

Dynamic simulation of relief line during loss of insulation vacuum of the ITER cryoline

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Abstract. The ITER cryoline (CL) system consists of 37 types of vacuum jacketed transfer lines which forms a complex structured network with a total length of about 5 km, spread inside the Tokamak building, on a dedicated plant bridge and in the Cryoplant building/area. One of them, the low pressure relief line (RL) recovers helium discharged from process safety relief valves of the different cryogenic users and is sent it back to the Cryoplant via heater and recovery system. The process pipe diameters of the RL vary from DN 50 to DN 200 and the length is more than 1500 m. Loss of insulation vacuum (LIV) of a CL is one of the worst scenarios apart from LIV in Auxiliary Cold Boxes (ACBs). The Torus and Cryostat CL is chosen to simulate the virtual LIV and to study the anticipated behavior of the RL. Both helium LIV (LIV due to leak in helium pipe) and air LIV (LIV due to air ingress in outer vacuum jacket of the cryoline) with and without fire) have been simulated during this study. After the brief description of the CL system, the paper will describe the EcosimPro® model prepared for the dynamic study. The paper will also describe the results like minimum temperature of RL, mass flow and maximum pressure in the RL which are essentially used to choose the type and location of safety relief devices to protect the CL process pipes.

1. Introduction

The ITER CL system [1] is part of the overall ITER cryogenic system [2] involving the Cryoplant (liquid helium refrigerators and liquid nitrogen system) and the Cryodistribution located in the ITER Tokamak building (B11), in Cryoplant building as well as plant bridge. Within the Tokamak building these lines are present at six different levels: L3, L2, L1, B1, B2M and B2 level. The lines are routed from the level L3 to level B2 through two dedicated shafts. The RL is important part of this network. The recovery of helium from safety valves is important for large cryogenic systems due to high cost and scarcity of helium as well as occupational safety. The recovery system at ITER is designed with such considerations. Like any complex system, there are inherent constraints on amount of helium gas that can be recovered due to space limitations and finite capacity of the recovery system. The purpose of RL [3] is to recover helium discharged from the process pressure safety valves (PSVs) of the different cryogenic equipment in the Tokamak as well as Cryoplant buildings and direct it to helium recovery system after heating the cold helium gas to room temperature in the heater as shown in figure 1. The RL inside B11 is vacuum jacketed to avoid condensation when cold helium flows inside. Once RL comes



outside the Tokamak building, it is bare all the way till the heater to take advantage of heat exchange with the atmosphere and to minimize the heater power requirement. Another set of RL is routed from the cold users inside the Cryoplant building up to the common heater (refer to figure 1).

Last part of the bare RL connects the gas bag to the recovery compressor (RC) and from RC to gas storage tanks. The operating condition of this line depends on the particular event (one PSV or multiple PSV's opening during LIV) and the combinations of failure events. Therefore, before finalizing among various options, it was important to analyse the integrated behaviour of the RL under these events.

