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Theoretical and Experimental Simulation of Accident Scenarios of the JET Cryogenic Components

Part II: The JET LHCD Cryopump

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Abstract:

A flexible mathematical model has been developed to simulate the transient thermal response of a number of nuclear fusion components, including cryogenic devices which operate inside the JET Tokamak. The present work reports on the simulation of an accident scenario, as well as on further studies on hypothetical off-normal scenarios concerning an out of vessel cryopump. These studies resulted in a complete safety protection system for the LHCD cryopump which has been implemented into the JET operating routines.

Keywords:

JET Tokamak, nuclear fusion, LHCD cryopump, modelling, safety, latent heat, freeze-up.

Abbreviations

JET Joint European Torus

LHCD Lower Hybrid Current Drive

LN Liquid Nitrogen

LHe Liquid Helium

1. INTRODUCTION

One of the ancillary systems in JET is the Lower Hybrid Current Drive (LHCD) waveguide assembly. It generates electromagnetic waves to drive currents in the plasma. The operation of this system requires a pumping unit to remove the gases created by electron and ion impact in the waveguides, which could otherwise cause electrical breakdowns (**1**). The whole assembly is illustrated in Figure 1.

The LHCD cryopump, which is installed outside the JET torus, has an overall height of about 3 m and diameter of about 1.5 m. Figure 2 indicates the Liquid Helium (LHe) and Liquid Nitrogen (LN) subsystems together with the water circuit of the LHCD cryopump. The pumping unit is attached to a hot launcher, which sends electromagnetic waves into the JET Tokamak. The launcher can be baked up to $\leq 450^{o}$C in operation. In case of a loss of coolant flow event, the water cooled circuits of the LHCD cryopump are at risk of boiling or freezing (depending on the boundary conditions) due to their proximity to the cold LN structure and the hot launcher.

