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JET Engineering Development towards D-T Operations in an ITER-like Machine Configuration

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ABSTRACT

The Joint European Torus (JET) has recently begun a series of experiments with deuterium-tritium plasmas (DTE1). These are the first plasma experiments with a 50:50 D-T mixture in a Tokamak with a Divertor.

The extensive technical work to ensure that the JET machine and its major subsystems were able to carry out an extended period of D-T operation is described. This includes the JET Active Gas Handling System (AGHS) and its commissioning to full closed-cycle operation. The AGHS has supplied around 40g of tritium to the JET Torus and Neutral Beam Injectors (NBI) and has reprocessed batches of tritium of over 11g returned from the cryopumps of the Torus and NBI.

The modifications to bring the NBI system to full tritium compatibility and its commissioning are described. The injection of tritium beams at up to 155kV energy and up to total powers of 11.3 MW has taken place.

JET had to be subjected to extensive deterministic analyses of Design Basis Accidents (DBAs) to establish changes required to protection systems for D-T operation and to satisfy the regulatory authorities. An example of the practical consequences of these analyses and a discussion of the methodology is included.

The history of a successful plant intervention to repair a small water leak in the Tritium Neutral Injector is discussed. The success of the Exhaust Detritiation System (EDS) in keeping environmental discharges to below management limits in this exercise, and the lessons learnt generally, are also presented.

I. INTRODUCTION

The Joint European Torus (JET) tokamak has a unique experimental capability to introduce tritium into a machine with a *divertor* configuration. The plasma shape of JET and the value of several of its dimensionless parameters, such as inverse aspect ratio ($\varepsilon = a/R$, the ratio of minor to major radii), and the safety factor (q), are similar to those of the proposed International Thermonuclear Experimental Reactor (ITER) [1]. These factors increase the Next Step relevance of deuterium-tritium (D-T) plasma experiments in JET.

The JET programme [2] called for a period of D-T experimentation in the 1996-7 period. These experiments are known collectively as *DTE1* (first Deuterium Tritium Experiment). The physics results from this ongoing campaign are described in a companion paper [3]. The present paper provides an overview of the specific engineering developments required for DTE1.

II. OVERVIEW

JET was designed from the outset with tritium capability and has also operated over the years with beryllium components in-vessel. These factors ensured that a sound basic platform existed for the DTE1 experiment. In particular, JET has fully remote operation and diagnosis capability as far as systems within the biological shield are concerned. JET has also established, in beryllium operations, a culture of strict contamination and personnel exposure control, on which to build the tritium operations.

Particular circumstances were instrumental in driving development for DTE1 however.

1. A limited tritium inventory was allowed on site for DTE1 (total 20g). This, coupled with an ambitious, time-limited experimental programme forced *operational reprocessing and supply capability to be operated as designed as a close coupled integrated facility*.
2. The need to demonstrate high safety margins against *Design Basis Accidents (DBAs)* forced a complete engineering analysis of transient fault conditions in the machine systems.
3. There is a requirement to re-use the tokamak immediately after DTE1 for deuterium and hydrogen plasma physics experiments. *Efficient tritium clean-up mechanisms* were therefore necessary.
4. The requirement to intervene post-DTE1, and rebuild the inside of the machine for the JET Divertor programme [2] forced development of existing systems into an *operational proven and reliable Remote-Handling ability*. This is discussed in [4], [5].

The main systems which had to be engineered specifically for DTE1 were:

- the Active Gas Handling and Introduction System (AGHS);
- the Tritium Neutral Beam Injector (TNBI);
- the Biological Shield Depressurisation Plant/Fire Suppression system.

These systems are described below, together with general aspects of the engineering required to bring JET up to D-T operation.In addition, the result of fault analysis led to Design Actions involving modification of protection systems and some changes to hardware. Examples of these are also given below.

Finally, the operational experience with tritium is described, including a plant intervention to rectify a fault on the tritium NBI system.

III. PRINCIPAL ENGINEERED SYSTEMS FOR DTE1

A. Active Gas Handling and Introduction System (AGHS)

The JET AGHS is a closed-cycle gas supply and reprocessing plant [6]. A schematic diagram, showing the component blocks of the AGHS and the Torus Systems which it supplies, is shown in Fig.1.

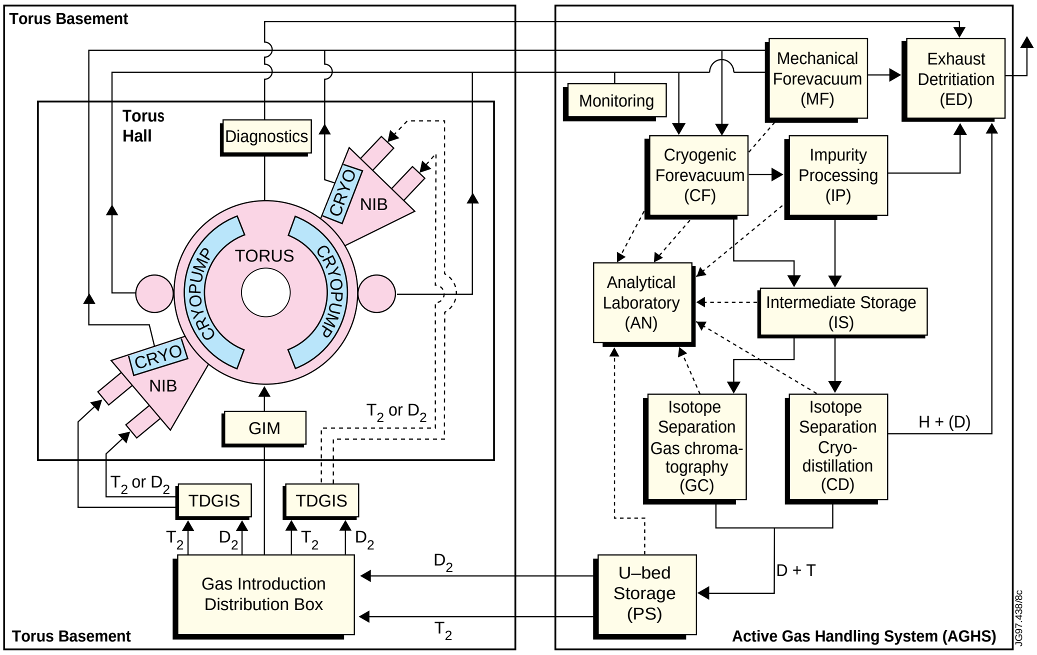

Fig.1 Schematic of the Active Gas Handling Systems (AGHS) and its relation to the tritium/deuterium distribution and pumping systems of the JET Torus and Neutral Injector.

