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Journal of Nuclear Materials 329–333 (2004) 223–227
journal of nuclear materials
www.elsevier.com/locate/jnucmat

Overview on the IFMIF test cell development

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Abstract

The major components of the test cell are the three test modules, the shield plugs and the test cell covers. The existing drawings of the IFMIF test cell and the internals were put together to have a common basis for discussion. The high-flux-test-module was redesigned. The rigs were designed with a flat plate geometry. They are equipped with an electric heater system, with which the temperatures in the specimens stack can be kept at temperature levels between 250 and 650 °C within a tolerance of 30 °C. The temperature level of each rig can be adjusted independently. First result of the optimization of the medium-flux-test-module are also described.

1. Introduction

The major components within the test cell of the International Fusion Material Irradiation Facility (IFMIF) comprises three test modules, shield plugs and test cell covers as shown in Fig. 1. The specimen testing areas must be capable of accommodating the wide range of environments associated with fusion reactor materials. This is achieved by partitioning the irradiation volume downstream from the neutron-producing lithium (Li)-target into a high-flux-test-module (HFTM)) with a damage accumulation of 20–55 dpa/full power year (fpy) and an available volume of 0.5 l, a medium flux region (1–20 dpa/fpy, 6 l) with two independent medium-flux-test-modules (MFTMs), and a low-flux region (<1 dpa/fpy, <100 l). The irradiation temperature might vary from 250 to 1000 °C in the high-flux and medium-flux regions, and range down to cryogenic temperatures in the low-flux zones [1].

The arrangement of the Li-target with the two beam tubes for the deuteron beams and the supply tubes including the quench tank below, the HFTM with the irradiation unit of the vertical test assembly (VTA 1), the MFTM of VTA 2 and the array of tubes, referred to as vertical irradiation tubes (VITs) in the low-flux region are shown in an elevation view in Fig. 1. The test cell has a steel liner which also serves as a vessel for the confinement of radioactive material. It will withstand an internal pressure of 0.5 MPa absolute. During irradiation the test cell will be evacuated. The secondary test cell confinement is at least 2.5 m of massive concrete. This confinement acts also as neutron and γ shieldings. It is gas-cooled to prevent overheating of the concrete.

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0022-3115/$ - see front matter
doi:10.1016/j.jnucmat.2004.04.341

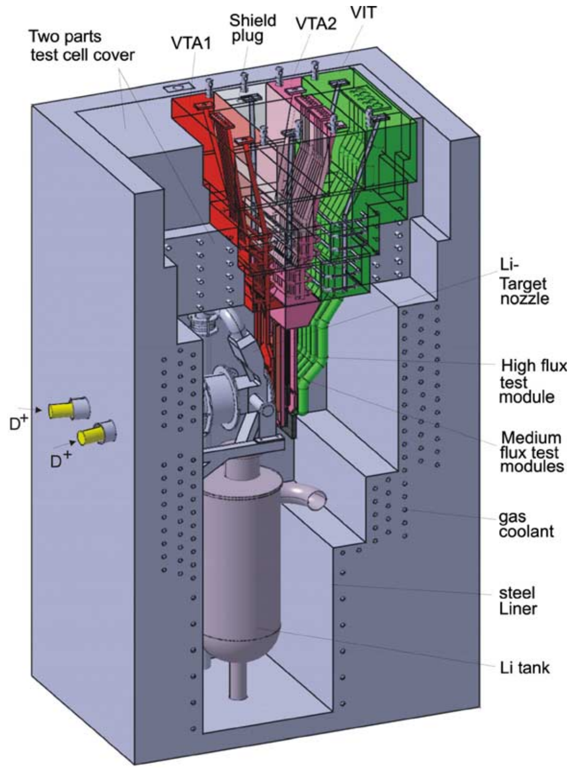

Fig. 1. Elevation view of the test cell with the test modules and the beam tubes for the deuteron beams, the lithium target with the lithium supply tubes and the lithium quench tank.

