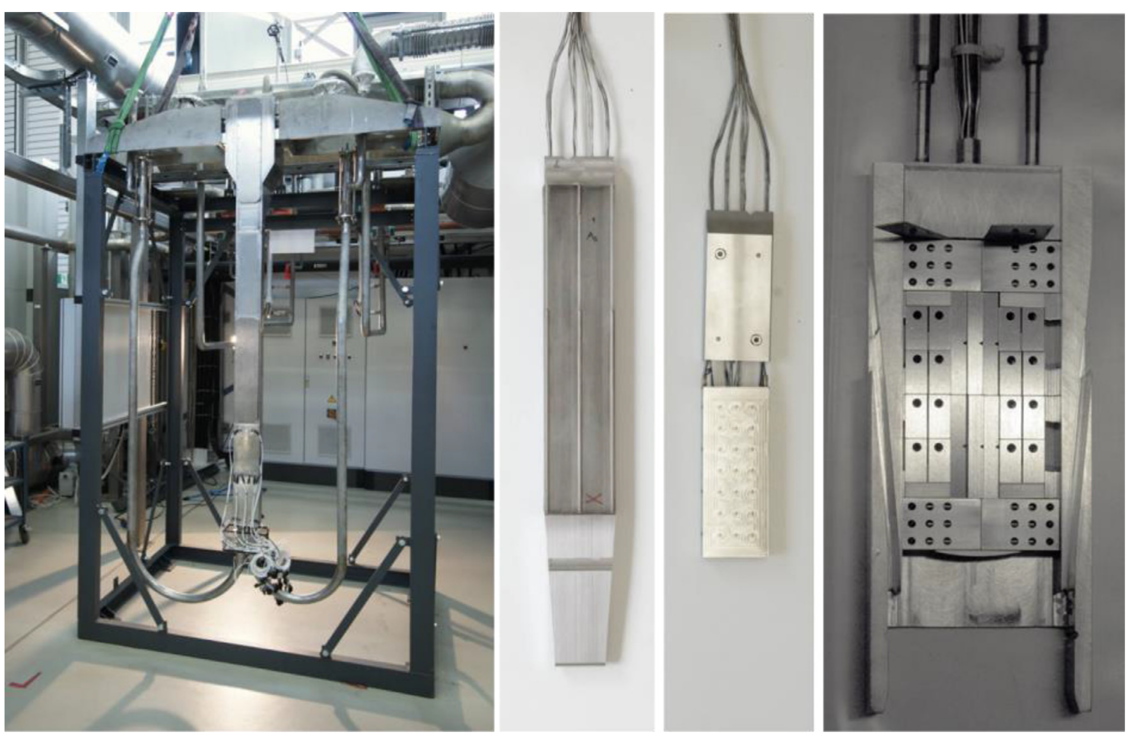

Fig. 6. Fabricated prototype items. Left: the HFTM double compartment prototype during installation in HELOKA-LP. Middle: a completed rig and a capsule with upper reflector. Right: the specimen stack in a so called assembly tray before insertion into the capsule.

- Capsule “K2” was irradiated at 2.7–3.3 W/g (middle rig position) at a temperature of 390 °C. This capsule was filled with NaK and specimens
- Capsule “K3” was irradiated at 1.25–2 W/g (top rig position) at a temperature *cycling* with a period of 32 min. between 250 and 440 °C. This capsule was filled with NaK and specimens

During the irradiation, temperatures and heater supply voltages and currents were measured along with reactor parameters (neutron flux, cooling water conditions, gamma heating). At breaks between the irradiation cycles, the insulation resistances of heaters and thermocouples were additionally measured.

