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T.T.C. Jones, D. Brennan, R.J.H. Pearce, D. Stork, K-D. Zastrow, N. Balshaw, A.C. Bell, L. Bertalot, H. Boyer, P.R. Butcher, C.D. Challis, D. Ciric, R. Clarke, S. Conroy, A.C. Darke, N. Davies, T. Edlington, G. Ericsson, C. Gibbons, L.J. Hackett, T. Haupt, M. Hitchin, A.S. Kaye, R. King, V.G. Kiptily, S. Knipe, G. Lawrence, R. Lobel, A. Mason, P.D. Morgan, B. Patel, S. Popovichev, M. Stamp, E. Surrey, A. Terrington, L. Worth, D. Young
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T.T.C. Jones[1], D. Brennan[1], R.J.H. Pearce[1], D. Stork[1], K-D. Zastrow[1], N. Balshaw[1], A.C. Bell[1], L. Bertalot[2], H. Boyer[1], P.R. Butcher[1], C.D. Challis[1], D. Ciric[1], R. Clarke[1], S. Conroy[3], A.C. Darke[1], N. Davies[1], T. Edlington[1], G. Ericsson[3], C. Gibbons[1], L.J. Hackett[1], T. Haupt[1], M. Hitchin[1], A.S. Kaye[1], R. King[1], V.G. Kiptily[1], S. Knipe[1], G. Lawrence[1], R. Lobel[1], A. Mason[1], P.D. Morgan[1], B. Patel[1], S. Popovichev[1], M. Stamp[1], E. Surrey[1], A. Terrington[1], L. Worth[1], D. Young[1]
and JET EFDA Contributors*

[1]*EURATOM/UKAEA Fusion Association, Culham Science Centre, Abingdon, OX14 3DB UK*
[2]*Associazione EURATOM/ENEA sulla Fusione, Frascati, Italy*
[3]EURATOM/VR Association, INF, Uppsala University, Uppsala, Sweden
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ABSTRACT

The JET Trace Tritium (TTE) programme marked the first use of tritium in experiments under the managerial control of UKAEA, which operates the JET Facility on behalf of EFDA. The introduction of tritium into the plasma by gas fuelling and neutral beam injection, even in trace quantities, required the mobilisation of gram-quantities of tritium gas from the Active Gas Handling System (AGHS) product storage units into the supply lines connected to the torus gas valve and the neutral beam injectors. All systems for DT gas handling, recovery and reprocessing were therefore recommissioned and operating procedures re-established, involving extensive operations staff training. The validation of Key Safety Related Equipment (KSRE) is described with reference to specific examples. The differences between requirements for TTE and full DT operations are shown to be relatively small. The scientific motivation for TTE, such as the possibility to obtain high-quality measurements in key areas such as fuel-ion transport and fast ion dynamics, is described, and the re-establishment and development of JET's 14MeV neutron diagnostic capability for TTE and future DT campaigns are outlined. Some scientific highlights from the TTE campaign are presented.

INTRODUCTION

The Trace Tritium Experiment (TTE) programme,using tritium plasma fuelling in mg quantities, took place in September - October 2003. The detailed planning ofthe technical preparations and experimental schedule started in early 2002. The programme offered unique scientific possibilities for fuel-ion transport and fast-iondynamics measurements. The TTE campaign alsoprovided the impetus to re-establish JETís technical andneutron diagnostic capabilities for deuterium-tritium (DT)operation, last fully utilised in the DT experimental campaign (DTE1) in 1997 [1]. The motivation andboundary conditions for TTE are discussed in Section 1.

Although the JET Joint Undertaking had an established Safety Case for DTE1, from 2000 JET's Authority to Operate under the management of UKAEA did not allow for operation with tritium before a detailed re-assessment had been completed of the fitness forpurpose of safety related equipment credited in the Safety Case. This requirement reflects modern developments inSafety Case engineering, in line with the practice adopted for nuclear licensed installations. These and othertechnical preparatory activities are described, with specific examples, in Section 2.

The perturbative nature of the T transport experiments dictated the need for fast-response (≈80ms) of the piezo-electric gas valve. Neutral Beam (NB) injection of T^0 atoms at energies ≈100keV in ≈100ms duration pulses from up to two beam sources was used to provide a central source of fast T^+ ions in the plasma core. Aspects of commissioning and operating these systems and the neutron diagnostics are discussed in Section 3.

Some key statistics of the TTE campaign, and data on T build-up and clean-up, are given in Section 4. Key experimental results from the TTE campaign are presented in Section 5.

