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ABSTRACT.

‘Trace Tritium Experiments’ (TTE) were successfully performed on JET in 2003. The Campaign marked the first use of tritium in JET plasmas since the Deuterium- Tritium Experiment (DTE1) Campaign in 1997, and was the first use of tritium in experiments under the EFDA organisation with the UKAEA as JET Operator.

The safety and regulatory preparations for the experiment were extensive. Since JET has been operated by the UKAEA the operations have followed the model of a licensed nuclear site. The safe operation of the JET torus is demonstrated in a safety case. Key Management Requirement (KSMR) and Key Safety Related Equipment (KSRE) are identified in the Safety Case for DT operation. The safe operation of the torus is within the bounds of, and under the control of, an Authority to Operate (ATO).

New technical challenges were presented by the need to inject and account for small quantities of tritium in very short pulses (~80ms), with an accurate time stamp.

The safety and operational management of the campaign are described. Valuable lessons were learned which would help in running future experiments. It is concluded that JET is in a strong position to run future trace tritium and full DT discharges.

INTRODUCTION

The Joint European Torus (JET) is the world’s largest magnetic confinement fusion experiment and has the unique capability to operate with tritium. JET has been continually developed and enhanced since first commissioning in 1984.

The‘Trace Tritium Experiments’ (TTE) marked the third use of tritium on JET. It was the first use of tritium in JET plasmas since the Deuterium-Tritium Experiment (DTE1) in 1997 [1]. Notably, since DTE1 there had been significant changes in personnel and the organisation under which JET was operated. JET was originally designed and operated by the JET Joint Undertaking, a European project focused organisation. Since 2000 JET operations has been performed under a contract between the EFDA organisation, (which own the JET facilities and determines the experimental programme) and the UKAEA as operator (having responsibility for the safe operation of JET). The TTE experiments were hence performed under these new organisational arrangements.’

1. SCOPE OF EXPERIMENT

The planning and preparation for TTE had to be started well in advance of the finalisation of the experimental programme. The preparations were hence made on the basis of the following agreed scope:-

- Direct torus injection (2.5-7.5mg)
- One Neutral Beam Injector (NIB) in tritium.
- Integrated injection of tritium into torus < 0.5g

- Daily tritium cryopump inventory < 0.5g
- Integrated 2.5MeV neutron production $<0.8\times10^{19}$
- Integrated 14MeV neutron production $<10^{19}$

2. SAFETY AND REGULATORY PREPARATIONS

2.1. REGULATORY ENVIRONMENT

The Nuclear Installations Act (1965) requires UK nuclear fission and related sites to be licensed to operate. The UKAEA holds such a licence for four sites in the UK. The licence is regulated and enforced by the Nuclear Installations Inspectorate (NII). It is issued against formal organisational arrangements and a safety case demonstrating compliance with ~36 general conditions. JET as an experimental nuclear fusion facilities falls outside this legislation and so is not subject to NII licensing. The activities on JET must, however, comply with the Radioactive Substances Act (1993) and the Ionising Radiation Regulations (1999).

The UKAEA, as operator of JET, has taken the model of a NII licensed site for the safety management arrangements at JET. A licence to operate (Authority to Operate (ATO)) is issued by the UKAEA, Culham Division Operation Director following approval by the Culham Safety Committee (CSC). This safety committee, which comprises of internal specialists, peers from licensed UKAEA sites and external members, expects standards akin to those required on NII licensed sites.

2.2. SAFETY CASE

To justify the safety of DTE1, the JET Pre- Construction Safety Report (PCSR) was produced. This was updated to form the Pre-Commissioning Safety Report (PCmSR) March 1996 [2]. The purpose of the PCmSR was to justify the radiological safety for the use of tritium in JET and the associated generation of neutrons. DTE1 acted as the “active commissioning phase” of JET in preparation for an active operational phase.

