



Ricerca di Sistema elettrico

Simulazione realistica della fase di pre-riscaldamento del prototipo del Target Assembly di IFMIF

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SIMULAZIONE REALISTICA DELLA FASE DI PRE-RISCALDAMENTO DEL PROTOTIPO DEL TARGET ASSEMBLY DI IFMIF

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Abstract

In the framework of the R&D activities of the International Fusion Materials Irradiation Facility (IFMIF), ENEA is engaged in the design of the liquid lithium target assembly (TA) with bayonet backplate whose development has recently progressed up to a well advanced stage which culminated in the construction of a full-scale prototype at ENEA Brasimone laboratory. However, many aspects still have to be addressed to finalize the TA design. One of the most important is relevant to the pre-heating of the system at start-up (before lithium injection at 250 °C) which is needed in order to avoid lithium freezing and unacceptable thermal stresses in the structure. This is accomplished by means of electric heaters arranged around the TA external surfaces. With the aim of identifying the most suitable electric heaters configuration and powers as well as to select the optimized operating procedure which allows to achieve the final temperature as much uniformly as possible, a thermal analysis campaign has been carried out in 2015 in collaboration with the University of Palermo by means of a finite element (FE) model implemented through a qualified software package. The resulting time-dependent action profile of the electric heaters allows the temperature of the TA mock-up components to be increased in a quite uniform way and, for that, this set-up procedure has been used in 2016 to perform a new thermal analysis of the start-up transient behaviour of the ENEA TA prototype in order to verify and optimize the time-dependent load profile when using the values of heat fluxes provided by heater datasheets. The results obtained have shown that the heat flux provided by the electric heater placed on the backplate (BP) needs to be increased as the BP cannot reach a uniform and sufficiently high temperature over large zones, particularly in the Lithium channel.

1 Introduction

The International Fusion Materials Irradiation Facility (IFMIF) is a joint effort of the international scientific community within the framework of the Broader Approach Agreement established between Europe and Japan. IFMIF is an accelerator-based neutron source which is devoted to test and qualify candidate materials to be used in future fusion reactors, allowing, in particular, the development of a material irradiation database for the design, construction, licensing and safe operation of the DEMO fusion power reactor. The IFMIF neutron source mainly consists of two 40 MeV continuous linear accelerators which deliver two 125 mA current beams of deuterons on a flowing liquid Lithium target, where D-Li stripping reactions take place, providing an intense neutron flux of about $10^{18} \text{ m}^{-2}\text{s}^{-1}$ characterized by an energy spectrum peaked at 14 MeV, which enables materials testing up to a damage rate of more than 20 dpa/y [1]. With the aim of having a stable liquid Lithium flow, a target system, consisting of a Target Assembly (TA) properly integrated with a Lithium loop, has been designed. The TA is mainly devoted to create, within its removable component, called bayonet Back-Plate (BP), a stable Lithium jet flowing at a nominal speed of 15 m/s to remove the 10 MW heat power released by deuteron beams and produce the desired neutron flux. A detailed description of the Lithium loop layout and of the target assembly can be found in [1,2]. The IFMIF project is currently in the Engineering Validation and Engineering Design Activities (EVEDA) phase which foresees the execution of experimental campaigns aimed at validating the main components and subsystems of the machine (e.g., accelerator sections, target system, lithium purification loop...). In particular, a mock-up of the target system with bayonet BP has been realized at ENEA Brasimone [3] in order to perform experimental activities aimed at assessing different aspects of the target design, with particular attention to the replaceable BP. The experimental activities which will be conducted on the target system mock-up will mainly concern the achievement of two principal goals.

The first goal regards the qualification of the remote handling devices designed to perform the maintenance operations on the target assembly.

The second goal consists in the reproduction of the initial phase (the so called pre-heating phase) of the IFMIF target system start-up [4], characterized by a time-dependent action of the electric heaters placed on the target structure, aimed at demonstrating the effectiveness of the foreseen pre-heating system as well as at determining the thermal field arising in the BP.

In order to support the activities aimed at reproducing the pre-heating phase of the IFMIF target system, a research campaign has been launched within the framework of the present Annual Realization Plan (Piano Annuale di Realizzazione, PAR 2015) of the ENEA-MSE Agreement by ENEA Brasimone in collaboration with the Department of Energy, Information Engineering and Mathematical Models (DEIM) of the University of Palermo to theoretically and numerically investigate the thermal behaviour of the target system mock-up under transient loading conditions [5], with the aim of setting up a proper electric heaters load profile able to increase, in a more uniformly way, the temperature of the whole system, avoiding at the same time the insurgence of thermal gradients of unacceptable entity within the mock-up structure. A theoretical-computational approach based on the Finite Element Method (FEM) has been followed and a qualified commercial FEM code has been adopted to perform the study. An iterative procedure, based on the analysis of the maximum temperature achieved within the mock-up most critical components, has been followed in order to determine the electric heaters load profile. These results will also be validated during the experimental activities to be conducted on the target mock-up at ENEA Brasimone laboratory, allowing a benchmark of the theoretical-numerical procedure followed.

2 IFMIF Target System Mock-up

A schematic overview of IFMIF is shown in Fig. 1, where the main facility sections are reported. The European concept of the IFMIF target system, proposed by ENEA [6], is characterized by a replaceable Back-

Plate (BP) and it mainly consists of the Target Assembly (TA), the Support Framework and the Lithium pipes. The TA is devoted to provide a fast, reliable and stable flow of Lithium and it is connected to the Support Framework by the TA arms and to the Lithium Loop by means of three Fast Disconnecting Systems (FDSs), two located in the TA Lithium inlet pipe and one devoted to attach the TA Lithium outlet duct to the Quench Tank. The TA mainly consists of an inlet and an outlet nozzle, a Back-Plate, a Target chamber, an interface frame and connecting flanges. A more detailed description of its lay-out may be found in [6].

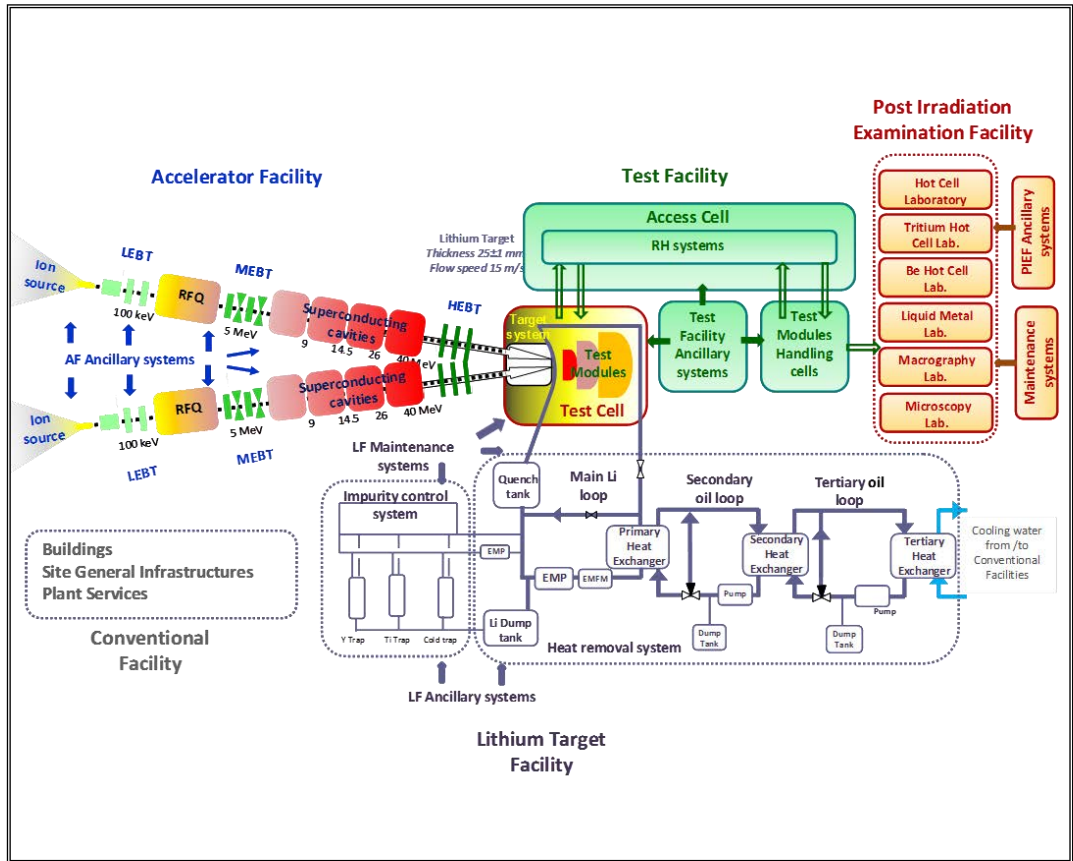


Figure 1. IFMIF schematic overview.

It has to be underlined that the BP is the most heavily loaded TA component, both from neutronic and thermo-mechanical point of view. In fact, it is devoted to house the beam footprint, resulting to operate, in IFMIF, under severe conditions of neutron irradiation damage. Therefore, its replacement, defined considering irradiation effects on material properties, is expected to occur once a year. For this reason, the reference European Target Assembly design is conceived with a remotely replaceable “bayonet” Back-Plate so that it can be easily replaced, thanks to a purposely designed skate system, using a remote handling device without removing the whole Target Assembly.

The Support Framework, directly fixed to the ground of the Test Cell by means of a proper bolt system, allows the sliding of one of the TA arms during all operation phases in order to allow the TA deformations and, at the same time, maintain the alignment between the deuteron beams and the Lithium footprint, ensuring the stability of the neutron flux generated in the beam footprint region by the deuteron-lithium interactions.

The Lithium Loop is articulated in a main loop and a purification loop, designed to operate for 30 years. The main loop stably supplies liquid Lithium at the adequate flow rate and temperature to the TA. It mainly consists of the target system, the quench tank, the electromagnetic pump, the dump tank and the primary heat exchanger. Inside the Test Cell, the Lithium inlet pipe is articulated in two sections, connected each

other by means of two Fast Disconnecting Systems (FDSs) and a gimbal expansion joint which are placed just before the TA system.

The connection of the Lithium inlet pipe sections by FDSs is one of the main characteristic of the IFMIF target system European concept. In fact, each FDS permits to easily and quickly connect and disconnect flanges by simply acting on only one screw, using a purposely designed remote handling device. Furthermore, a FDS is conceived with a passive Lithium leak detection system which continuously checks the sealing of the flanges connected. A more detailed description of FDS, the Lithium leak detection system and its components is reported in [6-7].

The gimbal expansion joint is able to compensate angular movements between the flanges of the two Lithium inlet pipe sections. It is aimed to compensate thermal expansions during all IFMIF operational phases and misalignments during target system installation. Further details on the gimbal expansion joint foreseen for the Lithium inlet pipe may be found in [6].

The purification loop consists of a cold trap and two hot traps, to remove various impurities, and of auxiliary supporting equipment devoted to perform the Lithium make up. Further details about the Lithium Loop may be found in [1].

It has to be underlined that all the design solutions adopted by the IFMIF project team for the acceleration system, the target system and the test cell need to be validated and, if necessary, further modified during the next phases of the IFMIF project.

Within the framework of the EVEDA phase, some validation activities are planned with the aim of conducting experimental campaigns in order to qualify the design solutions adopted for IFMIF, using purposely designed mock-ups of the critical subsystems and components (accelerator, target system, Lithium loop, test modules, etc...). Results obtained from these experimental activities will be carefully assessed and the most promising design solutions will be adopted to achieve the final IFMIF design, which will be developed during the next phases of the project.

In order to qualify the design of the IFMIF target system, a mock-up of the European concept of the TA has been realized at ENEA Brasimone [3]. It realistically reproduces the most recent design of the IFMIF Target Assembly, properly integrated with its Support framework and the entire Lithium inlet pipe, and it includes the following main components (Figure 2):

- the Lithium inlet pipe;
- the gimbal expansion joint;
- the FDSs;
- the Beam Duct;
- the Inlet Nozzle;
- the Back-Plate;
- the Interface Frame;
- the Target Chamber;
- the Outlet nozzle;
- the Support Framework.

