JET–P(92)07

M. Huguet, A.C. Bell, S.J. Booth, C. Caldwell-Nichols, A. Carmichael, P. Chuilon, N. Davies, K.J. Dietz, F. Delvart, F. Erhom, H. Falter, B.J. Green, B. Grieveson, R. Haange, A. Haigh, J.L. Hemmerich, D. Holland, J. How, T.T.C. Jones, R. Laesser, M. Laveyry, J. Lupo, A. Miller, P. Milverton, G. Newbert, J. Orchard, A. Peacock, R. Russ, G. Saibene, R. Sartori, L. Serio, R. Stagg, S.L. Svensson, E. Thompson, P. Trevalion, E. Usselmann, T. Winkel, M.E.P. Wykes and JET Team

Technical Aspects of the First JET Tritium Experiment

Technical Aspects of the First JET Tritium Experiment

M. Huguet, A.C. Bell, S.J. Booth, C. Caldwell-Nichols, A. Carmichael, P. Chuilon, N. Davies, K.J. Dietz, F. Delvart, F. Erhom, H. Falter, B.J. Green, B. Grieveson, R. Haange, A. Haigh, J.L. Hemmerich, D. Holland, J. How, T.T.C. Jones, R. Laesser, M. Laveyry, J. Lupo, A. Miller, P. Milverton, G. Newbert, J. Orchard, A. Peacock, R. Russ, G. Saibene, R. Sartori, L. Serio, R. Stagg, S.L. Svensson, E. Thompson, P. Trevalion, E. Usselmann, T. Winkel, M.E.P. Wykes and JET Team*

JET-Joint Undertaking, Culham Science Centre, OX14 3DB, Abingdon, UK

* *See Annex*

Preprint of Paper to be submitted for publication in
Fusion Engineering and Design

ABSTRACT.

The JET experimental programme has been extended from its former formal closing date, end of 1992, to the end of 1996. The extension allows the study of plasma operation with a pumped divertor installed in the vacuum vessel. As a consequence the final phase of JET, which involves the use of tritium to study D-T plasmas, will be delayed to 1996.

In order to gain timely information on the introduction of tritium into the tokamak, including retention of tritium in wall materials, operation of diagnostics, radiation monitoring and waste handling, it was decided in early 1991 to prepare for an experiment which would involve the use of a small quantity of tritium. It is also important to note that although tritium technology has become an important component of fusion development programmes worldwide, tritium has never been used so far in a tokamak or in any controlled fusion device.

TECHNICAL ASPECTS OF THE FIRST JET TRITIUM EXPERIMENT

M Huguet, A C Bell, S J Booth, C Caldwell-Nichols, A Carmichael, P Chuilon, N Davies, K J Dietz, F Delvart, F Erhorn, H Falter, B J Green, B Grieveson, R Haange, A Haigh, J L Hemmerich, D Holland, J How, T T C Jones, R Laesser, M Laveyry, J Lupo, A Miller, P Milverton, G Newbert, J Orchard, A Peacock, R Russ, G Saibene, R Sartori, L Serio, R Stagg, S L Svensson, E Thompson, P Trevalion, E Usselmann, T Winkel, M E P Wykes

JET Joint Undertaking, Abingdon, Oxon. OX14 3EA. United Kingdom

1 INTRODUCTION

The JET experimental programme has been extended from its former formal closing date, end of 1992, to the end of 1996. The extension allows the study of plasma operation with a pumped divertor installed in the vacuum vessel [1]. As a consequence the final phase of JET, which involves the use of tritium to study D-T plasmas, will be delayed to 1996.

In order to gain timely information on the introduction of tritium into the tokamak, including retention of tritium in wall materials, operation of diagnostics, radiation monitoring and waste handling, it was decided in early 1991 to prepare for an experiment which would involve the use of a small quantity of tritium. It is also important to note that although tritium technology has become an important component of fusion development programmes worldwide, tritium has never been used so far in a tokamak or in any controlled fusion device.

The experiment which would involve only a few plasma pulses. This would restrict the total amount of tritium used in the experiment such that the resulting activation of the vacuum vessel would not increase significantly above the level resulting from D-D operation during 1991 and early 1992. The impact of the first tritium experiment on the next major shutdown planned to start in February 1992 would therefore be minimised.

Preparations for the experiment included a physics programme to define the optimum plasma parameters, method of injection and diagnostics requirements, as well as a technical programme to design and install special equipment to inject tritium and recover tritiated exhaust gases. Safety aspects included the preparation of an overall probabilistic safety assessment and obtaining the requisite statutory and other approvals for the first tritium experiment. Further preparations included procurement of tritium, provision of a secure storage facility for tritium, training of staff, writing of emergency procedures, and the carrying out of emergency exercises as well as bringing the tokamak, its diagnostic equipment and auxiliary systems in a state of readiness for the first tritium experiment. Generally, only systems essential for the experiment were used. Pellet injectors and radio frequency systems and many diagnostics were not used and their vacuum systems communicating with the torus vacuum were isolated.

In parallel to the preparations for the experiment itself, a waste sorting facility was designed and manufactured and arrangements were made for the intermediate storage of tritiated components. The waste sorting facility will receive components and secondary waste loaded in transport containers from the JET tokamak during the next shutdown in which all internal vacuum vessel components will be removed to allow the installation of the components of the pumped divertor.

2 OBJECTIVES

The main motive for carrying out the first tritium experiment is to gain important technical and physics information essential for the full D-T phase of JET. The principal objectives can be summarised as follows:

(i) To establish a firm basis for prediction of the performance of future JET D-T pulses, including the question of fuel mixing.

(ii) To carry out accounting on tritium utilisation, including the assessment of tritium holdup in various components, especially in-vessel components and to assess the implication of tritium retention for future modifications, installation, repair work and waste handling.

(iii) To demonstrate the production of 1MW of fusion power for approximately 1 second.

3 PREPARATIONS FOR FIRST TRITIUM EXPERIMENT

After an initial scoping study for the feasibility to carry out a limited D-T experiment, two task force groups were formed to prepare for the experiment. One task force was charged with studying the physics issues, including definition of optimum plasma parameters to be used, prediction of expected performances, as well as the selection of the actual tritium injection scenario. The Physics Task Force's other duties included definition of the diagnostic systems to be used, as well as their testing and evaluation. A Technical Task Force was charged with the procurement of tritium, its safe and secure storage on the JET site, the design, testing and installation of tritium injection systems, as well as an exhaust gas collection system. Further activities included the preparation of the safety analysis report, establishment of interfaces with the UK Authorities to obtain statutory and other approvals to allow the experiment to be conducted, the installation of radiological protection instrumentation and preparation of waste management facilities and procedures to deal effectively with the aftermath of the experiment.

The Technical Task Force was also responsible for the training of staff, not only concerning the operation of special equipment, but also concerning the general handling of tritium. The latter involved a large number of JET staff. Other tasks included the preparation of a measurement programme to assess the tritium retention in the wall materials, during and after the experiment [2] and the preparation of a site emergency plan as well as the installation of an emergency control desk in the JET Control Room.