The completion of DTE1 hence dictated that the PCmSR was updated to form a Pre-Operational Safety Report (POSR) prior to an operational phase with tritium. The POSR was written to standards produced for licensed sites and issued in January 2001. This resulted in the following key changes:-

- Merging of the Torus and Active Gas Handling System (AGHS) safety cases under one safety case, so that analysis could deal with the operation of both plants acting in a complete process loop [3].
- Modification of the hazard and risk assessments to take into account the DTE1 operational experience and new assessment standards.
- Development of the safety management arrangements to reflect practices parallel to UKAEA licensed sites with the main responsibility for safe operation upon an ATO holder.
- The identification of Safety Mechanisms and Operating Rules, known as Key Safety Related Equipment (KSRE) and Key Safety Management Requirements (KSMR).

The POSR used a methodology for identifying systems as KSRE and KSMR, the basic definition is that a system is identified as ‘Key’ if its failure could result in an unmitigated dose of > 20mSv to a worker or 1mSv dose to a member of the public. In addition, further systems are identified as ‘Key’ on the basis of their significance in contributing to the aim of ensuring that the dose to any personnel is kept to As Low As Reasonably Practical (ALARP). Within the JET torus ATO the following systems were identified as KSRE:-

- The JET torus primary containment.
- Area tritium monitors (TM).
- Uninteruptable Power Supplies(UPS) supplying TMs.
- Torus high pressure interlocks (15mbar and 200mbar) and water isolation systems.
- Area gamma monitors.
- Primary and secondary containment boundaries of tritium feed lines.
- The personnel access control system for the torus.
- The torus hall removable shielding elements
- The torus hall bulk biological shielding
- The torus hall emergency stop pushbuttons
- Torus hall interlock on access labyrinth doors

Within the JET torus ATO the following systems were identified as KSMR:-

- Evacuation procedures in the event of tritium alarms.
- Tritium inventory control for the torus.
- Pre-operational shielding checks for the torus
- Radiation checks prior to opening the torus hall
- Search procedures prior to operating

The POSR contained a 10 point action plan which was required to be completed prior to further tritium operation. Significant elements of the action plan related to ensuring substantiation and maintenance of (K)SRE and review of procedures linked to meeting (K)SMR. The POSR set the envelope for future tritium operations, significantly beyond DTE1, as follows:-

- Maximum tritium inventory within the JET Torus and AGHS facility of 90g.
- Maximum tritium inventory within the JET Torus of 30g with maximum releasable inventory on the torus and NIB cryopumps of 20g.
- Maximum annual 14MeV neutron production of 5×10^{23} with a basic limit of 3×10^{19} neutrons per pulse revisable up to 1×10^{20} neutrons per pulse.

2.3. SPECIFIC TTE PREPARATION

The proposed TTE experiment fell well within the bounds of the POSR. The safety related preparations within the torus ATO were still extensive because:-

- Most of the hazard types associated with full DT operations were present, except high levels of machine activation. (~ 2g of tritium in feeds external to AGHS and ~ 8g of tritium to be cycled around the NIBs).
- Organisational, personnel, and design changes had occurred since DTE1. There was considerable expertise in handling the legacy of tritium retention but very few personnel had direct experience of operating the machine with tritium.
- A demonstration of traceability was required between stated safeguards in safety cases and actual operations.
- An aim of the TTE experiment was to demonstrate controls, required for full DT operations. The main safety related preparations within the torus ATO are given below.

2.3.1. Review of Operating Procedures, Local rules and Operating instruction.

For operations comprehensive safety, technical, and managerial requirements are detailed in a suite of 3 styles of document. The requirements of the KSMR are also put into practice through these documents.

The operating procedures detail how routine operational activities are performed and the response to alarms and abnormal conditions. Over 190 procedures were peer reviewed and the sources brought into one electronic document management system. Particularly important for TTE were procedures which related directly or indirectly to tritium operations, including regeneration of machine cryo-pumps, operation of the NIB[4] and operation of the torus tritium gas feed.

Twenty local rules, which define operational responsibilities, interfaces and policy were reviewed and appropriately updated. Specifically related to TTE the manning requirements were revised in the light of DTE 1 experience resulting in a slightly leaner operational team. Operation Instructions define the operating limits of the JET machine. Eleven were either specifically revised or brought in for TTE. Important for the safe operation of TTE were:-

- Control of torus hall depression (500Pa) as best practice to minimise workforce exposure in the case of a loss of tritium containment.
- Tritium injection limits and accounting responsibilities required to limit the tritium injection in a pulse and to control the inventory on cryo pumps.

