IFMIF Target and Test Cell – Towards Design Integration

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Abstract: The Target and Test Cell of the International-Fusion-Material-Irradiation-Facility (IFMIF) will provide an intense neutron source and qualified irradiation specimen for testing candidate fusion reactor materials. The progress achieved in the design integration of the Target and Test Cell subsystems will be reported with respect to CAD engineering models, the nuclear layout analyses and cooling capabilities by natural convection. A validated set of sophisticated methods, data and tools is now available to continue this ongoing task in the forthcoming EVEDA phase of IFMIF.

1. Introduction

The International-Fusion-Material-Irradiation-Facility (IFMIF) is an accelerator driven neutron source for irradiation tests of candidate fusion reactor materials. Two 40 MeV deuterium beams of 125 mA each will hit a flowing liquid lithium jet target, producing high energy neutrons up to 55 MeV at a rate of about 10^{17} per second. Those neutrons will penetrate the target back wall made of a thin EUROFER plate. In the attached High Flux Test Module (HFTM), a testing volume of 0.5 litres filled by qualified small scale specimens will be irradiated at displacement rates of 20-50 dpa/fpy in structural materials. The HFTM will also provide helium and hydrogen production to dpa ratios that reflect within the uncertainties the values expected in a DEMO fusion reactor. The Medium Flux Test Module (MFTM) comprises devices for in situ creep-fatigue and tritium release experiments, as well as for tungsten spectral shifter or reflector plates. Further down-stream the low flux region will provide irradiation tubes for additional material irradiation at lower fluence levels.

The objective of the present paper is to present the progress achieved in the design integration of the Target and Test Cell of IFMIF. First, work is reported on collecting and harmonizing the CAD designs provided by various international groups involved in the IFMIF Target and Test Cell development. Second, further efforts devoted to the general nuclear layout of the Target and Test Cell are described, taking into account nuclear calculations of responses such as nuclear heating, activation inventories, and dose rates based on most advanced nuclear data and calculational procedures. Finally, results of an extensive study are presented on the cooling capabilities of the Target and Test Cell by natural convection.

2. CAD Design Integration

The Target and Test Cell (TTC) is a cavity which contains, among others, the lithium target assembly and the test modules. Several international teams have developed different individual components with the objective to investigate the main functional characteristics and issues of each component separately. The engineering design has been elaborated to fulfil the requirements for that component only and has been neglecting mostly design integration issues.

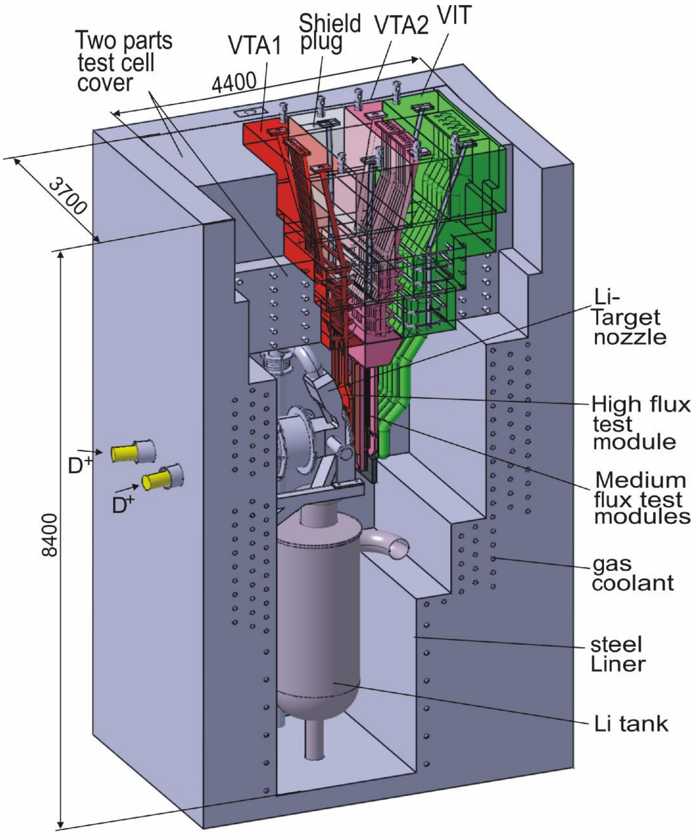

Fig. 1: Elevation view of the Target and Test Cell showing major components inside the cavity