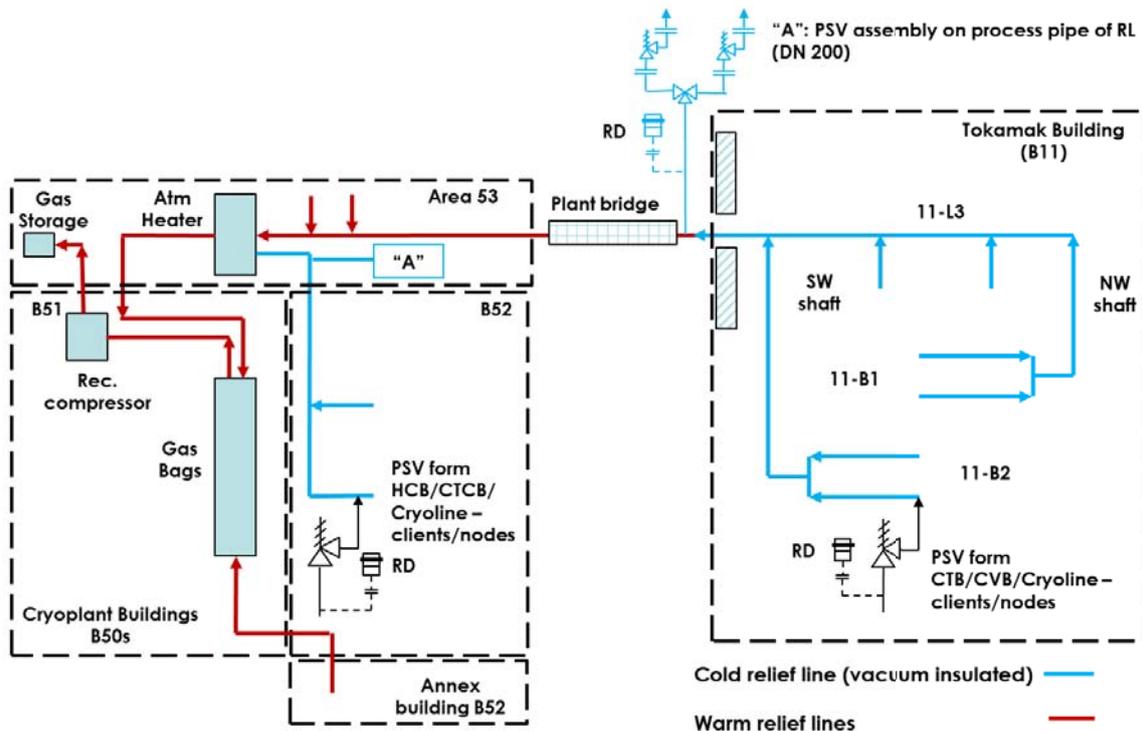


Figure 1. Simplified process flow diagram of RL

The RL is sized mainly to recover the flow due to static heat in leak; site power failure or loss of cooling power (LOCP) event. During the LIV events, the flow is much higher than in other cases and the line will not be able to collect all the flow from the PSVs. In such a case only partial flow is collected, sent back to the heater and the remaining flow is expected to be relieved outside B11 via PSV A (refer to figure 1). The Rupture Discs (RDs) which are sized to take care of fire load case will open to galleries and such helium will not be recovered into the RL. The design pressure of the RL is 10 bar (a), however, in order to reduce the backpressure to the PSVs connected to RL, PSV A is set at 0.3 bar (g). PSV A also helps to limit the quantity of helium to the recovery system. Figure 2 shows the three-dimensional (3D) schematic layout of RL along with Torus and Cryostat CL (TCC).

2. Event description, TCC CL and model set up

The design of the pressure relief system depends on the hazardous events that may lead to a pressure build-up in the cryogenic equipment (relevance vs credibility). It should be sized and selected to cope, at least, with the most relevant event that has the highest probability of occurrence (most credible event). Site power failure or LOCP, LIV in the Tokamak Cryostat (Cr LIV), LIV in the Tokamak Vacuum Vessel (VV LIV), LIV for CLs or ACBs are main scenarios for discharging gas in the RL. LIV of the CL is one of the worst scenarios apart from LIV in ACBs. As per the loads specification of CL [4], LIV of CL is category III (unlikely) event with the occurrence of 5×10^{-3} /year. It is expected that the event may happen once during the ITER life time.

