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ABSTRACT

JET has completed its first stage of active operations, processing more than 100g of tritium during the deuterium-tritium experiment (DTE1), the neutral beam intervention and remote tile exchange shutdown. The radiological safety of tritium handling operations has been of particular interest. A wide range of tritium operations has been carried out in the period 1995-98. This paper describes some of the radiological protection measures for work with tritium, and discusses Health Physics operational experience of handling tritium in this period.

Descriptions are given of active operations in the gas handling plant; in the torus hall during DTE1; in related interventions, and of the remote exchange of in-vessel divertor modules. Workplace contamination levels over 100DAC (HTO) have been encountered, tritiated water with activity of 2TBq/litre and tritiated carbon with activities of ~4TBq/g has been handled. Control measures involving the use of purge and extract ventilation, and of personal protection using air-fed pressurised suits are described. The project imposes tight limits on radiation exposures. Tritium doses to staff in this period have been very low (individual doses <170μSv/year, collective doses ≤2.1mSv/year). Aerial discharges have been <3% of annual authorised limits, and average environmental (HTO) levels have been a few Bq/m^3. Lessons have been learnt concerning exposure control, large-scale permeation effects, and the appearance of residual tritium on exposed surfaces.

Tritium operations at JET have been conducted without incident and with very low personnel exposures. The methodology of using containment and ventilation systems and tight radiological control has been successful in limiting doses. JET experience shows that large-scale tritium handling and exposure control can be achieved within stringent dose limits.

1. INTRODUCTION

With the commissioning of the active gas handling building in 1996, the campaign of torus operation in deuterium-tritium (DTE1) [1] in 1997, followed by the completion of a remote in-vessel divertor exchange shutdown in 1998, JET has gained substantial experience of handling tritium and working on tritium contaminated plant. The project has successfully completed these phases of its active operations, producing valuable physics and technical data. In addition it has demonstrated the technology for the large-scale processing of tritium in a closed fuel cycle, and shown that maintenance and upgrades of tritium contaminated systems can be achieved safely.

A wide range of tritium operations and maintenance tasks have been carried out in this period, and of particular interest has been the radiological safety measures required for routine operation of the tritium plant, and for work on contaminated systems. A comprehensive Health Physics service has been in place at JET providing radiological protection advice; workplace monitoring of radiation and contamination; sample assay; and worker training. External support is used for dosimetry, discharge sampling, and environmental monitoring. Although tritium is regarded as a low radiotoxicity nuclide, ($E_{\beta(mean)}$=5.6keV, $t_{1/2}$= 12.3y, ALI[1]=3x10^9Bq (ICRP30)) there may be significant exposure risks whenever large quantities are handled and it is in its more hazardous oxide form (HTO is considered to be 10,000 times more radiotoxic than HT).

The primary barrier for tritium control at JET relies on ultra high vacuum technology and high integrity double-metal containment. There remains a potential for public exposures during plant discharges and for worker exposure to tritium during containment breaches for maintenance or for repair activities. Work with in-vessel tritium exposed components has shown additional hazards from the presence of tritiated carbon particulate. The safety procedures used for work with tritium, and the Health Physics experience of exposure controls, and results of workplace monitoring are described below, in the context of JET's operations. Results of tritium doses accrued by workers, environmental monitoring results and descriptions of the tritium monitoring methods are also presented.

2. TRITIUM OPERATIONS OVERVIEW

The first small-scale tritium plasma experiments were carried out at JET in 1991 [3]. A quantity of 0.1g (37TBq) tritium was injected to the JET machine via a source local to the neutral beam injector, and exhaust gases recovered through a dedicated gas collection and recovery system.

For the full active phase at JET the Active Gas Handling System (AGHS) was constructed to provide on-site storage, supply, and recovery of tritium gas. The process systems are shown in Fig 1. The AGHS receives tritium on transport U-beds which is then transferred to larger storage beds. Plant systems supply tritium, and receive torus exhaust gases to process and purify using cryodistillation and gas chromatography techniques. The exhaust detritiation system (EDS) in the plant is designed to remove excess tritium from the gas stream prior to discharge via the building stack. EDS operates using catalytic recombiners and molecular sieve driers to oxidise tritium gas and trap the water vapour, at flow-rates of ~500m^3/hr, achieving detritiation factors of 1000 [4]. Regeneration of the driers produces tritiated water, which is collected and periodically emptied into transport drums.

In 1995-6 the AGHS was commissioned initially with 0.1g (37TBq) of tritium, and later with 3g (1.1PBq) [5]. Tritium was successively introduced to the various process systems, and these checked for operation and containment integrity. For the DTE1, a larger inventory of 20g (7.4PBq) was introduced.

Following extensive preparations and detailed formation of procedures, DTE1 was started in May 1997. Tritium was supplied to the torus by gas introduction and by neutral beam (NB) injection. The neutral beam injection systems [6] incorporate large liquid helium cryopanels onto which most of the tritium condenses before it reaches the torus. The torus divertor system

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[1] ALI (Annual Limit on Intake) defined as activity intake that would result in committed effective dose of 50mSv, ICRP's average annual dose limit for stochastic effects, ICRP-30

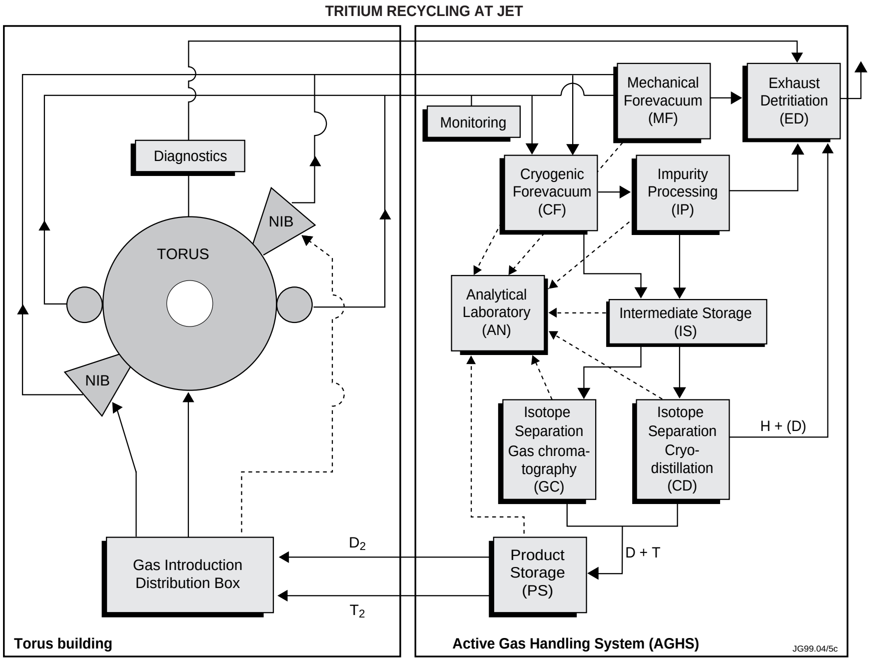

Fig.1: Process Systems in the Active Gas Handling Plant

also has cryopumps, onto which most of the tritium introduced into the torus is trapped. During a period of torus D-T operations, several grams of tritium can accumulate on the neutral beam and divertor cryopumps. Regeneration of these occurs periodically, allowing the trapped gases to be recovered by the AGHS. By the end of DTE1 in November 1997, some 99g of tritium had been supplied by the AGHS, effectively allowing repeated use of the 20g inventory. Approximately 35g was introduced to the torus, and of this, some 11.5g remained in the torus at the end of tritium operations. Clean-up operations, involving deuterium plasma pulsing, reduced this quantity further [7].