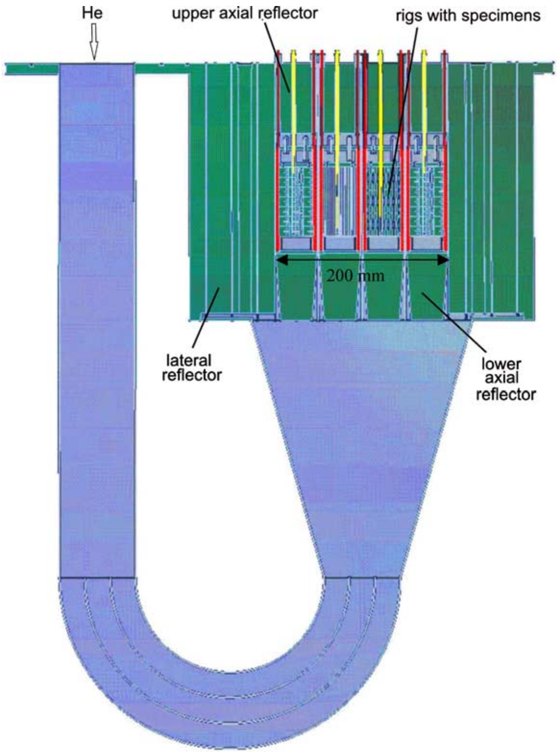

Fig. 2. Design configuration of the HFTM with the neutron reflector, helium inlet and 12 fully instrumented rigs with specimen capsules; container, reflector, rig and capsule walls are made from steel; helium inlet temperature and pressure are 50 °C and 0.3 MPa; helium flow rate 0.083 kg/s.

Circuit components like pumps and coolers are installed outside the test cell. The test cell cover is vacuum sealed to the liner during irradiation. It can be removed with a universal robot system to gain access to the entire test cell.

2. High-flux-test-module

The helium-cooled HFTM concept is basically a vessel with a number of irradiation rigs (Fig. 2) containing the encapsulated specimens at the desired irradiation temperature. In the present reference concept, the HFTM is designed for the irradiation of RAFM-(ODS) steels with specimen temperatures between 250 and 650 °C [2]. The temperature-homogeneity is ±17 °C at the irradiation temperature for practically each rig. An advantage of the basic concept is that the rig wall temperature is in general much lower than the specimen temperature. For vanadium and SiC/SiC the design to allow a specimen temperature window from 650 to about 1100 °C is necessary. The rigs inside the vessel are positioned vertically and can be individually loaded or unloaded after the test module is disconnected from the VTA1. The damage level in RAFM steels is about 20–50 dpa/fpy in the high-flux region. This damage level corresponds to maximum nuclear heating densities of ~5 W/g (40 W/cm^3) in bcc steels, (i.e. a linear power density of ~75 W/cm). For the sake of comparison, linear power densities in modern PWRs are ~400 W/cm. The HFTM vessel is subdivided into 4 compartments each containing three rigs. The rigs contain the specimens within capsules. The capsules are filled with Na/K which ensures the heat transfer between the specimens and the capsule wall. For high-temperature capsules, the samples are container in capsules without NAK. Design and experiment of this option is described in Ref. [3]. The capsules are provided with electric heaters which will adjust the temperature in the specimens stack during irradiation as well as during periods without the deuteron beam. Helium flows upward through the channels between the rigs and removes the nuclear power as well as the power of the electric heaters. All rigs have the same design. The temperature of each rig can be adjusted independently.

Rig and capsule walls are made from stainless steel (316). Container and later reflector are made from a single piece by spark erosion and milling. In a first version stainless steel is used. The manufacturing techniques are tested. For future design a material like EUROFER is encountered as it will exhibit much lower thermal stresses.

The nuclear calculations showed that the dpa/fpy can be increased by a few percent but more important the dpa gradients are reduced when a reflector surrounds the container. The reflector effect tends to reach an asymptotic value at a thickness of 100 mm. Accordingly, the container is equipped with lateral reflectors made of a reduced activation steel like EUROFER with 90% density. The remaining 10% provide space for cooling. Below and above the rigs extensions act as axial reflector elements with a 60% share of the cross section. The MFTM was assumed to have the same material density as the HFTM. Corresponding to the foot print of the deuteron beams, the HFTM dimensions, shown in Fig. 3 are:

- in the beam direction (z-axis): 50 mm
- perpendicular to the beam: 200 mm in horizontal direction (x-axis) and
- in vertical direction (y-axis) the Nuclear calculations show a significant neutron flux or displacement rate also outside of the footprint. This required enlarging the irradiation volume to achieve a volume of 0.5 l with a displacement rate greater than 20 dpa/fpy. In order to allow a stack of 3 test specimens of length 27 mm, the final height of the specimen stack is fixed at 81 mm.

