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Interlock and Protection Systems for JET In-vessel Cooling and Cryogenic Components

D Stork, P Ageladarakis, A C Bell, T A Browne,
T Budd, P R Butcher, N Dolgetta, C G Elsmore,
S Papastergiou, R J Pearce, D Young.

JET Joint Undertaking, Abingdon, Oxfordshire, OX14 3EA,

1. INTRODUCTION

The JET Vacuum vessel (VV) and Neutral Injector Boxes (NIBs) contain complex coolant systems (demineralised water and freon) for plasma facing and beam power handling components and for the in-vessel divertor coils. There are also in-vacuo cryopumps with liquid (LHe) or supercritical (ScHe) helium and liquid nitrogen (LN$_2$) shields. VV temperature during operations is 320^{o}C. Good VV and NIB vacuum conditions require continuous operation of all these services. The close proximity of water channels to masses of several tons at elevated temperatures ($\leq$ 593K in the case of the VV and in-vessel divertor target structure) or cryogenic temperatures ($\leq$ 77K in the case of the cryopumps and their supply lines) entails risk to component safety from boiling, freeze up or thermal stress if a Loss of Flow Accident (LOFA) occurs. In addition, there are more severe Loss of Coolant Accidents (LOCA) which might result in a VV breach (from the pressure surge of evaporating liquids); or potential Loss of Vacuum Accidents (LOVA) which, by raising the heat transfer within the vacuum envelope, enhance the boiling and freezing risks.

Although the probability of any severe accident (eg: a pipe break) is very low ($< 10^{-6}$ per m of pipe per annum) , the need to protect JET over several years from the expensive and time consuming consequences of an in-vessel LOFA, LOCA or LOVA has led to the development of PLC-based protection and interlock systems. These systems, the subject of this paper, have operated successfully, but had to be reanalysed for performance in event of failure modes for the JET first Deuterium-Tritium Experiment *(DTE1)* in 1997, to ensure high intergrity safety against activation release. This was successful and the experience is discussed below.

2. PROTECTIONS ACTIVE DURING COOLING & CRYOGENIC OPERATIONS

2.1 Vacuum vessel

Figure 1 shows a cross-section of the JET VV MkII configuration. The divertor configuration (see [1]) consists of four toroidally continuous freon-cooled copper coils for magnetic shaping, the coils being set in epoxy and doubly contained with a pumped interspace; a toroidal carbon tile target on water cooled Inconel structure; and a toroidally continuous ScHe panel with LN$_2$ shield and water cooled baffle shield, protecting the pump against direct radiation.

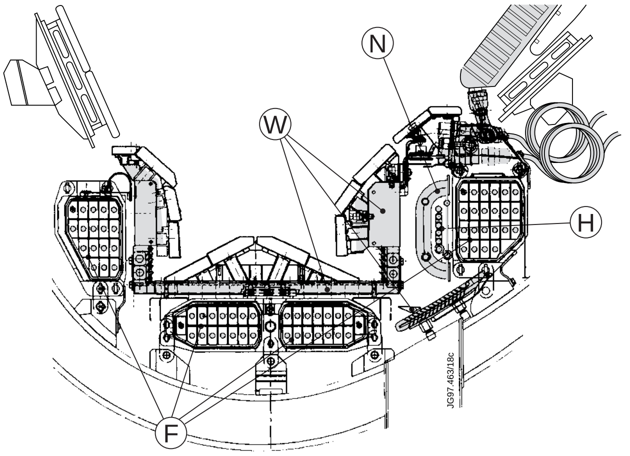

Fig 1: Divertor region configuration for DTE1. Shaded areas indicate cooled components. Key: 'F' = Freon; 'H' = ScHe; 'N' = LN$_2$; 'W' =water.

Potential faults which can arise are:

- *LOFA*: loss of water flow to target plate structure or cryogenic baffles; loss of freon cooling to the divertor coils; loss of cryogenic fluid to the pump.
- *LOCA*: loss of coolant in vacuo (eg: by pipe rupture) to either the water cooled circuits, the LN_2 shield or the ScHe cryopanels (LOCA to the doubly-contained freon is not considered). These LOCA might cause Loss of Vacuum Accident (LOVA).
- *LOVA*: either from the above causes or by breach of the vacuum vessel or its windows.