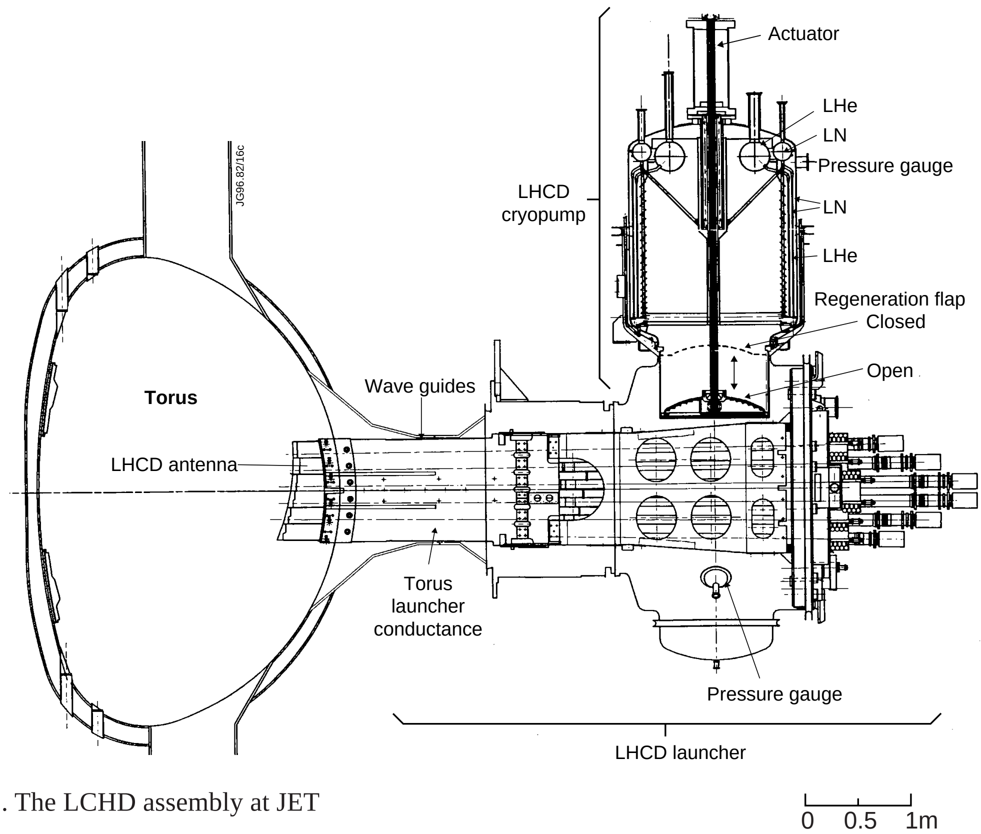


Figure 1. The LCHD assembly at JET

The LHCD cryopump is isolated from the torus chamber by its regeneration flap, which is water cooled. The flap, when in closed position, allows the pump to be kept operational and filled with LHe, both under glow discharge cleaning conditions and regeneration of the in-vessel divertor cryopumps (see (**2**)). These two processes produce pressures high enough to warm up the LHCD LHe panels. The flap also allows the regeneration of the LHCD cryopump without affecting the torus operation.

The measured pumping speed of the LHCD cryopump is 105,000 ls^{-1} ± 15% for Deuterium, D_2 (**3**).

2. GEOMETRY OF THE LHCD PUMP

The LHCD cryopump has been designed by the JET Cryogenics Group and manufactured by L'Air Liquide, France. The main parts are (see Fig. 2): the LN and LHe panels, the actuator, the vertical water cooled pipes which supply the flap at the bottom, and the separate water circuit which cools the grill and the external shield. The following paragraphs give a description of the cryopump to familiarise the reader with the parts studied in this analysis. For further details refer to (**4**), which contains an extensive description.