In June 1997, shortly after the start of D-T operations, a small water leak developed in a shutter mechanism in the vacuum of one of the two neutral beam injectors, stopping further tritium pulsing. The only feasible method of repair was by manned access into the affected Neutral Injector Box (NIB) to cut out the faulty pipework and weld in a replacement. The NIB had already been used for tritium injection, and even after regeneration of the cryopanels a large quantity was held up within the NIB components. The repair work represented a major breach of containment and demanded stringent exposure controls involving ventilation by EDS and personnel protection using airline full-suits [8].

At the end of DTE1, a two month period of clean-up operations (followed by a resumption of normal D-D operations) was successful in recovery of 5.5g of tritium. This left an estimated 6.0g still in-vessel, mainly absorbed on vessel walls, bulk graphite tiles and co-deposited in carbon flakes at the divertor. Two weeks before the start of the remote tile exchange (RTE) shutdown in February 1998, a programme of controlled venting, soaking and pumping of the torus volume took place, involving dry nitrogen and then moist air. The main objective in the RTE shutdown (February-May 1998) was to replace about 150 MkIIa divertor modules with replacement Gas Box carriers [8]. Given the high in-vessel dose-rates arising from D-T neutron activation, ~6mSv/hr, and the highly tritiated (and beryllium contaminated) nature of the tile modules, the exchange was to be done fully remotely using an articulated boom arm and a servo manipulator. No manned access was required in-vessel, but the torus volume was required to be open to two access enclosures docked to the torus, in which personnel would supply tools to the boom and carry out maintenance activities. (Figure 2a illustrates the tile carrier transfer facility (TCTF) docked to the torus, and the boom arm in use). With an estimated torus tritium content of several grams, opening of the vessel volume represented the largest breach of vessel containment at JET, and required extensive preparations to achieve. Personnel access to the enclosures was in air-line full suits, to guard against increases in tritium levels during removal and storage of the tile modules, and also against the presence of tritiated carbon in particulate forms.

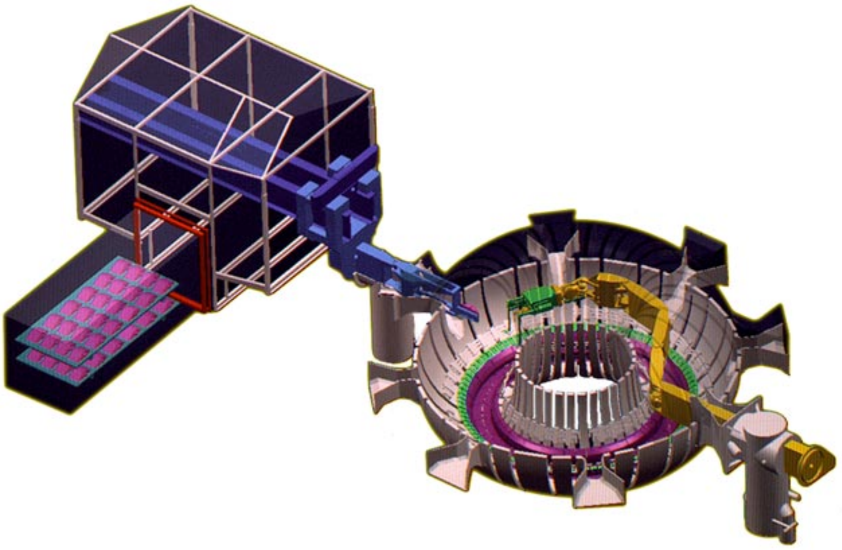

Fig.2a: Schematic View of Torus, TCTF and Remote Boom Arm In-Vessel

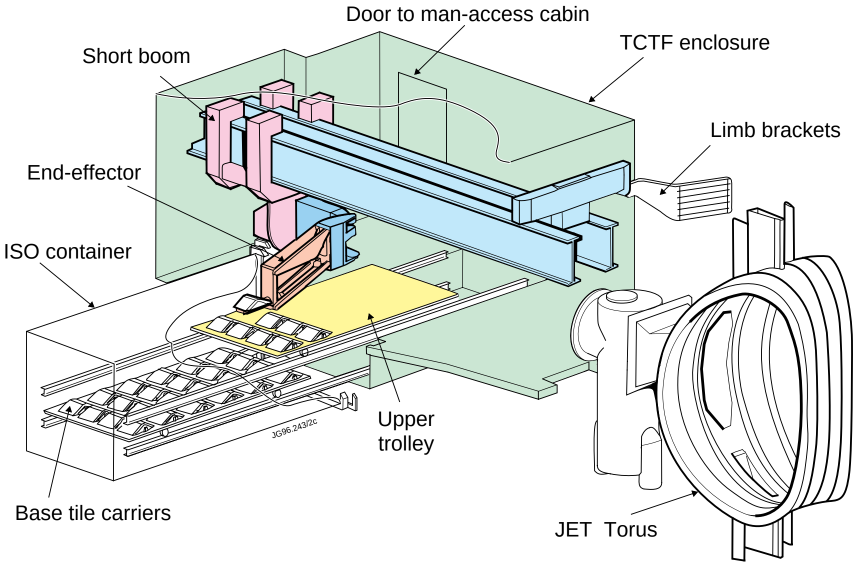

Fig.2b: Detail of TCTF, and Carrier Module Storage Iso-Container docked to the Torus

As well as the remote module replacement, further in-vessel tasks included surveys, modification of diagnostics, and vacuum cleaning and dust collection. A large number of ex-vessel tritium operations were also conducted in this shutdown, involving replacement and upgrading of diagnostics on the torus.

3. REGULATORY LIMITS AND SAFETY PROCEDURES

In the UK, the Ionising Radiation Regulations 1985, specify the standards for dose-limitation, control of work, dosimetry, monitoring and medical surveillance. The dose limits in these regulations (eg 50mSv/year whole body) relate to the 1977 recommendations of the ICRP [10]. The project's own policy on radiation exposure to workers under JET control is to restrict all dose to its classified persons to 5mSv/year, and 1mSv/year to all other staff. This limit is regarded as stringent even now, compared to forthcoming changes to statutory limits in response to the ICRP60 recommendations [11] and the European Council Directive [12]. In addition, JET practice was brought in line with the requirement for optimisation of doses under the European standards by prescription of job related operational dose constraints.

JET had to obtain regulatory approval to hold tritium and accumulate and discharge tritiated waste, in accordance with the UK Radioactive Substances Act, 1993. Prior to the use of tritium, JET also completed a Safety Case and an accident analysis to demonstrate to external auditors that it could safely handle gram quantities (PBq) of tritium. Although JET currently holds 20g, it has authorisation for up to 90g. Approvals have been granted for aerial and liquid discharges to the local environment. JET aims to limit discharges, so as to restrict off-site doses to the public to below 50μSv/year.

During the DTE1 phase, work procedures were refined to allow for the additional radiological hazard arising from tritium contamination. For discrete or major breaches of tritium systems such as the NIB intervention or for work in AGHS, detailed safety assessments were written describing the hazards, precautions, and work procedures to be adopted. Likewise for the RTE shutdown, several detailed safety assessments were raised governing the work in the TCTF and Boom enclosures and prescribing the methods for exposure control against particulate forms of tritium, as well as HTO. For work involving opening torus machine interspaces or stagnant volumes containing tritium, a supporting assessment was required, specifying in detail the tritium history for the system; the likely tritium content; the expected stack release; the control measures to be applied; and the personal protection to be used. Job specific dose constraints for both individual and collective dose were applied to all tritium-related work, and particularly for operations where there was an external radiation hazard present as well.