As now the engineering design has been advanced to start the Engineering Validation Engineering Design Activities (EVEDA) phase of IFMIF, efforts devoted to collect, integrate and harmonize the separate designs have been started already a few years ago. The TTC drawings, presented in *Fig. 1*, *Fig. 2*, and *Fig. 3*, have been made from a concise 3D model maintained with the CAD system CATIA V5 R16. They are based on drawings and additional information gathered from the design teams as follows: FZK has provided designs for HFTM [1] and MFTM [2] (Creep Fatigue Test Module, Tritium Release Module), JAEA a Lithium Target assembly with fixed back-plate [3]. An alternative concept with a replaceable bayonet type back-plate is under development at ENEA [4]. In addition, information has been extracted, where applicable, from the IFMIF reports CDA [5], KEP [6], and CDR [7].

During the process of incorporating this information into the existing CATIA-model of the TTC the need for adaptations has been realized. They refer mainly to interface issues between the test modules and between HFTM and Target Assembly. The overall dimensions of the TTC have been further modified to accommodate all components. It has now a depth of 6 m below the cover and a top surface of 2.5 m x 3.0 m. The walls are part of the surrounding building made of heavy concrete for the shielding of neutrons and gammas penetrating the interior and covered by a Reduced Activation Ferritic Martensitic steel, namely EUROFER, liner of 3cm thickness to maintain the gas tightness of the TTC.

The Vertical Test Assemblies (VTA) 1 and 2 and Vertical Irradiation Tubes (VIT) are inserted in the TTC cover to support the test modules. The removable cover has a thickness of 2.4 m to protect the equipment in the top access cell with the main gantry crane (Universal Robot System) and the Combined Manipulator System against the neutron and gamma flux.

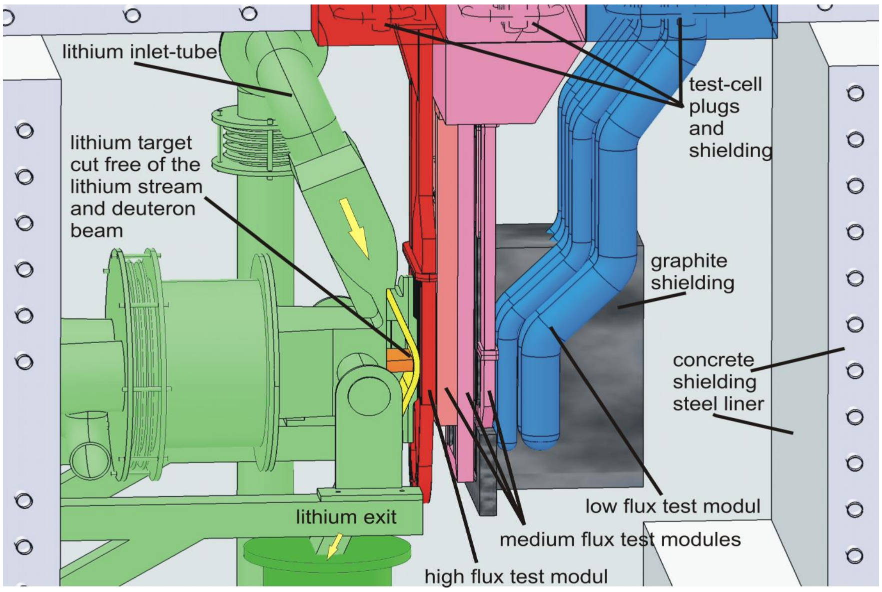

Fig. 2: Details of lithium target assembly and test module of the integrated CATIA model.