The diagram identifies the principal AGHS components.

1. *Cryogenic Forevacuum (CF)* system which provides the continuous pumping for the Torus, Neutral Injectors and Diagnostics during D-T operation. The CF system uses a combination of 77K coldtraps, 77K absorbers, 4K cryosorption and 20K distillation to pump all gases arising from operations and separate them into pure hydrogen isotope mixtures and separate impurity streams.
2. *Mechanical Forevacuum (MF)* system which provides the pumping for the Torus and NBI systems using three large ‘Normatex’ scroll pumps and Roots pumps.
3. *Gas Chromatography (GC*) system designed to separate H-D-T mixtures into pure T_2 and D_2 streams. This has a throughput of 20 moles per day and uses the isotopic dependence of hydrogen solubility on palladium.
4. *Cryodistillation (CD)* and *Impurity Processing (IP)* systems deal with hydrogen and deuterium weakly contaminated with tritium and with impurities (water, tritiated hydrocarbons) respectively.
5. *Exhaust Detritiation System (EDS)* detritiates the exhaust from the vacuum vessels and from any containment breach (either planned or accidental) [7]. Detritiation of this exhaust is achieved via catalytic recombiners for HT, tritiated methane etc to produce tritiated water. The water is then removed from the output stream by driers with an output capability of a detritiation factor > 1000 at the drier outlet. The EDS is capable of a 500 $m^3 \cdot hr^{-1}$ throughput and its outlet goes to the monitored stack.

B. Tritium Gas Handling Introduction System

The schematic of the components of the gas introduction and recycling loop to the Torus and the Neutral Injectors is also shown in Fig 1.

The Torus tritium Gas Introduction Module (GIM) and the Neutral Beam Tritium Deuterium Gas Introduction System (TDGIS) are both double contained units as is the pipework connecting them and the Gas Distribution Module to the AGHS. This practice is followed everywhere on JET where tritium is contained in vessels at pressures above 100Pa. The interspace between the double containment is flushed by dry nitrogen to the AGHS where it is monitored.

The Torus GIM is capable of supplying tritium gas at flows up to $18\mathrm{Pa}\cdot\mathrm{m}^3\cdot\mathrm{s}^{-1}$ to either the Torus midplane or the divertor region. It is built with tritium compatible valves as used in the AGHS [6].

The TDGIS, capable of supplying deuterium and tritium to the Ion Sources of the NB Injector, is described in more detail in IIIC below. The NB Injectors and the torus are equipped with liquid helium (LHe) or super-critical helium (ScHe) condensation cryopumps [9], [10]. These surfaces pump the majority of the tritium used and this is then returned in batches to the AGHS CF system during regenerations of the LHe or ScHe circuits.

C. Tritium Neutral Beam Injector

JET is equipped with two Neutral Beam Injector (NBI) systems [9] providing high velocity neutral atoms of hydrogen isotopes for plasma heating. These are each equipped with eight Positive Ion Neutral Injector (PINI) Ion source/accelerator units which provide the high velocity beams. These PINIs have been operated in a variety of combinations [11] to provide up to 13.6MW neutral deuterium power per Injector at energies up to 140kV (though not simultaneously). For the DTE1, both Injectors were converted to be tritium compatible, but only one Injector has been used to inject tritium (at up to 155kV energy).

The conversion to tritium operation involved a number of individually minor design changes, which are indicated on Fig.2. Most changes improved the defences against accidental release of tritium (metallic seals, pumped interspaces etc). The most important change was the construction and commissioning of a Tritium Deuterium Gas Introduction System (TDGIS) [8].

An overview of the TDGIS is shown in Fig.3. The TDGIS supplies gas to the PINIs at ground potential, avoiding the normal gas supply system which involves supply of gas via a frangible isolation break surrounded by SF6 in the High Voltage supply tower of the Injector. The TDGIS components have a secondary containment consisting of a pressure vessel with design pressure 1.1MPa.

The notable features of the TDGIS are [8]:

- supply of highly stable gas flows to eight PINIs for ~15secs (flow rates around $2.5\text{Pa}\cdot\text{m}^3\cdot\text{s}^{-1}$);
- simultaneous supply of tritium and deuterium to adjacent pairs of PINIs in the tritium NB Injector;
- fail-safe selection of the correct gas and avoidance of accidental gas mixtures being sent to a PINI. This is assured by a hardwired interlock system and connection to the JET Fast Beam Interlock System (FBIS) to terminate a beam pulse in case of fault [12].

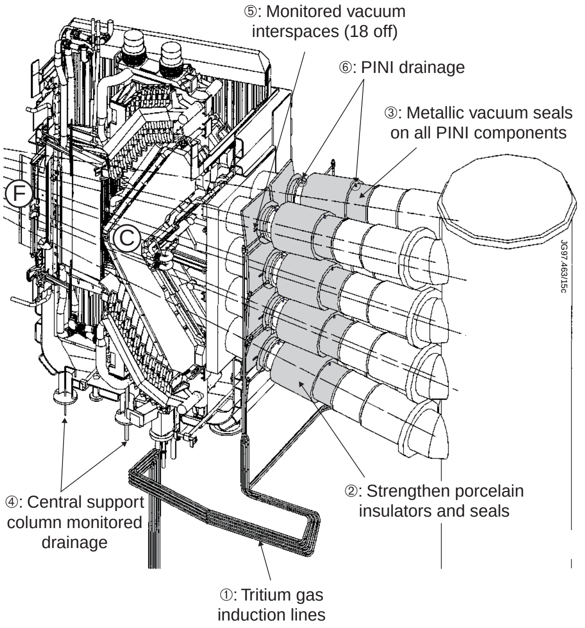

Fig.2 JET Neutral Beam Injector cutaway drawing showing the principal modifications for tritium injection ('F' marks the Fast Shutter component on which a leak developed and 'C' marks the Central Support Coloumn).