4. EXPOSURE CONTROLS

The methods employed at JET for limiting dose to individuals rely principally on engineering controls and ventilation systems. Prior to opening a tritiated volume, the free tritium release is reduced by pumping and venting the volume, using dry nitrogen, followed by moist air. This is repeated several times until the releasable tritium concentration, as measured by an ion-chamber, is below a set limit. For most volumes, pumping is by the EDS. This method was employed for the 50m^3 NIB boxes as well as the 200m^3 torus vessel for the RTE. Portable pump-purge rigs were utilised extensively for the RTE shutdown for the ex-vessel breaches of interspace and diagnostic volumes. Such volumes were typically a few litres to about 100 litres, and the limit on residual free tritium content was set typically at 8MBq to ensure a local concentration well below 10 DAC[2] (HTO) during the breach.

Widespread use was made of area ventilation to provide confinement of the tritium hazard and dilution of chronic releases. For opening of the NIB vacuum and the torus vessel, the torus hall volume was placed in a once-through ventilation mode, providing a containment velocity exceeding 1m/s across the partly open shield doors. Local exhaust ventilation is also used extensively in the torus hall and AGHS, the discharge being directed to the EDS or to the building stack.

A successful method practised during the RTE shutdown, to open tritiated volumes where the releasable content could not be readily reduced, involved use of PVC glove-bags, or isolators, to provide partial containment of the hazard. This method has been in use extensively for work on beryllium contaminated volumes at JET, and is a valuable tool when opening volumes where there is a mixed beryllium and tritium hazard.

5. HEALTH PHYSICS OPERATIONAL EXPERIENCE

5.1 Active Gas Handling Plant

In the period of commissioning and during routine operation of tritium processing systems with 20g in the DTE1, workplace contamination levels in the AGHS building were found to be very low. During the commissioning phase, air and surface contamination levels in most areas were below measurable limits. Throughout DTE1 tritium doses to plant operators were a few microsieverts at most. Building discharges through the stack have also remained low, with discharge levels typically 50 GBq/month (HTO), 200GBq/month (HT) during DTE1, and 550 GBq/month (HTO), 20GBq/month (HT) with the higher throughput during the RTE (Figs 3,4).

During maintenance tasks the use of purge techniques and ventilation controls has been largely effective and local concentrations have rarely risen above a few DAC (HTO). PVC isolators and box panels incorporating glove ports have been used to provide containment for some jobs. Protective clothing for these operations typically comprise coveralls, double PVC gloves and overshoes, and for work with tritiated oils and low activity water, aprons and boots. During one repair operation to replace a seal on a mechanical forevacuum pump, a concentration of 100DAC (HTO) was seen transiently in the worker’s breathing zone. In this instance,

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[2] DAC (Derived air concentration, 8x10^5 Bq/m^3 , ICRP30)

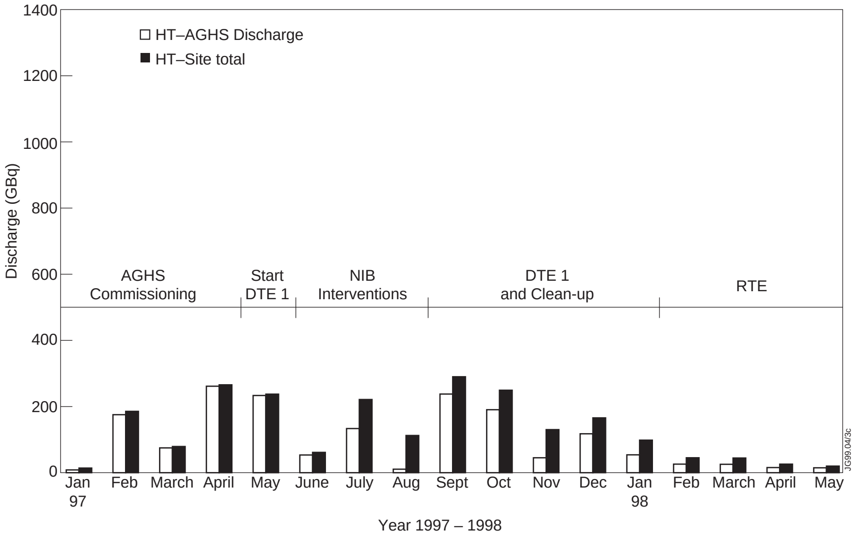

Fig.3: JET Site Aerial HT Discharge Jan-97 to May-98

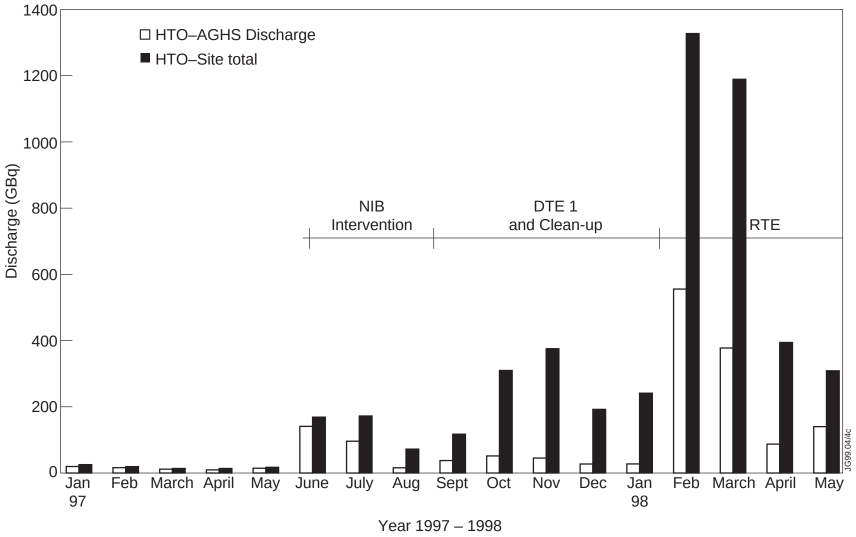

Fig.4: JET Site Aerial HTO Discharge Jan-97 to May-98

only dry nitrogen purging was possible, and the positioning of the local ventilation extract was atypical. The resulting committed effective dose to the worker was 80µSv. This task highlighted the need for proper positioning of extract ducts when used for exposure control. Tritium concentrations in the water collected during EDS regeneration rose to ~20 GBq/litre during DTE1. Tritium collection by the EDS at the start of RTE was much higher as a result of torus purging and ventilation. Increased airborne tritium concentrations were apparent during this period near the EDS driers and active drain tank during regenerations. Air concentrations of 13 DAC (HTO) were found locally and gave rise to some increased building discharges, but with only minor operator doses. Concentrations as high as 1.3TBq/litre were recorded following the first few regeneration cycles in the RTE, although as equilibrium conditions were reached, concentrations reduced to 200GBq/litre. Even so, the dose potential from exposure to a few millilitres of this water was high, consequently airline supplied pressurised suits were used for subsequent operations to transfer the active water into transport drums.

5.2 Torus Operations

The DTE1 phase of torus operations was conducted without any significant tritium or external radiation exposure. Continuous monitoring of the workplace was achieved by use of 20 on-line ion-chambers, 3 discriminating (HT/HTO) samplers [13], and a number of tritium bubbler instruments. Some monitors were located outside the torus hall near to beamlines, penetrations, or shield doors, and others in the main occupied areas adjacent to the torus hall and in the AGHS building. The most sensitive monitors showed levels between 10-500 Bq/m^3 in areas outside the torus hall, although increases of up to 1kBq/m^3 HTO and 70kBq/m^3 HT were found in some areas. These are thought to be due to partial entrainment of stack discharged tritium in the building wake. No levels higher than 1DAC (HTO) were found in any occupied areas during DTE1.