2.3.2. Assessment of fitness-for purpose of KSRE.

Licensed sites are required to perform “Engineering Substantiation”, the process of rigorously demonstrating that the equipment identified in a safety case is capable of performing the stated safety function including tolerance to faults. The formal process of Engineering Substantiation can become very detailed, requiring substantial resources. It was agreed that, as many of the JET safety systems had in their conception and design already been through significant peer review, that a basic ‘Fitness for Purpose’ studies on a number of the KSRE would suffice for JET. These studies resulted in a number of general improvements but none which were specifically TTE related [5].’

2.3.3. Review the compatibility of diagnostic systems with TTE.

A number of diagnostics isolated from the torus for DTE1 had subsequently been reconnected. These systems were re-assessed to ensure their tritium compatibility with TTE taking into consideration:-

- The number of containment barriers on vulnerable components
- choice of material for primary vacuum seals
- minimising exposure of staff during subsequent maintenance (ALARP)
- contamination of systems effecting performance
- possibility of neutron damage to detectors As a result, nine diagnostics were isolated from the torus.

2.3.4. Recommission SRE before TTE.

All safety-related systems were recommissioned prior to TTE. This involved the review and completion of ~44 commissioning procedures to test the operation of KSRE and supporting safety systems. The torus and NIB vacuum vessels, backing lines and interspaces were vacuum leak tested. Three diagnostic windows had leaks, which that were judged to be acceptable, because of further containment boundaries. A system which was not brought into commission for TTE which had been used in DTE1 was the torus hall nitrogen fire suppression system. This system brings the torus hall oxygen level down to 15% to suppress fires. It was considered that the activation of the machine would be sufficiently low to allow conventional fire fighting methods to be used if necessary.

2.3.5. Training of safety related staff for TTE.

JET normally operates five days a week, with two shifts per day. Shifts are managed by an Engineer in Charge (EIC) with the support of a shift technician (ST) and a number of subsystem operators. The experimental requirements for each pulse are detailed by a Session Leader (SL) and communicated to the EIC. The manning of the JET control room for the TTE campaign was very similar to that required for normal operation of JET. The main difference was that the Local Rules stipulated that the EIC remained on site while there was >0.1 g of tritium held on torus or NIB cryopumps necessitating that late shifts were extended to include the regeneration of cryogenic pumps holding tritium. None of eight EICs selected to run tritium operation had previously run tritium shifts. Their training was hence an important part of the preparations for TTE. This included training in procedures for delivery and recovery of tritium from AGHS to the Torus and NIB and tabletop exercises on delivery and accounting procedures. All STs had performed many regenerations to AGHS in deuterium and were on shift during DTE1, hence their training requirements were modest. Other subsystem operators received appropriate training. Short refresher courses on basic tritium radiological properties/principles were provided for wide range of operations staff.

3. NEW TECHNICAL CHALLENGES

3.1. TRITIUM INJECTION

The experimental request for the injection of up to 7.5mg of tritium in < 100ms presented a new challenge for the existing design of the tritium gas introduction module (GIM15) Fig.1. The JET developed piezoelectric valve is used for the injection of tritium Fig.2. The valve is absolute and sprung closed. The piezoelectric crystal is first fully expanded by the application of 1500V, one end is then clamped and the applied voltage reduced to open the valve. Initial trials with sub 100ms pulses gave insufficient gas flow and variations in the gas delivered of +/- 25%. The erratic opening was due to timing errors in calibration codes and memory effects in driving the piezo crystal with short pulses. These problems were solved by driving the piezo crystal with more direct, un-calibrated waveforms, which brought the valve from the closed position to a pseudo-closed position prior to opening. In the pseudo-closed position a very small leakage of tritium occurs through the valve seat into the torus. The pseudo-closed position was held for around 1 second to clear memory effects. The benefit of this mode of operating was faster opening and higher flow with the injection of up to 6mg of tritium in 80ms. Fig.3. shows the request waveform, voltage applied to the piezo valve, drop in reservoir pressure, and finally the Tritium Alpha ($T\alpha$) signal measured by a visible spectrometer looking horizontally from the puff location into the plasma. The $T\alpha$ signal hence gives a real time profile of the tritium puff and shows the peak of the puff 80ms after the requested start. There were 95 pulses in which between 1.5mg and 6mg of tritium was injected from GIM15. The quantity injected was as requested +/- 5%.