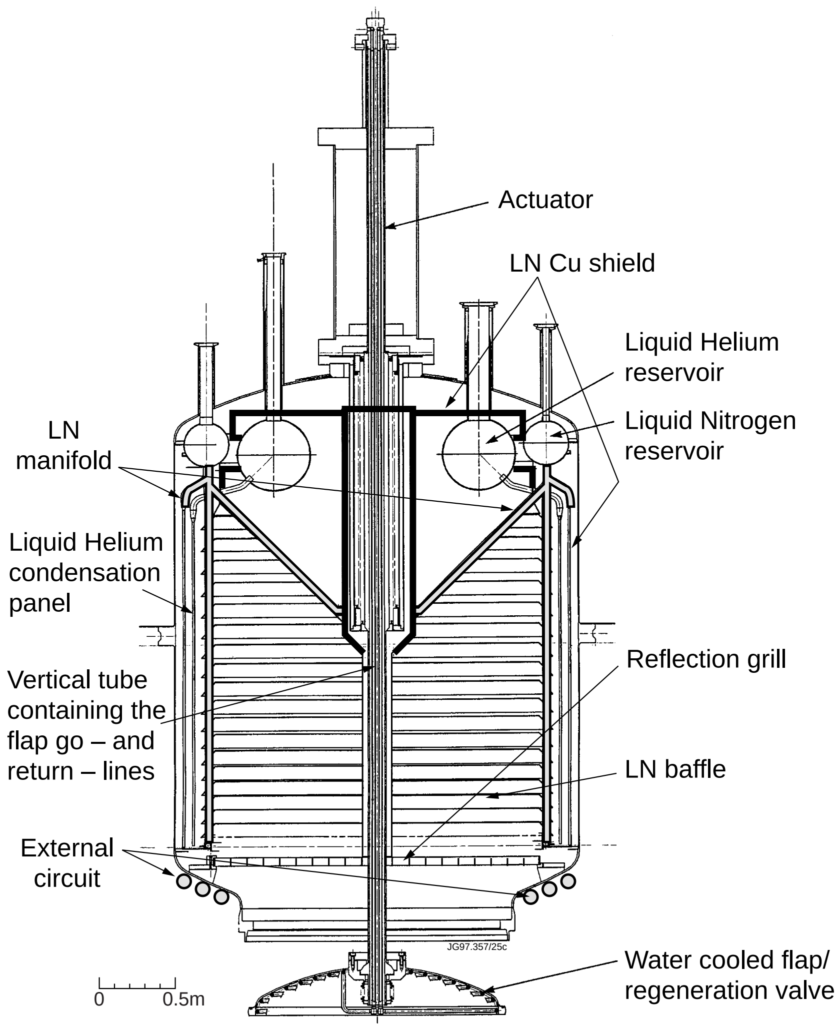


Figure 2. The LHCD cryopump

2.1 Cryogenic panels

The LHe structure consists of a cylindrical stainless steel condensation panel which is silver coated on both sides in order to minimise surface emmissivity. The LHe reservoir is at the top with a content capacity of 60 *lt.* The LHe cooled cryopumping surfaces are completely enclosed by a LN radiation shield to minimise thermal losses.

The LN panels can be divided into two parts: 1) the internal LN baffle, and 2) the LN radiation shield. The LN baffle is a cylindrical finned structure, made from blackened copper. It is brazed onto 6 equidistant stainless steel tubes, which are fed from a LN ring manifold, situated at the top of the pump (see Fig. 2).

The LN radiation shield is a thin (2 mm) curved copper (Cu) plate which is attached to the LN manifold. Due to its high thermal conductivity the copper plate has the same temperature as the

LN panel, and during operation it offers thermal protection to the LHe surfaces and reservoir at the top part of the pump. The complete cryopump is enclosed in a vacuum enclosure of about 1.5 m diameter and 2 m height. The cylindrical part is closed at the top with a dished end which incorporates the cryo-supply ports, the flap actuator, and the electrical feedthroughs for the instrumentation.

2.2 Water cooled circuits

The cryogenic panels are protected thermally by two separate water cooled systems. The first one includes an external shield and a reflection grill at the bottom of the pump which are cooled in series, and the second includes the flap and the vertical pipes.

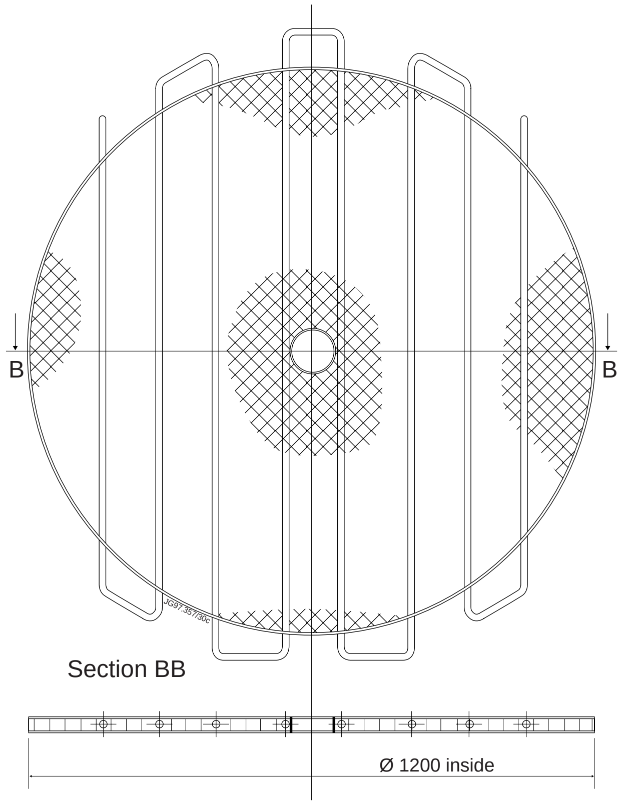
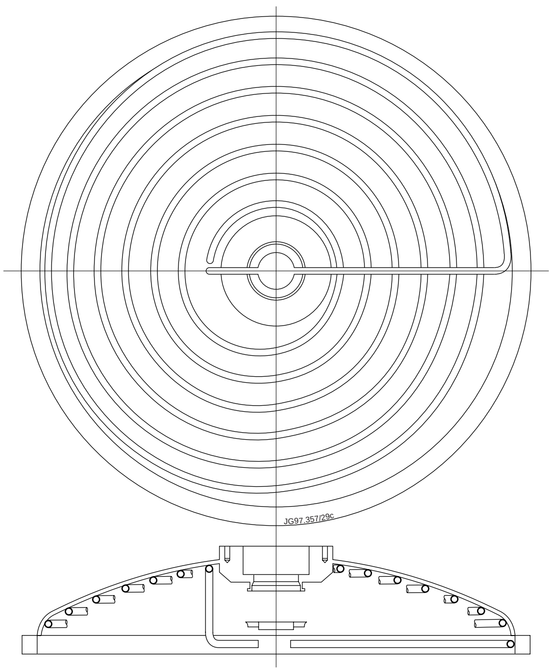