The TA is supported by the Target Chamber arms laying on the Support Framework, directly fixed to the ground by means of a proper bolt system, and it is welded to the Lithium inlet pipe.

Regarding structural materials employed for the mock-up construction, it has been realized using AISI 316 steel for the Back-Plate and AISI 304 steel for all the remaining components, differently from the IFMIF target system in which the European reduced activation ferritic/martensitic (RAFM) steel EUROFER has been selected as structural material for almost all the components.

A more detailed description of the target system mock-up realized at ENEA Brasimone can be found in [3].

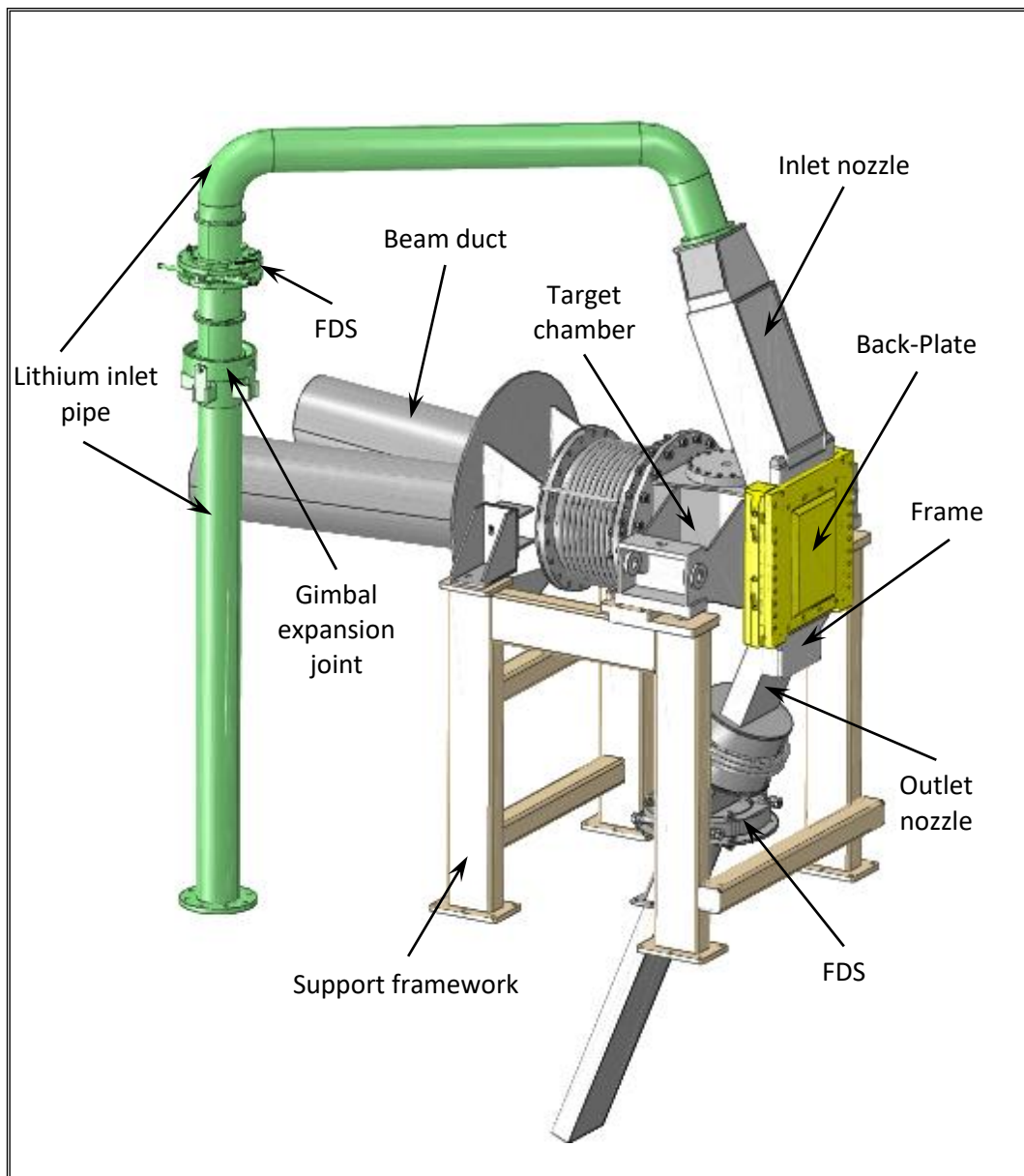


Figure 2. The mock-up of the IFMIF target system realized at ENEA Brasimone.

Differently from the IFMIF target system design, the mock-up realized at ENEA Brasimone is endowed with only one FDS in the Lithium inlet pipe region. Moreover, the presence of the accelerator system has been taken into account by constructing a double pipe, connected to the Target Chamber by a proper bolt system, which represents the Beam Duct foreseen in IFMIF.

It has to be underlined that the mock-up of the target system does not reproduce the whole IFMIF Lithium Loop, except for the TA Lithium inlet pipe. In fact, the target system mock-up does not foresee the presence of the liquid Lithium, being envisaged to allow the achievement of two main goals: the validation of the remote handling devices devoted to perform the maintenance operations on the target system and the reproduction of the electric heaters action foreseen during the initial phase of the IFMIF target system start-up.

As far as the remote handling procedures are concerned [8-9], they play a fundamental role in IFMIF maintenance phase, due to the high dose rate predicted in the Test Cell housing the target system. In fact, nuclear activation reactions will take place between neutrons, generated within the beam footprint region, and structural materials nuclei, making the Test Cell internals hostile to human presence. Therefore, the

periodic BP substitution and any maintenance activity foreseen for the target system must be executed using robotic devices governed by remote. Hence, experimental campaigns will be carried out on the target system mock-up in order to validate all the remote-governed devices, and the pertinent operative procedures, devoted to execute the BP insertion to and removal from the fixed interface frame of the Target Assembly and the FDSs tightening and detachment mechanical operations [8-9].

As far as the reproduction of the IFMIF start-up is concerned, and in particular the first of the three sub-phases in which it is articulated, named pre-heating phase [4], a proper set of electric heaters is necessary to perform the pre-heating of the structure before the Lithium begins to flow into the target system, in order to avoid the insurgence of particularly intense thermal gradients between the Lithium, that enters the target system at 250 °C, and the structure at room temperature. In fact, large thermal gradients may originate particularly intense stresses within the structure, jeopardizing the leak-tightness of the sealing gasket interposed between the BP and the frame. For this reason, particular attention should be paid to the thermal field arising within BP at the end of the pre-heating phase, since it is the most critical component of the entire target system and therefore an excessive temperature difference between the BP Lithium channel surface and the Lithium flow should be avoided in order to minimize the thermal induced stress within the component.

Furthermore, during the pre-heating phase, the electric heaters action needs to be properly tuned adopting a purposely set up time-dependent load profile, in order to avoid a non-homogeneous increase of the temperature within the structure, that may cause the insurgence of high thermal gradients between adjacent components. For these reasons, the experimental activity performed on the target system mock-up, aimed at reproducing the pre-heating phase, will be mainly focused onto the testing of electric heaters action and the mapping of the thermal field arising within BP.

It is obvious that the execution of the experimental activity aimed at reproducing the TA pre-heating phase has to be based on the knowledge of a purposely set up electric heaters time-dependent load profile, able to allow the mock-up temperature increase within the different components as uniformly as possible during the entire pre-heating phase of the transient operational start-up.

The research activity performed in the framework of the present ENEA-MSE Agreement for the current Annual Realization Plan (Piano Annuale di Realizzazione, PAR 2015) has been aimed at determining the time-dependent load profile of the electric heaters acting on the external surfaces of the IFMIF target system mock-up.

The electric heaters load profile obtained from this analysis will be adopted for the experimental campaign to be performed at ENEA Brasimone laboratory using the purposely constructed mock-up. Hence, the results of these experimental activities will allow the validation of the models and the procedure adopted in the present study.

3 Target system mock-up thermal analysis

As already mentioned, the present analysis has been aimed at assessing the thermal behaviour of the IFMIF target mock-up under the pre-heating phase of the start-up transient scenario [4], in order to set-up the time-dependent load profile of the electric heaters purposely arranged on the mock-up external surfaces with the aim to perform the heating of the structure before the Lithium begins to flow.

In order to determine the optimized electric heaters load profile, an iterative procedure has been followed, assessing the maximum temperature values achieved within the mock-up components. Attention has been focused on the maximum temperature achieved within the BP, since the pre-heating main goal is to increase, as uniformly as possible, its temperature up to the Lithium inlet temperature value of 250 °C. The research campaign has been performed adopting a theoretical-numerical approach based on the Finite Element Method (FEM) implemented through a qualified commercial software package.

3.1 Pre-heating phase of the start-up transient scenario

The pre-heating phase is the first of the three sub-phases in which the IFMIF start-up transient scenario is articulated. Further details about the IFMIF start-up loading conditions can be found in [4].

The pre-heating phase, in which no Lithium flows within the target system, is characterized by the action of a set of electric heaters arranged on the target system external surfaces, devoted to supply heat power to the structure in order to increase its temperature, as uniformly as possible, up to the Lithium inlet value of 250 °C. This strategy is mainly devoted to minimize the potential insurgence of intense thermal gradients within the structure when the Lithium at 250 °C will begin to flow. During the pre-heating phase, the action of the electric heaters has to be suitably tuned, by imposing an intermittent functioning (so as to reproduce the actual experimental conditions that will be realized in the ENEA laboratory), in order to avoid non-homogenous time evolution of the thermal field arising within the target system, which may lead to the insurgence of intense thermal gradients between adjacent components. Hence, the determination of an electric heaters load profile becomes fundamental to correctly define the pre-heating phase transient loading scenario.

An iterative approach, based on the assessment of the maximum temperature reached in the Lithium inlet pipe, the Inlet nozzle, the Target chamber, the Outlet nozzle and the BP of the mock-up, has been followed. In particular, a discontinuous functioning of the electric heaters has been assumed, making sure that the maximum temperature of the components could increase as uniformly as possible up to the value of 250 °C and, once reached this reference value, it could range between 240 °C and 260 °C, allowing the further heating of the structure.

As explained in the following, three different transient loading configurations, differing each other for the electric heaters spatial arrangement and for the BP external irradiation conditions, have been simulated, and a relevant load profile has been assessed for each configuration taken into account, following the aforesaid iterative procedure.

3.2 The FE model

A realistic 3D FEM model of the IFMIF target system mock-up realized at ENEA Brasimone has been developed. The model reproduces the Target Assembly integrated with its Support Framework and the entire Lithium inlet pipe. An overview of the 3D geometric model is reported in Figs. 3-4.

It has to be noted that the two FDSs, the gimbal expansion joint of the Lithium inlet pipe and the Beam duct, foreseen in the target system mock-up design (Fig. 2), have not been directly included in the 3D geometric model. Nevertheless, their thermal effects have been simulated, as explained in the following, imposing appropriate thermal boundary conditions and contact models which permit to simulate the thermal effects of the geometric regions not included in the 3D model on the calculation geometric domain. This simplifying assumption leads to a reduction in terms of calculation time without incurring in a significant loss of information.

A mesh independence analysis has been preliminarily performed to select an optimized spatial discretization which allows accurate results to be obtained saving calculation time. A mesh composed of about 5×10^5 nodes connected in some 2×10^6 linear tetrahedral elements, listed within FEM codes libraries, has been selected.

The most representative views of the selected spatial discretization are reported in Figures 5-7. The so formed spatial discretization allows numerical simulations to be carried out in a time ranging from 40 to 100 hours, depending on the load configuration taken into account.