1. MOTIVATION AND BOUNDARY CONDITION

1.1. SCIENTIFIC MOTIVATION

The use of gas puffing and Neutral Beam (NB)injection to raise the plasma tritium density concentration $n_T/(n_D+n_T)$ to $>\approx 1\%$ provides a powerful means to study transport of both thermalised T^+ and fast (suprathermal) T^+ ions. These experiments are fundamentally dependent upon the JET neutron diagnostics, especially the neutron camera which provides multiple line of sight measurements of the emissivity of 14MeV neutrons produced in D-T reactions. Information from the 2.5MeVneutron emission provides a strong additional constraint in the analysis, thus reducing or eliminating thedependence of the interpretation on other measured plasma parameters, such as plasma purity represented bythe effective charge Z_{eff}. In order to discriminate betweenthe 2.5MeV and 14MeV neutron counts, the neutron rates must be of comparable magnitude. For D→T beam-plasma and D-T thermal ion reactions, this is true when the T concentration is of order 1-3%. T-minority experiments with Ion Cyclotron Resonance Heating (ICRH) are also possible, as well as ICRH experiments with other minority species e.g. exploiting the proton-triton reaction.

Trace tritium experiments were previously carried out as part of the JET DTE1 campaign [1] in 1997. However,in DTE1, the T concentration was generally much higher than the few percent level. It is important that following T injection, the effect is observable as a clear transient perturbation, from the change in neutron emission, which implies that the background T concentration must be kept low. This was not feasible in DTE1 and the earlier trace tritium experiments performed were therefore rather limited; an important aim of TTE was to extend the range of plasma confinement regimes in which particle transport could be studied, e.g. to characterise the effects of Internal Transport Barriers.

1.2. TECHNICAL MOTIVATION

TTE would be the first use of tritium in JET since 1997, and also the first under the arrangements foroperating JET under UKAEA management on behalf ofEFDA. The regulatory framework for operation of the JET Facilities and safety case methodology are describedin [2,3]. As the introduction of *any* quantity of puretritium gas into the torus or NB injectors involves filling the transfer lines of the delivery and distribution system, significant quantities (2.3g) of tritium must be mobilised from the AGHS product storage [4]. Therefore, all the tritium delivery and recovery systems and operating procedures were required for TTE, thus restoring JET's tritium operation capability in virtually all respects. Only minor differences in requirements compared with full DT operation emerged from analysis carried out as part of the technical preparations, described in Section 2.

1.3. TTE BOUNDARY CONDITIONS

It was important to specify the constraints or boundary conditions of TTE in order to establish criteria against which to prepare and demonstrate safety controls, and to allow the experiments to be planned. Following aninitial assessment of possible experiments for TTE, carried out in 2001-2 within the EFDA-JET Task Force system under a lead Task Force dedicated to DT, an outline programme defining the campaign duration andmain experimental topics was proposed in early 2002. The programme was foreseen to occupy about six weeks of campaign time in 2003 (including technical and diagnostic commissioning)

1.3.1. Activation

The TTE planning had to ensure the machine activation would be below 320μSvhr^{-1} to allow manned entry into the JET vacuum vessel for installation of theJET-EP Enhancements in 2004. The dominant activation product in the JET vessel structure, in respect of activation levels six months subsequent to irradiation, is ^{58}Co (half life 71 days) and the activation rate for this isotope is approximately four times higher for 14MeV compared with 2.5MeV neutron exposure. Therefore, the total amount of 14MeV neutron production and the timing of the campaign were key constraints. The activation limit effectively defined the latest date for completion of the TTE campaign. The earliest start of the campaign was constrained by the need to complete all necessary technical preparations, for which a short prior machine intervention (requiring a vessel vent) had been foreseen. The calculation of machine activation took into account the past history of JET operation (due to the presence of long-lived activation products such as ^{60}Co) and the effect of the other high power DD campaigns planned beforeand after TTE. Estimates of the 14MeV neutrons from residual T during a three-week period of cleanup discharges following TTE were also included. The activation constraints implied a total 14MeV neutronproduction limit 1.0×10^{19} should be imposed. A 2.5MeV neutron limit (0.8×10^{19}) was also applied, taking into account the need for D-D set-up and clean-up pulses.

1.3.2. Tritium usage

Of order 1g of tritium introduced into JET in DTE1 remained locked up in the vacuum vessel. It should be noted that, for this reason, most of the systems and procedures required to ensure safe operation and maintenance of the contaminated machine have remained fully in place since DTE1. Although this tritium is mostly retained in a relatively stable form as co-deposited films [5], a potential release hazard still exists in the event of, e.g. a Loss of Vacuum/Cooling Accident (LOVA/ LOCA).All JET engineered Integrated Operation Protection Systems (IOPS) [6], some which have a role in preventing LOVA/LOCA or in mitigating the subsequent effects, had continued to be subject to formal periodic re-commissioning. Results from DTE1 [7] showed that up to 40% of tritium *freshly introduced* into the plasma would likely be retained in the short term, of which 23% was expected to be removed in tokamak cleanup pulses; the remaining 17% was assumed to add to the long-term vessel inventory. Therefore, this was an argument to limit the total tritium injected *into the plasma* to the minimum necessary.

A constraint was placed on the maximum daily inventory of condensed tritium on all cryopumps within the JET vacuum envelope, since this is considered to be in a more readily releasable form, dominated by the cryopump of the NB injector operating in tritium [8,9]. However, there was no over-riding safety-related reason to limit the integrated NB injector tritium throughput. This is because the NB cryopump inventory is promptly recovered on each daily regeneration.

