JOINT EUROPEAN TORUS

JET–P(93)17

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Preprint of a paper to be published in the course notes of
Eurocourse: Safety in Tritium Handling Technology, ISPRA, 1993
March 1993

ABSTRACT The first experiment in which the plasma in a tokamak was fuelled with tritium was carried out at JET in November 1991 using 0.1g of tritium. The design, construction and safety justification of the tritium handling plant for the final D-T phase at JET using 90g of tritium has been essentially completed. Valuable experience in tritium handling, clean-up and waste disposal has been gained which is directly relevant to the use of tritium in future JET operation and to controlled fusion research in general.

1 Introduction

The Joint European Torus (JET) is an experiment to establish the feasibility of controlled nuclear fusion as a means of energy production. It is part of the co-ordinated programme of research of the European Atomic Energy Community (as well as Sweden and Switzerland) and is situated adjacent to the UKAEA Culham Laboratory near Abingdon, England.

The JET machine (torus) uses magnetic fields to confine a plasma of ionised gas within a doughnut-shaped vacuum vessel of volume about $200m^3$ (Fig 1).

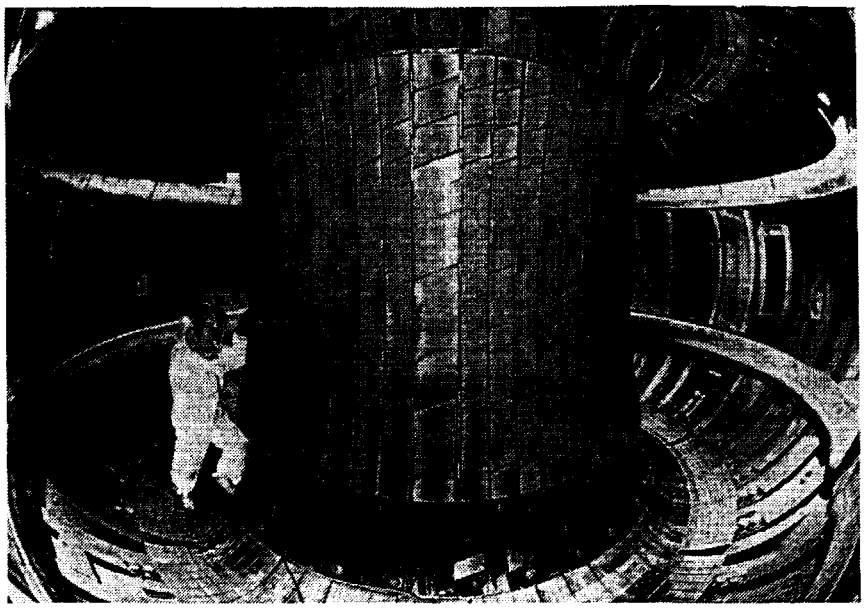

Fig 1 Interior of JET Torus

JET has operated since 1983 with hydrogen and deuterium plasmas. During deuterium operation, a small amount of tritium (0.2TBq) has been generated through D-D fusion reactions. In 1991, the first tritium experiment (FTE) was carried out in which a series of plasma discharges were fuelled by a mixture of deuterium and tritium. About 0.1g of tritium was used and a fusion power in excess of 1MW was produced. Whereas the early D-D operation required limited precautions with regard to tritium exposure or tritium content of waste to be taken, the FTE required careful preparation in terms of safety assessment, waste handling and maintenance intervention. This provided valuable experience for the full D-T phase of JET which is scheduled to take place in 1996. For this phase the torus exhaust gases will be collected by the Active Gas Handling System (AGHS) [1] and processed to remove tritium for re-injection into the machine, thus minimising the discharges to the environment. Commissioning of the AGHS is currently in progress.

2 Active Gas Handling System (AGHS)

2.1 PROCESS CONCEPT

A schematic of the main gas feeds and exhausts for the JET machine is shown in Fig 2. The feeds to the machine from the AGHS are:

i) Feed to the torus for pulse operation (D_2 and T_2 in proportions required).
ii) Feed to the neutral injectors (D_2 or T_2).
iii) Feed to the pellet injector (D_2 or T_2).

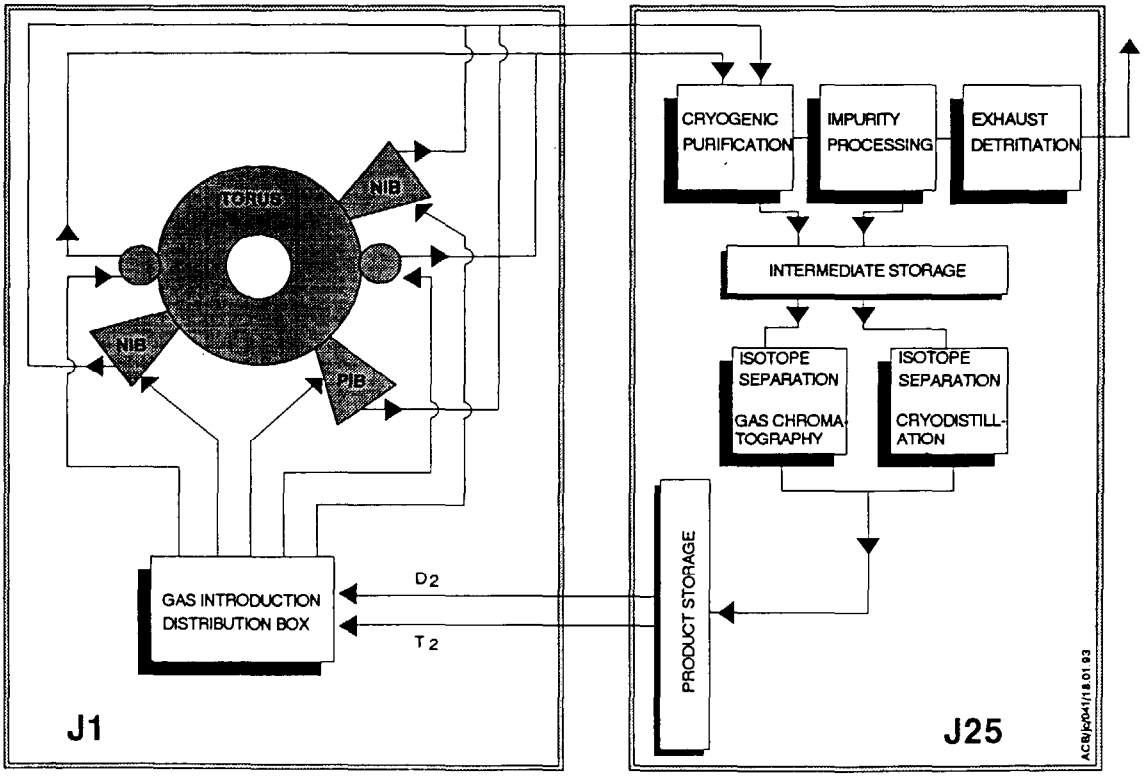

Fig 2 Interface between Torus and AGHS

The amount of tritium used per pulse may be of the order of 500mbl. Some of this may be exhausted through the torus turbomolecular pumps to the AGHS but the majority is collected on cryopanels or temporarily retained and slowly released from the torus walls. After a number of pulses and at least once per day, the cryopanels are regenerated and the evolved gases are exhausted to the AGHS. Periodic glow discharge cleaning is carried out to reduce the inventory of tritium and other gases in the torus walls.

The exhaust streams which require processing are:

i) Torus exhaust from pulse operation including pumped divertor cryopump regeneration and standby operation.
ii) Torus exhaust during glow discharge cleaning.
iii) Neutral injector boxes exhaust during regeneration.
iv) Pellet injector box exhaust during regeneration.
v) Pumpdown and maintenance of JET machine systems.
vi) Recovery for safe disposal of tritium from the baking plant and other streams requiring detritiation.

It should be noted that not all these streams can be processed simultaneously as some share common lines to the AGHS.

Torus and box exhausts are collected and the impurities removed in the Cryogenic Forevacuum (CF) system of the AGHS. Water and oxygen may be removed by a liquid nitrogen cooled cold trap and absorber and the other gases are collected by freezing on a liquid helium cooled accumulation panel which contains activated charcoal to permit helium to be pumped. Helium, hydrogen isotopes and impurities are separated by fractional distillation. In the Impurity Processing (IP) system, impurities (chiefly methane) are converted to water using a catalyst, and the water reduced over hot uranium or iron beds to hydrogen. The IP is also used for routine clean-up of certain internal gas streams within the AGHS. Hydrogen isotopes from IP and reservoirs in the CF are then transferred to the Intermediate Storage (IS) uranium beds (U-beds). The purpose of these is to provide the delivery pressure for one of the two isotope separation systems.