3.1 Physics Issues and Experimental Plans

Extrapolation of the best results obtained in D-D discharges during earlier experimental campaigns in JET to D-T pulses predicted that fuelling with 14% gas mixtures (1 part tritium to 6 parts deuterium) would yield a total fusion power of 0.9 to 2.4 MW depending on which prediction model is used (provided that the wall recycled material would be of similar isotopic composition). This tritium concentration in the plasma was used as the basis for the first tritium experiment [3]. Two methods of tritium fuelling of the plasma were considered, namely gas puffing and neutral beam injection. Both methods required enhancement of existing hardware. Eventually, gas puffing was kept only as a fall-back solution and tritium introduction, using two neutral beamline sources (PINIs) and neutralisers allowing more defined deeper fuelling into the plasma, was developed for one of the two JET neutral injectors [4].

The experiment was split into two phases. The initial calibration phase would use a very weak tritium-deuterium mixture (1% tritium in deuterium) for the 'tritium' PINIs and would include checking of diagnostics, especially neutron diagnostics. This phase would involve some 10 to 15 tokamak discharges. The second phase, the experiment proper, would use pure tritium for the two 'tritium' PINIs and would involve no more than 2 or 3 useful tokamak discharges.

One of the main constraints on the experiment was to keep the activation resulting from D-T neutrons at a low enough level for a prolonged period of work inside the vacuum vessel during the shutdown planned to start in February 1992. The total production of D-T neutrons was therefore restricted to $1\text{-}2.10^{18}$ resulting in an in-vessel dose rate of 25-50 μSv/hour some twelve weeks after the experiment. This dose rate is lower or comparable to that expected from D-D neutron activation ($\simeq$ 50 μSv/hour) during the 1991-1992 experimental campaign.

For this reason the total amount of tritium to be used was limited to 74 TBq (2,000 curies) which was sufficient for approximately 6 injection pulses of 2 second duration with 2 beams. Two or three of these pulses would be used for injection into the plasma, the others would be used as commissioning pulses of the tritium beams which would not involve injection of tritium into the torus.

3.2 Description of Special Equipment

For the full D-T phase of JET an exhaust gas processing system, the JET Active Gas Handling System (AGHS) will be available to remove impurities from the hydrogen isotopes, to separate purified hydrogen into isotopic fractions and to re-supply the isotopic fractions to the tokamak subsystems [5]. The installation of the AGHS is not yet complete and therefore for the first tritium experiment special equipment had to be installed. This not only involved a gas collection system, but also modifications to the neutral injectors for tritium introduction.

3.2.1 Tritium Injection

Two PINIs of one JET neutral injector were modified for tritium service in the experiment. The eight PINIs of the second neutral injector were left unmodified for deuterium injection For the "tritium PINIs" the gas was supplied from two uranium beds (U-beds), one loaded with deuterium (for commissioning) and the other with tritium (for fuelling) mounted close to the PINIs outside the beamline magnetic shielding. The modifications to these PINIs did not involve the vacuum boundary but were concerned with the internal flow distribution so as to allow tritium introduction at ground potential. A more detailed description is given in [4]. The remaining PINIs of the Octant 8 beamline were used for deuterium injection, both with and without concurrent tritium injection. The gas for the six deuterium PINIs was supplied from the neutral beam gas handling system which is the existing arrangement.

The gas supply arrangements for the 2 tritium PINIs are shown schematically in Figure 1. The U-beds are the Mark 4 Amersham-type, all valves are as used for tritium service in the JET AGHS with the exception of a few valves which are JET standard isolation valves. The pressure regulator is of the diaphragm-type specially designed for use in the AGHS [6]. The reference pressure is set by the admission of a fixed quantity of deuterium from the existing neutraliser gas supply. An absolute manometer (Transamerica, type BHL-4221-00-43) was used to measure the quantity of gas admitted to the PINIs.

All tritium primary containments and associated instrumentation were installed within a proprietary glass re-inforced plastic glove box (Marine and Industrial Plastics, UK, Mark 21). The glove box was connected by temporary ducting to an authorised discharge stack (authorised by Her Majesty's Inspectorate of Pollution, see Section 3.7) equipped with ionisation chamber and sampling system to monitor tritium releases [7]. Ventilation was induced by a fan in a temporary ducting to maintain the enclosure at a slight underpressure with respect to the Torus Hall atmosphere. The glove box was provided with glove ports to allow operator manipulations and feedthroughs for service cables. The U-beds were installed in the glove box and the associated pipework, valving and instrumentation were leak tested just before the start of the experiment.

3.2.2 *Description of the Gas Collection System*

The operational functions of the Gas Collection System (GCS) can be defined as follows:

(i) To act as a temporary tritium-compatible primary pumping system, in place of the Roots blowers and rotary pumps, for the limited duration of the first tritium experiment.

(ii) To constitute a measuring unit to account for tritium exhausted from the torus and the two neutral beam injectors.

(iii) To separate hydrogen isotopes from the residual exhaust gases and safely store those isotopes by circulation through and hydriding of ambient temperature uranium beds.

(iv) To store tritiated residual gases (such as methane) for future reprocessing in the JET AGHS system or, following measurement, discharging to stack if activity levels allow.

(v) To detect, safely handle and facilitate recovery from air inleakages into the torus, neutral injector, vacuum transfer lines or the GCS itself particularly with respect to the creation of hydrogen/air mixtures within the flammable range.

(vi) To assist the recovery from a water leak incident by providing a means of pumping and collecting water vapour from the torus or neutral injectors.

As shown in Figure 2 and described in detail in [8], the GCS is connectable to the torus pumping duct or to the neutral injector pumping ducts (torus crown or NIB crown). The valves connecting the ducts with their respective backing pumps were closed and blocked during the experiment until the amount of tritium released via this route was considered insignificant and could not readily be collected on the U-beds. The tubular cryopump (Cold Finger) which replaced the backing pumps is constructed of a stainless steel flexible hose which contains at its lower end circa 100 grams of activated charcoal (Goodfellow, type C 003550) and is immersable in a 250ℓ liquid helium dewar. At the operating temperature of 4.2K all condensable gases including protium, deuterium and tritium are pumped by cryocondensation in the upper part of the cryopump. The charcoal pumps helium by cryosorption. By warming up of the Cold Finger the gases can be collected in a 345ℓ reservoir. A scroll pump (Normetex) allows circulation of gases through the U-beds for hydrogen isotope extraction. This pump is equipped with a non-return valve in a bypass line to protect against excessive discharge pressures. The U-beds (UB1 and UB2) are of JET design [8] and each contains 4.3 kg depleted uranium. They have electrical bed heaters installed. In the event of bed deactivation due to accidental air inleakages, the U-beds can be reactivated by heating. All equipment required for re-activation was installed to the U-bed but with no external connections made.

The 345ℓ reservoir is instrumented with an ionisation gauge designed by JET (IC2) and two pressure gauges (P7 and P8). As shown in Figure 2, on the torus/neutral injector side of the interface valve V1 are facilities for gas sampling and composition and activity monitoring. Composition monitoring (principally to detect air inleakage) is done by a mass spectrometer (MS). Activity measurements are by the JET designed ionisation chamber (IC1) which allows the addition of nitrogen or protium to raise the gas pressure within the chamber to that corresponding to a calibration condition. This branch of the GCS also has a pressure gauge (P3) for real time measurement of the quantity of exhaust gas in the vacuum duct and a manual valve (V4) for connecting the branch to a molecular sieve drier to facilitate recovery in the event of air or water inleakages in the torus or neutral injectors.

