ABSTRACT

Since 1994 the International Fusion Materials Irradiation Facility is under development. Up till now only design activities have been performed aimed at providing a reference design, evaluating remaining design uncertainty, reducing the costs and the key technology risk factors to reach the specified requirements with sufficient availability and reliability.

From the beginning ENEA is engaged in the design of all the systems. In particular for the Lithium Target System, its activities are mainly focused on risk analysis, transient analysis, thermal-hydraulics and stability of lithium jet.

This paper deals with the analysis of the behaviour of the Lithium Target System under normal and incident conditions, performed with a version of the RELAP5/Mod3.2 code modified to allow for specific features of the system itself (Lithium and organic oil as cooling fluids).

1 INTRODUCTION

The development and qualification of radiation-resistant and low-damage materials is a key issue for the environmental acceptability, safety and economic viability of fusion power plants.

Some different concepts of neutron source to produce high energy neutrons at sufficient intensity were proposed to improve the knowledge on the behaviour of material candidate to work in a fusion reactor radiation environment. The first concept was developed by the Fusion Materials Irradiation Test (FMIT) Project (1978-84) [1,2] and later by the Energy Selective Neutron Irradiation Test Facility (ESNIT) Program (1988-92) [3].

In 1992 an international consensus on a D-Li stripping source was reached [4] and since 1994 a facility based on accelerated deuterons by LINAC, so-called IFMIF (International Fusion Materials Irradiation Facility), is under design.

The mission of the IFMIF is to provide flux equivalent to 2MW/m² (0.9*10^{18} n/m²s uncollided flux) or greater for testing sample of materials up to a damage rate of 200 dpa [5].

The facility consists of the following systems: 1) Accelerator System, that provides a continuous 250mA@40MeV accelerated deuterons by two LINAC, 2) Target System, which
produce a lithium flowing stream for the stripping reactions at 15÷20 m/s, 3) Test Cell System, where the samples of about 0,1/0,5/6 l are irradiated, and 4) the ancillary systems, which provide the functions necessary to the operation of the facility (heat rejection system; electrical power distribution system, etc).

At present the IFMIF Conceptual Design Activity (CDA) and Evaluation (CDE) phases are ended and since 2000 Key Element technology Phase (KEP) addressed to development of key element technology for breakthrough and reduction of cost is in progress.

In this phase ENEA with the SIET support is engaged to simulate the thermal-hydraulic behaviour of Lithium Target System in normal, incident and accident conditions.

The incidents and accidents to be analysed have been set up identifying the important accident initiators deriving from possible failure modes of the Target System component.

A version of RELAP5/mod3.2 code, modified to allow for lithium and organic oil as cooling fluids in addition to the commonly used fluids like light or heavy water, has been adopted for such analyses. A detailed nodalization has been set up simulating as better as possible the geometrical and material characteristics of the loop components and the connecting piping.

This paper reports the analyses carried out in ENEA in collaboration with SIET and finalised to study the behaviour of the Lithium Target System under normal and incident conditions.

2 IFMIF TARGET SYSTEM DESCRIPTION

The flow diagram of IFMIF Target System (TS) is shown in figure 1. The TS consists of four circuits: primary circuit (red colour), secondary circuit (green colour), tertiary circuit (bleu colour) and cold trap cooling loop (purple colour).

![Flow diagram of IFMIF target system](image)

**Figure 1:** Flow diagram of IFMIF target system

The primary circuit is mainly made up by two basic parts: the target assembly and the lithium loop. In the target assembly the high energy deuteron beam coming from the accelerators interacts with a stable lithium jet, where the kinetic energy of the beam is deposited and neutrons are produced. The lithium jet is maintained adherent to the back surface of the target assembly by the high speed and the properly designed curved surface profile. The pressure on the free surface of lithium is equal to the pressure of deuteron beam.
tube \((10^3 \text{ Pa})\) in order to avoid significant interference with deuteron beam and suppress lithium evaporation.

The lithium loop circulates the lithium to and from the target assembly by means of an electromagnetic pump (EMP) and removes the heat deposited by the deuteron beam (up to 10 MW). At the exit of the target assembly, the lithium is addressed to a Quench Tank for dumping eventual peaks of temperature, then it enters the EMP and the Lithium Cooler to transfer heat to the Secondary circuit. This loop also contains systems for monitoring and controlling the concentration of impurities (\(T, ^{7}\text{Be}, C, O, N\)) in lithium to maintain the high purity of the loop required for radiological safety and to minimise corrosion of the components by the hot flowing lithium.

The secondary circuit circulates organic oil to remove heat from the primary circuit. A centrifugal pump provides a constant flowrate between the lithium cooler and the organic cooler. A By-pass line with a control valve system maintains constant the lithium temperature at the lithium cooler outlet.

The tertiary circuit circulates water to remove heat from the organic cooler and discharges it to environment through the cooling towers.

The main specifications of IFMIF TS at full power conditions are listed in table 1.