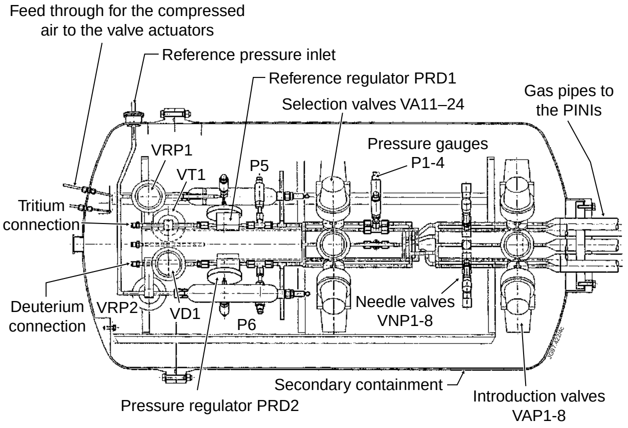

Fig.3 The Neutral Injector Tritium Deuterium Gas Introduction System (TDGIS).

D. Biological Shield Depressurisation Plant/Fire Suppression System

The JET Tokamak is situated inside the Torus Hall whose concrete walls and doors form a complete Biological Shield. Other elements of biological shielded areas on JET are the Access Cell to the Torus Hall and the Basement through which supplies are led to the machine. The tritium GIM and TDGIS units are in the Basement.

The regulatory requirements for JET [13] prescribe that any tritium permeating from the Torus into the Torus Hall or any activation products emitted through a containment breach must be discharged to atmosphere through a monitored stack.

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* System was commissioned to hold the areas inside 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 $1m^3 \cdot s^{-1}$ extraction giving a depression to the Torus Hall of -650Pa.

The normal JET 'Halon' fire-fighting system is undesirable in tritium operation as it might poison the AGHS catalysts (in the event of emergency pumping having to be provided by the EDS); it would also lead to the release of activated products (Br^{80}). It was thus necessary to commission a special *Fire Suppression System* using gaseous nitrogen to reduce the oxygen content inside the shield to < 15%, which is insufficient to support normal combustion.

A schematic of the Depressurisation Plant and Fire Suppression system is shown in Fig.4.

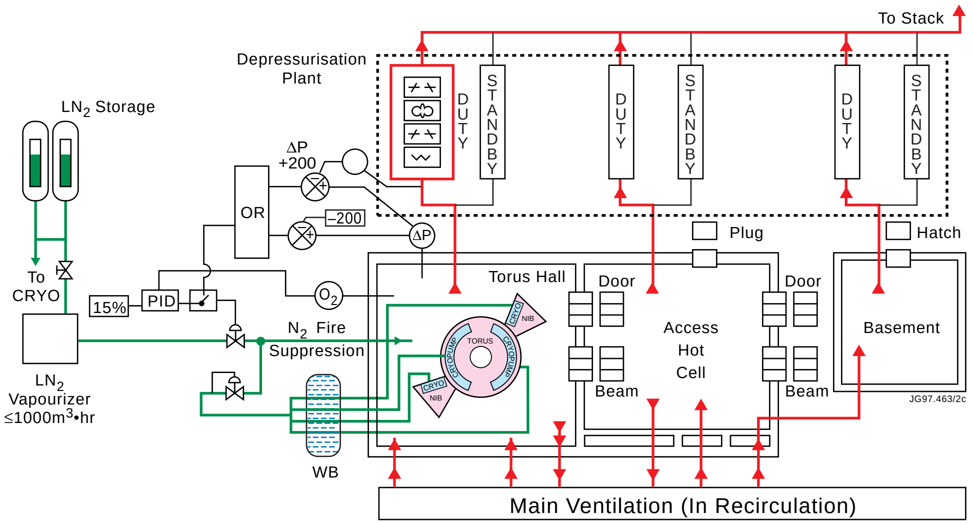

Fig.4 Schematic of the combined Depressurisation Plant and Fire Suppression System used in DTE1.

The Fire Suppression system used a baseload of gaseous N_2 from the boil-off of the LN_2 shields of all the Torus and NB Injector cryopumps and routed this back to the Torus Hall. This flow (typically ~ 900 - $1000m^3 \cdot hr^{-1}$) 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 depression rises too close to ambient.

This coupled system has been optimised to minimise tritiated water arisings from the atmospheric moisture removed by the ventilation system and also minimise LN_2 usage.

The system is capable of reducing the oxygen content within the Biological Shield from 21 to 15% in around eight hours. This is done each time there is a significant (> 0.1g or 37TBq) tritium inventory outside of the AGHS boundary in 'releasable' form (ie. on cryopanels in the vacuum or in the storage reservoirs and pipes of the GIM and TDGIS).

E. General engineering preparation for DTE1

A number of systems had to undergo changes before DTE1.

1. All vacuum windows and feedthroughs on the Torus or NB Injector vacua were double sealed and provided with a pumpable interspace.

   The interspaces were filled with Neon, connected together and monitored regularly in groups. An interspace leak to the vacuum could therefore be identified by the appearance of neon on the mass spectrometer. Any leaking interspace would be evacuated and isolated.
2. A thorough review and upgrade of reliability was performed on plasma diagnostics required for DTE1.
3. A back-up mode of operation of the JET cryoplant was commissioned so that, in the event of failure of the ScHe supply to the Divertor cryopump in the Torus [10], the pump could be supplied in a 'hot standby' situation by Liquid Helium (LHe) from the plant dewars. This would be necessary in event of a fault because the ScHe in the pump has very little mass (< 1kg) and would quickly be raised in temperature thus releasing the tritium into the hot Torus (at 573K). Although tritium inventories on the pumps are kept low by administrative measures (< 10g or $37\mathrm{Pa}\cdot\mathrm{m}^3$ at NTP), it is nevertheless undesirable to have tritium released at unplanned events.