The High Flux Test Module has been designed [1] to provide maximum space for miniaturized irradiation specimens, kept at well defined temperature levels between 300 and 650 °C. Cooling and temperature control equipment should claim minimum space within the HFTM. The present design envisages more than 1000 qualified specimens which can be irradiated simultaneously. They are housed in capsules, which are inserted in rigs. A total of 12 rigs filled by identical sets of irradiation specimen are installed within the HFTM container, which is segmented by stiffening plates into four compartments. Ribs and distance holders assure narrow cooling channels with 1 mm width on the long sides and 0.5 mm on the smaller sides. Helium is chosen as coolant as it will not be activated nor it is corrosive.
The temperature level can be adjusted independently in each rig by additional segmented electrical heaters within tolerances up to ±15 °C at most. They are wound and brazed into grooves rising spirally around the capsule wall. The heat transfer between the specimens as well as between specimens and capsule wall is guaranteed by filling up with sodium or eutectic sodium-potassium liquid metal.

The MFTM consists in the present reference design of a creep fatigue module (CFTM), a tritium release module (TRM) and a tungsten spectral shifter plate to tailor the neutron flux spectrum similar to the conditions in the blanket of a DEMO fusion reactor. The CFTM will provide several types of in-situ experiments on three specimens independently. They will be cooled by helium as well as the hollow frame of the module. A novel multi-jet cooling concept inside the specimen has been proposed to allow for a small temperature variation [8]. Behind the CFTM two tungsten plates of 30 mm thickness will shift the neutron energy distribution to lower energies to enhance the medium and low energy flux for the adjacent tritium release module. This will be used for measurements of in-situ tritium release in ceramic breeder and neutron multiplier materials as well as for compatibility tests during irradiation. For this purpose eight rigs equipped with disk, pellet or pebble filled capsules are incorporated in the test module and are kept at individual temperatures in the range of 400-900 °C. Tritium released from the specimen will be purged and swept up by Helium and analysed in the TTC control room.

Further optimization and amendments to the design of the TTC are needed e.g. with respect to the top cover shielding and mechanical details like mounting and interfacing of components.

The Target and Test Cell 3D model has been incorporated in a variant of the IFMIF building model (*Fig. 3*) to prepare for the detailed layout of auxiliary systems like helium circuit/inorganic circuit, top access room equipment etc.