Figure 3. The LHCD reflection grill



The reflection grill (Fig. 3), reduces the thermal radiation from the flap to the LN structure and reflects radio frequency waves which may heat the inner structure of the pump (**1**). The grill consists of a blackened copper grid with square openings of, 31x31 mm and 22 mm high, and it is water cooled by cooling pipes brazed on the grid. The external shield (see Fig 2) protects the outer bottom part of the cryopump from the relatively hot launcher on which the cryopump is located. The external shield and the pipework of the reflection grill are water-cooled in series.

Figure 4. The LHCD flap

The flap (shown in Fig. 4) is a stainless steel dished end with brazed cooling pipes at the bottom surface. It is fed separately from the top of the pump by a vertical stainless steel pipe (the go-line). The cooling water returns via another vertical pipe (the return-line), see Fig. 2. Both the go- and return- lines are inside an evacuated stainless steel tube which can be moved up and down (at a stroke of about 500 mm) by an pneumatic actuator. The flap is attached mechanically to this tube and follows its vertical movements, allowing the cryopump to be isolated from the launcher when necessary. However, the flap itself is not vacuum isolated from the launcher, and consequently the pressure conditions inside the flap/ tube are almost the same as those which prevail in the launcher and the torus vacuum vessel. On the other hand, the outermost surface of the tube is exposed to relatively low temperatures since it is enclosed by the LN copper shield at a distance of 22mm and for a height of about 1.5 m.

3. INSTRUMENTATION

A series of sensors are mounted on various parts of the LHCD cryopanels. In particular: temperature sensors (eight on the LN and five on the LHe panel), level sensors (four in each the LN and LHe structure), pressure transducers (five) as well as rupture discs (three).

4. REAL ACCIDENT SIMULATION

On 22/6/94, a loss of water flow accident took place without fast draining. The sequence of events was as follows: The LHCD cryopump was at operating temperature (ie, ~77K and ~4K for the LN and LHe panels respectively) and the flap was in the closed position. The vacuum inside the cryopump was high (i.e. > 40 mbar) and the existing safety system automatically stopped the supply of the cooling water, but did not drain it. In addition, the LN supply was not stopped until 30 min after the initiation of loss of water flow. By this time, the water circuits had already become blocked due to freezing. The ice finally melted after around 80 hours and the whole process was recorded by the JET data acquisition systems.

In order to simulate the above accident and to predict possible boiling and freeze-up time constants, of the water cooled circuits, under all possible boundary conditions, the thermal model developed for the JET in-vessel cryopump (**2**) was modified to account for the LHCD geometry. In (**2**) phase changes were not allowed to occur so that higher safety margins would be obtained. However, in this accident scenario a change of phase is known to occur (water freezing in the supply pipes) and therefore the model needed to be modified accordingly.

5. BOUNDARY CONDITIONS

The evacuated tube which contains the vertical pipes is exposed to the LN surfaces for a vertical height of about 1.5 m. For this reason the heat loss from the pipes to the LN panel is affected by the temperature of the latter and by the vacuum conditions. Since there were no sensors on the water cooling circuit of the pump the only recordings which could be used were those of the cryogenic panels. The accident simulation analysis mainly considers the measurements of the LN temperature sensors which are situated at the bottom of the pump and therefore are closer to the exposed part of the vertical tubes.