   Supply by LHe would be sufficient to keep the tritium inventory stable until restart of the ScHe turbines. Although fully commissioned, this back-up system has not had to be used in operation.
4. Specific instrumentation for interlock and monitoring purposes was also upgraded for DTE1.
   - a radiation hard Residual Gas Analyser (RGA) was installed for Torus Impurity measurements;
   - a radiation resistant Remote readout 'Baratron' system was installed for absolute pressure measurements during cryopump regenerations on the NB Injectors [14];
   - a hardware Bremsstrahlung Interlock system was installed to prevent injection by the high powered NBI systems into plasmas with insufficient density, thereby protecting in-vessel components against beam shinethrough [12].

IV. ENGINEERING ANALYSIS TO MEET THE SAFETY CASE

A considerable amount of engineering analysis has been done on the JET Torus, NB Injector and ancillary systems in order to establish the 'Safety Case' to the UK regulatory authorities for operation of JET with tritium. A previous exercise had been undergone on the AGHS. The Safety Case to establish for JET operations is a complex matter and is described in detail in [13].

Here we will restrict ourselves to giving an example of how the process affected the protection system engineering already installed on JET for routine deuterium operation.

The UK *Environmental Agency (EA)* has to give approval for radioactive materials on the JET site and for waste discharges. EA approval is for up to 90g tritium on site (only 20g was on site for DTE1) and limits JET's waste accumulation and discharge. Aerial tritium discharges are limited to 200TBq·yr^{-1} and tritiated liquid to 10TBq·yr^{-1}. These doses are based on keeping the off-site doses to an identified critical group at < 50µSv·yr-1. (Below these levels JET's policy is to limit environmental impact to much lower limits by setting management limits of 40GBq day^{-1} for airborne tritium and liquid concentration of 100MBq·m^{-3}.)

JET is also required to conform to United Kingdom Atomic Energy Authority (UKAEA) safety practice which includes compliance with Nuclear Installation Inspectorate (NII) Safety Assessment Principles. JET policy is to require no off-site emergency plan.

Severe accidents, which involve multiple failures are deemed to be *Beyond Design Basis Accidents (BDBA)*. For BDBA cases the dose limit is set by the assumed mobilisation of an entire inventory of tritium in a given location. An example would be the in-vacuo cryopump tritium inventory (≤ 10g or ≤ 3700TBq), but the loss of such an inventory could only occur if several failures occurred in a single accident (failures of containment, failures of the normal JET protection systems and failures of the basic Safety Case systems such as the EDS).

Although the BDBA involve the failure of several design components and protection system barriers, it has been necessary to show that single failure *Design Basis Accidents (DBA)* are limited on the JET system to the release off-site of doses at the level of annual routine doses ie. < 50µSv.

A *Deterministic Analysis* of the set of *DBAs* on JET has been undertaken. The methodology of the Deterministic Analysis is shown in Fig.5.

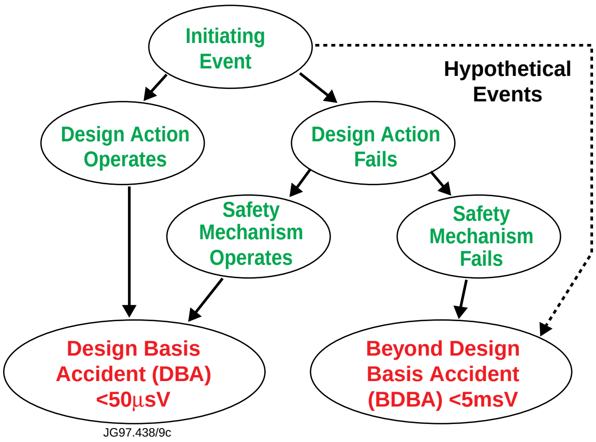

Fig.5 Methodology for Deterministic Analyses of Design Basis Accidents.

The wide range of *Initiating Events* of DBAs fall eventually into four basic types:

–	LOVA	Loss of Vacuum Accident
–	LOCA (i-V)	Loss of Coolant Accident (in-vacuo)
–	LOCA (e-V)	Loss of Coolant Accident (ex-vacuo)
–	LOFA	Loss of Flow Accident

The extensive Deterministic Analyses on several systems have established the thermodynamic behaviour of systems in response to accidents where fluids from the breach are subjected transiently to eg. high vacuum vessel temperatures coupled with the presence of condensation surfaces (from cryogenic or water supplies).

The *Design Actions* (see Fig.5) which have been taken to limit activation release are either:

- *passive*, such as double containment for tritium systems with pressure > 100Pa and double containment for vacuum windows; or
- *active*, using one of the existing JET protection systems.

The Deterministic Analyses have led to upgrade and modification of the existing protection systems on JET. These protection systems (such as the Draining and Refilling System (DRS) and the Direct Plant Interlock System (DPIS) already protect against boiling or freezing of components which might take place in LOFA, LOCA (in-vacuo) or LOVA. Their design has evolved over time as a result of previous fault analyses [15].

All DBAs are extremely conservative even though they only involve single failures. Examples, with reference to the in-vessel configuration in Fig.6, are:

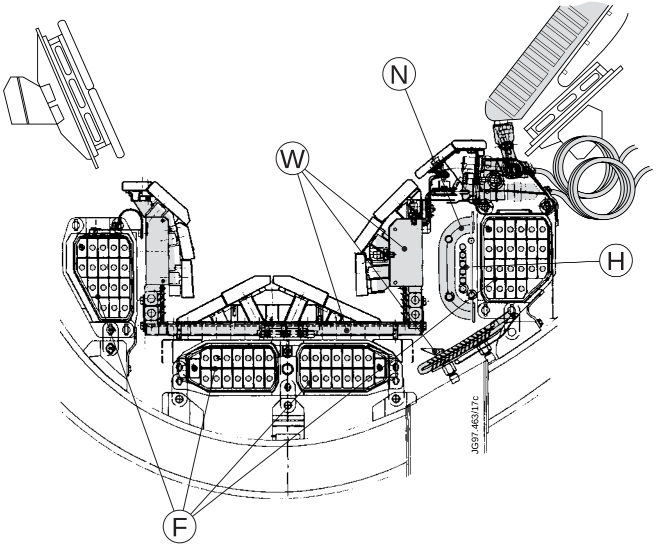

Fig.6 In-vessel configuration in the Divertor region for the JET DTE1. Shaded areas indicate components carrying coolant.