The Gas Chromatography system operates in batch mode and is suitable for processing up to $0.4m^3$ of deuterium and/or tritium per day. The Cryodistillation system operates continuously and is capable of processing $3.5m^3$ of hydrogen and $0.5m^3$ of deuterium and/or tritium per day. Hydrogen is stripped of tritium and disposed directly to atmosphere after monitoring. Deuterium and tritium 99% pure are transferred back to the Product Storage (PS) system U-beds and the cycle is repeated.

The Analytical Laboratory (AN) system incorporates a gas chromatograph, residual gas analyser and other instruments to measure the composition of gases. Permanently engineered connections have been designed to permit analysis of gas in any system of the AGHS. In addition there are other systems which are not used in the main process cycle but are required for process services, maintenance and detritiation. These include the cryogenics supply, Mechanical Forevacuum (MF) and the Exhaust Detritiation (ED) systems.

2.2 TRITIUM INVENTORY

The total amount of tritium permitted to be held on site is 90g and the daily throughput will be up to 30g. Tritium may be pure, or mixed with other hydrogen isotopes and/or impurities. It may also be held up in process components and bound irrecoverably in waste or as tritiated water. During normal process operation there may also be a minimum quantity of tritium necessary for correct functioning which is not strictly bound but may only be recovered by stopping the process. The maximum inventory of each system during normal operation is given in Table 1 below which also lists the forms in which the tritium is contained.

System	Maximum Inventory (TBq)	Form(s) of tritium
Gas Introduction	3000	Elemental gas plus contamination
Cryogenic Forevacuum	11000	Elemental, oxide and tritiated impurities
Mechanical Forevacuum	4	Elemental, oxide and tritiated impurities
Impurity Processing	2300	Elemental, oxide and tritiated impurities
Intermediate Storage	15000	Elemental
Gas Chromatography	12000	Elemental
Cryodistillation	12000	Elemental
Product Storage	33000	Elemental
Analytical Laboratory	2500	Elemental, oxide and impurities.
Exhaust Detritiation	10 (12000)	Tritiated water on molecular sieve beds

Table 1 Tritium Inventory in AGHS

2.3 SAFETY ASPECTS

Tritium-containing plant is built to standards equivalent to those in use in the nuclear industry. ASME VIII or equivalent is used for primary containment. U-beds (Fig 3) are extensively used for storage and pumping between sub-systems to avoid the use of mechanical pumps. These have the advantages of providing a hydrogen isotope pressure of about 1 bar at 420°C but a very low pressure, $<10^{-2}$mbar at room temperature (Fig 4). However, because of the pyrophoricity of uranium powder, it was necessary to carry out tests to show that the containment would not fail in the event of air ingress.

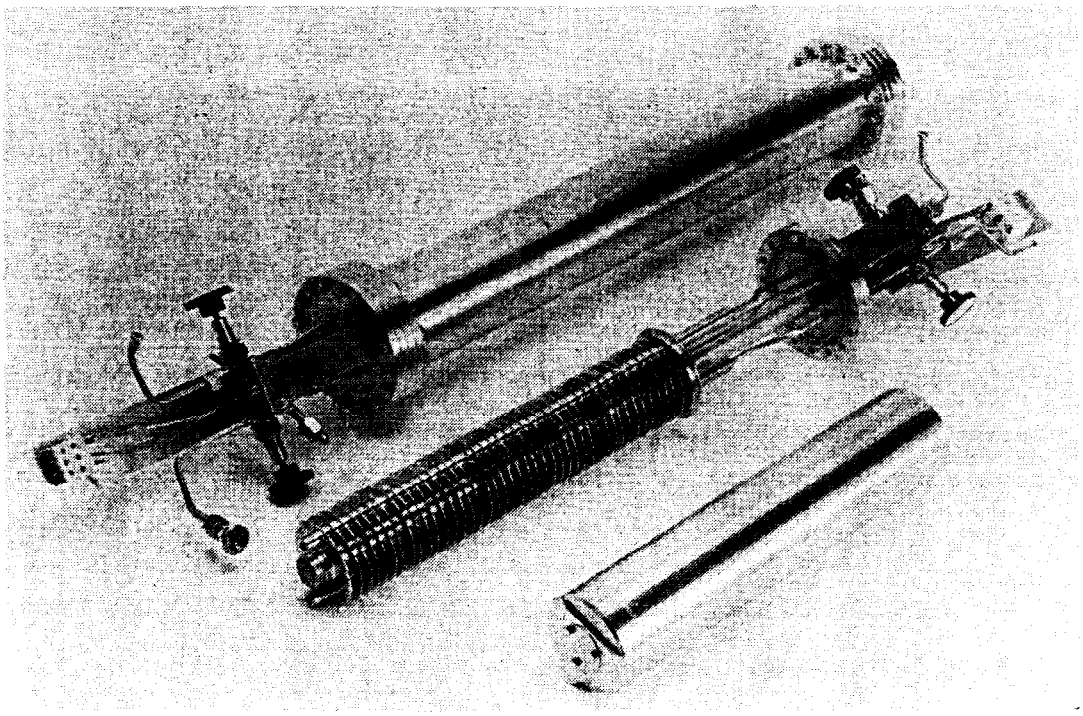

Fig 3 Uranium bed

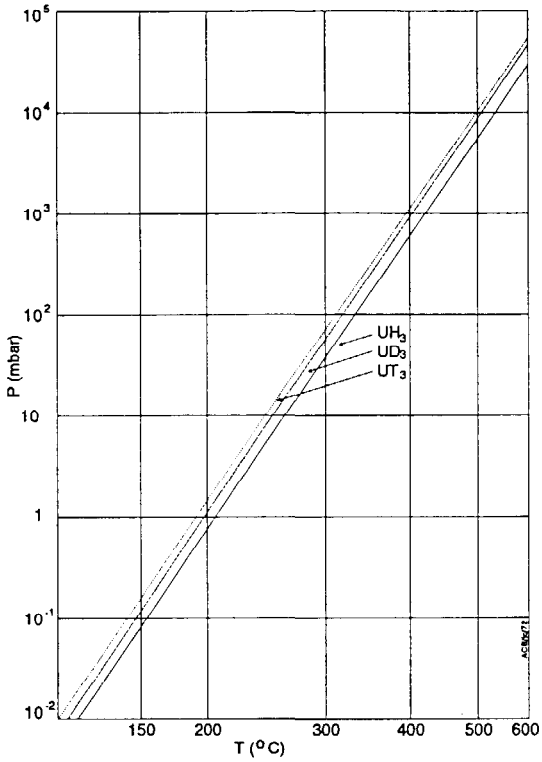

Fig 4 U-bed Characteristics

The plant is designed to take account of the possibility of leakage and permeation of tritium through components. All main processes are therefore carried out within double (or in some cases triple) containment which is continuously monitored for leakage. Process lines containing tritium at high concentrations are all doubly contained and there are also provisions for baking to reduce tritium hold-up and evolution prior to maintenance. The system of barriers [2] provides containment for primary and secondary boundary failures, recovery routes for releases into secondary containments and reduced emissions of any exhausted gases. The barriers, release routes and role of the secondary containments in mitigation of releases are shown in Fig 5.

