JET–P(99)23

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Preprint of a Paper to be submitted for publication in
Fusion Engineering and Design (Special JET–DTE1 Edition)

August 1999

ABSTRACT

In 1997, the JET device was operated for an extensive campaign with deuterium-tritium (D-T) plasmas (the ‘DTE1’ campaign). A comprehensive network of machine protection systems were necessary so that this experimental campaign could be executed safely without damage to the machine or release of activated material. This network had been developed over many years of JET deuterium plasma operation and therefore the modifications for D-T operation were not a significant problem. The DTE1 campaign was executed successfully and safely and the machine protection systems proved reliable and robust and, in the limited cases where they were required to act, functioned correctly.

The machine protection systems at JET are described and their categorisation and development over time are summarised. The management, commissioning and operational experience during DTE1 are discussed and some examples of fault scenarios are described. The experience with protection systems at JET highlights the importance of correct design and philosophy decisions being taken at an early stage. It is shown that this experience will be invaluable data input to the safe operation of future large fusion machines.

1. INTRODUCTION

The Joint European Torus (JET) has a unique experimental capability to introduce tritium into a machine with a *divertor* configuration and to perform substantial experimental campaigns with deuterium-tritium (D-T) plasmas. These factors, and the ability of the JET device to generate plasmas with a flexible range of dimensionless parameters, including in many cases similar values to those of the proposed International Thermonuclear Experimental Reactor (ITER) [1], make experiments of this kind highly relevant to the development of Next Step fusion devices.

The JET Tokamak performed a successful period of D-T experimentation from May to November 1997. These experiments were known collectively as *DTE1* (first Deuterium Tritium Experiment) [2]. This paper describes the engineering systems which were used to ensure the safe operation of the JET Tokamak with tritium. The Tokamak Gas Introduction and Neutral Beam Injector (NBI) systems were supplied with tritium during DTE1 by a specially designed Active Gas Handling System (AGHS). This system, which supplied tritium (T_2) and deuterium (D_2) to the Torus and NBI, processed the exhaust gases, enriched the T_2 and D_2 streams to re-supply essentially pure gases and detritiated the impurities to keep discharges below the approved daily release limits, is described in detail in a companion paper [3]. The AGHS has its own dedicated safety systems which were the subject of separate approval by the regulatory authorities and a separate *‘Safety Case’*. These are described in another companion paper [4], and will not be discussed here except in as much as they interacted with the safe operation of the JET Tokamak.

JET was designed from the outset with tritium capability and the Torus and peripheral systems are situated inside a Torus Hall whose concrete walls, floor, roof and doors form a complete Biological Shield. As the eventual capability of JET was foreseen to be a DT phase generating 5 10^{22} neutrons [5], the control and diagnostic systems have virtually no electronics within the Torus Hall itself and the device is capable of complete remote operation from the JET Control Room via the computerised Control and Data Acquisition System (CODAS) [6].

JET is a large and complex device, even without D-T operation, and its role to explore the boundaries of high plasma performance regimes implies many systems whose high power and high stored energy require rigorous interlock and safety measures to ensure operation without costly damage occurring. In addition, JET has also operated for many years with beryllium components in vessel. This has led to a strict contamination control requirement and a further imperative to prevent damage to machine and auxiliary system components (especially those *in vacuo*) as interventions to repair damage are made more complex and lengthy because of eg: the necessity for personnel to wear full protective suits. These factors ensured that a sound basic interlock system platform existed for the DTE1 experiment, consisting of several systems with a successful track record of preventing machine damage. This basic suite of interlock systems will be discussed in this paper and then the modifications to these systems made to ensure safe operation in tritium, and the extra interlock and safety systems which were commissioned, will be presented. It will be seen that the systems modifications were almost entirely concentrated on those networks whose function was to prevent a breach of the primary vacuum boundary in either the Torus or the NBI systems. Examples of the fault analyses underpinning the design modifications will also be given. These analyses formed part of the *'Torus Safety Case'* which was written as a companion to the document for the AGHS and was submitted to the regulatory authorities in parallel. The formal and regulatory aspects of this Safety Case are given in detail in ref. [4].

The DTE1 campaign was executed successfully and without major incident for the interlock and safety systems to handle. Some minor incidents before and during DTE1 gave an indication of the success of some interlock systems in dealing with problems and these will be discussed. Finally, some conclusions are drawn and possibilities for modifications and upgrades are highlighted.

2. CLASSIFICATION OF THE MAIN HAZARDS AND PROTECTION SYSTEMS IN JET MACHINE OPERATION

The hazards involved in operation of the JET machine fall into two broad categories.

i) *Pulsed Operation hazards*: these arise as a result of the high powers, high power densities, high stored energies and high forces involved in the production and heating of high performance plasmas.

ii) *Continuous Operation hazards*: these arise from the requirement for round-the-clock operation of the cooling systems, cryogenic pumping systems and vessel baking systems of

JET. This continuous operation (for periods of months at a time) is necessary to maintain extremely clean vacuum conditions; to enable the handling of high power loads on the in-vessel circuits during JET's long plasma pulses; and to avoid over temperature on in-vessel components during vessel baking.

These two classes of hazards are handled by several protection systems which assure that the basic safety and integrity of the JET machine and its peripheral (heating, fuelling and pumping) systems are maintained. Such systems are classified at JET as *Integrated Operation Protection Systems (IOPS)*. The engineering of these systems has to meet high standards, and is the subject of Design Review by a *Machine Protection Working Group*. However, because the systems have developed over many (>15) years, and because JET has been viewed as an experimental device, no major *standardisation* of protection system architecture has been possible. This point is addressed in the conclusions section with some recommendations.

The IOPS classification allows two levels:

- *Class 1 IOPS* are those systems ensuring *basic integrity of the JET machine* against out-of normal operation of any JET subsystem or of the JET plasma itself;
- *Class 2 IOPS* are systems aimed at avoiding significant programmatic or financial effects for the JET Machine and subsystems arising from such out-of-normal operation.

3. METHODOLOGY FOR DETERMINING THE ROLE OF MACHINE PROTECTION SYSTEMS IN D-T OPERATION OF JET

With a complex operational device such as the JET Tokamak it was necessary to carry out a screening process to determine whether or not modifications would be required to existing IOPS, or whether new IOPS or design actions were required to limit the radiological consequences of extreme accident scenarios. A HAZOP (Hazard and Operability) study was carried out. This involved a structured method of analysing the consequences of system deviations from normal operation and of identifying '*Initiating Events'* of accidents [7]. As described in ref. [4], the Pre Commissioning Safety Report (PCmSR), for the operation of the JET Torus with D-T plasmas, used this HAZOP study and applied a strict methodology. This had as a central principle from an engineering standpoint that any *single* failure of any system must be limited in doses to workers on-site to ≤ 5mSv (the JET management limit for annual exposure) or for off-site doses be limited to ≤ 50μSv. This involved analysing the potential tritium or radioactive material inventory mobilisable in any accident.

Initiating events were considered to lead to *'Design Basis Accidents' (DBA)* where specific provisions to minimise the consequences had been made in the plant either by passive design feature ('design action') or an IOPS network or individual protection. In this sense DBAs were seen to involve the concept of *single failure*. *Multiple simultaneous failures* were considered to be *'Beyond Design Basis Accidents' (BDBA),* a class which also included chains of events which were considered to be of such low probability that no mitigating systems were considered necessary. Analysis of the mobilisable radioactive inventories had to show that the off-site dose was ≤ 5mSv from any BDBA.

This process is illustrated graphically in Fig. 1. On reflection, it will be clear that where any Initiating Event could be reduced in probability or ameliorated by an IOPS network, this would automatically place it within the DBA category provided that the IOPS network was operational. Any IOPS which had to function in order to comply with the DBA dose limit was defined as a *Safety Related* protection system. Other IOPS which acted to limit the spread of radioactivity in ranges below the 5mSv (on-site) or 50µSv (off-site) level were defined as *Class 1(A) IOPS*. Such systems help JET comply with the ALARP principle, but were not formally credited in the Safety Case analysis [4].

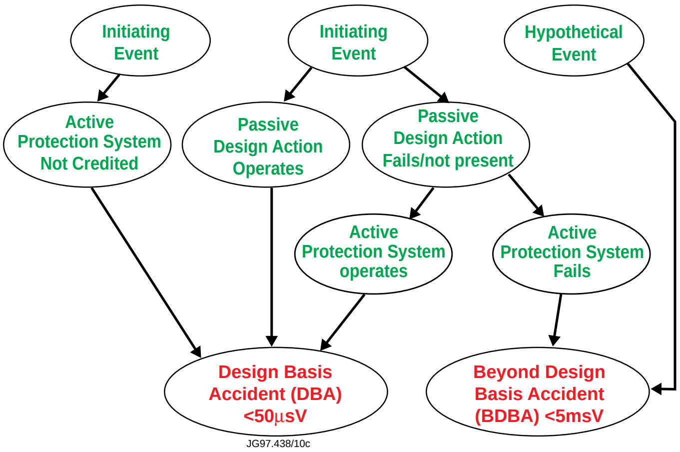


Fig.1: Methodology for classification of events-accidents chains.

For an Initiating Event to be allowed to have neither an ameliorating passive design action nor an active protection it had to be deemed “non hazardous”. This was done on the basis of the potential radioactive dose from an accident. Systems in which the potential dose from any accident (including severe hypothetical accidents) did not exceed 20µSv off-site were in the non-hazardous category. IOPS protecting against such initiating event-accident sequences were not subject to modifications for DTE1 and their classification was limited to Class 2 and Class 1(N). In any case, many Class 1(A) IOPS were able to perform their functions in DTE1 without modification due to their omission from formal credit in the Safety Case.

As will be seen in section 6, the accident scenarios which were envisaged during D-T operation were bounded by the worst case assumptions of either a catastrophic *Loss of Vacuum Accident (LOVA)* or a catastrophic *Loss of Coolant Accident in-vacuo (LOCA-iv)*. In this worst case the vacuum boundary of either the Torus or the Tritium Neutral Beam Injector Box (NIB) was assumed to be breached whilst a significant (up to 10g) tritium inventory was within the vacuum envelope in an immediately releasable form (ie. on the in-vessel cryopumps). In the case of the LOVA, the tritium released into the Torus Hall would remain within the Biological shield which was kept at sub-atmospheric pressure (see section 6). This would ensure that tritiated air would not leak out of the Biological shield before being vented to a monitored stack. Meanwhile the in-vessel tritiated air could be pumped back via the vacuum backing lines to the AGHS building where it could be detritiated in a dedicated Exhaust Detritiation System (EDS) before being vented through the monitored stack.

In the case of the LOCA-iv, the IOPS networks designed to protect against loss of coolant or flow would reduce the inventory of coolant available to feed a leak. The vaporisation of coolant inventories as a result of heat absorbed from in-vessel structures could then be limited such that overpressures and breach of the vacuum boundary could be avoided. This would involve pumping via the EDS.

If however the vacuum boundary were to be breached in a LOCA-iv, then the severity of the event would be equivalent to that of the LOVA and the same radiological consequences could be assumed.

The next sections give an overview of the IOPS networks protecting against pulsed (section 4) and continuous operation (section 5) hazards. The changes brought about to these networks in the preparation for D-T operation are then discussed for each category (section 6). In section 7 the special protection systems or modifications for DTE1 are outlined, together with examples of the hazards against which they protect. Section 8 deals with the operational experience on protection systems during DTE1, whilst section 9 attempts to draw some conclusions.

4. OVERVIEW OF PULSED OPERATIONS PROTECTION SYSTEMS

Interlock systems which are installed on the JET Tokamak and its subsystems to protect against hazards during pulsed operation are designed to carry out the following protective actions:

- prevention or termination of plasma operation which puts excessive mechanical or thermal stress on the vacuum vessel, on the in-vessel components or on the Tokamak's Toroidal and Poloidal field coils;
- termination of pulsed operation and prevention of further operation in the event of a fault in any of the Toroidal or Poloidal or in-vessel Divertor field coils;
- termination of pulsed operation and prevention of further operation in the event of a serious fault being identified in any of the Tokamak's pulsed Power Supplies;
- termination of pulsed operation and prevention of further operation in the event of LOCA *(in-vacuo)* or LOVA such that in-vessel components should not be overloaded or surfaces damaged;
- termination of high power additional heating (particularly Neutral Beams) and prevention of further operation in the event of LOCA (i-v), LOVA or other out-of-normal conditions;
- termination of pulsed operation of plasma and additional heating and prevention of further operation in the event of Loss of Flow Accident (LOFA) involving *any* of the *in-vacuo* or magnetic coil coolant circuits;

- termination of pulsed operation of plasma and additional heating and prevention of further operation in the case of the *Biological Shield* of the JET Machine not being complete or of restricted areas *not* being evacuated (eg: high voltage enclosures).

It is of course true that the *first line* of defence against serious damage in pulsed operation comes from a combination of robust and high specification mechanical and electrical design and sophisticated control systems which eliminate operator error and provide for programmed ‘soft landings’. The mechanical and control systems had been designed for DD operational capability of JET and had many years of proven operation prior to DTE1 [8], [9], [10].

In general, the IOPS networks used to handle the above fault situations had also been designed and commissioned and had several years of proven performance during JET DD operations prior to DTE1. The addition of tritium to JET plasmas, where the D-T fusion power production remained modest (≤ 16MW [2]) and did not significantly contribute to the stored energy of the system, did not require any major redesign to these systems. Such minor redesigns as there were are detailed in section 6.

The main IOPS networks devoted to the protection of the machine during pulsed operations are listed below.

4.1 Protection of magnetic coils and coil systems

A schematic cross-section of the JET device showing the positions of Toroidal Field (TF), Poloidal Field (PF) and Divertor coils is shown in Fig. 2.

There is a complex network of protection systems to handle potential faults on the coil set and faults on its power and cooling supplies. This network includes protection systems to avoid operation under conditions where the forces on the coils, or the temperatures under which the coils are operating, are such that they would lead to mechanical overstressing and damage to the coils, their support structure, or the vacuum vessel itself.

Clearly with a considerable stored energy in the magnetic fields of the JET tokamak (in the GJ range) there is enormous potential for damage, especially on the rapid disappearance of any particular field (eg: the plasma’s poloidal field during disruptions). The long period of

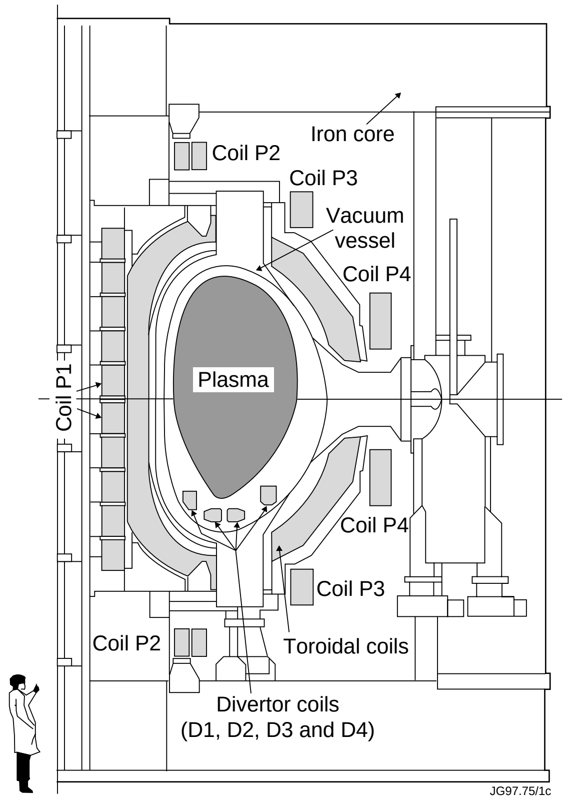


Fig.2: Schematic cross-section of JET showing configuration of toroidal, poloidal and divertor coils

operation of JET DD plasmas has seen the evolution of *Operating Instructions* which set limits to the allowable range of currents in the coils, plasma current, toroidal field and integrated I^2t. These limits are designed to avoid damage to the integrity of the vacuum vessel; to the integrity of the in-vessel coolant circuits; to the coils' mechanical structure and their coolant channels. Pre-pulse validation of the requested settings and voltage/current waveforms for the coils was instigated in the CODAS computers via so-called *'Level 1'* algorithms which provided the first line of defence against out-of-normal situations.

The analysis to determine whether or not any of the coil protections should be modified for D-T operations concentrated of the effects on any coil fault on a potential LOVA or LOCA (especially LOCA-iv). For potential fault scenarios two questions were posed:

(i) Is a fault scenario which could lead directly to a LOVA or LOCA prevented by the successful operations of a magnetic or coil protection IOPS network?

(ii) Does the action of a magnetic or coil protection IOPS increase the probability of a *related* LOVA or LOCA due to, for example, loss of plasma control and/or plasma disruption?

The resolution of these questions can be seen by discussing particular examples from the JET *Coil Protection System* and *Transverse Flux protection* IOPS.

The most sophisticated protection system for the coils is the JET *Coil Protection System (CPS)* [11]. CPS is a part-hardwired, part software-based system. Signals are taken from an extensive transducer network measuring current in the coils; voltage across coils; magnetic flux; and temperature of coil coolant and insulation. Interlocks are produced which act to remove the driving voltage from the coils (by thyristor blocking or current freewheel action) or to open circuit breakers on the coils' power supplies. A VME-based distributed system of microprocessors executes algorithms for calculation of forces on coils, effective ampere turns, integrated I^2t to give coil temperature etc. These algorithms produce 'soft-landing' instructions to the Plasma Position and Current control system (PPCC) [12] which runs down the coil power supplies (keeping the plasma shape) when around 103% of any preset Operating Instruction limit is reached. At around 106% of the limit, direct hardwired protections are executed by CPS to 'freewheel' supplies to the coils.

A schematic of the protections implemented in CPS at the time of the start of DTE1 (May 1997) is shown in Fig. 3.