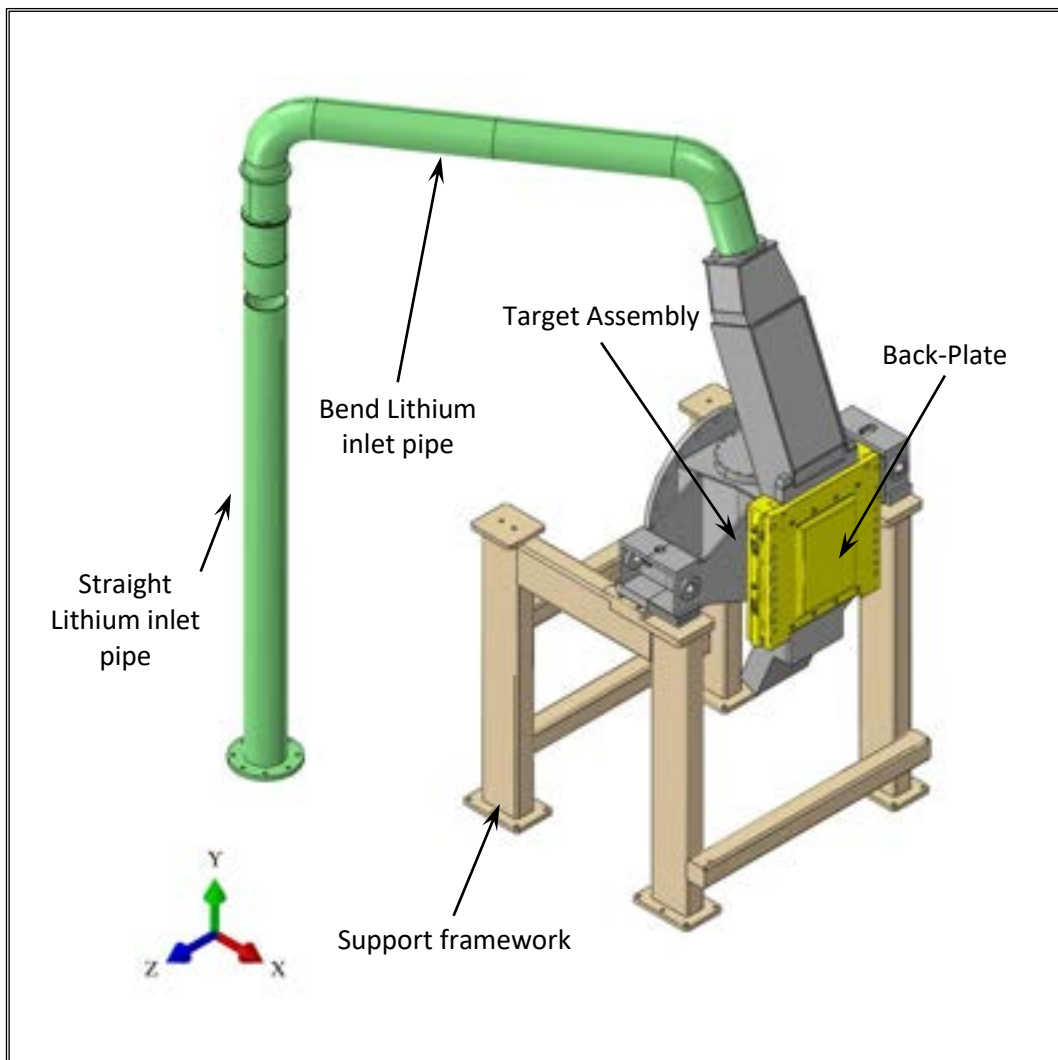


Figure 3. Mock-up 3D geometric model. General overview.

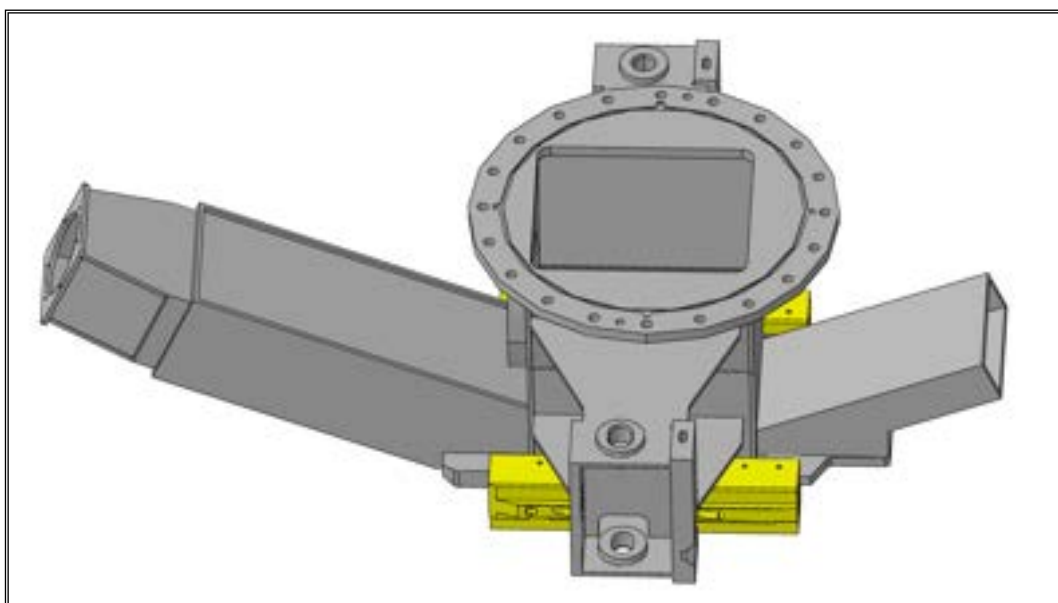


Figure 4. Mock-up 3D geometric model. Target Assembly and Back-Plate lateral view.

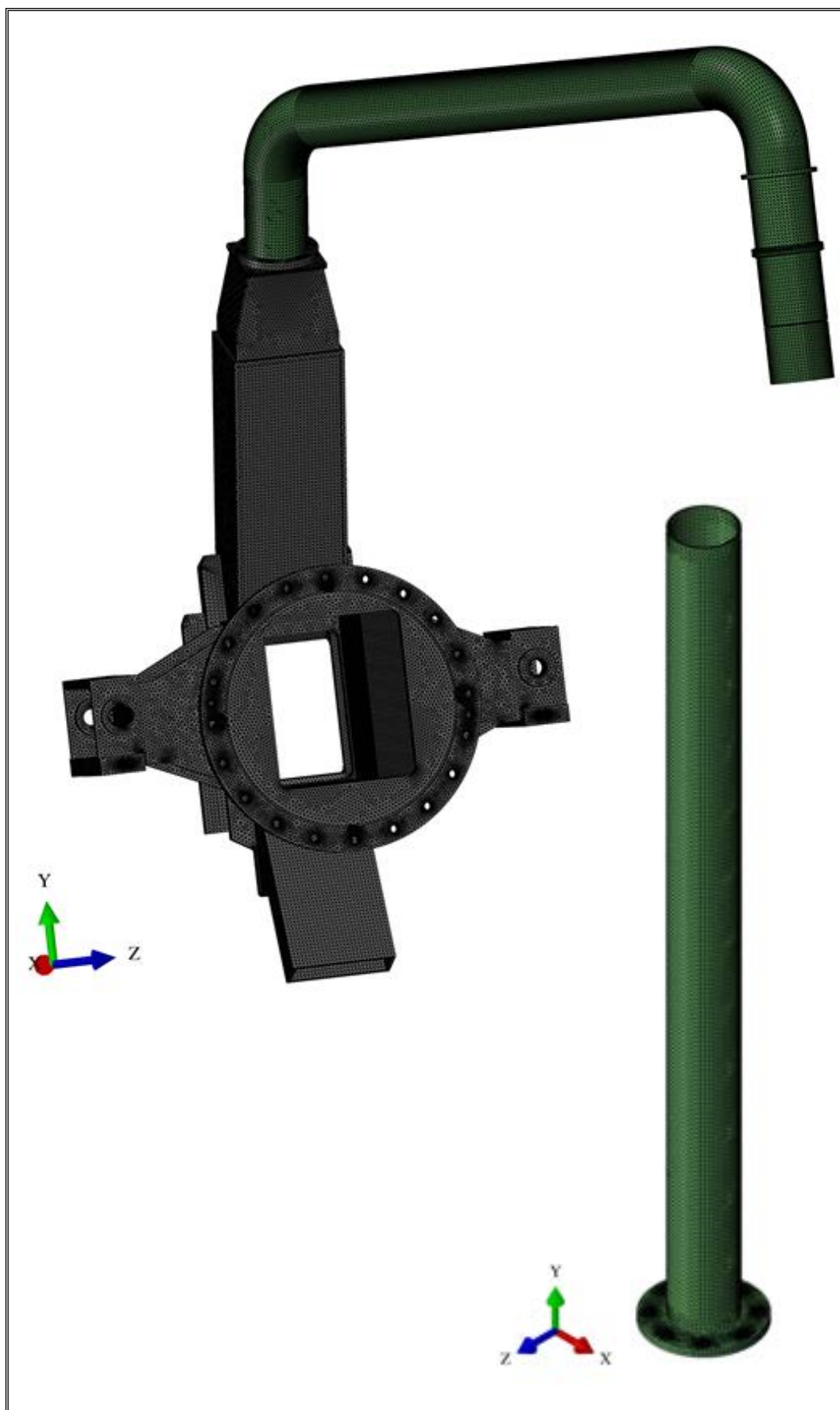


Figure 5. Mock-up FEM model. Target Assembly and Lithium inlet pipe exploded view.

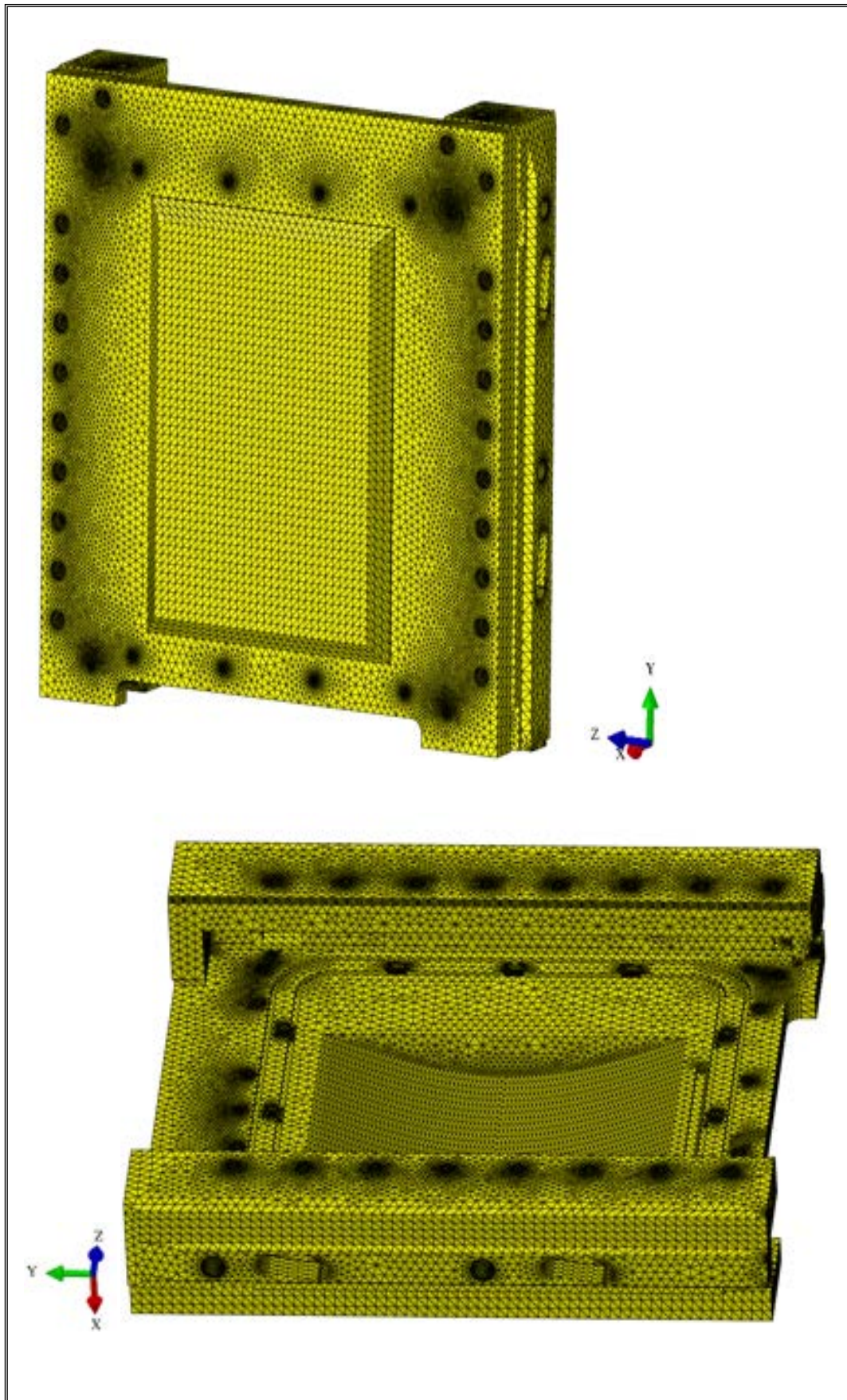


Figure 6. Mock-up FEM model. Particular of the Back-Plate.