2. TECHNICAL PREPARATION

As part of the annual review of JET's Authority to Operate (ATO) by the Culham Safety Committee (CSC), progress against a continually updated safety action plan must be demonstrated. After TTE was formally adopted into the JET programme in early 2002, an extended action plan [3] was agreed with CSC, completion of which would allow limited D-T operation for TTE in the annual renewal of JET's ATO the following year.

Safety systems and safety management processes are designated in the safety case documents [3] as *key* according to their role in mitigating the doses to workers and the public in fault scenarios, either on the basis of reducing the doses to levels 'As Low As Reasonably Practicable' (ALARP), or specifically, if their failure could result in doses exceeding 20mSv (worker) or 1mSv (public). Therefore, the classification as Key Safety Related Equipment (KSRE) depends on radiological source terms as defined in the safety case. The agreed action plan required appropriate reviews of'*fitness for purpose* of KSRE systems. Although the TTE boundary conditions appear stringent in comparison with DTE1, and with the ultimate limits imposed by the safety case (Table 1), the *fitness for purpose* assessment exercise was comprehensive. This is partly due to the relatively large amounts of tritium (2.3g) within the transfer lines of the distribution system and condensed on the NB injector cryopump (up to 0.5g). For tritium cryopump inventories >0.1g the manning and competencies for TTE operations were also reviewed, but remained essentially similar as for DTE1. Training of operations staff concentrated on procedures for delivery and recovery of tritium to and from the torus and NB injector box, since these were the main activities that had not been practised since DTE1.

2.1. PREPARATION ACTIVITIES: STAGE 1 (IN PARALLEL WITH CAMPAIGNS)

2.1.1 Key Safety Related Equipment

In order to prioritise the KSRE *fitness for purpose* assessments to be conducted before TTE operations, dose-rate scaling factors were derived from source term ratios, relative to fault scenarios considered in the safety case. This information was also used in the review of Local Rules and Procedures for TTE, such as definition of access restrictions to certain operational areas. For example, for hazards relating to loss of readily releasable tritium via a breach of the torus vacuum envelope, a dose-reduction factor of 12g/0.7g, i.e. 17, was taken. For hazards relating to activation products, the total neutron production ratio was used to derive the dose reduction factor, i.e. $(5\times10^{23}/2\times10^{19}\times6) = 4200$ (allowing for 14 and 2.5 MeV neutrons). [The factor 6 in the denominator arises under the pessimistic assumption that short half-life products dominate, so that activation is proportional to average neutron *rate* (≈2month campaign compared with the annualised figure in the safety case)]. For hazards from neutron exposure e.g. a shielding element failure event, the safety case assumed maximum neutron production per pulse of 1×10^{20}; for TTE, it was assumed that no pulse would produce more than 10% of the highest fusion yield pulse in DTE1, giving a dose-reduction factor of 2000.

The methodology adopted for the *fitness for purpose* assessment was to appoint an internal peer reviewer with appropriate expertise for each KSRE, who had no prior technical or managerial responsibility for it. The first stage was to establish the claims credited in the safety case, then to derive criteria (functionality, performance) against which to judge whether these claims could be substantiated. Finally, a number of checks relating to adequacy of design, as-built drawings, operating history and maintenance were applied in order to come to a conclusion of the overall ‘fitness for purpose’ of the KSRE.

In order to illustrate the entire process, a particular example of in-vessel Loss of Cooling/Vacuum Accident (LOCA/LOVA) is discussed. The safety case considers *“in-vessel LOCA water discharge into vacuum vessel”* events which could cause the vessel bursting disk to rupture due to steam formation in the hot (<320^{o}C) vessel, leading to expulsion of tritiated products into the Torus Hall. Even after taking into account the dose-reduction factor of 17 for this event, the worst-case worker exposure would still exceed the 20mSv threshold criterion. The relevant claim for this KSRE is that the quantity of water entering the torus would be limited below the mass of steam at 320^{o}C that would raise the torus to the bursting disk limit (75kg). In the case of the divertor target plates, there are eight interconnected modules, of which one is depicted in Fig.1. In order to prevent all modules from feeding a single leak, the pressure at the drain points must remain lower than the sum of the in-vessel pressure plus the water pressure head, due to gravity, between the leak location and the drain point. This is achieved by opening drain valves located at the low-point of the external pipework of each module to a drain tank maintained under strong depression (P_{abs}=20kPa). The overall safety system, referred to as ‘Draining and Re-filling System” (DRS) [6], comprises: multiply redundant 15mB pressure switches detecting the torus pressure rise; the hardwired logic controlling the cooling pumps, water circuit isolation and drain valves; the water-ring vacuum pump that maintains the drain tank under depression. No issues were identified relating to the design, implementation, or maintenance of the DRS, which as a JET IOPS was subject to periodic re-commissioning. However, the claim that the DRS *alone* was sufficient to limit the ingress of water to 75kg could not be fully substantiated, since up to 98kg can enter the vessel due to the ≤50kPa head of water within a single divertor module loop. Credit is taken in the safety case for condensation of about half of this water on cold surfaces, e.g. water pipes. The calculation of the amount of water that remains in the liquid phase depends on the equilibrium that can exist between boiling and condensation, as in a heat pipe. The boiling rate, equal to the condensation rate in steady-state, depends on the wetted area of the hot surfaces, according to the shape of the vessel components where water collects. However, another system of pressure-switches opens the bypass valves of the torus turbo pumps for P_{torus} > 200mB, whereupon about 45kg of steam will rapidly condense on the surfaces of the forevacuum line. The 200mB pressure switches/automatic bypass valve were therefore also assessed for ‘fitness for purpose’. Without the DRS, up to 700kg water would potentially enter the torus.