More significant was the gradual rise in tritium levels within the torus hall after the first introduction of tritium into the vacuum vessel in DTE1. With a vessel temperature of 320°C, it was expected that tritium would diffuse into the vessel bakeout loop. The typical torus partial pressure for tritium is 10^{-4} Pa, but rises to a few Pa during divertor cryopump regenerations. The increased permeation at high vessel temperatures and at large tritium partial pressures is thought to have caused increases in the helium gas loop to ~40TBq [14]. Permeation of tritium from the vessel and baking loop may also explain the steady rise in torus hall tritium levels, observed some three weeks after the first introduction of tritium into the vessel.

During tritium operations, the ventilation system in the torus hall is configured to provide a depression of a few hundred Pa. This provides one air-change per day in the torus hall volume, and allows neutron activated air products to decay. Under equilibrium conditions, tritium concentrations reached 0.3MBq/m^3 in the torus hall, giving rise to routine stack discharges of 10GBq/day. The concentration was found to be temperature related, and the HTO fraction approached 80%, supporting permeation as the source. Although the concentration was only 0.4DAC (HTO), it represented a potential source of exposure to personnel entering the torus hall, for example for maintenance activities. Furthermore, whilst there remained significant quantities of tritium in a releasable form on the cryopumps, there was a restriction placed on direct ventilation of the torus hall. Consequently, this tritium remained almost a constant exposure source throughout DTE1, and in the subsequent clean-up and D-D campaigns. Tritium was absorbed into many torus hall surfaces and into machine components.

Tritium was also found to permeate into the machine cooling loops. The neutral beam and poloidal coil cooling water concentrations increased with time to 8kBq/litre two months after the end of DTE1.

For the major maintenance activities at the start of RTE, vessel temperatures were reduced to ambient, and the torus hall atmosphere purged continuously.

5.3 NIB Intervention

Two NIBs are connected via rotary high vacuum valves to the torus, and form part of the tritium containment. The injector comprises several high-energy neutral beam sources and a large 8m high vacuum chamber containing neutralisers, deflection magnets, beam dumps, cryopump and a calorimeter [15]. Typically during D-T operations, 0.2g of tritium was fed for each pulse to one of the injectors at octant 8 of the torus. Only 1%-4% of this enters the torus, the rest being trapped on the liquid helium cooled cryopanels.

Shortly after the start of tritium operations in DTE1, a small water leak on a coolant hose to a shutter mechanism in one of the NIBs precluded further injection of tritium. The radiological condition of the box was such that even after several regenerations of the cryopump, ~100TBq remained in the 50m^3 box, both as an absorbed fraction and as free tritium. It was clear that manual intervention would be needed to repair the leak [16]. A sequence of pump-purge cycles reduced the in-box concentration from 32GBq/m^3 to 6GBq/m^3, but with an estimated outgassing rate >100GBq/day. A dose constraint was set at 2mSv/person, giving only 80 DAC-hours per person to complete repairs. To limit discharges, direct ventilation to the stack was not possible. At a ventilation rate limited to 5-6 air changes per hour, box concentrations were likely to remain >100 DAC. Given the restraint on exposure, the only feasible option was entry using airline supplied full suits. However there were considerable logistical difficulties in establishing suited access from the top of the box. Prior to access, the 7m high central support column, which was a major source of tritium itself, had to be removed. It was stored in the second, less tritiated NIB at octant 4. Access for the repairs was achieved by means of a purpose made change area cabin, assembled from modular fibre-glass panels. With the EDS system ventilating the box, suited entries were made initially at concentrations up to 100 DAC. Bioassay (urine) dosimetry sampling showed dose uptakes of 2μSv/hr. More than 200 hours of suited work was carried out over several weeks. The highest individual dose during the intervention, involving transfer of columns, establishing access, repairing the leak, was 70μSv, and the collective dose for ~65 persons was ~500μSv. Stack discharges for this period remained at <3% of the site authorisation, whilst some 29TBq was collected by the EDS. This intervention demonstrated the successful use of pump-purge, ventilation control, personal protection, and detritiation methods on a large scale to control operator doses and limit stack discharges.

5.4 Remote Tile Exchange (RTE)

The RTE, from February-May 98, was one of the most extensive maintenance shutdowns at JET involving radiological hazards. Exposure controls were necessary for both tritium and external radiation. As well as the remote in-vessel operations, a wide range of ex-vessel activities were carried out.

The radiological status of the torus at the end of clean-up operations in January 98 was such that an estimated 6g of tritium remained absorbed within vessel walls and divertor components, although the majority was not immediately releasable. The in-vessel gamma dose-rate was estimated at ~5mSv/hr, precluding personnel access there, whilst contact dose-rates on the machine exterior reached 600µSv/hr at known hot-spots.

For this shutdown, a dose-constraint of 3mSv/person was established. In addition, a ceiling of 3GBq/m^3 was set on the in-vessel concentration before the vessel doors could be opened. A two week period of nitrogen gas and moist air soaks/pumps commenced, which reduced the free tritium evolution in the torus by a factor of 30 to 450GBq/hr. Approximately 1g of tritium was collected by EDS in this time in processing the torus exhaust. At the same time, preparations for the remote in-vessel removal of the divertor modules was made by installing the Tile Carrier Transfer Facility and Boom enclosures and the other ancillary services and iso-containers in the torus hall (Fig 2b). Having established steady-state conditions in the torus, a continuous purge of the vessel was started using EDS, and the target concentration was reached within 3 weeks to permit opening of the torus doors, and begin the remote in-vessel activities.

The first phase of the RTE shutdown involved removal of the tritium exposed MKIIa divertor carriers. These were to be transferred entirely remotely to three separate storage iso-containers. In the second phase, a new set of divertor modules (for the so-called MkIIGB divertor) was to be posted into the TCTF and placed on a short boom for remote installation in-vessel.

Whilst no in-vessel personnel entry was necessary, access was required to both TCTF and boom enclosures. As well as the diffusion of torus tritium into the enclosures, and the off-gassing risk from the removed MkIIa modules, it was expected that small quantities of tritiated dust would settle out in the TCTF as the modules were removed and transferred. It was believed that some 30% of the tritium content of the torus was co-deposited on the divertor modules and structure, mainly as loosely adhered carbon flakes and dust [17]. The tritium content of the dust was estimated at 4TBq per gram. Although a limited phase of cleaning of the divertor structure was planned, most of the modules were extracted without pre-cleaning. Contamination controls were therefore required in the TCTF against both tritium as gas/vapour and in the form of a particulate contamination. The metal structure of the carriers was also expected to be activated due to D-T neutron exposure.

A range of contamination control measures were in place for the remote activities. The torus volume continued to be ventilated by the EDS. The aim was to provide a depression in-vessel so as to ensure inward flow. The evolution rates were too high to consider direct ventilation to the stack, however, the EDS flow-rate could provide only two air-changes per hour of the 200m^3 volume. The two enclosures were separately ventilated at 10-20 air-changes/hr, discharging to a filtered stack. With a vessel depression of only a few Pa, and two open ports, careful control of the system ventilation was required to minimise stack discharges. It was necessary to link the enclosure volumes independently, and attach a sleeve to one of the boom arms to effectively seal the port, and thus restrict flows out from the torus.