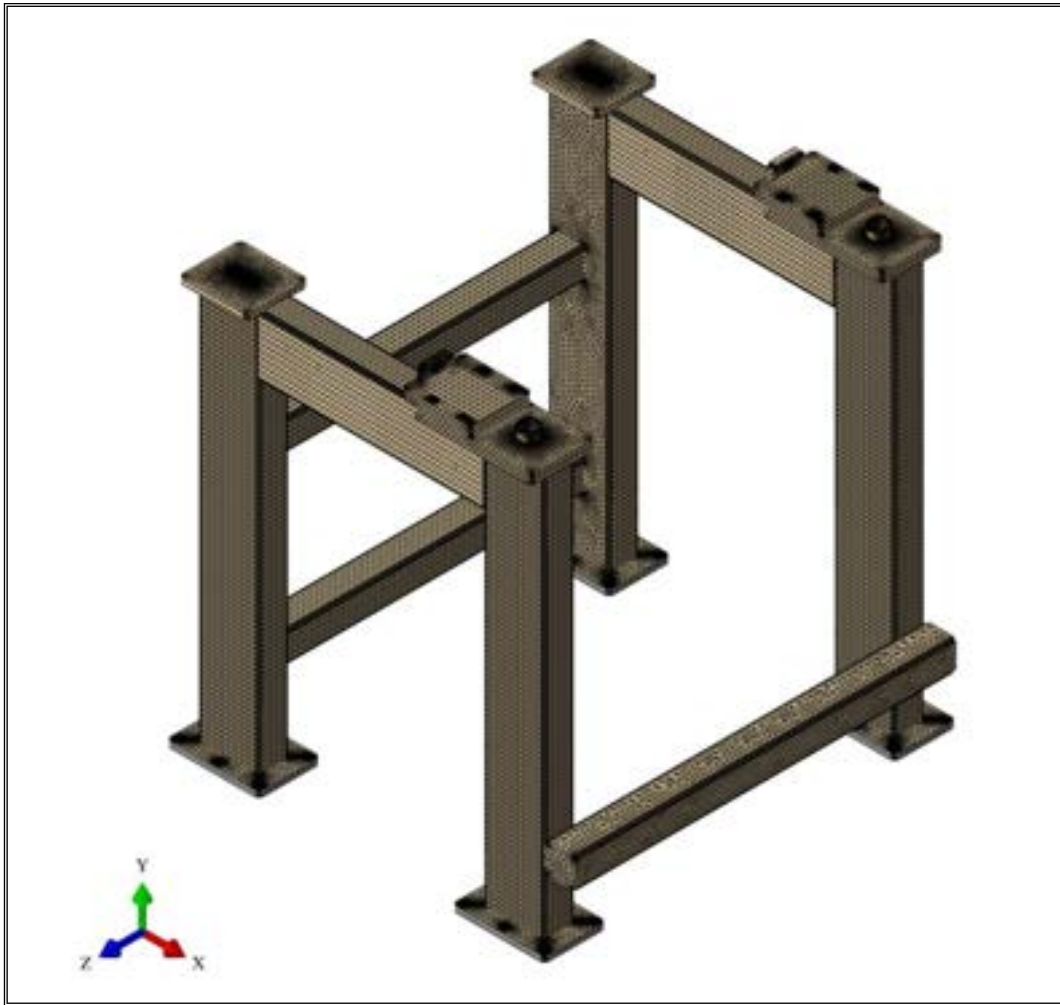


Figure 7. Mock-up FEM model. Particular of the Support framework.

3.2.1 Materials

According to the design of the IFMIF target system mock-up installed at ENEA Brasimone laboratory, AISI 304 steel has been assumed as the Target Assembly, Support framework and Lithium inlet pipe structural material. As far as the Back-Plate is concerned, it has been considered to be made of AISI 316 steel. The structural materials thermo-physical properties have been assumed to depend uniquely on temperature, as indicated in [10-12]. The thermo-physical properties values at room temperature of 20 °C are summarized in Tables 1 and 2, while temperature-dependent behaviour of the considered materials thermo-physical properties, normalized at the room temperature value, can be deduced from Figures 8-9.

Table 1. AISI 304 steel thermo-physical properties at 20°C [10].

| AISI 304 STEEL | |
|----------------|-------------------------------------|
| λ_0 | 14.28 W/m K |
| c_{p0} | 472 J/kg K |
| α_0 | $1.53 \cdot 10^{-5} \text{ K}^{-1}$ |
| ρ_0 | 7930 kg/m ³ |

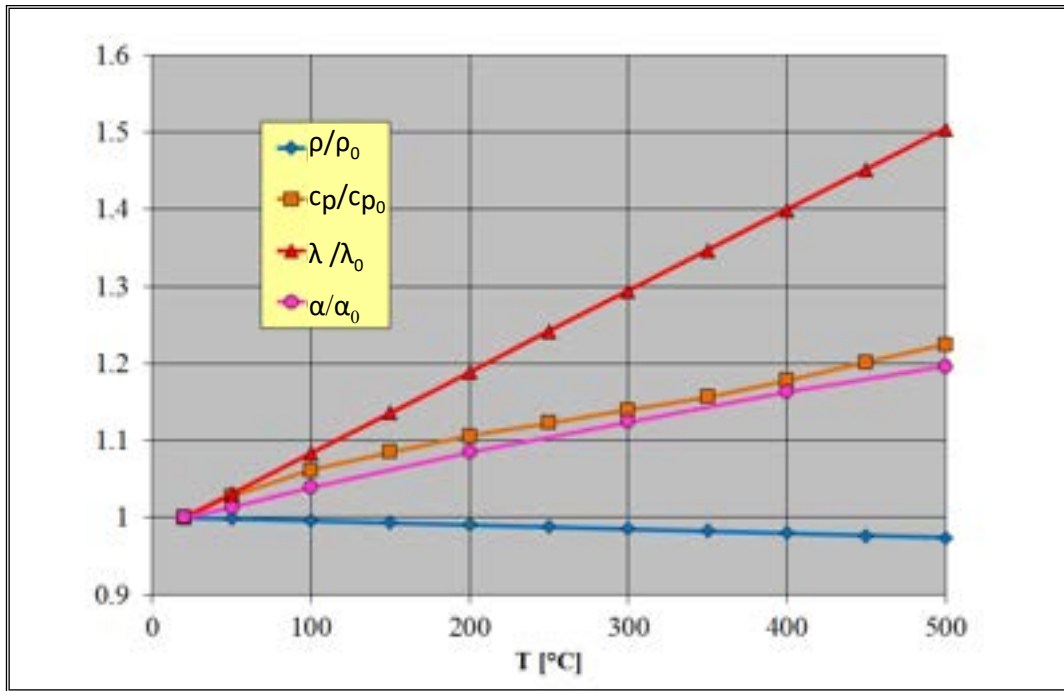


Figure 8. AISI 304 steel temperature-dependent thermo-physical properties.

Table 2. AISI 316 steel thermo-physical properties at 20°C [11-12].

| AISI 316 STEEL | |
|----------------|-------------------------------------|
| λ_0 | 15 W/m°C |
| c_{p0} | 452 J/kg°C |
| α_0 | $1.54 \cdot 10^{-5} \text{ K}^{-1}$ |
| ρ_0 | 7950 kg/m ³ |

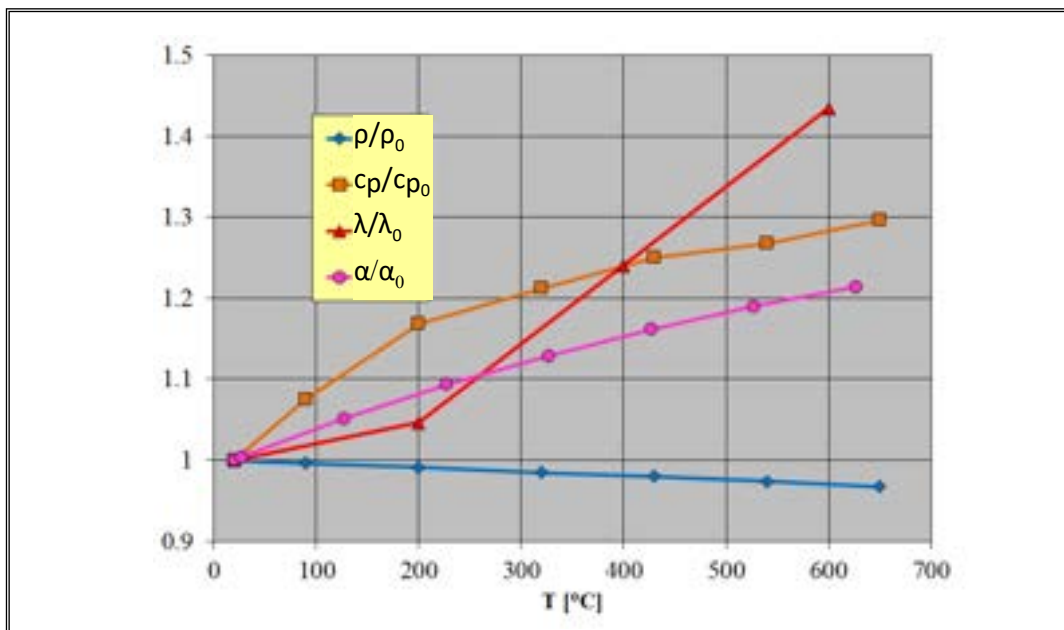


Figure 9. AISI 316 steel temperature-dependent thermo-physical properties.

3.2.2 Thermal interactions, loads and boundary conditions

The following thermal interactions, loads and boundary conditions have been assumed to simulate the TA, integrated with its Support framework and Lithium inlet pipe, thermal behaviour under pre-heating phase transient scenario:

- thermal interactions;
- heat transfer between Target chamber and Beam duct;
- time-dependent heat fluxes;
- internal irradiation;
- external irradiation;
- Target Assembly and Support framework natural convective cooling.

Thermal interactions between frame and Back-Plate have been simulated by a thermal contact model which foresees the following functional dependence of the heat flux between two coupled nodes i and j , q_{ij} , on their temperatures, T_i and T_j :

$$q_{ij} = H(T_i - T_j) \tag{1}$$

where H represents the thermal conductance between the two interacting components, which has been set to $2000 \text{ W/m}^2\text{C}$ [13,14]. All the other components of the model have been considered as a continuum from the thermal point of view. As to the gimbal expansion joint simulation, a proper coupling thermal model between straight and blend Lithium inlet pipe sections has been taken into account, as already done in [15].

Heat transfer between Target chamber and Beam duct has been simulated by imposing, according to [6], an effective convective heat transfer coefficient equal to $15.8 \text{ W/m}^2\text{C}$ on the Target chamber flange surface (red surface in Fig. 10) and a non-uniform bulk temperature, T_L , analytically derived from a 1-D simplified model of the beam duct conductive-radiative heat transfer, purposely set-up at DEIM for the previous research activities [4,15] developed within the framework of IFMIF R&D activities.