The situations where a protection system can be identified as being required to intervene *directly* to prevent a breach of the vacuum vessel or in-vessel coolant circuits are limited (protection of vacuum vessel against excessive forces from in-vessel Divertor coils, protection against overtemperature and damage to in-vessel coil insulation). The analysis showed that CPS protections were indeed present, but as any LOVA or LOCA i-v would have its consequences limited by the Continuous Operation Protection Systems (section 5), CPS itself was not credited in the Safety case. Any release of radioactive coolant from a coil fault would require a *simultaneous* failure of both the in-vessel systems *and* CPS itself. As has been discussed in section 3, such

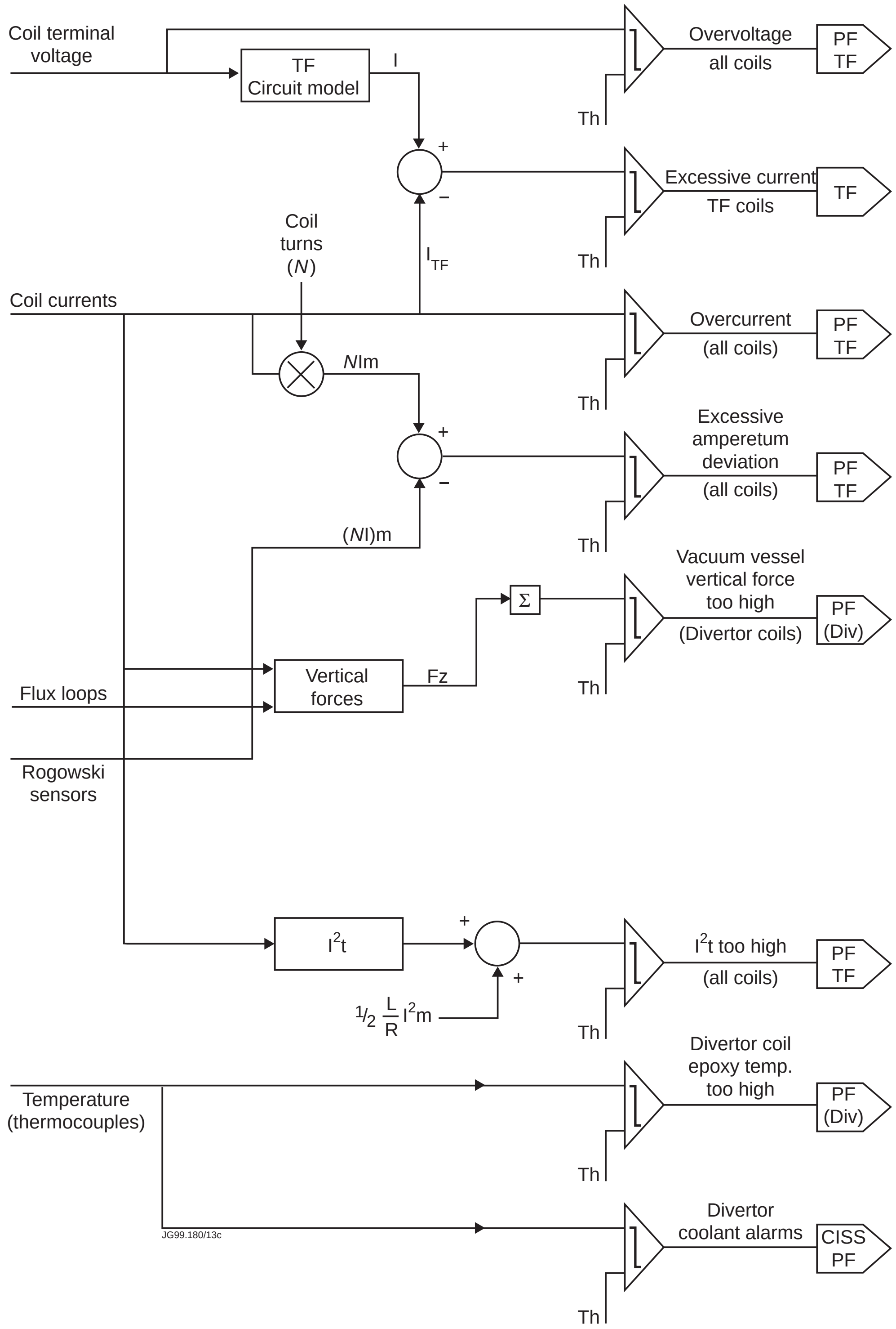


Fig.3: Schematic of protections provided by Coil Protection System at the time of DTE1.

double failures are regarded as *Beyond Design Basis Accidents*. The probability for these is so low that no extra protection chain is necessary. The existence of the extra protection of the Continuous Operation Protection systems makes JET extremely safe in this respect.

Some of the faults against which CPS protects directly would dissipate considerable stored energy and would lead to serious damage to JET's structure. An example is the potential for the central solenoid coil (P1) pancake windings to repel one another under fault conditions and blow the stack apart vertically. The direct damage from such an event would be taken up by the heavy Mechanical Structure in which the vessel is contained [8]. These considerations reduce to negligible levels the probability of a Coil Fault scenario leading directly to a LOVA or LOCA-iv. An ex-vessel LOCA might result if the coolant channels (carrying demineralised water for the PF coils and freon-113 for the TF and divertor coils) were breached by the acceleration forces in a severe accident. The emitted coolant would be relatively low in activity however and a spilled inventory could be dealt with by the Torus Hall Ventilation system provided inventory limits were low. Again it is the job of the Continuous Operation Protection Systems to limit such spilled inventories.

If CPS, or other coil protection networks, were to act precipitately to cut off coil voltages in a serious fault, the PPCC system would inevitably lose control of the plasma and a disruption would result. All plasma disruptions run the risk of damage to the vacuum vessel welds or windows from mechanical forces; or to in-vessel coolant pipes due to forces caused by the interaction of vessel structure ‘halo’ or eddy currents and the poloidal and toroidal fields, the latter having a slower decay time (fixed by the coils’ L/R time constants) than the plasma fields [13]. In the analysis of the protections it was deemed important that the operations of protections should lead neither to a significant increase in the probability of disruptions nor to disruptions in which the safety limits of in-vessel structures were exceeded. The latter point was dealt with by the application of the Operating Instructions and pre-pulse validation; the former was covered by the ‘Soft Landing’ strategies adopted in CPS and by the way that CPS acted in the foreground to provide ‘Soft Stops’ to avoid the harsh actions of ultimate hardwired protection. The interaction of CPS with one of these protections, the ‘Transverse flux’ trip, is described in section 6.

4.2 Neutral Beam Protection systems

JET is equipped with two Neutral Injector Boxes (NIBs), delivering a total of around 20MW of high velocity neutral atoms which heat the plasma. Each Injector is equipped with eight Positive Ion Neutral Injector (PINI) sources which normally accelerate deuterium (D) ions to either 140kV (injector at tokamak Octant 8) or 80kV (injector at tokamak Octant 4). The Injectors were originally designed to deliver 7.5MW each to the plasma [14]. Progressive improvements have led to the D^o injector at Octant 4 delivering ~ 13MW, ie. around 60% over the design value. At these levels, the tight geometry of the Injectors leads to power densities in the beams of ~ $300MW\cdot m^{-2}$, the highest values achieved in any neutral injection system [15]. The long pulse capability of the Injectors (10 s) implies a possibility of considerable potential for component damage. As a result, Operating Instructions have been drawn up to set limits to operational parameters and a sophisticated subsystem ‘Level-1’ software (the *‘Task Scheduler’*) has been developed to avoid operator error [16]. It has also been necessary to conceive interlock systems which guard against component damage which could arise from stray beams; caused either by component malfunction (eg: deflection magnets, which handle the unneutralised fraction of the beams, being set wrongly for the extracted voltage); or physics effects at the edge of parameter ranges (eg: the ‘reionised’ beam particles which result from neutral beam collisions with the background gas and are swept into the sidewalls of the Injector by the Tokamak fringe field). The component damage could, in extreme cases, lead to a LOVA or LOCA i-v in the Neutral Injectors. The individual interlocks were combined into an overall *Fast Beam Interlock system (FBIS)* [17]. This interlock system is based on the transmission and reception of 1kHz pulse-trains. These pulse-trains are processed by the Power supplies of the NB system and, in the event of their disappearance, the thyristors on the corresponding PINI power supplies are blocked in ≤ 10-20ms thus removing the beam power.

The hierarchical network of FBIS for one Injector is shown schematically in Fig. 4. The interlock is built to fail-safe standards which are guaranteed by the use of pulse-train detection circuits.

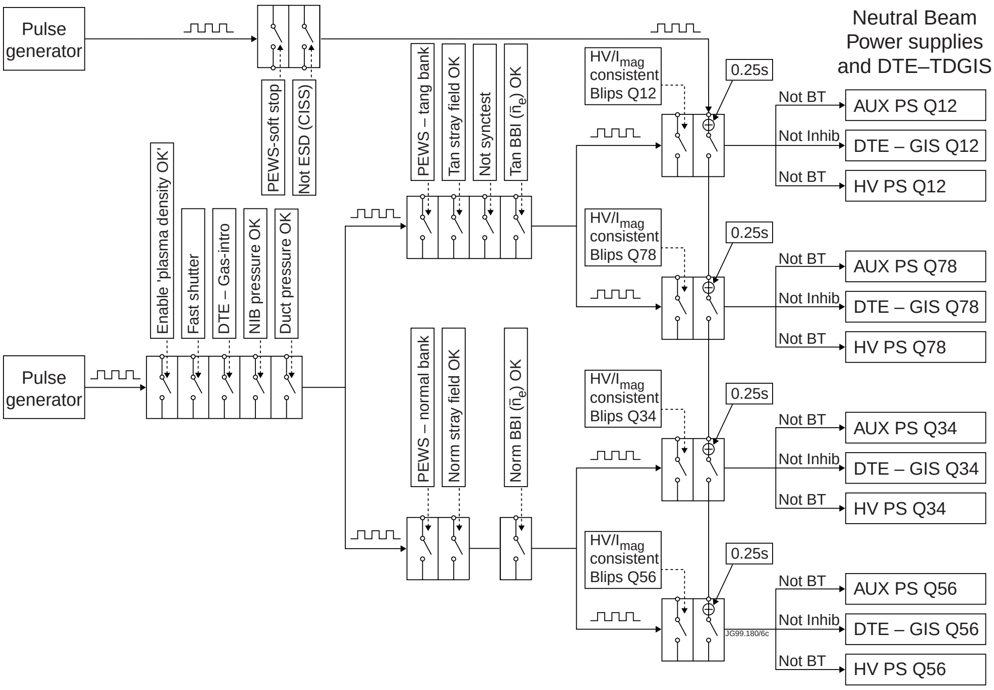


Fig.4: Schematic of the hierarchy of the Fast Beam Interlock System (FBIS) protection as implemented for DTE1. The diagram shows the system for one *Injector. A similar network exists for each Injector. Each relay is normally closed (thus crowbarring the passage of the pulse train) unless the equivalent input is energised.*

Key: PEWS – Pulse Enable Windows System input flagging that Plasma Current (Ip) and density ($\overline{n}_e$) are OK.
Tan – Tangential Bank of Injectors.
Norm – Normal Bank of Injectors.
BBI – Bremmstrahlung Beam Interlock (see sec. 6.3).
Aux – Auxiliary (Arc PS) of the PINI Ion Source.
HV – High Voltage PS of PINI Ion Source.
BT – Block Thyristors.
Inhib – Inhibit Gas Valves.

In the DTE1 experiment, the high voltage (Octant 8) Injector was converted to operate tritium (T^o) beams at 150-155kV: the details of this operation are described in a companion paper [18]. Some modifications were made to FBIS to accommodate T^o operation, and these are discussed in section 6. The basic fail-safe architecture remained intact however, and modifications were limited as the first operation of the NB system in hydrogen (H^o) and deuterium (D^o) had already been preceded by an extensive HAZOP type analysis. The failure-rate of the system had been subjected to rigorous operational experience before the DTE1 operation. Around 10,000 synchronous (SYNC) beam shots into the JET plasma had been performed and over 35,000 'Asynchronous' (ASYNC) commissioning and conditioning shots into the Injector calorimeters. In the SYNC shots, the rate of physics-oriented out-of-normal events was quite high (in the 40% range) due to the use of the NB system to generate high performance plasmas. In a careful analysis of the system from June 1994 to September 1997 (the earlier date being set by the implementation of a full computerised database recording the 'first fault' on system trips), it was seen that in around 2000 SYNC pulses on each Injector, a FBIS trip had occurred. These terminations of the Neutral Beams in abnormal circumstances were mainly due to plasma 'faults'. Just over half the cases related to Injection being inhibited either by plasma absence (disruption) or insufficient density or plasma current Around one-quarter were the result of 'SOFT' termination instructions from the CODAS microprocessor-based Pulse Termination Network (which included CPS inputs). A further 10% were attributable to high beam duct pressure (due to high gas puffing at the plasma edge) and a similar number to high stray magnetic field at the Injectors during plasma MHD events. In the case of the last set of out-of-normal events, these were mainly transient (lasting < 10ms) and the trip occurred due to the inability of the Field Compensation System of the Injectors to follow the rapid transient. This was improved prior to DTE1 by the addition of 'assert time' circuitry to avoid tripping on this particular input.

A very small number (< 20) of the trips were found to be caused by sensor faults which had to be corrected in the hardware. The network was found to have acted correctly in all ~ 4300 trip cases showing that the failure rate was $< 7\ 10^{-4}$ with 95% confidence. Some of the FBIS protections backed up further local networks which for example terminated the beams through a particular deflection magnet if the measured magnet current was > 3% different from the requested pre-pulse setting. In this way *multiple failures* of protection systems were required to generate such an accident putting it into the BDBA class. Any LOVA or LOCA i-v arising from an out-of-normal initiating event on the NBI system was capable of releasing the tritium adsorbed onto the cryopanels of the Injector or torus cryopumps. This inventory was kept below 10g (3700TBq) by management controls. The consequences of a LOVA or LOCA i-v thus generated would be limited by the Continuous Operation Protection Systems (section 5), but as FBIS had a direct role in removing the possibility of such events, it was given a Class 1(A) IOPS rating although it was not explicitly credited in the Safety Case.

4.3 Central Interlock and Safety System

The basic machine safety in pulsed mode is provided by a Programmable Logic Controller (PLC) – based network called the *Central Interlock and Safety System (CISS)* [19].

CISS has a network of safety-oriented Simatic S5-110F PLCs [20] and the newer S5-115F PLCs arranged in a subsystem hierarchy. The PLCs are self-checking (with dual processors running identical EPROMs). The number of inputs from the plant and outputs to the plant is limited to 128 each for the 110F PLCs. The 115F PLCs have higher capacity but a practical limit of 300 signals is set by the difficulties of testing large systems. All input signals are continually tested by the PLCs and are configured to be fail safe. In general, a plant sensor is configured to activate a volt-free contact which is used to switch a 24V supply from a CISS subsystem PLC back to one of the inputs of the PLC. A normally-open contact is thus energised by a safe condition on the plant and the presence of the 24V at the CISS input indicates normality. Outputs from CISS which keep the plant active (by, for example, keeping circuit breakers closed) are again of the maintained 24V type. Thus removal of the voltage is used to shut down the plant. CISS acts on a relatively slow (≥ 125ms cycle time) timescale to provide back-up for the hardwired interlocks such as those provided by CPS and FBIS. It also provides first-line basic protections for a wide range of general services where speed is not required.

CISS operates as a ‘State Machine’ and executes transitions between operational states according to changes in the input bit map. This is shown in Fig. 5. A list of the JET CISS subsystem PLCs and their basic functions is given in Table 1. The state of the JET machine *as a whole* is controlled through the CISS Supervisor (CISS-CS). In integrated operation, CISS-CS responds to a transition to a low state of readiness of one of the subsystem PLCs by itself transiting to an appropriately safer state and then instructing *all* subsystem PLCs to enter that state. Any subsystem PLC transiting to *‘Pulse Inhibited’* via a plant fault results in an *‘Inhibit Pulse’* transition on the whole system. The ‘Full Shutdown’ (FD) state (see Fig. 5) involves CISS instructions to open all circuit breakers on the Machine Pulsed Power Supplies. All FS transition requests outside of Pulse On come from Personnel Safety inputs (eg: high voltage area doors being open).

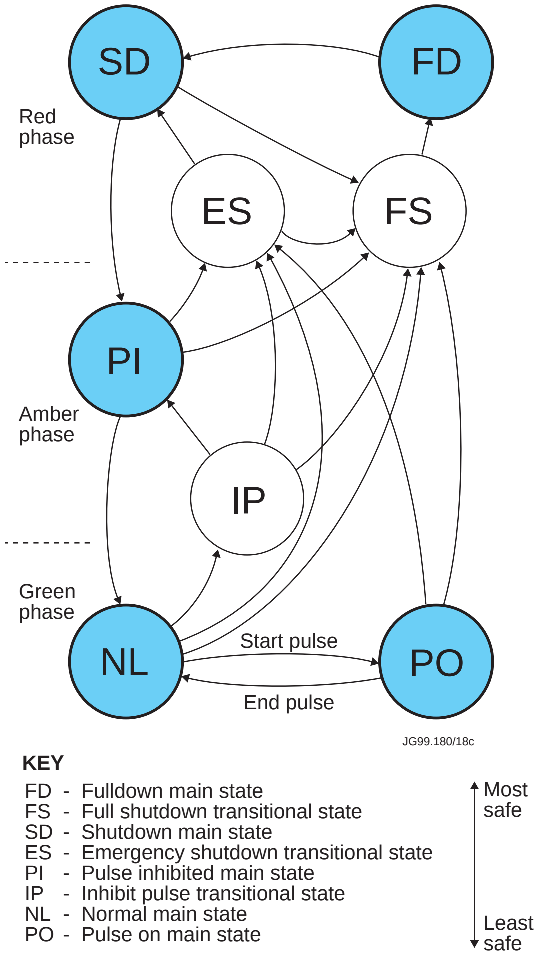


Fig.5: States of the Central Interlock and Safety System (CISS). Transitions between states are also indicated. The state diagram applies separately to each subsystem of CISS (see Table 1). Heavy circles represent the main states, lighter circles represent transitional states, and the arrows transitions between states. On an overhead display in the Main Control Room; IP is indicated on a subsystem by a flashing PI lamp; ES by a flashing SD lamp; and FS by a flashing FD lamp.

Table 1: The JET Central Interlock and safety system (CISS) subsystem PLCs and their basic functions prior to DTE1.