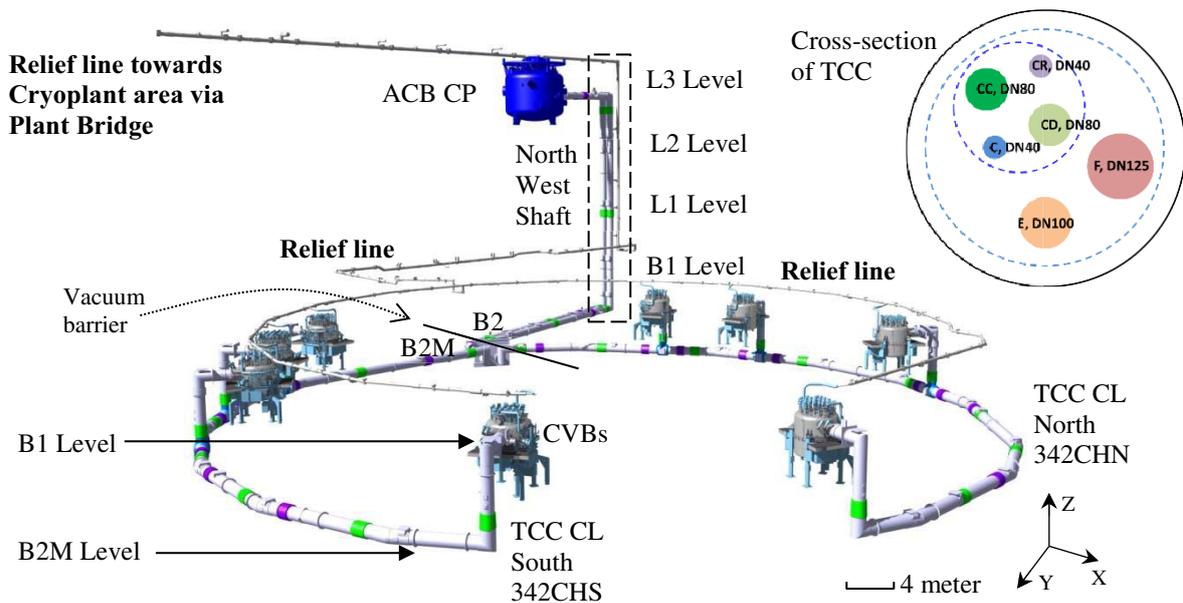


Figure 2. Schematic layout of the TCC CL with Relief line

2.1. TCC cryoline

Torus and Cryostat Cryoline, the TCC is, first CL among ITER complex lines to enter in to design phase and is chosen to simulate the LIV and to study the behaviour of the RL. TCC supplies helium from cryopump ACB (ACB CP at level L3) to the torus and cryostat cryopumps (at level B1). There are two different lines originating from ACB, one forming a semi-circular manifold towards the north designated as 342CHN and the other as 342CHS. Both the lines supplies four cryopumps each (3 torus and 1 cryostat cryopump) and have 6 process pipes (4 at 4.5 K and 2 at 80 K). Table 1 summarizes the functional parameters of the pipes. The length of 342CHN is 156 m (66 m from L3 to B2, 88 m from B2M to B1) and 342CHS is 147m. Both helium LIV and air LIV (with and without fire) have been simulated during this study. Several studies for TCC under LIV event have been performed by the industrial partner. However, the combined behaviour with the RL was not part of those studies due to the scope definitions during project execution. In order to analyse the integrated behaviour of the RL under these events, a dynamic mathematical model was performed using EcosimPro®. The software finds the numerical solution for a set large of algebraic differential equations (DAE). The model created has around six thousand equations with one thousand derivatives. It is composed of simple elements like pipes, valves, fluid sources and sinks. These were either created and validated at ITER organization or used from the cryogenic library Cryolib V1.6 initially developed and validated at CERN and now maintained by the EcosimPro® developer.