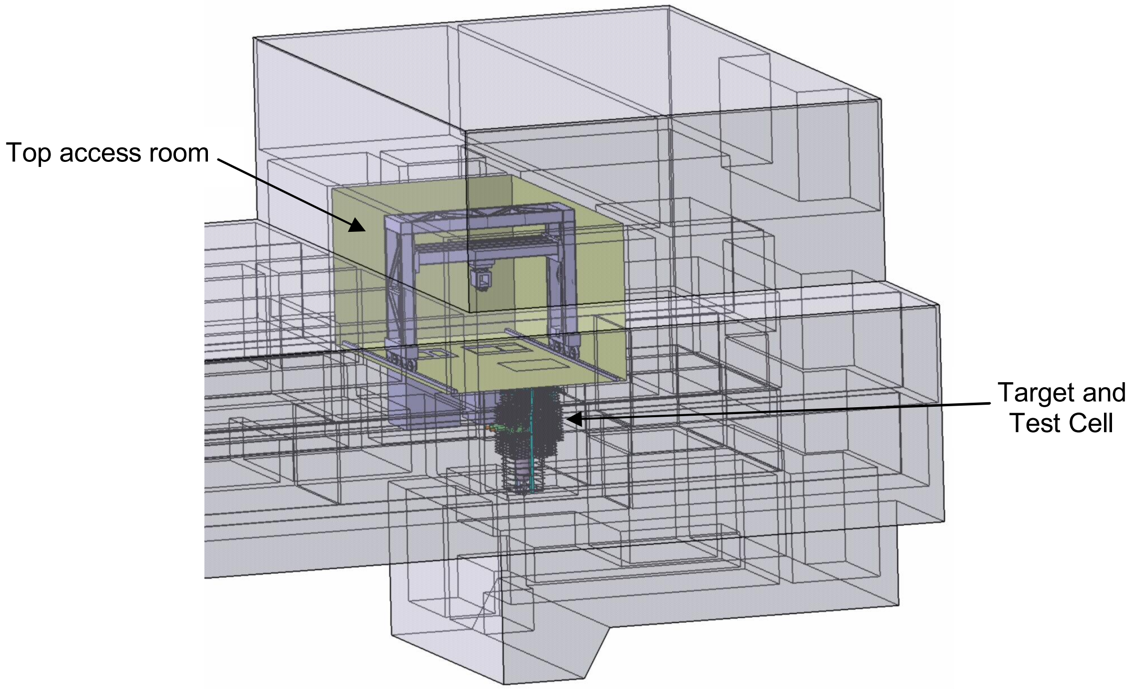

Fig. 3: CATIA model showing part of the IFMIF main building with Target and Test Cell and top access room.

3. Neutronics

Dedicated computational tools, data and models have been developed over the past few years for IFMIF neutronics and activation analyses [9]. In the following, specific work related to the design of the TTC will be described in some detail.

With regard to the deuterium-lithium neutron source, the Monte Carlo code McDeLicious [10] was developed as an addition to MCNP to simulate the neutron generation based on evaluated nuclear cross section data. Recently, a complete set of such data was prepared for the reaction system d+^{6,7}Li. McDeLicious has been extensively tested and validated [11] to assure its feasibility and performance for IFMIF applications.

To this end, a detailed and comprehensive 3D geometry model for MCNP has been devised based on data from recent CAD designs [9]. It includes the deuterium beam tubes, the lithium target assembly with backplate, lithium loop components within the TTC, the two VTA and VIT, and finally the cover, walls and floor. Due to the complexity of the model and in order to facilitate introducing changes as given by the engineering design, an interface program for the automatic transformation of CAD models to MCNP geometry description [12] has been applied to the IFMIF TTC model. The interface makes use of a specially tailored CAD model derived from the original one.

The major neutronics task for IFMIF is to provide the data required for the design and optimization of the test modules and the lay-out of the TTC. This data consists of neutron and gamma flux distributions and nuclear responses like radiation damage, nuclear heat and gas production. Extensive calculations have been performed in the past to assess the damage and gas production levels in the test modules and to assure that the irradiation requirements could be fulfilled. Those requirements refer to the total damage accumulation and the proper helium and tritium production rates. In addition, gradients in those distributions have been reduced by implementing reflectors made of EUROFER for the HFTM. The enhancement of the low energy neutron flux, needed for the TRM, has been achieved by a proper lay-out of graphite moderator envelope and tungsten spectral shifter plates.

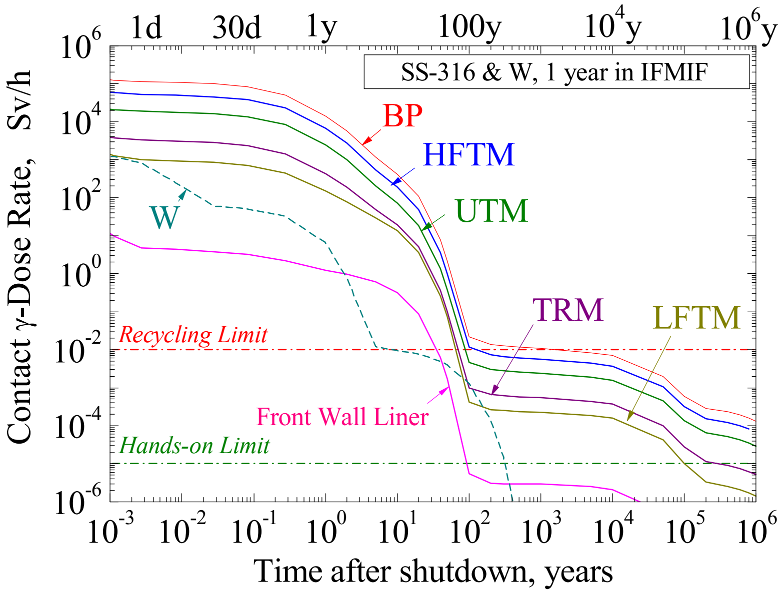

Fig. 4: Contact gamma dose rate after 1 year irradiation of several components in the Target and Test Cell, case of SS316 steel. BP target back-plate, W tungsten shifter, LFTM low flux test module, other abbreviations, see text.