Subsystem	Serving	Inputs to PLC from	Outputs from PLC to
CS	System supervisor	• subsystem PLCs	• subsystem PLCs
SS	Safety System	• Shielding Beams and Doors of the Biological Shield Personnel Safety and Access • Control system (PSACS) including: High Voltage Area Doors; Access turnstiles to Torus Hall, Basement, Roof Laboratory • CISS-CS	• CISS-CS • CISS-AH and CISS-YC • CISS-LH
PF	Poloidal Field System	• PF Flywheel Generator • PF Coil Amplifiers • Divertor Coil amplifiers • Transverse Flux Protection Plasma Position Control • Cubicle (PPCC) Coolant and Coil • Temperature Sensors Coil Protection System • (CPS) Processor • Direct PF Magnet Safety System • Plasma Density Control Status • CISS-CS and -OH	• CISS-CS • PF Flywheel Generator (Excitation Ccts + CBs) • PF and Divertor Amplifiers (Thyristors + CBs) • JET Master Pulse Timing Plasma Position Control Cubicle (PPCC)
OH	Ohmic Heating Supplies (Central Solenoid)	• OH Circuits and auxiliaries	• CISS-PF
TF	Toroidal Field System	• TF Flywheel Generator • TF Static Unit Supplies • Coolant temperature sensors • Coil Protection system processor • Direct TF Magnet Safety System • CISS-CS	• CISS-CS • TF flywheel Generator (Excitation Ccts + CBs) • TF Static Units (Thyristors + CBs)
GS	General Services	• Vessel Braking System • Reactive Power Compensation System • 400kV/36kV transformers • National Grid • 132kV/11kV transformers • TF and Divertor Freon • Cooling System • PF Demin water Cooling System • Torus Vacuum Sensors • Compressed Air Supplies • Beryllium evaporator status (in Torus) • Rotary Valve status (between Torus and NB Injectors) • CISS-CS	• CISS-CS • Reactive Power • Compensation System (shutdown) • Beryllium evaporators (Inhibit)

Table I Cont.

Subsystem	Serving	Inputs to PLC from	Outputs from PLC to
AH and YC	Neutral Beam Injectors (one per Injector)	• Vacuum sensors (NIB and Injection Duct) • Cooling supplies to the Injector • Stray magnetic field sensors • Magnetic field compensation coils • Fast Beam Interlock (FBIS) status • Injector Calorimeter status • Injector Fast Shutter status • Injector Neutraliser Gas Valves status • SF6 Tower and Transmission Line pressures • NB Power Supplies • Rotary Valve Status • Mode selected (ASYNC or SYNC) • CISS-CS	• CISS-CS • NB HV Power Supplies (Thyristors + CBs) • NB Auxiliary Power Supplies (Thyristors + CBs) • Gas Introduction Valves • NB master pulse timing • Rotary Valve (inhibit) • FBIS
RF	Radio Frequency Heating Systems	• RF plant status • Pressure sensors at RF feedthroughs • CISS-CS	• CISS-CS • RF HV Power Supplies (Thyristors + CBs) • RF Generators
LH	Lower Hybrid Current Drive System	• LH Plant Status • LH Launcher positions • LH hydraulic control • Pressure sensors on LH Interspace • CISS-CS and -SS	• CISS-CS • LH HV Power supplies (Thyristors + CBs) • LH Generators

In general CISS was not affected by the changes implemented for DTE1. It was generally established to be back-up protection and as such its historically achieved failure rate $\leq 10^{-6}$ was considered more than adequate. A number of new signals were added to CISS-GS (General Services) which produced ‘Inhibit Pulse’ transitions in the case of certain services being unavailable. These are discussed in section 6.

5. OVERVIEW OF CONTINUOUS OPERATION PROTECTION SYSTEMS

The JET Vacuum Vessel (VV) and NIBs contain complex coolant systems for demineralised water and freon for plasma facing and beam-power handling components and for the divertor coils. There are also *in-vacuo* cryopumps with liquid (LHe) or supercritical (ScHe) helium panels and liquid nitrogen (LN_2) shields. The VV temperature during operations is normally 320^oC, assured by an interspace gas baking system [21]. Good VV and NIB vacuum conditions require continuous operation of these services; in the case of the coolant, LN_2 and baking, for months at a time. The close proximity of water channels to masses of several tonnes at elevated temperatures (≤ 593K in the case of the VV and the divertor target structure), or cryogenic temperatures (≤ 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 LOFA occurs. The more severe LOCA-iv accidents might result additionally in a vacuum envelope breach, caused by the pressure surge of evaporating liquids. Such LOVA events have the feedback effect of raising the heat transfer within the vacuum envelope hence enhancing the boiling and freezing risks.

The probability of a severe accident such as a pipe break is very low for small pipe lengths (< 10^{-6} per m of pipe per annum), but the length of in-vessel water pipework is large (~ 800m in the VV; ~ 450m in each NIB). The need to protect JET over several years from the expensive and time-consuming consequences of in-vessel LOFA, LOCA or LOVA has led to the development of PLC-based protection and interlock systems.

5.1 Protection systems for Vacuum Vessel components

Figure 6 shows a cross-section of the divertor region JET Vacuum Vessel in the MkIIa configuration used in DTE1.

The divertor configuration [22] consists of four toroidally-continuous freon-cooled coils for magnetic shaping, the coils being set in epoxy and doubly-contained with a pumped interspace; a toroidal carbon tile target on a water-cooled Inconel structure; and a toroidally-continuous ScHe cooled panel for cryopumping with a LN_2 shield and water cooled baffle shield, protecting the pump against direct radiation.

Two protection systems have evolved over the previous JET campaigns to handle potential *in-vacuo* faults involving water and cryogenics. These are known as the *Draining and Refilling System (D&RS)* and the *Direct Plant Interlock System-2 (DPIS-D2).*

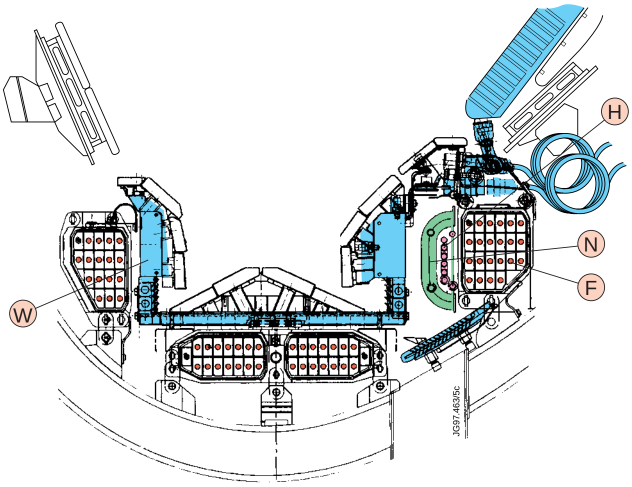


Fig.6: Cross-section of JET Vacuum Vessel in Divertor region showing MkIIa configuration used in DTE1. The letters indicate the various coolants supplied to in-vessel components: 'F' = Freon to the coils; 'H' = Supercritical Helium; 'N' = Liquid Nitrogen; 'W' = demineralised water.

The *Draining & Refilling System (D&RS)* is a partly-hardwired, partly PLC-based system which isolates and drains the water cooled components in the VV in the event of a LOFA or LOCA fault. A schematic of the supplies controlled by D&RS is shown in Fig. 7. D&RS controls over 100 water flow valves and supplies demineralised water to: all the divertor target and baffle components; the Lower Hybrid launcher (LHCD) cryopump shields; and the scrapers in the NBI ducts. It has an extensive water flow and water pressure sensor network. Prior to the modifications made for DTE1 (see section 6), it detected LOCA i-v events principally using Pirani gauge pressure measurements of the Torus vacuum.

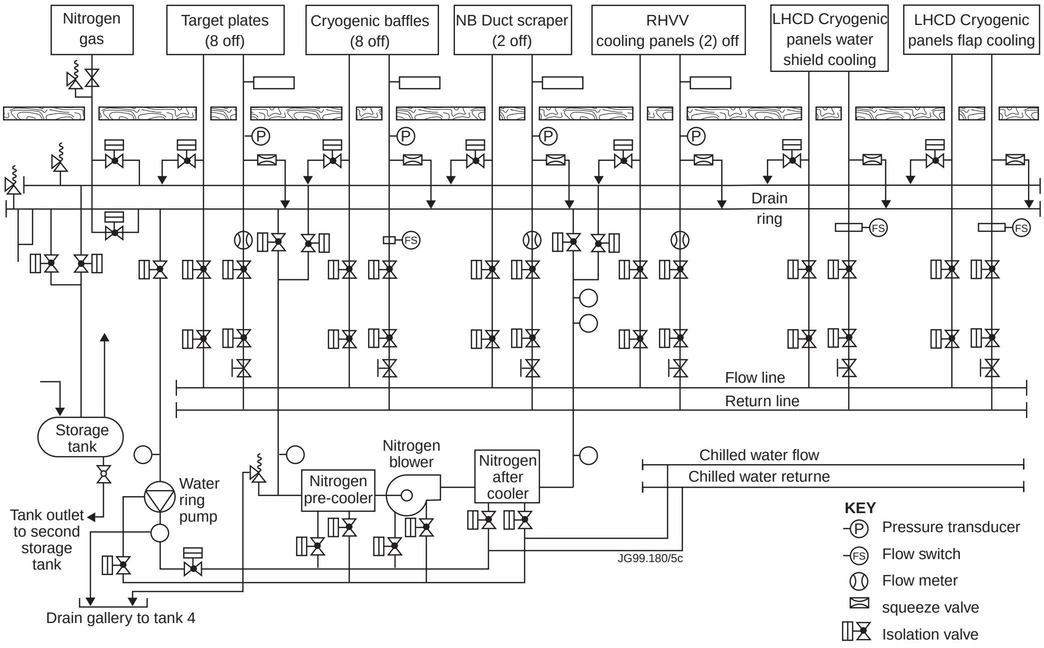


Fig.7: Schematic of the in-vessel circuits supplied by Draining and Refilling System.

The *Direct Plant Interlock System-2 (DPIS-D2)* is a PLC-based system which acts to back-up D&RS, and also has longer-term protections against LOFA with more sophisticated algorithms. DPIS-D2 is also responsible for protecting against LOCA (in-vacuo and ex-vacuo) involving the cryogenic supplies to the Pumped Divertor (PD) and LHCD cryopumps.

D&RS and DPIS-D2 algorithms and responses have evolved as the result of fault analyses [23] covering the timescales for freezing and boiling of components within the JET VV. The analyses show that as the pressure in the VV rises above ~ 0.1Pa, the mechanisms for freeze-up or boiling in components are enhanced by convective heat transfer. Once this happens, the timescales for which loss of flow can be withstood *without* any phase changes in the coolant circuits are reduced to matters of a few minutes. The protections drain components if these timescales are approached in LOFA cases. It is unwise to drain components unnecessarily because of the risks of thermal stresses to parts of the structure as the normal thermal

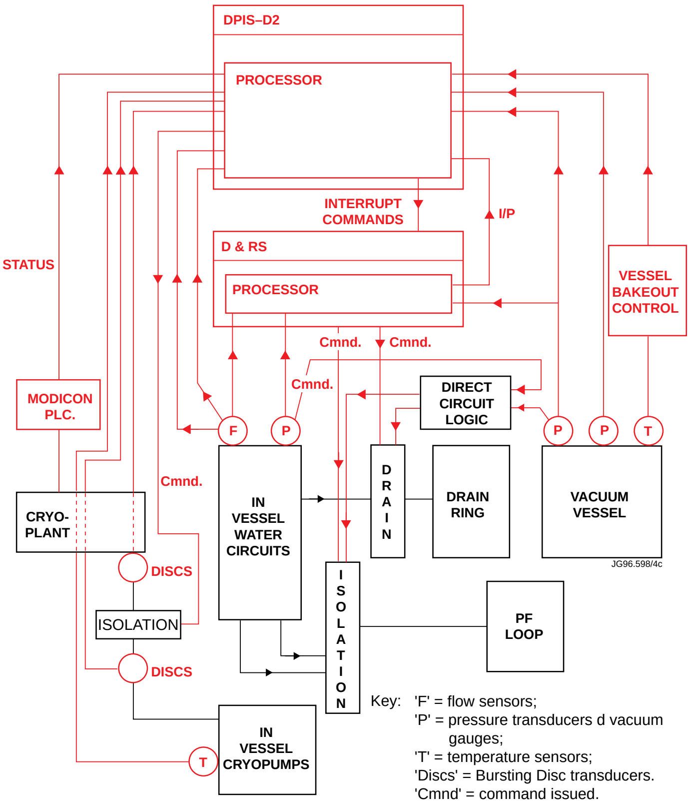


Fig.8: Relationship between Draining and Refilling System (D&RS) and Direct Plant Interlock System-2 (DPIS-D2).

balance is disturbed. The hierarchy of protections between DPIS-D2 and D&RS is shown in Fig. 8. Each system has Siemens S5-115 PLCs and those used by DPIS-D2 are dual-processor models, similar to CISS (section 4.3) for extra security. In common with CISS, inputs and outputs are configured to similar fail-safe standards.

An example of an anti-freeze-up/boiling protection algorithm implemented in DPIS-D2 is shown in Fig. 9.

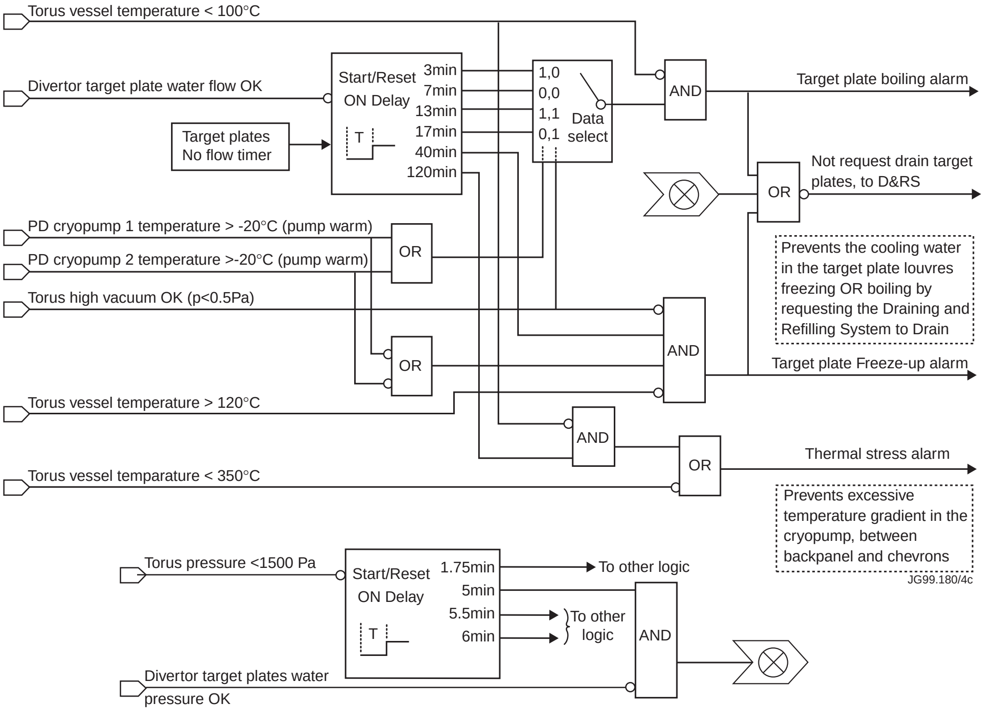


Fig.9: Example of one of anti-freeze-up/boiling component protection algorithms implemented in DPIS-D2. This algorithm refers to the divertor Target Plate coolant.

An analysis of the behaviour of in-vessel water and cryogenic leaks was undertaken as part of the HAZOP study for the DTE1 PCmSR. As a result, several modifications were made to D&RS and its auxiliary systems. Details of these will be given in section 6. Its central role in limiting the spread of tritiated water in the event of an in-vessel leak led to D&RS being a *Safety Related* protection system and the modified D&RS was credited in the Safety Case.

DPIS-D2 was not significantly modified for DTE1 operation. Its role was viewed mainly as a back-up for D&RS in LOCA/LOFA involving demineralised water. It has a more fundamental role in the avoidance of activity release in an in-vessel cryogenic LOCA. This was also analysed in the Safety Case but this protection was, as it turned out, backed-up by the hardwired modifications to D&RS. In this case, DPIS-D2 was not formally credited with a primary role in the Safety Case. It was however classified as a *Safety Related* protection system. Both D&RS and DPIS-D2 were also classified as *Class 1(A) IOPS* because some of their extensive set of protections fell within this lower category.

5.2 Protection systems for Neutral Beam Injector components

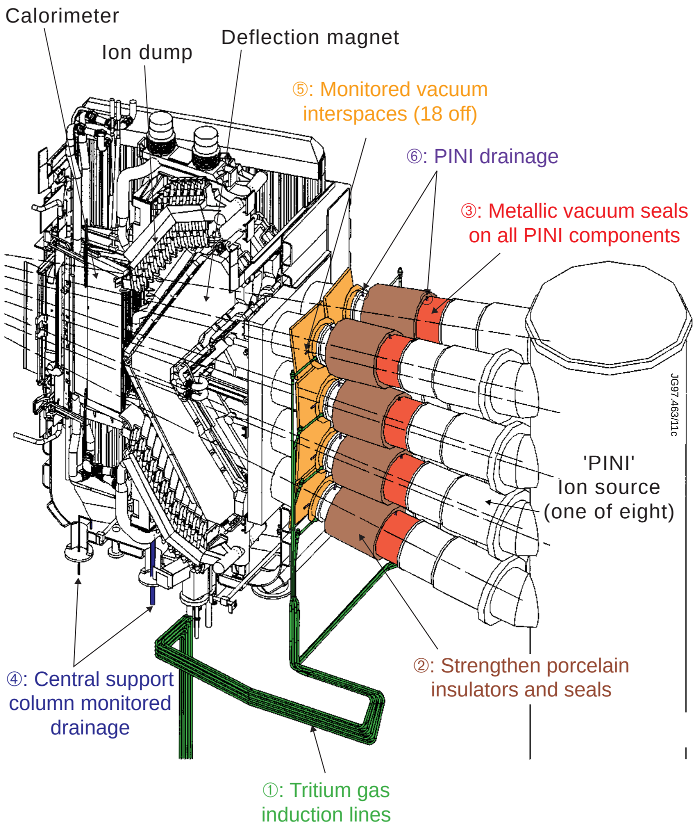


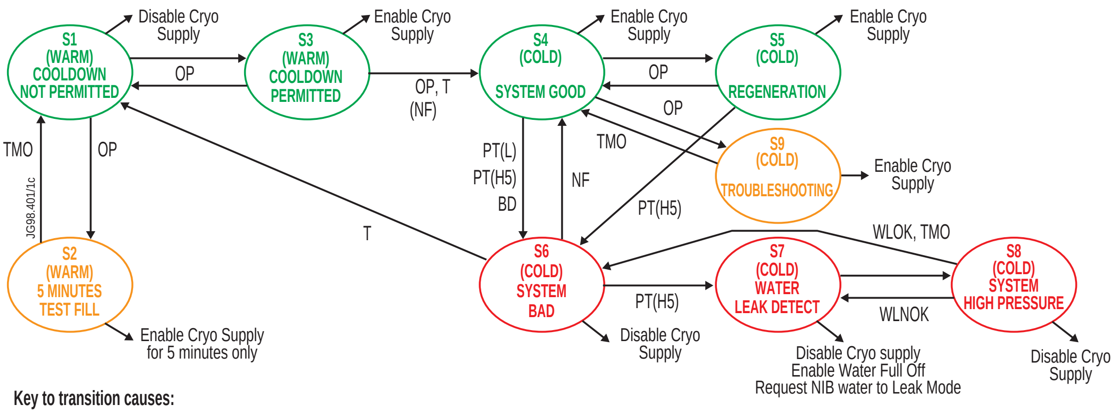
Fig.10: Cutaway of a JET Neutral Injector Box (NIB). Components indicated with numbers *are those where modifications were made for DTE1.*

A cutaway drawing of a JET Neutral Injector Box (NIB) is shown in Fig. 10, where some of the components at risk during continuous operation can be identified. Each NIB is lined with LHe cooled, LN_2 shielded 'open structure' cryopumps [24] with $6 \cdot 10^3 m^3 \cdot s^{-1}$ pumping speed for D_2. The whole of the beam deflection and dumping system and the Positive Ion Sources (PINIs) have to be actively cooled by high water-flow [14].