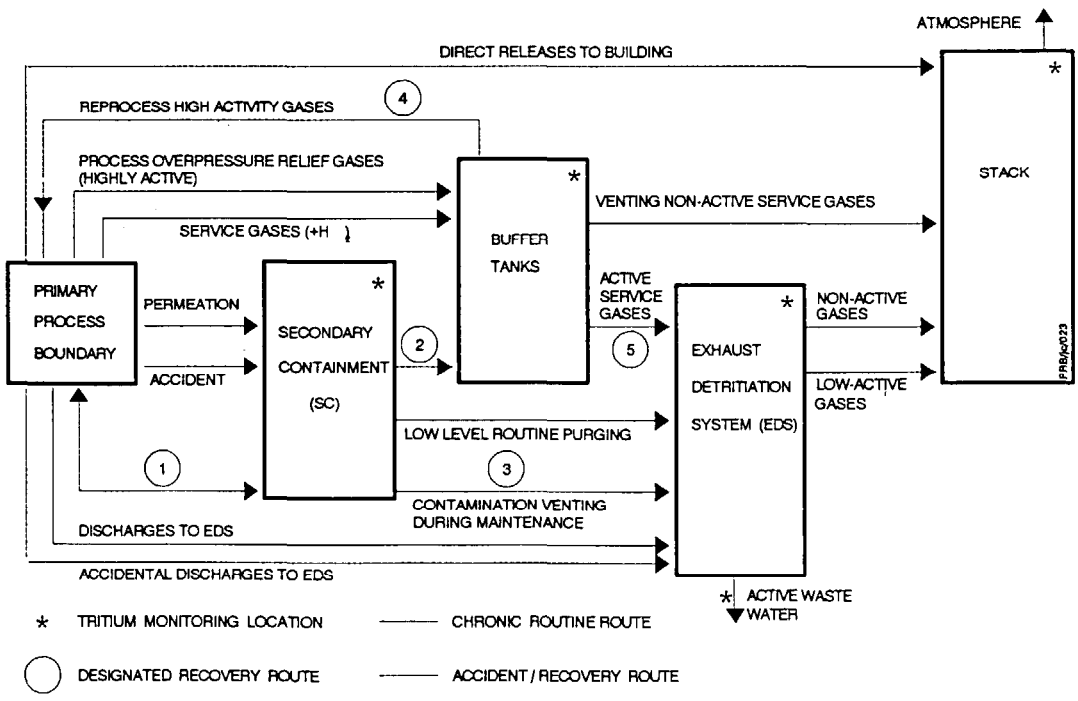

Fig 5 Accidental/Recovery and Chronic Release Routes

Recovery from secondary containments has been designed into the normal plant piping. Vacuum secondary containments have pump down connections which allow the released gases to be transferred either directly to the CF modules for reprocessing or to a buffer tank for later reprocessing. Box ionisation chambers will detect a tritium release into the box secondary containment and hardwired interlocks will isolate the contained system. Recovery is achieved via a connection to the house vacuum buffer tank resulting in a suction/purging of the box with subsequent transfer to CF or another system for reprocessing.

The ED [3] system provides mitigation against tritium releases by converting elemental tritium and tritiated hydrocarbons to water and absorbing this and tritiated water vapour on molecular sieve beds. The throughput is $500m^3/h$ and the design detritiation factor is 1000.

In accordance with the waste authorisations issued under the Radioactive Substances Act, all waste streams are monitored for activity including tritium. There are several individually monitored stacks which discharge to the atmosphere and a liquid waste pipeline which discharges through sampling delay tanks to the River Thames.

3 First Tritium Experiment (FTE)

The FTE consisted of two series of experiments [4]. In the first series, 2 out of 16 neutral beam sources were fed with a mixture consisting of 1% tritium in deuterium. The remaining 14 sources were fed with pure deuterium. During the second series the 1% mixture was replaced with nominally pure tritium. During and after the D-T plasma discharges, tritiated exhaust streams of the tokamak and neutral beam systems were collected by cryopumping and subsequent adsorbing onto U-beds. Only small fractions of the collected exhaust streams could not be adsorbed. These were released through a stack if the residual activity was found to be sufficiently low or, alternatively, processed at an elevated temperature with subsequent absorption. The bulk of the residual tritium which remained in the vacuum vessel and neutral injection system after the injection experiments was removed during the subsequent clean-up phase. This was followed by resuming normal experimental operation with deuterium plasmas. A few weeks after the FTE the torus exhaust could be reconnected to its normal mechanical backing pumps, whereas the neutral injection beam line used for tritium injection into the plasma required a much longer period of collection of the regenerated gases. This required that, in addition to the two installed U-beds with a total capacity for hydrogen of approximately 1000 standard litres, a further pair of U-beds had to be integrated in the Gas Collection System (GCS). Some two months after resuming routine experimental operation, the beam line system could finally be reconnected to its conventional backing pumps. During the collection of the exhaust streams, samples were taken for tritium analysis and the quantities of recovered gas including the tritium content was measured by means of instrumentation built into the GCS. Together with measurements and calculations of the injected amounts and the release through the stack, a detailed accountancy of the tritium was undertaken. The FTE aimed at only a few short plasma discharges restricting the usage of tritium such that the resulting activation of the vacuum vessel would not increase significantly above the level resulting from routine deuterium operation, hence minimising the impact on the major shutdown which started at the end of February 1992.

Maintenance activities inside the vacuum vessel (and neutral beam system) had therefore, for the first time in JET, to be carried out in a tritium contaminated environment. This also had a direct impact on the management of waste arising from these areas.

4 Preparations for the First Tritium Experiment

Preparations for the FTE involved obtaining statutory approvals, the submission of a safety assessment, the design, installation and commissioning of special equipment for the storage and introduction of tritium and for the collection of tritiated exhaust gases from the vacuum vessel and the neutral injection systems.

The installation of the AGHS had not yet been completed when the FTE was conducted and therefore special equipment had to be designed and commissioned for gas introduction as well as exhaust gas collection and the storage of tritium. However, some key components of the AGHS, such as pressure regulators, valves, pressure gauges, ionisation chambers, U-beds etc were able to be used.

4.1 TRITIUM INTRODUCTION SYSTEM

Two ion sources (PINIs) of one of the two JET neutral beam line systems were modified for tritium service in the experiment [5]. The six remaining PINIs of the beam line system and the eight PINIs of the second neutral injector were left unmodified for deuterium operation. For the modified PINIs, the gas was supplied from two U-beds (Mark 4 Amersham type), one loaded with deuterium for commissioning and one loaded with tritium for tritium injection. The U-beds and manifolds were enclosed in a ventilated glove box (Fig 6). A flow diagram is given in Fig 7. By heating the U-beds, absorbed gas is desorbed and can be expanded into a volume. During the pulse, tritium is fed between extraction grid no 4 and the first stage neutraliser at ground potential, allowing an all metal supply system without electrical breaks [6]. Either one or two PINIs could be used.

