The Model & Experimental Basis for the Design Parameters of the JET Divertor Cryopump Protection System including variations in Divertor Geometry & First Wall Materials

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ABSTRACT

A large In-Vessel Cryopump has been operational for several years as part of the JET Pumped Divertor. A model has been developed to analyse the behaviour of the Cryopump under all possible operating or fault conditions, and a suitable Protection System has been defined and implemented. It protects the Cryopump system during baking, "restart", normal operation, glow discharge cleaning, loss of vacuum, loss of cryogens or water flow (in the associated water cooled components). It ensures that no excessive thermal stresses are generated and no freezing or boiling occurs in the neighbouring water cooled components.

The model has been validated through a series of experiments and applied to other Cryopump devices at JET. A freeze-up incident that took place at the early operating stages of the LHCD Cryopump was well simulated.

The In-Vessel Cryopump Protection System has been adapted to respond to changes in the First Wall Material (C, Be) and Divertor Geometry.

1. INTRODUCTION

The large In-Vessel Cryopump system (Figs 1 and 2) has been operational for several years and greatly assisted the JET experimental programme [1], [2]. It demonstrated active density control of the plasma, and contributed in the production and operation of detached plasmas and high fusion performance [3].

The Cryopump system has been highly reliable, while the incorporation of a Cryopump inside the Vacuum Vessel, introduced no significant restrictions in the operations of JET. This was achieved because in the design, manufacture and installation phases, special attention was paid not only to the normal operation requirements, but also to accident scenarios. Under normal operation, the Cryopump has to cope with considerable thermal stresses and eddy currents. In addition, the system should be protected against accidents/abnormal events, like loss of water flow, cryogen flow and/or vacuum. During these events thermal stresses and water freeze-up or boiling (due to the hot Vacuum Vessel) are possible.

The introduction of special design features minimised thermal stresses and removed the need for controlled cool-down or warm-up of the system and for restrictions in the Vacuum Vessel temperatures during baking or normal operation [2].

Despite all these efforts, the Cryopump system is not inherently safe and a Protection System has been designed and implemented. This Protection

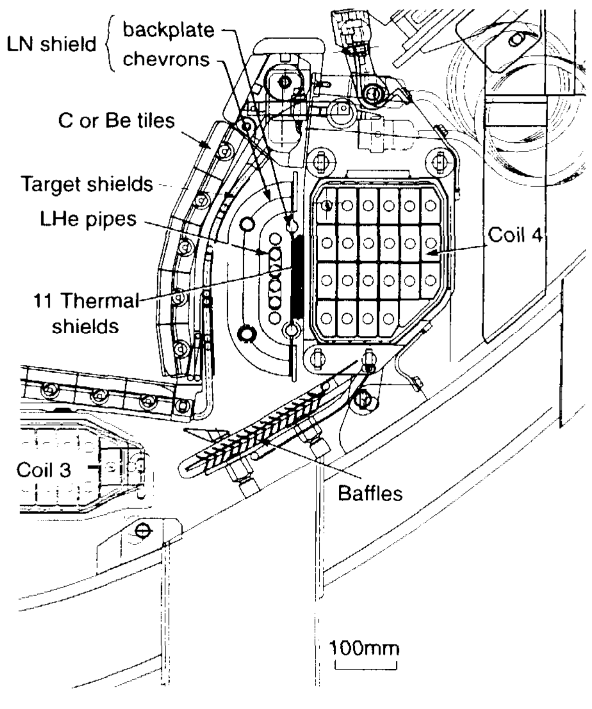

Fig 1. Cross section of the JET MK1 Divertor Cryopump system and its surrounding components