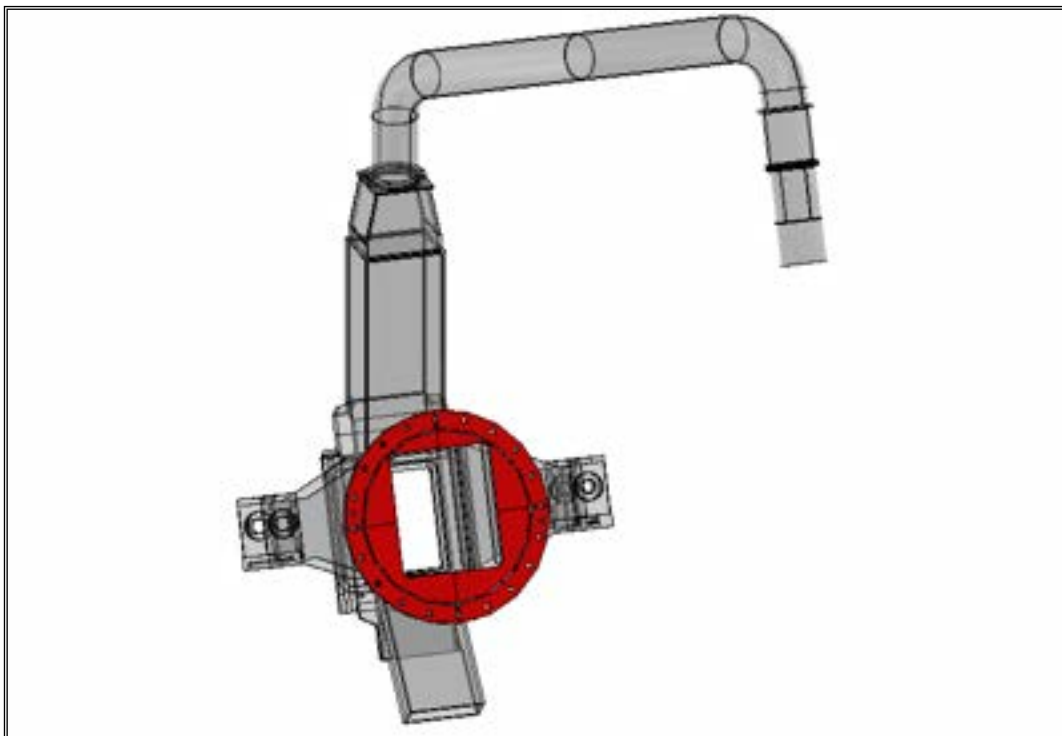


Figure 10. Target chamber flange surface.

In order to simulate the discontinuous electric heaters action in the pre-heating phase of the start-up transient loading scenario [4], a proper set of time-dependent heat fluxes has been imposed, by a purposely set-up FORTRAN routine, to the mock-up external surfaces, on the basis of the electric heaters spatial arrangement foreseen for the experimental campaigns on the TA mock-up (Fig. 11). The values of the heat fluxes have been assumed on the basis of the technical specifications of the electric heaters devoted to perform the experimental campaigns on the TA mock-up.

Since the present study has been devoted to set-up the electric heaters load profile able to ensure a temperature increase within the structure as uniform as possible, an iterative approach has been followed in order to determine the most appropriate electric heaters load profile. The iterative procedure has been based on modifications of the FORTRAN routine whenever a specific criterion, described in the following, based on the maximum temperature achieved within the most critical components has not been met.

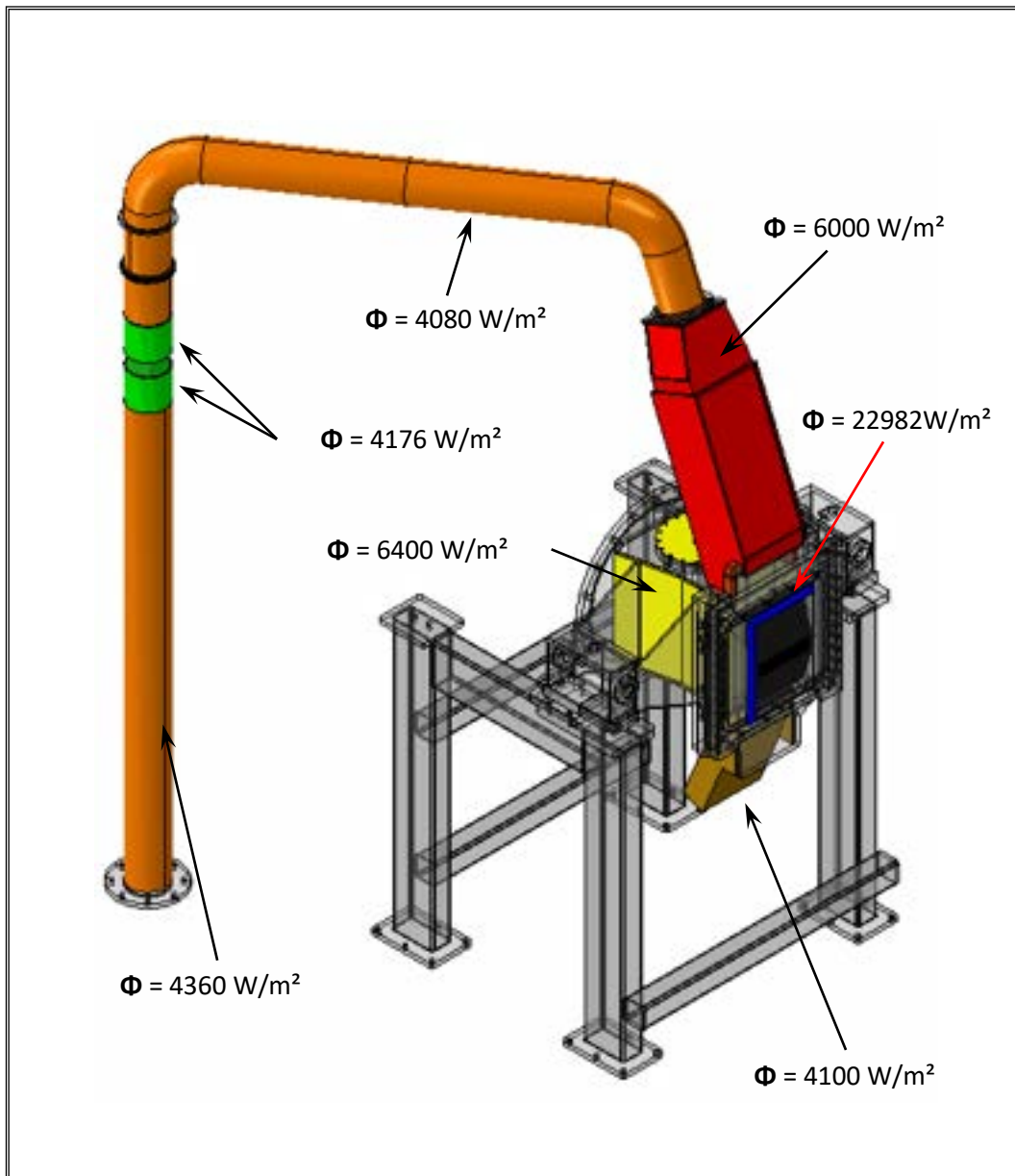


Figure 11. Heat fluxes from electric heaters.

Radiation heat transfer occurring internally, between the internal walls of mock-up, has been modelled adopting the cavity radiation formulation widely described in [16,17]. It is based on the definition of a

proper cavity articulated in mutually radiating surfaces, which result to be composed of collections of element facets.

Assuming that grey body radiation theory holds, considering only diffuse and, consequently, non-directional reflection from facets and neglecting radiation attenuation in the cavity medium, it is possible to derive, under the further hypothesis of isothermal and iso-emissive facets, the following analytical expression for the radiation heat flux, q_i , that the i -th facet receives from the rest of the facets belonging to the same cavity:

$$q_i = \frac{\sigma \varepsilon_i}{A_i} \sum_j \varepsilon_j \sum_k F_{ik} C_{kj}^{-1} (\theta_j^4 - \theta_i^4) \quad (2)$$

where σ is the Stefan-Boltzmann constant, A_i is the area of i -th facet, ε_i and ε_j are the emissivities of the i -th and j -th facets, F_{ik} is the viewfactor between the i -th and k -th facets, θ_i and θ_j are the absolute temperatures of the i -th and j -th facets and C_{kj} is given by:

$$C_{kj} = \delta_{kj} - \frac{(1 - \varepsilon_k)}{A_k} F_{kj} \quad (3)$$

with δ_{kj} representing the Kronecker's delta.

Since the mock-up structure is internally divided in six regions by means of internal plugs, a proper set of six radiation cavities, each reproducing one of the mock-up internal regions, has been defined in the 3D FEM model. The six radiation cavities set-up does not mutually interact from the radiation heat transfer point of view, due to the presence of the afore-mentioned dividing plugs.

The surfaces forming the six radiation cavities have been highlighted, using different colours, in Figure 12.

It has to be noted that no radiation has been allowed through the cavity opening at the top of the target chamber, since it is envisaged to be closed by the pipe simulating the presence of the beam ducts, and through the outlet nozzle exit section, since it is envisaged to be closed by a plug which reproduces the presence of the quench tank flange. Emissivity value of 0.3 has been adopted for all steel walls, as indicated in [18].

Radiation heat transfer occurring externally between the mock-up un-insulated external surfaces and the atmosphere of the containment building has been modelled applying the following simplified condition to element facets which are supposed to be un-insulated during the pre-heating phase of the start-up transient scenario:

$$q_{i0} = \sigma \varepsilon_i (\theta_i^4 - \theta_0^4) \quad (4)$$

where q_{i0} and ε_i are, respectively, the radiation heat flux and the emissivity of the i -th element facet, set to 0.3 both for AISI 304 and AISI 316, while θ_0 is the absolute temperature of the Test Cell atmosphere, set to 293 K. In the present study, all the surfaces housing the electric heaters have been assumed as not radiating towards the containment building atmosphere. Radiating surfaces are highlighted in red in figure 13.

Regarding Target Assembly and Support framework natural convective cooling, the following Cauchy's boundary condition has been imposed to the nodes laying on the mock-up non-insulated surfaces (Fig. 13), as already adopted in [15]:

$$q_j = h(T_j - T_{atm}) \quad (5)$$

where q_j is the normal heat flux at the j -th node of the mock-up non-insulated surfaces, T_{atm} is the uniform bulk temperature of the containment building atmosphere, set to 20 °C, and h represents the convective heat transfer coefficient, which has been properly assumed equal to 10 W/m²°C [15].