Table 1. Functional parameters of TCC CL

Process pipe (PP) description	Normal operation parameters			Pipe Size DN	Design pressure [bar (a)]	Test pressure [bar (a)]	Set pressure	
	Pressure [bar (a)]	Temperature [K]	Flow rate [kg/s]				PSV [bar (g)]	RD [bar (g)]
CC: 4.3 K supply	4	4.35	0.600	80	21	30	20	25
CD: 4.7 K return	3.5	4.7	0.600	80	21	30	20	25
C: 4.6 K SHe supply	5	4.7	0.130	40	21	30	20	25
CR: 5 K cold recovery	5	<6	0.110	40	21	30	20	25
E: 80 K supply	17.5-18.0	81.0	0.380	100	21	30	20	25
F: 100 K return	(17.5-18.0)-1.2	91.0	0.380	125	21	30	20	25
WL : Outer jacket	Vacuum	300.0	N.A.	500	External	N.A.	0.2	N.A.

2.2. Cases studied

The conceptual study showed that with the use of PSV on only one end of the CL, in case of LIV, the pressure in both the process pipes and RL goes beyond their test pressure value. Therefore, it was decided that for the CL longer than ~100 m, PSVs will be installed on both ends of the CL. The typical scheme proposed for the PSVs is shown in figure 3. These PSVs are located on the interface equipment on both end of the CL. For TCC they are located on ACB CP and cryopump Cold Valve Boxes (CVBs). As a general philosophy, it is preferable to have these PSVs on the ACB, which are within the part of cryogenic system (for better interface management). In order to confirm the proposal, the cases and the LIV scenarios detailed in table 2 were studied during the detailed design phase.

There is a vacuum barrier (VB) in TCC between B2 to B2M level (refer figure 4, 5) apart from VB at ACB and CVB. Both B2, B2M areas have different pressures and are different fire sectors. **The penetration between B2 and B2M acts as confinement barrier.** It is considered that only 1 event can happen at a time [4] and due to the presence of VB, the He LIV from L3 to B2 and from B2M to B1 is considered separately. Due to the presence of VB and both being different sectors, air LIV is also considered separately. Therefore, cases 1a, 1b and 2a are not foreseeable during the operation of ITER.

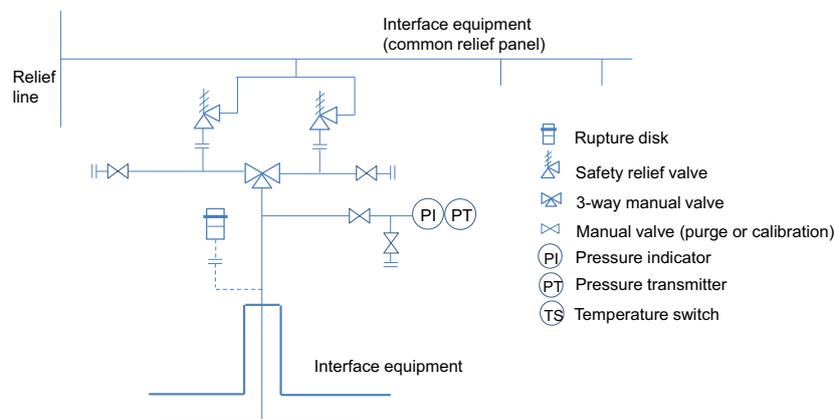


Figure 3. Relief port for the protection of the process pipes (only one process pipe represented)

Table 2. Cases studied in the simulation

Case Sr. No.	Description of the Case	LIV scenarios in TCC				
		He LIV		Air LIV		
		L3-B2+B2M (entire length)	Only B2M	L3-B2+B2M (entire length)	Only B2M	
			With fire	Without fire	With fire	
1	6 PSV of both sides (on last CVB18, ACB CP) of TCC	X [1a]		X [1b]		
2	6 PSV on CVB18 side and 6 RD on ACB CP side	X [2a]	X[2b]		X[2c]	X[2d]
3	2 PSV on CVB18 and 4 PSV/6RD on ACBs					X

2.3. EcosimPro® model

The model has 342CHN process pipes (longest between the two TCC), the PSVs, RDs attached to the process pipes, RL from B1 level until the atmospheric heater and gas bag along with the PSV protecting RL. Figure 4 shows one such model for Case 3 as defined in table 2. Components created in the model can be divided in two groups; (i) Resistive - which calculates mass flow rate using fluid properties and pressure on both sides of the component, namely: PSVs, RDs, joints indicated in colour blue in figure 4