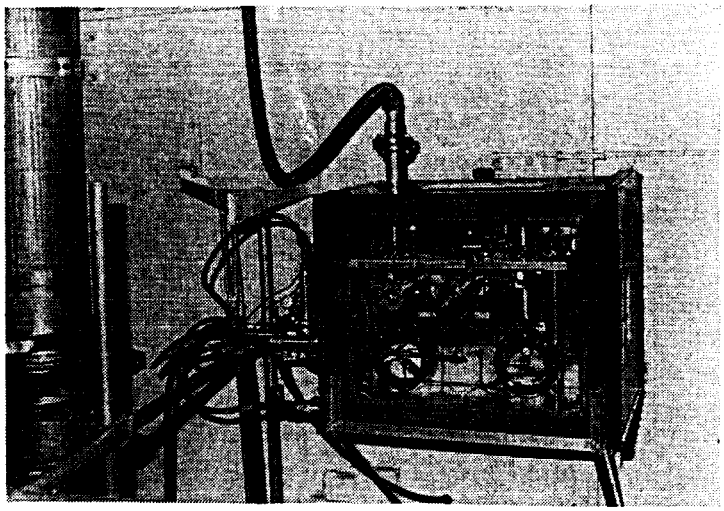

Fig 6 Tritium Supply Glove Box

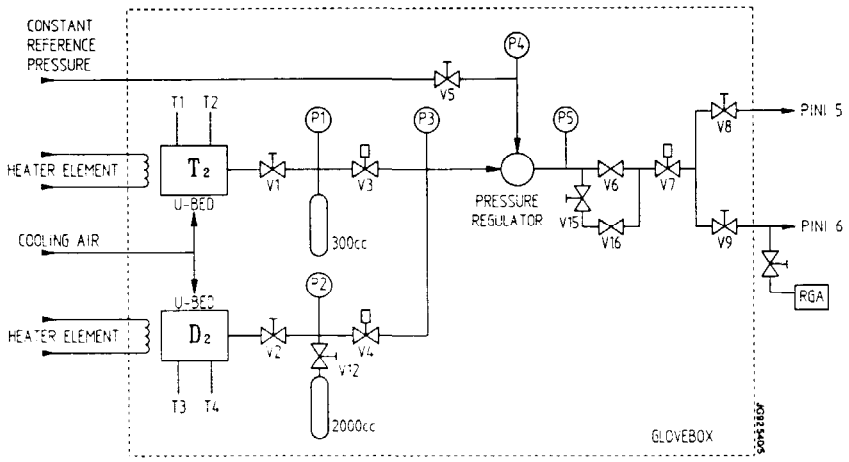

Fig 7 The Tritium Gas Introduction System

4.2 GAS COLLECTION SYSTEM (GCS)

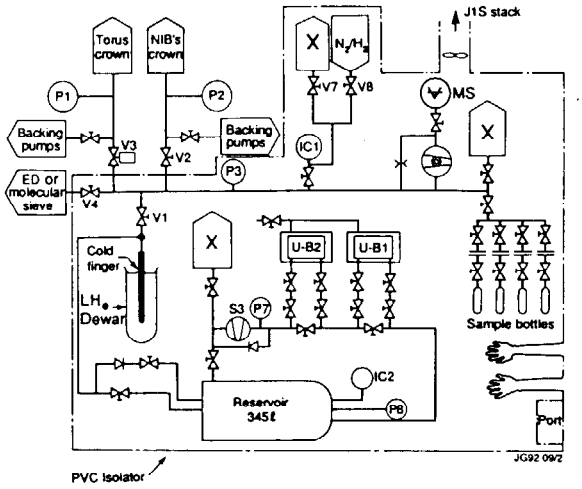

Fig 8 Gas Collection System

Fig 9 Gas Collection System Isolator

The GCS [7] designed for the FTE which is schematically shown in Fig 8, is connected via valves with the vacuum pumping ducts of the torus and the neutral injection systems. The system comprises an inlet manifold which contains various diagnostic elements such as ionisation chamber, mass spectrometer, sampling manifold and pressure gauge. Connected via a valve with the manifold is a tubular liquid helium cooled cryopump to condense exhausted gases. This cryopump contains a small amount of activated charcoal for crysorption of helium. By regeneration of the cryopump, gases can be expanded into a reservoir where again the tritium content as well as the pressure can be measured. This is followed by absorption of the hydrogen species on an U-bed. Two U-beds were originally installed with a total absorption capacity of approx 1000 standard litres of gas. Residual gases which could not be absorbed could then be pumped via a rotary pump out of the reservoir and discharged via a stack which was monitored for tritium, provided that the residual tritium activity did not exceed the daily discharge limit. The GCS was enclosed within a PVC 'isolator' connected to the monitored ventilation system (Fig 9).

4.3 TRITIUM MEASUREMENT

The GCS included a series of tapping points to enable samples of the torus exhaust gas to be measured. In addition, two ionisation chambers (Fig 10) were incorporated to provide on-line measurement of tritium concentration, one in the system reservoir and the other in the pumping manifold. Because the calibration of the chamber would be dependent on pressure and gas composition, provision was made for the second chamber to be backfilled with nitrogen to enable each measurement to be made under reproducible conditions. This had the additional advantage of permitting the chambers to be calibrated in the so-called ion collector mode. This mode occurs at low pressures, $< 10^{-2}$ mbar when the number of gas molecules ionised by ß particles is very small. However the current produced by 3He+ ions arising from tritium decay can be measured (Fig 11). This ability was found to be extremely useful for controlling the pumping process.

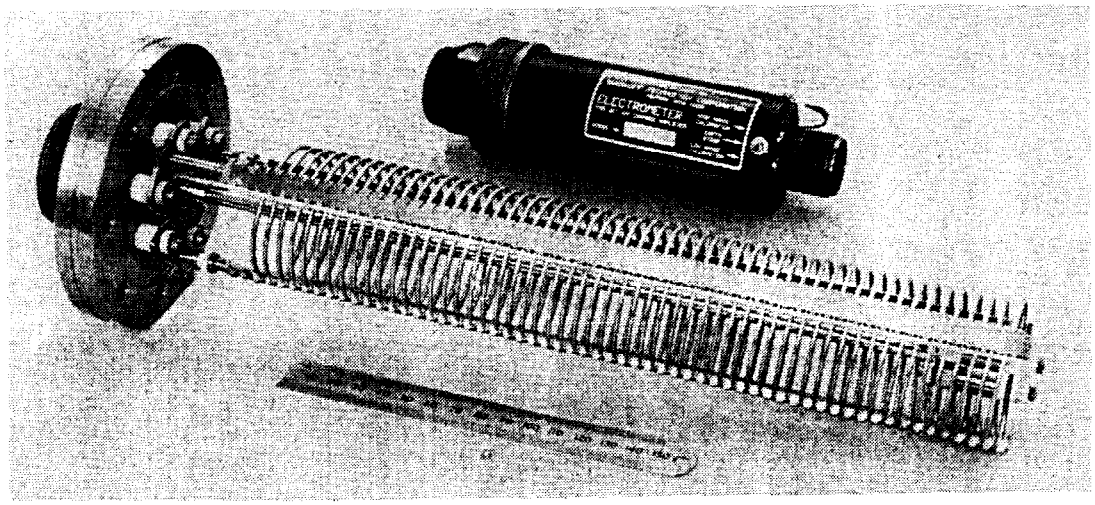

Fig 10 Ionisation Chamber

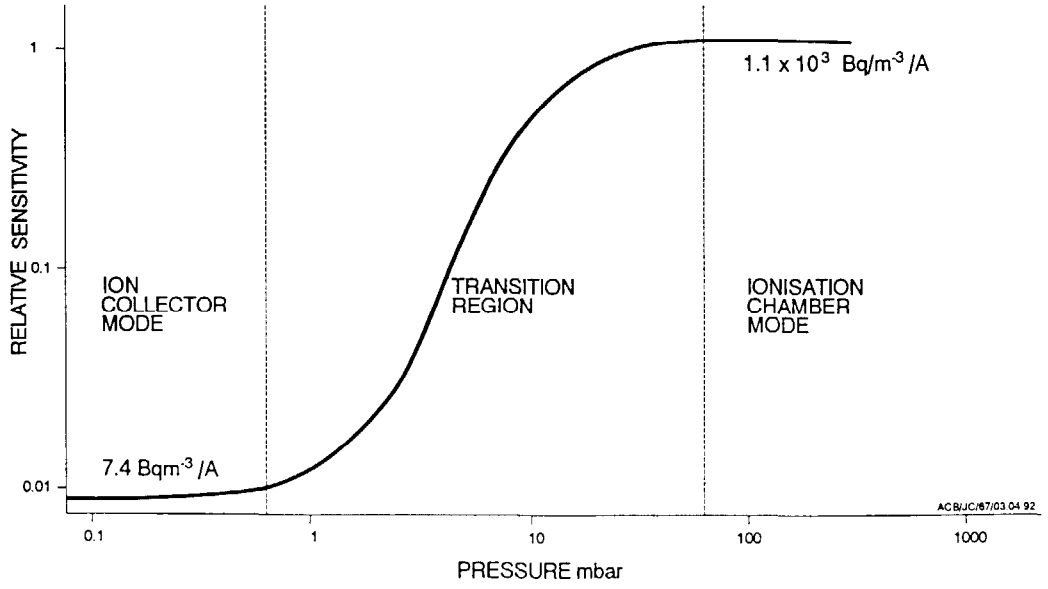

Fig 11 Ionisation Chamber Response

4.4 IMPURITY PROCESSING

A few days after the start of the clean-up phase the total activity contained in residual gas which could not be adsorbed by the U-beds exceeded JET's own imposed daily discharge limit. As it was expected that the majority of the activity would be due to tritiated hydrocarbons produced by the interaction of plasma with carbon wall materials, attempts were made to crack these on a hot U-bed. One U-bed was slowly heated up to 500°C whilst continuously circulating residual gas from the expansion reservoir through the hot U-bed followed by purging the cold U-bed. When the temperature exceeded 450°C the residual activity measured by the ionisation chamber in the reservoir started to decrease and a very low level remained when 500°C was reached. It is considered that tritiated hydrocarbons reacted with the hot uranium powder to form uranium carbide and that the released hydrogen species absorbed on the second cold U-bed.

4.5 STORAGE

Four Amersham Mark 4 type U-beds were activated at JET and their discharge characteristics were established. Tritium was loaded onto two U-beds by a commercial tritium supplier. The first one was pre-loaded at JET with deuterium to which 1.85TBq (50Ci) of tritium was added, giving an overall 1% tritium mixture. The second bed was loaded with 88.8TBq (2400Ci) of tritium. The other two U-beds were loaded with deuterium for tests.