The neutronic calculations were performed with the McDeLi Monte Carlo code which is an extension to MCNP with the capability to represent the IFMIF Li(d,xn) neutron source term in the neutron transport

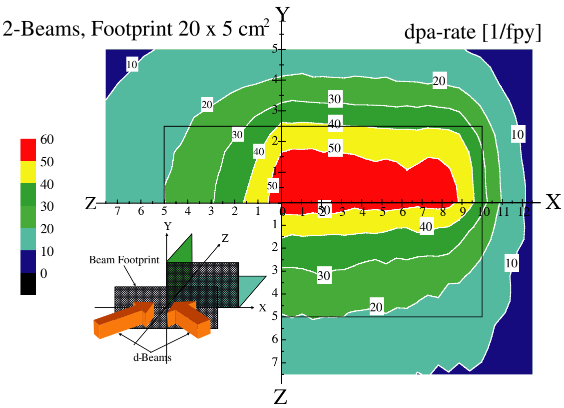

Fig. 3. The dpa rate spatial distribution in and outside the HFTM at full IFMIF performance operation with horizontally declined deuteron beams.

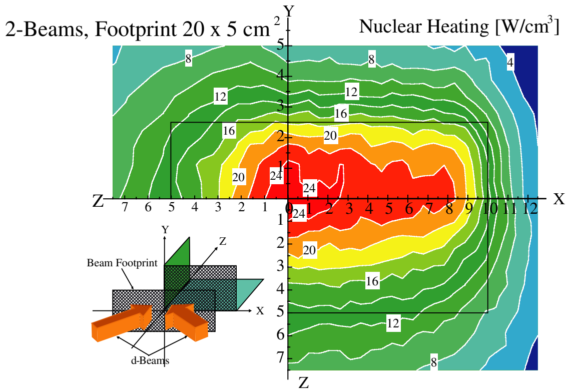

Fig. 4. Power density distribution in the HFTM due to nuclear heating.

calculation. High-energy cross-section data for neutron transport calculations are taken from the LANL 150 MeV data evaluations and from the FZK/INPE Obninsk intermediate energy evaluation.

The nuclear calculations also provide the power density for the thermo-hydraulic calculations shown in Fig. 4.

The thermo-hydraulic lay-out aims at providing maximum space for specimens which means minimum space for temperature adjustment i.e. for cooling, electric heaters and temperature sensors. The electric heaters have to balance the nuclear power distribution shown in Fig. 5. Whereas in x- and z-direction this is in the range of 10% over the rig dimension, in y-direction a variation of a factor 2 has to be balanced.

In addition the heaters have to accommodate the temperature increase of the helium and changes of the heat transfer coefficient along the narrow channels. This can be achieved by a triple heater system wound around the capsules. Thermocouples needed for the measurement of the specimen temperatures and the control of electrical power supply system – two thermocouples for each heating section – are inserted into the centre of the specimen stack at the required location. The design configuration of the rig with rectangular plate like cross section is shown in Fig. 5.

The thermo-hydraulic lay-out was done by use of the CFD (computational fluid dynamic) code STAR-CD (CD-adapco-Group). STAR-CD provides a variety of turbulence models to do the simulation calculations of the gas flow. In order to validate these models experimental investigations still have to be done. The results for several temperatures are given in Table 1. As can be seen for those cases with electric heating the temperature tolerances are in the range of 30 °C. This is well within the tolerances required.

