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TRITIUM ACCOUNTING DURING THE FIRST TRITIUM EXPERIMENT AT JET

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Abstract

This paper summarises the measuring procedures and the results of the tritium accounting during the first Tritium Experiment at JET, carried out in November 1991. The measurement of the amount of tritium injected into the Torus and of the quantity recovered from the Torus and the Neutral Injector Boxes is described and the accuracy of the data assessed. The new Gas Collection System used during the experiment is briefly described.

The tritium recovery data taken in the months following the experiment are reviewed, with special attention to the first three weeks after the experiment. The total amount of tritium collected in the Gas Collection System is compared with the data of tritium release from the Torus and the Neutral Injection Boxes. The analysis of the data allows us to estimate the residual tritium inventory in the Injection System and in the Torus.

1.0 Introduction

A series of plasma pulses fuelled with a mixture of deuterium and tritium was carried out for the first time at JET, during the First Tritium Experiment (FTE) [The JET team, 1]. One of the main aims of this experiment was to assess the effectiveness of tritium recovery techniques and to measure the tritium retention in the Torus systems, in particular in the vacuum vessel and in the tritium injection system [Huguet, 2]. The tritium was introduced into the plasma by high energy (78 KeV) neutral beam injection. JET has two Neutral Injector Boxes (NIB) on Octants 4 and 8, referred to as NIB 4 and NIB 8, each having eight beam sources - Positive Ion Neutral Injectors (PINI). Two of the NIB 8 sources (PINI 5 and 6) were modified for tritium injection [E. Thompson, 3].

The FTE was divided into three general phases:

1. The 1% experiments, where the two modified injectors were fed with a mixture of 99% deuterium and 1% tritium leading to ~0.1% tritium concentration in the plasma. This phase allowed the calibration of the diagnostics and the test of the recovery system and procedures.

2. The second phase consisted in two high power pulses, with 100% tritium injection from the two tritium PINIs, leading to ~11% tritium concentration in the plasma [The JET team, 1].

3. The clean-up experiment: the first two days after the 100% FTE were dedicated to the systematic study of tritium recycling. The evolution from pulse to pulse of the tritium concentration in the plasma and of the tritium release from the plasma facing surfaces was studied under a variety of plasma conditions [Horton, 4; Andrew, 5].

The global accounting of tritium during the FTE required the monitoring of the releases from the Torus and from the neutral beam injectors during the weeks after the FTE. The final account will be obtained only when in-vessel components are analysed for tritium content during the 1992-93 shutdown.

For the FTE, the JET forevacuum lines were modified to form a closed system, [Hemmerich, 6; Bell, 7; Caldwell-Nichols, 8]. Both the Torus and the Neutral Beams vacuum lines were isolated from the forevacuum pumping system and were connected to the Gas Collection System (GCS) as shown in Figure 1. All the gas coming either from the Torus or from NIB cryopanels regenerations was routed to the cryopump of the GCS and from there absorbed in two uranium beds (U-beds) [Hemmerich, 6]. The GCS was equipped to measure the total amount of gas reaching the system and its tritium content. The measuring rig was fitted with pressure gauges, two ionisation chambers (IC1 and IC2 in Figure 1) as well as with a gas sampling facility for off-line tritium assay (Culham Laboratory, U.K.). In addition, the tritium content of the exhaust gas from the Torus was measured by a quadrupole mass spectrometer (Residual Gas Analyser, RGA), situated in one of the main pumping chambers of the Torus.

The tritium accounting consists of a comparison of the measured tritium input to the injection system with the measured tritium recovered from the injection system itself and from the Torus. Before the FTE the procedures for the acquisition, collection and on-line evaluation of the relevant data were devised with the aim of keeping track in 'real-time' of the tritium inventory in the various Torus systems. The data from the various systems were collected and analysed by the tritium accounting responsible officers, checked for consistency and fed back to the relevant people involved in the FTE. The commissioning and first calibration of the two main measuring instruments, IC1 and IC2, were carried out during the 1% experiment. A further and more accurate calibration was carried out after the FTE when the U-beds containing all the tritium recovered to date were regenerated, which also allowed a global account of the total amount of the tritium collected. Finally, further consistency checks between the various measurements of tritium recovery were performed and the detailed tritium accounting established.

2.0 The Tritium Injection System

The choice of introducing tritium into the discharge via neutral beam injection was dictated by the need to minimise the tritium consumption and in-vessel inventory. The alternative of plasma fuelling by gas admission to the Torus has low efficiency (~10% of the input, [Sartori, 9]) and the central concentration of tritium depends on wall recycling [Horton, 4] and also on the achievable peaking of the density profile. In contrast, the fuelling of tritium via neutral beam injection is an effective way of depositing tritium in the centre of the discharge, thus minimising the overall amount of tritium introduced in the vacuum vessel. In the case of Neutral Beam fuelling about 80% [Thompson, 3] of the injected tritium (at 78 KeV of energy) is deposited within 0.5m from the plasma centre. The overall efficiency of the injection system is, however, only about 6% of the total tritium used, but with this fuelling option most of the tritium is confined within the Neutral Injection Box.

The gas introduction system for PINIs 5 and 6 was redesigned to feed the injectors with gas coming from U-beds storing deuterium (D) and tritium (T), instead of using the conventional gas supply system (figure 2). The detailed description of the hardware and of its commissioning and operation is found in [Thompson, 3]. From the point of view of the accounting, the accurate determination of the tritium usage and of the injected fraction (taking into account losses due to reionisation in the beam duct inside the Torus) are of paramount importance. The accurate accountability of the tritium usage required the calibration of all the volumes used for the gas expansion before the injection in the neutralizer. The calculation of the amount of tritium used for each pulse (conditioning and plasma pulses) takes into account the difference in temperature between the U-beds and the gas introduction pipework, the variation in temperature in the system caused by the fast expansion of the gas and the gas production from the U-bed during the pulse, although the latter is a very small effect. The composition of the gas delivered from the U-beds was nominally 1% T in D, and 100% T in the two phases of the experiment. Samples of the gas from the U-beds were taken for both the 1% and 100% injection and their composition analysed. The samples were analysed by Mass Spectroscopy at CEA[1] Valduc and CEA Bruyeres le Chatel (France). The results of the analysis are shown in Tables 1 and 2.

For the 1% experiment, taking into account that 0.1% of the tritium decayed before the analysis was carried out, it can be assumed that the actual composition of the gas was during the experiment the nominal 1%. The tritium content of the gas used during the 100% tritium injection experiment is, averaging the two results obtained in France, 95.10 vol % T in H, at the time of the analysis. When the radioactive decay of the tritium in the sample is taken into account, the fraction of tritium in the gas used for feeding the two tritium PINIs was 96.43% at the time of injection. Nevertheless, due to the higher ionisation efficiency for T than for H, the T fraction in the neutral beam was ~99%.The gas sample from the U-bed used for the 100% experiment was taken

[1]Commisariat à l'Energie Atomique

after the U-bed was removed from the neutral beam injection system. The N_2, O_2 and Ar detected in the analysis come from the sampling system, that was not UHV. Since the gas sample was taken after usage of the U-bed, some depletion of the tritium content is expected, due to an isotopic effect in the release of H, D and T from U-beds. This effect is small and it is not taken into account in the calculations.

The global tritium consumption during the FTE is summarised in Tables 3a and 3b, where the uncertainty associated to the data of gas consumption take into account the accuracy on volume calibration and pressure measurements. The other figures are based on the beam current measurements before neutralisation and on an estimate of beam neutralisation and transmission efficiencies and of the reionisation losses [Thompson, 3].

3.0 The Tritium Recovery System

3.1 The Gas Collection System (GCS)

The pumping system of JET was modified to provide a suitable closed system for the tritium collection (Figure 1). The backing pumps that normally provide the forevacuum for the Torus and neutral beam vacuum lines were isolated and their function replaced by a cryopump. The cryopump is connected to a calibrated volume and to two U-beds for the recovery and storage of hydrogen isotopes after regeneration. A detailed description of the GCS can be found in reference 6. The GCS is equipped with instruments to measure the total amount of gas in the line, its composition and tritium content. The cryopump and the connected sampling line can be connected to the Torus pumping duct (crown) via valve V_3 and to the neutral beam pumping duct (crown) via valve V_2. With this arrangement, the same tritium measuring system is used for the evaluation of the gas activity released from the JET vessel and from the NIBs.

