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and the JET Team

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ABSTRACT

D-T plasma operation has always been envisaged since the beginning of the JET Project and both the original design and subsequent modifications have been designed to take account of the requirements of D-T operation.

A limited tritium experiment was carried out in November 1991 which generated 1.7MW of fusion power. In addition to the physics objectives, this experiment was intended to provide results which would be important for the technology to be used in full D-T phase, such as tritium accounting and hold-up. Because of the limited usage of tritium it was possible to use a "once-through" system in which around 99% of the tritium was recovered.

It is currently planned to have a daily throughput of around 10g of tritium per day in the full D-T phase, introduced through neutral beam and/or gas puffing. As it would be neither environmentally acceptable nor cost-effective to discharge even 1% of this to the atmosphere, a tritium recycling plant, known as the Active Gas Handling System (AGHS) has been constructed and is currently being commissioned.

It was necessary to take several issues into consideration in the design of the AGHS to ensure that it and the JET machine would be capable of being licensed for handling tritium. These were ensuring that "Best Practicable Means" were used to limit routine discharges to the environment; ensuring that routine radiation exposure of the JET workforce would be minimised; and ensuring that the risk to the workforce and the public arising from accidents would be acceptably low. The technology involved, waste management and regulatory issues are discussed further in the paper.

I. INTRODUCTION

The Joint European Torus (JET) is the largest project in the co-ordinated programme of fusion energy research carried by the European Atomic Energy Community (EURATOM), Sweden and Switzerland. It was established in 1978 and is situated near Abingdon in the UK.

A prime objective of the JET Project is to study alpha particle production, confinement and plasma heating and the machine and associated systems have been designed to permit neutron production of 5×10^{23} per year and a throughput of around 30g of tritium per day. This has required the provision of massive biological shielding, a system for recovering tritium from the exhaust gas, and facilities for remote maintenance of components crucial for operation of the machine during D-T operation.

Fig.1 JET Vacuum Vessel

Plasma operation of the JET machine began in 1983 with ohmic heating and considerable enhancement has been progressively undertaken. This has included increase in plasma current to 7MA, RF and neutral beam additional heating and during the 1992/93 shutdown, installation of a pumped divertor.¹ In November 1991, prior to this shutdown, an experiment using a plasma containing about 10% tritium in deuterium was carried out which resulted in the generation of 1.7MW of fusion power. This experiment involved the handling of about 0.25g of tritium on the JET site and provided valuable experience of the issues involved; in particular in safety, tritium accountancy and waste handling.

II. JET PROGRAMME

The JET programme is currently approved to 1996 in which year a series of D-T experiments would be carried out. However, approval is being sought² for an extension to the end of 1999 which, following of the installation of the so-called MKII divertor assembly in 1995, would permit development of advanced divertor concepts relevant to ITER and a second D-T phase during 1999. It is currently foreseen that the 1996 D-T phase (DTE1) would result in the generation of the order of 2×10^{20} neutrons and the 2nd phase (DTE2) around 5×10^{21} neutrons.

A proposal is currently being considered for an intervention following DTE1 to replace divertor tiles using remote handling equipment for in-vessel operations.

Fig.2 Proposed JET Programme

III. TRITIUM PROCESSING REQUIREMENTS

During the first tritium experiment in 1991,³ approximately 0.1g of the available 0.25g of tritium was supplied to one of the neutral beam systems with two of the eight injectors set up for tritium operation. Tritium was supplied directly through a pressure regulating system from the uranium bed (U-bed) used for transport. The torus exhaust and gas evolved by neutral beam cryopump regeneration were collected on a helium-cooled cryofinger, transferred to a collecting tank and circulated through U-beds to remove hydrogen isotopes. Species which were not absorbed by the U-beds were discharged to atmosphere. Although some limited processing of hydrocarbons and water vapour could be achieved by operating U-beds in series with one at 450°C, the discharge to the atmosphere from the experiment, subsequent clean-up operations in deuterium and venting at the start of the shutdown was around 1% of the throughput of tritium.