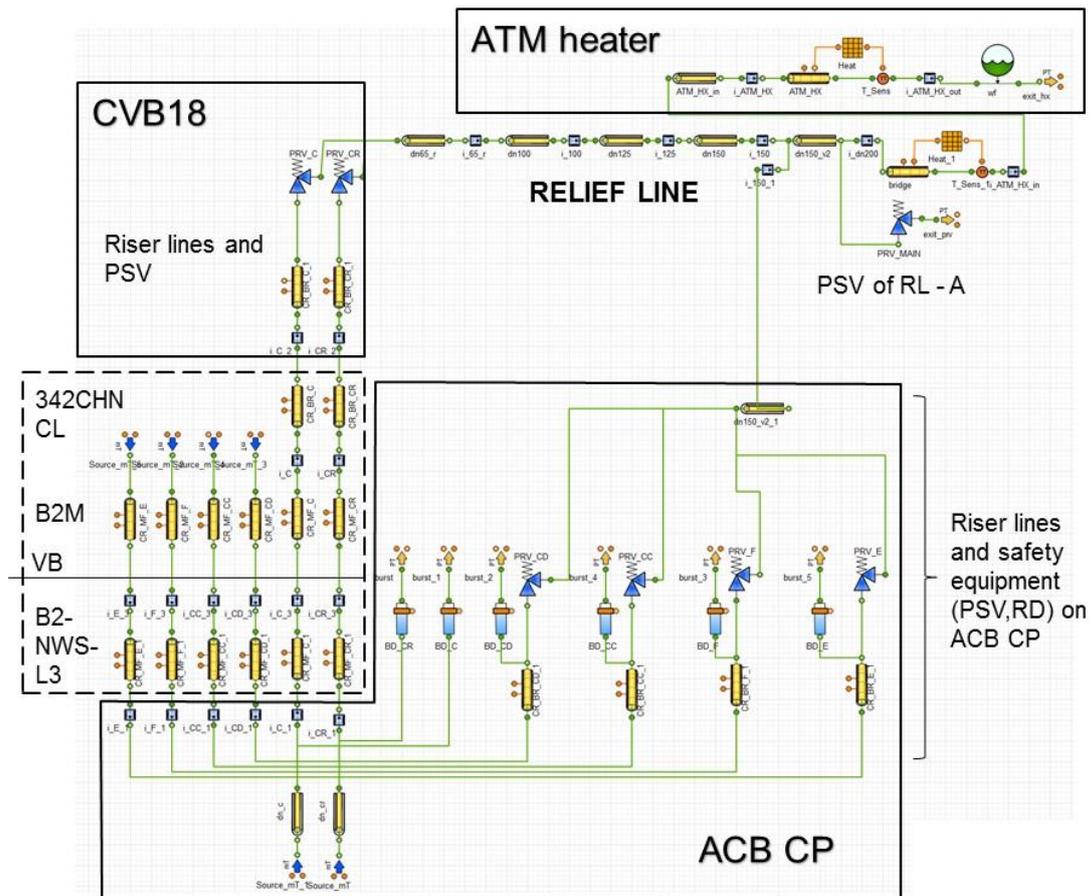


Figure 4. Ecosimpro model (case 3) used for the study

(ii) Capacitive - which calculates pressure using fluid properties and mass flow on both sides, mostly pipes as indicated in colour yellow in figure 4. The model uses full mass, internal energy and inertia balance for each connection. Additionally in case of TCC which is exposed to high heat flux, the line is discretized into 20 control volumes for each PP to calculate mass energy balance between this control volumes to increase accuracy of model during high transients. The model is created for all the three cases as per table 2, they are schematically shown in figure 5.