A secure storage facility for tritium which includes an intruder alarm and tritium monitor, both hardwired to a permanently manned site incident desk, was prepared at JET for storage of the tritium before and after the FTE.

5 Safety Aspects of the First Tritium Experiment

As tritium was processed and handled in bulk quantities for the first time during the experiment, safety arrangements and approvals required considerable revision compared with those for D-D and hydrogen operation [8].

The areas which required revision included:

i) Radioactive Discharge Authorisations.
ii) Safety justification for the tritium handling systems and torus.
iii) Emergency arrangements.
iv) Training.

The legal position with regard to JET tritium operation is as follows:

i) Nuclear sites in the UK, such as reactors and reprocessing plants, are regulated by the UK Nuclear Installations Inspectorate (NII) which is part of the Health and Safety Executive (HSE). The NII have decided that JET is not required to be licensed by them but would be subject to the normal regulations governing the use of radioactive materials in industry.
ii) JET is required to be registered by Her Majesty's Inspectorate of Pollution (HMIP) to keep or use tritium and other radioactive substances. The storage and disposal of tritiated and other radioactive wastes is also required to be authorised by HMIP.
iii) JET has a duty under the JET Statutes to satisfy the UKAEA (on whose site JET has been constructed) in advance of any radioactive operation taking place, that the arrangements conform to the UKAEA standards. As the radioactive operations of the UKAEA are licensed by the NII, this means that in effect JET must conform to the standards required under a licence.

The safety of proposed operations was examined by the Fusion Safety Committee. This committee was analogous to Nuclear Safety committees on sites licensed under the Nuclear Installations Act and included several members from outside the JET project. Formal

approval to start operation with tritium was given by the Safety and Reliability Directorate (SRD) of the UKAEA.

iv) The Ionising Radiations Regulations require JET to meet certain specific requirements which include limits for occupational and public exposure, dosimetry service approval, agreement on measurement of losses and contingency planning.

5.1 RADIOACTIVE DISCHARGE AUTHORISATIONS

Prior to the experiment, JET had been negotiating with HMIP for a number of years to obtain the level of authorisation appropriate for the full D-T phase and this was granted in mid 1991.

Species	Monthly limit	Annual limit	Individual dose	Collective close
Tritium excluding HTO	25TBq	110TBq	<1μS	0.9manSv
HTO	20TBq	90TBq	6.3μSv	
Aqueous discharge	2TBq	10TBq	0.12μSv	0.23manSv

Table 2 Discharge Limits

The likely maximum level of routine discharges of tritium, activated air and dust to atmosphere, and tritium and activation products to the River Thames, were calculated on the basis of 5 x 10^{22} neutrons per year using up to 90g of tritium with 30g in daily circulation. HMIP required estimates of tritium losses by permeation and leakage, and assumptions about the clean-up efficiency of the AGHS were used to justify the proposed authorisation [9].

The largest potential source of tritium releases in oxide form is the torus baking plant. The torus vacuum vessel is double skinned to permit gas to be circulated to maintain the temperature at 300°C and between the segments of the inner wall are bellows sections with a thickness of 2mm and total surface area of 236m^3. If the tritium partial pressure in the vessel is assumed to be 10^{-4}mbar during operation and glow discharge cleaning for 3000h/year, the permeation through the bellows in the absence of inhibition as a result of oxide layer formation would be 120TBq/year. However with a more realistic inhibition factor of 100, a bypass clean-up loop can be used to recover the tritium, and the losses to atmosphere for full D-T may be reduced to around 2TBq. Tritium permeation through this route during the FTE was too small to be reliably measured [10].

Only tritium and deuterium are recovered for re-injection when cryodistillation is used for separation of hydrogen isotopes. Protium (hydrogen) is discharged and will contain trace quantities of tritium. The discharge is normally vented direct along with the nitrogen off-gas. In the event of upset conditions the discharge can be vented via the ED. Assuming a product purity of 10^{-7} (compared with design value of $5x10^{-9}$) leads to an annual discharge of 7.5TBq of HT from a daily throughput of 30g.

Dispersion was calculated using a modified gaussian plume model which took into account the effect of building entrainment. Doses were then calculated using meteorological data in 12 sectors based on readings taken over a period of 7 years from an airfield 10km away. To take into account ingestion pathways, a specific activity model was used assuming for individuals that 0.3 of the water intake came from local sources. This would result in a dose to a hypothetical individual living at the site boundary 250m from the release point of

7.1 x 10^{-2}μSv per TBq. The nearest point of permanent habitation is several hundred metres from the boundary where the dose rate would be approximately half this value. The effect of the prevailing meteorological variations can be seen in Fig 12 which shows dose contours around the site boundary for the releases in Table 2.

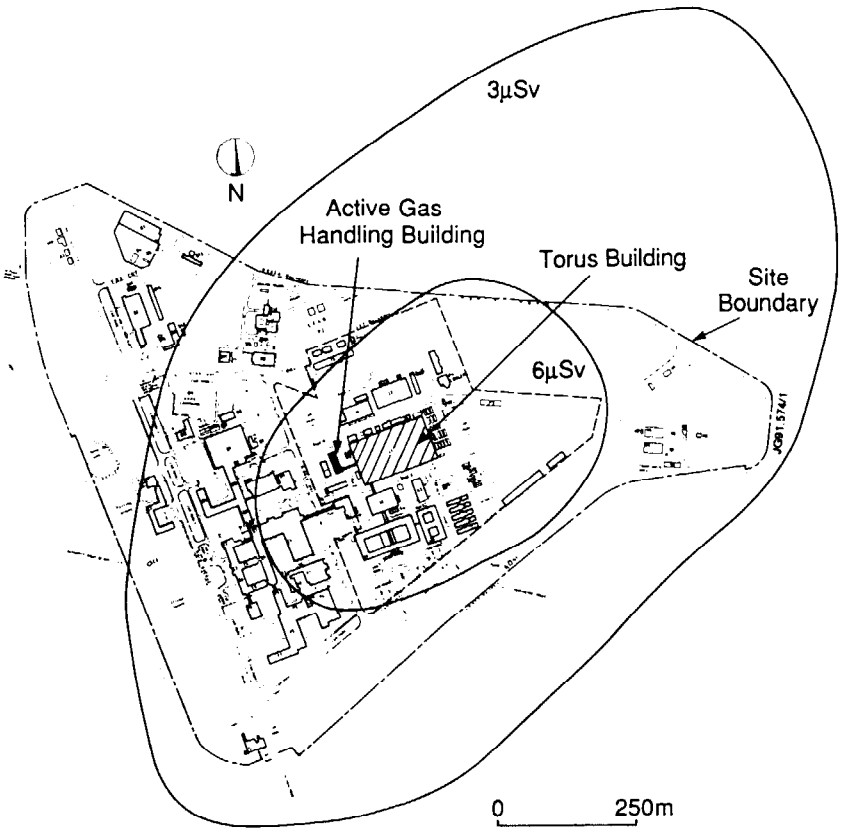

Fig 12 Annual Dose from JET Tritium Releases

As described above, some releases will be in the form of HT which will result in doses which are primarily dependent on the ratio of conversion of HT to HTO in the environment. For the purposes of assessing critical group dose, it was assumed that the resultant dose to an individual is 10% of the equivalent HTO discharge. A more rigorous assessment of the HT dose using the ETMOD [11] code has now shown that this assessment is conservative and the dose from HT will be approximately 1% of the numerically similar HTO discharge.

In addition to releases in the form of HT and HTO, some of the tritium released from JET may be in the form of methane or higher hydrocarbons. With the operation of JET with a beryllium first wall, the fraction of tritium exhausted from the torus in hydrocarbon form will be significantly lower than for carbon first wall and is expected to be less than 2% [12]. Even if tritium in this form is considered to be of the same radiotoxicity of HTO, the additional contribution to dose from this source is negligible.

The collective dose was also calculated using the specific activity model, but in this case assuming all the water intake is obtained at the point of habitation. The collective dose to the UK population from the gaseous releases is 0.9manSv assuming conservatively, because conversion of HT to HTO is more likely over larger distances, that the dose from HT is the same as that from HTO.