Control Room Alarms raised as result of protection system actions (such as DRS) require a response defined in written procedures; such documents are one example of the type of Control Room Operating Procedures that were peer reviewed and re-issued prior to TTE [3].

Of 19 KSRE identified in the safety case 17 were subject to ‘fitness for purpose’ assessments before TTE. Of these, 9 were prioritised for assessment on the basis of D-D operation alone. The full sets of KSRE are listed in [3,10]. No issues were identified that prevented satisfying fitness for purpose criteria. A significant number of KSRE improvements were recommended and implemented, such as installation of cameras to aid search procedures in connection with the Personnel Safety and Access System, and revised maintenance procedures.

2.1.2. Tritium compatibility of diagnostics and ancillary systems

Three aspects were considered: vacuum integrity of diagnostic windows, tritium compatibility of diagnostics with vacuum systems communicating with the torus, and integrity of isolation of ancillary systems not tritium compatible or where tritium contamination should be avoided due e.g. to future maintenance difficulties. A number of diagnostics were determined not to be tritium compatible. This was due to safety considerations, such as only single containment barriers (e.g. bellows) or unsuitable seal materials. Other cases were due to possible detector damage from tritium or neutrons. These diagnostics had to be valved off, fitted with blanks or removed prior to TTE. Other diagnostics which communicate with the torus vacuum system and with forevacuum systems exhausting to a ‘diagnostic crown’ routed to AGHS [11], remained in operation for TTE.’

2.2. PREPARATION ACTIVITIES: STAGE 2 (INTERVENTION)

A pre-TTE campaign machine intervention of five weeks duration was included in the overall planning, which allowed for a vessel vent. The main purposes of the intervention were: to blank or repair any unacceptable diagnostic window or feedthrough leaks; to disconnect redundant equipment from torus vacuum and forevacuum system (such as the Fast Pellet Gun vacuum tank); to perform an extensive vacuum leak test of the torus and NB boxes including forevacuum lines; and to upgrade the instrumentation of the torus Tritium Deuterium Gas Introduction Module, TDGIM, also known as GIM15 [3].

2.3 PREPARATION ACTIVITIES: STAGE 3 (NON-ACTIVE COMMISSIONING)

Following the pre-TTE machine intervention, a six-week re-start phase was planned. *All* IOPS and KSRE safety systems were formally commissioned according to some 44 newly approved commissioning procedures, covering basic ‘end-to-end’ integrity checks and ‘live’ functional tests e.g. partial venting of vacuum systems to exercise 15mB and 200mB pressure switch full interlock paths. Machine systems, required according to JET Local Rules when >0.1g T is held on cryopumps, were also re-commissioned at this time, e.g. the Torus Hall ventilation system operated at stronger depression. The only relaxations compared with the Local Rules for DTE1 or full DT operation were attributable to the lower activation radiological hazards. Certain areas in the vicinity of the vessel gas bake-out circulation plant remained accessible, and the Torus Hall Fire Suppression (N2 enrichment) system was not used as there would be insufficient activation to prevent emergency access to the machine.

The TDGIM and the Tritium Deuterium Gas Introduction System (TDGIS) [8] of the Octant 8 NB injector were commissioned using deuterium supplied from AGHS. The purpose was to check all technical systems and to rehearse all procedures for gas supply and recovery, including tritium accounting. Actually, the NB TDGIS was operated in deuterium before the pre-TTE shutdown in case any intervention within the secondary containment vessel might be required. There were however no TDGIS problems and there was no need to disturb the system. Due to the particular characteristics of the TDGIS feed to the Positive Ion Neutral Injector (PINI) beam sources, which had been upgraded from 30A to 60A extracted ion current since DTE1 [12], there was some loss of NB performance [9] from limitation of beam current due to gas starvation effects.

The TDGIM was required to introduce enough T atoms to obtain the necessary plasma concentration, in an interval sufficiently short compared with the characteristic time of redistribution in the plasma i.e. for transport from the edge source location to the core. The typical requirements were for delivery of 2.5-7.5mg tritium within <80ms. The temporal pulse shape of the source in the plasma was measured from Balmer-α radiation by a telescope viewing the plasma at the TDGIM entry port. Localisation of the signal due to the edge source was confirmed from the magnitude of Zeeman splitting characteristic of the low-field side of the torus.

Operation of the torus TDGIM in D2 and H2 was used to confirm the mass scaling of flow-rate and of time constants relating to delays between opening the valve and observing the gas puff in the plasma. The results also showed that more precise control of the piezo-electric valve actuator was required to obtain the necessary gas pulse characteristics with good reproducibility [3], successfully achieved before switching to tritium.