Personnel access to the enclosures was in full-pressurised suits, to guard against tritium excursions during removal and storage of modules, and to guard against the presence of tritiated dust and beryllium contamination. The interior of the TCTF was spray coated beforehand with a PVA formulated solution (Gramos 6121) to provide a thin peelable membrane as a contamination barrier. Floor surfaces were extensively covered with plastic sheeting. At the end of the MkIIa carrier removal, a further spray coating was applied to fix any loose dust contamination. A procedure of routine vacuum cleaning of TCTF and boom surfaces was carried out, and floor sheeting replaced periodically. During the MkIIa carrier removal the highest surface contamination level in the TCTF found was 2MBq/cm^2 on the floor surfaces and associated with dust from removed carriers, although more typically levels were in the range 100-1000Bq/cm^2. Off-gassing rates from individual carriers were measured at 0.6GBq/hr (inner carrier module). Average concentrations remained below 10 DAC (HTO), although readings up to 60 DAC were observed in the enclosures. Particulate activity in air in the TCTF reached 130kBq/m^3, although it declined quickly. Most readings were below an assumed DAC value of 50kBq/m^3. This value was based on the dose coefficient for (inorganic) particulate with a slow absorption rate [18]. The radiation hazard from the open vessel port and the removed modules was minimised by limiting the occupancy of the TCTF and using shielded storage iso-containers. Typical doses to the suited operators were ~5µSv/hr gamma, and <0.1µSv/hr for tritium. Stack discharges in the early part of RTE reached 200GBq/day, although these reduced down to below 10GBq/day for the remainder of the shutdown.

In parallel with the in-vessel remote activities, a wide range of ex-vessel diagnostic and support operations were carried out. In many instances these operations required a breach of an interspace between the diagnostic and vacuum vessel boundary. In others a direct breach into the vessel containment was necessary. Tritium was also expected and found in diagnostic volumes outside the torus hall where it had permeated through containment windows and migrated down beamlines.

Assessments were made prior to each such operation of the likely tritium release due to the breach, the consequential personnel dose and the likely stack release. Ventilation controls and containment measures were also agreed upon prior to the operation. Initial assessments and measurements showed that the tritium build-up in interspaces due to permeation effects was typically in the range 10-100GBq/m^3, although one diagnostic interspace breached soon after DTE1 had a content of 1000GBq/m^3. The interspace volumes ranged from 10-200 litres. In each case a portable pump-purge rig was used to perform a controlled sequence of gas or moist air purging. Generally an upper limit of 8MBq of residual free tritium in the volume was set for breach, and initial experience showed that for the larger volumes this could take a whole day of pump-purging to achieve. The 8MBq content ensured that local concentrations remained well below 10 DAC, avoiding the need for respiratory protection against the tritium. For volumes where there could be tritiated particulate or beryllium contamination due to migration through open torus valves, a plastic containment isolator was used. For a breach through an isolator, the ceiling figure was set at 80MBq, or 800MBq if the isolator itself was ventilated.

Stringent precautions were in place, particularly where the removal of a diagnostic involved an opening of the vessel containment. Given the potential for back diffusion of the torus tritium content, and the risk for exposure to particulates, such breaches were usually made through containment isolators. Filtered air inlets were provided on the isolator. Initially the vessel ventilation system drew air through the isolator, and once the diagnostic port could be closed, a valved connection was opened to a flexible ventilation hose extracting directly on the isolator. The ventilation hose extracted through a filter, thereby preventing dust contamination entering the ventilation system. The opening of a lower vertical port carried greater risks of exposing trapped particulate, and a system of double isolators was used successfully.

Exceptionally, when the use of isolators was found to be impractical, a direct opening into the torus was permitted, but sufficient inward flow had to be assured by closing the two main horizontal ports and ceasing in-vessel operations. The largest port opening was still limited to 100mm diameter in this case, and personal protection in the form of air-line supplied half-suits was used as a precaution.

In most cases local extract ventilation was provided in addition to reduce breathing zone tritium levels from local releases, or arising due to permeation through the isolator. Levels measured outside the isolator were generally <1DAC, although higher levels were observed transiently when volumes were breached without use of ventilation; a concentration of 100 DAC was found during disconnection of inert gas supply lines to a torus secondary containment. In many cases, the removed diagnostic had a combination of beryllium and tritium contamination, and an activation dose-rate around ~50μSv/hr. Such diagnostics were transferred to ventilated enclosures, in the JET Beryllium Handling Facility for inspection and modification prior to re-installation.

Two Positive Ion Neutral Injectors (PINIs) were also extracted from a NIB system during RTE. The NIB involved, (octant 4), had not been used to inject tritium beams, but contamination from tritium had occurred via backflow from the torus vacuum vessel. NIB concentrations were gradually reduced to 0.5GBq/m^3 before it was ventilated through the EDS at a flow rate of 10-15m^3/hr. Pressurised half-suits were also used for the PINI removal. Off-gassing rates of 6-30 MBq/day were observed from the tritiated PINIs.

For most of the RTE operations, the torus hall was placed in a once-through ventilation mode, providing 4 air-changes per hour of the 33,000m^3 volume. For the initial breaches of the torus volume and other direct openings of the vessel, the torus hall doors were partly closed such that the velocity across the opening was ~4ms^{-1}. Tritium levels in the torus hall generally remained low, once vessel temperatures were reduced, levels declined to an average of 300 Bq/m^3 (Fig 5).

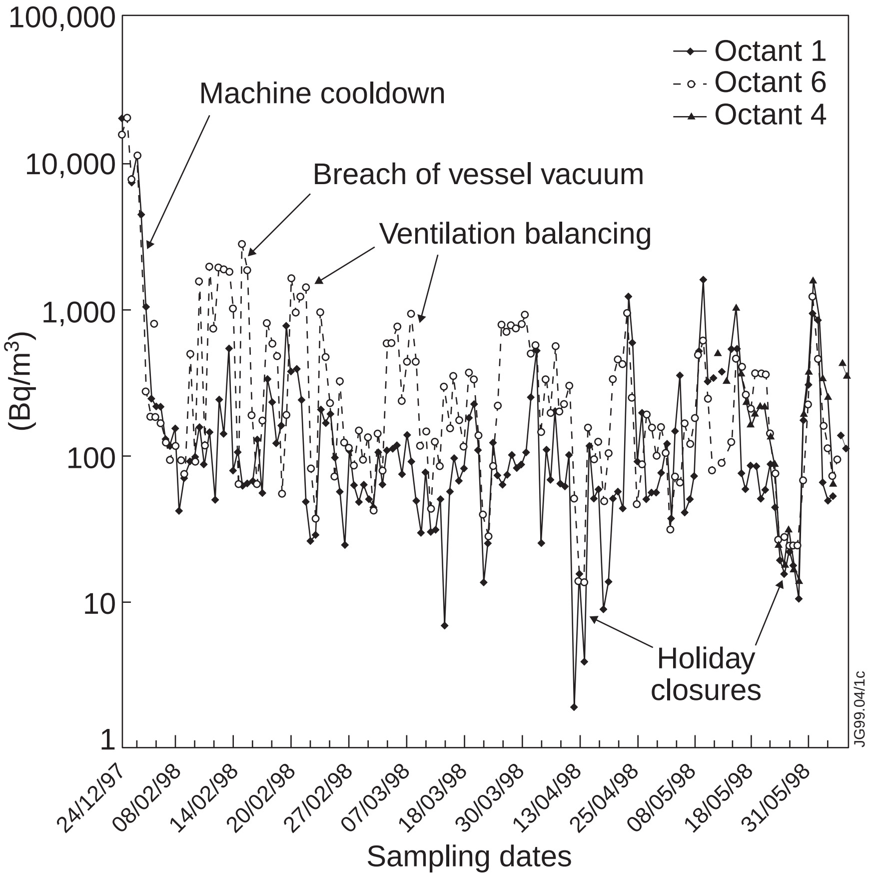

Fig.5: Torus Hall HTO Concentrations during RTE Shutdown by Bubblers

More than fifty separate assessments for ex-vessel operations were made during the RTE involving breach of a tritiated volume. Results of workplace monitoring showed that contamination controls were successful in preventing releases and spread of contamination. All operations were concluded without incident or anomalous dose. Exposures were a fraction of the set constraint.