For liquid discharges, the highest dose would be received by a person supplied with drinking water from the outfall. However this is not considered to be realistic and the

members of critical group used for assessment purposes are those drinking water abstracted from the River Thames and consuming foodstuffs grown using irrigation water taken from the River Thames immediately downstream of the JET outlet. The dose per unit discharge is about an order of magnitude lower than the dose for the same amount of tritium as released to the atmosphere as HTO.

These levels could be justified as the dose to the most exposed individual off-site (<20μSv/year) was well within the absolute limit of 0.5mSv/year imposed by HMIP and the internally agreed limit for the Project of 50μSv/year. However the authorisations impose an overriding requirement that BPM (Best Practical Means) must be used to limit the environmental impact of the operations.

This had several implications, the most important being that even though the Authorisation would permit discharge of the full amount of tritium used for the experiment, BPM required that options other than direct discharge had to be considered, and led to the requirement for collection of as much of the tritium as possible using the technology of cryogenic pumping and absorption of hydrogen isotopes on U-beds. A review of the likely performance of the GCS and the evolution of tritium from the torus indicated that a daily discharge of <10GBq should be achievable. This value was set as a management target above which a special BPM case would need to be made. Although the evolution of tritium from the machine was somewhat different to that estimated before the experiment in that clean-up of the neutral injection system took much longer than expected, it was found to be a reasonable operational limit. It was exceeded only by a small margin on a few occasions when there were significant quantities of unprocessable gas.

5.2 SAFETY JUSTIFICATION FOR THE FIRST TRITIUM EXPERIMENT

The radiation dose to persons on and off the site which would result from the accidental release of radioactive materials had also been calculated for the full D-T case. For a release of tritium as HTO from the top of the torus building under class F weather conditions, the maximum dose on-site was 12μSv/TBq and off-site 0.6μSv/TBq. The off-site dose calculations were confirmed independently by CFFTP, Canada, using the ETMOD code and had been extended to include a dose from HT (0.003μSv/TBq).

Staged safety submissions were made to ensure that potential delays were identified early. In particular a Preliminary Safety Report was prepared which specified the design features and operational limits so that agreement in principle could be obtained from the Fusion Safety Committee and SRD on key issues such as the form of containment, operating pressures and inventory limits. This was then justified through a Safety Analysis Report (SAR) which had three main functions: to describe the final design configuration for the machine and ancillaries; to specify the accident sequences which could lead to a release of tritium (this having been identified in the preliminary analysis as the major hazard) and perform a probabilistic analysis; and to compare the public and worker risks against standards.

Faults on the JET machine such as vacuum leaks were reviewed and the steps taken to mitigate against their effect were discussed. From this and the other accident sequences identified from the hazard assessment, a number of accident sequences which required fault tree assessment to demonstrate their acceptability, were selected. These events included failure of PINI insulator or vacuum windows, overheating of U-beds and leakage from tritium containment systems.

The criterion for the acceptability of the design for JET tritium systems agreed with SRD is that for any single accident sequence, the product of the frequency and the amount released is less than 0.37TBq/year. This has been applied through the design safety review of the AGHS as a means of ensuring that the overall risk targets are met.

The UKAEA standard for public risk is that the total risk of premature death to the member of the public most at risk from all fault sequences on the whole site should not exceed 10^{-6}/year and the risk from any particular fault sequence should not exceed 10^{-7}/year. Even with pessimism arising from the use of non-average conditions and hypothetical

members of the public, the public risk for the FTE was shown to be 1.4×10^{-8}/year which is well within the above target. The criterion of 0.37TBq/year corresponds to a risk from any accident sequence of 7×10^{-9}/year thus ensuring compliance with the individual accident sequence risk target given above.

5.3 PROCEDURES AND TRAINING

Operation of all tritium handling equipment was carried out according to formal operation procedures which were approved through the JET management control system. Any deviation from approved procedures required formal approval. Significant changes, eg the addition of a pair of U-beds after the FTE, were separately safety assessed and endorsed by the Fusion Safety Committee.

JET was obliged to demonstrate that its staff had received adequate training in all aspects which were necessary for safe operation of the experiment. An auditable training programme had been in operation for a number of years and this was extended to deal with the new requirements which were in three forms:

i) General training on tritium, its properties, methods of detection and emergency response were given to all staff affected by the FTE.
ii) Specific training for operators of tritium plant. Although detailed written procedures were provided for this plant and tested out inactively prior to the experiment, it was essential that with full shift working, there were sufficient personnel to be able to deal with abnormal events.
iii) Training for those with specific emergency duties.

5.4 EMERGENCY ARRANGEMENTS

JET has set up an Emergency Plan which forms a framework for the various procedures, facilities and communications which are necessary. For the full D-T phase, the plan is capable of being extended to cope with the assessment and communications necessary to determine the need for and implementation of off-site restrictions in the event of a large accidental release.

The quantity of tritium available for the experiment was 0.25g (about 90TBq) which, if it were all released as HTO under adverse weather conditions, would lead to maximum short term doses of about 1mSv on-site and about 50μSv off-site. The emergency arrangements were therefore concerned primarily with the protection of on-site personnel.

6 Tritium Operations

6.1 FIRST TRITIUM EXPERIMENT

D-T plasma discharges were carried out in two distinct phases.

Phase 1 covered a two day period during which a total of nine plasma discharges with 2 neutral injection sources (PINIs) injecting beams consisting of 1% tritium in deuterium were carried out. This allowed testing of all systems including the recovery of tritiated gases and their measurement. During the second phase, two plasma discharges with 2 PINIs injecting 100% tritium were carried out. Both discharges resulted in a peak D-T fusion power in the range of 1.6MW. During a few preliminary conditioning pulses and the 2 injection pulses the U-bed supplying tritium remained at a temperature of > 400°C. This gave rise to permeation of 16GBq tritium through the hot wall of the U-bed thereby requiring a BPM justification for exceeding the JET imposed daily discharge limit of 10GBq. During the 1% and 100% experiments, 0.925 and 36.18TBq of tritium were discharged from the U-beds. Regeneration of the cryopumps in the neutral beam line system together with the gas recovered after the tritium injection pulses, showed that within the error of measurement nearly all of the injected tritium had been recovered after phase 1. Of the calculated amount

of tritium injected during phase 2, approximately 27% was collected in the torus exhaust stream within approximately 1.5 hours of the experiment. The bulk of the tritium deposited in the neutral injection system was recovered when the injector cryopump was regenerated a few hours after the second tritium plasma discharge.

6.2 CLEAN-UP OF TOKAMAK AND NEUTRAL BEAM SYSTEM

A few days after the injection experiment, operation was resumed aimed at releasing as much as possible of the remaining torus and neutral beam system tritium inventory for collection by the GCS.

6.2.1 Clean-up of Tokamak The release of tritium from the torus dropped rapidly from initially 2.2 x 10^{10}Bq to approximately 10^{9}Bq per pulse after 15 pulses. Several other techniques were tried, however the release kept falling and the torus was reconnected to its mechanical backing pumps some 3 weeks after the start of the clean-up phase. The decrease in the release of tritium per pulse is shown in Fig 13.