In the event of LOFA in the NIB, there exists the 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 enhanced if inadequate flow occurs during cryopump regenerations, where the released hydrogenic gas can raise the NIB pressure into the 100Pa range, in which convective heat transfer is enhanced. In H_2/D_2 operation of the NIBs from 1986-1997, an inventory limit of H_2/D_2 adsorbed on the LHe panels had been established at $\leq 3\ 10^4$ Pa·m^3. This inventory, if regenerated in the 50m^3 NIB volume would lead to a pressure of ≤ 600Pa once the gas has equilibrated to room temperature ie. well into the convective transfer pressure range. The inventory was set to avoid any possibility of a flammable (H_2/D_2)/air mixture in the event of an air leak in the NIB. It was reduced for the *tritium* Injector in DTE1 (see section 6).

To ensure the safety of NIB components, and adequate waterflow maintenance, a system known as *Direct Plant Interlock System-1 (DPIS-D1)* has been in operation since 1987 to handle the NIB water, cryogenic and vacuum interactions. In common with DPIS-D2, this system has a S5-115F Simatic dual-processor PLC. It acts on the PLCs which control the cryogenic supplies and water cooling to the NIBs, and also has direct control of supply valves and pumps. Similarly to DPIS-D2, D&RS and CISS, DPIS-D1 is configured in a 'state-machine' logic. An overview of the state machine including the causes of state transitions is shown in Fig. 11.

From the HAZOP study for the DTE1 PCmSR event sequences for water and cryogenic LOCA i-v in the NIB were clarified. Some modifications were thus made to DPIS-D1 and some



Key to transition causes:
OP = Operator; BD = Bursting disc fault; PT(L) = Pressure trip; PT(H5) = Pressure trip (5mb); WLNOK = Water leak; WLOK = No waterleak; TMO = Timeout; NF = No faults
T = Temperature level.

Fig.11: State diagram for the DPIS-D1 protection network.

systems were added as backup and these are discussed in section 6. The modifications limited the credit which DPIS-D1 was given in the Safety Case. It was nevertheless classified as a *Class 1(A) IOPS*.

6. CHANGES TO PROTECTION SYSTEMS FOR DTE1 OPERATION

6.1 Passive protection

As a result of the HAZOP analysis and the preparation of the Safety Case, many *Design Actions* were taken to improve the *Passive Safety* of the system. These were principally in the form of double-containment for certain systems.

i) All systems supplying tritium gas to the plant were provided with double containment where the pressure was expected to be > 100Pa. This included supplies of tritium to the Torus Gas Introduction Module (GIM) system and to the Tritium-Deuterium Gas Introduction System (TDGIS) of the Octant 8 NBI system [18]. In addition the pipework/vessels in which the tritium was contained were operated at sub-atmospheric pressure. The secondary interspace around the tritium supply was continually flushed with nitrogen gas. This gas was routed back to the AGHS [3] where it was sampled and alarms were raised if any tritium content was detected.

A considerable tritium inventory (around 2.3gr or 850TBq) was held in the supply pipework to the GIM and TDGIS because of the long routing of pipes through the JET buildings from the AGHS. Operating Instructions insisted that this inventory was pumped back into the AGHS Uranium beds when machine operations were suspended for any length of time (including overnight).

ii) All windows and instrumentation feedthroughs on the Torus Vacuum Vessel and NIBs were made into doubly-contained units before DTE1 [25]. The interspaces thus formed were filled with neon gas at ~ 500mb and were linked together in a number of groups. The pressure in each group could be monitored visually by observing gauges which were accessed by personnel entering the Torus Hall. This was a disadvantage, as access was not always possible because of the operation of the Fire Suppression System (section 7) which did not leave a breathable atmosphere in the Torus Hall. Leaks at the *inner* layer of the interspace (ie. into the vacuum of VV or NIB) could be detected remotely however by the check for neon in computer-based RGA spectra from the vacuum instrumentation on the VV and NIBs. This was performed at frequent intervals as part of the operating regime.

Prior to DTE1, one in-vessel system had already been engineered to have double containment. The Freon cooling system, used to cool the in-vessel divertor coils (Fig. 6) had, as was mentioned in section 5.1, double containment with a pumped interspace which was continually monitored.

This system did not therefore need upgrading for DTE1, and no *active protection* against leaks was necessary. Double containment of the in-vessel water and cryogenic systems was not feasible on the other hand and the upgrades to their protection systems are discussed below.

6.2 Upgrades to Continuous Operation Protection Systems

6.2.1 Torus Systems

In a strong pressure rise in the Torus, caused by a LOVA or LOCA i-v, the aim of the Design Actions which brought changes in the Continuous Operation Protection Systems was to prevent the rupture of the Bursting Disc on the Torus VV. This disc was set at 50 mbar (gauge) ~ 105 kPa mean absolute pressure. Rupture of the disc would lead to expulsion of some of the tritiated VV inventory into the Biological Shield. Although this expelled inventory would go up the monitored stack, this could lead to significant dose rates in the absence of protection systems to reduce the burden. If the management limit of 10gr (3700TBq) of tritium were condensed on the PD cryopumps in the vessel and a water leak were to lead to disc rupture via steam production, then a release of tritiated water where a significant proportion of the tritium inventory was converted to HTO [4] would give an off-site dose (1km) of >1mSv. The post-accident on-site contamination would also cause problems in clean-up. The DBA's which were analysed to recommend the Design Actions were extremely conservative. Examples are:

- *LOVA*; a DBA would be a large breach (by a 50mm diameter hole) in the vacuum envelope;
- *LOCA (i-v)*; a DBA would be the rupture of a single large (20-30mm diameter) *in-vacuo* pipe for the water cooling or cryogenic circuits.

The LOCA i-v could lead to vessel rupture if unchecked, depending on the inventory of coolant available to feed a leak. For cryogens, the Torus pressure rise which would follow an in-vessel cryogenic leak would cause DPIS-D2 to shut off the cryogenic supply valves if the pressure were to rise above ~ 5Pa. Only the 'local' cryogenic inventories would then be available to supply the leak. In-vessel local inventories for the LN$_2$ and ScHe in the Divertor cryopumps are quite low (12.5ℓ and 20ℓ respectively in each of the two separately-fed halves of the pump).

To this must be added the inventories in the long coaxial transmission lines [26] through which cryogens are supplied to the JET cryopumps. These lines are downstream of the supply valves closed by DPIS-D2. The lines are up to 90m long, and the largest inventory (LN$_2$) is ~ 50ℓ. The total LN$_2$ inventory to supply a leak from any one of these sources would still not be enough to breach the VV even if the inventory were raised to vessel temperature of 320^{o}C in the leak. The most serious inventory in this respect is the 120ℓ of LN$_2$ in the Appendage Cryopump attached to the Lower Hybrid (LH) system. The pump is connected via a low conductance to the Torus VV [27] and the spillage of such an inventory would lead to a VV pressure of ~ 90kPa when equilibriated at 320^{o}C (1ℓ LN$_2$ yields 0.7m^3 of nitrogen gas at NTP). It can therefore be seen that, in the event of an in-vessel cryogenic spill in the VV, *provided DPIS-D2 functioned to cut off the cryogenic supplies*, the rupture of the VV Bursting Disc could be avoided. Secondary effects such as pipe-freezing and boiling would however have to be considered.

The analysis of the DBA for in-vessel water leaks yielded more serious possible consequences.

A section of the water cooling circuit for the in-vessel divertor structure is shown in Fig. 12. This corresponds to an *octant* (ie. one-eighth) of the structure. The cooling channels flowing through the Divertor structure and the in-vessel manifolding are shown. A leak in one of the 'French horn' pipes near to the Divertor structure (see Fig. 12) would be fed initially by water from the ex-vessel pipes which would drain under a > 50kPa gravity 'head'. A considerable volume of water would be available to feed the leak in its initial stages. The situation would be exacerbated further as all the octant sections are joined into one integral unit. This was done to minimise temperature differentials along the Divertor unit to avoid misalignments of the Divertor structure, which needs to be aligned with very high accuracy [28]. Thus any potential leak in the bottom Divertor structure would be fed by *all* the water in the Inlet and Outlet manifolds of all eight octants.

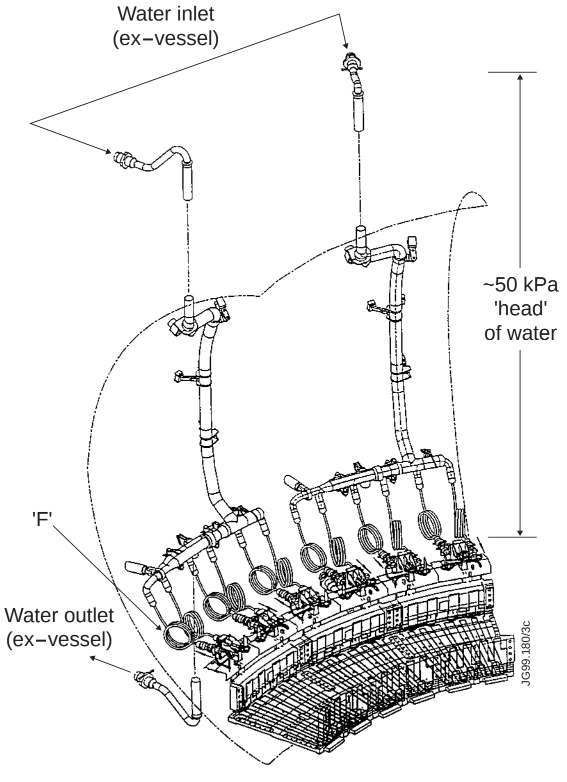


Fig.12: Divertor structure octant plus supply pipes. 'F' indicates 'French Horn' pipes (see text).

A drain-down facility would be available through D&RS. It was realised however that the existing drain-down to pipework at *atmospheric pressure* (100kPa (a)) would *not* short circuit the flow of water between octants (see

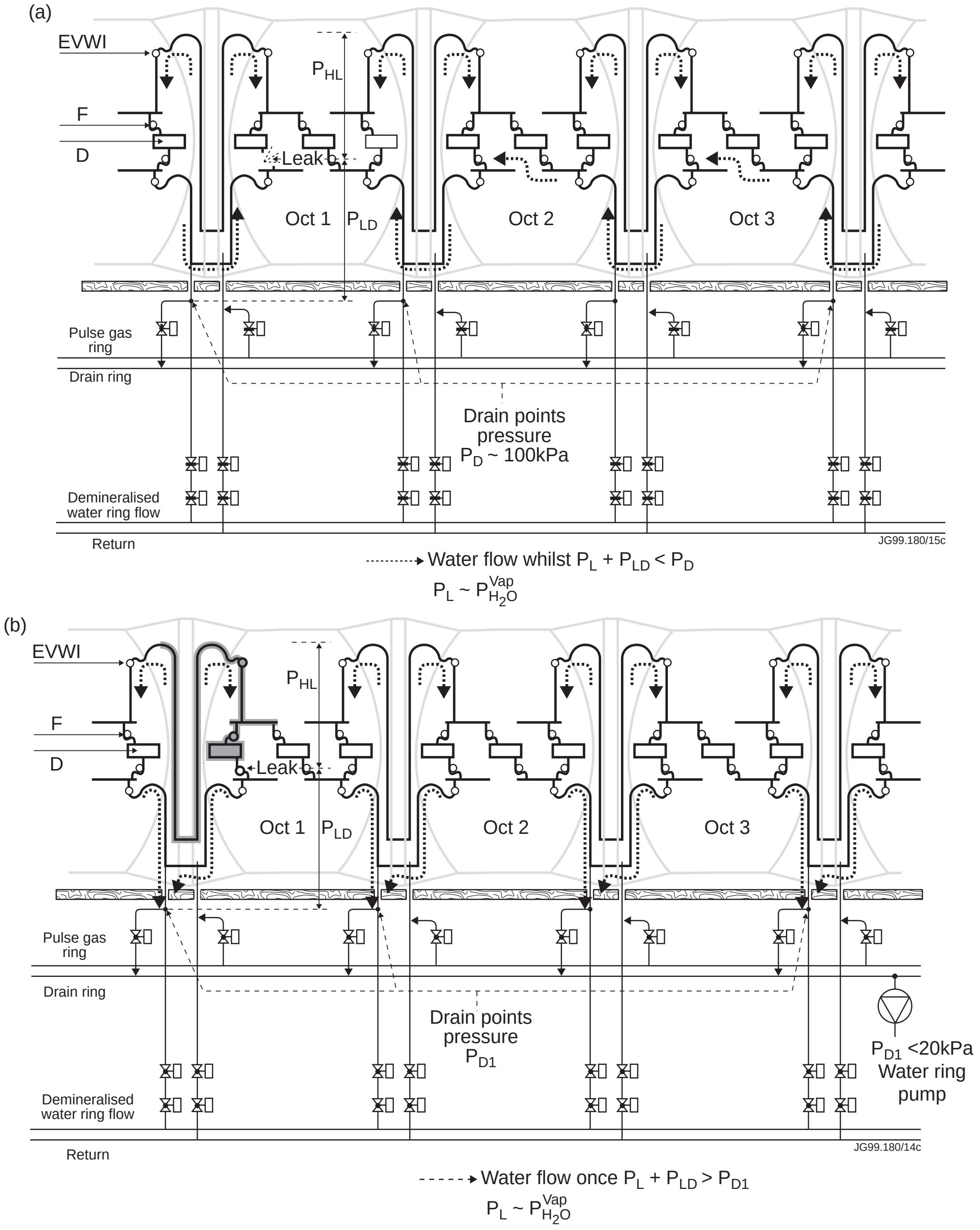


Fig.13: Flow of water during a LOCA i-v in the Divertor structure (shown schematically): (a) With the Drain Ring at atmospheric pressure (~ 100kPa); and (b) With the Drain Ring evacuated (using a Water Ring Pump) to a pressure below 20kPa.

Key:	*EVWI*	*External Vessel Water Inlet*
	P_{HL}	*header pressure between Inlet and Leak*
	P_{LD}	*header pressure between Leak and Drain Points*
	F	*French Horn pipe*
	D	*Divertor Structure plate.*

Fig. 13(a)) as the pressure at the leak point (P_L in Fig 13) would be ~ $p_{sat}^{H_2O}$ where $p_{sat}^{H_2O}$ is the saturated vapour pressure of the steam forming from the in-vessel leak. There is a 10kPa ‘head’ pressure between the postulated leak and the ex-vessel drain points (P_{LD} in Fig 13). As a result, no drain would occur until $P_{sat}^{H_2O} + P_{LD}$ exceeded ~ 100kPa, by which time the rupture of the

Torus bursting disc would be imminent. In order to overcome this, a drain to an *evacuated ring main* at a low pressure (< 10kPa) was implemented. This would then short out the flow of water between octants [Fig. 13(b)] and limit the amount of water available to feed the leak. The pipework layout and schematic of the system for one octant is shown in Fig. 14. The evacuated drain ring was kept at low pressure by a Water Ring pump system. The water available to feed the leak was calculated to be limited to that in the shaded area of Fig. 13(b), a total of around 98kg: without the evacuated Drain Ring a quantity > 700kg would have been available to feed the leak. The quantity of water which, when turned to steam at 320°C would yield 100kPa pressure in the vacuum vessel volume is ~ 75kg. Thermodynamic analyses showed that the cool in-vessel water piping surfaces would condense a further ~ 45kg of steam even in a catastrophic break. Thus the 98kg of water available to feed the leak would not exceed the pressure of the bursting disc (105kPa) and the system had a margin of safety against release of tritiated steam into the Torus Hall. As this margin was not entirely passive in origin, however, the D&RS action was backed up by Bypass Valve Interlocks which opened the vessel to pumping via the EDS if the in-vessel pressure rose above 20kPa. These are discussed in section 7.

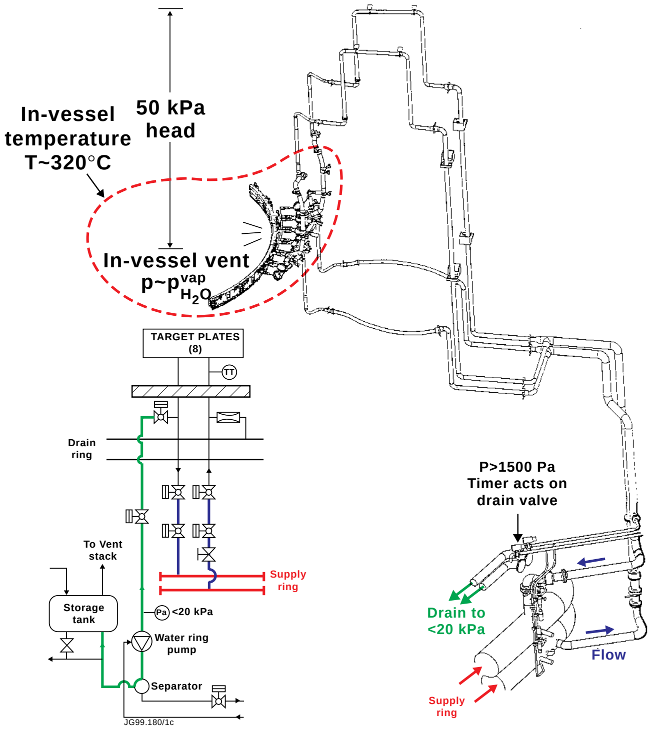


Fig.14: Schematic of drain of Divertor Structure to evacuated Drain ring.