3.2. TRITIUM ACCOUNTING FOR EXPERIMENTAL PURPOSES.

The accounting of the quantity of tritium injected into the plasma is made from the drop in pressure of the tritium reservoir of GIM15 (0.81 litre). The small quantity of tritium to be injected in TTE meant that very small changes in pressure had to be measured accurately. In DTE1 the piezo resistive gauge used to measure this pressure did not have the requisite ability to resolve small pressure changes accurately. A high accuracy capacitance manometer was installed and connected through to a 16- bit ADC. Particular attention was given to shielding and earthing to minimise noise pickup over the long cable run in the JET environment. Figure 4 shows the drop in reservoir pressure for a 1.5mg tritium injection. The new capacitance manometer signal is compared with the best that could be achieved with the piezo resistive gauge. The pressure in the GIM15 reservoir, which for TTE was normally set to ~1000mbar, could be resolved to 0.1mbar. Overall the quantity of tritium leaving GIM15 for the TTE shots could be accounted to +/- 1%.

3.3. TRITIUM EXHAUST MEASUREMENTS

The direct measurement of tritium in the exhaust from JET, with existing ion chambers, was expected to be particularly difficult, due to surface contamination with highly-tritiated hydrocarbons remaining from DTE1. A new contamination-resistant ion chamber was hence developed to be tested in TTE [6].

4. TTE OPERATIONS AND EXPERIENCE

4.1. APPROVAL

The ATO to cover tritium operations was issued after approval of the CSC. This was followed by progressive expansion of the tritium boundary from AGHS.

4.2. THE CAMPAIGN

The TTE campaign ran as planned between 20 September and 31 October 2003. A total of 95 JET discharges were run with tritium injected, as gas, into the plasma, with typically 1.5-6.0mg per shot, totalling ~380mg over the entire campaign. The JET Neutral Beam Injectors were used to inject fast (105keV) tritium atoms into the plasma in 95 pulses. Altogether in the Campaign over 500 JET pulses were run with tritium concentrations between 5×10^{-4} and 3×10^{-2}. Overall the operations were very successful with strong scientific output [7]

4.3. SESSION MANAGEMET

It was the aim to test procedures that would be equally applicable to an extensive tritium campaign. To this end, the paper systems used allowed demonstration of a very high level of control over the operations. In addition new software based controls were brought in and used in parallel. Prior to each pulse the Session Leader made a paper declaration of main pulse parameters, importantly the planned tritium usage and the neutron production. This was checked by the EIC against Operating Instructions and the integrated allocation of tritium and neutrons for an experiment. The demand waveforms for the tritium injection were then also checked by the EIC. A Diagnostic Co-ordinator ensured that the necessary diagnostics systems were ready. Subsystem Operators finally had to sign for their state of readiness and then the EIC initiated the running of the pulse.

A post pulse declaration was made after each pulse to confirm consistency with what was requested. In addition the EIC filled out the tritium accounting log so that a running total of the amount of tritium on each cryo pump could be maintained via paper records.

Once familiarity had been obtained with the new controls, the overhead was found to be small with pulse repetition rates of 1 per 25 minutes being commonly achieved.

4.4. DETRITIATON OF WALLS

Minimising tritium recycling from the walls was important to keep the 14Mev neutron production down. During and following the campaign, various methods were used to reduce the tritium inventory of the vessel walls. A new result on JET, in this area, was the high effectiveness of deuterium glow discharge cleaning in the removal of tritium[8].

4.5. TRITIUM ACCOUNTING

Accounting of tritium injected into the torus and NIBs was carefully performed. Conductance models were used to estimate the distribution of tritium between torus systems and pumps. The quantity of tritium injected from NIB to torus was typically calculated at ~25µg per injector used. End of day delivery and return figures for tritium supply lines calculated in AGHS were problematic because the tritium usage was within the error bar of the Pressure, Volume, Temperature (PVT) measurements [9]. A variety of methods of different accuracy were used to analyse the tritium exhaust concentration of the torus and NIBs. Overall the error bars were such that it was not possible to accurately determine the retention contribution from the TTE experiment to the ~1g of tritium still retained from DTE1.