Two protection systems handle the potential VV faults involving water and cryogenics.

i) The *Drain & Refill system (D&RS)* is a part-hardwired, part PLC-based system which isolates and drains water cooled components in the VV in the event of a fault. The D&RS controls over 100 water flow valves and supplies water to all the divertor target and baffle components and to the Lower Hybrid (LHCD) cryopump shields and the Neutral Beam Duct Scrapers. D&RS has an extensive water flow and water pressure sensor network.

ii) The *Direct Plant Interlock System-2 (DPIS-D2)* is a PLC-based system which acts to back up D&RS and has additional longer-term protections against LOFA with more sophisticated algorithms. It is also responsible for protecting against LOCA involving the cryogenic supplies. DPIS-D2 has an extensive network of 30 temperature, flow, vacuum pressure and cryogenic inputs.

D&RS and DPIS-D2 algorithms and responses have evolved as a result of fault analyses [2] covering the timescales for freezing or boiling of components within the JET VV. These analyses show that, as pressures above 0.1Pa are reached in the VV, the mechanisms for freeze-up or boiling in components are enhanced by convective heat transfer, with timescales for which loss of flow can be withstood being shortened to matters of minutes. The protections drain components if these timescales are approached in LOFA cases. It is unwise to drain unnecessarily because of the risks of thermal stresses to parts of the structure (eg: the cryopumps) as the normal thermal balance is disturbed. The schematic relationship between DPIS-D2 and D&RS

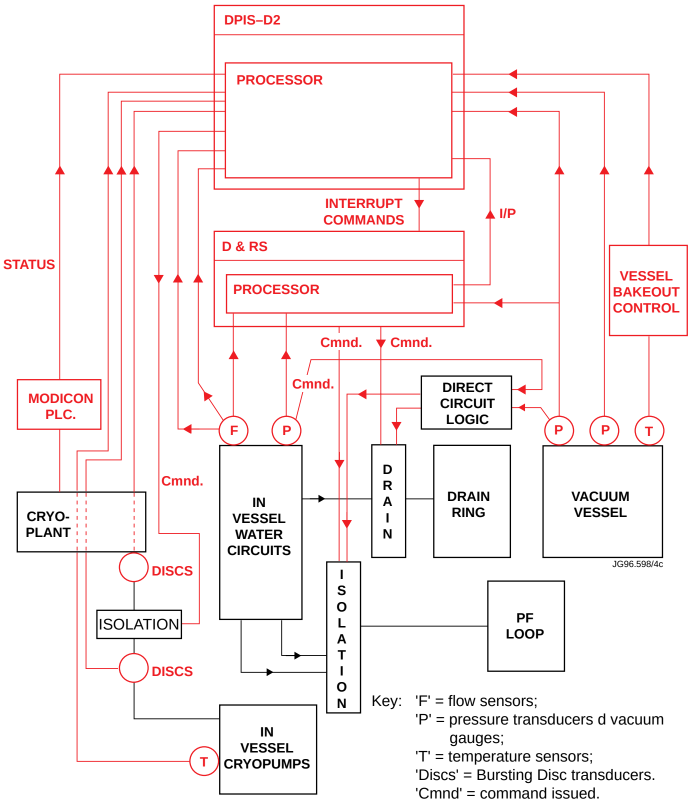

Fig 2: Above Schematic relationship between DPIS-D2, D&RS and in-vessel components.

is shown in Fig 2. Each system has Siemens S5-115 PLCs. DPIS models have dual processors for extra security.

In addition, for the tritium operation of DTE1, the potential in-vessel accidents were reanalysed to ensure that the *Design Basis Accident (DBA)* LOCA would not lead to an unacceptable risk of breach of the vacuum vessel. These analyses are described in more detail in [3,4]. Some modifications to D&RS, to include a direct hardwired 1500Pa (15mb) pressure interlock on the VV pressure were included. An example of how D&RS and DPIS would cope with a strong pressure rise (caused by LOVA or severe in-vessel LOCA) is given below, the aim being to prevent the Torus Bursting Disc (set at 5kPa gauge) from rupturing.

In a strong torus pressure rise (to atmospheric pressure in < 10 minutes), the instrumentation would not be able to distinguish initially between a LOVA and an in-vessel LOCA or identify the leaking fluid. Actions by D&RS and DPIS-D2 would be.

1) At in-vessel pressure (PT) > 5Pa, DPIS-D2 closes the LN_2 and ScHe supply valves to the in-vessel cryopumps (limiting the potential inventory to feed any leak).
2) At PT > 100Pa the VV turbopump valves are closed to prevent damage. VV is isolated.
3) At PT > 1500Pa (15mb) a water leak is suspected. Hardwired D&RS stops cooling flow to the in-vessel components. Water locked into individual circuits is pressure tested by automatic interlocks. If water pressure remains high then there is no leak in a circuit and individual circuits are then reflowed by D&RS/DPIS-D2 to avoid boiling or freezing the stagnant water.