Although this complied with the requirements to ensure that radioactive discharges were "As Low As Reasonably Practicable" (ALARP) given the limited quantity of tritium involved, it would not be acceptable for an extended D-T phase in which the daily throughput could typically be 10g.

The Active Gas Handling System (AGHS)⁴ has been designed to recover and recycle tritium for re-injection into the machine. To provide a margin to cope with variations to the experimental programme and for recirculation of internal process streams, the plant has been designed for a daily throughput of 30g of tritium within overall limits of 20 moles of mixed D/T and 150 moles of H₂ per day. The latter is designed to permit the use of a high speed pellet injector with protium driver gas although this is not currently included in the programme for the D-T phases. Tritium and deuterium of purity better than 99% will be separated for re-injection into the machine. H₂ and impurities will be discharged in accordance with strict environmental limits and the site inventory of tritium is limited by regulatory requirements to 90g. For full operation of the AGHS, a minimum inventory of 35g is necessary but more limited operation can be achieved with an inventory in the order of a few grams. The AGHS is currently being inactively tested and tritium commissioning is planned to start during 1994.⁵

The main elements of the AGHS are shown in figure 3.

Fig.3 AGHS Block Diagram

The turbomolecular pumps on the torus neutral injection and pellet boxes are backed during operation by the Cryogenic Forevacuum (CF) system which separates helium, hydrogen isotopes and impurities. Gases evolved from regeneration of machine cryopumps are also collected in the CF system. The mixed hydrogen isotopes are directed to Intermediate Storage (IS) on U-beds, and impurities are sent to Impurity Processing (IP).

In the IP sub-system, hydrocarbons are oxidised to CO₂ and water which is collected on a cold trap. The water is then reduced on hot iron beds and hydrogen isotopes collected on a U-bed.

Two isotope separation systems, Cryodistillation (CD) and Gas Chromatography (GC) are available, both with similar daily throughput of tritium and deuterium. The GC system, which uses

hydrogen as the eluant, is designed to separate deuterium and tritium with a purity of better than 99%.⁶ The CD system can process 150 moles of H₂ per day and is designed to permit this to be discharged directly to atmosphere with a H/T separation of better than 10⁻⁷.

Separated D and T are transferred to Product Storage (PS) U-beds from where they can be passed through calibrated volumes in the Gas Introduction (GI) for re-injection into machine systems.

The Mechanical Forevacuum (MF) is available for initial pump-down of the torus and the Analytical Laboratory (AN) can be used to analyse gas in any of the AGHS systems. In addition there is a dedicated Oxygen Monitoring system (OMS), within MF,⁴ which can detect the presence of combustible mixtures in the gas batches from the torus in the millibar range of pressures. Such gas mixtures can be directed to a dedicated CF module for removal of oxygen, thus preventing cryocondensation of potentially explosive mixtures in the normal CF cryopump.

An additional safety-related system is Exhaust Detritiation (ED).^{5,7} This provides depression in the torus during an up-to-air accident and during active phase maintenance, removing tritium from the exhaust gases and converting to water for subsequent disposal or reprocessing. It also provides for detritiation of various exhaust streams from the AGHS.

IV. REGULATORY REQUIREMENTS AND DESIGN SAFETY PRINCIPLES

Under the statutes which govern its operation, JET is required to comply with the safety standards of the UKAEA and to obtain their approval for radioactive operation. In addition there are legal requirements for waste disposal and operations with ionising radiation which must be obeyed. In effect these mean that JET must apply standards similar to those of a nuclear fission reactor or fuel processing plant of equivalent hazard potential. The standards include both deterministic and probabilistic assessment requirements and the provision of arrangements for control of safety during operation, maintenance and modification.