The gaps width between the capsule and the rig walls are filled with stagnant helium. The gap width decides

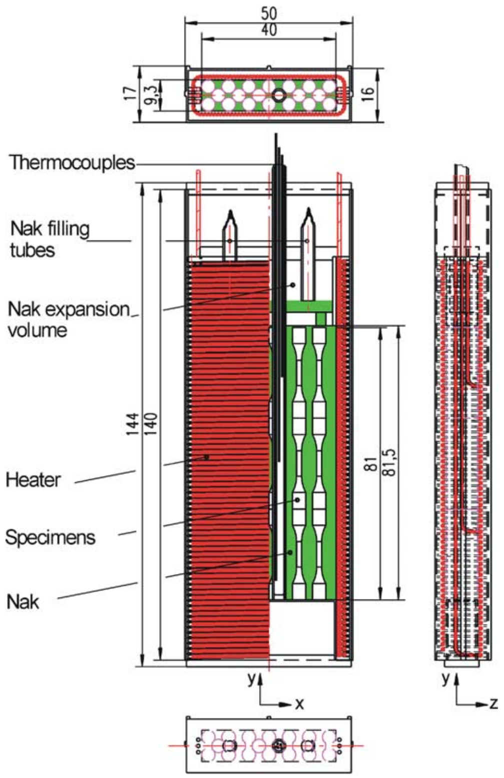

Fig. 5. Design configuration of the capsule with rectangular plate like cross section, the electric triple heater is wound around the capsule in three independent axial units; all dimensions given in mm.

on the thermal isolation. The design was done with a width of 0.5 mm in order to get a unified design. If the width is accommodated to the required temperature level lower temperature tolerances in the specimens stack can be achieved.

The temperature distribution in the lateral reflector and the container wall calculated with STAR-CD was used for stress analyses. Assuming the data of a stainless steel (316) the thermal stresses and the stresses due to an internal pressure of 0.3 MPa exceed the yield stress. The cooling channels in the reflector will be redesigned accordingly. If in a future design steels like EUROFER can be used, the thermal stresses will be much lower than the yield stresses.

3. Medium flux test module

The MFTMs are being investigated in several design variants. A major result of neutronics calculations for the MFTMs is that the irradiation conditions for in situ creep-fatigue and in situ tritium release experiments could be substantially improved by W plates acting as 'neutron spectral shifter' and an additional carbon jacket acting as 'neutron reflector'. Those reflector materials will have an impact on the flux distribution within the HFTM. Therefore the MFTM is presently redesigned with the methods as were used for the optimization of the HFTM. The first results show that the specimens can be kept at the desired temperature by combined heater systems.

Table 1
Results off the thermo-hydraulic calculations for the temperature distribution in the specimen stack for nuclear plus electric heating as well as for electric heating only

Case	1a	1b	2	3a	3b	4a	4b	5a	5b
Parameters									
Eff. He gap size (mm)	0.5	0.5	0.5	0.5	0.5	0.8	0.8	0.25	0.25
Lower cap	Thin	**Thick**	Thick	Thick	Thick	Thick	Thick	Thick	Thick
Heating	Nucl.	Nucl.	**Nucl./ El.**	Nucl./ El.	**El.**	El.	**Nucl./ El.**	Nucl./ El.	**El.**
El. power in section									
Upper (W/cm^3)	–	–	71	**149**	194	147	108	65	111
Middle (W/cm^3)	–	–	–	**90**	199	148	39	–	118
Lower (W/cm^3)	–	–	74	**158**	206	154	110	70	124
Results									
Maximum specific temperature (°C)	403	404	465	650	655	650	650	337	339
Maximum temperature difference in specimens (K)	121	121	30	31	35	13	22	33	33
Maximum helium velocity (m/s)	478	479	504	550	547	514	518	501	499

The nuclear power was assumed as for the first row i.e. with the highest nuclear heat load; the assumptions for the helium flow are: inlet temperature 50 °C, inlet pressure 0.3 MPa, mass flow rate 0.083 kg/s; see more details in text.

4. Conclusions

The HFTM was optimized for maximum space for the specimens which means minimum space for the temperature control i.e. electric heater, temperature sensors and flow channels for the helium cooling. The analyses done with the CFD code STAR-CD showed that the temperature can be independent in each rig at levels between 300 and 650 °C. STAR-CD and the low-Reynolds-number turbulence model was compared with good agreement with an experiment from the literature. However the validation still has to be demonstrated with experiments with the narrows channels characteristic of the HFTM geometries. Appropriate experiments are under construction. First stress analyses show that the container will withstand the thermal stresses.

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