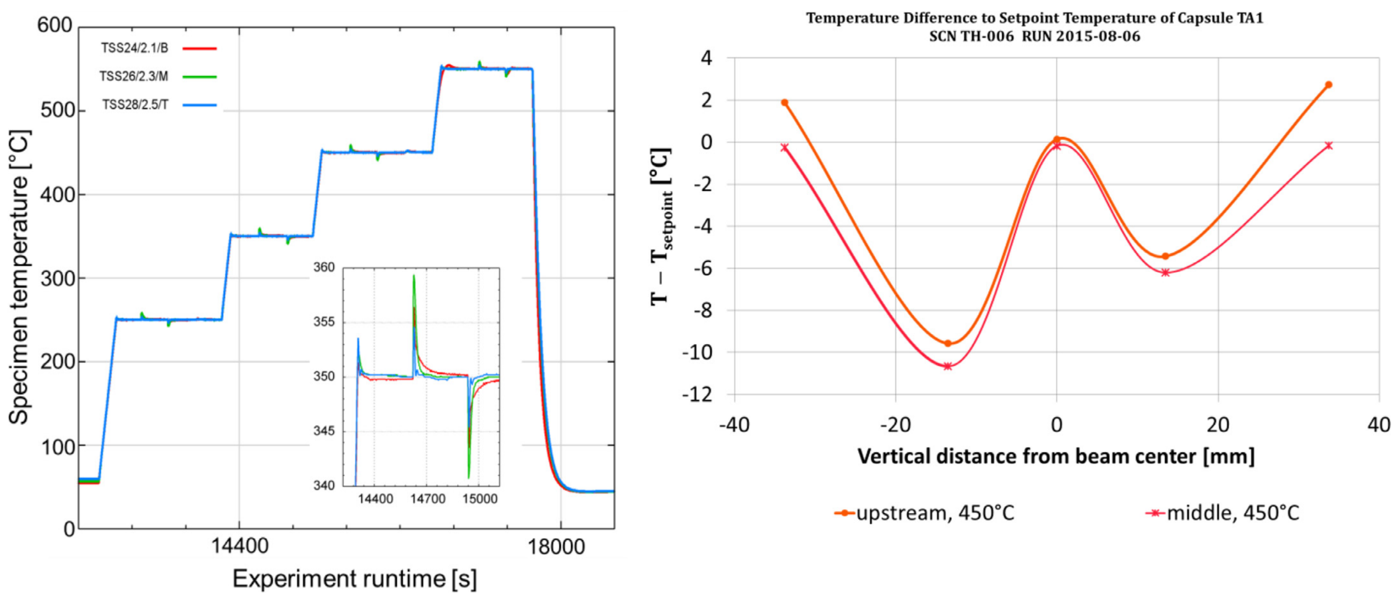

Fig. 7. Experimental results from HFTM-DC. Left: setpoint changes from 250 to 550 °C. The insert shows the temperature response of a beam-on/beam-off event. Right: axial temperature profiles in the capsule.

Some reactor events and a failure of the electrical cabinet produced a discontinuous operation of the capsules. Nonetheless, very important observations were secured from the experiment:

- The electrical resistance of the Ni Cr 80 20 resistive heater wire increased during irradiation, but saturated at about +10%
- The insulation resistance (compressed MgO powder) varied over the irradiation time in a non-continuous manner (increase/decrease), and resulted in loss of several heater circuits. It is not possible to discriminate the effects from pre-damaging during manufacturing of the capsules (heaters had been repaired) from possible radiation induced effects. Heater wires without pre-damaging survived the irradiation to the end.
- The Capsule #3 mechanically failed after ~650 thermal cycles and leaked NaK. This identified a weak weld seam construction that was improved in the follow-up design.
- The thermocouple reading in the capsule without NaK indicated an acceptable homogeneity of the temperature field (less than 5 K spread measured by 6 thermocouples at 1.5 W/g) even without the homogenizing effect of the NaK. This encourages the possibility to use capsules without NaK (to improve lifetime and reduce manufacturing complexity) under some circumstances.

5.3. Thermal-hydraulic and mechanical testing in HELOKA-LP

The HFTM double compartment prototype was tested in the HELOKA-LP helium loop for the full range of operation conditions, concerning pressure, mass flow rates, (surrogate) nuclear heating and capsule temperatures 250–550 °C. The full temperature range was successfully demonstrated (see Fig. 7, left). The temperature control of the capsule is swift and precise. Perturbations from changes in the coolant flow conditions do not imprint on the capsule temperature signals. A step response of 100% of the capsule (surrogate) nuclear power only results in a short temperature deviation of less than 10 K. The maximum measured temperature spread inside the capsule is less than 15 K for the axial profile (Fig. 7, right) and less than 8 K for the transversal profile. This corresponds to 1.5% of absolute temperature spread. To cool down the specimens from 550 °C to 200 °C, 109 s are needed, much less than the required 15 min. In a loss of coolant scenario with capsules heated according to decay heat production, it took more than 2 h to reach a maximum of 150 °C in the setup.