JET is not a nuclear plant and the majority of its systems are not concerned or affected by the handling of radioactive materials. To avoid the need to apply onerous and expensive requirements to all JET systems, they have been categorised in accordance with QA arrangements into four classes. For tritium systems, class 1 and 2 which correspond roughly to primary and secondary containment, are subject to rigorous standards, class 1 generally in accordance with ASME Section III and ANSI B31.3. In many cases these standards have been incompatible with UHV and cryogenic requirements and special case procedures have had to be used to justify, for example UHV flanges and ceramic feedthroughs. The above is one of many "Design Safety Principles" which have governed the design and safety assessment of the plant. Many of these are ALARA type statements that are justified in most cases by showing that the overall risk from the plant is acceptable. More explicit ones are:

1. No single failure should result in doses to workers or to the general public greater than the annual legal limits (50mSv and 5mSv respectively);
2. All systems containing tritium should, where practicable, be doubly contained. In particular this applies to systems which potentially can operate above atmospheric pressure and to systems operating at elevated temperature where permeation may be significant;
3. Components forming the torus vacuum envelope must be designed to minimise the risk of catastrophic loss of vacuum and to permit orderly venting of the machine. This implies windows, feedthroughs, and in several cases, bellows with testable interspaces;
4. All exhausts from the machine must be routed to the AGHS for processing/monitoring;
5. Off-site doses from routine operations must be less than 50 Sv/year;
6. Provisions should be made for decontamination prior to maintenance of systems eg by bake-out.

Safety submissions to UKAEA follow the same standards as for nuclear plants and consist of:

1. Preliminary Safety Report (PSR) setting down the basic safety principles and an overall assessment of the hazard;
2. Pre-Construction Safety Report (PCSR) giving a detailed analysis of the proposed design (or modifications in the case of the torus). This would be supported by appendices including individual Design Safety Reviews and dose/consequence assessments;
3. Pre-Commissioning Safety Report (PCMSR) setting down the arrangements for safe active commissioning of the plant and specifying the necessary tests on safety systems;
4. Pre-Operational Safety Report (POSR) presenting the results of commissioning and showing that operation can be carried out within the constraints of the safety case made in the proceeding documents.

In the case of the AGHS, because of changes in the requirements during the course of assessment, documents 2) and 3) have been combined.

The overall assessment must show that probabilistic criteria for operator and public risk from radiation accidents must be met. Based on a risk to an individual of premature death of $5 \times 10^{-2} \text{Sv}^{-1}$, these are:

On-site staff $10^{-5}/\text{year}$;

Public off-site $10^{-6}/\text{year}$;

Public (single accident) $10^{-7}/\text{year}$.

In addition, for the AGHS, a frequency/release limit of 0.37TBq/year was set for individual accidents sequences to ensure that the above limits would be likely to be met. This was necessary as the AGHS was designed and assessed in parallel. It would not have been

possible on the required timescale to complete the design and then carry out the PRA. About 400 accident sequences were analysed and the overall risk from the AGHS determined to be:

On-site staff 2×10^{-6} /year;
Public off-site 1×10^{-7} /year;
Public (single accident) 2×10^{-9} /year.

V. SAFETY RELATED TECHNOLOGY

A. Preliminary Tritium Experiment (PTE)

The tritium handling systems for the PTE were "once through" and considerably simpler than that of the AGHS to be used for future tritium operation. Because of the limited quantity of tritium used (0.25g) the design principles for public dose could have been met without any secondary containments. However, to comply with the basic design principles, a secondary containment was installed and routed to a high-level discharge stack onto top of the JET building. This took the form of a glass-fibre glovebox for the tritium supply system in the torus hall⁸ and a PVC "isolator" with glove ports as shown in figure 4 for the gas collection system. The prime purpose of these was to protect the operator in the event of a failure within the system.⁹

Fig.4 Gas Collection System Isolator

All the secondary containments were individually monitored for tritium. The alarm level was set at 4MBq/m^3 to give early warning of leakage and to enable action to be taken before significant personnel exposure took place.

B. Active Gas Handling System (AGHS)

The vacuum lines from the torus cannot be subject to a pressure greater than atmospheric as they are protected by relief paths through the ED system. They are therefore singly contained (apart from bellows and ceramic breaks with testable interspaces) up to the point at which they enter the CF and MF systems. Special valves with double bellows stem seals connect with the

CF and from this point on all the AGHS process systems, with the exception of the ED system, are doubly contained. Three types of secondary containment are employed:¹⁰

1. Vacuum containments capable of tolerating an overpressure of several atmospheres. These are used in cryogenic systems (figure 5) and systems with potentially high inventories such as U-beds. Any leakage into these containments can be recovered back into the process systems.