Key: ‘F’ = Freon; ‘H’ = Supercritical helium; ‘N’ = Liquid nitrogen; ‘W’ = water.

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

The Freon cooling system, which is used to cool the Divertor Coils, is not considered for LOCA (i-V) as all the in-vessel Freon circuits are double contained with pumped interspace.

A. Design Basis Accident example : strong Torus pressure rise

In a strong pressure rise in-Torus, caused by severe LOVA or LOCA (i-V) as above, the aim of the Design Actions is to prevent the Torus Bursting Disc from rupturing. This is set at 5 10^3Pa (gauge). If the Torus Bursting Disc were to rupture, the EDS would still be capable of pumping activation products from the Torus (which would remain in depression), but the post-accident activation would be more difficult to clean-up.

In a strong Torus pressure rise (which might vent the Torus to atmospheric pressure in under 10 minutes), the instrumentation would not be able to distinguish between LOVA and LOCA (i-V). The sequence of Design Actions for this accident has been fixed as follows.

1. At in-vessel pressure (PT) > $5 \cdot 10^{-2}$mb (5Pa) the DPIS closes the LN_2 and ScHe supply valves to the in-vessel cryopumps (to limit the relevant inventories available to feed a leak).
2. At PT > 1mb (100Pa) the turbopump valves shut to prevent damage. The vessel is now isolated.
3. At PT > 15mb (1500Pa) a water leak is suspected and the DRS stops the water cooling flow to in-vessel components. The water is locked into individual circuits and the pressure is tested by automatic interlocks.

   If the water pressure remains high then it is determined that there is no leak in the circuit and individual circuits are reflowed by DRS/DPIS to avoid boiling or freezing of stagnant water. If the water pressure drops in a given circuit, then a *water leak* is hypothesised and this

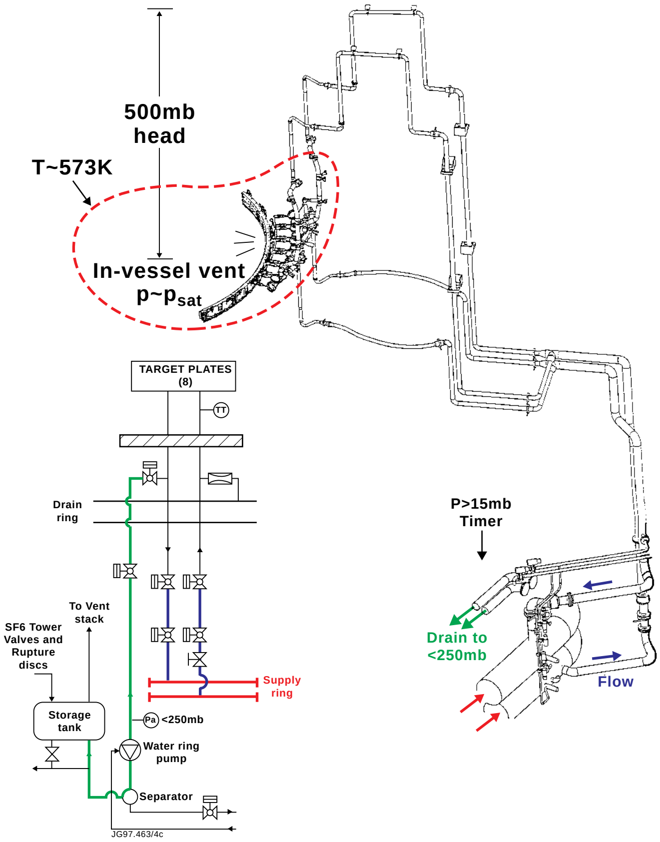

Fig.7 Pumping arrangements to evacuate one octant of the Divertor structure water cooling in the event of an in-vessel leak.

circuit is drained automatically by DRS to a drain ring kept at Pd < 25kPa by a Water Ring Pump. An example of this circuitry is shown in Fig.7. This evacuated drain is necessary to avoid feeding of the leak via the ex-vessel pipework which can have a gravity ‘head’ of > 50kPA.

The Design Actions taken by the existing JET protection systems have thus aimed to limit the inventory of fluids so that their vapour pressure would be insufficient to rupture the bursting disc if they were superheated to 573K. If these Design Actions prove insufficient however, the Safety Mechanisms are now called upon to act. The emergency pumping, as the sequence continues, is shown schematically in Fig.8.