If water pressure drops in a given circuit then a *water leak* is hypothesised and this circuit is automatically drained by D&RS to a drain ring kept at PD < 25kPa (250mb) by a Water Ring Pump (Fig 3). The evacuated drain avoids feeding the leak by the ex-vessel pipework having a gravity ‘head’ of > 50kPa. The water ingress is limited to ≤ 120kg.

4) These actions are estimated [3] to be enough to keep the VV pressure (from evaporating water) at below ~ 34kPa. In the event of problems back up is by the JET emergency pumping to the Exhaust Detritiation System (EDS), ensuring the pressure stays below ~ 85kPa [3,4,5].

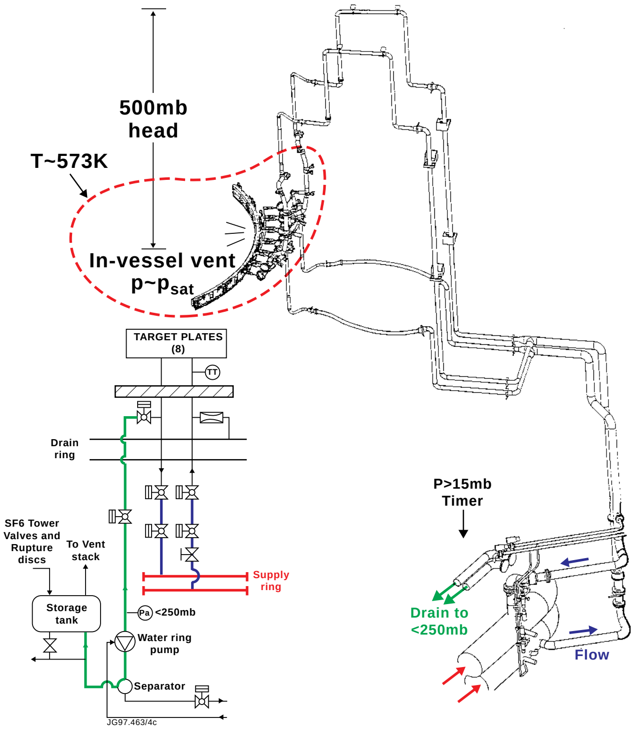

Fig 3: Left Pumping arrangements to evacuate one Octant of Divertor structure water cooling in event of an in-vessel leak.

2.2 Neutral Injection System

Two Neutral Injector Boxes (NIBs) have been used on JET since 1986, with minor modifications for DTE1 [3,6]. The NIB is lined with LHe ‘open structure’ cryopumps with 6 $10^3 m^3 s^{-1}$ pumping speed (D_2) [7] with LN_2 shields. The whole of the beam deflection and dumping system and the Ion Sources (PINIs) have to be actively cooled by high water flow [8]. In the event of LOFA in the NIB, there exists a strong risk of freeze-up due to the large mass (4.8 tonnes) of cold cryopump in the vicinity of the water circuit. This risk is greater if inadequate flow exists during cryopump regenerations, where the 3 $10^4 Pa.m^3$ of deuterium gas regenerated from the pump can send the $50m^3$ NIB volume to a pressure of 500Pa (5mb) and convective heat transfer is enhanced.

To ensure safe interaction between components, and adequate waterflow maintenance, another DPIS system *(DPIS-D1)* handles the NIB water, cryogenic and vacuum interactions. In common with DPIS-D2, this system has a S5-115F Simatic dual processor. It acts on the PLCs which control the cryogenic supplies and water cooling. Similar to DPIS-D2 and D&RS, DPIS-D1 is configured in ‘state-machine’ logic. An overview of the state machine including causes of state transitions is shown in Fig 4.

