Safety analysis of the DONES primary heat removal system

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The development of a neutron source able to reproduce the irradiation conditions typical of a nuclear fusion reactor, in order to test candidate structural materials, is the main goal of the Work Package Early Neutron Source (WPENS) of the EUROfusion action. This source, named Demo Oriented NEutron Source (DONES), is a facility where neutrons are produced by means of D-Li interactions. More in detail, a beam of 125 mA deuterium ions at the energy of 40 MeV strikes a lithium jet flowing in a purposely shaped channel in order to obtain an intense and stable neutron flux for the irradiation of material samples.

In the framework of these activities, safety analyses are a key aspect in the DONES design and development. Among the postulated initiating events identified during the preliminary Failure Mode Analysis, the Loss Of Flow Accident (LOFA) in the Primary Heat Removal System of the lithium loop, due to a trip of the electro-magnetic pump, is one of the most severe. In fact, the loss of lithium flow, combined with the failed stop of the accelerator, could lead to the destruction of the lithium flow channel in correspondence of the component named Back-Plate. For this reason, it has been chosen to investigate the LOFA adopting the deterministic system code RELAP5-3D.

Results obtained are critically discussed and compared with those obtained by a similar calculation carried out with MELCOR 1.8.6 code, in order to assess the RELAP5-3D capability of describing systems adopting lithium as working fluid.

Keywords: DONES, Relap5-3D, lithium loop, PHRS, safety analysis, MELCOR

1. Introduction

The study, test and qualification of new performing structural materials to be adopted in future nuclear fusion power plants is one of the several activities foreseen by the European fusion roadmap [1]. In order to achieve this goal, the reproduction of working conditions expected to be reached in a fusion power plant is a key-point for the successful characterization of these new structural materials. To this purpose, among the R&D activities carried out by the EUROfusion consortium [2]-[3], it is foreseen the construction of a neutron source able to fulfil these requirements, the so-called DEMO Oriented NEutron Source (DONES) [4]-[5].

DONES is a neutron source derived from IFMIF [6], where neutrons are generated from the interaction between accelerated deuteron ions and a flow of liquid lithium. Differently from IFMIF, in DONES one deuteron beam of 125 mA accelerated at the energy of 40 MeV (instead of two) will interact with the liquid lithium in order to produce an intense neutron flux (~$5\cdot10^{18}$ $n\cdot m^{-2}\cdot s^{-1}$) to irradiate material samples. It is foreseen to reach a damage level of 20-30 dpa (NRT) in less than 2.5 years in a volume of 0.3 l and a damage of 50 dpa (NRT) in <3 years applicable to 0.1 l volume [5].

Interactions between the D^+ beam and the liquid lithium will take place in the Target System and in particular in the component called Target Assembly (TA). Going more in detail, Li(d,xn) reactions happen in correspondence of the Back-Plate (BP), where lithium flows with a velocity of 15 m/s and a thickness of 25 mm in order to both produce neutrons and remove the heat power (5 MW) generated by the afore-mentioned reactions. It has to be underlined that the stability of the lithium flow is a key point in the DONES operation, since a reduction of few millimetres in the lithium thickness, if not detected, could cause the destruction of the BP. In fact, in correspondence of the beam foot-print on the lithium jet the BP thickness is just 1.8 mm, in order to reduce, at the lowest level possible, the neutron shielding towards the specimens to be irradiated in the HFTM (Fig. 1).

It is therefore interesting to investigate the behaviour of the lithium loop when a Loss Of Flow Accident (LOFA) happens, identified as one of the possible Postulated Initiating Events (PIEs). The study has been performed adopting the RELAP5-3D code [7] and obtained results are compared with those obtained in [8], where an analogous study adopting the MELCOR code version 1.8.6 for fusion applications has been performed.

2. The Primary Heat Removal System

The DONES Primary Heat Removal System (PHRS), dotted line in Fig. 1, is composed of two main regions: the Lithium Target System and the main lithium loop (Fig. 2).