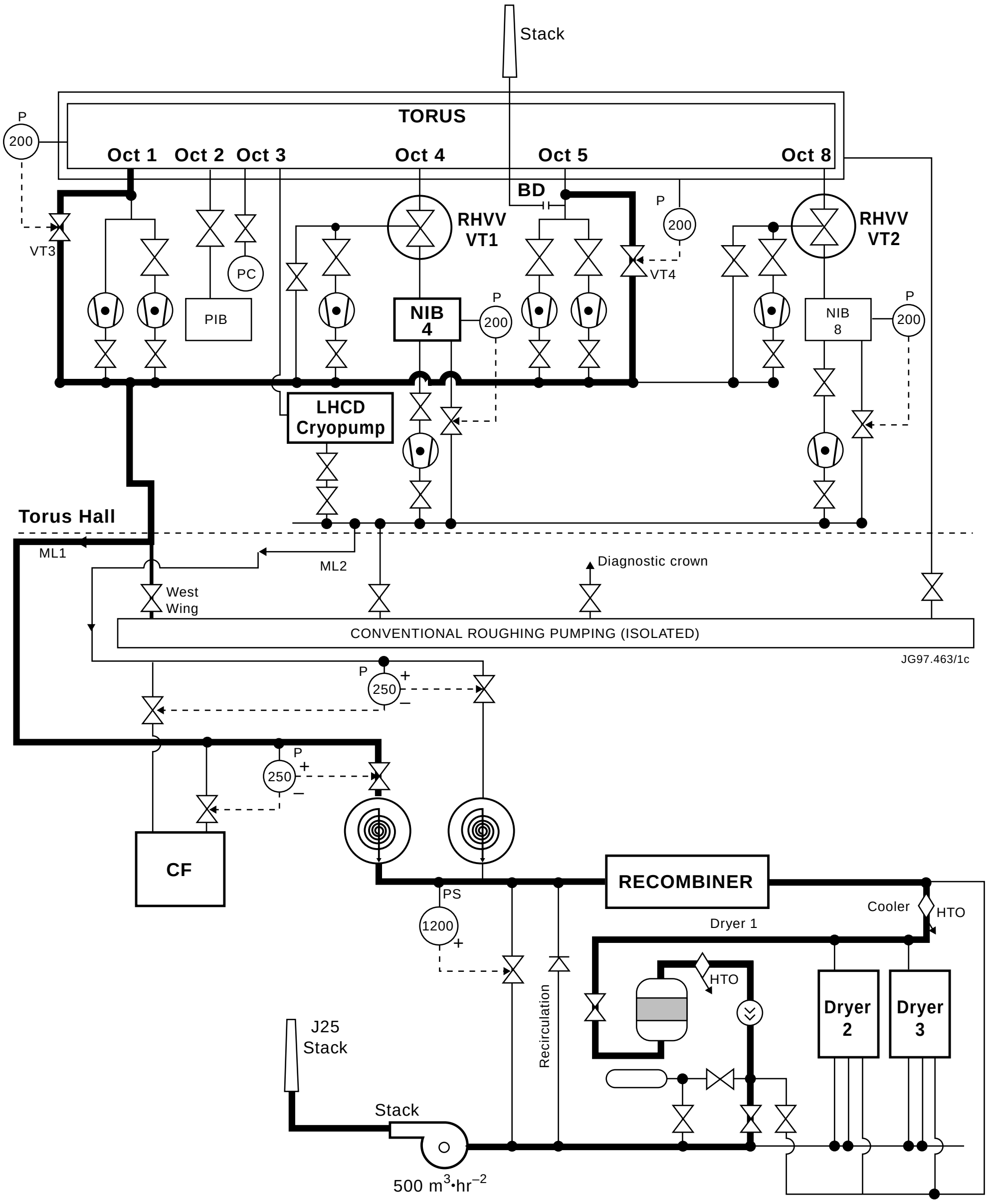

Fig.8 Emergency pumping route (shown in bold) for the Torus in the event of a LOVA or in-vacuo LOCA. (Route shown is activated for Torus pressures above 25kPa.)

4. At PT > 200mb (20kPa) the turbopump Bypass Valves open and connection is prepared to the AGHS Mechanical Forevacuum (MF).
5. At PT > 250mb (25kPa) the pumping is cut off from the Cryogenic Forevacuum (CF) and the MF 'Normatex' scroll pumps ($650m^3 \cdot hr^{-1}$ at 300mb) pump the Torus to the EDS.
6. The exhaust stream now passes through the EDS recombiner drier system which reduces the contamination of the stream below required discharge limits. The discharge is then vented to the stack via the EDS blower which is required by the Safety Case to have always one drier on standby [16]. The blower has a capacity of $500m^3 \cdot hr^{-1}$, corresponding to $40g \cdot sec^{-1}$ of superheated steam at 573 K.

V. OPERATIONAL EXPERIENCE WITH TRITIUM

A. AGHS

The AGHS went through three periods of commissioning prior to its integrated operation with the JET Torus. These stages of *Inactive Commissioning*, *Trace Tritium Commissioning* (involving the use of 0.1g tritium) and *Full Tritium Commissioning* (with 3g tritium) are described in detail in [17].

In the period January-April 1997, the AGHS underwent *Torus Inactive Commissioning* in tandem with the JET Tokamak. In this phase, the AGHS Cryogenic Fore-vacuum (CF) was used to pump the Torus continuously and to handle the regenerated gas from the Torus and NB Injector cryopumps. Deuterium was also supplied from the U-beds for the commissioning of the Neutral Beam TDGIS.

After the inactive commissioning, *Trace Tritium Commissioning* was commenced with the Torus and NBI systems. A 1% tritium in deuterium mixture was used to 'expand the tritium boundary' outside the AGHS to include the basement gas introduction systems (GIM and TDGIS). Use of trace tritium as a leak detection marker was employed. This phase was completed successfully with no leaks. The NBI was used to inject 1% T in D neutral beams into the plasma to provide a source of 14MeV neutrons for diagnostic calibration.

The *Integrated Tritium Operations* commenced on 27 May 1997 with the Tritium Neutral Beam Injector commissioning (see below). By 9 June, one complete reprocessing of 11.4g of tritium returned from the Injector had been completed, and a total of 23g of tritium had been supplied (11.4g to the NBI and 11.6g to the Torus GIM).

The AGHS CF system proved capable of supplying an adequate backing pressure for the Torus turbopumps (< 0.1mb at $0.3m^3 \cdot s^{-1}$) and of handling regenerated tritium/deuterium mixtures from the cryopumps up to $3\ 10^4 Pa \cdot m^3$.

The AGHS Gas Chromatography (GC) system produces deuterium and tritium streams of satisfactory quality (> 99.2% pure) from a mixed input. This is important because the NBI system needs a 99% pure supply to avoid stray beam damage to components of the Injector. The ion beam deflection magnets have to be set for the selected isotope. An unneutralised ion from a different isotope would then be deflected outside the ion dumps.

B. Tritium NBI

The deuterium commissioning of the TDGIS proved invaluable in eliminating all the problems. Only one major problem was encountered, involving leaks across the valve seat of the absolute and selection valves inside the TDGIS. This was due to the all-metal construction of this seat, involving a hard ‘stellite’ tipped valve body and a stainless steel seat. After a few tens of cycles the stellite tips began to extrude the softer material of the seat and cause the valves to leak. Absolute tightness is required across these valve seats [8] and so a new set of valves were qualified with ‘Vespel’ seats. After careful alignment and cycling checks, these valves proved to keep the required leak tightness after 5000 cycles.