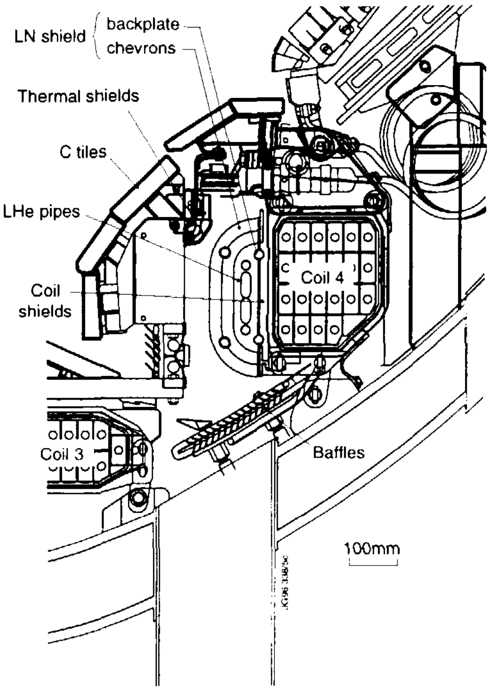

Fig 2. Cross section of the JET MK 2 Divertor Cryopump system and its surrounding components.

System assures that no excessive thermal stresses are generated during abnormal events and controls the draining and refilling of the water circuits within specific time constants, in order to avoid water freeze-up or boiling which may stress the pipework and lead to component failure. The equations that determine the system behaviour during the abnormal events are general, developed from first principles and therefore they can account for variation in the Divertor Geometry, First Wall material and can be applied to other Cryopumping devices at JET (LHCD Cryopump).

2. MODEL & EXPERIMENTAL BASIS

The mathematical model which simulates the system behaviour during the abnormal events together with the experimental validation have been published in Reference 1. The equations are basically heat transfer equations which calculate the bulk transient temperatures of the several system components. They account for all three modes of heat transfer and are solved with a step-by-step integration method. High levels of agreement have been achieved between the model predictions and experiments done either inside the Vacuum Vessel or in a test tank, outside the Machine to allow the safe simulation of abnormal events [1].

Due to the nature of the equations involved, the model can be adjusted to predict the heat transfer behaviour of other Cryopumping (or general heat transfer) devices at JET.

Figure 3 shows the JET LHCD Cryopump. The water circuits of this components are in danger of freeze-up or boiling (from the hot Launcher) should the water flow fail and the system is not drained fast enough. During the early stages of commissioning of this Cryopump a freeze-up incident occurred and the system took a very long time to recover.

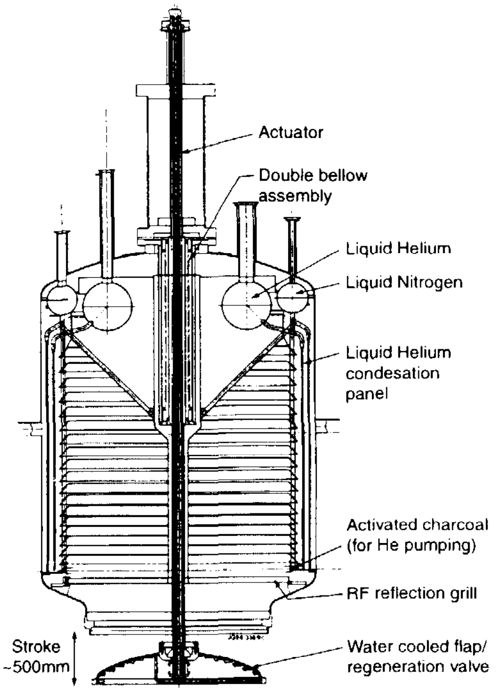

Fig 3. The JET LHCD cryopump.

Figure 4 shows the simulation of this event by the heat transfer model. There is good agreement between the predicted and measured temperatures of the Liquid Nitrogen (LN_2) shield during the long recovery of the system.

Figure 5 indicates in detail the predicted freeze-up time constants during the incident and shows that freeze-up events can be very fast indeed.