The pressure of the Drain Ring was sensed by a trip circuit connected to the CISS-GS subsystem. If the pressure rose above 20kPa, a CISS Pulse Inhibit was generated and further Tokamak pulsing was suspended. Operating Instructions were then invoked to regenerate the tritium inventory from the cryopumps and return it to the AGHS.

Additional modifications were made to the D&RS protection network:

- the Drain Down command was instigated in a hardwired fail-safe manner by using four absolute pressure gauges on the Torus volume, which replaced the Piranis and set the Drain Down in motion if two out of four of these gauges registered a pressure > 1500Pa; and
- because the Drain Down would involve thermal cycling of in-vessel components, which was considered undesirable as it might lead to leaks, a hardwired system of timed circuits was implemented to test that the pressure rise actually corresponded to a water leak (rather than LN_2, LHe or air leaks) and hence to drain only these components found to be leaking.

Thus if the Torus pressure $p_{vv} > 1500$Pa, the cooling water to all VV circuits would be stopped by the D&RS hardwired interlock. Water would be locked into the individual circuits and hardware timers started on each circuit. Pressure gauges were attached to each circuit and any leaking circuit would see a strong pressure drop (normal supply pressure in the pipework was ~ 330kPa). If the water pressure in an individual circuit were to fall below the trip level within the timeout, then D&RS hardwired interlocks would drain that circuit to the evacuated Drain Ring. If the water pressure remained high, then after the expiry of the hardware timeout, the water flow would be restarted by opening the flow valves in the circuit in question. To avoid freezing or boiling with double-certainty, DPIS-D2 would also instruct the D&RS PLC to re-open the flow valves as a back-up.

These modifications to D&RS not only enhanced the protection offered by the system in non D-T operation, but also led to a considerable improvement in the *diagnosis* of any fault situation , allowing the separation of identification of a *water* leak from those due to other fluids.

6.2.2 Neutral Injector Box Systems

The Octant 8 NB Injector was, as already indicated, used to inject high energy (E_B Û 155kV) neutral tritium beams (T^o) into the plasma during DTE1. Ref [18] shows that each PINI Ion source operating at 155kV/28A in T^+ ions uses about 80mg of T_2 to supply 1.4MW of T^o power to the plasma for a 5 sec. pulse length. Only about 1.9% of tritium used ends up inside the Torus. Of order 5.5% is driven into Ion dumps and scrapers in the beamline and the rest is pumped onto the LHe panels of the NIB cryopumps. Including start up and conditioning shots (into the Beamline Calorimeter) a successful day's operations using all eight PINIs with more than ten shots would leave several grams of tritium on the cryopanels. As with the PD cryopumps (sec. 6.2.1), a management limit of 10gr (3700TBq) of tritium was imposed before the NIB cryopumps were regenerated. The control systems were configured so that the amount could be logged accurately and pulsing was suspended by software interlocks with alarms if this limit was reached. This inventory (corresponding to $3.73\ 10^3$ Pa m^3) was a factor of 8 below the historically-used D_2 inventory limit (sec. 5.2) and so inflammable T_2/air mixtures were impossible during regenerations.

Nevertheless, there would be considerable scope for activity release in the event of serious LOVA or LOCA i-v in the Octant 8 NIB. The bursting disc on the NIB is set higher than on the torus (300 mbar (gauge) or ~ 130kPa mean absolute pressure within the NIB). As there is no significant source of heat within the NIB outside a pulse, any *in-vacuo* water leak would not rise much above ~ 1500Pa unless the NIB were open to the Torus (ie. the absolute Rotary High Vacuum Valve connecting the two were open). The NIBs are only open to the Torus during operational periods, but since these are up to 16 hours long, this scenario has to be considered in the worst case for a LOCA i-v involving water.

The DBA's considered for the NIB were similar to those for the torus ie. large vacuum breach (50mm diameter) for a LOVA and guillotine fracture of 20-30mm diameter cryogenic or water piping for the LOCA i-v.

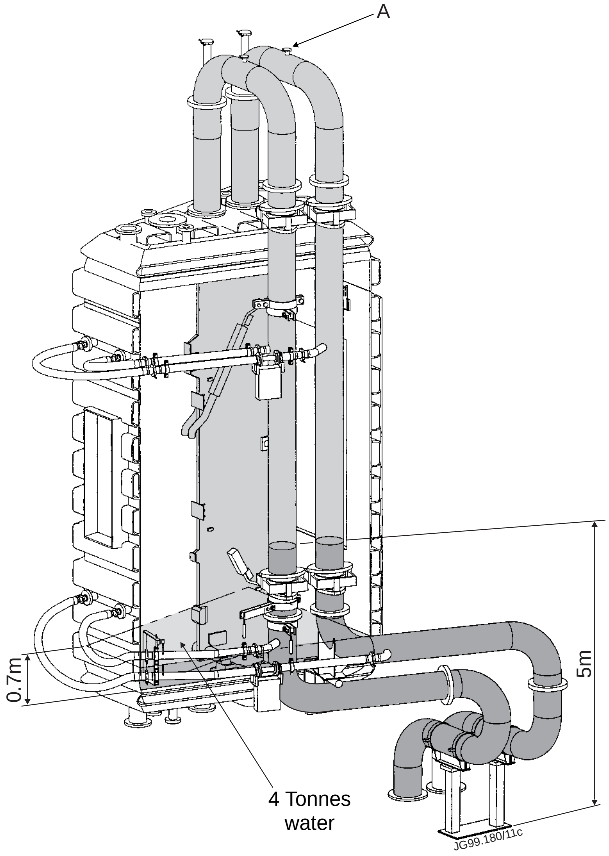


Fig.15: Cross section of NIB showing equilibrium situation in a large in-vessel LOCA with demineralised water.

In the case of the water pipe fracture, a very large quantity of water is available to feed the leak. Figure 15 shows schematically that the available water even under no flow conditions (zero pump pressure) is contained in the 'Central Column' of the NIB, which carries the Ion Dumps and calorimeter (2.5m^3 of water) and also in the large flow and return pipes which provide ~ 5m^3 of water. In addition, the NIB loop is fed by an exchange of flow with the water circuit of the Poloidal Field (PF) Coils' cooling. This exchanges water between the two loops at ~ 100 m^3 hr^{-1} (acting as a heat exchanger). The valves to this loop had always (prior to the changes for DTE1) been ensured to fail-open by DPIS-D1 and the hardwired interlocks. This was designed to avoid complete loss of flow so that freeze-up could not occur if failure occurred eg: during cryopump regenerations. This 'open-at-all-costs' policy had to be modified for DTE1 otherwise a potential water spillage of *tens of tonnes* of water into the NIB was possible in theory as a DBA.

If the valves to the PF loop could be shut and the water pump stopped, then even in the event of a severe leak, as shown in Appendix 1, the inventory into the NIB would be limited to less than 4m^3 (4 tonnes). If the RHVV were shut, isolating the NIB from the Torus, this water would not cause a vacuum breach, and could be handled safely into the Active Drain system [29]. If the NIB were connected to the Torus, the volume of water would be less than *one third* of the quantity which would 'spill over' into the VV (a volume of 16·5m^3 is contained below the NIB-Torus duct - see Fig. 15). Water would be vaporising in the NIB and passing over into the Torus VV which would raise the pressure in the VV above the 1500Pa trip level at which point the Torus interlocks described in sec. 6.2.1 would operate. This would occur in a matter of seconds. It is possible, however, using elementary considerations (see Appendix 1) to show that, *provided that bodily movement of liquid phase water between the NIB and VV could be avoided* (ie. the available volume was kept to < 15m^3), the torus VV pressure would not rise much above 2·3kPa and the system would have a measure of passive safety, thus allowing the control room operators time to close the RHVV and isolate the NIB (in fact the Safety Case assumed that their reaction time was 15 minutes).

In order to limit the inventory available for a water-based LOCA i-v, DPIS-D1 was modified in logic and hardware. The NIBs were fitted with dual absolute pressure transducers of the type used in the D&RS interlock. Trip levels were set at ~ 500Pa, a pressure which was out of reach for tritium liberated in regenerations on the cryopump (p_{regen} Û 75Pa even at NTP) and would not normally be reached by *deuterium* regenerations except after the gas had fully equilibrated to ambient, a process taking several hours (see sec. 5.2). In the event of a severe water leak these pressure trips would put DPIS-D1 into a *'(Cold) Water Leak Detect'* state (see Fig. 11). The water system would be put into Full Down (pump stopped and isolated from PF loop). A leak detection would then be made by testing for a *'Low level'* trip in the water loop's expansion tank. If this was not detected after nine minutes a serious water leak would be deemed very unlikely and then DPIS would restart the system flow. The nine minutes was chosen as this elapsed time without flow at pressure Ú 500Pa could bring water in the most vulnerable components close to the maximum density (4¯C) by convective cooling from the cryopumps. In the event of no water leak then *Standby* water flow would have to be restarted to avoid problems of overcoming buoyancy in the long vertical supply lines within the NIB. The system would then transit to *'(Cold) High Pressure'* and the cryogenic flow be kept disabled so that the cryopumps could warm up removing the risk of freeze-up. The sensitivity of the Leak Detection method was to detect leaks Ú 0.3 ℓs^{-1} the lower limit being a factor ~ 40 below the Design Basis Accident leak.

It should be noted that considerable passive safety exists in an operational NIB for handling the more likely leaks, those whose size is well below the DBA postulation. This is provided by the high pumping capability for water vapour of the NIBs' LN_2 panels. During the early NB operations on JET (1987-8), water leaks *in vacuo* did occur on the NIBs (on four occasions). These were due to delamination of electro-deposited copper covering cooling channels, and to work-hardening of Inconel bellows in the water manifolding pipes. In both cases the designs were abandoned in favour of more robust technology (gun-drilled copper and double-ply stainless steel bellows) and the faults did not recur. During the faults, water leaks ~ 0.01 - 0.02 $\ell\ s^{-1}$ occurred. These were handled quite comfortably by the cryopump for several hours with NIB pressures in the range of 10^{-3} - 10^{-2}Pa and extra heat loads on the LN_2 panels of ~ 1-3kW (10-30% above normal). The data on the behaviour of the NIBs and ancillary circuits during these leaks was a valuable aid to determining strategy during DTE1 and provided clear evidence that the LN_2 panels would be able to aid in the management of LOCA i-v(water) up to the ℓs^{-1} range.

For serious leaks of cryogenic fluids into the NIB, the worst case is provided by the LN_2 panels of the cryopump where the inventory in the panels plus transfer lines is ~ 250ℓ. DPIS-D1 would cut the flow of cryogens once pressure in the NIB exceeded ~ 1Pa. The initial outflow of

LN_2 from the DBA guillotine pipe break would be ~ 7.4 ℓs^{-1} and this would take ~ 0.7s to trip the DPIS-D1 interlock. The supply valve closure was timed at ~ 0.7s and so some 10ℓ LN_2 would spill before isolation. The total (250 + 10) ℓ inventory, if vented into the NIB and equilibriated to ambient (which would take some hours) would give a pressure of ~ 364kPa, well above the NIB bursting disc limit. Although the foreseen accident would take several hours to develop, the NIBs, like the Torus VV, were provided with Bypass Valve Interlocks which opened them to pumping via the EDS if the NIB vacuum pressure rose above 20kPa. These are discussed in section 7.

6.3 Upgrades to Pulsed Operation Systems

The IOPS for Pulsed Operation Protection were not overhauled to any great extent in the preparations for DTE1. The results of HAZOP exercises showed, as indicated in 4.1 and 4.2, that the protection chain for any fault included a Continuous Operation Protection System in the main, and thus design changes were concentrated in the latter systems.

A number of individual signals from D-T related plant were added as inputs to the various CISS sub-systems and these indications of plant abnormalities were used by CISS to inhibit Pulsing of the JET machine and auxiliary systems. Examples of these are: the pressure switch signal on the D&RS evacuated Drain Ring (sec. 6.2.1), indicating that the ring pressure was < 20kPa; the temperature trip signal indicating that the catalytic beds of the EDS were not at high temperature (> 350^{o}C), and that hence the EDS' detritiation capabilities were compromised (see sec.7); and the signals indicating no pressure trips from the tritium NBI *Tritium-Deuterium Gas Introduction System (TDGIS).*

Although no changes were made to the basic coil protection IOPS such as CPS, analyses of the management of fault situations led to changes in the sequence of planned interventions. This was exemplified by the *Transverse Flux protection*. A particularly dangerous fault during JET operations at the highest values of plasma current (I_p) and toroidal field (B_T) is the occurrence of excessive out-of-plane forces on the TF coils. These originate from the cross product of poloidal field ($B_{pol} \propto I_p$ and $\propto$ PF coil currents) and the current in the TF coils ($I_{TF} \propto B_T$). A hardwired IOPS network, the *Transverse Flux protection*, had existed for several years to provide a CISS Emergency Shutdown (CISS-ES) to the coil Power Supplies in the event of detection of a high value of Φ_{PF} x I_{TF} at the TF coils (Φ_{PF} is the poloidal field flux). The PF flux is measured by Flux loops attached to the surface of the TF coils in the regions of maximum stress. These are at the *ring tooth* and *collar tooth* support areas of the coil circumference (shown in Fig. 16). Excessive out of plane forces here could damage the coil insulation and, ultimately shear the tooth supports, the replacement of which would require substantial disassembly of the machine [30]. Two flux loops exist at each region, and there are loops on two of the 32 TF coils. The hardwired protection derived from these signals and the Rogowski coil which measures the current in the coil (I_{TF}) is shown schematically in Fig.17. The four trip signals giving $^{1}/_{2}$ (Φ_{PF1} + Φ_{PF2}) $*$ I_{TF} trips at each support location on each coil are daisy-chained and used by CISS to

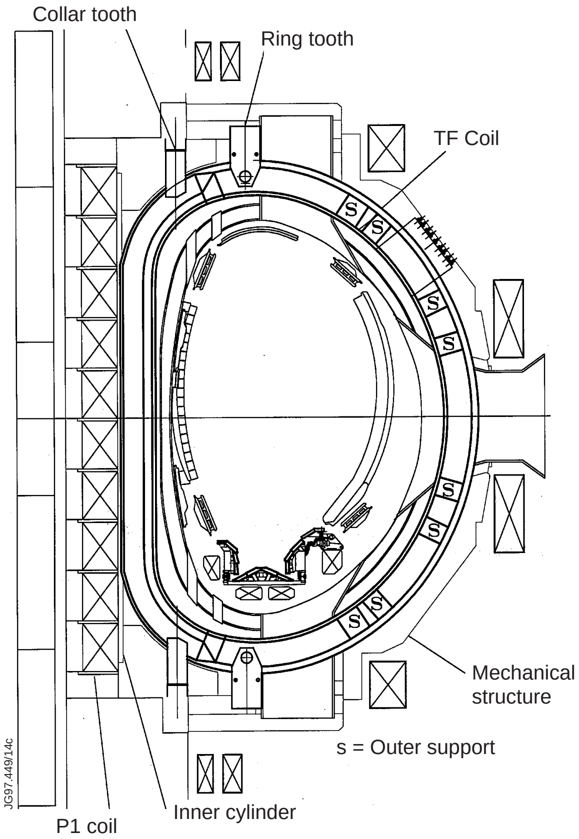


Fig.16: Toroidal field coil cross-section showing support areas including at the Collar and Ring Tooth locations of high stress. Flux loops are positioned close to these areas.

provide a *Full Shutdown* to the PF and TF power supplies opening their circuit breakers. This is a very drastic action and entails complete loss of control of the plasma. As the plasmas involved (at high I_p and B_T) inevitably have high stored energy the resulting disruptions are very severe. To avoid possible LOVA consequences, a staged protection was implemented involving CPS acting prior to the hardwired Transverse Flux protection. The flux loop and Rogowski diagnostics were wired in parallel to CPS, which calculated the (Flux $*$ current) values in software. CPS trip levels were then set at values of the (Flux $*$ current) somewhat below the maximum to enable CPS to start 'Soft Stop' sequence involving run down of the plasma currents via PPCC before the Transverse flux protection acted. Intermediate trip levels were also used by CPS to instigate a faster 'voltage Off' command to the coil Power Supplies if the Transverse Flux continued to increase after the Soft Stop command to PPCC. The protective sequence, with representative values for the Transverse Flux product, is shown in Table 2.

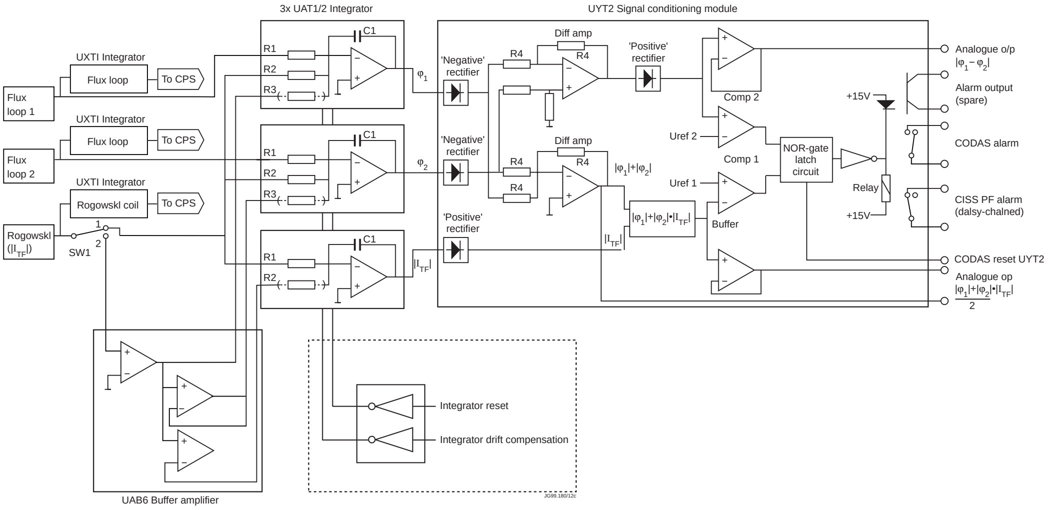


Fig.17: Circuitry for Transverse flux protection (one of four circuits shown).