2.4. Inputs for simulation

During the LIV the heat will be exchanged between outer jacket and the thermal shield, thermal shield and the 4 K PPs. Assuming the PPs at their nominal temperature, the heat transferred during helium LIV event (without fire) is estimated based on flux of 0.6 W/cm^2 for 4 K PPs with Multi-Layer Insulation (MLI) [6] and 0.2 W/cm^2 for 80 K. This heat transferred summarized in table 3, is confirmed from the detailed design performed by the industrial partner (W3, W5, W3a, W5a as per code). The overall heat transfer coefficient and heat flux during air LIV (with and without fire) is estimated using new ISO 21013-3 code. The DN sizes of the PSVs used are estimated based on these heat flux and the TCC parameters from table 1, using codes. In case of fire, it is assumed that the MLI will stay in place since the thermal inertia of the cryoline (outer jacket, thermal shield, process pipes, fixed point etc.) is higher compared to the thermal inertia of helium.

As far as the mechanical criteria is concerned, it has been decided to limit the maximum pressure in process pipes of the CL to the test pressure as allowed by code. In case of RL, being the low pressure line which will be functional every time there is a LIV event in the CL and to limit the back pressure to the PSVs connected to the RL, it is decided to limit the maximum pressure as the design pressure.

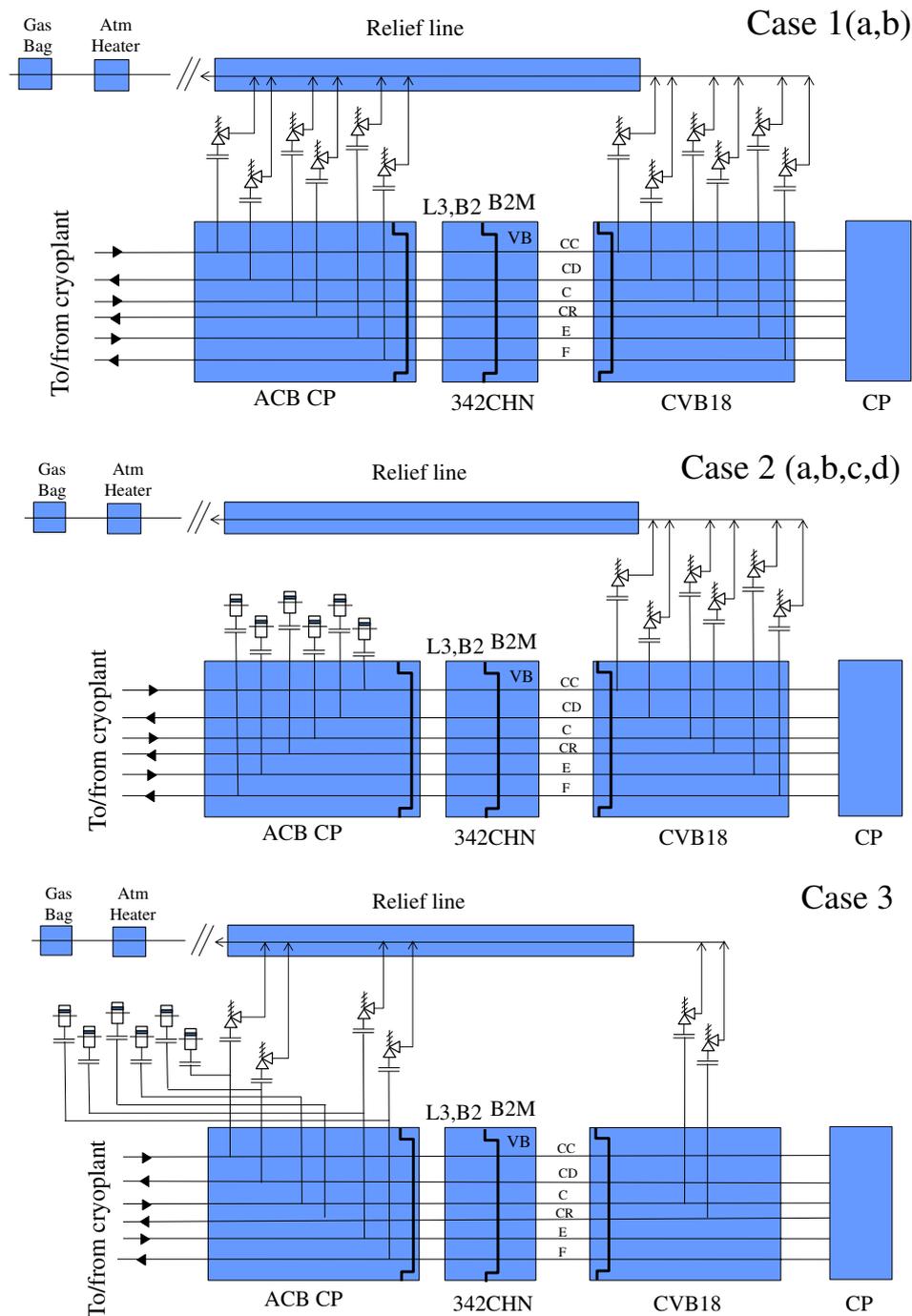


Figure 5. Various cases used for the simulation as per table 2

2.5. Boundary conditions

In general, the only boundary condition which was used are the exhaust to atmosphere which is at 1 bar (a) and exhaust to gasbag which was set to 1.05 bar (a). Both sides of the TCC are closed means zero flow in both directions simulating closed process or isolation valves in ACB and CVBs which in reality will be closed as soon as the LIV will be detected. Initial conditions in the model for TCC is as per table 1 and the RL is at 1bar (a) and 300 K.

Table 3. Heat transferred estimated using code, used in the simulation