In the event of an accidental torus air inleakage in the range that has historically occurred during JET operations, the torus would take days to vent to near atmospheric pressure. The humidity of the inleaked air and high temperature environment within the torus vacuum vessel would result in most of the tritium being in the oxide form in the latter stages of venting thereby offering the possibility of removal from the exhaust stream by molecular sieving. To mitigate such an accident the molecular sieve drier was installed as shown in Figure 2. The drier consists of two parallel banks each comprising two zeolite granule (CECA, France, type Siliporite NK 20) filled 210ℓ drums with interconnecting pipework and valves. The torus exhaust (inleaked air and tritium) is drawn through the drums by an industrial vacuum cleaner with water breakthrough detection by a hygrometer. The discharge is subsequently routed directly to the monitored stack. Based on supplier's data, the maximum water capacity of each granule filled drum at humidity breakthrough is circa 25ℓ. One row of molecular sieve drums includes a catalytic convertor which may be heated to 500°C allowing conversion of hydrogen isotopes and methane to water vapour which is subsequently absorbed in a molecular sieve drum.

The components of the GCS containing tritium during normal operation are enveloped within PVC isolators. The isolator is provided with glove ports to allow the operators to manipulate the appropriate valves. The isolators are ventilated by a fan and connected by leaktight temporary ducting to the monitored discharge stack.

3.3 Supply and Storage of Tritium

Five Amersham mark 4 type U-beds filled each with 320 grams of uranium were activated at JET. These beds can store up to 18.7 bar ℓ or 2 PBq (54,000 Ci) of tritium as uranium tritide and therefore measurements were carried out to define discharge characteristics of these beds with the very small quantities of gas used for the first tritium experiment. These experiments confirmed that more than

74 TBq (2000 Ci) can be recovered from a U-bed loaded with 88.8 TBq of tritium (2400 Ci, simulated with deuterium).

Tritium was loaded on the U-beds at the premises of a commercial supplier of tritium in the UK. In case of the 1% tritium mixture the bed was pre-loaded at JET with deuterium and 1.85 TBq of tritium with a certified purity of 99.4% was added at the tritium supplier. During loading a small sample of the tritium was taken and analysed at the AEA Harwell Laboratory (UK). The analysis resulted in a much lower than certified tritium purity, ie approximately 94% tritium (in the form of T_2, HT, DT), the main impurity being approximately 5.1% protium (in the form of H_2 and HT). However, the mass spectrogram indicated background impurities and protium could therefore be largely the result of impurities in the mass spectrometer. In order to resolve this discrepancy, a sample was taken of the 1% tritium mixture before removing the U-bed from the neutral injector glove box. This sample was analysed using a mass spectrometer at the CEA Valduc Laboratory (France). The 1% tritium mixture yielded total contents of tritium, deuterium and protium of 0.97% (±0.05), 98.47% (±0.1) and 0.44% (± 0.04) respectively. The relative amount of protium is higher than in the Harwell analysis and could have been introduced as an inherent impurity of deuterium, which according to the suppliers' brochure may contain up to 0.6% protium.

For the second phase of the first tritium experiment an empty U-bed was charged at the supplier of tritium (from the same source as used for the 1% T in D mixture) with 88.8 TBq (2400 Ci) tritium. After the experiment, the unused tritium was returned to the supplier. A sample was taken from the U-bed and analysed at the CEA Bruyere le

Chatel Laboratories (France). The result confirms the relatively high protium content already detected previously (T/D/H = 95.11% / 0.74% / 4.15%).

The Amersham U-beds were stored on the JET site inside a safe storage facility.

Existing control access arrangements to the JET Torus Hall were used to safeguard the U-beds whilst mounted near the neutral injector. The GCS area was made into an access controlled area using a computer controlled turnstile system. The area was monitored by television cameras with pictures relayed to and recorded in the JET Control Room. For the duration of the tritium experiments and for the week thereafter, access was further controlled by a permanently manned entrance post. Maintenance work in nearby areas was controlled and restricted to an absolute minimum. Transfer of U-beds on JET Site is controlled by formal procedures which involve Health Physics inspections.

3.4 Safety Analysis Report

A detailed probabalistic safety analysis report was prepared to appraise the radiological risks, principally those resulting from the introduction of tritium into the torus and subsequent collection in the first tritium experiment. Due to the fact that failure rate data on components used in the plasma environment are very limited, failure rates based on JET operating experience since 1983 were widely used in the report thereby taking account of factors intrinsic to JET design and operation. The safety analysis demonstrated that for all foreseeable worst cases of each category of accident, the estimated risks (based on conservative assumptions as to occurrence probability and release consequences) adequately satisfied the AEA standards for public and worker risk.

3.5 Radiological Protection Instrumentation (RPI)

3.5.1 Glove Box Monitoring

The glove box for the neutral injector gas introduction and the isolators for the GCS were monitored for tritium leakage by connecting standard portable RPI type instruments with their own sampling pump into the exhaust ducting. The exhaust duct for the injection system joins the other ducts in the GCS. The gas sampling points to the ducts were made outside the JET biological shield thus avoiding the need for shielding of the instrument.

3.5.2 Working Area Monitoring

Gamma and neutron monitoring instruments were installed at fixed locations early in the JET programme in the areas around the Torus Hall to which personnel have access. They are fully commissioned and operational. In addition, there are high level gamma and neutron monitors in the Torus Hall and two medium level instruments. One medium level instrument has remote electronics which is used to monitor radiation levels prior to personnel entering the Torus Hall. Tritium area monitors designed for the full D-T phase were installed and commissioned prior to the first tritium experiment. The levels of radiation of all working area instruments are displayed on the

JET computer data acquisition system (CODAS) and they also alarm locally. Their sensitivity is more than adequate to ensure that exposure of individuals is kept well below specified JET limits. A number of portable instruments and sampling units was made available for health physics surveys.

3.5.3 *Stack Monitoring*

Releases to the environment are measured by monitoring the Torus Hall and Basement air conditioning stacks for tritium, radioactive gas and radioactive particulate. Monitors were installed prior to the first tritium experiment. The Torus Hall exhaust was routed via the air conditioning stack for the experiment [7]. The discharge stack for the glove box, isolators and backing pump exhaust ducts was instrumented with an ionisation chamber as well as a sampling system consisting of silica gel columns and a low temperature catalyst for conversion of hydrogen isotopes to water. Stack samples were scheduled to be analysed weekly.

3.5.4 *Environmental Monitoring*

A programme of air, rain water, ground water and river sampling has been in operation for a number of years. Tritium environmental monitoring equipment has been installed at several points within the Culham Laboratory Site boundary since mid 1990. This has enabled a level and variability of the background of tritium in the atmosphere around the JET buildings to be assessed. In addition passive tritium, gamma and neutron monitoring devices have been installed around the site boundary for assessment of accidental doses. Crop sampling within the Culham Site was in operation before the experiment. The above programme will enable the JET Project to clearly demonstrate that no significant environmental effect has resulted from the first tritium experiment.

3.6 Training of Staff

JET Staff members were trained in the operation of the tritium injection systems as well as the GCS. The latter involved 24 hour operation, ie three shift schedule. A large number of JET staff peripherally involved with the first tritium experiment attended training sessions on the general handling of tritium and in particular on the handling of tritium during the first tritium experiment. This included the detailed response to incidents which might occur.