The former corresponds to the part of the lithium loop inside the Test Cell. It is mainly composed of the Interface Shielding Plugs, the inlet and outlet pipelines, the Target Assembly and the Quench Tank. A more detailed description can be found in [9]. The latter consists of the Electro-Magnetic Pump (EMP), the Electro-Magnetic Flow-Meter, the different valves and instrumentation present in the circuit, the Dump/Storage Tank and the relevant piping [10].

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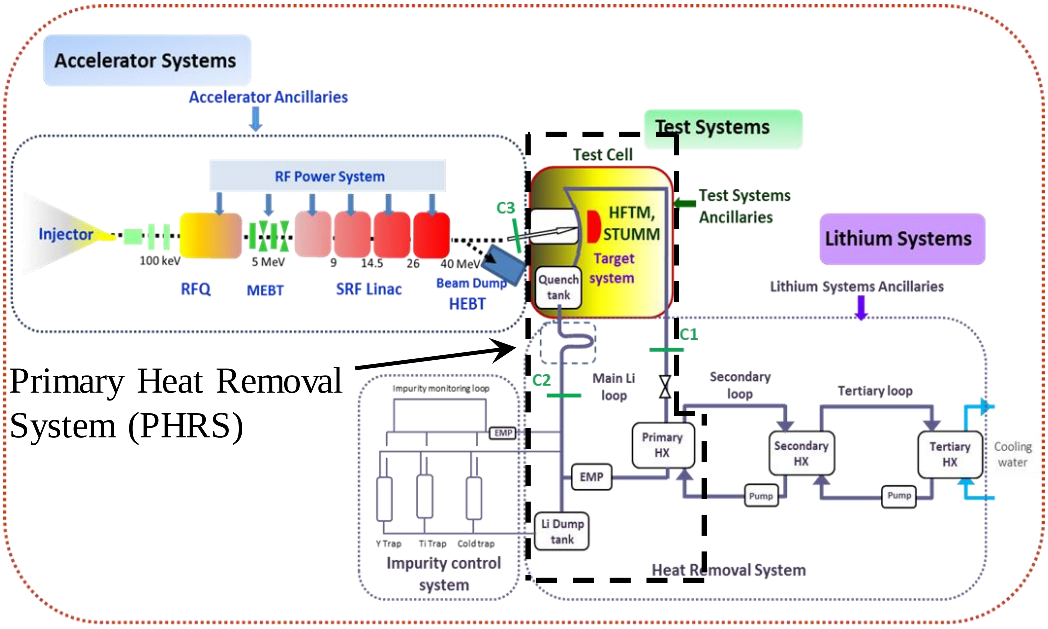

Fig. 1. Overview of DONES conceptual lay-out.