Process pipes (PPs)	Heat transferred during He LIV (kW)		Heat transferred during Air LIV (kW)		
	L3-B2+B2M (entire length)	Only B2M	L3-B2+B2M (entire length)		Only B2M
			With fire	Without fire	
CC/CD	287	162	652	170	407
C/CR	139	79	361	94	225
E	366	206	588	48	368
F	273	153	589	47	368

3. Results and discussion

It is observed that, since the heat flux due to LIV is very high, the pressure in 4 K pipes reaches to 20 bar (g) (PSV set pressure) within 3-6 sec. There is not much difference in the time to reach the PSV set pressure, in case the heat flux is applied on the wall of process pipes instead of helium.

At the beginning, Case 1a, He LIV for the entire length of the TCC is analysed. It was observed that the maximum flow upstream PSV A is ~11 kg/s which is beyond the capacity of the recovery system and can have adverse impact on it. The maximum pressure values in PP of TCC are below the test pressure. The maximum pressure in the RL is 8.2 bar (g) which is below its design pressure and acts as the back pressure downstream the PSVs. **In case of air LIV with fire (1b)** for entire length of TCC, both the maximum pressure in process pipes of TCC as well as RL goes beyond the respective test pressures.

In the next step, to reduce the quantity of flow to the recovery system and to limit the pressure in the process pipe, PSVs on ACB side are replaced by RDs (Case 2). As summarized in table 4, it can be seen that for all the 4 possible scenarios in Case 2, the maximum pressure in RL as well as TCC process pipes stays below the design pressure and test pressure respectively.

In order to reduce the equipment at CVBs (project requirement), in Case 3, the PSVs on CVB side are moved to ACB side where it is easier for interface management as well as maintenance. Only air LIV + fire scenario (with maximum flux) has been studied in this case. Here as well, the maximum pressure in RL as well as TCC PPs stays below the design pressure and test pressure respectively.

The minimum temperature of the RL is 10 K in all the cases.