6. ENVIRONMENTAL DISCHARGES AND MONITORING

Stack discharges of tritium were monitored using on-line ion-chambers and integrating HT/ HTO silica gel based samplers. Figures 3 and 4 show the aerial discharges of tritium in relation to the tritium phases at JET. These phases were, January-April 97 (pre-DTE1), May-June 97 (start DTE1), July-August 97(intervention), September 97-January 98 (DTE1 and clean-up), February-May 98 (RTE).

The majority of the site aerial discharge of tritium during DTE1 and RTE was related to the torus hall depression stack and discharges from AGHS. The process exhaust from recycling of tritium in AGHS contributed to the discharges throughout 1997 during both AGHS commissioning, and in the DTE1 operation mainly as HT (Fig 3). The elevated levels of HTO in June-July 1997 can be related to the NIB intervention (Fig 4), whereas the higher discharges of HTO later (October 97-January 98) can be attributed to ventilation discharge of torus permeated tritium. For the 32-week period covering DTE1 and the intervention in 1997, the total site discharge was 1.28TBq (HTO) and 1.31TBq(HT). Some 55% of the HTO total was from the torus hall depression stack, representing permeation effects as a sizeable proportion. For the RTE phase, stack discharges of HTO (Fig 4) reach 1350GBq/month in February 98, due mainly to enclosure exhaust and AGHS discharge. Discharges for the 18 week period were 3.2TBq(HTO) and 0.1TBq(HT). The sum of discharges for both phases was <3% of JET's annual regulatory authorisation.

Measurements of the environmental concentrations at a point near the site boundary using a HTO sampler is shown in Fig 6. Monthly averaged levels are seen to reach 2.5 Bq/m^3 at most, closely following the HTO stack discharge (Fig 4), and correspond with the predominant SW wind direction. These levels imply a negligible environmental impact due to JET's discharges.

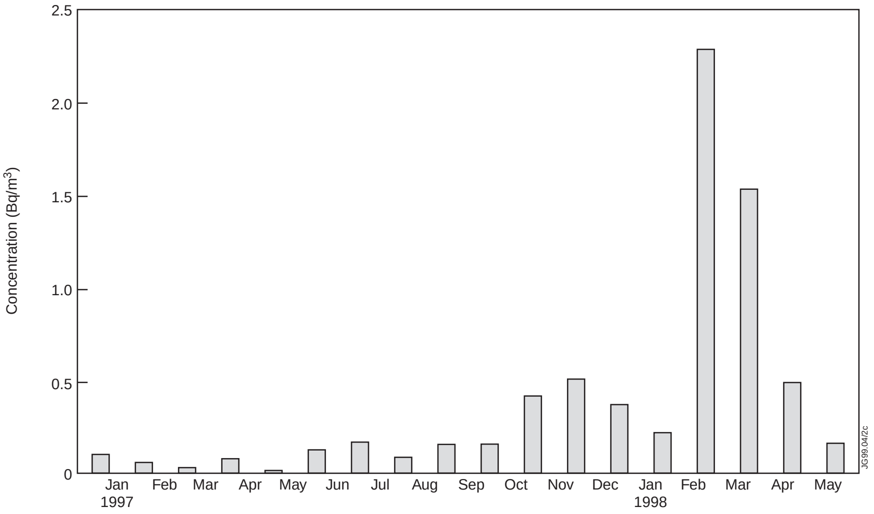

Fig.6: Site Environmental HTO Levels Jan-97 to May-98

7. PERSONNEL DOSES

Urinanalysis is the standard dosimetric method of assessing committed effective dose following exposure to HTO. Counting by LSC (liquid scintillation counting) which has a detection limit 100Bq/litre, is sensitive enough to allow doses <1μSv to be measured. JET policy has been to sample all persons making access to tritium handling areas. Routine sampling is by provision of fortnightly samples, or for single entries, a few hours after completion of the work. Measured committed effective doses are described below.

a) **AGHS**. During the active operation of the AGHS, 30 operators and support staff have been on routine monitoring. Doses to this group were barely detectable in the commissioning and DTE1 phases, although due to the higher quantities processed in RTE, doses to a few individuals rose to 10-30μSv. The highest individual dose was 130μSv, and some 80μSv of this was related to a breach of primary containment, the repair of a seal on a forevacuum pump.

b) **DTE1**. With torus hall tritium levels at an average of 1/3 DAC, there was a potential for dose to all torus hall entrants. Individuals involved in diagnostic refurbishment in the torus hall received doses of ~30μSv, whilst a dose of ~135μSv was received during pumpout of machine interspaces which contained elevated levels of tritium.

c) **NIB Intervention**. Of the 65 persons involved in this intervention, the highest dose was 70μSv, and the collective dose 500μSv.

d) **RTE**. Despite the greatly increased radiation hazards in the RTE, operations were stringently controlled. In consequence, doses were kept very low. The highest tritium dose was 100μSv, accrued by a vacuum technician involved in pump-purge activities. A total of 148 persons were monitored. Of these, 99% received a dose below 30μSv, and 80% received a dose below 10μSv.

The standard method of measuring exposure to β,γ radiation at JET is by thermoluminescent dosimeter (TLD), Panasonic UD800 series. This dosimeter is favoured because of its sensitivity to low doses. The readout of one such badge to a worker involved in a tritium containment breach in AGHS indicated an apparent TLD dose of 18mSv. The worker was exposed briefly to about 100DAC (HTO). It appeared that the tritium had become incorporated within the thermoluminescent lithium borate elements in the TLD, such that it led to an apparently genuine exposure effect. This was proven by exposing test TLDs to tritium levels of a few DAC. In each case, the elements showed doses of a few mSv. As a result of this experience, for the RTE shutdown, it was decided to issue tritium workers with film badges in parallel to TLDs, to provide a degree of assurance that TLD results were genuine external exposures. Film-badges were found not to show the same exposure effect with tritium.

8. PERSONAL PROTECTION.

The standard form of protective clothing worn for work in low level tritium areas consists of disposable ‘tyvek’ type coveralls, double gloves, and overshoes. This assists in avoiding spread of contamination and minimises skin contact with contaminated surfaces. Short PVC outer gloves are worn over longer rubber gloves, and the outer pair replaced periodically. For work with tritiated oils, additional protection involving PVC apron and boots have been used. When tritium levels higher than 10 DAC (HTO) are expected, or for long duration work at lower levels, respiratory protection in the form of airline supplied equipment is prescribed. The JET air-fed pressurised suit is a one piece PVC or polyurethane unit with integral hood and gloves. The suit material has a thickness of 0.3mm, and is used with compressed air at a flow-rate of 320litres/min. A plastic oversuit (0.15mm) is also worn, particularly where high levels of surface contamination is likely to be encountered. Experience during the NIB intervention showed that the JET full pressurised suit could provide a protection factor of ~500 when worn with an oversuit, at concentrations up to 100DAC for periods of 2 hours. In the RTE shutdown, the full-pressurised suit was favoured for use in the TCTF and Boom enclosures, to optimise protection against airborne HTO, tritiated carbon particulate, and beryllium. For operations where the use of a full suit is impractical, an airline supplied half-suit (blouse and hood) has been successfully used, with a protection factor ~100. Contamination levels on suit surfaces after use have been ~20 Bq/cm^2, allowing re-use after wet decontamination.