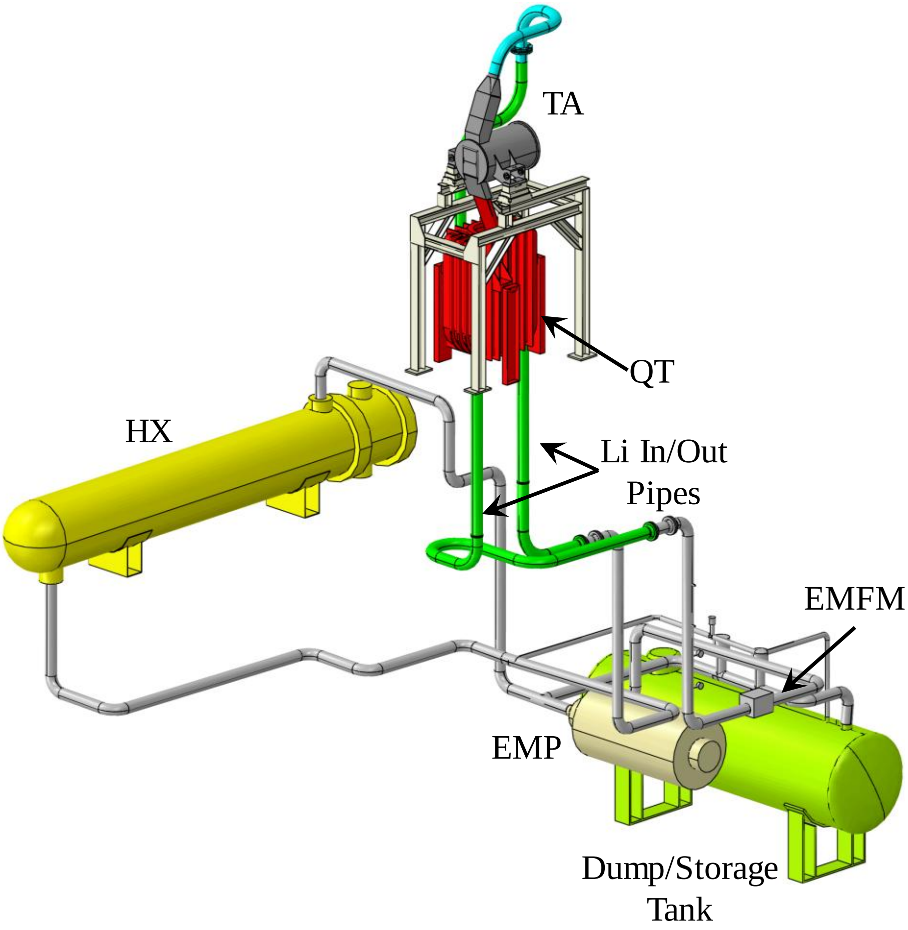

Fig. 2. The DONES PHRS.

The power released by deuterons within the lithium flow is removed from the PHRS by the Secondary Heat Removal System (SHRS). The interface between these two systems is the lithium/oil Primary Heat Exchanger (HX). Even though this component belongs to the SHRS [10], for the purposes of the present study it has been considered as part of the PHRS.

Moreover, since the DONES design should be carried out in a way that the upgrade to IFMIF could be possible without big changes [5], the HX reported in [10] has been modified. A maximum thermal power of 10 MW has been therefore assumed. Values considered for the new HX are reported in Table 1.

Table 1. HX main parameters.

	Oil side	Li side
T_{in} [°C]	185.0	300.0
T_{out} [°C]	220.0	250.0
Mass flow [kg/s]	127.7	49.5
Fouling factor [m²·°C/W]	1.76E-04	3.53E-04
Tube diameter (ext) [mm]	26.9	-
Pitch/Diameter ratio	1.25	-
Nr. of tubes (Double pass)	420	
Length of tubes [m]	3.0	

3. RELAP5-3D nodalization

The schematic layout of the DONES PHRS reproduced in RELAP5-3D code is reported in Fig. 3.

The 6”-Sch.40 piping and mostly of the components have been modelled adopting the RELAP5-3D *Pipe* component and they have been connected by means of the *Branch* card. The *Pump* component has been taken into account for the EMP, while *Valve* junctions have been adopted for the reproduction of the different valves present in the circuit.

The vacuum in the target area and in the upper part of the Quench Tank has been reproduced by a proper Argon volume (#021) connected to a *Time Dependent Volume* (#023) by means of Valves #022 and #024, able to maintain the pressure at the desired value.

The Dump/Storage Tank has been modelled as a stack of volumes. In particular, the first two contain liquid lithium while the other three are filled with argon cover gas. The tank is connected with the *Time Dependent Volume* #077 by means of Valve #076. This valve is normally closed and can be used to regulate the pressure inside the tank. Draining lines connecting the PHRS with the Dump/Storage Tank have been reproduced as well.