The commissioning of the PINI Injectors in tritium took ~ 50 pulses into the NBI calorimeter (‘ASYNC’ pulses) and was achieved in parallel to JET operations. The PINIs reached 155kV operation with tritium beams with reasonable ease.

The highly stable gas supply from the TDGIS helped to avoid major problems with the PINI plasma source arcs. Fig.9(a) shows traces of a PINI ASYNC pulse in tritium (T°) in comparison with the lower voltage and lower neutral power pulse in deuterium (D°). The beam profile of the T° beams was of the same acceptable quality as that of the D° beams [(see Fig.9(b)].

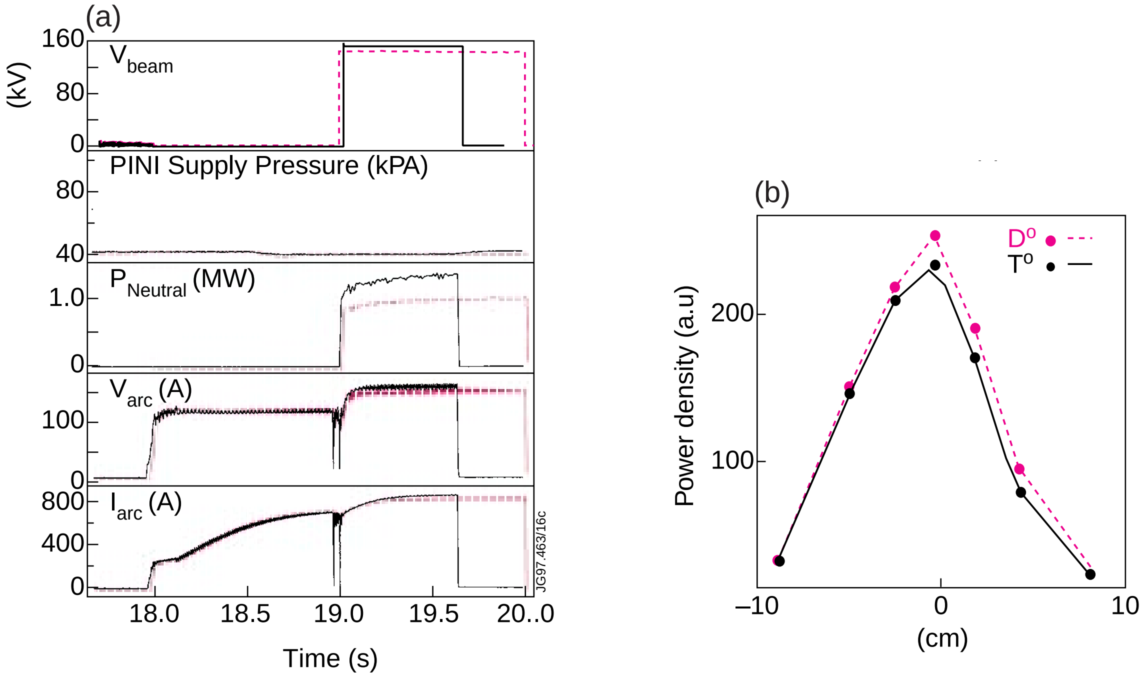

Fig.9 (a) Comparison of tritium beam extraction (solid) and deuterium beam extraction (dashed) on a single PINI. (b) Comparison of tritium beam profile (at 155kV) with deuterium beam profile (140kV) as measured on the NB calorimeter.

PINI operation was optimised to economise on the use of tritium. The arc stabilisation time was minimised before beam extraction [Fig.9(a)]. The results from operation show that a 5s beam pulse from a 155kV/28A PINI, which supplies 1.4MW T° atoms to the plasma, uses only 80mg of tritium. Also important in economising tritium was the rapid changeover from one isotope to another in PINI operation. Changeover from D° operation to T° operation on a PINI, and vice-versa, can be accomplished in only five pulses: three where the PINI filaments are outgassed (gasless pulses) and two arc discharges in the new isotope.

C. Waste and Environmental Discharges

JET DTE1 operations have been accomplished with waste arisings and environmental discharges well below the JET management target limits. (Which are, in themselves, well below the authorisation set by EA.)

For the total gaseous discharges during the main period of full tritium commissioning and of DT plasma and NBI operations, the daily average was only 5-10% of the JET management limit of $40\text{GBq}\cdot\text{day}^{-1}$.

For tritiated liquid waste arisings, there are two discharge routes. One sends *high volume, low activity* waste to the River Thames (management limit < $2\text{TBq}\cdot\text{month}^{-1}$) and the other stores *low volume, high activity* waste in drums for return to the suppliers.

The EDS, which is required by the Safety Case for certain operations (including maintenance) to avoid uncontrolled releases, is the source of most of the high activity liquid arisings (from the EDS driers). Arisings in commissioning and operation were less than 1% of the monthly limit for high volume, low activity. Arisings from the EDS have been dominated by the one major plant intervention which has taken place: the intervention to repair a water leak in the tritium NB injector.

D. Intervention to repair the Tritium NB Injector

The tritium NB Injector is situated at Octant 8 of the JET tokamak. It is thus known as Neutral Injector Box (NIB) 8.

On 4 June 1997, there were indications of a *water leak in NIB8* associated with operation of the Fast Shutter [18] between the Injector and the Torus. The presence of water was detected at a very early stage by routine operating procedures using the NIB mass spectrometer and the Penning gauge instrumentation. There was no possibility of any tritium release from the all-metal fully-sealed UHV system of the NIB8

Operations on NIB8 were suspended whilst the pressure (with cryopumps on) was still below $5\ 10^{-7}$mb. This is two orders of magnitude below the Interlock trip level from the Fast Beam Interlock System which would inhibit pulsing. The NIB8 cryopumps were regenerated and operations on this NIB suspended in order to gain entry to identify and rectify the fault. Although the water leak was very small (3cm^3 of water were estimated to have leaked into the

NIB8 vacuum), it could not be tolerated for NIB operations.

