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Lithium Loop and Purification System of DONES: Preliminary Design

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The Demo-Oriented NEutron Source (DONES) is an essential irradiation facility for testing candidate materials for DEMO reactor and future fusion power plants. An intense flux of highly energetic neutrons is generated by the nuclear reactions of a 125mA beam of deuterons at 40MeV striking a liquid lithium target. The main lithium loop and the related purification system have to generate a stable lithium jet at the target and guarantee: a high speed flow to evacuate the deposited heat (5 MW) and avoid boiling or significant evaporation of the lithium; a constant shape and thickness of the jet to assure a constant neutrons flux and prevent impingement of the beam on the back-plate, being the latter the surface just behind the jet; and an adequate level of chemical impurities solved in lithium. The preliminary design of the two systems is concluded. In this work, the lay-out of the loops, piping dimensioning, pressure drop evaluations, definitions of supports and piping stress analysis are described in detail.
Keyword: DONES, lithium loop, lithium purification

1. Introduction

The Demo-Oriented NEutron Source (DONES) is an irradiation facility for testing candidate materials for DEMO reactor and future fusion power plants, [1]. The purpose of the facility is to provide a high energy (14 MeV) neutrons field for irradiation of samples allocated in a Test Module (TM). The neutron flux (10^{19} n/m^2/s peak) is generated by the impinging of a D^+ beam (40MeV and 125mA) into a liquid lithium target, with a footprint of 200mm nominal width and 50mm nominal height. The target is a lithium jet, generated from a double-reduction nozzle, which flows on a curved surface, the Back-Plate (BP). In the TM, placed behind the target, the neutron flux generates a damage rate of 8-23 dpa/fpy in a volume of about 0.3 l with a helium production rate of ~10-13 appm He/dpa. A lithium loop and the related purification system have to assure the generation of the lithium jet and guarantee: a constant flow rate, to assure a stable shape and thickness of the jet; a high speed flow, to remove the deposited heat and avoid boiling or significant evaporation of the lithium; and an adequate level of chemical impurities solved in lithium.

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The DONES facility consists essentially of three sub-systems: a deuteron accelerator (Accelerator Systems); a lithium loop (Lithium Systems); and systems for containing, conditioning and handling the materials to be tested (Test Systems). The Lithium Systems (LS) includes: Target Assembly (TA); Heat Removal System (HRS) and Impurity Control System (ICS). A simplified 3D CAD model of the loops is shown in Figure 1.

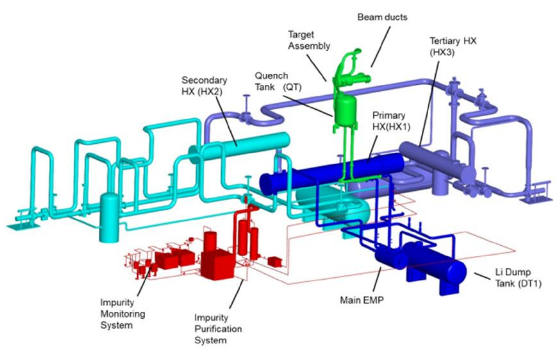
The TA is designed to generate the lithium jet and includes a flow straightener, the double reduced nozzle and the BP. The HRS is designed to supply a constant mass flow rate to the TA and remove the heat deposited by the beam in the target (5 MW), to maintain a defined Li temperature at the TA inlet. The system consists of a Primary Heat Removal System (PHRS), i.e. the main Li loop which circulates the Li from the electromagnetic pump to the TA, and a Secondary Heat Removal System (SHRS), which transfers the heat to the cooling water system of the plant and includes three heat exchangers: Li-oil, oil-oil and oil-water.

The ICS is a side branch of the PHRS and is designed to ensure a low concentration of impurities in the lithium such as nitrogen (N), hydrogen (H), oxygen (O) and corrosion products. The ICS consists of two sub-loops: the Purification Loop (PL) and the Impurity Monitoring

Loop (IML); the first one includes the traps aimed to remove the lithium impurities, while the second one is a sampling/analysis system.

This paper relates to the preliminary design of the PHRS and ICS. The preliminary design of SHRS and TA are reported in [2] and [3] respectively. The LS design of DONES is developed on the results of the engineering design activity of IFMIF project, [4].

Figure 1 Simplified 3D CAD model of the Lithium Systems



2. Impurity control system

The major impurities in the Li loop are the hydrogen isotopes, ^{7}Be, and other non-metals like N, C, and O. Nitrogen has a very high solubility in Li and cannot be reduced to the required concentration level by cold trapping, therefore a hot trap is utilized, which consist of a solid getter able to entirely remove N. During normal operation, the rooms containing the entire Li loop are in Argon atmosphere and no external N contamination of the Li is expected. Therefore, the N purification is made utilizing the getters allocated in the lithium storage tank, Dump Tank (DT), of the PHRS, which will be operated in static condition on the whole Li inventory, before the first start-up of the plant and after the stops for maintenance. The getter material has not been finally defined yet, but it will be chosen among Titanium, Titanium alloys or Niobium. In order to provide sufficient reactivity, the trap is operated at 500-600 °C nominal temperature: because of this high value, the trap will be realized in SA-240 316H. The amount of nitrogen is calculated assuming a maximum initial content of ~ 3450g (767 wppm) and an annual recontamination of ~ 35 g (7.8 wppm) during the maintenance procedure of the loop. The trap, dimensioned to cover the DONES lifetime, is then required to manage up to ~ 4500 g of Nitrogen. The hydrogen isotopes and others impurities (O, C, ^{7}Be, etc.) will be removed online in the purification branch through two types of traps:

- A cold trap to extract oxygen, carbon and corrosion products as binary or ternary compounds based on their solubility. The getter material is stainless steel wire mesh. The trap is operated at 200ºC. Li with a temperature of 280ºC passes first through an economizer and is cooled along the trap by an external Ar cooling circuit. The trap is sized based on the oxygen source term assuming an initial content of ~ 1050g (233 wppm) and an annual recontamination of ~ 10g (2.2 wppm) due to the maintenance. The trap is dimensioned to cover the DONES lifetime, is then required to manage up to ~ 1350 g of Oxygen.
- A hot trap to extract hydrogen isotopes, which are continuously produced in the target during beam operation. The getter material is Yttrium, which shows a higher affinity to hydrogen than Li. The trap operates in the temperature range of 280-300ºC. The trap is sized to extract the annual production of hydrogen isotopes (83.3moles, 93% deuterium and 4% tritium), and is scheduled to be replaced annually during the maintenance period. The initial content of hydrogen assumed as design basis is 720g, which is to be removed during the commissioning phase.

The ICS includes also a monitoring branch, which contains:

- Li samplers, to collect Li samples for off-line analysis. The unit is arranged to allow sampling and extraction of the sampler during beam operation.
- Online monitoring systems: a Resistivity Meter to measure the electric resistance of the Li, which is indicative of the non-metallic impurities content, with a higher sensitivity to nitrogen and hydrogen; and an Electrochemical Hydrogen Sensor, [5].

3. Piping design data

Lithium is an alkaline metal with a melting temperature of 180.5° C, which reacts with water, nitrogen and oxygen generating fires and caustic residues. Welded connections are preferred to flange connections, the last limited to components to be replaced during the lifetime of the facility. Lithium interacts with most of the carbon-based and ceramic-based polymer materials, which must be excluded in sealing elements or components of the instruments in contact with the fluid.

The Li target has a flow cross-section 260x25 mm and a nominal flow velocity of 15 m/s yielding a flow rate of 97.5 l/s, in the main loop. To reduce the amount of Li in the loop as much as possible, as required from the safety requirements related to Tritium inventory, and keep the flow velocity in the pipes < 6 m/s, to limit erosion

effects, a 6" ND sch. 40S piping and 2-1/2" ND sch. 40S for the PHRS and related drain lines are selected respectively. The design flow rate of the ICS is 0.65 l/s, about the 0.6 % of the main loop, and 3/4" ND sch. 40S piping is selected.
The total amount of lithium in the loops is about 8200 liters. Lithium temperature during operation ranges from 250°C to 280°C. Austenitic Stainless Steel SA 312 TP316L for piping is selected. The material properties considered in the modelling are acquired from ASME B&PV 2007 Code, Section II, Part D, [6]. Appropriate valves have been selected from the market and the related technical data used in the calculation.
The design conditions and the sizing parameters of the Li loops are summarized in the Table 1:

Table 1Design parameters for the lithium loops

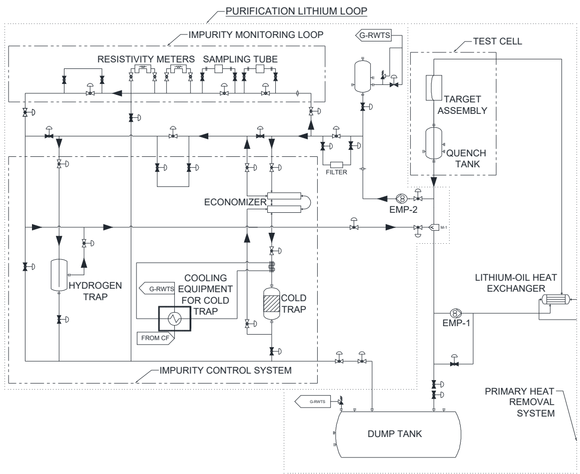
Fluid	Liquid Lithium
Design temperature	350°C
Design pressure	0.76 MPa (PHRS); 0.16 MPa (ICS)
Maximum Flow Rate:	
PHRS	104 l/s (16 m/s in the Li jet)
ICS	0.65 l/s
Purification loop	90% 0.65 = 0.585 l/s
Monitoring loop	10% 0.65 = 0. 065 l/s
Flow velocity	< 6 m/s
Material	316L