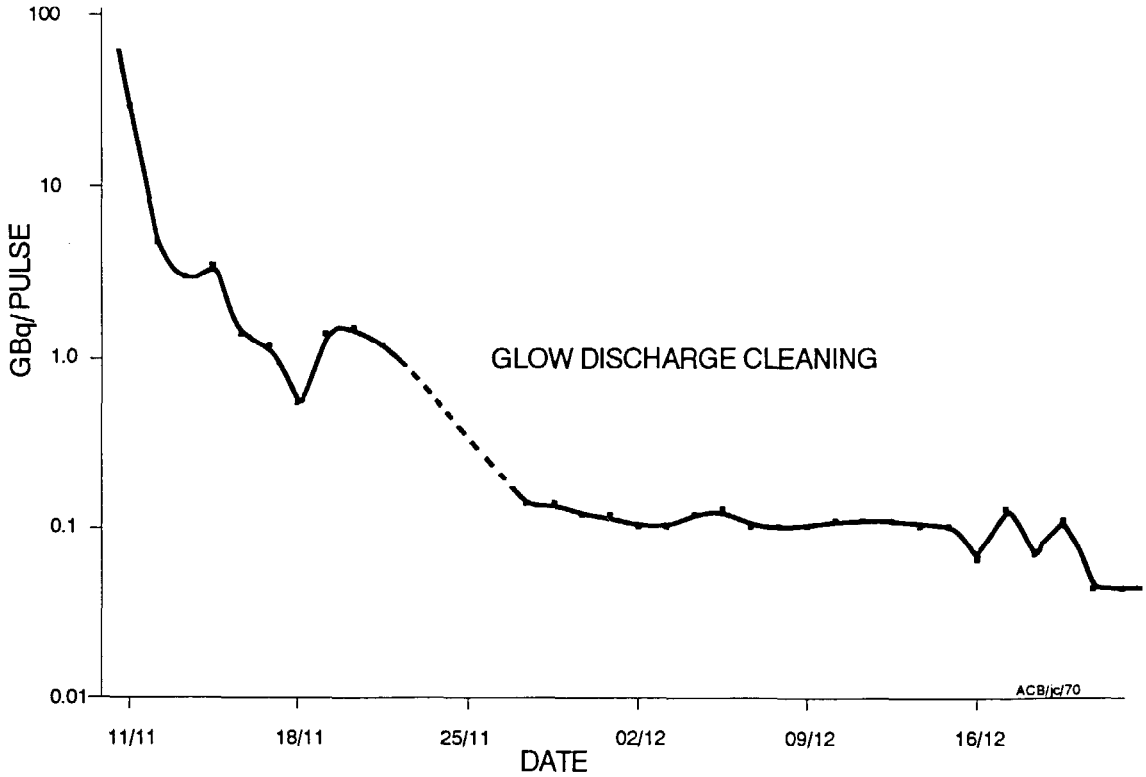

Fig 13 Evolution of Tritium from the Torus

6.2.2 Clean-up of Neutral Beam System The tritium remaining in the neutral beam system was thought to be on the blackened (anodised) liquid nitrogen cooled cryopanels which are known to have a water inventory of several hundred grammes, or implanted in the beam stopping elements. The release of tritium from the elements was attempted by exposing them to deuterium beams. Work on the JET neutral beam test-bed had shown that the efficiency of this technique could be monitored by measuring the neutron detector signal from the resulting fusion reactions [13]. This showed that this technique was highly successful in reducing the implanted tritium to a small fraction of the initial amount. The amount of tritium released during successive regenerations remained however at such a level that the tritium had to be absorbed onto the U-beds of the GCS for a much longer time than had

originally been anticipated. The continued release of tritium required installation of 2 additional U-beds when the first 2 U-beds became fully charged with approx 1000 bar litres of hydrogen species. Connecting into tritium contaminated pipework was achieved without any measurable release of tritium into the secondary containment. Transfer of the absorbed gas loads from the first 2 U-beds onto the new ones in relatively large batches allowed a more accurate measurement of tritium content than had been possible for the large number of small amounts of gas of varying batch size and gas composition, thereby obtaining an improvement in the overall accountancy accuracy. It took approximately 2 months before the neutral injection system used for tritium injection could be re-connected to its normal backing pumps [14]. At that time, ^{3}He injections were being carried out and the GCS was unable to process the larger quantity of argon used for pumping helium. At the start of the shutdown, it was necessary to vent the Neutral Injector Box (NIB) with air. This was done initially at a low rate to ensure that the discharge of tritium was controlled and heating to the permissible limit of 50°C was carried out. After purging for a few months, the concentration of tritium in the box reduced to that at which man-access would be permissible. Fig 14 shows the quantity of tritium discharged from the NIB.

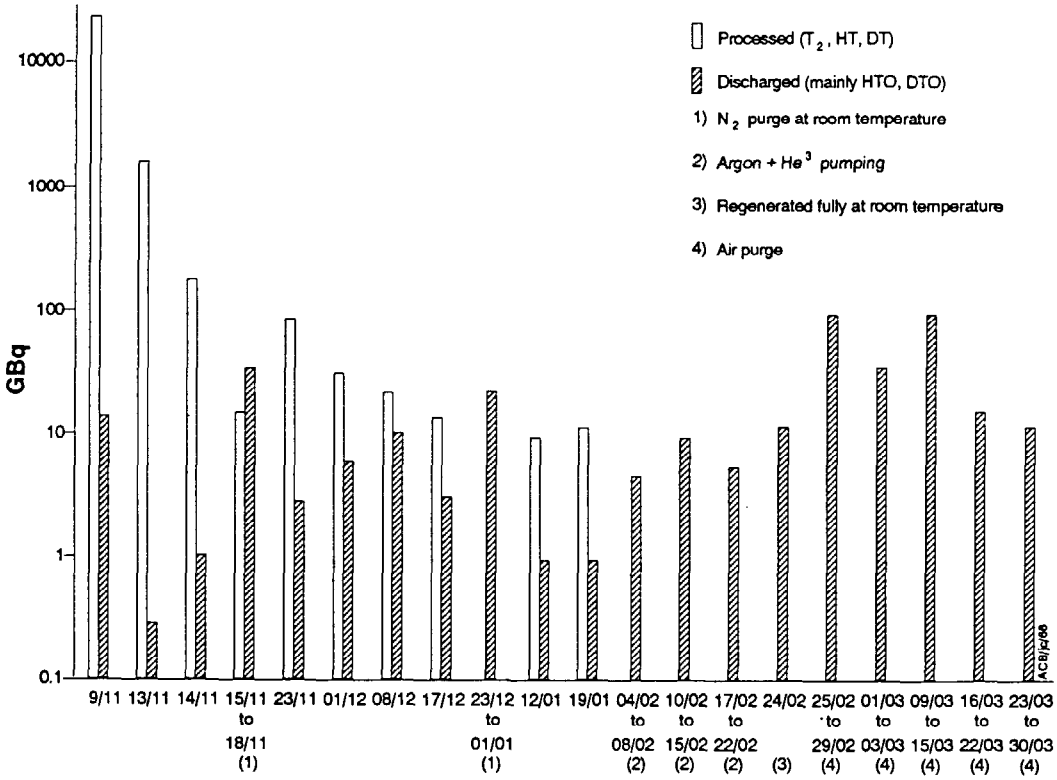

Fig 14 Octant 8 NIB Regeneration/Pumping

6.3 TRITIUM LEVELS DURING THE DIVERTOR SHUTDOWN

Personnel access was gained into the vacuum vessel at the beginning of March 1992 at the start of the shutdown operations. These involved complete removal of all internal vessel components followed by cleaning of the inner shell by a wet grit blasting technique [15] before commencing installation of the divertor coils and finally the other internal components. Initially measured tritium and air concentration in the (ventilated) vacuum vessel was 86Bq/m^3 which decreased to approximately 10Bq/m^3 after 20 weeks of shutdown work when the in-vessel cleaning started. A few weeks after the vessel cleaning the level

dropped to approximately 1Bq/m^3. Surface contamination levels were up to 7000Bq/cm^2 at the beginning of the shutdown but, after removal of the main components and vessel decontamination, dropped generally to below level of detection. Vacuum pipework from the GCS, despite having been exposed to tritium partial pressures of several mbar, was relatively free of tritium contamination with many surface smears at or below the clearance level of 0.5Bq/cm^2. The tritium level of components removed from the vacuum vessel and surface outgassing was generally such that a contaminated component had to be stored in areas connected to a ventilation system discharging through a monitored stack. For interim storage, machine components are stored in insulated ISO containers which are connected to the stack of the AGHS, fitted with on-line tritium monitoring as well as samplers. Possibly up to 50% of material stored in the ISO containers will be eventually declared waste.

6.4 WASTE MANAGEMENT

The transition to D-T operation of the JET machine necessitated considerable enhancement of the waste management facilities at JET. Additional holding tanks and a doubly contained radioactive drain were installed to comply with the requirements of the discharge authorisations. A new Waste Management Facility was constructed to permit the sorting of waste into different categories and the separation of re-usable components [16].

Liquid discharges which arise from vacuum vessel, component and suit washing amounted to approximately 1GBq during 1992. Solid waste arisings consist mainly of secondary wastes (clothing, tents etc) with tritium content up to about 8Mbq/kg, which can be disposed of as LLW (limit 12MBq/kg) in the UK facility at Drigg after compaction. The volume of LLW generated is shown in Fig 15.