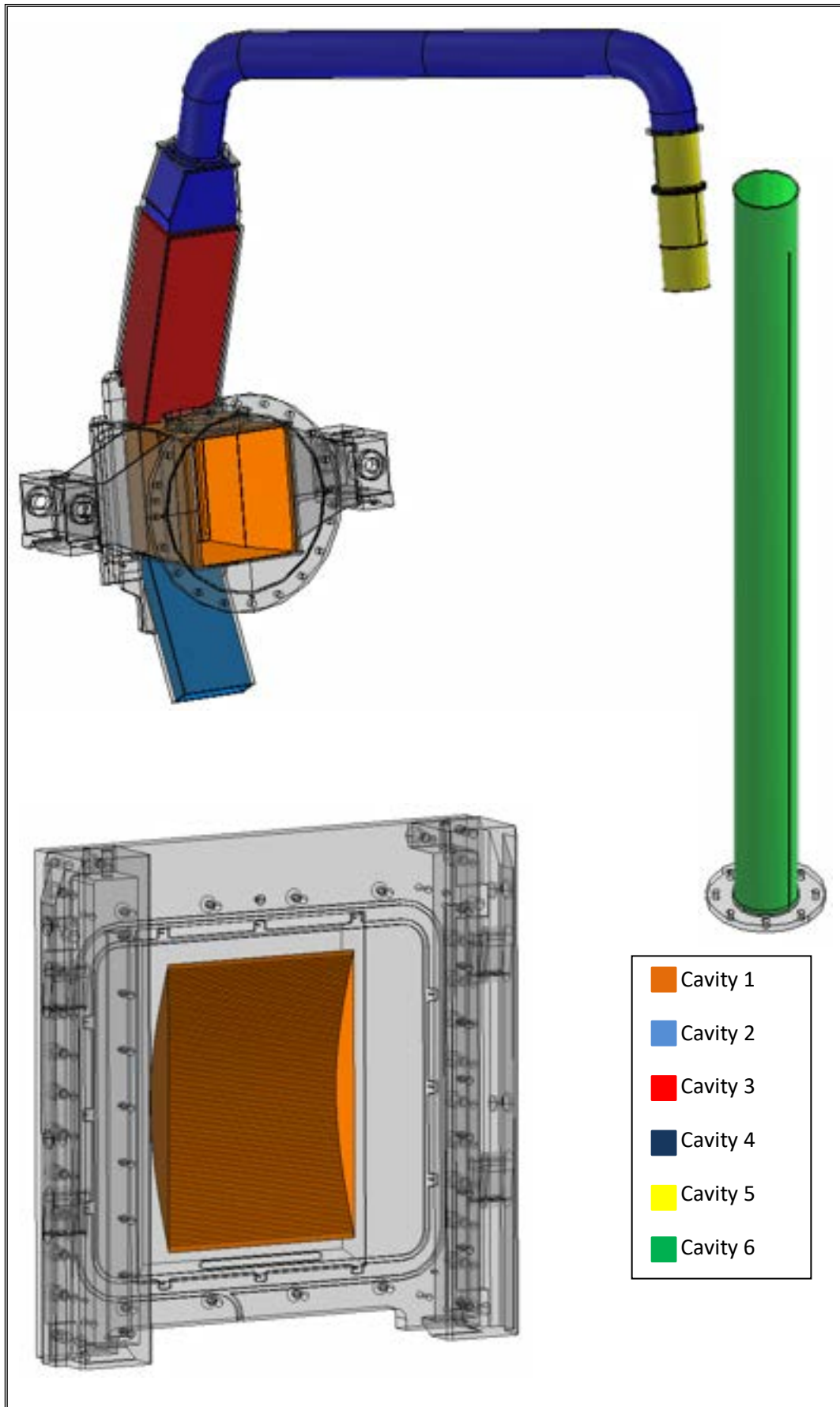


Figure 12. Radiation cavities surfaces.

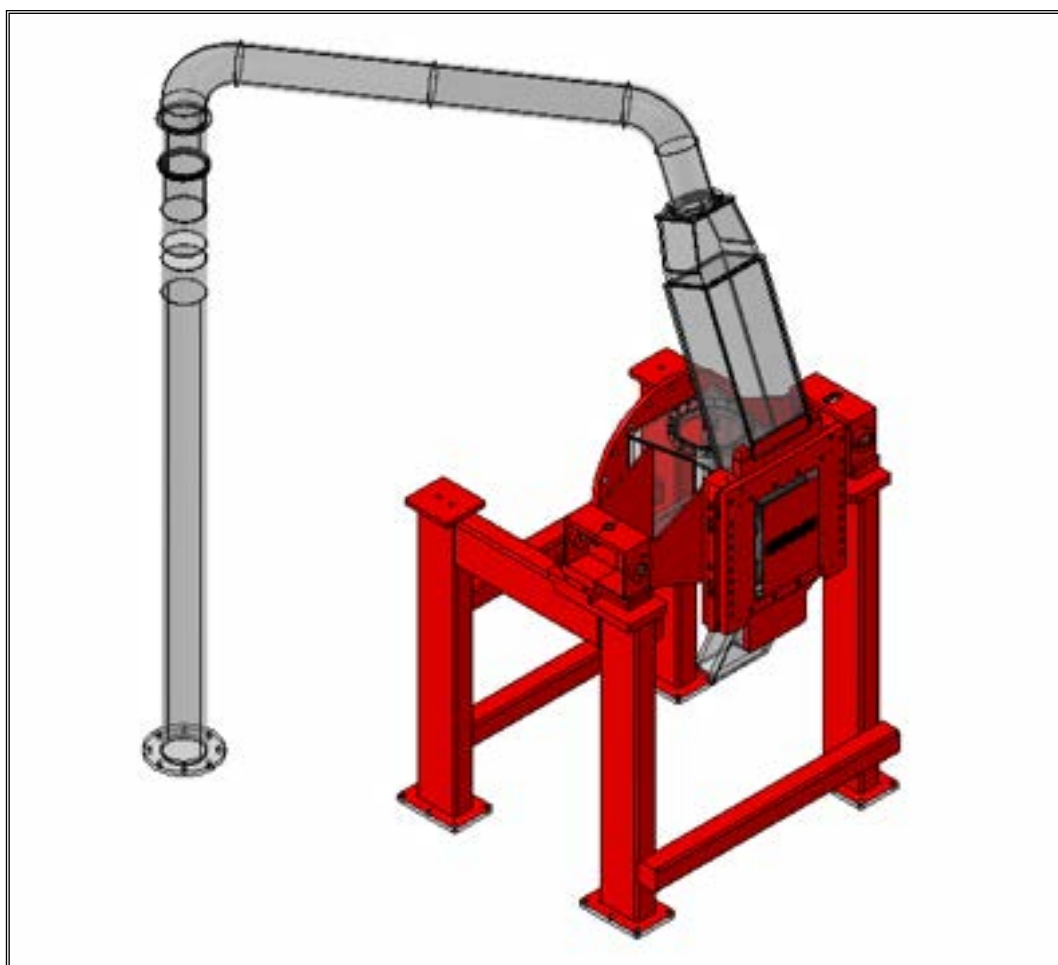


Figure 13. Radiating surfaces.

3.3 Transient analysis and results

A campaign of thermal transient analyses has been carried out to investigate the target system mock-up thermal behaviour under the pre-heating phase of the IFMIF start-up loading scenario, in order to set-up the electric heaters load profile able to allow a structure heating as uniform as possible.

An iterative procedure based on the analysis of the time evolution of the maximum temperature achieved within each component housing an electric heater has been set up in order to obtain a proper load profile for the heaters. In particular, the electric heater load profile has been modified whenever the maximum temperature increase within the above-said components was not sufficiently uniform. Moreover, once the maximum temperature of a component raised up to the reference value of 250 °C, the load profile was further modified in order to keep the maximum temperature of that component in the range between 240 °C - 260 °C, allowing the heating of the other components up to 250 °C. Adopting this criterion it has been possible to determine the relevant electric heater load profiles.

Analysis results have shown that, adopting this duty-cycle for the electric heaters, the steady state conditions are reached after a period of 320 minutes. Although the heater on the BP is switched-on for the whole duration of the pre-heating phase, the maximum BP temperature is ~220 °C in the region housing the electric heater, while it remains well below 200 °C in the central region of the lithium flow channel (~125 °C). Results obtained in terms of maximum temperature time distributions are shown in Figures 14-17, while the thermal field arising at the end of the pre-heating phase is shown in Figures 18-19. The electric heater load profiles have been reported in Tables 3-6.

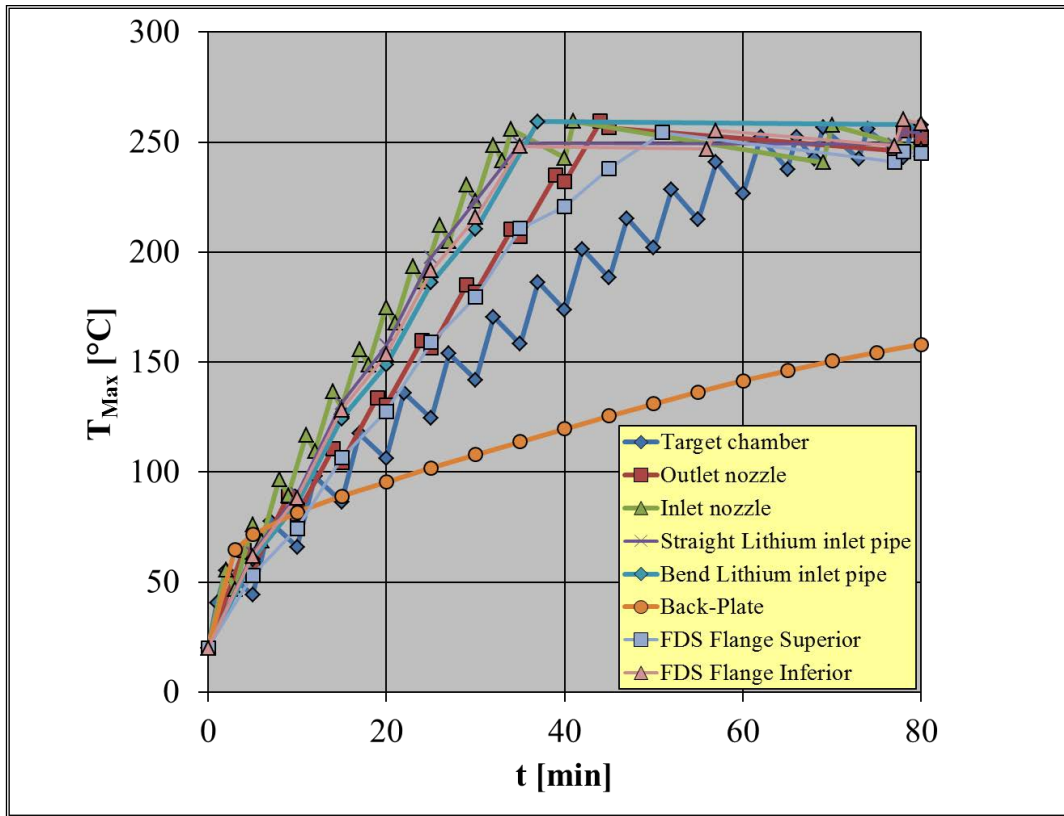


Figure 14. Maximum temperature vs time. 0-80 minutes.

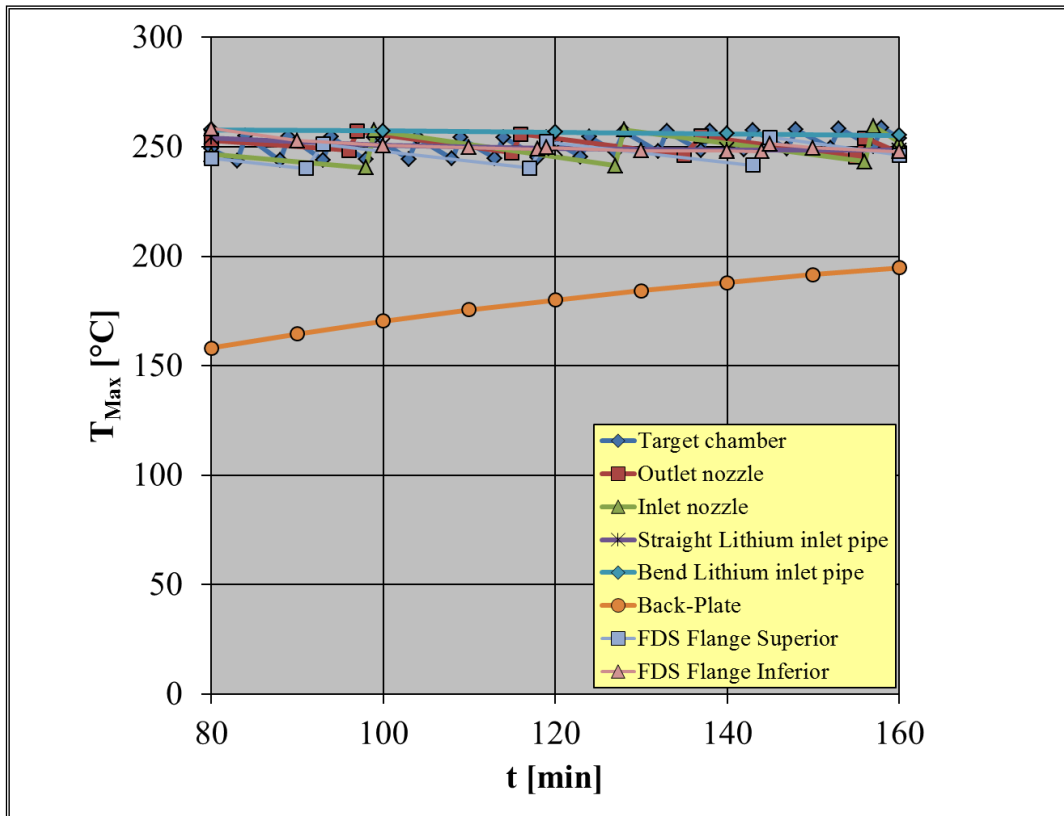


Figure 15. Maximum temperature vs time. 80-160 minutes.