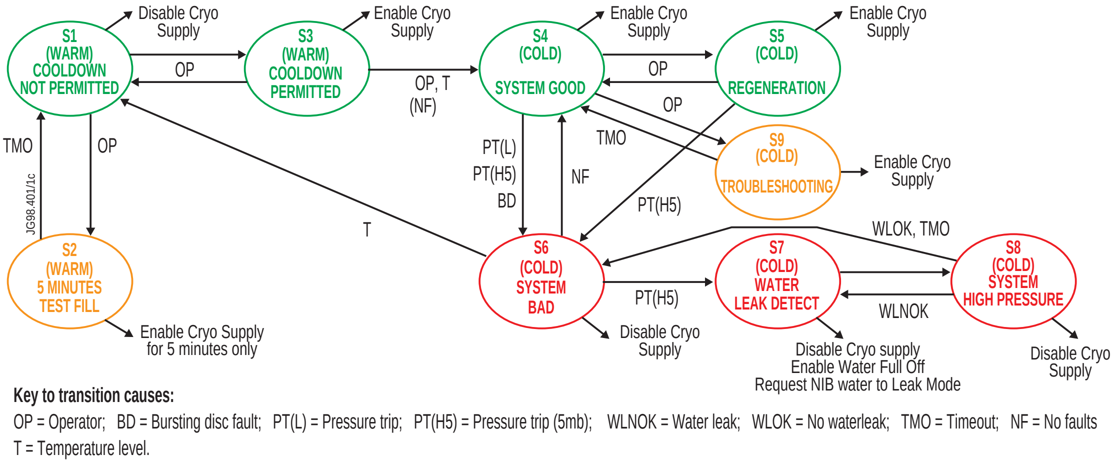

Fig 4: State diagram for the DPIS-D1 protection network.

For tritium operation in DTE1, the main upgrade to DPIS-D1 was the addition of a ≥ 500Pa (5mb) interlock which was designed to detect a severe (pipe rupture) water leak in the NIB and isolate the water flow until the valve isolating the NIB vacuum from Torus vacuum could be closed. In similar manner to the VV case, DPIS-D1 initiates a water leak detection in the control system. If the water system’s level detector does not trigger after nine minutes, then the water flow is restarted, to avoid any component freeze-up in the NIB. In the event of a severe water leak, the presence of cold cryogenic surfaces would limit the NIB pressure to below ~ 1500Pa. No such limit would exist for LN_2 or LHe leaks from the cryopumps or a severe LOVA. In the case of the cryogens, DPIS-D1 shuts off the cryo supply valves to limit the pressure excursion.

There is still a panel inventory of ~ 250ℓ of LN_2 available to feed a leak and this is capable of reaching > 88kPa pressure by evaporation. As a result the NIBs are also provided with an emergency pumping system whereby the bypass valves on the NIB turbopumps are opened by hardwired interlock at 20kPa, the NIBs being pumped out by the EDS pumping system.

3. OPERATIONAL EXPERIENCE

The D&RS and DPIS networks have worked successfully to protect JET VV and NIB components. Each system is extensively commissioned before the start of a campaign after a machine shutdown. This commissioning, which is carried out according to witnessed procedures, includes a complete bench test of the PLC logic; end-to-end test of the signals from local plant sensors; and full ’live’ drain-down and emergency pumping tests involving the higher pressure (500Pa, 1500Pa, 25kPa) interlocks. The systems have a fully working computer based mimic interface and produce audible control room alarms to alert fault conditions.

As far as operation of the VV components is concerned, there have been no water or cryogenic leaks into the vessel. The D&RS and DPIS systems and their instrumentation are protected against power supply failures by UPS back-up. In the one case (prior to tritium operations) where a fire occurred in the D&RS cubicle (leading to a fail-safe drain), DPIS-D2 took appropriate action on the cryogenic supplies and kept a back-up alarm log.

D&RS and DPIS-D2 have been subjected to one test due to operator error, which vented the VV to atmosphere in the run-up to DTE1. D&RS correctly isolated components, established that there was no water leak, and then restarted the flow, all within five minutes of the incident. DPIS-D2 isolated the cryo supplies and also kept them isolated when a ScHe line bursting disc blew (ex-vacuo) as a result of the condensing air heat load on the in-vessel pump. The time-stamped alarm log kept by both systems was an invaluable aid to troubleshooting.

There has not been a significant water leak on the NIBs for nearly 10 years. A minor leak which occurred during DTE1 was identified by the NIB vacuum instrumentation whilst it was still four orders of magnitude below the DPIS-D1 problem level (0.1Pa) and eight orders of magnitude below the high level (500Pa) trip for serious leak detection [9].

In the substantial water leak which occurred in 1988, the DPIS-D1 network handled the protection correctly and avoided component damage. This leak developed over a period of ~ 9 hours whilst the cryogenic systems were warmed up and the further freeze up risk removed. Around $1m^3$ of water was produced in this leak. Note that the sensitivity of the ‘large’ leak detection which DPIS-D1 initiates on a 500Pa trip is around $\geq 1.2m^3.hr^{-1}$, making it a very unlikely scenario.

4. REFERENCES

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