9. RADIOLOGICAL MONITORING AND OPERATIONAL TECHNIQUES

All non-routine operations with a potential to give rise to worker exposure in AGHS, torus hall, waste handling and decontamination areas, are covered by a Health Physics technician. The technician provides direct surveillance of the work area, and issues first-hand advice on contamination control and worker protection. Workplace monitoring confirms the adequacy of exposure control methods and gives feedback on the effectiveness of measures to avoid spread of contamination. Typically, continuous measurements are made of breathing zone levels, and surface contamination surveys are conducted during and on completion of the work. Exposure limits set for the operation are carefully followed and the work halted if conditions stray outside prescribed limits.

For tritium areas with well defined contamination conditions, or for work with minimal exposure risk, continuous sampling is provided by installed ion-chambers, which have pre-set local alarms which repeat to control room display panels. Additional monitoring is by bubbler (HTO) sampling and routine smear surveys. A large number of surveys are conducted at locations peripheral to tritium handling areas, and general access areas, to demonstrate the absence of contamination.

JET’s installed tritium radiological protection instrumentation, which comprises on-line ion-chambers, off-line HT/HTO samplers for area and stack sampling, has been in place since 1990[13]. For operational cover, more than 20 portable ion-chamber instruments are used, mostly Overhoff SP1400, and Scintrex 209/309 instruments, with detection limits varying from 0.25-1 DAC (HTO). Contamination of ion-chambers in use often left instruments with high reading backgrounds, necessitating categorisation of the instrument pool for allocation according to the levels to be measured.

The HTO levels in many areas are monitored continuously by means of bubbler samplers. The system at JET uses two dreschel bottles in series, 180ml analar water in each and a flow-rate of 4 litres/min. Collection efficiencies >95% have been measured, and detection limits of a few Bq/m^3 can be achieved based on 12-hour sampling, and 10-minute liquid scintillation counting. The bubbler method has been of benefit for confirming the low levels in many areas, and for measuring high levels >100 DAC, which would otherwise contaminate an ion-chamber. More than 20 bubbler stations were in use during the RTE operations, for measuring averaged area levels, duct sampling, and for off-gas measurements. However, the method is labour intensive for many samplers, and bottles can also become contaminated following use with high levels.

Figure 5 shows the measured bubbler readings in the torus hall during the RTE shutdown. The variation between individual readings shows the sensitivity of measurements to changes in tritium evolution rates, due for example to humidity changes and work activities.

Two different methods of surface contamination determination are used. Routine monitoring of HT/HTO surface contamination is by gas-flow proportional counting (Harwell Instruments) of 5cm diameter aluminium foil smears. Surfaces areas ~ 500cm^2 are wiped, and smears can be counted very quickly. Detection efficiencies of ~30% are achieved. For monitoring of areas where tritium-containing particulate is present, 5cm diameter Whatman cellulose papers are wiped over the surface, and soaked in water, and the water counted by LSC. By applying correction factors for the dissolution of tritium in particulate forms, and for the soak time, fast counting of samples is possible. This method is also applicable for air-samples, and the counting of high activity foil smears where contamination of gas-flow counters might otherwise be a problem.

Tritium in water assay is by LSC techniques (LKB 1411, 1219 instruments). Samples are taken of the main coolant loops and active drain water, and large numbers of bubbler samples are processed. Techniques have also been developed for oil and freon samples.

10. TRANSFER AND CONTROL OF MATERIALS

One consequence of the presence of permeated tritium in the torus hall, during DTE1 and the clean-up campaigns was that ex-vessel components showed evidence of tritium absorption. Although smears taken of the external structure, including the hotter surfaces showed no levels > 1Bq/cm^2, samples taken at the end of DTE1 showed there was evidence of measurable tritium in bulk material. Samples of hydrogenous material, including plastics, rubber, paint and mineral insulation all showed levels between 100-12000Bq/gram. Most of the metal samples showed absorption below 0.4 Bq/gram, although higher levels were found on thin sheet metals. Whilst the metal samples showed evidence of neutron activation to ~1000Bq/gram dependent on their proximity to the torus, in the case of tritium absorption there was no correlation of levels with location in the torus hall. In the UK, a threshold level of 100 Bq/gram applies to designation of material as radioactive for the purposes of accountancy and workplace control. An even lower figure applies for designation as radioactive waste.

Given these results, during the start of maintenance activities in RTE, all neutron and tritium exposed items in the torus hall were declared as potentially radioactive and procedures adopted requiring radiological monitoring, labelling, and documenting of all transfers and removals. Of particular interest were ex-vessel components with a history of exposure to tritium in DTE1, but showing no evidence of removable surface contamination. Posing no radiological hazard, such items were free for release to any area on-site, but were nevertheless regarded as subject to control for disposal or off-site transfer, and labelled accordingly. In many instances where the component was mostly composed of bulk metal, assessments and measurements of tritium content permitted free release off-site, but other items with a large plastic or rubber content, or of thin metal construction, remained subject to controls.

A feature of the exposure of clean components to the high tritium levels in the vessel in RTE was the resulting levels of contamination pick-up. Remote handling tools which had been exposed to in-vessel concentrations of ~100MBq/m^3 for even a few hours were found to have residual contamination between 10 Bq/cm^2 to 100kBq/cm^2, suggesting an absorption effect, although the highest levels were suspected to be due to contact with particulates. Smears taken of tools after decontamination showed them to be below the acceptance level of 4Bq/cm^2, however repeat smears taken of the items the next day showed that contamination had re-appeared on surfaces to about twice this figure. This had significant implication for the clearance of tritium exposed items. In consequence a procedure was adopted which necessitated a 24-hour delay between decontamination of an exposed item and its survey for clearance.

Another observation was that tritium absorption on in-vessel carrier tools exposed to the vessel atmosphere (100 DAC, HTO) for a few days was sufficiently high to later give rise to off-gassing effects to levels of 1MBq/hour. Even components protected inside an isolator showed an off-gassing effect of 1MBq/day. Like the torus hall components, these tools had to be restricted to on-site use.

Tritrated carbon dust and flakes, deposited in the torus were collected by vacuum cleaning the divertor surfaces. With its high spectre activity, ~4TBq/g, an argon purged glovebox was required for handling the material, to off-set the high off-gas rates. In particulate form, its dosimetric properties are quite different to that of HT/HTO. The assessed value of the dose coefficient was more than a factor 10 higher than that for HTO, as described in §5.4 earlier. Investigations of the dosimetric features of this material are planned.