3. FINAL COMMISSIONING WITH TRITIUM

3.1. GAS INTRODUCTION AND NEUTRAL BEAMS

The different stages of the gas distribution system, torus TDGIM and NB TDGIS were successively filled with tritium and the secondary containment was carefully monitored within AGHS to confirm the integrity of the entire primary tritium boundary up to the TDGIM and NBTDGIS outlet valves (“expanding the tritium boundary”). Detailed operating characteristics of the TDGIM and the two PINIs to be used in tritium had been established during commissioning in deuterium, and from these the initial settings for tritium were derived then optimised in tritium operation. The commissioning of T^0 beams on two PINIs was completed in two days’ operation within the 0.5g daily cryopump inventory [9].

3.2. NEUTRON DIAGNOSTICS

3.2.1. Neutron yield

Total neutron flux is measured with three sets of ^{235}U and ^{238}U fission chambers distributed around the machine; Si diode detectors were previously developed on JET [13] to measure the 14MeV neutron flux. These are susceptible to neutron damage and became degraded since installation before DTE1; four new detectors of different sizes were installed before TTE to cover the range corresponding to total plasma neutron emission from 10^{13} to 10^{18} ns^{-1}. Diamond detectors have much greater radiation hardness and their development is important for ITER. Natural Diamond (ND) detectors and, for the first time, a Chemical Vapour Deposition (CVD) diamond detector were tested during TTE [14]. The Si diodes were calibrated against measurements of activation in thorium and indium samples exposed to 14MeV neutrons from the plasma (Fig.2).

In these calibration pulses the 14MeV yield was varied over more than two decades, utilising the effects of triton burn-up in high-power D-D plasmas, tritium gas puffs and T^0 NB 'blips'. The absolute calibration relies on calculations of neutron transport for the machine structure using the MCNP code that were validated in DTE1 [13]. The ND and CVD detectors were cross-calibrated against the Si diodes and shown to be linear. Other neutron and gamma diagnostics, including measurements of energy spectra, are described in [14,15,16].

3.2.2. Neutron emissivity spatial profile

The JET neutron camera (Fig. 3) consists of two fan-shaped arrays of collimated lines of sight, viewing the plasma along 10 quasi-horizontal and 9 quasi-vertical chords. Each channel is equipped with three detectors: a NE213 liquid scintillator for simultaneous neutron (2.5 and 14MeV) and gamma measurements with energy discrimination, a Bicron BC418 plastic scintillator for 14MeV neutron yield, and a photodiode gamma detector [15]. The system was fully operational and cross-calibrated against the Si diodes for 14MeV neutrons during the final commissioning phase with tritium.

4. CAMPAIGN SUMMARY

4.1. STATISTICS

The TTE campaign started on time on the very day as planned, and the five week experimental phase was extended by just 1/2 an operational day. All experimental proposals received experimental time, except one on pellet fuelling that was dropped due to non-availability of the pellet centrifuge (non TTE-related fault). The 14MeV neutron production of 4×10^{18} was well within the constraint, as was the tritium injected into plasma (380mg) in over 80 JET pulses with T_2 gas puff . The integrated NB T^0 injection was equivalent to 20 beam.seconds in 74 successful beam pulses; a further 19 beam pulses were lost to NB power supply trips [9] (which still consumed tritium). A total of 5g tritium was supplied to the NB injector, including the T^0 beam commissioning requirement. The peak machine activation reached 590µSvhr^{-1}, well within the projection.

4.2. TRITIUM ACCOUNTING AND VESSEL CLEANUP

The tritium supply quantities were logged manually using PVT measurements pulse by pulse; the procedure for the NB TDGIS system is described in [9]. A similar procedure was adopted for the torus TDGIM. The NB TDGIS and torus TDGIM were 'topped up' as required on a batch basis, and independent PVT measurements of the tritium leaving AGHS were also recorded. All data was reconciled at weekly tritium accounting meetings. AGHS recorded the quantity of tritium recovered from each regeneration using ion chamber (IC) data or analytical gas chromatography (ANGC). The data on recovered tritium, though available on a daily frequency, were not particularly useful for determining in-vessel T retention because the batches of regenerated gas included tritium from the NB injector, which was always dominant (13 times greater total throughput than the torus). The absolute error on the IC and ANGC measurements was larger than the expected T retention figure of ≈20% of plasma throughput i.e. ≈70mg (only 1.4% of total recovery of >5g including NB injector). The same remark applies to a comparison of total AGHS T inventory from PVT measurements made before TTE and after the final reprocessing of all recovered gas, and subject to measurement errors of ±1% on an AGHS inventory of ≈10g, implying a change of inventory of +30mg ±100mg. During the 3-week cleanup period many L-mode plasma pulses with moderate ICRF heating and high D2 fuelling were run as this was the most effective T removal technique in DTE1. The background plasma concentration $f_T = n_T/(n_D+n_T)$, estimated from the 14MeV neutron yield is plotted versus pulse number, over the course of TTE and clean-up phase in Fig.4. The effect of interspersed clean-up/experimental pulses is clearly seen. Also plotted is a prediction based on a pulse by pulse summation of the empirical model derived from the JET Preliminary Tritium Experiment (PTE) in 1991, also applied in DTE1 [7]. For TTE, the prediction is much better if the T removal is scaled according to D_2 fuelling:

$$F_T(n) = \sum_{j=1}^{n-1} \frac{Q_j^T}{Q_0^T}\, F\left(\sum_{i=j}^{n-1} \frac{Q_i^D}{Q_j^D}\, F\right) \tag{1}$$

where in PTE F(n) described background T level after n pulses with constant Q_0^D D atoms fuelled per pulse, following introduction of $Q0^T$ T atoms in two successive pulses (n=1, 2). This model does not describe the rate of transfer of tritium into *long-term* retention, only reservoirs that *exchange* with the plasma. During the post-campaign cleanup period, a further 22.3mg (6% of plasma throughput) was recovered, including vessel GDC and warm-up of the LN_2 cryopump panels. In DTE1, up to 40% throughput was initially retained, of which ≈20% was recovered promptly. The fact that only 6% of TTE throughput was recovered in the post-campaign cleanup phase is not surprising as most prompt release is expected to have occurred from the interspersed clean-up pulses. The recovery/inventory measurements, though of limited precision, do suggest that long-term retention was lower than the figure expected from DTE1 i.e. 17% of 0.38g throughput or 65mg, cf. an observed *decrease* of 30mg ±100mg in the torus.

4.3. DIAGNOSTIC EXHAUST EVENTS

Two occurrences during TTE involving the ‘diagnostic crown’, into which the exhaust from tritium-compatible diagnostic forevacuum pumps discharges [11], revealed design weaknesses and led to a decision to improve the diagnostic exhaust arrangements; in both cases, a larger than expected amount of tritium entered the diagnostic crown. In one case, this was due to the removal, since DTE1, of an X-ray filter that also screened the diagnostic beamline from the TDGIM gas entry port. In the second event, a valve isolating a non-tritium compatible diagnostic from the torus failed to seal during regeneration of the divertor cryopump. The required improvements to the diagnostic exhaust system are described in [3].

5. SCIENTIFIC HIGHLIGHTS

5.1. PARTICLE TRANSPORT

Particle transport coefficients for the minority T^+ species (diffusion coefficient D_T, convection velocity v_T) were derived from modelling of the expected neutron emissivity profile evolution following the T_2 puff [17]. At the simplest level of interpretation, comparison with the neo-classical transport theory based on Coulomb collisions and toroidal effects, indicates the importance of turbulent transport in different confinement regimes. Figure 5 illustrates the procedure, and also a typical result that D_T and v_T are significantly larger than the neo-classical values. The measured particle transport coefficients do approach neo-classical values in certain regimes, such as close to Internal Transport Barrier (ITB) layers, and in the core of high-density, high-current (low q_{95}) discharges [18], implying turbulence suppression.

5.2. FAST PARTICLE DYNAMICS

The spatial and temporal re-distribution of fast ions, such as beam-injected D^+, T^+ or ICRF accelerated T^+ was observed from the neutron emissivity profile, due to reactions of the fast ions with the thermalised background ($D \rightarrow T$ and $T \rightarrow D$). Experiments were designed to test fast ion source terms and the classical nature of the thermalisation process (important e.g. for describing NB current drive), and to investigate effects of MHD instabilities. One important experiment gave direct experimental evidence of fusion α-particles from NB injected $T \rightarrow D$ reactions from γ-ray measurements of the $^9Be(\alpha,n\gamma)^{12}C$ reaction at threshold energies related to the fusion α-particle energy. The decay time of the γ-ray intensity following the T^0 beam ‘blip’ matched the classical α-particle slowing-down time, except when orbit losses were enhanced at low plasma current or with low poloidal field in the core (‘current holes’) [18].

CONCLUSIONS

The technical capability of JET to run D-T experiments has been re-established. The great majority of all systems and procedures for operation with tritium were validated, re-instated and commissioned, including neutron diagnostics. The scientific value of a DT campaign has been amply demonstrated, as well as the feasibility to conduct it within tight operational constraints. This experience has shown that future similar campaigns with limited tritium usage could be conducted on a more routine basis, and is an important enabling step towards full D-T operation in JET.