3.2 Instrumentation Used

The main instruments used to measure tritium were two ionisation chambers, IC1 and IC2 in Figure 1. During plasma operations, the typical pressures measured in the line do not exceed 10 Pa, hence IC1 was operated in the ion-collector mode [Barnes and Gibson, 10; Hemmerich, 6]. In this mode of operation the ^3He product of tritium decay is collected at the negative electrode of the instrument. In this pressure range the number of secondary ionisations is negligible and the current reading is directly proportional to the density of tritium atoms, i.e. it is independent of the total pressure. Moreover, in this regime the current reading is not affected by the gas composition. This latter point is of importance from the accounting point of view, since the exhaust gas from the Torus can contain a small fraction of hydrocarbons, typically of CD_4, the amount of which varies depending on the plasma operations [Sartori, 9]. On average the CD_4 fraction is of the order of 2-3% of the total gas exhaust. The

water vapour fraction is normally neglegible. IC1 and IC2 have been absolutely calibrated in the normal ionisation chamber mode at Los Alamos National Laboratories for JET with air at ~7.5 x 10^4 Pa of pressure [Caldwell-Nichols, 11]. Several calibration points for IC1 used as ion collector were obtained during the FTE, by backfilling the measuring chamber with N_2 at 7.5 x 10^4 Pa of pressure. The procedure, results and some comments on their accuracy are discussed later.

The expansion volume connected to the cryopump and to the U-beds system was equipped with another ionisation chamber, IC2. This volume was used to collect and measure gas coming from the regeneration of the cryopump at equilibrium pressures ranging from ~5 x 10^2 Pa to ~5 x 10^3 Pa. In this pressure range the sensitivity of the instrument depends on the total pressure and on the gas composition. In particular, for the same tritium partial pressure, the sensitivity increases with both total pressure and impurity concentration. IC2 was calibrated on-line, after the 1% experiment, using the gas recovered from NIB 8 after regeneration. This first calibration has been used during the FTE for the day by day evaluation of the tritium recovery. A second calibration run was carried out at the end of the experiment after isolating the GCS from the Torus pumping line [Hemmerich, 6]. Additionally the sampling line, the Torus and NIB crowns and the collection volume were equipped with absolute pressure gauges to measure the total amount of gas reaching the system. IC1, IC2 and some of the pressure gauges (P_1, P_2, P_3 and P_8) were interfaced to the JET computer system (CODAS) for permanent storage of the data. The data were recorded continuously 24 hours a day, with one minute sampling rate. For each plasma pulse, a faster 0.1Hz data acquisition programme was started automatically and the data recorded separately. A standard continuous recording graphic facility allowed the data to be displayed in real-time. A mimic of the plant, showing the location and the measured values at the instruments, was available from CODAS. A console was installed at the GCS site and another allocated to the tritium release monitoring in the JET Control Room.

3.3 Measurement Procedures

3.3.1 Recovery of Tritium from the Torus

Most of the release of tritium from the vacuum vessel was associated with plasma pulses. At the beginning of each JET pulse, valve V_1 was closed (V_3 is always opened when JET is operating) and kept closed for 600s. The gas coming from the vacuum vessel built up in the closed volume defined by the Torus pumping crown and the sampling line (6.162 m^3). The time evolution of the total pressure and of the tritium concentration in the gas are measured by P_3 and IC1 respectively.

The final value of the IC1 current allows an on-line evaluation of the tritium recovered in the 600s after the pulse. 600s after the discharge, V_1 was opened and the gas in the line pumped onto the cryopump until the next pulse. The

procedure was repeated until between 5 and 10 x 10^2 Pa.m^3 was collected in the cryopump. The cryopump was then regenerated and the gas transferred to the collection volume (0.345 m^3), the tritium content was measured with IC2 and the total gas with P_8. From the collection volume the gas was absorbed onto a U-bed. Occasionally, V_1 was kept closed after a pulse for as long as forty minutes, to measure the outgassing rates near steady-state conditions. On some occasions, typically overnight, the natural outgassing of tritium, long after plasma pulses, was measured by keeping V_1 closed for a chosen length of time. These measurements provided information on the background release rate of tritium (and deuterium) from the vessel walls.

Most of the IC1 data presented refer to the integrated tritium released over 600s after a plasma discharge, whilst IC2 measured the tritium released from the cryopump after a regeneration and consisted of gas collected over many pulses or a NIB regeneration. In some cases, in particular during IC2 calibrations and NIB regenerations, the gas was expanded from the collection volume to the IC1 chamber, to allow a cross-reading of the two instruments.

3.3.2 Tritium Recovery from the Neutral Beam Injectors

The two neutral beam injector boxes are connected to a common vacuum line, shown in Figure 1. During the regeneration of either box, the Torus was isolated from the GCS by closing V_3.

The procedure for handling the large amounts of gas (of the order of 1 x 10^4 Pa.m^3) released by the neutral beam cryopanels was modified during the experiment. The first gas collection was done in several batches, later all the gas was processed in only two steps. After NIB cryopanel regeneration the gas is either collected by first condensing it on the cryofinger and then regenerating it into the 0.345 m^3 volume, or expanded into the large volume of the NIB crown, sampling line and collection tank (6.769 m^3 in total), depending on the quantity of gas to be processed. The gas was then pumped into the U-beds, In both cases, the measurement of the total activity was available from IC2, occasionally the IC2 data were cross-checked taking IC1 readings at 7.5 x 10^4 Pa of N_2 pressure.

3.4 Accuracy of the Data

Four parameters of varied importance enter into the calculation of the tritium recovered. These are:

1. Volume calibration
2. Pressure reading
3. Current measurement on IC1 and IC2
4. Calibration coefficients for IC1 and IC2

Before the FTE the calibration of all the relevant volumes for gas collection (pumping crowns, sampling line, vacuum manifold connecting the cryofinger

to the collection volume) was performed by pV measurements using a known amount of gas from the 0.345 m^3 reservoir and expanding into these volumes. The reservoir volume had been previously calibrated with an accuracy of 1%. All the pressure gauges used were absolute manometers and in the pressure range used for calibration their error is very low, $\leq$0.5% of the reading, hence the uncertainty of the volumes measurement is <2%. The absolute manometers fitted to the GCS were used as a rule in their ideal range of operation, keeping the error on the pressure reading less than 0.5%. For the tritium count the most important pressure gauge is P_8. It measures the total pressure in the collection volume before gas absorption on the U-beds. Accuracy and most importantly stability of this pressure reading was needed since IC2 operates in a regime where its sensitivity is pressure dependent. Tests carried out on P_8 showed that the drift of the gauge was less than 1% over a one month period. The error on the volumes measurement is very small, affecting systematically the calculation of the absolute amount of T recovered, whilst not affecting the trends. The uncertainty introduced in the tritium accounting by the pressure readings is even smaller; both are neglected in the calculations.

The output current reading for IC1 is measured by an electrometer, within a nominal range between 10^{-14} to 10^{-9} A, but in fact the electrometer has shown to work reliably at even lower currents. The sensitivity limit is ~10^{-16}A. The uncertainty on the tritium concentration data from IC1 depends on which mode of operation is used. When IC1 is used as an ionisation chamber the total uncertainty is ± 10% [Caldwell-Nichols, 11], which is typical for an ionisation chamber in this mode of operation. In the ion collector mode, the uncertainty on IC1 tritium concentration data comes from the error on the benchmark calibration at atmospheric pressure and from the error on the current measurement. The calibration of IC1 as ion collector was carried out in parallel to the actual measurements, typically on gas coming from the Torus after a plasma pulse. The calibration was obtained in-situ by closing valve V_9 at the end of the gas collection time, and backfilling the chamber with N_2 to the benchmark calibration pressure of 7.5 x 10^4 Pa (in the ionisation chamber regime). This procedure was carried out several times, in particular after the two 100% T injection pulses and during the clean-up experiment. Calibration points were taken in the range of concentrations from ~2 x 10^{10} Bq m^{-3} to 4 x 10^7 Bq m^{-3}. Care was taken that the reading of IC1 in the ionisation chamber mode was taken after a sufficient time from the N_2 introduction (~10 minutes), to allow the complete mixing up of the gases in the measuring chamber. The calibration factor for IC1 as ion collector, obtained as an average over ten calibration points is 7.363 x 10^{21} [Bq A^{-1} m^{-3}], with ± 20% statistical error. The uncertainty is reduced to <15% for high activity gas, and goes up to approximately 25% in the low concentration range, the sensitivity is ~5 x 10^{+7} Bq m^{-3}. Further details on the calibration procedures are found in reference 6.