3. THE DIVERTOR CRYOPUMP PROTECTION SYSTEM

Following computer simulations, using the heat transfer model, of all possible accident events in the Divertor Cryopump components, a suitable control Protection System has been implemented. This acts as follows:

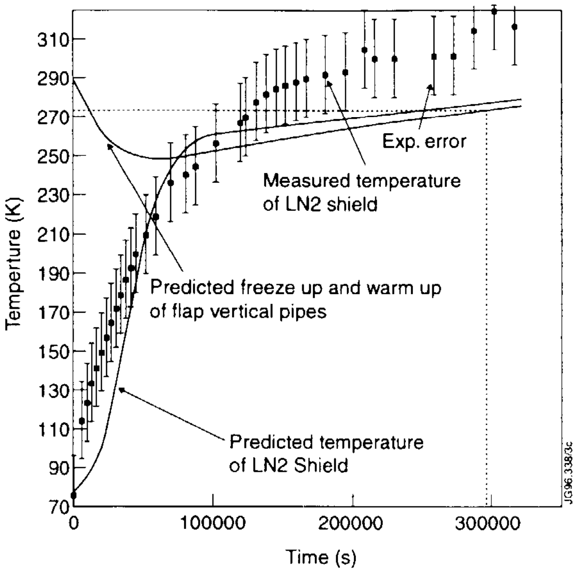

Fig 4. Comparison between model prediction and the LHCD cryopump system behaviour during a freeze up incident.

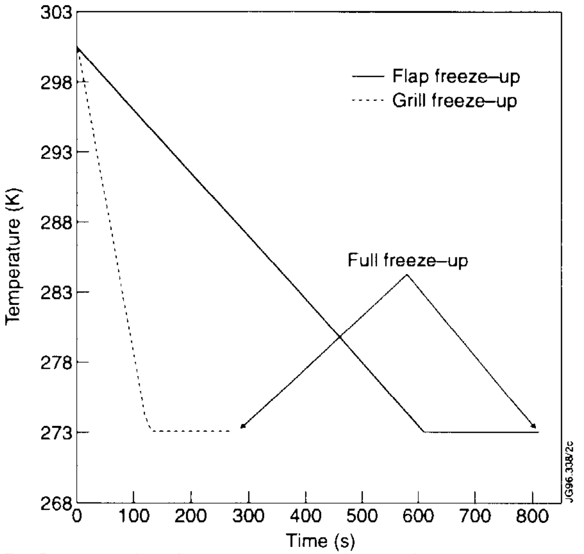

Fig 5. Predicted freeze up of Flap and Grill of LCHD cryopump.

a) It does not permit operational modes which could potentially result in excessive thermal stresses. For example, it does not allowthe cryopump cooldown, prior to the water introduction inside the Vacuum Vessel, if the Vessel temperature is higher than 100°C.

b) It requests stop of LN_2 flow after a period of time, following a complete loss of water flow inside the Vacuum Vessel, in order to avoid potentially excessive thermal stresses in the LN_2 circuit of the Cryopump

c) It controls draining and refilling of the water circuits within specific time constants to avoid water freeze-up or boiling with loss of water flow.

3.1 Effect of First Wall Material

During the 1994-95 Experimental Campaign, JET operated with two First Wall Materials, C and Be. The emissivity and other properties of Be differ significantly from C. Therefore the mathematical model simulated all abnormal events which are influenced by the different properties of Be. The new First Wall material affected mainly the target shields (Figure 1) behaviour and freeze-up time constants altered. With Be, freeze-up was much faster (within ~200s) while with C considerably slower (~1000s), in the case of loss of water flow and bad vacuum. This was expected since the high emissivity of the hot C delays the onset of freeze-up.

It was thus necessary to recalculate all new accident time constants and make sure that the draining and refilling of the water circuits was compatible with these new restrictions.

3.2 Divertor Geometry

During the 1995-96 shutdown a new Divertor Geometry was installed inside the Vacuum Vessel. This new geometry affected the heat transfer equations of the Protection System. For instance different view factors and different component emissivity in the boundaries affect the exchanged radiated power. In addition it was realised that thermal shields, Fig 2, would significantly improve the system protection against freeze-up incidents. These thermal shields were indeed incorporated and designed to withstand eddy currents and maximise the heat transfer benefit.