4. Pressure drop calculation

The main Li loop (PHRS) circulates Lithium through the TA by the main electro-magnetic pump (EMP-1). Inside the TA lithium flows through a flow straightener and a double reducer nozzle to generate the Li target; it is then discharged, through a special duct, into the QT, submerged about 20 cm under the free surface to avoid surface waves, and goes back to the pump. Both the QT and the TA are maintained at a pressure of 10^{-3} Pa. The highest elevation of the lithium over the pump is about 12 m. The design flow rate is based on the maximum velocity of the Li jet, 16 m/s. The flow velocity in the pipes at the design flowrate (0.104 m^3/s) results of 5.58 m/s.
The pressure drop of the ICS is calculated considering the two sub-loops PL and IML. In normal operation 10% of the flow rate goes through the IML. Since all pipes are ¾" diameter and pressure drops across the two sub-loops are different, to balance the flow rate, a regulating valve is equipped on the IML loop. The velocity in the common pipe at the required flow rate (0.65 l/s) is 1.82 m/s. The P&ID of the ICS is shown in Figure 2.
The general Darcy's equation is used to determine the pressure drop through the loops. The friction factor is given by the full-range Churchill-Usagi equation, [7].
The absolute roughness ε has been assumed to be 30μm.

The resistance through valves and fittings are expressed in terms of resistance coefficients. The calculated overall pressure drop for the PHRS results 0.4 MPa. Considering a margin of 10% the head required to the electromagnetic pump EMP-1 is 0.44 MPa.
Two scenarios have been evaluated to estimate the pump head for the ICS: if the entire flow rate goes through the PL, the calculated pressure drop is 93 kPa; if 90% of the flow rate goes toward the PL, while 10% goes toward the IML, the calculated pressure drop is 89 kPa. Considering the back-pressure at the connection point to the PHRS, 2.54 kPa, the higher total pressure drop results 95.5 kPa. The head required to the electromagnetic pump of the ICS (EMP-2), considering a margin of 10%, results hence 0.105 MPa.

Figure 2 Simplified P&ID of PHRS and ICS



5. Stress Analysis

For the preliminary design of the piping lines, a piping stress analysis has been developed. The model has been set using criteria as for ASME ND for Class 3 Piping and Components, [6].
The following general assumptions are adopted:

- No specific restraining condition limiting the piping displacement to a specific value has been used.
- Supports have been appropriately placed along the pipeline to reduce stresses on piping.
- In a conservative way, all in line components (tanks and pumps) have been considered as fixed points and no thermal anchor displacement is taken into account.
- No thermal effects on supports (displacement) have been taken into account for the verification performed.

Component inlet\outlet nozzles are represented in the piping model as anchoring points restraining the piping against displacements and rotations about all directions. The in-line components (valves, filters, etc.) have been modelled into the piping model as linear rigid elements with a specific weight. Total deadweight is calculated considering the weight per unit length of the pipe and the density of fluid inside the piping. A design pressure of 0.76 and 0.16 MPa, for PHRS and ICS respectively, and two different operating thermal conditions are applied to the system: all the pipelines are at design temperature of 350 °C; different branches are at 21.1 °C and 350 °C, which could occur during the start-up phase. The two different operating thermal conditions have been considered and combined with other load cases to evaluate the most stressing condition for the system. The response of the line to hydraulic test conditions is also evaluated. The test pressure is 1.25 times the design pressure as provision of ASME ND Code, [6].

For seismic event, Service Level Condition D (Faulted Condition) has been considered, as per provision of ASME B&PV 2007, Section III, Div. Paragraph ND 3655, [6]. The design has been performed considering static equivalent analysis method with acceleration equal to 0.25g in the three orthogonal directions and an amplification factor of 1.3. Seismic actions in horizontal and vertical direction have been combined with the SRSS method. Basic Load Cases and Load Combinations have been considered for the design.

Verification of the piping line has been performed considering ASME B&PV code, [6]. The results of the analysis showed for both PHRS and ICS and for each load combination, that the maximum stresses remained lower that the allowable stresses.

Piping Supports calculation

The preliminary design of piping support has been performed using the FE calculation program GTStrudl 32.0. Verification has been done considering prescription of ASME Code section NF, [6]. Carbon steel type ASTM A36 material has been considered and two different types of supports have been considered in the model: Type A, restraint in both vertical and horizontal direction perpendicular to pipe axis; Type B: restraint only in vertical direction. Connections between supports and external steel structures are welded or bolted joints. Connection to concrete civil structures is made by means steel plates and mechanical anchors.

The design of piping supports has been performed considering maximum enveloped acting loads on all supports, obtained from the pipe stress model.

The pipe load on support 6" ND results F_h = 16.7 kN in horizontal direction; F_v = 46.4 kN in vertical direction.

The pipe load on support 3/4" ND results F_h = 2.3 kN in horizontal direction F_v = 2.0 kN in vertical direction

No friction loads have been considered acting along pipe axial direction. In addition to concentrated load, also effects due to support shape have been considered; in particular dead load and seismic load. The seismic loads have been evaluated considering seismic accelerations combined in the space by the SRSS method. Load combinations for support design in GTStrudl models have been considered.

6. Conclusions

The preliminary design of the lithium loop and related purification system is carried out. The 3D model of the loops, pressure drop evaluations, piping stress analysis, supports dimensioning are concluded and show satisfactory results. The design of the traps is not completely concluded.

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