Some deviation from the expected linearity of the current reading versus concentration are observed: in particular at high tritium concentrations the concentration measured is below average, while the opposite effect occurs at low concentrations. The variation of the background activity in the GCS line was

also taken into account during the data evaluation. In particular, the base line reading of IC1 increased from $<1 \times 10^{-15}$ A during the 1% experiment to $\sim 1 \times 10^{-14}$ A at the end of the clean-up experiment limiting the capability of IC1 to measure low tritium concentrations.

One week after the 100% experiment, the IC1 chamber and manifolds became contaminated by HTO, coming from a regeneration to room temperature of NIB 8. No data from IC1 have been used for the accounting after that date, until after the isolation of the GCS from the Torus line. IC1 was then decontaminated using the internal heater and used again during the final calibration of IC2.

IC2 is equipped with a picoammeter that has a higher limit of the sensitivity of 10^{-13}A but a very low intrinsic error. The associated uncertainty in the current reading goes from 1% to 0.1% at the highest current (2×10^{-3}A). In the range of pressures at which IC2 was operated (from $\sim 5 \times 10^2$ to 5×10^3 Pa) the current measured depends not only on the tritium partial pressure but on the total pressure, because of secondary ionisation processes, and on gas composition since it affects the ionisation cross-sections. A first calibration of IC2 in a limited pressure range ($P<1.5 \times 10^3$ Pa) was carried out during the NIB 8 regeneration, immediately after the 1% experiment. A batch of gas coming from the NIB was admitted to the GCS sampling line and to IC1. IC1 was then isolated and backfilled with N_2 to give an accurate determination of the tritium concentration. The remaining gas was then transferred to the 0.345 m^3 collection volume mixed and left to equilibrate, taking readings from both P_8 and IC2. The gas was then gradually absorbed on the U-beds, whilst recording the output reading from P_8 and IC2.

The sensitivity function S (p) was calculated from the formula:

$$S(p) = \frac{I(p)}{P.C_t} \quad [A\ m^3\ Bq^{-1}] \qquad (1.)$$

Where P is the pressure in the reservoir in Pa, J(p) the corresponding current reading on IC2 in A and C_t the initial tritium concentration as measured by IC1 in Bq m^{-3} Pa^{-1}. The calibration curve obtained was used during the experiment for the on-line evaluation of the recovery data.

After the disconnection of the GCS from the Torus pumping line, two further U-beds (not shown in Figure 1) were installed besides the original two. All the gas collected was transferred from the 'old' U-beds to the 'new' U-beds, providing the data for the global accounting of the tritium recovered. During this transfer, two other calibration runs were carried out, using the same method described above in the pressure range 1.5×10^2 to 1×10^4 Pa. Moreover, samples of the gas were taken to be analysed in Culham for tritium content by scintillation counting, providing a calibration check for IC1. The agreement between the two measurements was within 5% and an average of the data was used in formula 1. Two further gas samples were taken during the calibration and sent at a later stage to CEA Valduc (France). One sample was analysed for

the tritium content. The method used was the same used in Culham, i.e. oxidiation and scintillation counting. The results of the tritium counting is compared to the two earlier measurements in Table 4a. The agreement between the three measurements is satisfactory. The second gas sample was analysed by mass spectrometry, to check the purity of the gas (Table 4b). The concentration of hydrocarbons was very small, and it could not be measured with accuracy. However, the presence in the spectrum of both mass 19 and 20 would indicate the presence of very small amounts of CHD_3 and CD_4.

The calculated S(p) from the two calibration runs are virtually identical, but for the very low pressure points ($<3 \times 10^2$ Pa) where some variation due to residual impurities coming from the vessel walls can be expected. This is not very significant from the accounting point of view, since the relevant pressures in the collection volume were usually above 8×10^2 Pa. The second set of calibration points is believed to be more accurate compared to the very first calibration carried out after the 1% experiment, since the gas used came directly from a U-bed, i.e. is composed of only hydrogen isotopes, in contrast to the very first calibration where it is possible that a small fraction of hydrocarbons was contained in the gas used, especially at low pressures. The 'new' S(p) curve has then be used, and all the tritium recovery data re-evaluated. The typical average variation is around +10%.

In the analysis of the tritium release data as measured by IC2, a source of error comes, as already mentioned, from the variation of the gas composition, typically pollution of deuterium/tritium mixture by hydrocarbons. This error is quite difficult to quantify in general, since it is related to the particular batch of gas being measured. Since the sensitivity of a ionisation chamber is higher for hydrocarbons than for pure D/T mixture, the presence of impurities introduces an overestimate of the activity. This error is very small for tritium counting of gas from the NIBs, which has a very high degree of purity. Apart from the effect of composition, the uncertainty on IC2 data is ~10% including the calibration errors, provided that the total pressure exceeds $\sim 8 \times 10^3$ Pa.

The last factor affecting the detailed tritium accounting comes from the finite pumping speed of the neutral beam boxes on the Torus. Each box is connected to the Torus via two valves, a slow rotary valve and a fast shutter. The role of the fast shutter is to minimise the conductance between the vacuum vessel and the NIB, since the full pumping speed of each NIB with the fast shutter open, is of ~50 m^3s^{-1}, to be compared with 8.8 m^3s^{-1} total pumping speed of the turbomolecular pumps on the Torus. Routine operation of the NIB with the fast shutter open would cause an unnecessary overload of the NIB cryopanels. During plasma operations the rotary valve is usually open, while the fast shutter opens only 100 ms before beam injection and closes approximately 100 ms afterwards. The effective pumping speed of each NIB with the fast shutter closed, was measured after the FTE. It was found that the resting position of the fast shutter blades (1 m high) varies with use, causing a variation in the width of the gap between blades, i.e. of the effective pumping speed. The results of these tests are summarised in Table 5.

From the point of view of the accounting of the residual activity in the vacuum vessel, the fraction of the gas going to the NIBs needs to be taken into account. In fact, with the rotary valves opened the two boxes provide an additional pumping to the Torus equivalent to ~60% of the pumping provided by the turbopumps, for D_2. However, the accuracy of the global tritium accounting is not affected by the uncertainty in the NIBs pumping speed measurements. In fact the tritium pumped by the NIBs is measured in the GCS after the regenerations of the NIBs cryopanels.

3.5 Other Measurements of the Tritium Concentration

The GCS is equipped with a gas sampling facility connected to the main measuring rig via valve V_{12} (Figure 1). The sampling system holds up to five bottles of 10^{-5} m^3 that can be filled independently. Due to the limited number of sample bottles available gas samples were not taken routinely but for selected events, mainly after some plasma pulses. The bottles were then removed from the GCS, tested for external contamination and sent for analysis [Goodall, 12]. The sampled gas was mixed with hydrogen and excess oxygen in a combustion chamber and ignited. The resulting tritiated water collected, weighed and mixed with additional distilled water and a scintillant. The tritium content was then determined using a LKB scintillator counter at JET. The combustion of samples was performed in order of increasing activity (as measured by IC1) in order to keep cross-contamination at very low levels. The combustion chamber is baked and periodically flushed to reduce further the residual activity in the system. The nominal accuracy of this method is about 10%, the sensitivity (using 1×10^{5} m^3 samples) of approximately 4×10^{7} Bq m^{-3}.

The amount of tritium being pumped out of the Torus was also measured using a quadrupole mass spectrometer located in one of the pumping boxes [Andrew, 5]. Mass numbers 2, 3, 4 and 5 and the total Torus pressure (as measured by Penning gauges in the same pumping box) were monitored for 1000s after the start of a plasma pulse. The tritium is detected as a D-T molecule (mass 5), the T_2 concentration being negligible for T/D <0.01. The behaviour of the background signal for mass 5 (HDD ions created in the quadrupole itself) was characterized before the FTE, to scale as the product of HD and D_2 partial pressures. Using this correlation, the HDD intensity could be predicted with 10% accuracy. The sensitivity of this method is about 5×10^{-5} T/D, below which the background HDD^+ becomes dominant. The uncertainty on the data comes from calibration factors (± 30%), uncertainty in interpolation of signals (up to ± 20%, depending on the quality of the data) and uncertainty in the HD background (± 5×10^{8} Bq/pulse).

4.0 Global Tritium Accounting

Two extra U-beds were installed in the GCS as the first had become full and further gas from the NIBs still needed to be processed. The collected gas was transferred to the new U-beds and this allowed accurate measure of all the

tritium collected to date. The gas was taken out from the U-beds in batches of approximately 40 barl at a time, corresponding to a maximum activity per batch of the order of 4×10^{12} Bq for the gas coming from the first U-bed and to $\sim 8 \times 10^{10}$ Bq for the gas coming from the second U-bed. The total amount of tritium collected was measured with IC2. The data are summarized in Table 6 and from the figures, we can conclude that, within the measurement uncertainties, all the tritium used during the FTE has been recovered in the GCS. This result shows that the methods used to contain and control the tritium inventory during the FTE have been highly successful. In particular the GCS has proven to provide a safe tritium collection and storage system, as well as a good diagnostic system. However, these global data do not provide separate information on the detailed residual inventory in the NIBs and in the vacuum vessel.