Concerning the HX, the Dowtherm A oil, whose thermodynamic properties are available in RELAP5-3D, has been considered as secondary fluid. In fact, Dowtherm A is very similar to both Dowtherm HT and Dow Chemical, oils candidate to be employed in the DONES SHRS [11].

A simplified model has been set-up for the oil (tube) side of the HX. It consists of two *Time Dependent Volumes*, reproducing the environments immediately before the inlet (#400) and after the outlet (#420), a *Time Dependent Junction* (#405) to impose the oil mass flow rate, two ten-volume *Pipes* reproducing the two passes of the oil tubes (#410 and #415) and three *Branches* accounting for the inlet, mixing and outlet oil collectors. Concerning the thermal coupling between the 20 lithium volumes (*Pipe* #045) and the 20 oil ones, it has been assumed that the 10 lithium volumes of the lowest HX shell are coupled with the first tube-pass (blue line in Fig. 3), while the remaining lithium volumes in the upper part of the HX are coupled with the second tube-pass (red line in Fig. 3).

Finally, *Heat Structures* reproducing the steel thicknesses have been adopted, in order to take into account the thermal inertia of the structures during transient scenarios. Heat structures are reported in Fig. 3 as dashed rectangles.

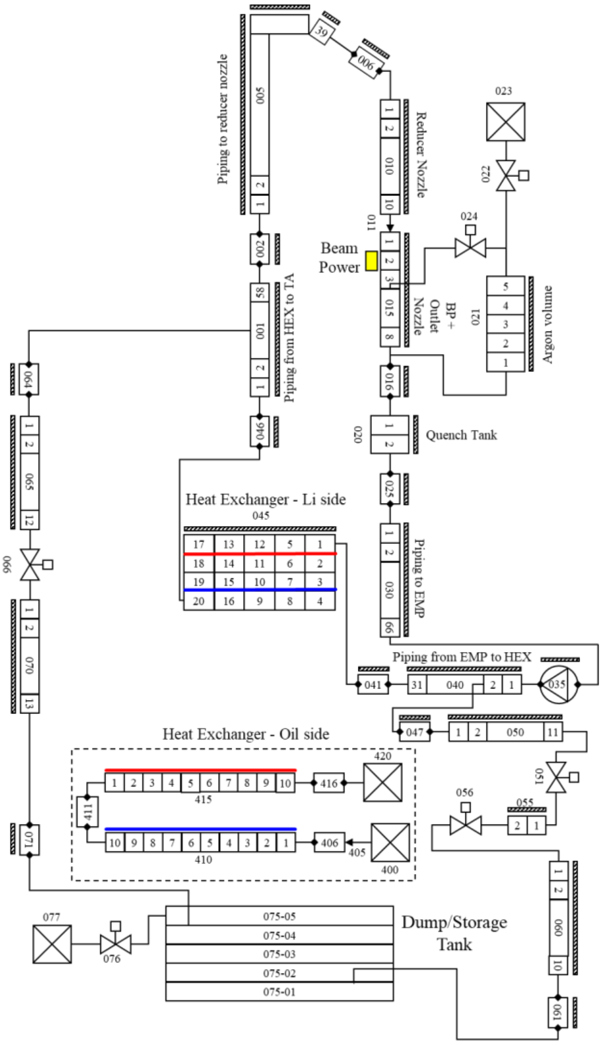

Fig. 3. RELAP5-3D nodalization of the PHRS.

The deuteron beam power of 5 MW is released in a lithium volume of 250 cm³, corresponding to the 5×20 cm² beam foot-print surface multiplied for its nominal thickness of 2.5 cm.

Due to the very low inertia of the EMP, a linear coast-down of 10 seconds has been assumed for the pump, as done in [8] and [12].

Concerning the stop of deuteron beam, according with information from accelerator team, it has been assumed that it happens 0.1 s after that the lithium mass flow rate detected by the flow-meter is lower than 35 kg/s, corresponding to the 70% of the nominal value [8]. Moreover, since both the pump coast-down and the accelerator beam shut-down could considerably vary, a parametric analysis has been carried out, adopting values reported in Table 2.