Fig.5 Cryogenic Forevacuum Containment

2. Stainless steel flat-sided boxes which operate under a nitrogen atmosphere at 3 to 15mb below atmospheric pressure. There are fourteen such boxes connected to common manifolds for purging and venting through the ED system. The boxes are normally isolated but are purged and vented periodically to maintain the oxygen content low and to compensate for thermal effects and inleakage. In the event of a tritium alarm, the box is isolated and tritium can be recovered for reprocessing or treatment through a buffer tank. The Analytical Laboratory boxes are fitted with glove ports and glove ported lids may be fitted on the other boxes during maintenance.
3. The MF system mechanical pumps were too large to be installed within a stainless steel box and a sealed concrete room, ventilated through the ED system in the event of a tritium release, has been constructed to house them.

To meet the requirement that systems should be bakeable to assist in decontamination prior to maintenance, all metal components have been used as far as practicable. Additional requirements have arisen from the need for valves to operate in an evacuated secondary containment. This has required the development of special valve actuators, pressure regulators and ionisation chambers. All welded construction has been adopted as far as practicable with demountable connections on process systems via UHV flanges or Cajon VCR fittings. These systems are required to be leak tight to better than 10^{-10} mbar l/s.

Secondary containments, the ED system, and water drainage systems may use non-metal seals.

C. Torus

The JET machine was originally designed for tritium operation and certain basic features, such as massive concrete shielding were incorporated during construction. In addition, the vacuum vessel is double skinned to enable hot gas to be circulated to control the vessel temperature. As well as providing an additional barrier in case of inner wall failure, this permits tritium permeating through the wall to be removed from the circulated helium and recovered or processed via the AGHS. This removes the main source of routine release of tritium during D-T operations (estimated at 200TBq/year). There are approximately 50 diagnostic windows on the machine and these have been identified as the component with the greatest potential for catastrophic loss of vacuum. This would lead to immediate regeneration of vessel, neutral beam and pellet cryopumps. The ED system in the AGHS is designed to cope with this event by providing depression in the torus. Failure of the ED system would then lead to tritium release into the torus hall.

To lower the demand on the ED system and lessen the probability of a full area failure of a window, double windows have been specified for the D-T phase and are being progressively installed. (During the PTE, the small amount of tritium at risk permitted the safety targets to be met without double windows).

Another safety-related design change concerned the means of gas introduction to the neutral beam injector.

It was not considered acceptable to pass tritium to feed the ion source through an insulating break subjected to a potential of 160kV. Modifications were made to permit feed at ground potential through the neutraliser. These were tested on the JET neutral beam test bed and successfully employed for the two tritium PINIs used in the PTE.¹¹

Fig.6 Double Window

VI. TRITIUM PROCESS INSTRUMENTATION

One of the main issues investigated during the PTE and subsequent clean-up operations was the tracking of tritium in the supply and processing systems and in particular in the machine. It was expected from previous evidence that considerable tritium retention in first wall components would be expected and to ensure that this could be determined, accurate measurement of the isotopic content of the tritium supplied, of supply flowrates and of recovered tritium were made. The last measurement was performed using a number of ionisation chambers which were calibrated both in the near atmospheric pressure range and also in the so-called β collector range below 1mb where the sensitivity is of the order of 200 times lower.

Process measurements were supplemented by measurements of the tritium activity in tiles removed during the 1992/93 shutdown,¹² and by measurement of neutron generation in the neutral injector beam stopping elements.¹³

As the uncertainty in the amount of tritium injected into the machine would represent several tens of grams of tritium when projected to an extended D-T phase, it was essential to develop methods of more accurately accounting for tritium injected into the machine and stored in the various AGHS U-beds.

An isothermal calorimeter system of high accuracy has been developed for use with the transport U-beds used for the initial loading of the AGHS with tritium. With non-active heat sources this has given an accuracy of better than ± 10 W, equivalent to 12GBq.