In hydraulic tests, the mass flow rate per compartment was adjusted up to 34.8 g/s (mean velocity ~558 m/s), where a pressure drop of 1.78 bar occurred. At the typical mass flow rate of 16 g/s, the pressure drop was 0.32 bar.

In the pressure test, the HFTM was tested with 5.2 bar(g). During all operations, the maximum recorded strain was 0.04% in the container wall. During operation, the HFTM flexes away from the beam by about 1 mm. This is attributed to the asymmetric arrangement of the helium feed pipes. No flow induced vibrations were observed.

6. Complementary studies

6.1. Handling of small scale SSTT specimens

The full cycle of specimen insertion, NaK filling and accounting and closing of the capsule, as well as the reverse process of NaK draining, cutting open of the capsule, safe retrieval and cleaning of the specimens has been successfully practiced. It was also tested to assemble the specimen stack with manipulators in a hot cell simulator. Specialized gripping tools and supporting devices were developed. It was shown that the small specimens can be handled, and the tight tolerances of the specimen stack can be achieved. The total operation time to assemble a specimen stack (80 specimens) with the manipulator is about 2 h.

6.2. Behavior of NaK-78 and Eurofer

Specimens are immersed in NaK for 1 year at elevated temperatures. For studying potential impacts on the properties of the specimens, two capsules filled with NaK and specimens were operated for 3 respectively 6 months at cycling temperatures between 470 and 500 °C. Subsequent mechanical tests did not show any deviation beyond the scatter band of the base material's tensile properties. The specimen surfaces were also investigated by Scanning Electron Microscopy/Energy Dispersive X-Ray. It was found that the layer where Sodium, Potassium, Oxygen and Carbon were enriched and Chromium was depleted was limited to a depth of 5 µm.

Other tests investigated the wetting of NaK on Eurofer surfaces, which is relevant for the NaK filling process during capsule assembly. It was shown, that a good wetting behavior can be expected for temperatures of 300 °C and above. In order to guarantee good wetting also at 250 °C, additional vibration should be applied. Once wetted, surfaces keep up the adhesion also at room temperature. NaK wetted specimens can be cleaned by applying a series of ethanol baths (which reacts the NaK to C_2H_5–ONa and C_2H_5–OK and (inflammable!) H_2) assisted by ultrasound. To keep reaction speeds and temperatures moderate, petroleum with a low fraction (20%) of ethanol can be used for the first bath.

7. Conclusions and outlook

As a major contribution to the IFMIF/EVEDA phase, the High Flux Test Module (vertical setup) has been developed with the objectives of high specimen payload and high quality irradiation conditions. Validated engineering tools were used to analyze the design. Neutronic analyses show the DEMO relevancy of the irradiation conditions, with a specimen volume of 337 cm^3 (about 960 SSTT specimens) at high dpa rates offering accelerated testing. The design analyses show that the requirements for temperature homogeneity during irradiation can be fully met.

The design process was integrated in the IFMIF/EVEDA systems engineering and according interfaces to the ancillary systems, safety-, maintenance- and control processes, waste disposal and further were specified as outcome of the design phase.

An extensive testing program was supporting the design process. A series of production trials and prototype components led up to the construction of a 1:1 length scale HFTM double compartment prototype with heated rigs for test in a helium loop and fully featured specimen loaded capsules for irradiation in the BR2 reactor.

The irradiation tests showed shortcomings in the heater lifetime and the mechanical stability of the capsule against cyclic thermal loading. These observations have already triggered improvements to the design, which will be tested in the next design phase.

The tests in the HELOKA-LP helium loop have confirmed the excellent thermal performance predicted by the design analyses, concerning the operation temperature range 250–550 °C, very low temperature spreads in the specimen payload and agile transient control behavior. Stresses and vibrations in the HFTM structure were well below a critical level.

Accompanying studies concerned critical processes, such as the filling and the behavior of NaK, and the manipulator based handling of SSTT specimens.

Based on the results, the chosen design principle is considered valid for its designated task. In the next design phase, performed in the frame of EUROFUSION Work Package Early Neutron Source, improvements aimed at increasing the robustness and reliability of the irradiation capsule are the major objectives.

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