Table 2. Parametric analyses: values and cases.

Variable	**Values**		
Pump coast-down [s]	10	5	3
Beam shut-down [s]	0.1	1	10
Case	**Pump trip [s]**		**Beam off [s]**
#1	10		0.1
#2			1
#3			10
#4	5		0.1
#5			1
#6			10
#7	3		0.1
#8			1
#9			10

4. Results

The set-up RELAP5-3D model has been run for a *null-transient* of 500 s, in order to achieve the DONES nominal conditions [13]. Nominal lithium mass flow rates and temperatures, as well as the circuit pressure drop have been reproduced with a very low error. Table 3 reports the main values and the relative errors.

Table 3. Reference and RELAP5-3D calculated values.

Variable	**Ref. [10]**	**Calc.**	**Error**
Beam power [MW]	5.0	5.0	0.00%
Mass flow rate [kg/s]	49.5	49.5	0.00%
Li temp. target in [°C]	250.0	250.2	-0.10%
Li temp. target out [°C]	275.0	274.5	0.19%
Pressure loss [MPa]	0.383	0.382	0.35%

In order to speed-up the convergence of the calculation, a pressure of 1 bar has been imposed in the volume #023. It has to be underlined that this modelling choice does not affect results, since lithium thermo-physical properties does not vary with the pressure [7].

At this point the pump trip has been simulated, considering the three different coast-down values. Fig. 4 reports the lithium mass flow rate at the junction 46 of *Pipe* #030, the junction where the Electro-Magnetic Flow-Meter (EMFM) is placed. It has been also imposed that the oil mass flow rate is stopped once the beam is shut-down, in order to avoid lithium freezing inside the circuit [10]. It can be observed that lithium mass flow rate decreases with a quasi-linear behaviour until the value of 10 kg/s is reached. Oscillations in the mass flow rate reported in Fig. 4 are due to fluid sloshing before the equalization of the lithium free surfaces inside QT and pipes is reached. It can be also observed that when the mass flow rate at the exit of the nozzle (orange dashed lines in Fig. 4) reaches zero it does not have any oscillations because the nozzle is almost empty.

The green line in Fig. 4 represents the lithium mass rate value that activates the interlock for the beam off signal. Being this value equal to the 70% of the nominal value, assuming a linear dependence between the mass flow rate and the pump velocity, this threshold value should be achieved after the 30% of the coast-down time. It can be noted that these rough hand-calculations are confirmed by obtained results, due to the linear dependence between the two variables in the first instants of the transient.

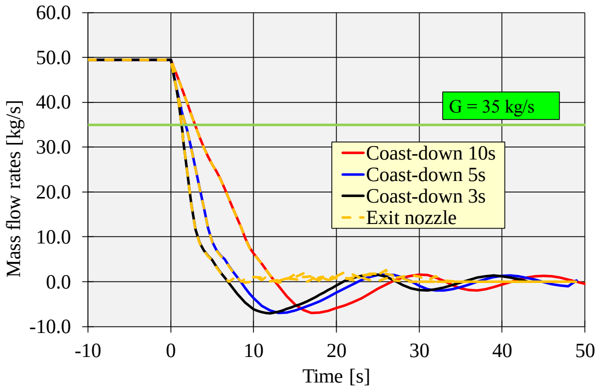

Fig. 4. Li mass flow rates for different pump coast-down times.

The sensitivity analysis on the beam shut-down has allowed to highlight that for all the assessed pump coast-down times, a beam shut-down delay of 1 s can be tolerated, being the maximum lithium temperature equal to 305.4 °C. Fig. 5 shows the lithium temperatures calculated in correspondence of the beam foot-print when it is shut-down 1 s after the detection of the limit lithium mass flow rate in the EMFM. The three dots represent the moment in which the minimum mass flow rate is detected.