Conduction between the flap and the pipes is included in the accident simulation, the flap being warmer because it faces the hot launcher. Because the launcher surrounds almost half of the cryopump's cylindrical vessel, see Fig. 1, its temperature is an important input parameter. In the following analysis it was taken to be 150^{o}C. The effect of launcher temperature on the results is examined in Section 7. The temperature of the water cooled circuits was assumed at 20^{o}C at the initiation of the loss of flow accident, while the cryogenic LN panels were assumed to be at 77K initially.

The torus vacuum was good (i.e. $< 10^{-6}$ mbar) and therefore the vacuum inside the evacuated tube and the vertical pipes was also considered good (since the same vacuum conditions exist on these two parts). It is assumed that the launcher vacuum is the same as the torus vacuum (there are some differences between them but during the event both were below the value of 10^{-6} mbar).

The vacuum inside the LHCD pump was recorded as bad (> 40 mbar). The model assumes air circulating inside the pump at a pressure of 40 mbar, apart from the vertical pipes which have the torus vacuum. Although the launcher and torus vacuum are good when the flap is in the closed position, the LHCD cryopump is isolated from the launcher and therefore separate vacuum conditions can exist. However, the flap was opened about 50 min after the initiation of the event to increase the temperature of the water cooling circuit. From that time onwards the LHCD cryopump had good vacuum, because with an opened flap the torus vacuum condition prevails. All these events were incorporated into the simulation of the accident.

6. ANALYSIS

The freeze-up incident occurred because the stagnant water was not drained. LN flow continued 30 min after the loss of water flow and the ingressed air (at 40 mbar) was removing heat from the cooling circuits for almost 50 min (until the flap was opened). The leak medium was at very low temperatures due to the cold LN surfaces.

Figure 5 shows the comparison between the experimental data (with ± 5% temperature signal error (**6**)) and the predicted temperature evolution of the LHCD LN panel and vertical water cooled pipes. The agreement between the theory and the measurements of the LN circuit warm-up is good considering the large time constant. Although the grill and flap froze first followed by the vertical flap and supply pipes the warm-up time constant is dominated by the vertical supply pipes. The freeze-up and the subsequent warm-up of the vertical water supply pipes is therefore illustrated in Fig. 5.

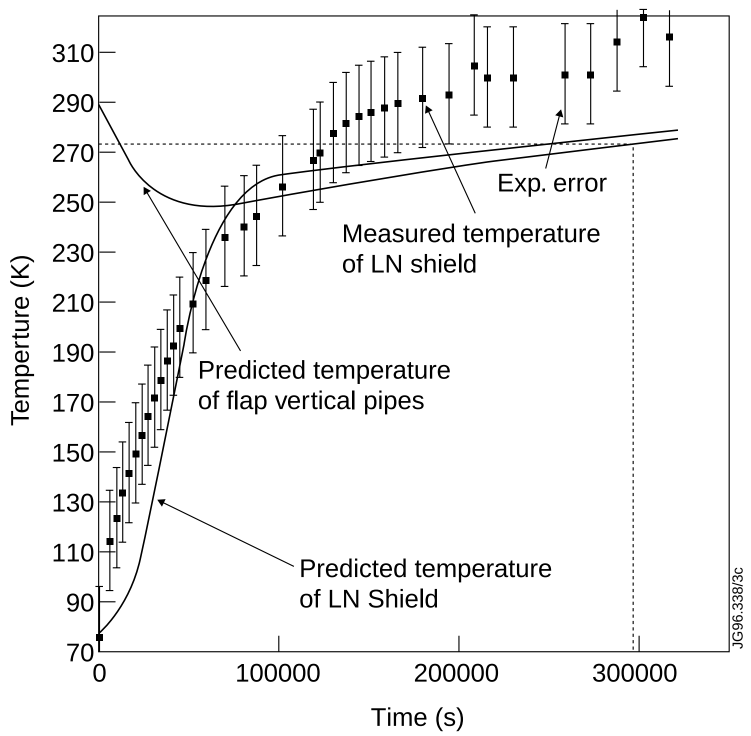


Figure 5. Comparison between model prediction and measurements of the LHCD cryopump system during a freeze-up incident.