**Table 1: IFMIF target system main specifications**

<table>
<thead>
<tr>
<th>Primary Loop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Deuteron Beam:</strong></td>
<td></td>
</tr>
<tr>
<td>energy</td>
<td>(30 \div 40 \text{ MeV})</td>
</tr>
<tr>
<td>current</td>
<td>250 mA</td>
</tr>
<tr>
<td>power</td>
<td>10 MW</td>
</tr>
<tr>
<td>deposition area on lithium jet</td>
<td>0.2 m x 0.05 m (width x height)</td>
</tr>
<tr>
<td><strong>Lithium Jet:</strong></td>
<td></td>
</tr>
<tr>
<td>thickness</td>
<td>0.025 m</td>
</tr>
<tr>
<td>width</td>
<td>0.26 m</td>
</tr>
<tr>
<td>velocity in the minimum section area</td>
<td>15 m/s (range 10 (\div 20) m/s)</td>
</tr>
<tr>
<td>target lithium inlet/outlet temperature</td>
<td>250/300 °C (523/573 K)</td>
</tr>
<tr>
<td>flowrate (for the above conditions)</td>
<td>48.4 kg/s</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Secondary Loop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Organic oil:</strong></td>
<td></td>
</tr>
<tr>
<td>Lithium Cooler inlet/outlet temperature</td>
<td>200/220 °C (473/493 K)</td>
</tr>
<tr>
<td>flowrate (for the above conditions)</td>
<td>230 kg/s</td>
</tr>
<tr>
<td>Organic cooler inlet temperature</td>
<td>220 °C (493 K)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Tertiary Loop</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Water:</strong></td>
<td></td>
</tr>
<tr>
<td>Organic cooler inlet/outlet temperature</td>
<td>32/37 °C (305/310 K)</td>
</tr>
<tr>
<td>flowrate (for the above conditions)</td>
<td>472 kg/s</td>
</tr>
</tbody>
</table>

3 TARGET SYSTEM MODEL

3.1 Computer code

For simulating the thermal-hydraulic behaviour of the TS primary, secondary and tertiary circuits a modified version of the Relap/Mod3 2.2 Beta computer program has been employed for its capability and flexibility to adequately represent the main characteristics of this innovative facility.

The code has been modified to include specific features of IFMIF itself, in particular the use of lithium and organic oil as primary and secondary coolant respectively.

New correlations for viscosity, thermal conductivity and surface tension have been introduced for the new fluids and a new convective heat transfer correlation has been added to account for liquid metals. The thermodynamic physical properties of Lithium and Organic oil (liquid state only) have been included too.
3.2 Code nodalization

A scheme of the nodalization adopted for RELAP5 is reported in figure 2. It consists of several pipe, branch and single junction components and heat structures aiming at the simulation of different parts of the system. Moreover a time dependent junction and time dependent volumes are also included to simulate the EMP and to impose pressure at the top of the Quench Tank, and in the secondary and tertiary circuits.

The heat structures are constituted by the effective metal wall of the pipes. Power has been provided to the heat structures of the primary and secondary circuits in order to simulate the electric heaters, that maintain the lithium and oil temperature at 523 K (specified temperature in the plant at zero beam power) compensating the heat losses.

The three circuits are assumed to be thermally insulated toward the environment (environmental temperature equal to 293 K) and the heat transfer coefficient with air is imposed to be 2 W/(m²K). The material of all the circuits is assumed to have the thermal characteristics (conductivity and heat capacity) of AISI 304.

All the fluid flow paths have been represented by cylindrical pipes, including the rectangular channel of the target assembly. In this case the schematisation has been performed simulating the rectangular section channel by means of a circular section flow path with the same hydraulic diameter.

The free jet surface has been simulated with a volume full of liquid moving at high speed (pipe). The pressure is determined by the Quench Tank vacuum system simulated in the code with a time dependent volume, where it is possible to impose a certain pressure curve as a function of time.

Due to the impossibility in Relap5 code of generating power directly in the fluid, in the simulation, power is supplied to the lithium jet by means of several heated structures related to the target volumes in correspondence of the beam footprint.

Figure 2: IFMIF target system nodalisation
Regulation valves located on the Organic cooler By-pass line and at the Organic cooler inlet are controlled automatically by a proportional-integral regulator and specific functions conditioned to certain events. In particular the valve control system is based on: 1) the temperature error with respect to the specified set point (lithium temperature at the Target inlet equal to 523 K); 2) the Target power; and 3) the oil temperature at the cooler outlet in order to limit fast strong oil temperature decreasing following the Organic cooler valve opening during the start-up phase. It has been assumed that at full power the By-pass valve is open at 15% and the Organic cooler valve is open at 85%, without any temperature error.

The oil pump control system is based on beam power.

The tertiary circuit has been partially simulated, in particular the shroud side of the Organic cooler has been reproduced for the code simulation. Water flowrate and inlet temperature have been imposed as boundary conditions by means of time dependent volumes and junctions.