4.6. TRITIUM RELEASE

During TTE problems with design and operation of the JET diagnostic exhaust line were identified when ~200GBq (2% of the monthly discharge authorisation), all HT, was rapidly released into the Torus Hall. This release had no radiological implication for personnel but triggered detailed investigation and a short suspension of operations. Gim15 had its inlet at the torus end of a diagnostic beam line. When this beam line had its isolation valve open, a fraction of the gas injected by GIM15 was pumped by the diagnostic's pumping system into the diagnostic exhaust line. A window in the beamline reduced the tritium entering this diagnostic pumping system in DTE1. This window had subsequently been removed to extend the wavelength of operation of the diagnostic.

To allow completion of the TTE experiment whilst minimising discharges. The diagnostic exhaust was connected through to the Exhaust Detritiation System (EDS) [9] which was configured to provided a strong depression (~50mbar). In this configuration tritium entering the diagnostic exhaust was recovered, including tritium (~600 GBq) pumped by a further diagnostic which pumped the torus when its torus isolation valve failed.

4.*6.1. Improvements and Lessons from the Release.*

The design and operation of the exhaust crown is now being changed so as to enhance the capability to safely operate in tritium in future. The new design will operate at sub-atmosphere pressure and will have provision to monitor its integrity.

The POSR brought attention to the need to better control and analyse modifications. JET is now run such that there are a number of controls in place to stop plant being modified without the modification being adequately assessed. The removal of the beam line window, without such analysis, highlights the importance of such new controls. The GIM15 inlet is being moved to significantly reduce tritium entering the diagnostic beam line in a tritium pulse.

The release underlined the importance of extensive tritium in air monitoring for a complex device like JET. The JET system is to be further enhanced.

4.7. TRITIUM PERMEATION

JET was operated at 473K for TTE where as for DTE1 it was at 593K [10]. In TTE regeneration of torus cryopumps were performed using new turbo-molecular pumps so as to minimise the residence time of the regenerated gas in the torus [11]. Tritium permeation to the torus interspace was below detectable limits, at least a factor 50 below that attributable to the reduction in source term. In DTE1 there was also a small chronic release of tritium (< 100GBq/week) [12] into the torus hall, some of which can be attributed to torus wall permeation. In TTE the activity levels in the torus hall, attributable to permeation, were below detectable limits. Consequently it is expected that future experiments of DTE 1 magnitude could be managed to produce significantly lower contamination in the Torus Hall than seen from DTE1.

CONCULSION

Under the EFDA organisation with the UKAEA as JET Operator ‘Trace Tritium Experiments’ (TTE) were successfully and safely performed under safety management arrangement based on a UK nuclear licensed site. New technical solutions were implemented to deal with the requirements of fast injection of small quantities of tritium. Systems have been tested and experience gained which will help minimise the preparations necessary for future more extensive tritium injection. A small tritium release was valuable in identifying weaknesses that are currently being rectified. JET is now in a strong position to run future trace, 100% tritium and full power DT operation.