3.7 Authorisations

The safety analysis report was reviewed by the Safety and Reliability Directorate (SRD) of the UK Atomic Energy Authority (AEA) and endorsed by the JET Fusion Safety Committee in which SRD is represented. This formed the basis for the decision by the AEA to allow the experiment to proceed. The decision to carry out the experiment was taken by the JET Council.

All radioactive discharges and waste disposals must be made in accordance with an authorisation granted by Her Majesty's Inspectorate of Pollution (HMIP) and must be recorded. In good time before the experiment, JET lodged an application with HMIP for authorisations required for the full D-T Phase of JET. These were granted before the first tritium experiment. The aerial and aqueous discharge limits are given in [8]. Furthermore, HMIP issued a Certificate of Registration to JET for holding up to 33 PBq (900 000 Ci) tritium on site.

In addition there is the overriding principle that Best Practical Means (BPM) must be used to limit discharges, even though they are within the authorised limit. Details are given in [9].

3.8 Emergency Plans

An emergency plan for the full D-T Phase had already been produced well ahead of the first tritium experiment and emergency instructions were specifically written for the experiment and endorsed by the JET Fusion Safety Committee. The JET Control Room was modified to include a separate Incident Desk and other modifications were made to enable the JET Control Room to function as an Emergency Control Centre. Site warning alarms and additional instrumentation such as wind monitoring equipment were installed. Two emergency exercises were held to test the response of the JET incident response team and the interaction between the various staff groups involved in an emergency.

3.9 Information to the Public

Two months before the tritium experiment, details were given to local organisations including the County Council, District and Parish Councils. Information was also given to local farmers to explain the use of tritium and seek their approval for crop and milk sampling for environmental monitoring analysis.

3.10 Waste Handling

3.10.1 Vessel Components

A survey of the waste expected to arise during the 1992/1993 shutdown has been carried out. Predictions made for the induced activity in components to be removed from the vacuum vessel during the 1992/1993 shutdown together with the additional predicted activity due to tritium (after a 3 month clean-up phase) show typical levels for first wall components in excess of the conditions for acceptance as Low Level Waste (LLW) for the Drigg waste repository in the UK. The waste components will therefore have to be classified as Medium Level Waste (MLW) unless the tritium levels can be reduced. JET aims to develop suitable decontamination techniques to reduce the levels to below the upper threshold for LLW at Drigg (12 kBq per gram). This may include baking and surface treatment of components. To gain knowledge on the distribution of tritium hold-up inside the vacuum vessel, graphite tiles will be removed from various poloidal and toroidal positions and measured for tritium.

During the 1992/93 shutdown all internal components will be removed from the JET vacuum vessel. Transport of the materials from the Torus Hall will be in sealed, standardized (ISO) freight containers to a waste sorting facility which is being constructed and will be commissioned before the start of the shutdown. Radwaste monitoring and determination of tritium levels of components will be carried out in this waste sorting facility as well as packing in waste containers. Many components will not be classified as waste but will require temporary storage until they are either re-used or declared waste. A number of freight containers will be prepared for interim storage of contaminated and activated components. Tritium levels will be monitored by connecting the containers to a central suction header which exhausts through a stack comprising on-line and integrating samplers.

3.10.2 Tritiated Water

A water leak incident in the neutral injector during the tritium experiment could have conceivably resulted in a few cubic metres of tritiated water. To facilitate recovery from such an incident the injector box has been fitted with a drain valve and suitable storage drums, together with a local filling facility all of which has been designed and procured prior to the experiment. Drying out of the neutral injector box would be done by nitrogen gas purge which can be exhausted through the molecular sieve drums in the GCS.

4 IMPLEMENTATION OF THE FIRST TRITIUM EXPERIMENT

Installation, commissioning and operation of the additional equipment was done according to procedures established and approved within the JET Project. During the experiment, daily meetings were held between the two task forces where all aspects of the experiment were discussed and the programme for the next day decided. Any changes of procedures that became necessary were fully discussed and decisions recorded. In one instance the changes required operation not covered by the existing Safety Analysis Report. In this case the modifications were rigorously safety assessed and the analysis was submitted to SRD for review.

4.1 Plasma Discharges with 1% T in D

During this phase of the experiment, the two tritium PINIs were fed with a mixture of 1% tritium deuterium. The other fourteen PINIs were fed with deuterium.

This phase of the experiment was carried out over a two day period. In total 9 plasma discharges with tritium injection were carried out with a total tritium usage of 0.925 TBq (25 Ci) of which 0.048 TBq and 0.877 TBq are estimated to have been injected into the plasma and retained in the neutral injector box respectively. The amount of gas pumped by the Cold Finger was measured by expanding it into the 345ℓ reservoir and its tritium content was measured with the ionisation chamber installed therein before absorption onto a U-bed.

After the two day experiment, the neutral injector was regenerated. The adopted procedure for this required many small batches to be taken onto the Cold Finger. The regenerated gas in the neutral injector was therefore transferred much more slowly than for routine regenerations. This resulted in a cooldown of the neutral injector box which may have been the cause of an air inleakage occurring during the processing of the last few batches. Several countermeasures to avoid re-occurrence of such a leak were taken including a change of procedure enabling much larger batches of gas to be taken from the neutral injectors. A further regeneration was carried out prior to the 100% tritium injection experiment to prove these countermeasures. Inleakage did not reoccur and has not been detected since.

From the recovered quantities of tritium it may be deduced that within the errors of measurement all or nearly all tritium that had been utilised was recovered.

During transfer of the 1% T in D mixture from the U-bed to a 2ℓ volume in the glove box, the hot U-bed walls permeated some tritium which, when extrapolated to the 100% tritium experiment, would indicate that this could constitute a substantial fraction of JET's own imposed daily discharge limit of 12 GBq. Following the 1% T in D experiment, two days were used to prepare for the 100% T in D experiment.

4.2 Plasma Discharges with 100% T

During this phase of the experiment, the two 'tritium PINIs' were fed with pure tritium, while the remaining fourteen PINIs were fed with deuterium.

The total amount of tritium used during the 100% T experiment has been measured and calculated to be 36.15 TBq (977 Ci). It should be noted that during injection the U-bed was open to a small pre-filled buffer volume and it is therefore difficult to calculate accurately the amount of gas transferred from the U-bed during the pulse [4].

After two conditioning pulses were run for the two 'tritium' PINIs, two plasma discharges with two PINIs injecting tritium (and 14 PINIs injecting deuterium) were carried out. Both discharges achieved a peak D-T fusion power of approximately 1.7 MW. Physics results compare very well with predictions and are detailed in [3].

Of the total amount of tritium used, 1.9 TBq has been estimated to have been injected into the plasma, 34.8 TBq remaining in the neutral injector box, and approximately 0.17 TBq implanted in components in the interconnecting duct between the neutral injector and torus. Following the two successful plasma discharges, some 40 minutes time was allowed for the torus to de-gas and the Cold Finger was warmed up approximately $1^1/_2$ hours after the second plasma pulse. The collected amount of tritium was measured prior to absorbing onto the U-beds. The total recovered tritium was found to be 0.26 TBq, ie approximately 13.5% of the injected amount. The cryopump of the tritium neutral injector was regenerated (warmed up to LN_2 temperature) a few hours after the second tritium plasma discharge and 36.5 TBq of tritium were recovered. The cryopump of the 'non-tritium' neutral injector was also regenerated and 14.8 GBq of tritium were recovered. This small amount was higher than expected as the result of pumping by the neutral injector cryopumps from the vacuum vessel. The pumping speed is minimised by fast shutters which limit the conductance of the interconnecting duct to nominally 100 ℓ/s.