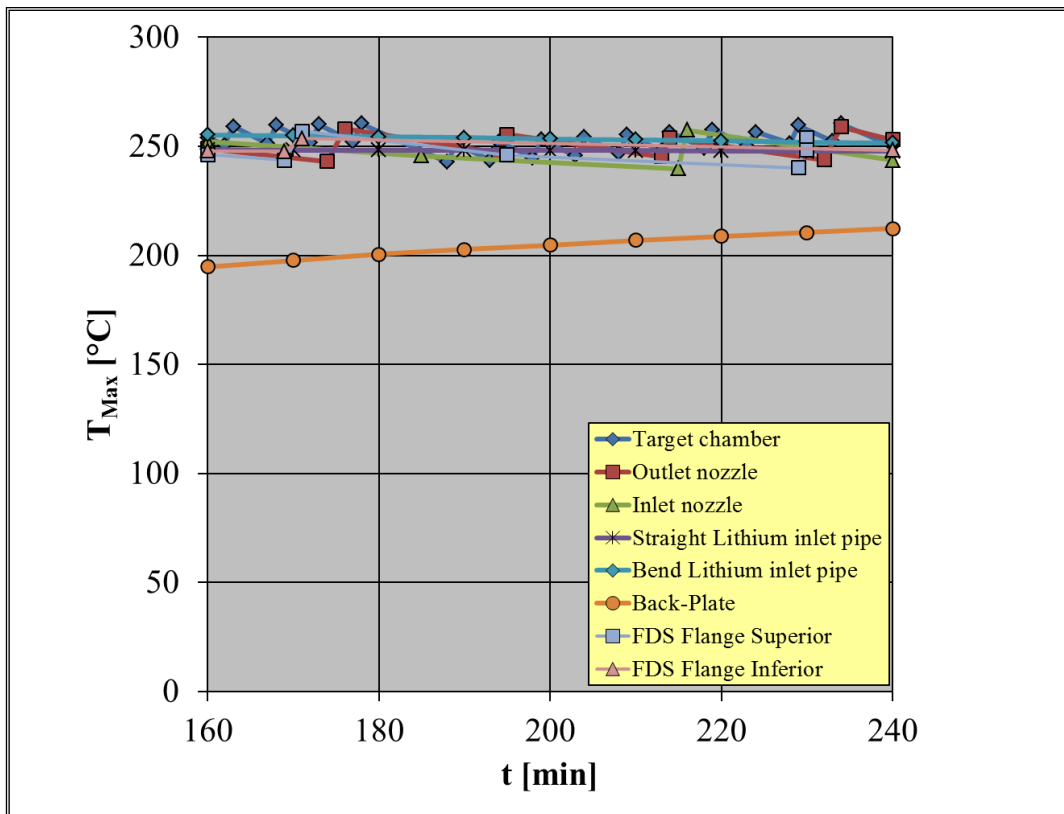


Figure 16. Maximum temperature vs time. 160-240 minutes.

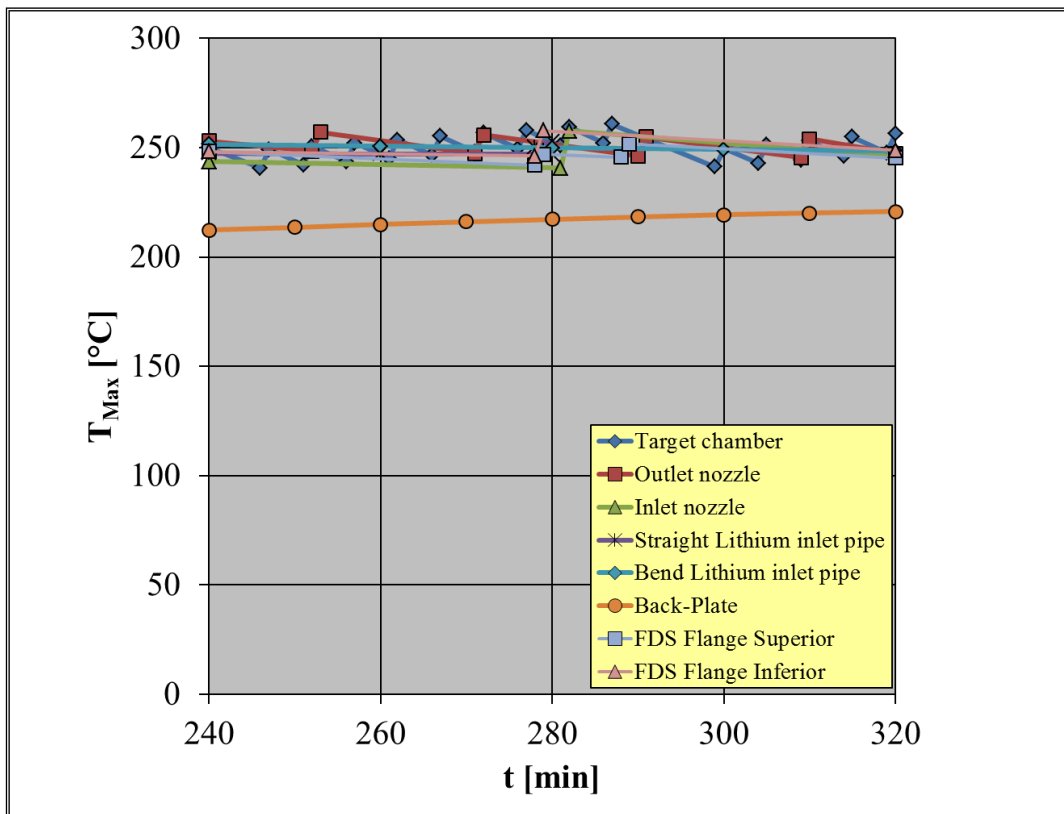


Figure 17. Maximum temperature vs time. 240-320 minutes.

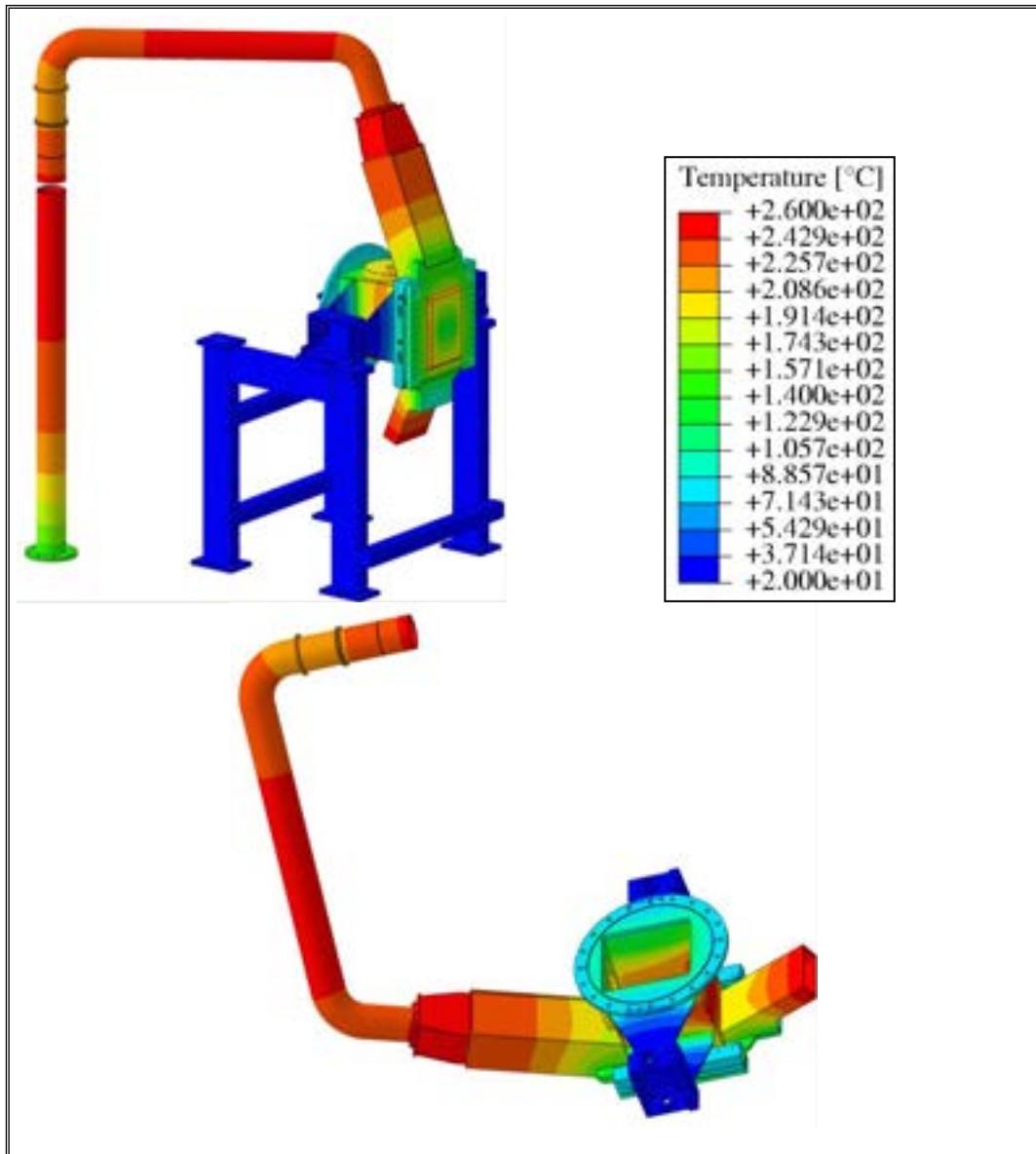


Figure 18. TA thermal field - t = 320 minutes.

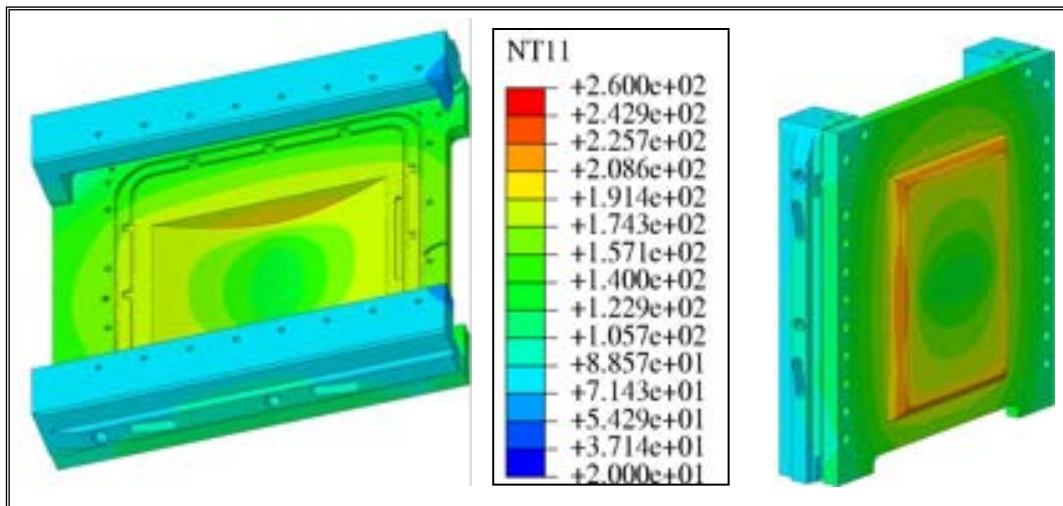


Figure 19. BP thermal field - t = 320 minutes.