In addition, a system of quasi-adiabatic calorimetry has been established for the JET storage U-beds. These, with a capacity of up to 27 moles of hydrogen isotopes, are enclosed within a double vacuum containment with excellent and measurable thermal insulating properties. A direct measurement of the tritium inventory of a bed to an accuracy of better than 1g will be possible.¹⁴ This system will also enable safety case requirements for segregating tritium inventory to be demonstrated. Gas supplied to the torus can be measured by PVT plus a number of analytical instruments including gas chromatography, omegatron and RGA mass spectrometers and ionisation chambers. These methods will enable a better estimate (with an accuracy of a few grams) to be made of the tritium hold-up in the torus.

VII. WORKPLACE, ENVIRONMENTAL AND DISCHARGE MONITORING (FIGURE 7)

JET working areas are monitored where applicable by gamma, neutron and tritium fixed monitors giving direct readout and alarms. These are supplemented by portable instruments and Health Physics monitoring equipment for surface contamination and tritium in air. During JET operation and in particular after the PTE, radiation dose rates have been consistent with prediction. Tritium-in-air levels have generally been low and below the sensitivity of the on-line monitors apart from the case of specific operations such as monitoring tritium content of pump

oil where levels of the order of 1 DAC were experienced during initial sampling. In-vessel levels have been low, ranging from 55Bq/m^3 at the beginning of the shutdown to $<1\text{Bq/m}^3$ at the end after cleaning operations and removal of the majority of in-vessel components. Environmental monitoring is mainly concerned with tritium and is measured in air, rain and groundwater, river water and crops. Air is analysed using HT/HTO discriminating samplers which can measure down to environmental levels of around 30mBq/m^3 and are based on silica gel columns with a wet-proofed catalyst for HT oxidation. The results have generally been consistent with JET discharges when the previous atmospheric conditions are taken into account. Environmental monitoring included on-site cooling towers where the circulated water exchanged with atmospheric moisture containing tritium and thereby produced an additional discharge route for water from the site.¹⁵

Fig.7 Environmental Monitoring

Discharge monitoring to demonstrate compliance with tritium discharge authorisations is based on similar HT/HTO samplers, one of which is installed on each of the 8 stacks at JET which potentially may discharge tritium. The columns are sampled weekly and have operated reliably since October 1991.

VIII. WASTE MANAGEMENT

The management of wastes at JET became a major issue following the introduction of beryllium components into the machine in 1989.¹⁶ The Torus Access Cabin (TAC) was used to control contamination spread and to permit transfers of components and waste in and out of the vessel, control of personnel in pressurised suits and sorting of the "housekeeping waste" generated by in-vessel operations.

This provided valuable experience on procedures and systems required for dealing with activated and tritium contaminated

Fig.8 Torus Access Cabin

wastes.¹⁷ In preparation for the PTE, a waste handling facility was constructed to enable waste to be segregated from re-usable components and soft waste to be compacted with a volume reduction of 6:1.

All the waste dealt with by JET comes into the LLW category ($<12\text{GBq/t}$) apart from some first wall tiles which exceed this level because of tritium content. No facility for disposal of ILW exists in the UK at present and steps are being taken to develop techniques to bring the tritium content down to LLW to permit disposal at the UK facility at Drigg. This will be essential for components removed after DTE1 which are likely to have tritium levels about 100 times higher than the PTE.

Cost is a major issue of waste disposal, particularly in the case of housekeeping waste where compacted volumes generated at the start of the 1992/93 shutdown were $\sim 3\text{m}^3$ per week. In the UK, the level at which waste can be cleared for uncontrolled disposal is 0.4Bq/g . This applies to all nuclides including tritium. It is not possible to measure tritium at this level directly (in contrast to, for example, Co60) and any housekeeping waste from tritium controlled areas could potentially be LLW.

A waste quarantining system has been adopted which involves holding housekeeping waste from a controlled area each day until the result of contamination checks on the area are available. If they show that the area remains uncontaminated, the housekeeping waste can be declassified. This procedure has allowed the volume of waste to be reduced by a factor of 2.