It may be seen that the model predicts initiation of freeze-up (i.e. water temperature < 0^{o} C) at about 2000 seconds and warm-up (i.e. water temperature >0^{o}C) at 300000 seconds. These predictions are in agreement with the observations made during the accident. The controlling parameter of the phenomena involved is the latent heat of the cooling water both during freezing and melting. Almost two thirds of the transient time-interval (ie from 10000 sec onwards) is consumed for the water phase change, from solid to liquid.

The ability of the model to simulate a real loss of water flow accident in a geometry different from that for which it was originally developed demonstrates its flexibility and increases confidence in the results.

Figure 6 highlights some details of the freeze-up incident as predicted by the model. Figure 6(a) illustrates the onset and full freeze-up of the flap and grill and Fig. 6(b) shows the result for the supply pipes for the case of good and bad vacuum. The calculation of full freeze up is based on the latent heat of the water.

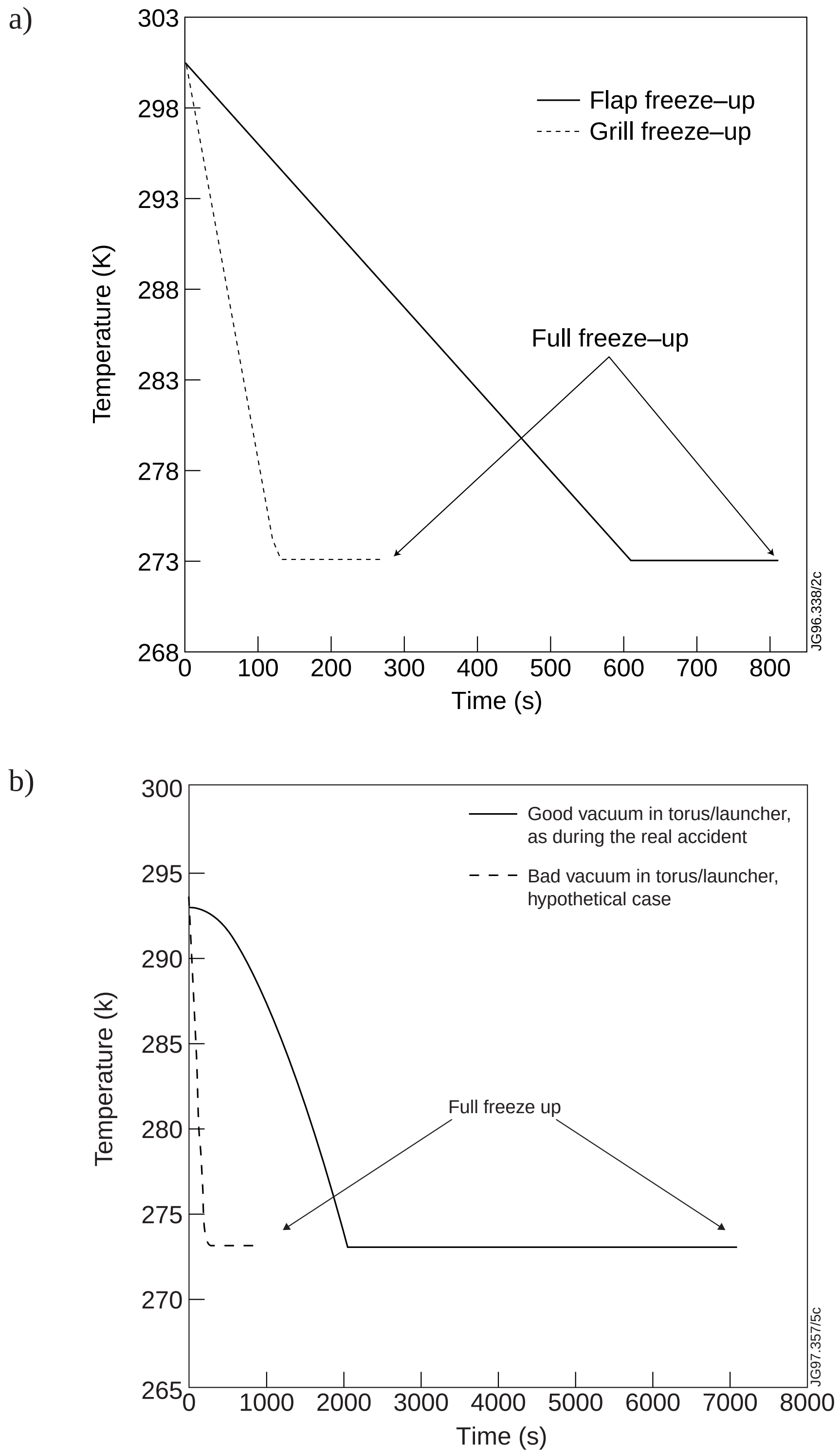