Table 3. Electric heater load profile. 0-80 minutes.

| Time [min] | Target chamber | Outlet nozzle | Inlet nozzle | Straight Lithium inlet pipe | Bend Lithium inlet pipe | FDS flange inferior | FDS flange superior | Back-Plate |
|------------|----------------|---------------|--------------|-----------------------------|-------------------------|---------------------|---------------------|------------|
| 0-1 | ON | ON | ON | ON | ON | ON | ON | ON |
| 1-2 | ON | ON | ON | OFF | OFF | OFF | OFF | ON |
| 2-3 | OFF | ON | OFF | ON | ON | ON | ON | ON |
| 3-4 | OFF | ON | ON | OFF | OFF | OFF | OFF | ON |
| 4-5 | OFF | OFF | ON | ON | ON | ON | ON | ON |
| 5-6 | ON | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 6-7 | ON | ON | ON | ON | ON | ON | ON | ON |
| 7-8 | OFF | ON | ON | OFF | OFF | OFF | OFF | ON |
| 8-9 | OFF | ON | OFF | ON | ON | ON | ON | ON |
| 9-10 | OFF | OFF | ON | OFF | OFF | OFF | OFF | ON |
| 10-11 | ON | ON | ON | ON | ON | ON | ON | ON |
| 11-12 | ON | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 12-13 | OFF | ON | ON | ON | ON | ON | ON | ON |
| 13-14 | OFF | ON | ON | OFF | OFF | OFF | OFF | ON |
| 14-15 | OFF | OFF | OFF | ON | ON | ON | ON | ON |
| 15-16 | ON | ON | ON | OFF | OFF | OFF | OFF | ON |
| 16-17 | ON | ON | ON | ON | ON | ON | ON | ON |
| 17-18 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 18-19 | OFF | ON | ON | ON | ON | ON | ON | ON |
| 19-20 | OFF | OFF | ON | OFF | OFF | OFF | OFF | ON |
| 20-21 | ON | ON | OFF | ON | ON | ON | ON | ON |
| 21-22 | ON | ON | ON | OFF | OFF | OFF | OFF | ON |
| 22-23 | OFF | ON | ON | ON | ON | ON | ON | ON |
| 23-24 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 24-25 | OFF | OFF | ON | ON | ON | ON | ON | ON |
| 25-26 | ON | ON | ON | OFF | OFF | OFF | OFF | ON |
| 26-27 | ON | ON | OFF | ON | ON | ON | ON | ON |

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|-------|-----|-----|-----|-----|-----|-----|-----|----|
| 27-28 | OFF | ON | ON | OFF | OFF | OFF | OFF | ON |
| 28-29 | OFF | ON | ON | ON | ON | ON | ON | ON |
| 29-30 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 30-31 | ON | ON | ON | ON | ON | ON | ON | ON |
| 31-32 | ON | ON | ON | OFF | OFF | OFF | OFF | ON |
| 32-33 | OFF | ON | OFF | ON | ON | ON | ON | ON |
| 33-34 | OFF | ON | ON | OFF | OFF | OFF | OFF | ON |
| 34-35 | OFF | OFF | OFF | OFF | ON | ON | ON | ON |
| 35-36 | ON | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 36-37 | ON | ON | OFF | OFF | ON | OFF | ON | ON |
| 37-38 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 38-39 | OFF | ON | OFF | OFF | OFF | OFF | ON | ON |
| 39-40 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 40-41 | ON | ON | ON | OFF | OFF | OFF | ON | ON |
| 41-42 | ON | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 42-43 | OFF | ON | OFF | OFF | OFF | OFF | ON | ON |
| 43-44 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 44-45 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 45-46 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 46-47 | ON | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 47-48 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 48-49 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 49-50 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 50-51 | ON | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 51-52 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 52-53 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 53-54 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 54-55 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 55-56 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 56-57 | ON | OFF | OFF | OFF | OFF | ON | OFF | ON |
| 57-58 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

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| 58-59 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 59-60 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 60-61 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 61-62 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 62-63 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 63-64 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 64-65 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 65-66 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 66-67 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 67-68 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 68-69 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 69-70 | OFF | OFF | ON | OFF | OFF | OFF | OFF | ON |
| 70-71 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 71-72 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 72-73 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 73-74 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 74-75 | OFF | OFF | ON | OFF | OFF | OFF | OFF | ON |
| 75-76 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 76-77 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 77-78 | OFF | ON | OFF | OFF | OFF | ON | OFF | ON |
| 78-79 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 79-80 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

Table 4. Electric heater load profile. 80-160 minutes.

| Time [min] | Target chamber | Outlet nozzle | Inlet nozzle | Straight Lithium inlet pipe | Bend Lithium inlet pipe | FDS flange inferior | FDS flange superior | Back-Plate |
|------------|----------------|---------------|--------------|-----------------------------|-------------------------|---------------------|---------------------|------------|
| 80-81 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 81-82 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 82-83 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 83-84 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 84-85 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

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|---------|-----|-----|-----|-----|-----|-----|-----|----|
| 85-86 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 86-87 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 87-88 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 88-89 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 89-90 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 90-91 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 91-92 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 92-93 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 93-94 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 94-95 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 95-96 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 96-97 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 97-98 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 98-99 | ON | OFF | ON | OFF | OFF | OFF | OFF | ON |
| 99-100 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 100-101 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 101-102 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 102-103 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 103-104 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 104-105 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 105-106 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 106-107 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 107-108 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 108-109 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 109-110 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 110-111 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 111-112 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 112-113 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 113-114 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 114-115 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 115-116 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |

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| 116-117 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 117-118 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 118-119 | ON | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 119-120 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 120-121 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 121-122 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 122-123 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 123-124 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 124-125 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 125-126 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 126-127 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 127-128 | ON | OFF | ON | OFF | OFF | OFF | OFF | ON |
| 128-129 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 129-130 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 130-131 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 131-132 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 132-133 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 133-134 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 134-135 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 135-136 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 136-137 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 137-138 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 138-139 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 139-140 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 140-141 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 141-142 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 142-143 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 143-144 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 144-145 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 145-146 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 146-147 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

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| 147-148 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 148-149 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 149-150 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 150-151 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 151-152 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 152-153 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 153-154 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 154-155 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 155-156 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 156-157 | OFF | OFF | ON | OFF | OFF | OFF | OFF | ON |
| 157-158 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 158-159 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 159-160 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

Table 5. Electric heater load profile. 160-240 minutes.

| Time [min] | Target chamber | Outlet nozzle | Inlet nozzle | Straight Lithium inlet pipe | Bend Lithium inlet pipe | FDS flange inferior | FDS flange superior | Back-Plate |
|------------|----------------|---------------|--------------|-----------------------------|-------------------------|---------------------|---------------------|------------|
| 160-161 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 161-162 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 162-163 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 163-164 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 164-165 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 165-166 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 166-167 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 167-168 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 168-169 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 169-170 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 170-171 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 171-172 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 172-173 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 173-174 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

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|---------|-----|-----|-----|-----|-----|-----|-----|----|
| 174-175 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 175-176 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 176-177 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 177-178 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 178-179 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 179-180 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 180-181 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 181-182 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 182-183 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 183-184 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 184-185 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 185-186 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 186-187 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 187-188 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 188-189 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 189-190 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 190-191 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 191-192 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 192-193 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 193-194 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 194-195 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 195-196 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 196-197 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 197-198 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 198-199 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 199-200 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 200-201 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 201-202 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 202-203 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 203-204 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 204-205 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

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|---------|-----|-----|-----|-----|-----|-----|-----|----|
| 205-206 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 206-207 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 207-208 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 208-209 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 209-210 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 210-211 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 211-212 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 212-213 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 213-214 | ON | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 214-215 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 215-216 | OFF | OFF | ON | OFF | OFF | OFF | OFF | ON |
| 216-217 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 217-218 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 218-219 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 219-220 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 220-221 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 221-222 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 222-223 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 223-224 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 224-225 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 225-226 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 226-227 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 227-228 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 228-229 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 229-230 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 230-231 | OFF | OFF | OFF | OFF | OFF | OFF | ON | ON |
| 231-232 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 232-233 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 233-234 | ON | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 234-235 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 235-236 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

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|---------|-----|-----|-----|-----|-----|-----|-----|----|
| 236-237 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 237-238 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 238-239 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 239-240 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

Table 6. Electric heater load profile. 240-320 minutes.

| Time [min] | Target chamber | Outlet nozzle | Inlet nozzle | Straight Lithium inlet pipe | Bend Lithium inlet pipe | FDS flange inferior | FDS flange superior | Back-Plate |
|------------|----------------|---------------|--------------|-----------------------------|-------------------------|---------------------|---------------------|------------|
| 240-241 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 241-242 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 242-243 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 243-244 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 244-245 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 245-246 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 246-247 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 247-248 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 248-249 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 249-250 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 250-251 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 251-252 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 252-253 | OFF | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 253-254 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 254-255 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 255-256 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 256-257 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 257-258 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 258-259 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 259-260 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 260-261 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 261-262 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 262-263 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |

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|---------|-----|-----|-----|-----|-----|-----|-----|----|
| 263-264 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 264-265 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 265-266 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 266-267 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 267-268 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 268-269 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 269-270 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 270-271 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 271-272 | ON | ON | OFF | OFF | OFF | OFF | OFF | ON |
| 272-273 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 273-274 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 274-275 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 275-276 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 276-277 | ON | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 277-278 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 278-279 | OFF | OFF | OFF | OFF | OFF | ON | OFF | ON |
| 279-280 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 280-281 | OFF | OFF | OFF | OFF | OFF | OFF | OFF | ON |
| 281-282 | ON | OFF | ON | OFF | OFF | OFF | OFF | ON |
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4 Conclusions

Within the present PAR 2015 of ENEA-MSE Agreement, a research campaign has been launched in collaboration with the Department of Energy, Information Engineering and Mathematical Models (DEIM) of the University of Palermo to numerically investigate the thermal behaviour of the IFMIF target system mock-up installed at ENEA Brasimone, in order to assess the time-dependent load profile of the electric heaters devoted to reproduce the pre-heating phase of the IFMIF start-up transient operational phase.

A theoretical approach based on the Finite Element Method (FEM) has been followed and a qualified commercial FEM code has been adopted to perform the study.

In order to properly select the electric heater load profile which allows a maximum temperature increase within the different components as uniform as possible, an iterative procedure based on a *try&fail* approach has been followed. In particular, the electric heater load profile has been modified, firstly, in order to ensure a uniform heating of the different components up to 250 °C and, secondly, whenever the maximum temperature achieved within each component has gone outside the temperature window 240 °C - 260 °C.

Results obtained have shown that, with the load profile adopted for the electric heaters, the steady state conditions are reached after a period of ~320 minutes. The maximum temperature calculated for the BP is ~220 °C, lower than the reference value of 250 °C. Moreover, although the electric heater on the BO external surface is switched-on for the whole duration of the pre-heating phase, the temperature reached in the central part of the lithium flow channel is ~125 °C, well below the 250 °C.

The BP electric heater power and shape needs therefore a revision in order to ensure the achievement of higher temperatures within the BP and the lithium flow channel in particular.

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6 Abbreviations and acronyms

| | |
|--------|--|
| BP | Back-Plate |
| DEIM | Dipartimento di Energia, Ingegneria dell'informazione e Modelli matematici |
| EVEDA | Engineering Validation and Engineering Design Activities |
| FDS | Fast Disconnecting System |
| FE | Finite Element |
| FEM | Finite Element Method |
| HFTM | High Flux Test Module |
| IFMIF | International Fusion Materials Irradiation Facility |
| MSE | Ministero dello Sviluppo Economico |
| PAR | Piano Annuale di Realizzazione |
| RAFM | Reduced Activation Ferritic Martensitic |
| SDC-IC | Structural Design Criteria for In-vessel Components |
| TA | Target Assembly |