The green line in Fig. 5 corresponds to the Li saturation temperature at the target pressure (10^{-3} Pa), equal to 342 °C. It is clear how the maximum lithium temperature remains well below the saturation value. Thus, the surface lithium boiling in correspondence of the beam can be excluded.

Concerning the case in which the beam should not be shut-down, the temperature behaviour in correspondence of the beam foot-print is depicted in Fig. 6. Results show that in case of 10 s coast-down for the EMP, lithium surface boiling is achieved after ~8 s. The same point is achieved in ~4.3 s and ~2.8 s when the pump coast-down is equal to 5 s and 3 s, respectively. These results highlights, once again, that the reliability of the beam control system represents an aspect of primary importance for the safety of the circuit. In fact, its malfunctioning could lead to the lithium evaporation in the beam target with the following destruction of the back-plate.

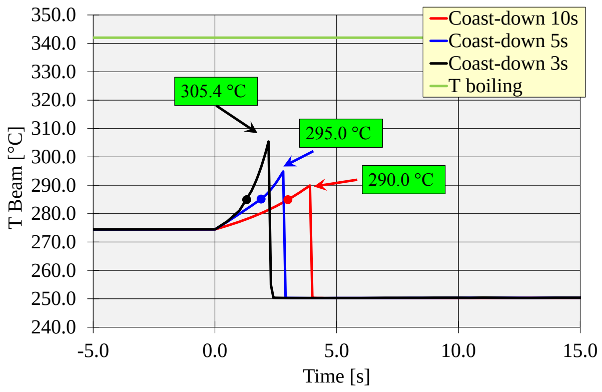

Fig. 5. Li temperatures in correspondence of beam foot-print – Beam shut-down after 1 s.

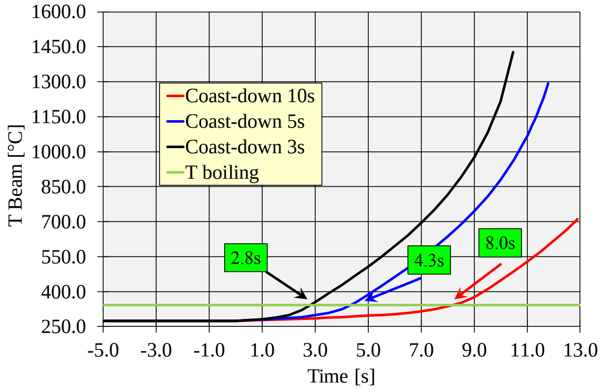

Fig. 6. Li temperatures in correspondence of beam foot-print when beam is not shut-down.

Finally, concerning the comparison between MELCOR and Relap5-3D calculations, results obtained for Case 1 are in good agreement with those carried out in [8], even though a slight discrepancy in the achievement of the minimum lithium mass flow rate is observed (4.6 s [8] vs. 3 s in the present study). Concerning the maximum temperatures reached in lithium beam foot-print when a pump coast-down of 10 s is analysed, results obtained are very similar with those reported in [8] with exception of the case in which the beam is switched-off with a delay of 10 s (Case 7), where a difference of 135 °C is predicted (575 °C in [8] vs.710 °C in the present study).

5. Conclusions

Within the EUROfusion research activities on DONES, a first deterministic analysis adopting the RELAP5-3D code has been carried out, focussing the attention on the investigation of a LOFA scenario.

Since this kind of accidents are driven by the pump coast-down and that for DONES this values are not available, different scenarios have been investigated.

Results obtained have highlighted that, whether the beam shut-down system works properly, a sufficient margin against the surface lithium boiling in the beam foot-print area is maintained, since the beam interlock system should be able to interrupt the beam in 0.1 s. Moreover, results have shown that also a delay of 1 s is widely-sufficient to avoid lithium boiling, preventing the back-plate from its own destruction.

Acknowledgments

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