Figure 6. Predicted freeze-up of LHCD components (a) flap and grill of the cryopump (b) flap supply pipes.

The model of Part I (**2**) is modified to incorporate the effect of latent heat effect as follows: The thermal behaviour of the fluid is calculated as before (**2**). When the transient temperature reaches a phase change point (e.g., 0^{o}C for a liquid to solid change at 1 bar) a subroutine is activated requiring a value of the medium's latent heat and mass. The simulation then continues with the temperature unchanged until the heat flux becomes equal (within a specified tolerance) to the given latent heat, over a time interval. At the end of this interval, the phase change is deemed to have occurred and the temperature is allowed to vary according to the prevailing conditions.

7. SIMULATION OF HYPOTHETICAL ACCIDENT EVENTS

Following the simulation of a real accident the model was used to predict freezing or boiling time constants at different parts of the system under different boundary conditions.

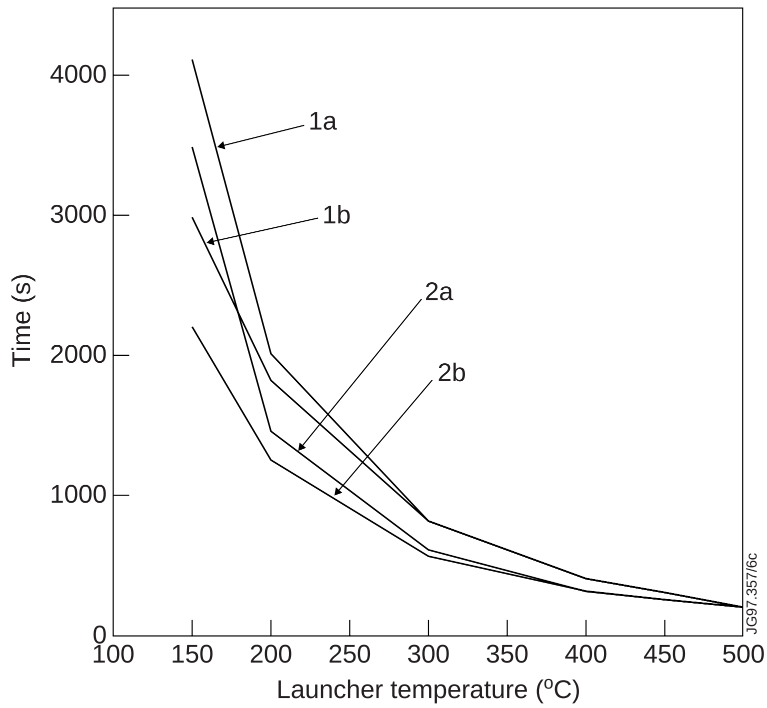


Figure 7. Boiling times of the LHCD flap versus launcher temperature in a hypothetical loss of water flow incident. (For curve labels see text).