It is also observed that the PSV of the RL opens after 2 seconds of opening of PSVs of TCC and relieves the helium to the atmosphere in all the cases.

Table 4. Summary of results from EcosimPro® simulation

Cases/ Scenarios	Maximum pressure in process pipes (first 25 sec)			Maximum pressure in RL PP (bar)	Minimum temp of RL in B11 (PSV entry node at CVB/ACB) (K)	Minimum temp of RL along the length in B11 except entry nodes at CVB/ACB (K)
	(bar)	(bar)	(bar)			
	CC/CD	C/CR	E/F			
1a	28	28	23	8.2	10/50	10
1b	>30	>30	>30	>10	10/10	50
2a	26	26	22	6.2	10	120
2b	25.5	25.5	20	5.6	10	125
2c	25.5	25.5	18	6.7	10	125
2d	26	27.5	21.5	8.2	10	100
3	26.5	27.5	21.5	7.6	10/50	100

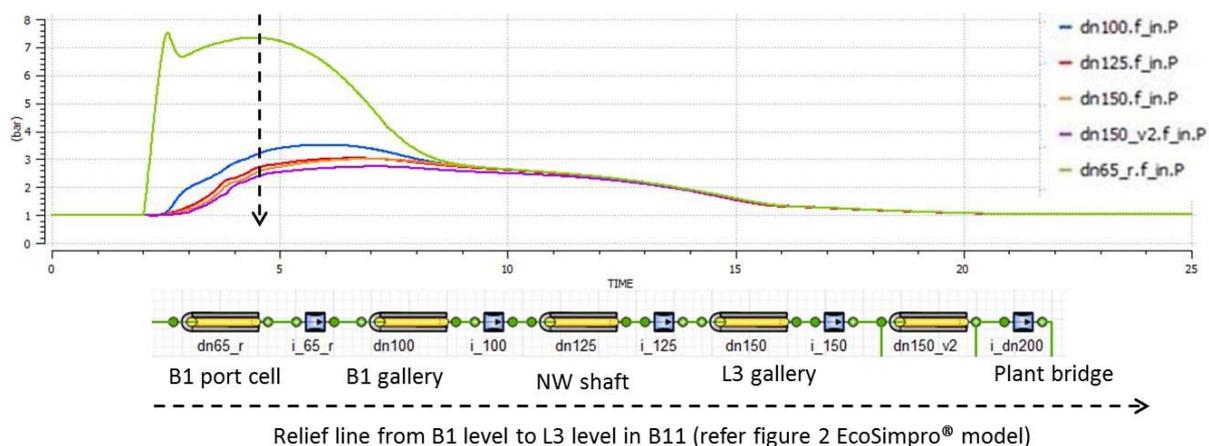


Figure 6. Pressure variation along the length of RL

4. Conclusion

The integrated simulation of LIV events in one of the ITER CL and behaviour of the RL under those scenarios have been studied. The study confirms the conceptual proposal of installation of the PSVs on both ends of the CL. It was necessary to verify the RL behaviour before finalizing the optimized location of PSVs/RDs. From the results, it can be concluded that, during LIV of TCC the pressure inside the RL will stay within the design pressure and the pressure in TCC PPs will stay within the test pressure. The chosen option with only two PSVs on CVB and four remaining PSVs, six RDs on cryopumps ACB satisfies all the design requirements defined for both the TCC and RL. This option is now being used for the manufacturing and installation of the respective interfaces. Similar studies are planned for the other CL's.

Acknowledgments

Authors would like to thank the colleagues from ITER-India in Gandhinagar, India and ITER Organization in St. Paul Lez Durance - France as well as industrial partners namely Air Liquide Advanced Technologies (ALAT), France and INOX India Limited as well as its consortium partner A S Scientific Products, UK for their contribution to ITER Cryolines project.

Disclaimer

The views and opinions expressed herein do not necessarily reflect those of the ITER Organization and ITER-India.

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