In the following section the tritium recovery data are analyzed in detail, separating the Torus from the NIB releases, and a detailed accounting provided. All the tritium recovery data, from JET pulsing and NIB regenerations, that were analysed individually during the experiment are reviewed. The global accounting is then compared with the detailed tritium recovery data. The analysis of these data provides information on the achieved accuracy and reliability of the measuring systems used, as well as on the time history of the tritium release.

5.0 Detailed Tritium Accounting

5.1 Tritium Recovery From The Neutral Beam Boxes

Tables 3a and 3b show that most of the tritium delivered from the U-beds feeding the two tritium PINIs was retained inside the neutral beam box mostly on the liquid He cooled cryopanels. During routine deuterium injection operation, a NIB needs to be regenerated when the load on the He cryopanels is about 5×10^4 Pa m^3, i.e. approximately once a week. During the FTE the NIBs were regenerated immediately after the 1% and the 100% tritium injection experiments, even if the total load on the panels was only $\sim 1 \times 10^4$ Pa m^3, to remove the tritium from the box and transfer it to the U-beds. In the weeks following the tritium injection the boxes were regenerated several times, either keeping the liquid N_2 in the cryopump shields or allowing the whole box to warm-up to room temperature. The amount of tritium recovered in each occasion was measured, providing information on the efficiency of the decontamination procedures. After having regenerated the NIB 8 after the 1% experiment, it was decided that it was necessary to regenerate to the GCS the gas from NIB 4 as well due to possible contamination of the line.

The activity found in the gas released from the NIB 4 (which was operated only with deuterium) is the tritium contaminated gas pumped by the NIB cryopanels from the Torus while the rotary valve was opened. A summary of the activity recovered from the two boxes is given in Table 7a and 7b. Moreover, as far as the regenerations after the 100% tritium experiment are concerned, the amount of

tritium expected to reach NIB 4 via the Torus was high enough to require the gas released by warming up the cryopanels to be sent to GCS for storage. At a later stage (December 1991) NIB 8 was warmed up to room temperature, for a few hours first and later for one week. The activity released was monitored, only 1.85×10^9 Bq and 7.03×10^9 Bq respectively were released. The total amount of Tritium recovered from NIB 8, 3.895×10^{13} Bq $\pm$ 3.11×10^{12} is to be compared with the estimated initial inventory of 3.509×10^{13} Bq (see Tables 3a and 3b). The total release figure and the total input differ by approximately 10% and it is concluded that within the experimental uncertainty all the tritium in the NIB 8 has been recovered.

The progressive decrease of the activity released upon regeneration was a second valuable piece of information to assess on-line the effectiveness of the recovery techniques. For some of the regenerations a measurement of the tritium concentration was taken both with IC1 and IC2. The internal consistency of the two data is excellent, the two differing by <5%. The overall accuracy of the data for NIB 4 is somewhat poorer than for NIB 8, mainly because of procedural problems. The estimated error bar is ~$\pm$25%. The activity measured from NIB 4 is compared with the estimated amount pumped by the NIB from the Torus in the next paragraph. The activity collected in both boxes needs to be subtracted from the in-vessel inventory.

5.2 Tritium Recovery from the Vacuum Vessel

The estimate of the residual tritium retention in the vacuum vessel requires the separate analysis of the activity release data connected to plasma operations. The tritium concentration in the exhaust gas coming from the Torus was measured by IC1 on a shot by shot basis, while the total recovery (including the outgassing between pulses and overnight between operational sessions) was accounted for by measuring with IC2 the tritium content of the gas collected on the GCS cryopump after regeneration. The release of tritium due to plasma operations will be briefly compared to the release measured after soaking the vacuum vessel in D_2 and during glow discharge cleaning.

5.2.1 Tritium Release by Plasma Pulsing

Table 8 summarises the tritium recovery data as measured by IC2 (column 2). The figures in the third column are calculated from the IC2 data, taking into account that the gas collected into the GCS is a fraction of the gas released by the Torus walls, a part of it being pumped by the NIBs. The correction due to the additional NIB pumping is bound to be approximate because the effective pumping speed of NIB 4, in particular, was measured to vary by ~25% from time to time, probably because of the variation of the gap width as a result of fast shutter movement. The measured pumping speeds (with H_2 and D_2) are scaled down appropriately to take into account that tritium is released from the walls predominantly as a DT molecule. The data in Table 8 includes all the recovery data collected during the operation of the GCS.

The last column of Table 8 shows the calculated amount of activity in NIB 4. This figure has to be compared with the measured tritium recovered from the NIB during regenerations; this comparison allows a cross-check on the measured NIB pumping of the Torus thus providing information on the accuracy of the estimated residual tritium inventory in the vessel. The calculated amount of activity in NIB 4 is 3.049×10^{11} Bq, and the measured recovery is 2.435×10^{11}. The discrepancy between these two figures, of the order of 20%, is acceptable, and indicates that, within the approximations used for the calculations, the evaluation of the residual in-vessel inventory is reliable.

Three weeks after the first injection of tritium in the machine, the release of tritium during plasma pulses had decreased to very low levels, and it was decided to restore the normal pumping system to the Torus. The exhaust gas from the Torus were routed to a monitored stack [Caldwell-Nichols, 8] , and the activity release measured. The daily amount of tritium removed by pulsing dropped from an initial ~3.7×10^9 Bq down to ~ 1×10^9 Bq in one week and was below 1×10^7 Bq per pulse at the end of operations. The total amount of tritium removed from the vessel since the restoration of the normal pumping system ranges from 3.7×10^{10} to 7.4×10^{10} Bq in total. This amount of activity was not collected on the U-beds, but routed to stack.

The measurement of the tritium release in 600s after each plasma pulse of the first two days of operation after the 100% tritium injection (the 'clean-up' phase) is shown in Figure 3. The points on the graph are based on IC1 measurements, corrected by the effect of the NIB pumping, where appropriate. The plasma configuration of the so called 'standard cleaning pulse' was the same as for the two 100% tritium injection discharge, i.e. single null configuration on the upper carbon target plates [The JET team, 1]. In contrast with the two tritium discharges, the standard cleaning pulse had a very low neutral beam power, only for diagnostic purposes.

The tritium release per pulse dropped with successive pulses, from 2.2×10^{10} to ~6×10^9 Bq per pulse after 15 pulses. This could indicate a progressive depletion of tritium from the target plates, part of which is removed from the vacuum vessel after the pulse, and part simply redistributed on all the plasma facing surfaces. Some indication of the spread of the tritium from the target plates to other parts of the machine, comes from the increased tritium removal observed after a 'bounce around' cleaning pulse (pulse No. 10 of the series, indicated by a cross in figure 3). In this particular pulse, the plasma was moved to touch both belt limiters, and the inner wall protection tiles.

Another result comes from the comparison of the tritium removal efficiency of ^{3}He fuelled cleaning pulses to the standard deuterium fuelled cleaning discharge. Although the magnetic configuration of those discharges was identical, i.e. the surfaces interacting with the plasma were the same, the tritium release dropped by approximately a factor of 3 after the ^{3}He plasmas, compared to the previous and to the following deuterium cleaning pulses. This observation suggests that the predominant mechanism for tritium release from

plasma-facing components is recombination of DT molecules and desorption after the pulse. The depletion of deuterium concentration on those surfaces causes a drop in the tritium release rate.

When additional heating was applied to the standard cleaning pulse, the observed tritium release was enhanced, but by less than a factor of two. It is probable that the amount of energy dumped onto the target plates ($\leq$15 MJ) was not sufficient to increase their temperature and boost the outgassing rates. Lastly, high density plasmas terminating with a disruption caused a higher tritium release from the vessel, but their efficiency decreased sharply in few pulses. After the clean-up experiment, the normal JET experimental programme was resumed. The average tritium release per pulse continued to drop with time, as expected. After two weeks the average tritium recovery per pulse had dropped to 7-10 x 10^8 Bq and one week later to less than 2 x 10^8 Bq per pulse.