This strategy proved effective, and the hardwired protective action of the Transverse Flux network did not occur in any operational situations during DTE1. It has been kept in operation

Table 2: Protective Sequence against excessive Transverse Flux from Coil Protection system (CPS) and hardwired Transverse Flux (TFH) as existing at the time of the DTE1 Experiment (values of Current Flux product valid up to toroidal field (B_T) = 3·45T.

Location	CPS			Transverse Flux Hardware Protection	
	Trip level $(I_{TF}*\Phi_{PF})_{CPS}$ (kA· Wb)	Action at trip level	Action at 102.5% of trip level	Trip level $(I_{TF}*\Phi_{PF})_{CPS}$ (kA· Wb)	Action at trip level
Ring tooth region (2 sense circuits)	16.0	1) SOFT STOP to PPCC 2) Initiate CISS delayed Emergency Shutdown	Voltage Off command to all PF and TF power supplies (except Fast Radial Field Amp)	17.0	Trip all Circuit Breakers on all PF and TF supplies except Fast Radial Field Amp (executed via CISS)
Collar tooth region (2 sense circuits)	10.4	1) SOFT STOP to PPCC 2) Initiate CISS delayed Emergency Shutdown	Voltage Off command to all PF and TF power supplies (except Fast Radial Field Amp)	12.0	Trip all Circuit Breakers on all PF and TF supplies except Fast Radial Field Amp (executed via CISS)

Note: In subsequent JET operations up to B_T = 4T, the sequence has been refined further but remains similar in principle.

since. There were occasional pulses where the second level ‘Voltage Off’ protection acted. These occurred principally where sudden changes in plasma stored energy, caused by loss of plasma confinement in high performance modes, led to a sudden radial movement of the plasma. The PF coils’ supplies tried to cope with this movement causing a transient increase in Φ_{PF} and excessive $\Phi_{PF}* I_{TF}$. An instruction to Soft Stop in these cases caught the PPCC network in the conflicting situation of trying to stop plasma movement whilst reducing all coil currents in a staged manner. The result was inability to reverse quickly enough the increase in transverse flux and hence the operation of the CPS ‘Voltage Off’ protection. In all cases this second action was sufficient. An example is shown in Fig. 18.

The FBIS network for protection against out-of-normal faults on the NBI system was also modified during the period prior to DTE1. A shown in Fig. 4, the NBI Power Supplies are blocked when there is insufficient plasma density/current for injection. This is to avoid excessive ‘shine through’ of NBI beam power on the Torus vessel surfaces due to insufficient beam absorption in weak plasma [14], [15]. Prior to DTE1 this interlock input to FBIS came from a software-based system, the Pulse Enable Windows System (PEWS) which interpreted its input signals from the JET Far Infra Red (FIR) interferometer for plasma density (n_e) and from the Tokamak magnetic diagnostics for plasma current (I_p). It was decided to use this interlock as a back-up input and implement a direct ‘hardwired’ density detector as a ‘first-line of defence’ to switch the NBI power off in the event of insufficient density. This was based on detection of

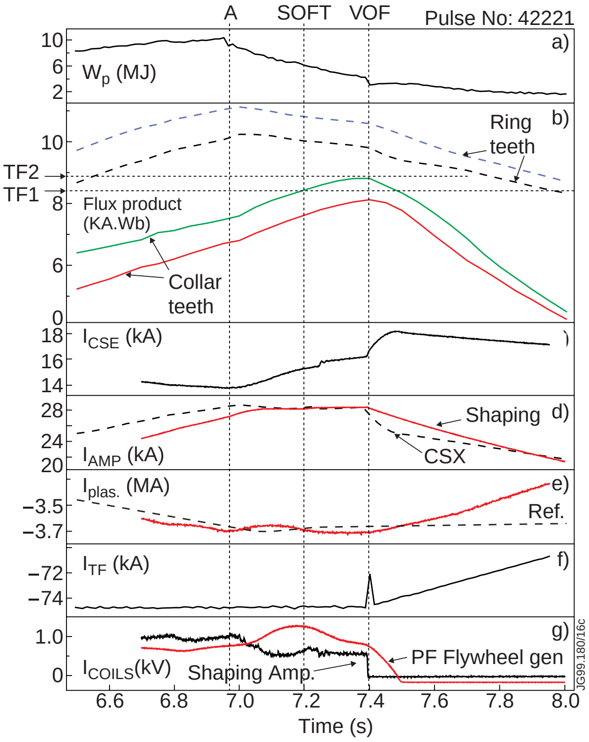


*Fig.18: Action of CPS on coil currents during high performance pulse in which Transverse Flux limits were exceeded. Pulse shown is a 3·6MA/3·7T development pulse for high performance (pre DTE1 development). Traces show: (a) Plasma stored energy (W_p); (b) Measured transverse flux product ($\Phi_{PF}*I_{TF}$) at Ring and Collar teeth locations; (c) Central solenoid end coils current (I_{CSE}); (d) Shaping coil current and Central solenoid central coils current (I_{CSX}); (e) Plasma current (I_p) (sign convention indicates clockwise direction); (f) Current in TF coils (I_{TF}) (sign convention as in (e)); (g) Driving voltages on shaping amplifier and PF Flywheel Generator. At around 6.95s (A) the plasma loses energy due to an MHD event. In coping with this the Plasma Position & Current Control exceeds the Transverse Flux lower trip (TF1) (set low for this development pulse) and initiates a CPS SOFT Stop (7·2s). This has little effect at the Collar teeth (close to the central solenoid) as PPCC is trying to hold the plasma. The second Transverse Flux trip (TF2) is exceeded at 7.4s and CPS issues Voltage Off (VOF) to all Power Supplies. This removes amplifier voltages (g) immediately, and the Flywheel Generators in a relatively short (L/R) time constant (~ 50-100ms). Ip and B_T are reduced along with all the Poloidal Coil Currents. The flux product at the Collar Teeth then reduces and the hardwired (Φ_{PF} *I_{TF}) trip (at 10kA·Wb) is not required to act.*

visible bremsstrahlung radiation from the plasma where the density is related to the spectral radiant intensity of the plasma (dN/dλ) at wavelength λ by:

$$\frac{dN}{d\lambda} = \text{const}\ \bar{g}\ \frac{n_e^{2} Z_{eff}}{\lambda^{2}\sqrt{T_e}} \quad (\text{W m}^{-3}\ \text{nm}^{-1}\ \text{sr}^{-1}) \qquad (1)$$

where $\bar{g}$ is a factor (the 'Gaunt' factor)weakly dependent on plasma temperature;

T_e is the plasma temperature;

Z_{eff} is the effective 'ion charge' (∝ purity) of the plasma;

n_e is the plasma electron density.

Equation (1) indicates the strong dependence on density, enabling a good trip level of sharply defined nature.

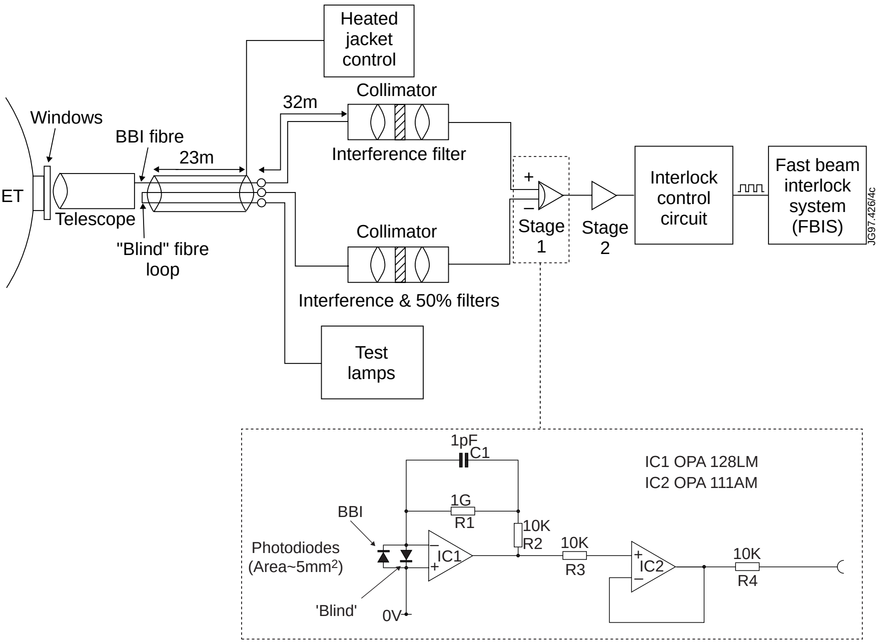


Fig.19: Schematic of Bremmstrahlung Beam Interlock (BBI) circuitry.

The diagnostic developed was known as the *Bremmstrahlung Beam Interlock (BBI)* and its construction, commissioning and operation are described in detail in ref. [31]. A schematic of the BBI system is shown in Fig.19. Amongst the key features of the system are:

- radiation resistant 'front end' in the Torus Hall with heated optical fibre to anneal radiation damage [32] and minimise transmission losses, and large diameter fibre to minimise optical opacity effects;
- 'blind' compensating fibre and detector to remove effects of γ rays produced in the fibres from neutron scattering and capture events during JET discharges [33];
- large area (5mm^2) photodiodes with very high gain (10^{11}) Instrumentation Amplifier electronics situated outside the Biological Shield to avoid radiation damage;
- test of the blind fibre (and its photodiode) integrity before each pulse using test lamps.

The BBI system proved to be a reliable and robust interlock and was always seen to act correctly in both D-D and D-T discharges. The action was calibrated against the more sophisticated density inputs used by PEWS and found to be reproducible. Background signal from D-T 14MeV neutrons was accurately compensated using the blind fibre. Figure 20 shows the BBI signal from two pulses with similar plasma density (and purity and

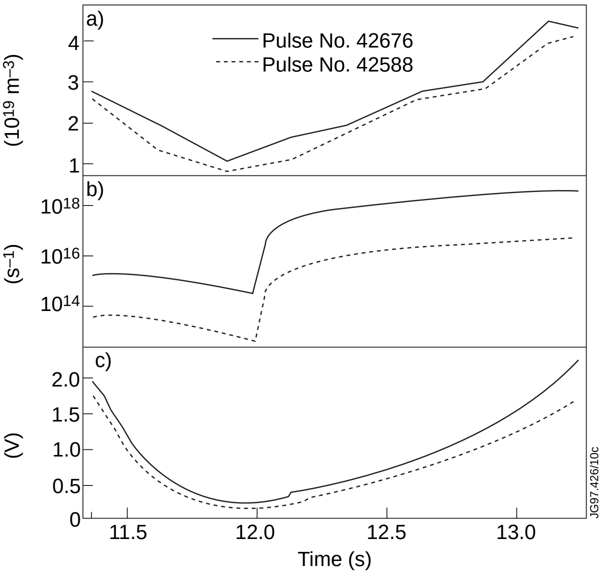


Fig.20: Comparison between JET pulses 42676 (DT) and 42588 (DD) showing a) plasma electron density, b) total neutron rate, c) BBI voltage.

temperature) one in D-D, the other in D-T. In spite of a neutron production rate of ~ 80 times greater in the latter pulse, the compensated BBI signal shows no effect. The BBI is compatible with the final active phase operation of JET ie. with neutrons rates ~ $5\ 10^{18}\ s^{-1}$.

7. PROTECTION SYSTEMS SPECIFIC TO D-T OPERATION

7.1 Emergency pumping of the JET Vacuum vessels

As indicated in section 6.2, there were modifications to the continuous Operation Protection Systems prior to DTE1 to limit the amount of fluid spillage in a LOCA i-v. Calculations showed that even allowing for these pressures in the VV and NIBs could come close to values which might lead to breaches of the vacuum envelope and release of tritium and activation products.

In cases such as these, and also to keep the vacuum pressure down in LOVA and avoid 'blow back' incidents leading to activation release through the LOVA breach, a system of emergency pumping was installed on JET consisting of *Bypass Valve Interlocks* and a connection to an *Exhaust Detritiation System (EDS).*

The Bypass Valve Interlocks use radiation resistant pressure switches attached to each of the NIB and VV volumes. At an *in-vacuo* pressure of 20kPa they trip the circuits opening the Bypass Valves for the turbomolecular pumps on each of these volumes. This provides high conductance pumping through to the 'crown' manifolds of the Mechanical Forevacuum (MF) pumping and eventually to the EDS.

The EDS is a tritium removal system where tritium and tritiated gas species are oxidised at high temperature to water over a catalyst bed. The water is trapped on a dry molecular sieve. Saturated molecular sieves are regenerated by heating, the desorbed humidity being collected in coolers and finally stored in drums if the tritium concentration is high [29].

The system is designed to reduce the incoming tritium concentration by more than a factor of 1000 [34]. The EDS is regarded as a *Safety Related* protection system and it is always required to have one EDS drier on standby. The EDS catalytic recombiner beds had to be ready at temperature otherwise a pulse inhibit was generated by CISS and tokamak and NBI pulsing were suspended.

A schematic of the pumping path during an emergency in which the torus pressure gas > 20kPa is shown in Fig. 21. At a torus VV pressure of 20kPa the turbopump Bypass valves would be opened by the hardwired interlock. A software start would be made of the relevant 'Normetex' scroll pump which would provide pumping to the EDS. At a crown pressure of > 25kPa, hardwired interlocks would isolate the Cryogenic Forevacuum (CF) of the AGHS, which provides the normal exhaust pumping for the torus [3] and open the bypass valves to the Normetex pump. These scroll pumps have a maximum throughput of $450m^3\ hr^{-1}$ at ~ 30kPa suction pressure. A rotary blower is attached to the exhaust of the EDS to pump the de-tritiated exhaust to stack. This is capable of $500m^3\ hr^{-1}$ throughput, compared to the Normetex capability ~ $400m^3\ hr^{-1}$ at 100kPa inlet pressure. The analysis of the DBA involving serious water

LOCA i-v in the torus (sec. 6.2.1) showed that close to 100kg of water was available to leak into the VV and could not be prevented by interlock systems. An analysis of the thermal and thermodynamic behaviour of this water in the VV showed a production rate for steam of ~ 23gr sec^{-1} due to boiling from a pool of liquid in contact with the hot vessel initially at 320°C. Some of this steam would condense in the cold vacuum crown when the Bypass Valves opened but, in any case the 500m^3 hr^{-1} throughput of EDS blower (at NTP) corresponds to the production of ~ 240gr sec^{-1} of steam in the VV at 320°C. The EDS blower was the only pump which was assumed to operate in all circumstances, even if the Normetex pumps tripped, and hence it can be seen that sufficient pumping capability would exist to stabilise the VV pressure even without the passive safety arising from condensing steam.

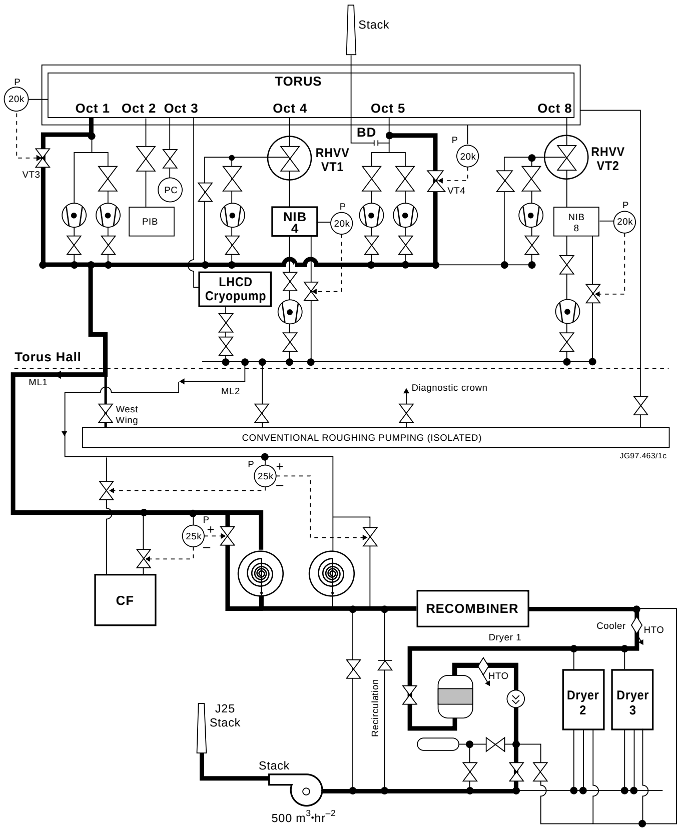


Fig.21: Emergency pumping route (shown in bold) for the Torus in the event of a LOVA or in-vacuo LOCA. (route shown is activated for Torus pressures above 25kPa). Trip levels are indicated in Pa.

In the event of other interlock failures, if the *discharge* pressure of the Normetex pumps rose above 120kPa, the pumps would trip but the EDS blower would remain pumping through the Normetex Bypass to avoid a breach of the vacuum crown whose bursting discs are rated at approximately 130kPa.

7.2 Depressurisation Plant and Fire Suppression System

The JET Tokamak is situated inside the torus Hall whose concrete walls, doors, floor and roof form a complete Biological Shield. Other elements of biologically-shielded areas in the JET buildings are the Access Cell to the Torus Hall and the Basement through which supplies are led to the machine. The tritium Torus Gas Introduction Module (TGIM) and NBI TDGIS units are in the Basement.

The regulatory requirements for operation of JET prescribe that any tritium permeating through the Torus or NIB vessels into the Torus Hall, or any activation products emitted through a containment breach into the Torus Hall or Basement, must be discharged to atmosphere through a monitored stack. To this end, the leaks in the Biological Shield due to penetrations for supplies and diagnostics were carefully filled prior to the commencement of DTE1, to minimise the leak rate. In addition, a *Depressurisation Plant* was commissioned to hold the Biological shield at sub-atmospheric pressure to ensure a positive in-leak. The Depressurisation Plant consists of three Duty-Fan systems, one for each area of the Biological Shield. Each fan system has built in redundancy with automatic starting of a Standby Fan in case of Duty Fan failure. The Depressurisation System is capable of 1 m^3 s^{-1} extraction rate giving a maximum depression within the Torus Hall of - 650Pa.