Figure 7 illustrates the boiling risk of the LHCD water cooled flap, against launcher temperature, should there be a loss of water flow event and without draining action taking place. A number of different cases are considered. The curve labelled 1a corresponds to the case when the flap is open and LN flowing . Curve 1b illustrates the case when LN panels are at ambient temperature (i.e. empty of cryogens). In the latter case boiling occurs more quickly until the launcher temperature reaches 300^{o}C. For temperatures beyond 300^{o}C the effect of the LN flow on the boiling time is negligible. The curve labelled 2a represents the case when the flap is closed, LN is flowing and there is good vacuum in the pump, but loss of torus vacuum (air at 1 bar). Finally curve 2b demonstrates the boiling time constants when there is an additional loss of vacuum inside the LHCD pump. For launcher temperatures higher than 200^{o}C, the boiling time constants are shorter in the last two cases due to the enhanced convection heat load from the gas leaks. However, when the launcher is at 150^{o}C boiling starts somewhat earlier in case 1b than in case 2a, because the radiant heat from the relatively hot LN panel in the former case counterbalances the convective heat load.

			Separate circuit	**One circuit**	
Vacuum in the LHCD	Torus Vacuum	Flap position	Grill time constant (s)	Flap time constant (s)	Vertical pipe time constant (s)
Bad	Good	Closed	*Freezes* **120**	*Freezes* **600**	*Freezes* **2000**
Bad	Bad	Closed	*Freezes* **500**	*Boils* **2200**	*Boils* **10960**
Bad	Bad	Open	*Boils* **2900**	*Boils* **1100**	*Boils* **12600**
Bad	Good	Open	*Not realistic*	*Not realistic*	*Not realistic*
Good	Good	Closed	*Freezes* **600**	*Freezes* **5700**	*Freezes* **3200**
Good	Bad	Closed	*Boils >* **12000**	*Boils* **3500**	*Boils* **1700**
Good	Bad	Open	*Not realistic*	*Not realistic*	*Not realistic*
Good	Good	Open	*Boils >* **13800**	*Boils* **4100**	*Boils >* **14000**

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Table 1. Freeze up and boiling time constants for the LHCD Grill, Flap and vertical supply pipes, with total loss of water flow, the launcher at 150^{o}C and the cryopump cold.

* with the flap in the open position it is assumed that the torus vacuum pumping system is able to pump out a possible leak in the LHCD pump.

** with the flap open and bad torus vacuum the LHCD has also bad vacuum conditions, since the small capacitance LHCD cryopump is not able to remove a possible torus leak.

A set of time boiling - freezing time constants is given in Table 1. The main parameters are: the LHCD vacuum, the torus vacuum and the flap position, which defines the heat load and the pump pressure conditions (i.e., with the flap open the LHCD vacuum is identical to the torus vacuum). “Good vacuum conditions” means pressure lower than 10^{-3} mbar while “bad vacuum implies pressures higher than 10^{-3} mbar.

With regard to freeze-up risks and with launcher temperature higher than 150^{o}C, the time constants given in Table 1 will increase. So, if the cryopump is safeguarded against freeze-up risk according to Table 1, the system should be protected adequately. From Figure 7 and Table 1 it becomes apparent that when the launcher is very hot, boiling can occur within 7 minutes of the loss of water flow. This implies that if water flow stops accidentally it should be reinstated within 7 minutes in order to avoid any boiling risk. The implemented protection systems allow the detection of spurious alarms within the above time constant.

8. CONCLUSIONS

This work examines the behaviour of the JET LHCD cryopump under accident conditions. It extends the model developed in (**2**) for the analysis of the JET in-vessel cryopump to a component with different geometry and operating conditions. An accident scenario has been simulated and good agreement between the model and observations was found. Subsequently recommendations for the operation of the LHCD device have been proposed.

ACKNOWLEDGEMENTS

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