5.2.2 Consistency Check with Other Tritium Measurements

The tritium content of the gas coming from the Torus was measured by IC1 and by two other diagnostics, the residual gas analyser (RGA) situated in a pumping port and the gas sampling system on the GCS line. The results obtained by the RGA and gas samples are compared to the ion collector measurements in Figure 4 which shows the total tritium recovery per pulse for a collection time of 600s, except for a few pulses where the collection time is 2400s. The agreement between gas samples and IC1 data is excellent, over a wide range of tritium concentrations in the gas exhaust from ~5.0 x 10^8 Bq m^{-3} to ~2 x 10^{10} Bq m^{-3} (the highest concentration measured with both methods).

Part of the discrepancy observed between the two sets of data reflects the increased tritium background level in the vacuum line. The concentrations calculated from the ion collector data have the background subtracted (where appropriate), whilst the gas samples do not of course. If the tritium recovery as calculated from IC1 data, is recalculated without the background subtraction the agreement with gas samples results is within ± 20%, also at low concentrations.

The comparison of IC1 data with the RGA tritium release measurements is restricted to a narrower concentration range, due to the relatively high chronic background level of mass 5 in the RGA spectra. Moreover, a meaningful comparison is restricted to deuterium fuelled plasmas, since the accuracy of the RGA calculations is very much reduced for ^{3}He fuelled plasmas due to the masking of the HD signal in the spectrum by the ^{3}He peak. Nevertheless, for tritium concentrations above ~ 6 x 10^8 Bq m^{-3}, the agreement between the two sets of data is satisfactory. In average, the total tritium release after a pulse as calculated from RGA data is 20-25% higher than the ion collector measurement. The analysis of the tritium recovery trends, pulse by pulse, give consistent results with the two methods. The systematic overestimate of RGA data vs IC1 (and vs gas samples) could be partially due to systematic errors in the calibration factors used in the RGA data analysis.

5.2.3 Torus Soaking in D2 and Glow Discharge Cleaning

Alternative methods to plasma pulsing, aimed to remove tritium from in-vessel components, were tried. The first method consisted of isolating the Torus from the pumping system, and filling it with D_2 gas at ~2 Pa of pressure. The gas was left in the vessel for a time varying from one to four hours. In one case, the D_2 gas was flushed through the vessel, instead of being left static. In either case, the gas used was collected onto the cryopump in the GCS and after regeneration the tritium content measured. The results of the gas soakings are summarised in Table 9. Taking into account the time required to set up the machine for a soaking, and the gas load for the U-beds in the GCS it was concluded that this method is less effective than plasma pulsing.

Glow discharge cleaning could not be used as a method to remove tritium from the machine, until the normal pumping system was restored. Glow discharge cleaning is usually performed with a continuous flow of gas through the vessel. Due to the finite capacity of the U-beds collecting the gas from both Torus and NIBs, this method was not practicable in the first weeks after the FTE. Once the normal pumping system was restored, D_2 and ^4He glow cleaning were run and the efficiency for tritium removal compared, by using the release data from the monitored stack. The first glow discharge was performed in deuterium (25.11.91) the observed release rate was approximately 1×10^9 Bq h^{-1}, to be compared with a 'natural' outgassing rate for tritium of ~ 6×10^7 Bq h^{-1}. In the following days some experiments were done, alternating D_2 to ^4He glow discharge. The absolute rate of tritium desorption decreased from day to day for the same working gas. At the same time D_2 glow discharge increased the release rate of tritium above the 'natural' rate by approximately a factor of 5, whilst ^4He glow discharge did not increase the release above the background, but, if anything, it slightly depressed it. This observation is consistent with the reduced efficiency for tritium removal of He plasma pulses compared with D plasmas.

5.2.5 Estimate of the Residual In-Vessel Inventory

The residual in-vessel tritium inventory is estimated by adding-up all the contributions to the release, as detailed in the previous paragraph. In particular, with reference to Table 8, the balance is done using the estimated tritium release figures, i.e. taking into account the losses to the NIBs.

Going back to the data on Table 3a and 3b, the total tritium input into the vacuum vessel was of $2.006 \times 10^{12} \pm 2.26 \times 10^{11}$ Bq. This figure must be compared with the total amount of tritium removed, $1.838 \times 10^{12} \pm 2.94 \times 10^{11}$ Bq, that includes the release after pulsing, the gas soaking and glow discharge cleaning. The estimated residual inventory in the vacuum vessel taking into account the uncertainties in the input and in the recovery figures can vary from 0 to 5.6×10^{11} Bq. The large uncertainty in the residual inventory

derives mostly from the uncertainty in the calculation of the NIB pumping contribution.

It is possible that most of the residual inventory is concentrated in NIB 8 copper duct scrapers. The tritium lost by reionisation of the beam, was deeply implanted in the duct elements, being at much higher energy (78 KeV) than a tritium ion escaping from the plasma (typical energy ~ 100 eV). Moreover, the duct surface is not directly exposed to plasma. Another indirect confirmation of this hypothesis comes from the increased tritium release observed during high power ^{3}He injection, compared to D injection. Since the trajectory of $^3He^+$ ions in the duct are the same as for T ions, during ^{3}He injection the same spots of the duct hit by the reionised tritium are hit by high energy $^3He^+$, possibly causing desorption of the tritium. Finally, some indication that the tritium inventory in the near surface layer of in-vessel components is very low, comes from the very small tritium release observed during an air leak in the machine, in January 1992. Although the vacuum vessel was pressurised up to ~4 x 10^4 Pa of air, at 300°C of wall temperature, the total tritium released was only ~8 x 10^9 Bq, indicating that the total amount of tritium available for isotope exchange with the water vapour in the air was very low.

5.3 Total Tritium Account

The validity and reliability of the detailed tritium release measurements which provided all the 'on-line' information on the tritium recovery during the experiment can be checked by comparing the measured total tritium inventory on the GCS U-beds (paragraph 4.0) to the sum of the partial tritium recovery data, from both the Torus and the NIBs. The sum of all the tritium recovery figures gives a total of 4.05 x 10^{13}Bq (± 4.1 x 10^{12} Bq), differing from the measured tritium inventory on the GCS U-beds by +1.4%. The good agreement between the two results indicates that the instrumentation and the experimental procedure used during the FTE were suitable for tritium accounting purposes. The error in the detailed measurements due to the variation of the impurity content in the gas collected becomes very small, when the total tritium account is made. In fact, the large amounts of activity were collected from the regeneration of NIB 8 cryopanels, i.e. when the carrier gas was very pure. The impurity content is likely to have affected more significantly the counting of tritium in the gas coming from the torus, which however represents only ~5% of the total activity.

6.0 Conclusions

For the first time in fusion research, tritium was used at JET to fuel a plasma discharge and produce fusion thermal power. Tritium recovery procedures were devised and implemented, allowing detailed accounting of all the tritium releases from the tokamak systems.

The instrumentation and the experimental procedures used to measure on line the tritium usage and recovery during the FTE have been proven adequate.

The detailed accounting of the tritium release from the Torus and from the NIBs provided at the time of the experiment the necessary information on the efficiency of the recovery procedures and a reliable estimate of the variation in time of the tritium inventory in the JET systems involved.

Hardware and software tools were designed for the data acquisition, storage and handling. A large database on the tritium release data after plasma discharges and the technical information on the decontamination procedures of Neutral Beam Injectors are now available.

The comparison of the detailed tritium recovery data with the measured total inventory collected by the GCS U-beds shows that the two measurements are in very good agreement, their discrepancy being less than 2%.

The amount of tritium recovery in two months after the FTE equals the amount injected. This discrepancy between the total input and the total recovery is less than 10%. The estimated residual tritium inventory in the vacuum vessel is from 0 to 5.6×10^{11} Bq.

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Table 1: Composition of the gas feed into the neutral beam injectors, for the 1% experiment.

T_2 - total	0.97% ± 0.05 (volume %)
H_2 - total	0.44% ± 0.04 (volume %)
D_2 - total	98.47% ± 0.1 (volume %)
He_3	< 0.05% (detection limit)
Tritiated Methane	< 0.04% (detection limit)
N_2	< 0.01% (detection limit)
O_2	< 0.01% (detection limit)
Ar	< 0.01% (detection limit)
CO_2	< 0.01% (detection limit)
H_2O	None

Table 2: Composition in vol% of a gas sample from the U-bed used for the 100% experiment. The results of two analysis of gas from the same sample are reported.