The normal JET fire-fighting system within the Biological shield used ‘Halon’ gas. The use of this in tritium operation is undesirable as it might poison the AGHS catalysts in the event of emergency through-breach pumping having to be provided by the EDS. Use of Halon would also lead to the release of activated products (^{80}Br). For the DTE1 operation it was thus decided to commission a special *Fire Suppression System* using gaseous nitrogen to reduce the oxygen content of the atmosphere inside the Biological Shield to < 15%, which is insufficient to support normal combustion. A schematic of the joint Depressurisation Plant/Fire Suppression System is shown in Fig. 22.

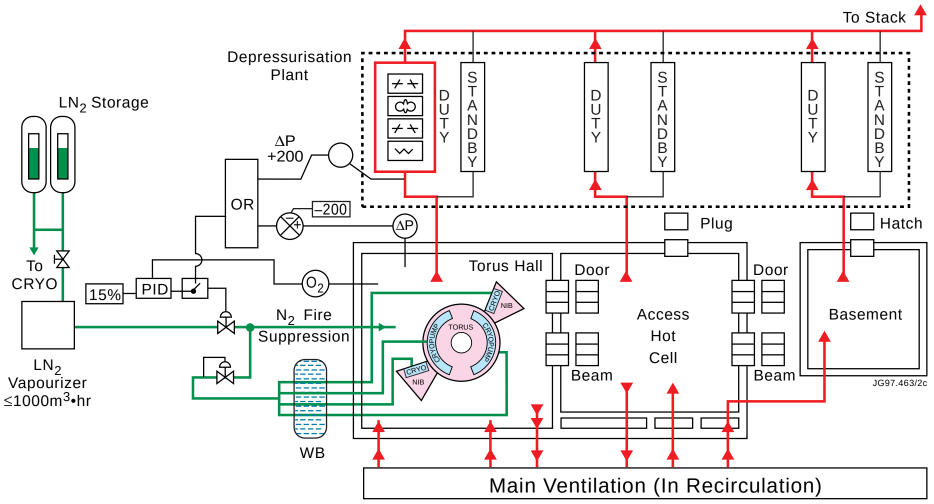


Fig.22: Schematic of the combined Depressurisation Plant and Fire Suppression System used in DTE1.

The Fire Suppression System uses a baseload of gaseous N_2 from the boil-off of the LN_2 shields of all the torus and NB Injector cryopumps and routes this back to the Torus Hall. This flow (typically ~ 900-1000 m^3 hr^{-1}) is supplemented by gaseous N_2 from an evaporator. The supplementary supply is under feedback control from a Torus Hall oxygen monitor, and is disabled if the Biological Shield depression becomes too small. This coupled system has been optimised to minimise tritiated water arisings from the atmospheric moisture removed by the ventilation system and also to minimise LN_2 usage. The typical operating depression of the Torus Hall during DTE1 was ~ 350Pa.

The system is capable of reducing the oxygen content within the Biological Shield from 21 to 15% in around eight hours. Operating Instructions for JET demand that the combined system is used at any time when there is ‘significant’ (> 0.1 gr. or 37TBq) tritium inventory outside the AGHS boundary in ‘releasable’ form (ie. on the cryopanels within the vacuum or in storage reservoirs and pipes associated with the TGIM or TDGIS).

7.3 Safety Measures on the NBI tritium gas feed

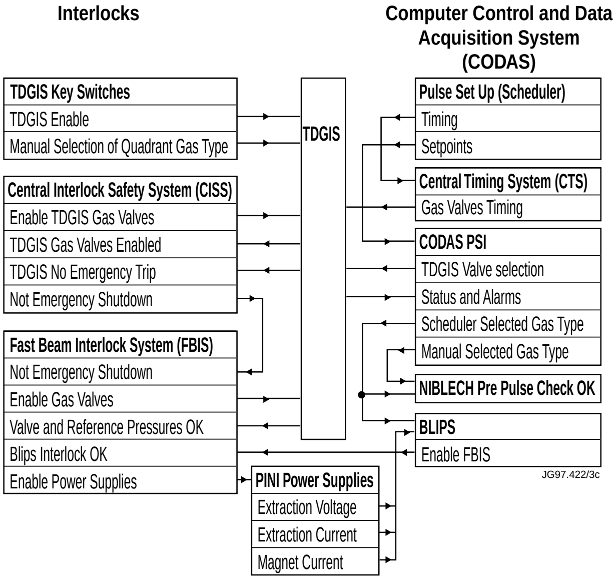


Fig.23: Schematic of Interlock and Control relationships involving the Neutral Beam Tritium-Deuterium Gas Introduction system (TDGIS).

The tritium gas feed to the Octant 8 Injector was done via the TDGIS unit. This specially-designed unit [35] consisted of a doubly-contained system with pumped interspace: the inside of the system containing selection valves; pressure regulators; pressure transducers; flow restrictors and storage reservoirs. The interlock network associated with the TDGIS is shown schematically in Fig. 23. The most important interlock function involved the selection of the *correct gas* (tritium or deuterium). The extracted ion beam from the PINI sources is only partly neutralised and transported to the JET plasma. A high power (> 50% of the extracted power) remains in the form of ions which are magnetically deflected onto Ion Dumps. The correct setting of the magnetic field to match the extracted beam voltage is vital for safe-handling of the power. This consistency of setting is assured pre-pulse by the *'Task Scheduler'* program (sec. 4.2) and the Deflection Magnets are also energised and checked pre-pulse by a check program *('NIBLECH')*. During beam extraction the consistency is measured in real time by a microprocessor-based system *('BLIPS')* whose outputs are used to terminate the beams via FBIS in the event of an out-of-normal condition (as shown in Fig. 4). The interlock protection is seen to be multi-level in this respect but *all* checks depend on the *correct isotope* (D_2 or T_2) having been identified for injection, since the relationship between magnet current and beam voltage is mass dependent. Thus the correct gas type (as demanded from the supply Uranium beds of the AGHS [3]) had to be identified to the various interlock systems and control software. Since the TDGIS was capable of supplying different *quadrants* (pairs of PINIs) on the Injector with different species [18], it was also important not to mix gases accidentally in a storage reservoir. The changeover of gas in a quadrant was thus only allowed if the storage volume was first pumped out to < 100Pa (checked by a pressure switch). Only at that point could the energisation of the valves supplying the replacement gas be performed by introducing a unique keyswitch (there was a separate 'deuterium' and 'tritium' keyswitch for each quadrant). The normal supply pressure of the storage volumes in the TDGIS was ~ 40-45kPa. The procedure for changeover thus ensured that the possible cross contamination of gas was < 0.25%. At this point the potential stray power from a contaminant (ie. wrong isotope) ion beam would be < 2-3W cm^{-2}. The keyswitch inputs were checked for consistency and any inconsistency, or inconsistency in the valve status, was used to Inhibit the pulse (if detected pre-pulse) or produce a CISS Emergency Shutdown (if detected within the pulse).

8. OPERATIONAL EXPERIENCE DURING DTE1

The DTE1 campaign began in May 1997 and was completed in November 1997. Prior to the start of DTE1, all IOPS were commissioned using written *Commissioning Procedures* which had been given formal approval by the Machine Protection Working Group and Co-ordination Meetings. Such formal Commissioning Procedures had been in operation for some time, but were tightened up with the approach to DTE1 including approval by the Authority To Operate (ATO) Holder for Torus Operations. On completion of a particular Commissioning Procedure, a *'Readiness for Operations'* (RFO) form was completed by the responsible team and lodged, with the completed Commissioning Procedure, in the Quality Assurance Archive thus forming a completely auditable system. The ATO Holder also received copies of all completed RFO forms. Some of the Commissioning Procedures for the Safety Related and Class 1(A) IOPS were extended to include complete 'live' simulations of response to particular DBA scenarios. An example of this was the simulated LOVA on the torus performed by admitting gas which tripped the 1500Pa and 20kPa interlock levels on the D&RS and Bypass Valves Systems. All tests of this type were performed under safe conditions with the Torus at ambient temperature. Once commissioned, activities such as maintenance, fault-fixing, recalibration and trip level setting were strictly controlled on IOPS networks by a series of *Intervention Documents.* These were individually numbered, 'travelled with the job' and were archived for traceability once signed-off. Each intervention had to be formally approved by the duty Engineer-in-Charge or, where a change impinged on the provisions of an Operating Instruction, by the Principal Engineer. During the DTE1 period 114 individual Intervention forms were completed. None of the recorded interventions were of any significant severity. Note that all interventions have to be completed with a recommissioning statement. Given the strict regime, the number of interventions (which averaged around 1.5 per operational day) was quite modest. Interventions include the bypassing of protection signals. During this period no signals involved in Class 1(A) or Safety Related IOPS were bypassed.

8.1 Experience with Passive Protection

Since its installation in the 1996 Shutdown (nine months prior to DTE1), the vacuum interspace system for torus windows and feedthroughs had, by January 1999 suffered 14 leaks of which seven were associated with vacuum windows. There have been no leaks on NIB Interspaces. In all cases it has been possible to identify the leak via the loss of interspace pressure and to evacuate and isolate the interspace. This procedure has led to significant improvements in machine down time.

There have been no leaks on the other significant double containment systems ie. the secondary containment evacuated interspace surrounding the in-vessel Divertor Coils and the secondary containment lines and vessels associated with the tritium gas introduction systems (TGIM and TDGIS).

8.2 Pulsed Operation Protection Systems

As indicated in sections 6.3, the Pulsed Operation Protection Systems functioned correctly during the DTE1 (and in subsequent campaigns). Out of normal events such as Loss of stability of the plasma (leading to disruptions); overpressure in the Neutral Beam Duct (leading to fast beam termination via FBIS); and NB termination due to insufficient plasma density occurred on several occasions in DTE1 and were handled correctly.

8.3 Continuous Operation Protection Systems

During the DTE1 period (and in subsequent operation) there were no serious LOVA, LOCA i-v or LOCA *ex-vacuo* events. In this sense the Continuous Operation Protection systems were not tested in a live event. The only LOCA i-v which occurred in the period was a small in-vacuo water leak in the stainless steel flexible hose bellows supply water to the Fast Shutters of the tritium NIB8. The presence of this leak (which occurred with the NIB cryopumps in operation) was detected by routine operating procedures monitoring the Penning Gauge and Residual Gas Analyser signals from the NIB vacuum. The detection was achieved whilst the NIB pressure was approximately $5 \cdot 10^{-5}$ Pa, a factor of 100 below the trip level at which FBIS would have switched off the beams during a pulse (although no pulse was in progress). Note however that the normal out of pulse pressure in the NIBs is 10^{-6} Pa. This small leak was pumped adequately by the cryopumps, but operations were suspended and the cryopumps warmed to ambient temperature (after the NIB had been isolated from the Torus). The small amount of tritiated water produced was pumped out as water vapour via the EDS. An intervention took place to repair the leaking bellows. This intervention and repair are described in more detail in refs [18] and [36]. After the intervention successful operation resumed with no further problems.

During the DTE1 period some minor problems occurred on the EDS which led to periods where one or other of the driers was out of action. The redundant design, with three driers, meant that one drier was always on standby. The problems related to:

- valves on the regeneration loop of the driers which failed to open properly thus preventing the regeneration of a drier (the molecular sieves of the drier eventually becoming saturated and hence useless for detritiation); and
- worn bearings on the blower unit of one drier.

The valve problems were traced to corrosion on the interior of the valves. Valves were replaced whilst the EDS was kept operational. The type of valves will be replaced with a new design in the 1999 JET Shutdown.

A potentially more serious problem with the EDS occurred in the period of ‘clean-up’ of the Torus using pure deuterium plasmas after DTE1. (This clean-up period is described in a companion paper [37].) The Safety Case requires that there is a main and back-up power supply to the EDS and that in the event of a loss of power to the system an autochangeover unit switches to the back-up. On one occasion both main and back-up power supplies failed. As a result, the autochangeover also burnt out. The EDS was without power for 1hr 40mins. There were no radiological consequences arising from this power failure, which has been the only loss of availability of the EDS in three years of operation.

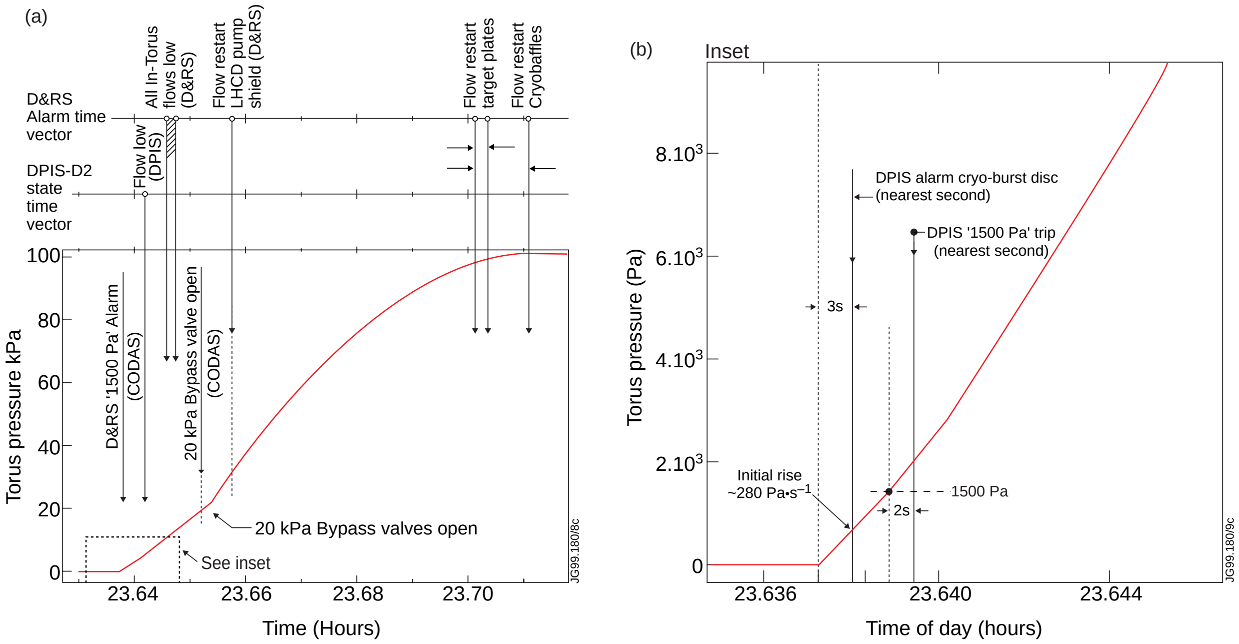


Fig.24: Measured time behaviour of Torus pressure (from absolute Baratron gauge) during the accidental vent on 29 April 1997. Also shown are the times (to the nearest second) of alarms registered by D&RS (through CODAS) and the DPIS-D2 PLC. a) Overview of pressure history and alarm recording b) Inset of initial pressure rise.

Note: i) *The data of the pressure is recorded at ~ 3s intervals.*

ii) *When the Bypass Valves Opened, because the EDS pumping was not in operation, the Torus pressure increased more rapidly. In operational mode in DTE1 and subsequently this event would slow down the pressure rise.*

A few weeks *prior* to the start of the DTE1 campaign, and the introduction of tritium to systems outside the AGHS, an accident occurred which led to a strong LOVA event on the Torus (the NIBs were isolated at the time). The event, on 29 April 1997, involved the unintentional venting of the Torus through an incomplete system which had an angle valve connection to the Torus backing line. This vented the Torus to atmospheric pressure in 4·5-5·0 minutes. The Torus pressure trace in this event was monitored (as usual) by an absolute ‘Baratron’ gauge and the computer trace of the pressure is shown in Fig. 24. The protection system actions of D&RS, DPIS-D2 and the Bypass Valve Interlocks were time-stamped by signals to the CODAS Alarm recording and so these can also be seen marked on Fig. 24. Note the Alarm Package, which cycles the status of many thousands of points on the plant, records only with an accuracy of 1-2 seconds. Nevertheless, the history of the event is well reconstructed. From Fig. 24 we can see the sequence of events where the 1500Pa direct interlock of D&RS tripped and isolated all the water in the in-vessel components (leading to low flow alarms). This locked-in water was pressure-tested as described in sec 6.2.1, with a successful pass (since there was no water leak). The flows were then restarted to the various components. Note that the flows were restarted after different time intervals. This reflects the fact that different in-vessel circuits have differing characteristic times before they are at risk from freeze-up or boiling [23]. The component most at risk is the water cooled shield which protects the appendage cryopump on the Lower Hybrid launcher (LHCD cryopump) from the radiation of the hot launcher assembly. A freeze-up in this component (because of close proximity of the shield to the cryogenically-cooled surfaces [27]) is predicted in ~ 1-2 minutes if flow stops whilst the vacuum pressure is in the > 100Pa pressure range. Thus the protection systems only allow water flow to be stopped for ~ 1 minute before restarting flow (in the event it can be seen that the hardware timer allowed ~ 43 secs). Other more robust components have flow stopped for up to 5 mins. Of course a decision to drain (in the event of a real water leak) would occur in a matter of seconds.

Also seen in Fig. 24 is the appearance of alarms indicating a Bursting Disc rupture on the ScHe loop of one half of the cryopump. This helium circuit rupture disc vented the ScHe contents of the line into the Torus Hall. The volume vented has no connection with the Torus vacuum and the Disc is set to go at an overpressure of 10bar(g) in the ScHe line [~ 1·1MPa(a)]. The pressure rise occurred due to condensation of a fraction of the large amount of initial air influx into the Torus. Using the known conductance of the throat to the PD pump (see Fig. 6) and the measurements of the initial Torus pressure increase rate (about $280 \mathrm{Pa \cdot s^{-1}}$ from Fig. 24) it was possible to estimate that about 20% of the incoming air was condensed onto the ScHe cooled surfaces of the two halves of the pump. The air flow onto each half of the pump was estimated at ~ $5500 t_{pv}$ $\mathrm{Pa \cdot m^3 \cdot s^{-1}}$ (where t_{pv} is the post-vent time in seconds).

The turbulent ScHe flowing through the pipes has a heat transfer rate of:

$$Q_{ScHe} = \alpha \cdot A \cdot \Delta T \tag{2}$$

where α is the heat transfer per unit area and per degree difference between pipe material and helium; A is the pipe surface area and ΔT the temperature difference between pipe and ScHe bulk.