On the day that the injection took place, the tritium supply U-bed was heated and remained hot during the PINI conditioning pulses and the tritium plasma discharges. This gave rise to permeation of 16 GBq of tritium through the hot wall of the U-bed exceeding the JET imposed daily discharge limit (10 GBq).

4.3 Clean-up Phase

Approximately one day of effort was required to bring back neutron diagnostics in a configuration suitable for deuterium operation. Other diagnostics and systems that had been isolated prior to the tritium experiment were individually assessed for risk of tritium contamination during the clean-up phase and re-connected progressively.

At the start of the clean-up phase some 1.6 TBq of tritium was estimated to be left in the torus, whereas all the tritium injected into the neutral injector had already been accounted for within the accuracy of measurement. The subsequent tritium neutral injector regenerations delivered 1.85 TBq and 0.26 TBq, whereas the tritium recovery from the tokamak rapidly dropped from some 16.6 GBq per discharge during the first operational day after the injection experiment, to 0.93 GBq per discharge during the eighth operational day after the injection experiment. Several techniques, ie glow discharge cleaning, gas purging, etc, were tried out [2]. However, the rate of evolution kept falling and allowed the torus to be reconnected to its normal backing pumps, exhausting directly into the monitored discharge stack three weeks after the start of the clean-up phase.

During the clean-up phase, two facts emerged that generated doubt as to the low conductance of the fast shutters which limit the conductance between torus and neutral injectors. Firstly some hydrocarbons were found in the neutral injectors and secondly subsequent regeneration of the 'non-tritium' neutral injector continued to show levels of tritium very much higher than would be consistent with the conductance of 100ℓ/s. Therefore, the fast shutter conductances of the 'tritium' and 'non-tritium' injectors were measured again and showed levels similar to the conductance between the torus and the main turbomolecular pumps, ie approximately 2000 and 3000ℓ/s respectively. This much higher than expected conductance explains the activity found in the 'non-tritium' injector and the hydrocarbon content found during neutral injector regeneration. The accounting of the torus inventory can only be finalised when samples from vessel wall materials are removed at the start of the next shutdown and analysed for tritium.

After a few regenerations, the amount of tritium recovered from the 'non-tritium' injector fell to below 3 GBq per regeneration and as the storage capacity of the U-beds was limited, the regenerated gas was routed directly to the monitored stack. Whilst the amount of tritium recovered from the tritium injector decreased sharply after the first few regenerations, it then declined much more slowly. The amounts recovered remained of the order of 0.1 TBq which was considered too high to stack directly when applying BPM considerations. However, one month after the start of the clean-up phase, the storage capacity of the two U-beds had been exhausted. The introduction of two additional U-beds was therefore considered in detail. A safety assessment for the installation of new U-beds and transfer of the hydrogen isotopes to them from the existing U-beds was prepared and submitted for review to SRD. After endorsement of the safety assessment by SRD, the two new U-beds were activated (using protium) and then installed. The connection to the pipework of the existing system was made by removing a redundant pressure gauge whilst a small air inleak was established and maintained via a Cajon coupling into the GCS, thereby avoiding the release of tritium into the isolator atmosphere. During and after installation, no tritium contamination was detected inside the isolator, either by ionisation chambers monitoring the atmosphere or on smear probes of internal surfaces.

During the transfer of gas between the U-beds, the amount of gas transferred was measured accurately using the 345ℓ reservoir with its pressure gauge and ionisation chamber. Transfer of gas occurred by direct absorption of gas from the reservoir by the new U-beds without having the facility to circulate gas through the U-beds by means of the scroll pump. Whilst the initial takeup of gas was very rapid, it showed that when the pressure decreases the absorption process slows down considerably without the use of the circulation pumps. This feature may lead to reconsideration of the U-bed designs in the AGHS where the intermediate storage system at present does not include circulation pumps. During gas transfer, cross calibrations were made between the ionisation chamber installed in the main manifold of the GCS (IC-1) and the ionisation chamber installed in the 345ℓ reservoir (IC 2)in order to improve the calibration accuracy. Details are given in [8]. The total amount of tritium transferred to the newly installed U-beds was measured to be 39.9 TBq (1078 Ci). This is some 7% more than the accumulated measurements made during the gas collection of the exhaust gases from torus and neutral injector systems. Due to the better controlled conditions during transfer between U-beds and the additional benefit of improved calibration of the ionisation chamber, the higher value is assumed to be more accurate.

The assumed accuracy of the amount of tritium used is ±7% and the assumed accuracy of the measurement of the transferred amount of tritium is ±10%. This means that a maximum possible positive difference of 37.87 TBq (102 Ci) exists between used and recovered amount of tritium at the time when the transfer between the U-beds took place and therefore this is considered the upper limit of the amount of tritium still inside the system at that time.

Following the transfer of gas to the new U-beds, two further regenerations of the 'tritium' injector yielded activities in excess of 1 Ci (27 GBq) each time. The recovered gas was therefore loaded on the U-beds. Over the 1991/92 Christmas and New Year period the cryopanels (liquid helium and liquid nitrogen) of the 'tritium' injector were warmed up to room temperature and a small bleed of nitrogen gas was established into the injector box which was pumped by its mechanical backing pump into the monitored discharge stack after opening the valves connecting with the pumping duct, maintaining a pressure of approximately 1 mbar inside the injector box. The overall discharge was approximately 30 GBq during this period starting off with a daily discharge of 9 GBq and finishing with 2 GBq. This was considered the appropriate procedure for starting decontamination of injector internal components in preparation for maintenance work during the 1992/93 shutdown period.

When operations resume early in 1992, it is expected that after a few regenerations the small residual activity released will allow the tritium injector to be disconnected from the GCS and re-connected to its normal backing pump.

Table 1 summarises the total amounts of tritium used (injected into neutral injector box and tokamak), tritium collected on the U-beds, and the measured stack releases of tritium at the end of the FTE clean-up phase. The table also gives a derived 'best estimate' of the remaining tritium holdup in the tokamak and neutral injector boxes.

4.4 Stack Releases

Of the monitored stacks, only the discharge stack for the glove box, isolators and backing pump exhaust released tritium measurable by the on-line monitor. The quantity measured by the ionisation chamber as well as by the sampling system showed that the released activity amounted only to a very small fraction of the radioactive discharge authorisation which would indicate that BPM criteria were applied very successfully.

It was observed that the stack ionisation chamber readings were consistently higher than the sample analysis. This phenomenon has been investigated and will lead to some modifications to the sampling system. Further details are given in [7].

5 FUTURE ACTIONS

The following is required to be carried out before the first tritium experiment can be considered to be completed:

(i) Continue collecting gas from the tritium neutral injector until the regenerated tritium activity is insignificant and can be discharged directly through the stack.