Component	First Analysis	Second Analysis
H_2	0.132 ± 0.007	0.137 ± 0.007
HD	0.053 ± 0.006	0.058 ± 0.006
HT	7.77 ± 0.12	7.81 ± 0.12
D_2	0.005 ± 0.003	<0.015◊
DT	1.38 ± 0.03	1.38 ± 0.03
T_2	88.00 ± 0.25	87.92 ± 0.25
^3He	0.23 ± 0.10	0.264 ± 0.10
^4He	<0.005	<0.005
N_2	2.32 ± 0.04	2.30 ± 0.04
O_2	<0.002	<0.009
Ar	0.031 ± 0.005	0.031 ± 0.005
CO	<0.005	<0.005
CO_2	0.003 ± 0.002	<0.005
ΣCH_4	0.08 ± 0.02	0.085 ± 0.02
$H/\Sigma Q$	4.15 ± 0.07	4.18 ± 0.007
$D/\Sigma Q$	0.740 ± 0.016	<0.752
$T/\Sigma Q$	95.11 ± 0.07	95.07 ± 0.07

◊ Data affected by a relatively high D_2 background signal.
ΣQ=total of hydrogen isotopes

Table 3: Summary of the Tritium injected into the Neutral Beam Box, Torus and its distribution in NIB and Torus components -
3a: 1% experiment, 3b: 100% experiment.

The first line of the tables contains the total tritium consumption for the two experiments, the other lines detail how the tritium was distributed in the various machine components, including the vacuum vessel.

Table 3a:

$(9.25 \pm 1.85) \times 10^{11}$ Bq	Tritiated Gas Input to NIB (Total T Consumption)	
$(4.81 \pm 1.11) \times 10^{10}$ Bq	Injected into plasma	Torus Inventory
$(5.55 \pm 1.85) \times 10^{9}$ Bq	Implanted into duct scrapers	Torus Inventory
$(1.11 \pm 0.37) \times 10^{10}$ Bq	Implanted into box scrapers	NIB Inventory
$(4.44 \pm 1.11) \times 10^{10}$ Bq	Into ion dumps	NIB Inventory
$(8.15 \pm 2.23) \times 10^{11}$ Bq	Into cryopanels	NIB Inventory

Table 3b: (Includes Conditioning Pulses)

$(3.618 \pm 0.25) \times 10^{13}$ Bq	T_2 Gas Input to NIB (Total T Consumption)	
$(1.77 \pm 0.14) \times 10^{12}$ Bq	Injected into plasma	Torus Inventory
$(1.83 \pm 0.73) \times 10^{11}$ Bq	Implanted into duct scrapers	Torus Inventory
$(3.57 \pm 1.07) \times 10^{11}$ Bq	Implanted into box scrapers	NIB Inventory
$(2.08 \pm 0.17) \times 10^{12}$ Bq	To ion dumps	NIB Inventory
$(3.57 \pm 0.36) \times 10^{11}$ Bq	To calorimeter	NIB Inventory
$(3.143 \pm 0.30) \times 10^{13}$ Bq	To cryopanels	NIB Inventory

Table 4a: Measurements of the specific activity of the gas used for the calibration of IC2.

IC1 (Bq m^{-3})	Culham (Bq m^{-3})	CEA Valduc (Bq m^{-3})
$4.329 \times 10^{10} \pm 10\%$	$4.181 \times 10^{10} \pm 10\%$	$3.682 \times 10^{10} \pm 15\%$

Table 4b: Composition in vol% of the gas used for the calibration of IC2. Analysis carried out at CEA Valduc (France).

Component	Vol%
T_2 total	<0.01
H_2 total	2.16 ± 0.1
D_2 total	97.76 ± 0.2
ΣCQ_4	<0.04
N_2	<0.01
O_2	<0.01
Ar	<0.01

Table 5: Pumping speed of the two NIBs on the Torus. The values for DT gas are calculated from the measured speed in D_2.

NIB/GAS		Pumping Speed [m^3s^{-1}]	Estimated gap width [mm]
NIB 4	(D_2)	3.120 ± 0.693	3.8 ± 0.8
NIB 4	(DT)	2.791 ± 0.620	
NIB 8	(D_2)	2.075 ± 0.096	2.5 ± 0.1
NIB 8	(DT)	1.856 ± 0.086	

Table 6: Comparison between the total tritium usage in the FTE and the total tritium recovered at the GCS side.

Total Tritium Usage [Bq]	Tritium Collected On U-beds [Bq]	Consistency
$(3.711 \pm 0.268) \times 10^{13}$	$(3.99 \pm 0.4) \times 10^{13}$	within 7%

Table 7a: Tritium Recovered From NIB 8

Date	Activity [Bq]	Comments
06.11.91 (1% experiment)	1.479×10^{12}	Room temperature Estimated uncertainty ~20%
07.11.91 (1% experiment)	3.7×10^{10}	70K Large uncertainty, $\pm 1.8 \times 10^{10}$ Bq
08.11.91	2.32×10^{10}	70K both IC1 and IC2 data available - ~10% uncertainity
TOTAL OF 1% EXPERIMENT	1.549×10^{12}	Estimated Uncertainty: $\pm 3.6\ 10^{11}$ Bq
09.11.91 100% experiment	3.425×10^{13} 5.55×10^{11}	70K ~10% uncertainty
13.11.92	2.12×10^{12}	70K ~20% uncertainty
14.11.91	2.66×10^{11}	70K data from IC1
15.11.91	2.59×10^{10}	70K not stored on the U-beds
23.11.91	9.21×10^{10}	70K 10% uncertainty
01.12.91	4.99×10^{10}	70K 10% uncertainty
08.12.91	3.68×10^{10}	70K 10% uncertainty
TOTAL OF 100% EXPERIMENT	3.731×10^{13}	The estimated uncertainty is $\sim 3.73 \times 10^{12}$ Bq
GRAND TOTAL	$3.895 \times 10^{13} \pm 3.9 \times 10^{12}$	

Table 7b: Tritium Recovered From NIB 4

Date	Activity [Bq]	Comments
6.11.92 1% experiment	4.44×10^9	70K Probable large error
9.11.91 100% experiment	$\sim 3.7 \times 10^{10}$	70K Estimated from IC1 reading
11.11.91	1.109×10^{11}	70K
18.1.92	6.77×10^{10}	70K
23.11.91	1.41×10^{10}	Room temperature
01.12.91	8.14×10^9 1.18×10^9	70K to stack
TOTAL:	2.435×10^{11}	Overall uncertainty $\geq$20%

Table 8: Tritium Recovery after plasma pulses

DATE/PULSE INTERVAL	T COLLECTED AT GCS SIDE [Bq]	ESTIMATED TOTAL TRITIUM RELEASE [Bq]	TRITIUM TO NIB 4 (calculated) [Bq]
4.11.91 26094 - 26098	8.36×10^9	1.276×10^{10}	2.63×10^9
4.11.91 Overnight Outgassing*	4.87×10^9	4.87×10^9	-
5.11.91 26099 - 26107	8.67×10^9	1.169×10^{10}	1.81×10^9
5.11.91 26108 - 26118	1.58×10^9	2.44×10^9	5.2×10^8
TOTAL AFTER 1% EXPERIMENT	2.352×10^{10} $(\pm 3 \times 10^9)$	3.178×10^{10} $(\pm 5 \times 10^9)$	4.96×10^9
9.11.91 26147 - 26148	3.417×10^{11}	4.843×10^{11}	8.584×10^{11}
9 to 11.11.91 Natural Outgassing*	1.125×10^{11}	1.857×10^{11}	-
11.11.91 26149 - 26156	2.823×10^{11}	3.715×10^{11}	8.88×10^{10}
11.11.91 26157 - 26160	8.325×10^{10}	1.095×10^{11}	2.64×10^{10}
12.11.91 26161 - 26174	6.31×10^{10}	8.288×10^{10}	1.994×10^{10}
12.11.91 26175 - 26189	6.10×10^{10}	8.473×10^{10}	1.935×10^{10}
13.11.91 26190 - 26211	4.99×10^{10}	7.178×10^{10}	1.572×10^{10}

* Part of the gas coming from the Torus in the hours after the 100% tritium injection experiment was mixed up with gas coming from NIB 8. The estimated tritium release takes this quantity into account, whilst the collected amount (1st column of data) was actually measured at GCS side.

Table 8 contd.