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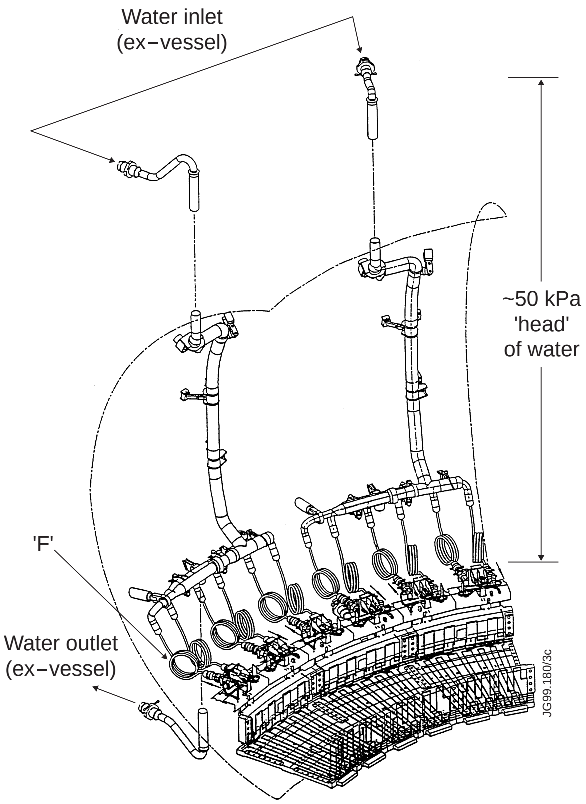

Figure 1: Single divertor module cooling circuit

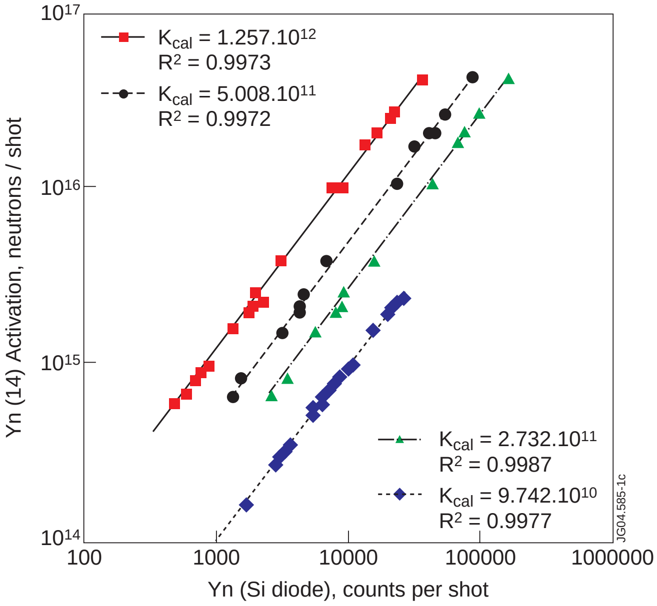

Figure 2: Linear cross-calibration and correlation coefficients of Si diode detectors for 14MeV neutrons against activation samples

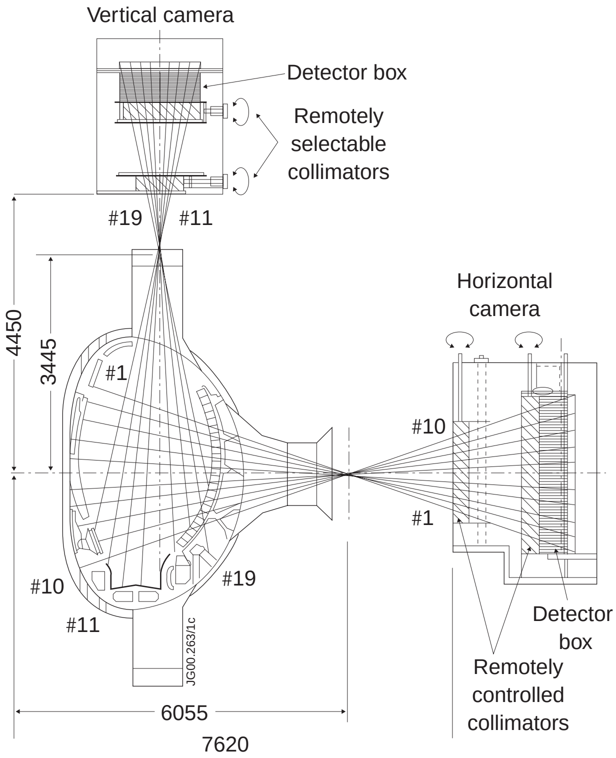

Figure 3: JET neutron camera diagnostic

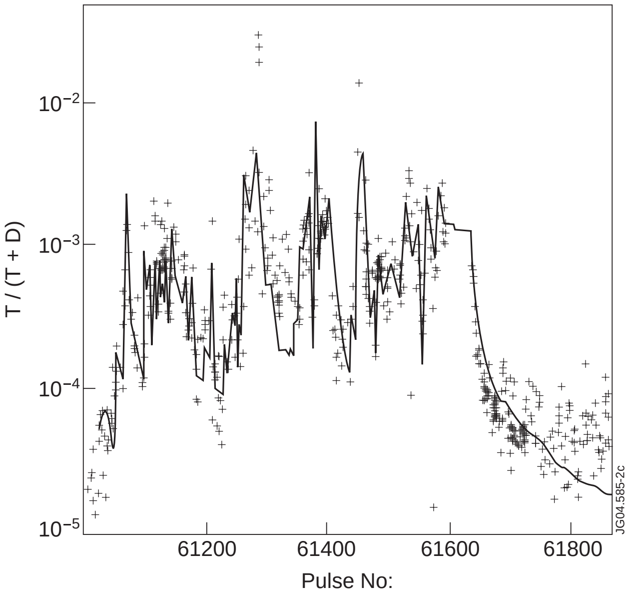

Figure 4: Background plasma T concentration: + measured from 14MeV neutrons and model prediction (solid line)