4 TARGET SYSTEM THERMAL-HYDRAULIC BEHAVIOUR

The behaviour of the Target system has been assessed against normal, incident and accident conditions. Some of the more representative transients are described in the following sub-sections.

4.1 Start-up and shut-down operating conditions

The TS shut-down and start-up have been simulated in a single calculation, starting from a full power steady state down to a zero power steady state and up again to full power steady conditions. The imposed power curve is reported in figure 3.

In the simulation, the EMP is represented by a time dependent junction providing a constant flowrate in the time. The Primary circuit flowrate and the Secondary circuit global, by-pass and organic cooler flowrates are shown in Fig. 4. It is possible to observe how, during the different phases of the transient, the by-pass and organic cooler flowrates adjust in order to maintain the Target inlet lithium temperature at 523 K. In the shut-down phase the global oil flowrate passes through the by-pass. The primary flowrate is constant during the transient, because the EMP is represented by a time dependent junction.

Target inlet and outlet temperatures are shown in figure 5. At full power steady state the Target temperature increase is of about 50 K, corresponding to 10 MW power provided to the lithium jet. The shut-down phase is characterized by a target outlet temperature that follows the power decreasing; whereas the start-up phase appears more unstable due to the control
system operation. The temperature presents a first strong downward peak (12 K width), followed by a few little temperature oscillations (less than 3 K width). The plant reaches a new steady condition at full power in less than 400 s.

The oil temperatures at the Lithium Cooler inlet and outlet are shown in Fig. 6.

At zero power steady state the lithium temperature is maintained at 523 K by means of electric heaters, that compensate the heat losses to the environment, estimated in 50 and 70 KW respectively for the primary and secondary circuits.

4.2 Beam trip from full power to zero power

This incident resulting from the loss of all the accelerators (2 out of 2) is characterized by a power reduction from full power steady state to zero power in 10 µs (figure 7). At the end of the transient the Target system has to reach the zero power steady state conditions as soon as possible in order to allow a new start-up.

The control system regulates the By-pass and Organic cooler valves so that the lithium temperature in primary circuit quickly reaches the specified value (523 K – figures 8 and 10); after the beam trip, it isolates the secondary from the tertiary circuit to avoid an unwanted oil cooling (figure 9).

Since 620 s the electric heaters provide a power of 50 and 70 KW to the primary and secondary circuit to compensate the losses to environment.

The steady state at zero power is reached at time 750 s (figures 8 and 10). The primary and secondary temperatures are equal to 523 K, whereas the flowrates are equal to the nominal values.
The evolution of the total oil flowrate and the By-pass and organic cooler flowrates are shown in figure 9.

Figure 9 Total oil flowrate, By-pass and organic cooler flowrates

4.3 Beam trip from full power to 50% power

In this incident, resulting from the loss of an accelerator (1 out of 2), the beam power varies from 10 MW to 5 MW in 10 µs (figure 11). At the end of the transient the Target system has to reach a steady state characterized by a Target outlet and inlet temperature difference equal to 50 K (required by the IFMIF specification) to allow a quick return to the full power steady state.

As the beam power is reduced by 50 %, the lithium flowrate is reduced to half the nominal value by means of time dependent junction (EMP) to maintain the same values to the Target outlet and inlet temperatures. At the same time the oil pump control system acts on the oil flowrate reducing removed power.

The valve control system controls the secondary circuit valves (By-pass and Organic cooler) so that the lithium temperature in primary circuit maintains the same value of the specified Target temperature increase (50 K – figure 12). After the beam trip, it regulates the secondary flowrate so that once halved it is divided for 52% in the By-pass and 47% in Organic cooler.

In secondary circuit the rise in temperature maintains the same value of nominal one (20 K), but both the temperatures increase.

Water flowrate is reduced by 50% in 5 s by means of time dependent junction.

After the power halving, the Target system reaches a new steady state at time 1000 s (figures 12,13,14).

Figure 11 Target power

Figure 12 Target inlet & outlet temperatures
5 CONCLUSIONS

In the frame of Key Elements technology Phase ENEA and SIET are engaged in the analysis of the thermal-hydraulic behaviour of the IFMIF target system under normal, incident and accident operating conditions. Up to now the performed work concerns the behaviour in normal and incident operating conditions, described in this paper.

The obtained results in the simulation by RELAP 5 of the transients performed show that the plant well answers to the transients and it is able to reach new steady conditions in a short time.

Moreover the performed activity encourages further development of the code to simulate the innovative component, like assembly with a free lithium jet surface, free jet assembly.

Future activities will concern the simulation of the following accidents conditions: 1) loss of heat sink due to loss of tertiary circuit; 2) loss of lithium flow due to EMP stop (LOFA); 3) loss of coolant accident in primary circuit (LOCA); and 4) loss of oil flow due to pump stop (LOFA in secondary circuit).

REFERENCES


Proceedings of the International Conference Nuclear Energy for New Europe, Kranjska gora, Slovenia, Sept. 9-12, 2002