With the new In-Vessel Geometry (Fig 2) all abnormal events were re-evaluated and found that:

a) Baking of the systems is not affected, when compared with the MK1 configuration. (Fig 1).

b) The Cryopump and Baffles operational behaviour do not alter significantly i.e. the Cryopump can be baked and operated, following water introduction inside the Vessel, with Vessel temperatures up to 350°C without any restrictions. The Cryopump can withstand any accidents under these conditions.

c) Following loss of water flow in the Louvre, water boiling can occur within ≥6 min depending on the boundary conditions

d) After loss of water flow in the Baffles, freeze-up can occur within ≥20 min (with Vessel at 20°C) or boiling after ≥ 12 min (with Vessel at 320°C) depending again on the boundary conditions.

After the 1996 Experimental Campaign, JET will again alter the Divertor Geometry through a remote handling In-Vessel intervention due to the high radiation levels of the vacuum vessel after the D-T experiments in 1996-1997. The Divertor Cryopump Protection Control System is able again to account for such a change in the Divertor Geometry.

4. DRAINING AND REFILLING OF WATER CIRCUITS

The Divertor Cryopump Protection System requests draining of the water circuits after loss of water flow, to prevent water freezing or boiling. This draining is rather difficult due to the complex In-Vessel Geometry, which incorporates horizontal pipes in parallel. An analysis has therefore been undertaken to determine the minimum percentage of a horizontal pipe cross-section that needs to be drained in order to avoid plastic deformation of the pipe if water freezes.

Figure 6 indicates that practically irrespective of the pipe diameter, thickness and strength of material, more than 10% draining of a horizontal pipe is safe and results in no plastic deformation of the pipe following a freeze-up incident.

Refilling with water is done with the equipment in low temperatures to avoid water boiling and thermal stresses. The hot Vacuum Vessel or the hot LHCD Launcher can raise quickly the temperature of the drained circuits. In the absence or failure of temperature measurements, in these circuits (for instance in the Baffles (Figure 2)), refilling can be permitted only after lowering the Vacuum Vessel temperature. Such an action can result in a major loss of experimental time and undesirable thermal cycling of the Torus. Therefore our computer model, was used to calculate the time constants under which, following a draining action, refilling is permitted. In addition gas cooldown of the circuits to be filled, prior to the water introduction, without significant reduction in the Vacuum Vessel temperature, has been quantified in order to minimise loss of experimental time and to reduce thermal cycling of the Torus.

CONCLUSIONS

The mathematical model developed to determine operational safety of the Divertor Cryopump has been applied successfully to other Cryopumping devices at JET.

This model provided the basis for the JET Divertor Cryopump Protection Control System and accounted for variations in the Divertor Geometry and First Wall material.

This Control System prohibits operational modes which may result to high thermal stresses during abnormal events, like loss of water and/or cryogen flow or loss of vacuum.

In addition it calculates the time constants which control the draining and refilling of the water circuits to prevent water freeze-up and boiling.

The effectiveness of protective actions like draining has been analysed and quantified.

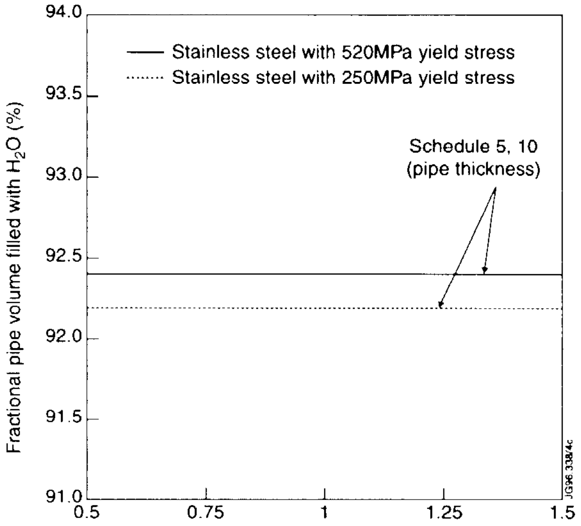

Fig 6. Maximum allowable horizontal pipe cross sections filled with H20 (%) so that plasticity is prevented in the case of a water freeze up incident.

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