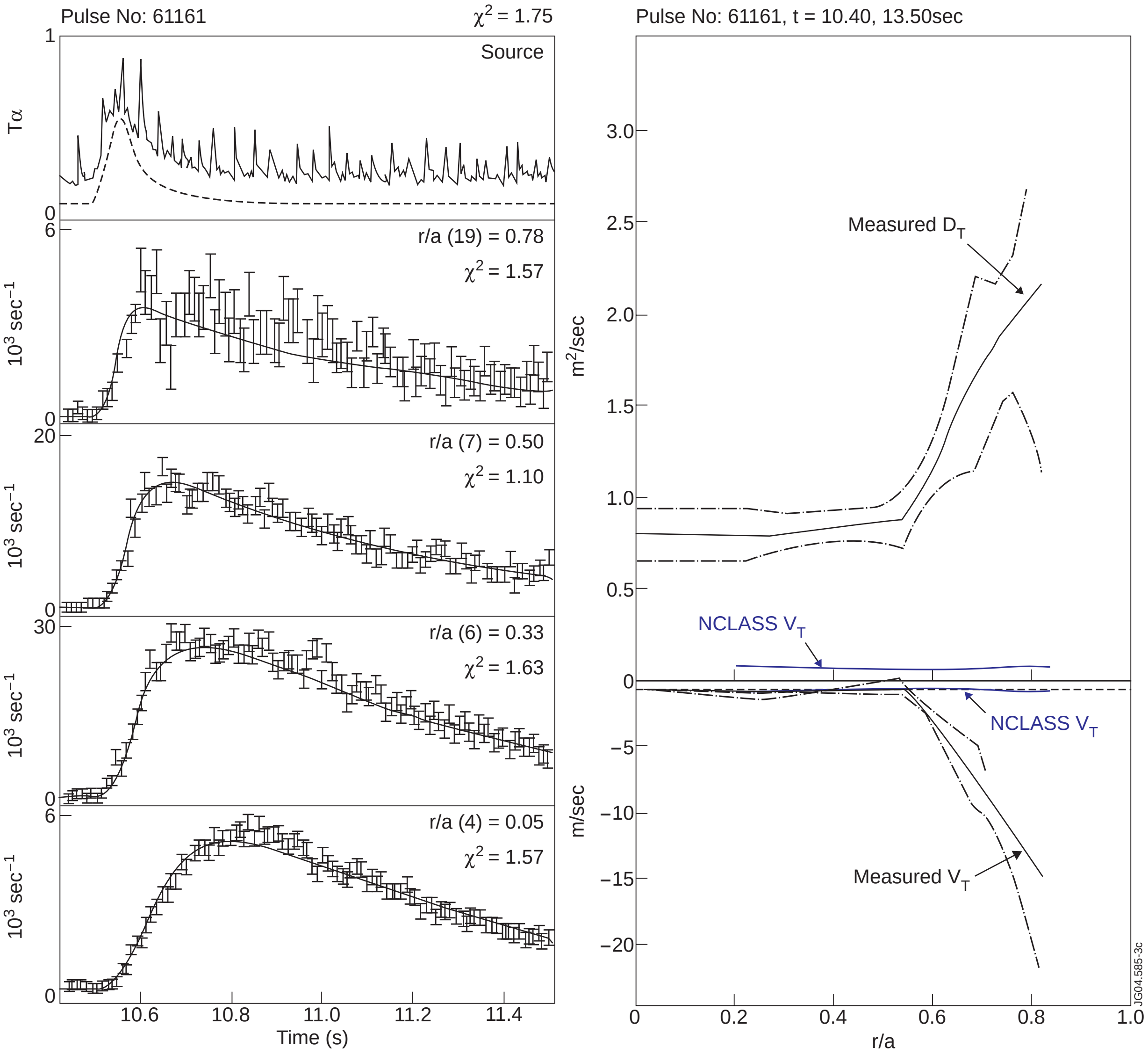

Figure 5: Neutron camera time traces from different chords, and fit to transport model for diffusion coefficient and convection velocity values shown (with confidence limits, dashed lines), and neo-classical values (NCLASS); medium density ELMy H-mode plasma, 2MA/2.4T, P_{NB} = 15MW, P_{ICRH} = 2MW, $n_a = 2.8\times10^{19}$ m^{-3}.

Constraint	TTE	DTE1	SC
T inventory 'in prosses' not bound on U - Bed	12g	20g	30g
T within vacuum envelope	0.7g*	10g	20g
T plasma throughput	0.5g	35g (actual)	–
Total 14MeV neutron production	1×10^{19}	2.5×10^{20}	5×10^{23} (annual)

JG04.585-4c

**In most readily releasable form, assumed to be that condensed on cryopumps plus ≈20% long-term vessel T retention*

Table 1:
Boundary conditions for TTE compared with DTE1 and full DT operations considered in JET Safety Case (SC)