DATE/PULSE INTERVAL	T COLLECTED AT GCS SIDE [Bq]	ESTIMATED TOTAL TRITIUM RELEASE [Bq]	TRITIUM TO NIB 4 [Bq]
14.11.91 26212 x 26233	9.26×10^{10}	1.421×10^{11}	3.045×10^{10}
14.11.91 26234 - 26243	2.18×10^{10}	3.33×10^{10}	6.92×10^{9}
15.11.91 26244 - 26258	1.961×10^{10}	2.582×10^{10}	6.22×10^{9}
16.11.91 26259 - 26271	1.11×10^{10}	1.461×10^{10}	3.51×10^{9}
18.11.91 26272 - 26285	9.21×10^{9}	9.21×10^{9}	-
19.11.91 26286 - 26296	1.161×10^{10}	1.161×10^{10}	-
19.11.91 26297 - 26309	1.221×10^{10}	1.865×10^{10}	3.85×10^{9}
20.11.91 26310 - 26324	1.44×10^{10}	2.105×10^{10}	4.55×10^{9}
20.11.91 26325 - 26333	8.88×10^{9}	1.214×10^{10}	1.40×10^{9}
21.11.91 26334 - 26362	2.016×10^{10}	3.082×10^{10}	6.40×10^{9}
TOTAL	1.218×10^{12} $(\pm 1.2 \times 10^{11})$	1.711×10^{12} $(\pm 2.7 \times 10^{11})$	3.00×10^{11}
GRAND TOTAL (including 1%)	1.241×10^{12} $(\pm 1.2 \times 10^{11})$	1.743×10^{12} $(\pm 2.8 \times 10^{11})$	3.049×10^{11}

Table 9: Measured Tritium release after D_2 soaking of the Torus. (in chronological order)

Duration (h)	Recovery [Bq]	Comments
2.5	8.51×10^9	IC2 data
1	5.92×10^9	IC2 data
4	3.33×10^9	IC2 data to stack
~5	$(2.59 - 3.7) \times 10^9$	IC2 data includes release after gas flush
TOTAL	2.15×10^{10}	

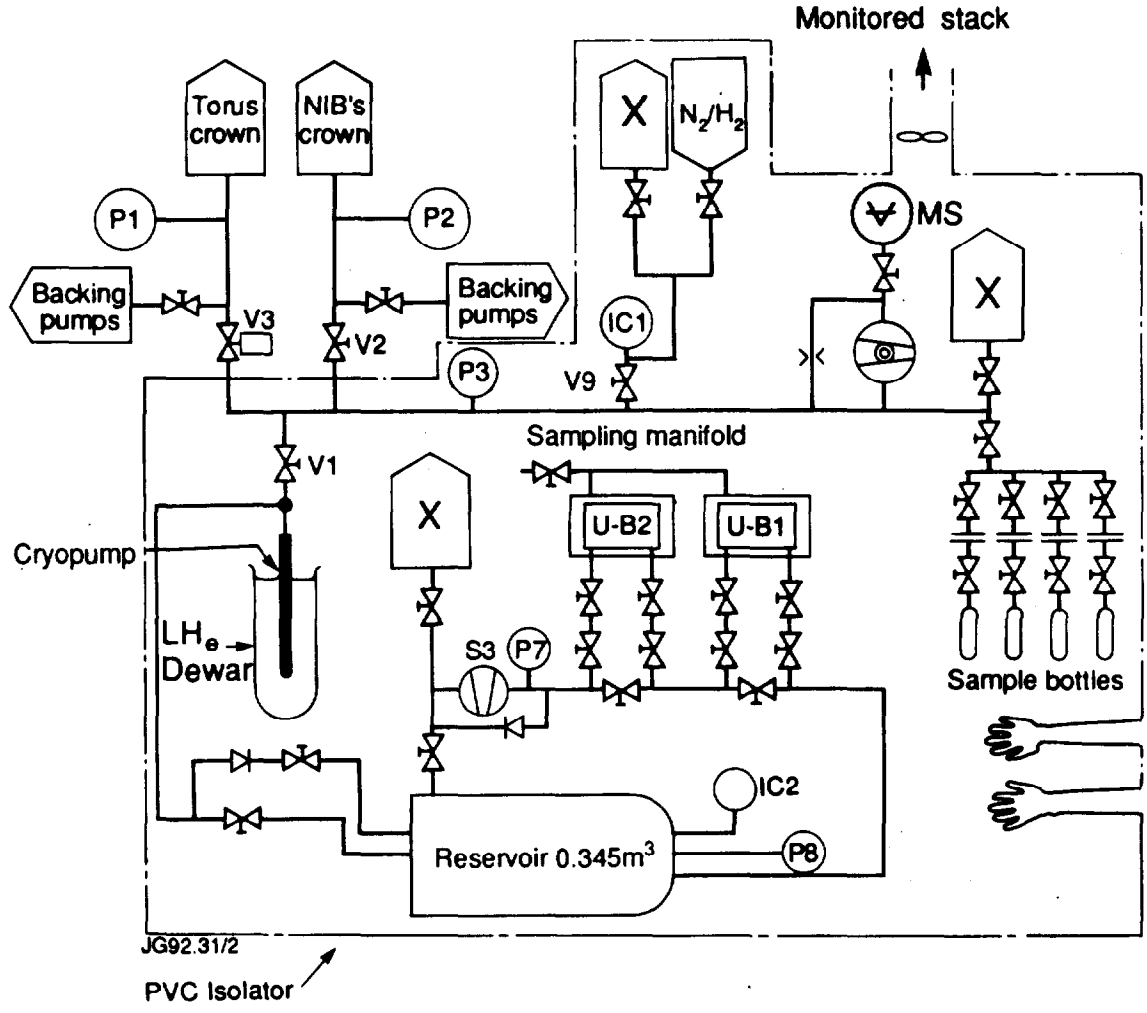

Figure 1: The Gas Collection System (GCS). The X indicates a connection to the stack.

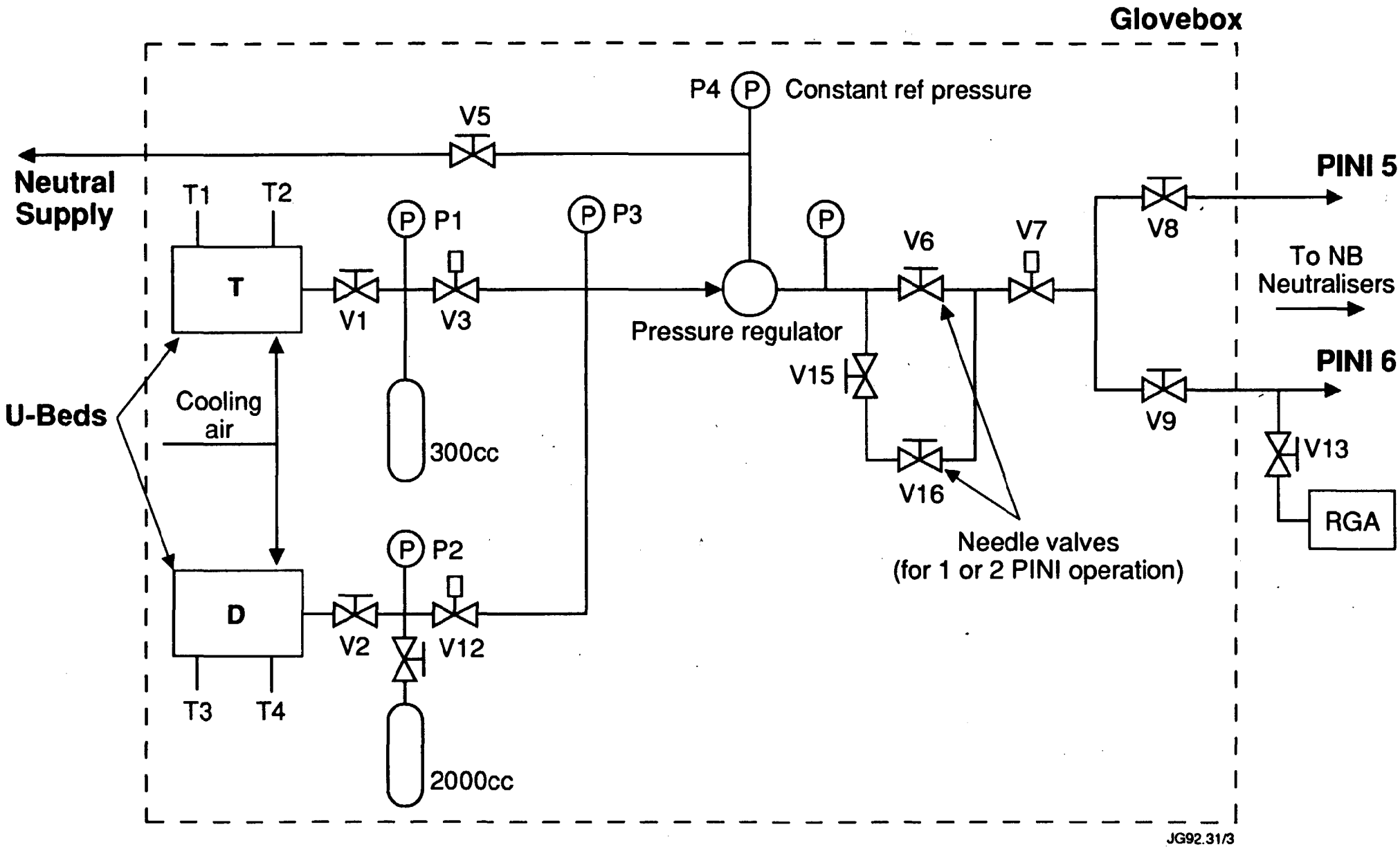

Figure 2: The Gas introduction system to PINIs 5 and 6 of NIB 8.