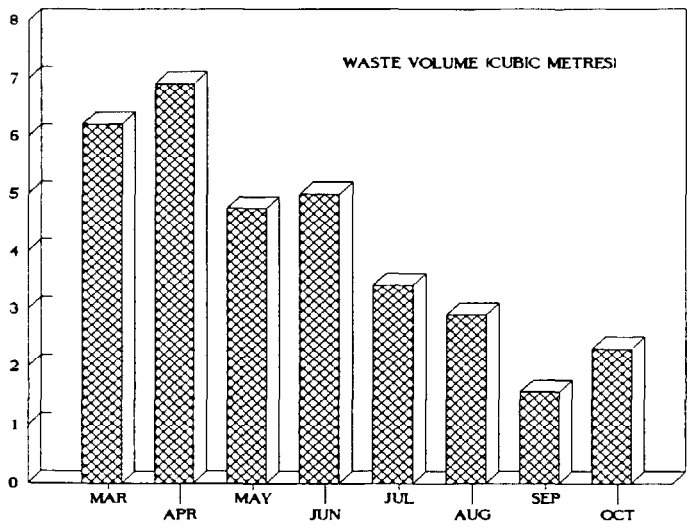

Fig 15 Monthly LLW Arisings (Compacted)

Tritium levels in secondary waste are determined routinely by measuring the tritium concentration in the air of each bag or drum. This method, supplemented by destructive tests, has the limitation that the lower limit of sensitivity is 120Bq/g. As the threshold for exemption from disposal as radioactive waste is 0.4Bq/g, all waste from tritium contamination controlled areas must be regarded as radioactive waste. With current disposal costs ~£4000/m^3 there is considerable incentive to reduce these volumes and work is in progress to evaluate other methods with higher sensitivity.

Components removed from the machine include first wall carbon tiles which with a tritium content of between 2.5 and 250kBq/g may be above the threshold for LLW. Methods of decontamination will be developed for those components to be disposed of as LLW.

6.5 TRITIUM MONITORING

Tritium monitoring was carried out using a combination of ionisation chambers and HT/HTO discriminating samplers. Working areas were monitored by fixed open-wall ionisation chambers (Fig 16) with sensitivity of 0.02MBq/m^3 and portable instruments with a sensitivity

of 0.08MBq/m^3. The latter instruments were also used for the monitoring of the glove boxes used for the FTE tritium supply and collection equipment.

The discriminating samplers which consist of a silica gel column for HTO absorption, a re-humidifier and wet proofed catalyst, and a second column for absorption of oxidised HT are used for stack and environmental monitoring (Fig 17).

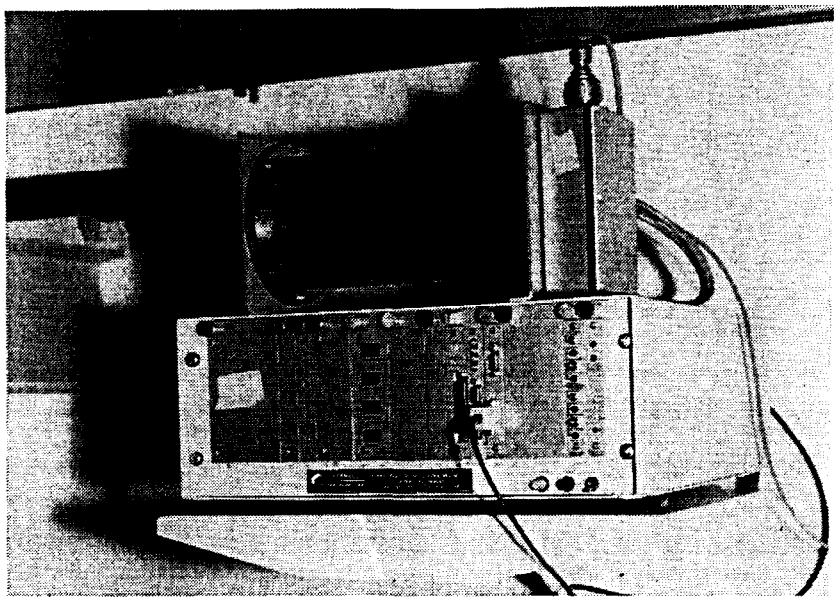

Fig 16 Area Tritium Monitor

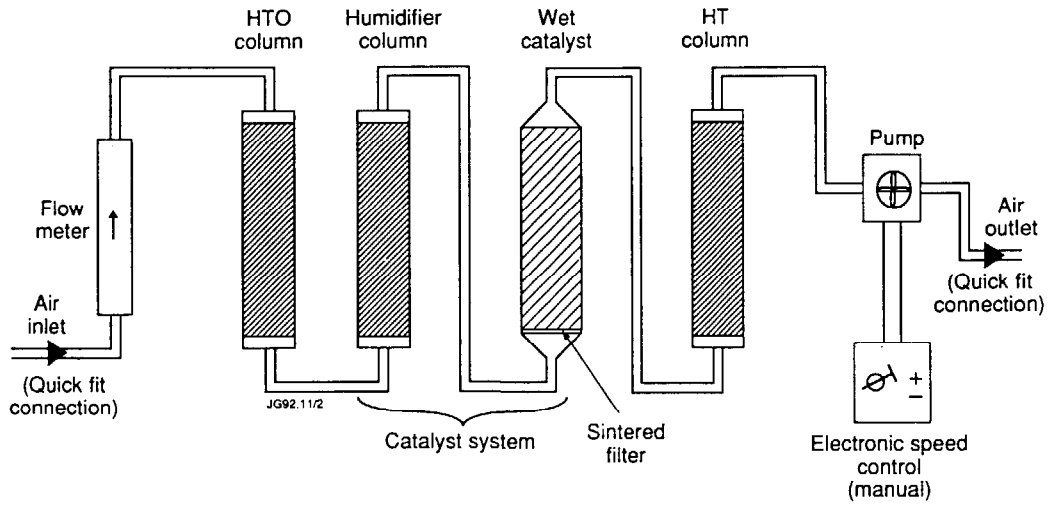

Fig 17 Discriminating Sampler

An extensive programme of environmental monitoring for tritium has been carried out for a number of years. It includes rain, river and bore-hole water, HT-HTO in air and free water and OBT in local crops including special garden plots on the JET site. The results during the FTE and subsequent clean-up were consistent with the stack discharges. Background HT and HTO levels were 30 to 100mBq/m^3 and peaked at ~400mBq/m^{-3} at the time of maximum

discharge. An interesting observation was that significant exchange took place between HTO discharged and water in the site cooling towers (which were generally downward of the discharge stack) in which tritium levels of around 200Bq/ℓ were measured.

The health physics arrangements at JET follow the accepted practice for tritium handling facilities with particular emphasis on urine sampling for workers potentially exposed to tritium. Gas flow proportional counters are used for surface contamination smear tests with a lower working limit of 1Bq/cm^2. Up to and including the in-vessel cleaning campaign, in-vessel operators had to wear full air line suits due to the presence of beryllium. The tritium levels did not require this, although the suits did of course limit the exposure of personnel by a large amount and consequently urine sampling did not result in tritium dose rate credited to any in-vessel operator. For firefighting, gas tight suits for use with self-contained breathing apparatus were available, giving a protection factor of ~3500.

6.6 TRITIUM ACCOUNTANCY

There are no formal requirements of tritium accountancy in the UK, although the Health and Safety Executive inspector must be satisfied that the requirements for accounting for losses laid down in the Ionising Radiations Regulations are complied with. An indication of the difficulty of tritium accountancy measurements in fusion machines is given by the results of the FTE. Measurements were made by PVT supplemented by gas composition and activity analyses. On the basis of the tritium balance calculations the total amount of tritium injected into the NIB was 40 ± 4TBq, of which 2 ± 0.23TBq was injected into the torus. At the start of the shutdown, a residual inventory of 0.28 ± 0.28TBq remained in the vessel. Subsequent measurements by destructive analysis of tiles led to a revision of the in-vessel inventory to approximately 0.06TBq.

7 Conclusions

The first tritium experiment at JET has provided valuable experience relevant to full D-T operation in future, in particular in the following areas:

i) Testing of AGHS components.
ii) Obtaining safety and regulatory approval.
iii) Establishing monitoring arrangements.
iv) Emergency planning.
v) Tritium decontamination.
vi) Waste management.

The experiment showed that the effort required for operational safety (operational procedures, training etc) is significant and should not be underestimated.

Tritium inventory measurements during and after the experiment showed that tritium accounting in fusion systems will be extremely difficult and is likely to be of low accuracy.

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