(ii) Disconnect special equipment and decontaminate, possibly by purging with air (wet air preferably).

(iii) Prepare for removal of the special equipment . Decide whether the equipment can be scrapped or should be stored for re-use. Store tritium U-beds in safe store.

(iv) Take samples from torus first wall materials for tritium analysis (during shutdown) to allow accounting to be completed.

(v) Install waste sorting facility and develop detritiation procedures to allow first wall components to be classified as low level waste.

(vi) Carry out analysis of environmental samples taken during and after the tritium experiment.

6 CONCLUSIONS

The first JET tritium experiment has proven extremely valuable as preparation for the full D-T phase of JET. It required the preparation of a safety case and obtaining statutory and other approvals. It required establishing adequate communication and information channels with local authorities, organisations and residents in the vicinity of the JET site. The experience thus gained will be essential when the same work has to be repeated for the use of much larger quantities of tritium.

A special programme management structure was set up to prepare the experiment, monitor its implementation and discuss, approve and record modifications to previously agreed plans. This structure worked well for the first experiment and will form the basis of a more formal organisation for the full D-T phase.

Up to the time of writing this report, ie 10 weeks after the start of the clean-up phase, only approximately 0.2 TBq of tritium were discharged. This amounts to 0.25% of the total amount of tritium handled and represents a very small fraction of the radioactive discharge authorisation, indicating that the injection system and Gas Collection System operated very well and that BPM criteria were applied very successfully.

Special equipment which is based on components used in the JET Active Gas Handling System worked very well and according to specifications. The experience gained with some of the components may however lead to some modifications in the JET Active Gas Handling System, in particular with respect to U-beds for intermediate storage and stack sampling systems.

Valuable information has already been gathered on the torus decontamination and tritium retention of vacuum vessel walls and in-vessel components. However, due to error bars associated with measurement accuracy, the residual amount of tritium inside the tokamak can only be finally quantified when samples of first wall materials are analysed during the 1992-1993 shutdown.

Decontamination of the tritium neutral beam injector took longer than originally estimated. As a consequence, additional U-beds had to be installed to recover tritiated exhaust gases, which required the preparation of a special safety assessment. Preparations for the full D-T phase will have to take this situation into account.

The tritium experiment has initiated a study of the waste arising from tritium operation. The study revealed that detritiation of in-vessel components would be required. Decontamination techniques which may include baking and surface treatment are now under investigation. A waste handling facility to be used during the 1992-1993 shutdown and later during the full D-T phase is under construction.

During the two 100% tritium injection pulses, up to 1.7 MW of D-T fusion energy was released for the first time in a controlled fusion experiment. This has strengthened the case for the development of fusion energy for peaceful use.

7 REFERENCES

[1] M Huguet et al, JET Status and Prospects, Proc 14th Symposium on Fusion Engineering, San Diego, USA, 30 September - 3 October, 1991, to appear.

[2] G Saibene et al, Tritium Accounting during the First JET Tritium Experiment, this Journal.

[3] The JET Team, Fusion Energy Production from a Deuterium-Tritium Plasma in the JET Tokamak, to be published in Nuclear Fusion.

[4] E Thompson et al, Injection of Tritium Beams for the First JET Tritium Experiment and Subsequent Decontamination, to be published.

[5] R Haange et al, Status and Prospects of JET Tritium Operation, Proc 4th Topical Meeting on Tritium Technology in Fission, Fusion and Isotopic Applications, Albuquerque, USA,
29 September - 4 October, 1991, to appear.

[6] J L Hemmerich et al, Key Components of the JET Active Gas Handling System - Experimental Programme and Test Results, Fusion Engineering and Design 11 (1989) 93 - 100.

[7] C Caldwell-Nichols, R Russ, N Davies, Radiation Monitoring, Environmental and Health Aspects during the First JET Tritium Experiment, this Journal.

[8] J L Hemmerich et al, Gas Recovery System for the First JET Tritium Experiment, this Journal.

[9] A C Bell et al, Safety Aspects and Approvals for the First JET Tritium Experiment, this Journal.

TABLE 1 Summary of total amounts of tritium injected into tokamak and neutral injector, tritium collected on U-beds, tritium released through stack, and estimated tritium hold-up at the end of the PTE clean up phase.

ITEM	AMOUNT OF TRITIUM [Bq]	COMMENT
Total injected	$(3.711 \pm 0.268) \times 10^{13}$	Tokamak and Neutral injector
Collected on U-beds	$(3.99 \pm 0.4) \times 10^{13}$	Four U-beds
Released through stack	1.65×10^{11}	Based on integrated samples
Hold up	$(2.8 \pm 2.8) \times 10^{11}$	Expected that analysis of components will give more accurate result see [2]