11. LESSONS LEARNT

In addition to some of the issues on tritium handling already described, some of the findings of Health Physics interest were;

a) Leak detection equipment used in AGHS and in the torus hall on tritium contaminated volumes often absorbed tritium to the extent that local releases of tritium occurred when the detector pumps were subsequently run, giving a potential for exposure. Such leak detectors were thereafter solely designated for use on tritium contaminated systems. Both leak detectors and pump-purge rigs required storage in ventilated areas. Vacuum cleaners used for particulate decontamination in the RTE also showed a similar effect.

b) In the torus hall, some minor spills of water from the PINI and Poloidal Field coil cooling circuits occurred during the RTE shutdown. Regular sampling of these loops had shown a build-up to 8kBq/litre. However it was found that spill water samples taken from the floor of the torus hall showed levels more than ten times higher. The majority of the activity in the spill water was due to exchange with the tritium on ex-vessel surfaces and on the painted surfaces of the torus hall floor. Some spill samples recorded levels of 400kBq/litre.

c) Whilst in-building tritium levels in the occupied areas remained at very low levels throughout the active phases, there were noticeable rises in buildings near the torus hall and AGHS building at particular periods. These were attributed to entrainment of stack discharged tritium in the building wake.

d) The permeation of tritium from the torus and bakeout systems gives rise to low chronic exposures in the torus hall. Further, tritium in the condensate from the torus hall air-conditioning systems increased during DTE1. The presence of high-voltage electrical equipment in the torus hall necessitated low humidity conditions. The effect of this was the collection of water with activities of ~1MBq/litre, with the added need for its disposal or discharge [19].

e) The practice of using a detritiation system to process purge gases and tritium from ventilation streams as a means of reducing environmental discharges has the effect of generating large quantities of high activity water which has to be transferred off-site for tritium recovery. The dose potential to the worker from handling activities of ~0.2-1 TBq/litre as collected by EDS, in the event of even small releases or spills are significant. There is a need for careful justification of practices which reduce environmental discharges and public doses, but which may disproportionately increase the potential occupational dose.

f) One of the simplest and most effective forms of exposure control was found to be local extract ventilation ducts. The large number of tritium related operations liable to be undertaken in a machine shutdown implies a demand for controls such as containment isolators and local ventilation. Adequate supply and provision of these controls is essential, as is their correct use during work on contaminated systems.

g) Training on radiological safety issues took place prior to the start of each phase of JET’s active operations for the staff involved. All site staff attended courses on emergency procedures, and training and exercises in emergency response were conducted. In addition, for some of the major tritium operations, detailed briefings took place to provide workers with Health Physics information and advice. Training and regular emergency exercises were an essential part of preparations for safe handling of tritium, as was the preparation of work procedures and safety assessments that specified in detail the hazard conditions and controls to be applied, particularly where mixed radiological and chemical hazards were involved.

h) Phenomena such as the delayed emergence of tritium from highly exposed items and the absorption of low levels of tritium in materials in the torus hall have prompted the refinement of radiological clearance methods and procedures. JET has some experience of working with tritiated carbon particulate, but the radiological protection properties of this material need to be investigated further.

i) The implementation of a policy restricting doses to a level below the legal requirements has been an essential part of the JET's demonstration of keeping worker doses as low as possible. JET practice has shown that cautious assessment of hazards and the prescription of dose constraints and exposure controls on a task by task basis has been important in minimising doses.

12. CONCLUSIONS

JET has completed an extensive range of tritium operations involving planned tasks and unplanned interventions. An important aim during JET's active operation has been the demonstration of radiological safety of personnel and public. DTE1, the RTE shutdown and other tritium operations have been conducted without radiological incident. Tritium exposures to staff have been well controlled, with very low exposures achieved. Individual doses have been 170µSv/year at most, and collective doses were 1.46 mSv (1997), and 2.1mSv (1998). Operational discharges have been minimal and carried insignificant environmental impact. Health Physics input has been essential to the safe execution of operational tritium work, from the early planning and preparation stage, in the assessment of work procedures, the setting of dose constraints, the prescription of safety measures and controls, through to monitoring of the work, and measurement of doses and discharges. Lessons have been learnt concerning operational Health Physics issues, involving monitoring techniques, exposure control methods, limitations of instrumentation, and the procedures for working with mixed radiation, tritium and beryllium hazards. Some of the problems encountered have been unique to the fusion research environment.

The methodology of using containment and ventilation techniques, with tight radiological controls has been found to be important for minimising worker dose. Future operations at JET will extend the concept of mixed hazard environments with manned work inside the contaminated torus.

In its current active phase, JET has accomplished much technically, gained valuable physics data, and proven tritium technology relevant to fusion energy production. Its added achievement has been that it has accomplished these tasks safely. Radiological safety issues will continue to be of importance for worker and public protection, and even more so with reduced statutory dose limits. JET experience has shown that an important stimulus to minimising radiation exposures through the use of both engineering and procedural controls, has been a stringent dose-limitation policy. The JET dose-limit which was instituted at the concept stage of the project's design has been a prime factor in attaining compliance with the principle of ALARA, which has importance in all modern radiation protection practice.

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REFERENCES

[1] A Gibson and the JET Team, Physics of Plasmas **5** (1998), 1839

[2] ICRP Publication 30, Annals of the ICRP No.2 (1979)

[3] The JET Team, Nuclear Fusion **32** (1991), 967

[4] R Lasser et al., 'Overview of the Performance of the JET Active Gas Handling System during and after DTE1' - this volume

[5] R Lasser, N Bainbridge, A C Bell, D Brennan, L Dörr, B Grieveson, J L Hemmerich, G Jones, S Knipe, J Lupo, J Mart, A Perevezentsev, N Skinner, R Stagg and J Yorkshades, 'Latest results of tritium commissioning of the JET Active Gas Handling plant', contrib paper 17th IEEE/NPSS Symposium on Fusion Engineering, San Diego (1997), published in the proceedings, Vol 1, p 292

[6] T T C Jones et al., 'Tritium operation of the JET Neutral Beam Systems' - this volume

[7] P Andrew et al., 'Tritium retention and clean-up in JET during and after DTE1' - this volume

[8] B Patel et al., ' Initial Experience of Tritium Exposure Control at JET', proceedings International Radiation Protection Association Conf., Prague 1997

[9] A C Rolfe, P Brown, P Carter, R Cusack, A Gaberscik, L Galbiati, B Haist, R Horn, M Irving, D Locke, A Loving, P Martin, S Mills, R Minchin, J Palmer, S Sanders, S G Sanders and R Stokes, 'A Report on the First Remote Handling Operations at JET', contrib paper 20th Symposium on Fusion Technology (SOFT), Marseille (1998), to be published in Fusion Engineering and Design

[10] ICRP Publication 26, Annals of ICRP No. 3 (1977)

[11] ICRP Publication 60, Annals of ICRP No. 21 (1991)

[12] Council Directive 96/29/Euratom (May 1996), L159 Official Journal of European Communities

[13] C J Caldwell-Nichols, R M Russ, A C Bell, N Davies, A D Haigh, H D Jones and L Serio, ' Radiation Monitoring, Environmental and Health Physics Aspects during the first JET Tritium Experiment', Fusion Engineering and Design, **19** (1992) 149

[14] R J H Pearce, P Andrew, S Bryan and J L Hemmerich, ' The JET Gas Baking Plant for DT Operation and Analysis of Tritium Permeation..' contrib paper 20th SOFT, Marseille (1998), Fusion Technology 1998, Vol 2, 1001

[15] G Duesing, H Altmann, H Falter, A Goede, R Haange, R Hemsworth, P Kupschus, D Stork and E Thompson, Fusion Technology **11** (1987), 163-202

[16] M J Watson, A C Bell, A J Dines, F H Hurd, J G Lundqvist, B J Macklin, J C Orchard, and B Patel, ‘Intervention to repair a tritiated JET Neutral Beam Injector’, contrib paper 20th SOFT, Marseille (1998) ibid [13], Vol 1, 485

[17] A T Peacock, P A Andrew, J P Coad, R Cusack, F H Hurd, S Mills, R-D Penzhorn and M Pick, ‘Deposits, Flakes in the JET MkIIa Divertor - a major source of Tritium and Deuterium Inventory’, contrib paper 20th SOFT, Marseille (1998), ibid [15], 233

[18] ICRP Publication 71, Annals of the ICRP No. 25 (1995)

[19] A Haigh et al., ‘Waste Management Aspects of DTE and RTE Campaigns’, this volume