Even though waste may arise from a tritium contaminated area, its tritium level may be low enough to permit uncontrolled disposal. "Sniffing" techniques on drums have been used, but these are only capable of detection down to 100Bq/g . A technique for assessment below 0.4Bq/g is being developed. This involves heating a sample of the material in a moist nitrogen stream to promote extraction of a proportion of the tritium as HTO. Reproducible results have been obtained which have been calibrated against destructive analysis. It is hoped to put the system into practice once the regulator is satisfied with the QA arrangements.

Large differences in the tritium uptake of diverse components exposed to tritium during the PTE have been measured, depending on their surface condition. In addition to the first wall tiles discussed earlier, the following conditions have been observed:

1. Equipment manufactured to UHV standards and operated at room temperature showed undetectable surface tritium contamination after exposure to a tritium partial pressure of a few tens of mbar for several hours.
2. Paintwork on equipment such as ventilation ductwork from the torus hall contained sufficient tritium to prevent uncontrolled disposal (30Bq/g) after exposure to an average of 50Bq/m^3 HTO and 250Bq/m^3 HT for several weeks. Outgassing and/or isotopic exchange with air water vapour was effective in reducing the tritium content by a factor of 1000.

3. Liquid nitrogen cooled cryopumps were exposed to tritium during pulses and for several hours during successive regenerations of the helium-cooled cryopanel at a tritium partial pressure of around 1mbar. Tritium retention corresponded to about 1% of the total quantity of tritium trapped by the LHe panels during the PTE. About half of this amount was released during venting of the neutral injector box (NIB) at the beginning of the shutdown and the remainder was retained. The implications of this for DTE1 are being considered.

IX. SAFETY ANALYSIS

Safety analysis has been carried out to demonstrate that the regulatory requirements specified in Section IV are met. Specific issues which have been addressed are:

1. The safety of U-beds in the event of air ingress was justified through JET tests, supported by the results of other tests at Ontario Hydro.¹⁸ Air ingress to a JET U-bed led to a reaction terminated at 150°C by argon blanketing.
2. Torus window failure and subsequent air ingress was analysed to show that runaway graphite oxidation would not occur. The main issue for this event is the ability of the ED system to maintain depression in the torus and prevent expulsion of the tritium contaminated air as it is heated through contact with in-vessel components.¹⁹
3. Demonstration of interlock reliability for computer-based systems has proven not to be cost effective as features such as redundant software would be required. All interlocks credited in the safety case are hard-wired and readily analysable.
4. The paucity of relevant reliability data has made parts of the PRA reliant on nuclear plant and generic data which is usually conservative. In certain cases, JET-specific data has been sufficient, using if necessary a Bayesian approach. Analysis of the radioactive hazard potential for each JET sub-system has been carried out. Systems in which the release of a credible amount of radioactive material leads to an off-site dose of less than 20 Sv or a worker dose of 500 Sv are classed as low hazard and are not subject to PRA.

Maximum off-site doses (calculated for the design basis neutron production of 5×10^{23} in one year) used in the initial classification analysis are listed below.

Substance	Source Term Assumed	Off-site dose
Tritium	20g	5mSv
Freon 113	1m ³	1.1mSv
St707 Getter	500g	200 Sv
SF ₆	30m ³	37 Sv
Coil Epoxy	1kg	17 Sv
Cable Insulation	1kg	10 Sv
Tokamak Dust	1g	4 Sv
Torus Hall Air	30,000m ³	0.4 Sv
Liquid Nitrogen	770ℓ	3×10^{-3} Sv

Additional mitigating factors, such as HEPA filtration in the torus hall ventilation, and the use of more realistic neutron production rates, will reduce all of these values significantly, apart from tritium (torus cryopump inventory) which will then dominate the off-site hazard potential.

X. CONCLUSIONS

JET has adopted appropriate technology and design principles which enabled the first tritium experiment to be carried out safely and with insignificant environmental impact. Lessons have been learned from this experiment, particularly in the fields of tritium analysis and waste management, which will be put into practice in future experiments.

Stringent regulatory guidelines have been complied with and demonstrated through the safety analysis giving confidence that the next set of D-T experiments can be carried out safely.

XII. ACKNOWLEDGEMENTS

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