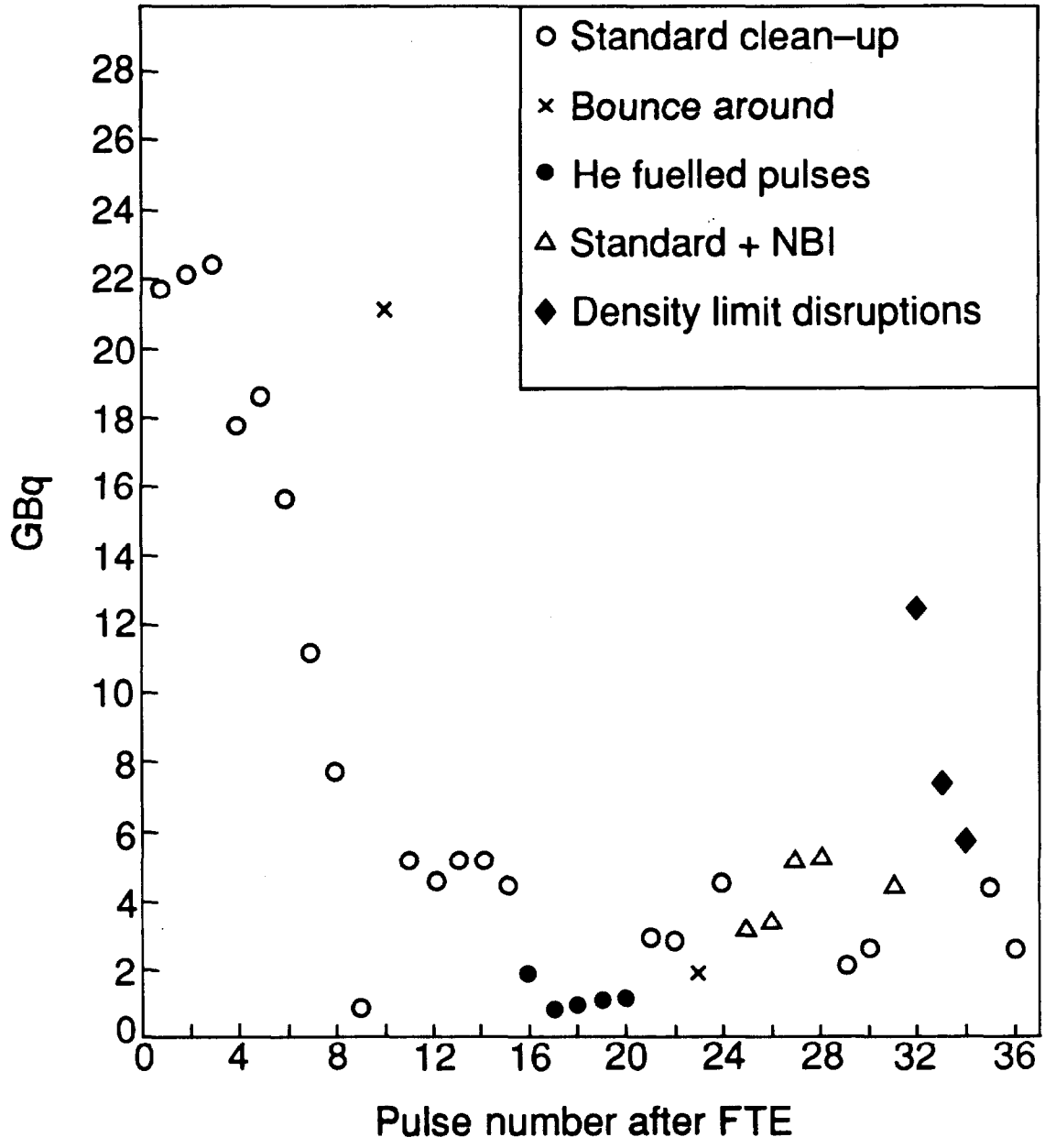

Figure 3: Tritium release after plasma pulses during the clean-up experiment. Each data point represents the integrated tritium release in 600s after the pulse.

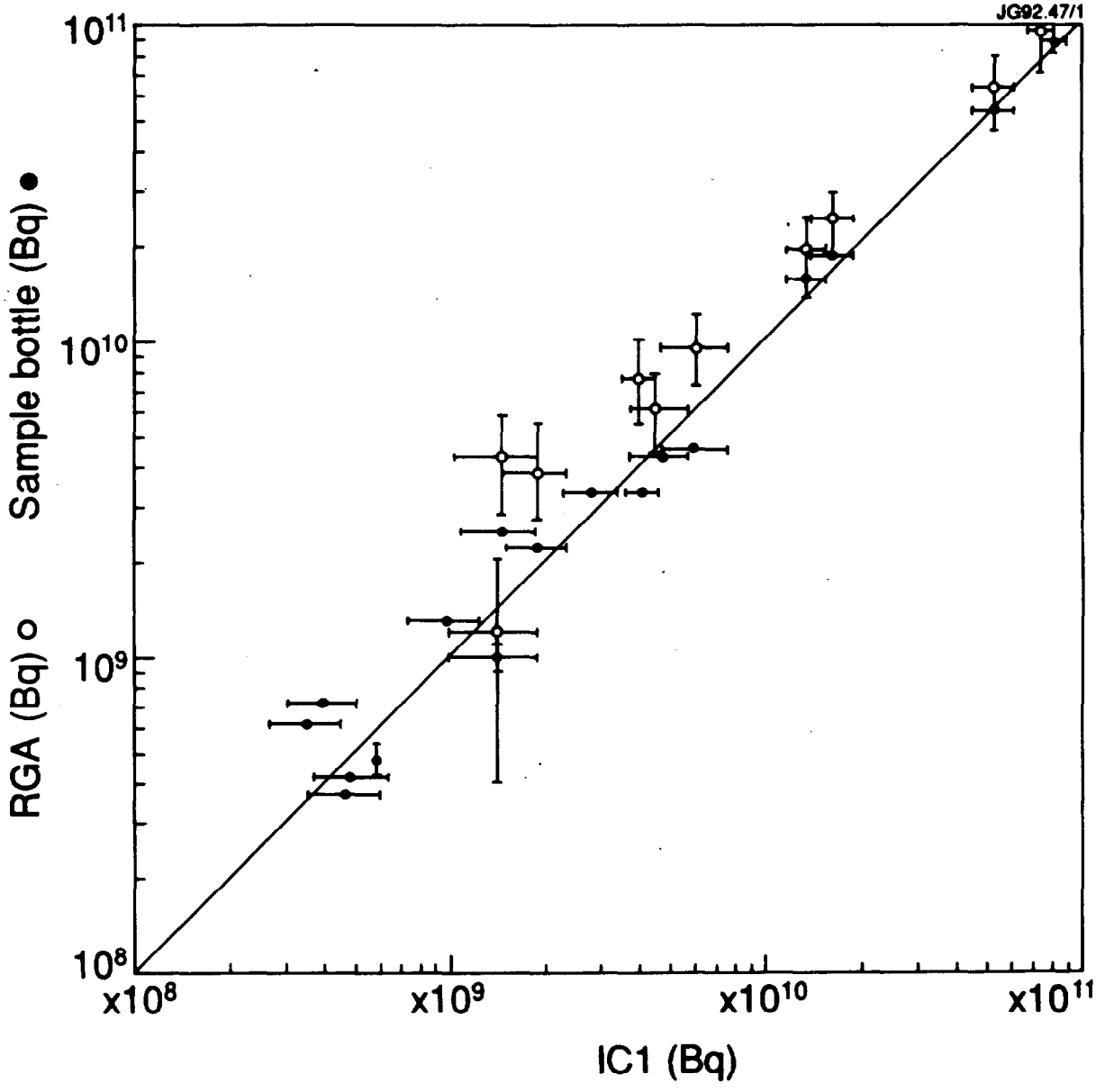

Figure 4: Comparison of the tritium recovery measurements after plasma pulses, as measured by IC1, RGA and scintillation counting of gas samples.

ANNEX

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