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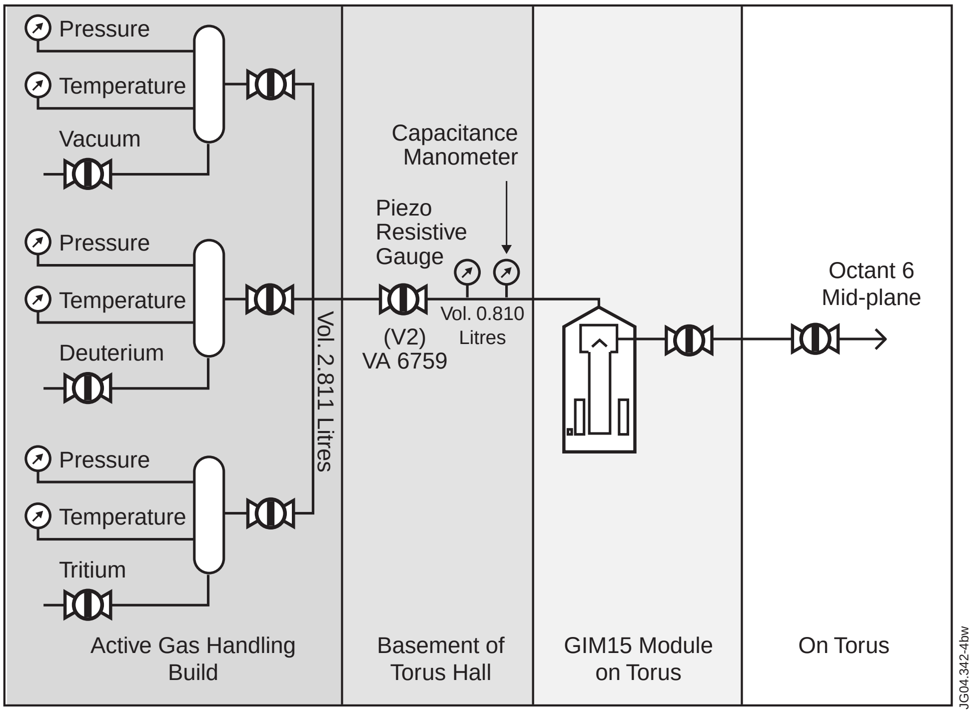

Figure 1: Torus tritium injection system

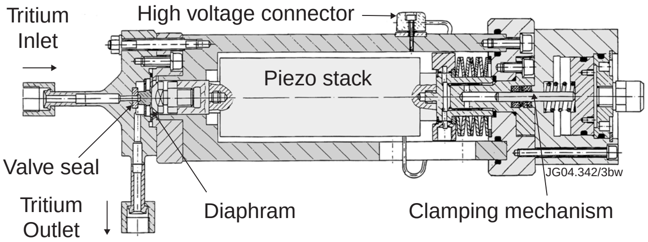

Figure 2: Piezoelectric tritium flow control valve.

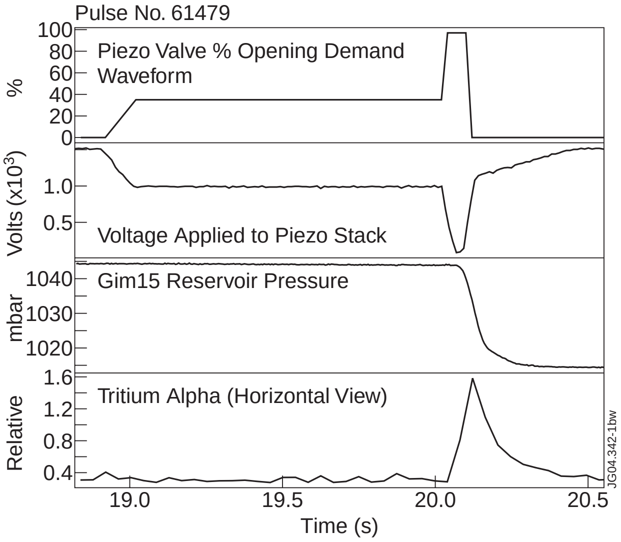

Figure 3: Tritium injection waveforms

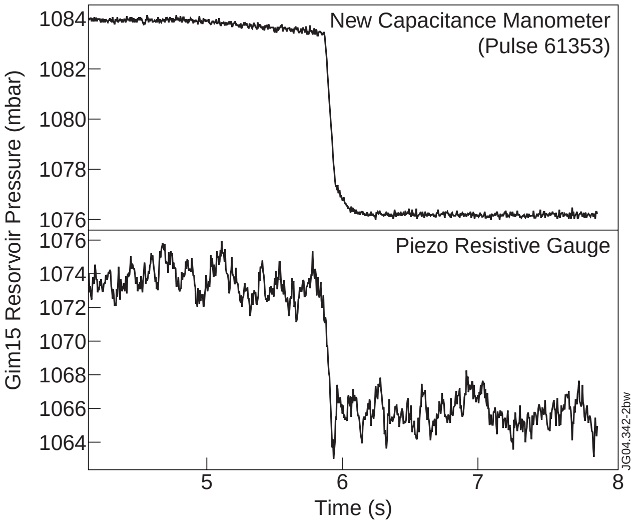

Figure 4: Pressure measurements on tritium reservoir.