Activation analyses of the entire TTC have to rely on complete sets of corresponding nuclear data for all target nuclides and energies involved. The IEAF-2001 activation library has been developed and validated for that purpose and was used for inventory and transmutation calculations with the ALARA code [13]. The contact gamma dose-rates for the TTC components made of SS316 steel after 1 year irradiation were shown (*Fig. 4*) to decrease below the recycling limit of 10 mSv/h after 50-80 years, below the hands-on limit of 10 µSv/h in about 10^5 years. However, using the reduced activation steel EUROFER would reduce the radioactive inventory in the decommissioning phase of IFMIF due to minor contributions of Al, Ni and Mo in EUROFER.

To treat the deep penetration problem of the bulk shield walls, a computational approach has been developed coupling McDeLicous with the deterministic TORT code. It is based on a combined geometry model which consists of the 3D global TTC model for the Monte Carlo transport simulation and a S_N mesh model of the access/maintenance room behind the test cell with surrounding walls for the TORT calculation [14]. The peak dose rate in the access/maintenance room is shown (*Fig. 5*) to be below the design limit of 10 µSv/h with a front wall of 400 cm heavy concrete.

For the estimation of the cooling requirements of the TTC a neutronics study has been performed to provide a detailed distribution of the nuclear heat production in the TTC walls including the cover. This has been used as input for the assessment of natural convection cooling capabilities of the TTC, as described in the following chapter.

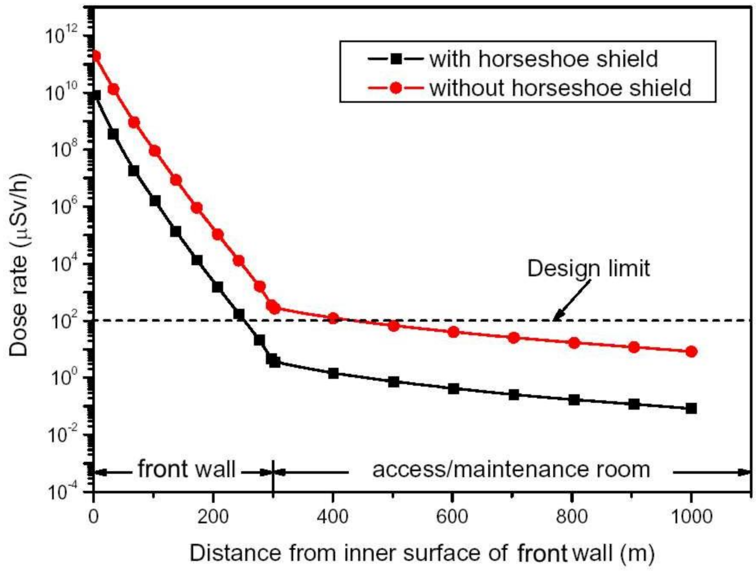

Fig. 5: Dose rate as a function of distance from the Target and Test Cell front wall (beam direction). A design variant with an additional shield encompassing the test modules ("horseshoe") has been studied for comparison.

4. Natural Convection Cooling

Within the Target and Test Cell cavity the lithium loop components have temperatures of 250°C to 320°C. Excessive nuclear heat is produced within the concrete walls of the TTC by neutrons and photons leaking from the Test Modules. To investigate the feasibility of natural convection cooling inside the cavity, a validation study has been conducted using the CFD code STAR-CD [15]. The results obtained suggested to use the k-ω high Reynolds number turbulence model for the qualified simulation of helium and argon atmospheres. As helium will not be activated, it was chosen for the subsequent analyses.

To this end, a detailed model of the TTC with interiors, in particular the elements of the lithium loop, has been constructed (*Fig. 6*). Lithium loop components are acting as surface heat sources, whereas nuclear volumetric heat in the TTC walls have been provided by detailed McDeLicious calculations, as mentioned above. A wall depth of 50 cm was adopted since there the nuclear heat deposition is already decreased by more than one order of magnitude.