α can be evaluated using equations for turbulent flow (Dittus-Boelter equation) and, at the time of the event, for the measured ScHe flow rates was between 360 and 440 $\mathrm{W \cdot m^{-2} \cdot K^{-1}}$ for the two pump halves. Thus equation (2) gave the heat flux which could be transferred in the $4 \mathrm{m^2}$ area of the ScHe pipes as between 1.44 and $1.76 \mathrm{kW \cdot K^{-1}}$. The condensing air was inputting ~ $30 t_{pv}$ kW to each half of the pump and so a temperature differential of 10-20K between ScHe and panel surface was established in less than 1 sec after the vent. Using the temperature-entropy diagram for ScHe it was possible to establish the heat input needed to raise the pressure of

ScHe from the normal operating pressure (280kPa) to the Bursting Disc rupture pressure (1100kPa), and to iterate and find the time at which the Bursting Disc was at risk (t_{BD}) and *panel surface* temperature at this time [T_{PS} (t_{BD})].

If T_{PS} (t_{BD}) was below the condensation temperature of N_2 at the Torus pressure at time t_{BD} [ie: $p_{sat}^{N_2}$ ($T_{PS}(t_{BD})$) < p_{VV} (t_{BD})] then condensation of air would remain the controlling heat input mechanism up to the rupture of the disc. This happened on one half of the pump. The calculations showed that the ScHe reached 1·1MPa at t_{BD} ~ 1·2s after the vent. At this time the panel surface temperature T_{PS}(1·2) was at ~ 35K where $p_{sat}^{N_2}$ is < 0.15Pa, negligible compared to the p_{VV}(1·2s) ~ 330Pa. The rupture of the Bursting Disc, due to a pressure wave which could not be relieved along the long transferlines to the cryoplant, was thus explained. The other half of the PD pump was still being filled with ScHe (after a regeneration) at the time of the accident. The starting temperature of the loop was thus higher (average ~ 15K against ~5K). Initially in the vent the air condensed on this half of the loop as in the other half. The temperature of the panel surface was however driven to > 50K before the internal pressure reached 1·1MPa. At this temperature the $p_{sat}^{N_2}$ is in the range 600-700Pa. The condensation of nitrogen onto the helium panels was thus stopped and heat transfer by normal convective means took over. This heat transfer is more than an order of magnitude lower than the heat input by condensation. In addition, the oxygen in the air would be still condensing on the much larger LN_2 panels which shield the ScHe panels. Thus the thermodynamics of the system were able to provide a plausible explanation of the *non-rupture* of the Bursting Disc on the second half of the PD pump. The computed trends of the system behaviour are shown in Fig. 25.

The analysis of this episode showed that the Bursting Disc design

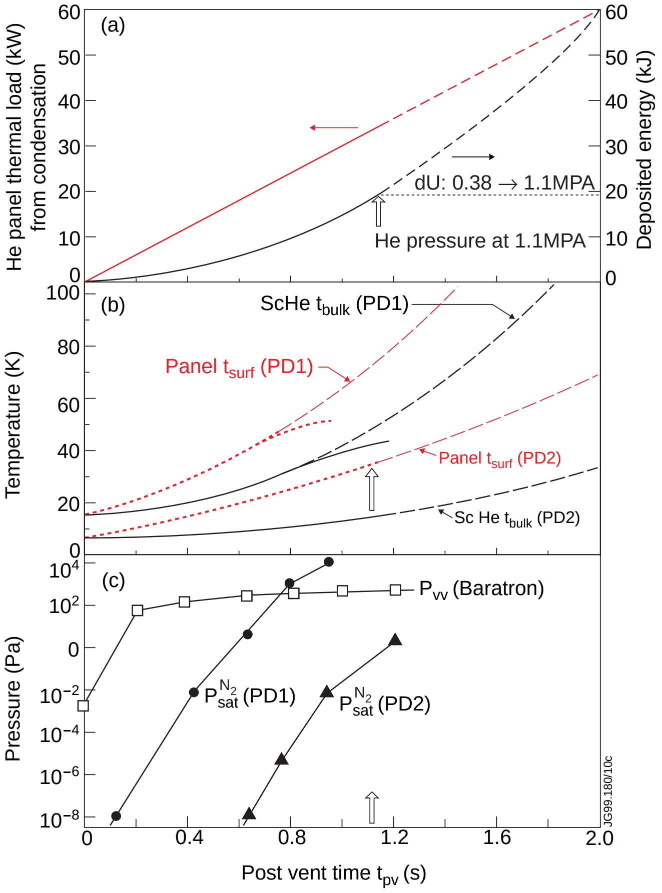


Fig.25: Calculated quantities relating to the behaviour of the in-Torus Supercritical Helium cryogenic loops during the early time following the accidental Torus vent on 29 April 1997.

a) *Calculated power and heat input to the ScHe from condensation of Nitrogen from the vent.*
b) *Calculated ScHe bulk (t_{bulk}) and Panel surface (t_{surf}) temperatures for both halves of the in-vessel pump. Note that the starting temperatures (at t_{pv}=0) come from* measurements *of sensors.*
c) *Interpolated in-vessel measured pressure (p_{vv}) compared to calculated saturated vapour pressure of Nitrogen at the panel temperatures from (b).*

was correct to prevent rupture of the in-vessel cryopump surfaces during a serious LOVA. It also demonstrated the correct action of DPIS-D2 in cutting the cryogenic supplies in the event of a leak. The experience gained in this pre-DTE1 LOVA provided confidence in a wide-range of protection systems and passive safety features.

The only other damage occurring in the vent was the stripping of fan blades on one of the four Torus turbomolecular pumps due to the high pressure of the throughput. These pumps are isolated by the protection systems as the Torus pressure reaches 100Pa, but the finite closing time of the isolation valves allowed the violent pressure surge to cause some damage. The damaged pump was replaced before the DTE1 campaign. Neither the damage to the pump nor the Bursting Disc damage led to any breach of the primary containment and thus would not have led to the dispersal of activity from a tritiated Torus if it had occurred in DTE1.

The accident leading to the vent was excluded as a possibility during DTE1 because by the time DTE1 commenced the system behind the angle valve had been completed.

9. CONCLUSIONS

Operation of JET during the DTE1 period and subsequently, has been achieved in complete safety both for pulsed operation with plasma and for the continuous operation of the machine’s ancillary services.

The Continuous Operation Protection Systems for JET were not called upon to act within the DTE1 period, but were extensively tested prior to DTE1 and a significant number of them were exercised (correctly) in the single serious LOVA event which occurred prior to DTE1.

The Pulsed Operation Protection systems have continued to act in a correct manner to avoid disruptive events, damage to the JET coils and damage to the Neutral Beam system. As JET spends a significant part of its operational time near to performance limits these protection systems are essential.

All protection systems have a high reliability, and do not contribute significantly to the down time of the system. In particular, no time was lost during DTE1 due to protection system unavailability.

The experience with protection systems on JET shows the benefit of several design and management decisions.

i) The system and its controls and protection circuits were designed *from the outset of the project* with the case of high yield tritium operation in mind. This determined the layout (biological shield, no electronics in the Torus Hall, remote monitoring and control, etc) and raised the level of engineering which would be required from control and interlock sensors and actuators at an early stage. A base level of high integrity protection and monitoring circuits thus existed to which the modifications for tritium operation could be added in a relatively seamless transition.

ii) The JET machine has always operated with very high operational availability between major shutdown modifications. This is driven by the obvious need to ensure a cost-effective programme. Its practical consequences are that the ‘vessel conditioning’ services (vacuum vessel baking, LN_2 and LHe cryogenic supplies, in-vessel water and freon cooling) need to operate around the clock for periods of months on end. This drove, from an early stage in the design, the necessity to develop sophisticated protection systems to protect the vessel from leaks and to avoid down-time from the effects of thermal stress or thermo-mechanical damage to in-vessel components. Such protection systems were then extended in a natural manner for tritium operation.

iii) The upgrading of JET from its original configuration of a limiter plasma, with plasma current (Ip) up to 4·8MA and toroidal field (B_T) up to 3·4T, to a shaped divertor-plasma with $Ip \leq 6{\cdot}0MA$ and $B_T \leq 4{\cdot}0T$, combined with the long pulse operation, were powerful driving forces in the development of sophisticated and reliable Pulsed Operation Protection Systems. The upgrades were extensively analysed and this generated an awareness of machine limitations which was used as valuable input to protection system redesign.

iv) The decisions on the IOPS networks which were brought into force a few years before DTE1: to submit them to centralised review; to commission to standardised Commissioning Procedures; and to control rigorously, via traceable Intervention Documents, any changes during operations, were important in ensuring reliable and safe operation, and in being able to demonstrate this to regulatory bodies.

There are ongoing improvements to protection systems on JET. In particular, since DTE1, some site power outage problems have highlighted the need to improve the capabilities of Uninterruptible Power Supplies (UPS) networks which serve IOPS and their ancillaries. These outages have not caused problems of protection *per se* but have led to unnecessary cycling of Continuous Operation protection systems due to lack of power. These issues are being successfully addressed.

In addition, JET is moving away from having local microprocessors in the protection circuits between field sensor and PLC. This was present in some systems (eg: DPIS-D1 and DPIS-D2) where vacuum gauges’ signals are used to determine protective action. Although the microprocessors have been reliable and have never led in practice to any unsafe condition, the standardisation philosophy at JET is moving towards *direct* field sensor input into the PLC. In a similar manner, for obvious reason, local microprocessors in the output (action) circuitry of the PLC-based protection systems have been removed (except where the relationship is the cascading of two safety-oriented PLCs eg: DPIS-D2 and D&RS – see Fig. 8).

Regarding the passive protection, an inconvenience of the Interspace Monitoring system was that the Interspace pressure itself could not be monitored remotely during DTE1. This is a significant shortcoming as personnel cannot enter the Torus Hall for several hours after operation partly because of the short-lived radioactivity induced on the machine during the D-T pulses, and partly because of the time taken to flush the Torus Hall with breathable air, removing the effect of the Fire suppression system.

In future plans for the JET machine, the Interspace Monitoring gauges are being given remote readout capability. This will be necessary for futher DT campaigns, such as the proposed ‘DTE-2’ experiment generating $\leq 5\ 10^{21}$ neutrons [38], where the increased 14MeV neutron yield will produce higher levels of post-operational radioactivity. It will also enable trouble-shooting to occur at a much earlier stage.

As indicated in the earlier sections of this paper, because the protection systems at JET have developed over a period of 15 or more years, and because JET has been viewed as an experimental device, no standardisation of protection system architecture and philosophy has been possible. Thus, for example as indicated above, some protection systems have local micro-processors (especially in input loops), others do not. Whilst this has not created any *safety* problems, it does lead to unnecessary design effort; to inefficiencies in maintenance and commissioning (both from effort expended by personnel and from provision of spares); to difficulties in analysing the safety of design solutions; and to difficulties in establishing adequate internal (to the Project) regulation of Machine Safety. It is certain that future Fusion research machines of JET-size or larger (reactor) size should address these problems early in the design phase and establish project-wide design practice on interlock and protection systems. Some practices and codes from fission reactors will be applicable to fusion. There will also be the necessity to develop practices which address specifically the pulsed nature of a fusion device. The experience on JET will be invaluable data in addressing these issues.

APPENDIX 1

Equilibrium in-vessel pressure reached during major Neutral Injector water-leak

This section aims to show that there is a measure of passive safety during a water leak in the Neutral Injector Box (NIB) even if the absolute valve (the Rotary High Vacuum Valve – RHVV) remains open between the NIB and the Torus Vacuum Vessel (VV).

The water circuit of the NIB is shown schematically in Fig A1.1. In the event of a large water leak (eg: the Design Basis Accident of a guillotine break in a 30mm diameter pipe), the discharge rate of water is given by the sub-cooled orifice equation:

$$\dot{M}_w = C_d A(2\rho\cdot\Delta P)^{0.5} \quad \text{kg.s}^{-1} \qquad \text{A1(1)}$$

C_d = 0.61

A = discharge orifice area (m^2)

ρ = density of fluid ($kg.m^{-3}$)

ΔP = Pressure differential (Pa)

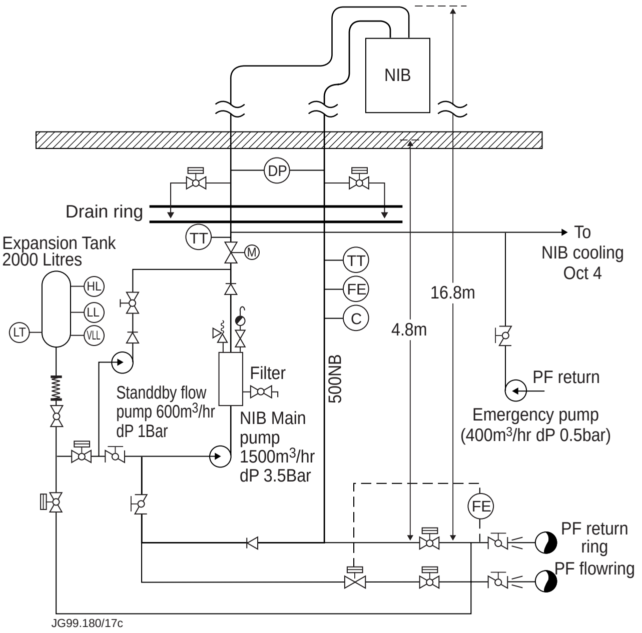


Fig.A1.1: Schematic of the NIB water loop.

For the NIB water circuits the *average* ΔP would be 550kPa and thus $\dot{M}_w \sim 14.2 kg.s^{-1}$. Such a water output could easily lead to heat input to the LN_2 and LHe assemblies of the cryopanels sufficient to blow their external Bursting Discs. Although the panels have masses of several tonnes, their long term help in condensing the water could not be relied on. At the discharge rate from equ. A1(1), a quantity of water ~ $1m^3$ would very quickly (~ 70 secs) be delivered to the floor of the NIB.

Operating Instructions for JET operation insist that the RHVV connecting the NIB and Torus is only open when the NIB cryopanels are filled with LHe and when the shields are full of LN_2. In this case considerable cooling power exists to bring the water temperature down.

It is not the purpose of this note to describe in detail the transient phase of a major spillage, rather to cover the longer term passive safety of the situation. Nevertheless, some points can be noted.

i) The evaporating water vapour would condense on the LN_2 and LHe panels giving considerable heat input. This would already be in the MW range at a pressure of 100Pa. There is considerable heat capacity in the LN_2 filling the panels (200ℓ requiring of order 40MJ to evaporate completely), but much less in the LHe panels (150ℓ requiring of order 0·45MJ for evaporation). Both cryogenic liquids are supplied at a pressure ~ 110-140kPa and the lines have *ex-vacuo* bursting discs set at 1MPa.

The heat input required to reach this pressure differs by over a factor of 30 between the helium inventory and the nitrogen inventory because of the lower mass and specific heat of helium. In addition, the helium gas would reach 1MPa at a panel temperature at which heat input from water vapour was still occurring (~ 40-50K), whilst the nitrogen gas could rise to the ambient temperature before reaching the critical pressure. These considerations show that the helium line bursting disc would be likely to rupture in such an incident but the nitrogen line would almost certainly remain intact.

ii) The heat capacity in the 4.8 tonnes of aluminium cryopanels to warm up to 0°C is around 660MJ. This compares with the heat loss of ~ 420MJ required to cool 1m^3 of water from 20°C to 0°C and freeze it. Thus we can see that in the initial stages of the leak the water would undergo considerable cooling, although it is doubtful that a proper ice layer would form on the water on the floor of the NIB. The NIB pressure would rise relatively quickly (in the first minute or two) above the 500Pa trip level (this is the vapour pressure of ice at ~ -5°C).

At the 500Pa pressure the pumps would be stopped (by DPIS) and the NIB water loop would be isolated from the Poloidal Field (PF) loop and provided this happened, then the amount of water which will enter the NIB would be limited. The quantity of water in the Central Column of the NIB (Which carries all the beamline transport components) plus the large pipes is 7·5m^3 above the torus Hall floor level (see Fig 15). The total quantity of water in the *isolated* NIB loop (see Fig A1.1) is different for each Injector being in the range of 13·3-16·2m^3. For water to spill bodily into the Torus from the NIB, a volume of 16·5m^3 is needed in the NIB. This is unavailable if the loop is isolated. In reality, much less than this quantity would enter the NIB. The ‘gravity head’ which water has to overcome to pass from the pump in the basement to the high point in the system (point ‘A’ in Fig 15) is ~ 170kPa (16.8m). The massive loss of water being considered would certainly cause the pumps to cavitate and trip, leaving the loop unpressurised. The pressure in the water vapour in the NIB, where there is no significant source of heat, would not rise above ambient (~ 20°C) where the vapour pressure of water is ~ 2.3kPa. Thus the suction provided by the NIB would be ~ 97.7kPa and would not be enough to bring water bodily from below floor level into the NIB. The equilibrium situation would be as shown schematically in Fig. 15 and the amount of water in the NIB would be limited to ~ 4m^3, a depth of 0·7m on the NIB floor. This is not enough to pass bodily over the duct lip into the Torus VV.

Ingress into the Torus VV would be limited to molecular flow of water vapour down the Neutral Beam duct. The duct has conductance for water vapour $C_w \sim 16{\cdot}5m^3{\cdot}s^{-1}$ as long as the Rotary Valve remains open. Thus the 50m^3 NIB would equalise in pressure with the Torus with a time constant ~ 3 sec.

The pressure in the Torus would be limited to the water vapour pressure in the NIB which would always be ~ 2·3·kPa. At this pressure the Torus emergency draining sequence (actuated at 1·5kPa) would have come into action, and presumably a null-result regarding an in-Torus water leak would have been registered. The pressure would be loo low for the emergency pumping to operate, but even if the Torus were to remain at 320°C, the heat exchanged between gas in the Torus and that in the NIB, would not be enough to raise the temperature of the NIB its components and the spilled water by any significant amount. This is easily seen by noting the huge masses of the NIB (43 tonnes) and Central Column (32 tonnes) compared to the small heat capacity of a couple of kilograms of hot water vapour in the Torus. The long-term isolated in-vessel pressure would not therefore rise significantly above 2·3kPa and the system has a good measure of passive safety, provided (accidentally!) by the design of the NIB.

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