NIB8 had operated in tritium. Altogether 11.4g of tritium had been supplied and it was estimated that up to 0.3g (100TBq) might be held up in the ion dumps, neutralisers and beam scrapers, having been driven in by incident T° or T^+ beams [19]. It was clear that, even after a period of decontamination, entry into NIB8 in *air fed suits* would be necessary. These suits, the same as those used in entry to the JET Torus in a beryllium-contaminated environment, offer a protection against tritium inhalation dose of up to a factor 1000 for the duration of an eight hour shift.

A Tritium Control Access Cabin was built to place on the top of NIB8 to allow suited-entry. Whilst this was in progress, one week of clean-up operations took place to remove as much tritium from the Torus walls as possible (approximately 4g had been loaded there during the D-T plasma operations [3]). After the regeneration of all the in-vessel cryogenic circuits, the Torus was brought from 300°C to room temperature and filled with dry nitrogen to immobilise the remaining tritium and maintain Torus conditioning. Also in parallel the NIB8 was subjected to moist air soaks and pumpdowns via the EDS to remove tritium from the internal surfaces.

The Injector Central Support Column (CSC) (which carries most of the beamline components – see Fig.2) had to be removed to work on the probable location of the leak in the Fast Shutter. The CSC in the Octant 4 (deuterium) Injector, which was only lightly contaminated, was first removed to the JET Assembly Hall to the Beryllium Handling Facility (BHF), connected to the monitored stack and ventilated. The NIB8 CSC, which was too active to be connected to an ordinary stack, was then put into Octant 4 NIB and sealed, being connected to the EDS for pumping.

Twenty days after the isolation of NIB8, the Tritium Control Access Cabin was placed on the top of NIB8 which was then continuously pumped by the EDS at $250\text{m}^3\cdot\text{hr}^{-1}$. With the major source of outgassing (the CSC) no longer in the NIB8, the tritium concentration dropped quickly below $80\text{MBq}\cdot\text{m}^{-3}$ (100DAC) inside the NIB. At this level the suits provide a reduction in personnel dose to levels which are one order of magnitude below JET workers' routine exposure limits (1DAC). Twenty-two days after the isolation, suited entry was made to the NIB8 box and the leak was identified (in a flexible hose in the Fast Shutter water feed) by helium leak testing in full suits.

The leak was repaired in solid piping and after qualification of the repair the CSC was returned to NIB8 and the NIB4 CSC was returned from the BHF to NIB4. The Injectors were then evacuated and returned to UHV conditions 56 days after the initial leak discovery. Recommissioning of the Injectors was then commenced.

In summary, the following points may be made about this intervention process.

1. Using the EDS at $250\text{m}^3\cdot\text{hr}^{-1}$ to pump NIB 8 during the intervention proved successful to keep tritium levels down to << 100DAC (<< $80\text{MBq}\cdot\text{m}^{-3}$) throughout the intervention.

The highest individual personal dose received was 70μSv (compares to the JET individual annual dose limits of 5mSv), and the dose received by the workforce as a whole was 500μSv.

2. The isolation Rotary High Vacuum valve of NIB8 proved invaluable in maintaining Torus conditioning (moist air was excluded from the Torus vessel).
3. The EDS driers and catalysers kept the total airborne discharge (over 56 days) to < 600GBq (about ¼ of the JET management limit).
4. The liquid arisings from the EDS driers were 29TBq.
5. During the deuterium plasma discharges for four days to clean tritium from the Torus walls about 2.7g of tritium was left in the surfaces (out of 4.4g loaded from a throughput of 11.5g).
6. About 0.1g of tritiated water/hydrocarbons were regenerated from the LN_2 shields of the Divertor cryopump after the clean-up operation.

E. Second period of D-T operation

JET commenced its second period of operation with tritium on 20 September 1997 and is still, at the time of writing, in operation.

The world record for fusion power production in a D-T plasma (12.9MW) has been set in these experiments [3]. The tritium NBI has been continually in action and over 60 pulses with T° beams heating JET have been made. Tritium neutral powers of up to 11.3MW have been delivered to the plasma and the longest pulse length (at 10.8MW) has been 3.5s. Over 20 pulses at > 10.5MW have been injected. During this time the total NBI power injected (including the 80kV D° beams on the Octant 4 Injector has reached 21.4MW, with 22% of the pulses at > 19MW.

The AGHS has continued to work faultlessly. It has now handled over 100 cryopump regenerations involving more than $4.8\ 10^5$ $Pa.m^3$ of gas and has supplied over 25g to NBI and 15g to the Torus).

VI. CONCLUSIONS

The engineering development to produce the JET Active Gas Handling System (AGHS) and Tritium Neutral Beam Injector (TNBI) has culminated in the successful operation of these systems.

Successful complete cycle operation of the JET AGHS has been achieved:

– over 40g of tritium has been supplied of the Torus and NBI systems;

– a tritium reprocessing cycle takes four days and has now been completed four times;

– the Gas Chromatography system produces > 99.2% pure streams of tritium and deuterium from the mixed regeneration products from the Torus and TNBI cryopumps;

– the waste discharges to the environment have been kept at the level of a few percent of JET's management limit, which is itself about 5% of the regulator's monthly limit.

The JET TNBI has successfully injected over 11MW high energy T° atoms to the JET plasma and has produced pulse lengths of up to 5s. The Injector operates successfully at 155kV.

The safety protection systems, including the Depressurisation Plant and Fire Suppression systems for the Biological Shield, have been commissioned and could now deal with Design Basis Accident LOVA and LOCA without breach of containment. In the one serious fault which has been encountered in DTE1, the monitoring systems proved capable of identifying a tiny leak in the TNBI system (about 7 orders of magnitude below the Design Basis LOCA [i-V]). Operations were suspended safely.

A successful intervention into the TNBI to rectify the small water leak was accomplished in full suits in under two months and, using the full capability of the Exhaust Detritiation System, led to personnel doses of < 1% of JET's annual dose limits.

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