First scoping calculations showed immediately the need for additional thermal insulation of the hot lithium parts. A mineral glass type material has been selected and applied to the lithium loop pipes and quench tank. A comparative study revealed that an insulation layer of 50 mm thickness would be sufficient and that it can be simulated by an additional thermal resistance of the hot surfaces without side effects on the flow hydrodynamics. A conceptual wall cooling system has been devised featuring two cooling surfaces at depths of 10 cm and 30 cm. With these modifications, the maximum temperature of the walls does not exceed the value of 80°C on the TTC front wall (beam direction) and at the wall openings for the lithium pipes (see *Fig. 7*). Finally, helium slightly below atmospheric pressure was considered as a reference because it allows easiest control of the Target and Test Cell atmosphere and prevents outside leakage in addition to sufficient cooling capabilities of the concrete walls.

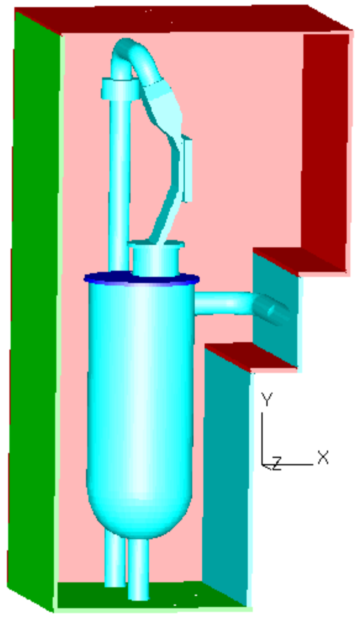

Fig. 6: Natural convection geometry model of the Target and Test Cell for STAR-CD.

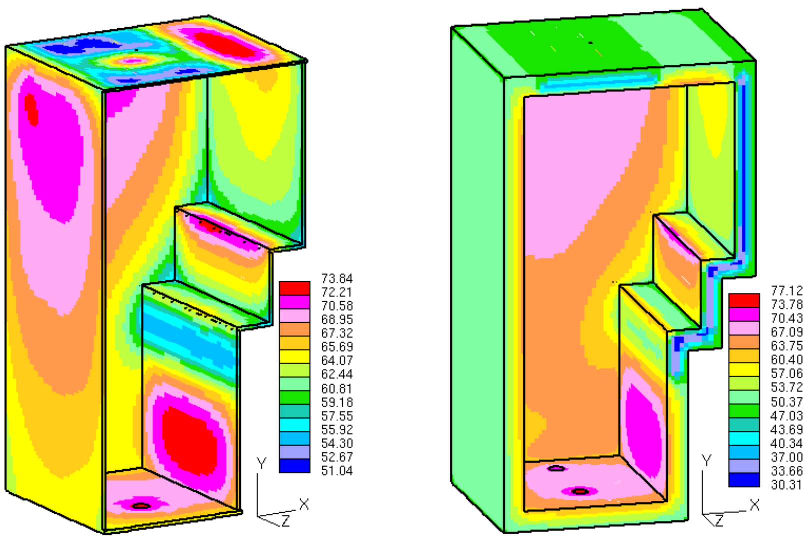

Fig. 7 Temperature (given in °C) of steel liner (left) and concrete wall (right) with helium atmosphere of 1 bar inside the Target and Test Cell cavity.

5. Conclusions

The IFMIF Target and Test Cell will house the Lithium Target Assembly and the Test Modules developed by different international design groups. In the forthcoming EVEDA phase of IFMIF the designs have to be integrated in a common concept of the TTC, which in turn will be integrated with accelerator, remote handling and auxiliary systems facilities in the IFMIF plant. It has been shown that sophisticated methods and tools are available to perform successfully this important task. Besides the integration of CAD drawings and providing common models for calculations, it has been realized, that neutronics, thermohydraulics and mechanical analyses are needed in a concerted way to achieve a reliable design of the TTC. Within EVEDA this work will continue to validate experimentally the performance objectives and reliable operation of all major subsystems in the TTC, as well as a sound engineering design for licensing and procurement.

Acknowledgement

This work, supported by the European Communities under the contract of Association between EURATOM and Forschungszentrum Karlsruhe, was carried out within the framework of the European Fusion Development Agreement. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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