FIGURE CAPTIONS

Fig 1 Layout of gas supply for PINIs

Fig 2 Layout of Gas Collection System

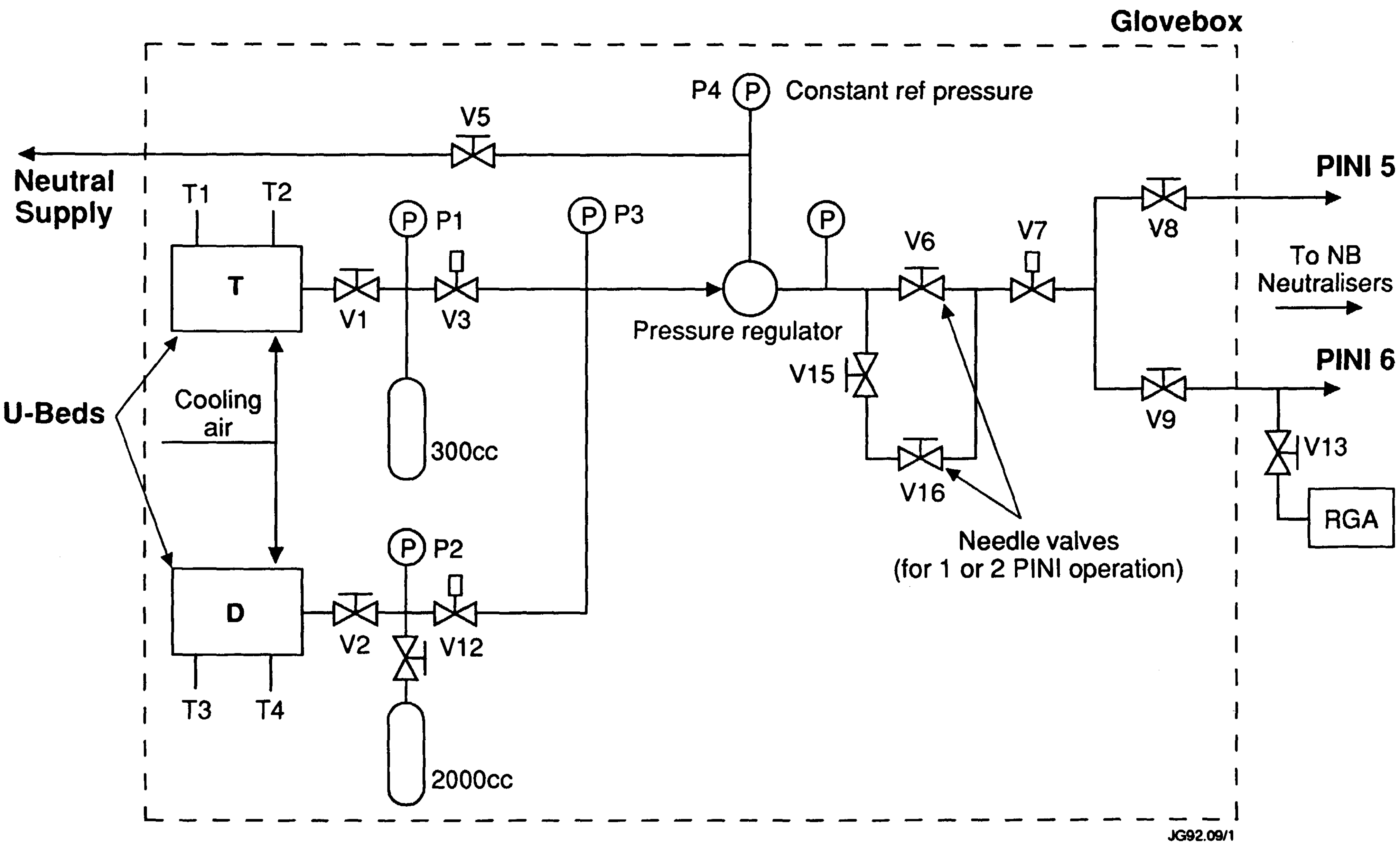

Fig. 1 Layout of gas supply system for PINI's

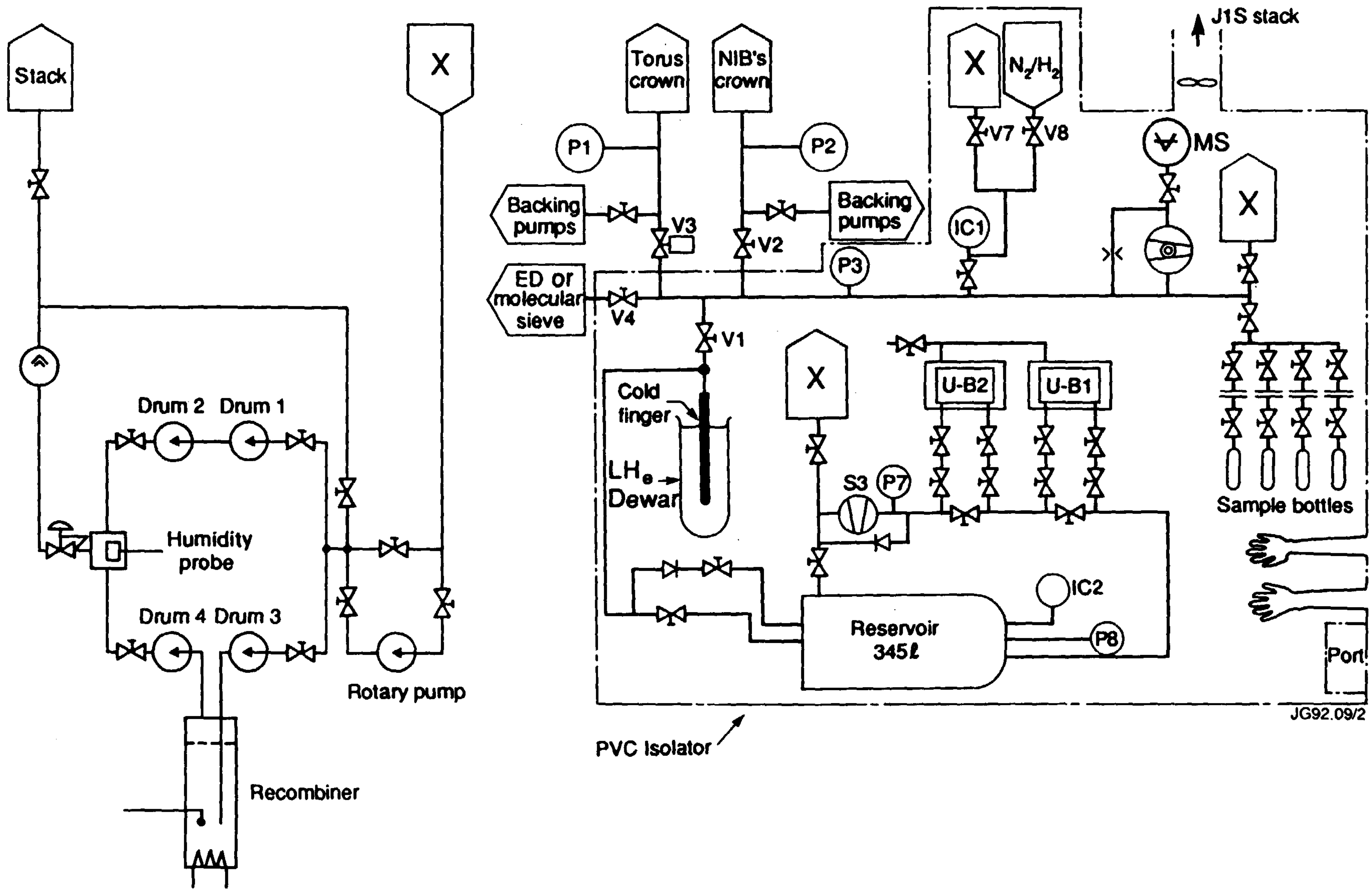

Fig.2: Layout of Gas Collection System

ANNEX

P.-H. REBUT, A. GIBSON, M. HUGUET, J.M. ADAMS[1], B. ALPER, H. ALTMANN, A. ANDERSEN[2], P. ANDREW[3], M. ANGELONE[4], S. ALI-ARSHAD, P. BAIGGER, W. BAILEY, B. BALET, P. BARABASCHI, P. BARKER, R. BARNSLEY[5], M. BARONIAN, D.V. BARTLETT, L. BAYLOR[6], A.C. BELL, G. BENALI, P. BERTOLDI, E. BERTOLINI, V. BHATNAGAR, A.J. BICKLEY, D. BINDER, H. BINDSLEV[2], T. BONICELLI, S.J. BOOTH, G. BOSIA, M. BOTMAN, D. BOUCHER, P. BOUCQUEY, P. BREGER, H. BRELEN, H. BRINKSCHULTE, D. BROOKS, A. BROWN, T. BROWN, M. BRUSATI, S. BRYAN, J. BRZOZOWSKI[7], R. BUCHSE[22], T. BUDD, M. BURES, T. BUSINARO, P. BUTCHER, H. BUTTGEREIT, C. CALDWELL-NICHOLS, D.J. CAMPBELL, P. CARD, G. CELENTANO, C.D. CHALLIS, A.V. CHANKIN[8], A. CHERUBINI, D. CHIRON, J. CHRISTIANSEN, P. CHUILON, R. CLAESEN, S. CLEMENT, E. CLIPSHAM, J.P. COAD, I.H. COFFEY[9], A. COLTON, M. COMISKEY[10], S. CONROY, M. COOKE, D. COOPER, S. COOPER, J.G. CORDEY, W. CORE, G. CORRIGAN, S. CORTI, A.E. COSTLEY, G. COTTRELL, M. COX[11], P. CRIPWELL[12], O. Da COSTA, J. DAVIES, N. DAVIES, H. de BLANK, H. de ESCH, L. de KOCK, E. DEKSNIS, F. DELVART, G.B. DENNE-HINNOV, G. DESCHAMPS, W.J. DICKSON[13], K.J. DIETZ, S.L. DMITRENKO, M. DMITRIEVA[14], J. DOBBING, A. DOGLIO, N. DOLGETTA, S.E. DORLING. P.G. DOYLE, D.F. DÜCHS, H. DUQUENOY, A. EDWARDS, J. EHRENBERG, A. EKEDAHL, T. ELEVANT[7], S.K. ERENTS[11], L.G. ERIKSSON, H. FAJEMIROKUN[12], H. FALTER, J. FREILING[15], F. FREVILLE, C. FROGER, P. FROISSARD, K. FULLARD, M. GADEBERG, A. GALETSAS, T. GALLAGHER, D. GAMBIER, M. GARRIBBA, P. GAZE, R. GIANNELLA, R.D. GILL, A GIRARD, A. GONDHALEKAR, D. GOODALL[11], C. GORMEZANO, N.A. GOTTARDI, C. GOWERS, B.J. GREEN, B. GRIEVSON, R. HAANGE, A. HAIGH, C.J. HANCOCK, P.J. HARBOUR, T. HARTRAMPF, N.C. HAWKES[11], P. HAYNES[11], J.L. HEMMERICH, T. HENDER[11], J. HOEKZEMA, D. HOLLAND, M. HONE, L. HORTON, J. HOW, M. HUART, I. HUGHES, T.P. HUGHES[10], M. HUGON, Y. HUO[16], K. IDA[17], B. INGRAM, M. IRVING, J. JACQUINOT, H. JAECKEL, J.F. JAEGER, G. JANESCHITZ, Z. JANKOVICZ[18], O.N. JARVIS, F. JENSEN, E.M. JONES, H.D. JONES, L.P.D.F. JONES, S. JONES[19], T.T.C. JONES, J.-F. JUNGER, F. JUNIQUE, A. KAYE, B.E. KEEN, M. KEILHACKER, G.J. KELLY, W. KERNER, A. KHUDOLEEV[21], R. KONIG, A. KONSTANTELLOS, M. KOVANEN[20], G. KRAMER[15], P. KUPSCHUS, R. LÄSSER, J.R. LAST, B. LAUNDY, L. LAURO-TARONI, M. LAVEYRY, K. LAWSON[11], M. LENNHOLM, J. LINGERTAT[22], R.N. LITUNOVSKI, A. LOARTE, R. LOBEL, P. LOMAS, M. LOUGHLIN, C. LOWRY, J. LUPO, A.C. MAAS[15], J. MACHUZAK[19], B. MACKLIN, G. MADDISON[11], C.F. MAGGI[23], G. MAGYAR, W. MANDL[22], V. MARCHESE, G. MARCON, F. MARCUS, J. MART, D. MARTIN, E. MARTIN, R. MARTIN-SOLIS[24], P. MASSMANN, G. MATTHEWS, H. McBRYAN, G. McCRACKEN[11], J. McKIVITT, P. MERIGUET, P. MIELE, A. MILLER, J. MILLS, S.F. MILLS, P. MILLWARD, P. MILVERTON, E. MINARDI[4], R. MOHANTI[25], P.L. MONDINO, D. MONTGOMERY[26], A. MONTVAI[27], P. MORGAN, H. MORSI, D. MUIR, G. MURPHY, R. MYRNÄS[28], F. NAVE[29], G. NEWBERT, M. NEWMAN, P. NIELSEN, P. NOLL, W. OBERT, D. O'BRIEN, J. ORCHARD, J. O'ROURKE, R. OSTROM, M. OTTAVIANI, M. PAIN, F. PAOLETTI, S. PAPASTERGIOU, W. PARSONS, D. PASINI, D. PATEL, A. PEACOCK, N. PEACOCK[11], R.J.M. PEARCE, D. PEARSON[12], J.F. PENG[16], R. PEPE DE SILVA, G. PERINIC, C. PERRY, M. PETROV[21], M.A. PICK, J. PLANCOULAINE, J.-P POFFÉ, R. PÖHLCHEN, F. PORCELLI, L. PORTE[13], R. PRENTICE, S. PUPPIN, S. PUTVINSKII[8], G. RADFORD[30], T. RAIMONDI, M.C. RAMOS DE ANDRADE, R. REICHLE, J. REID, S. RICHARDS, E. RIGHI, F. RIMINI, D. ROBINSON[11], A. ROLFE, R.T. ROSS, L. ROSSI, R. RUSS, P. RUTTER, H.C. SACK, G. SADLER, G. SAIBENE, J.L. SALANAVE, G. SANAZZARO, A. SANTAGIUSTINA, R. SARTORI, C. SBORCHIA, P. SCHILD, M. SCHMID, G. SCHMIDT[31], B. SCHUNKE, S.M. SCOTT, L. SERIO, A SIBLEY, R. SIMONINI, A.C.C. SIPS, P. SMEULDERS, R. SMITH, R. STAGG, M. STAMP, P. STANGEBY[3], R. STANKIEWICZ[32], D.F. START, C.A. STEED, D. STORK, P.E. STOTT, P. STUBBERFIELD, D. SUMMERS, H. SUMMERS[13], L. SVENSSON, J.A. TAGLE[33], M. TALBOT, A. TANGA, A. TARONI, C. TERELLA, A TERRINGTON, A TESINI, P.R. THOMAS, E. THOMPSON, K. THOMSEN, F. TIBONE, A. TISCORNIA, P. TREVALION, B. TUBBING, P. VAN BELLE, H. VAN DER BEKEN, G. VLASES, M. VON HELLERMANN, T. WADE, C. WALKER, R. WALTON[31], D. WARD, M.L. WATKINS, N. WATKINS, M.J. WATSON, S. WEBER[34], J. WESSON, T.J. WIJNANDS, J. WILKS, D. WILSON, T. WINKEL, R. WOLF, D. WONG, C. WOODWARD, Y. WU[35], M. WYKES, D. YOUNG, I.D. YOUNG, L. ZANNELLI, A. ZOLFAGHARI[19], W. ZWINGMANN

[1] Harwell Laboratory, UKAEA, Harwell, Didcot, Oxfordshire, UK.
[2] Risø National Laboratory, Roskilde, Denmark.
[3] Institute for Aerospace Studies, University of Toronto, Downsview, Ontario, Canada.
[4] ENEA Frascati Energy Research Centre, Frascati, Rome, Italy.
[5] University of Leicester, Leicester, UK.
[6] Oak Ridge National Laboratory, Oak Ridge, TN, USA.
[7] Royal Institute of Technology, Stockholm, Sweden.
[8] I.V. Kurchatov Institute of Atomic Energy, Moscow, Russian Federation.
[9] Queens University, Belfast, UK.
[10] University of Essex, Colchester, UK.
[11] Culham Laboratory, UKAEA, Abingdon, Oxfordshire, UK.
[12] Imperial College of Science, Technology and Medicine, University of London, London, UK.
[13] University of Strathclyde, Glasgow, UK.
[14] Keldysh Institute of Applied Mathematics, Moscow, Russian Federation.
[15] FOM-Institute for Plasma Physics "Rijnhuizen", Nieuwegein, Netherlands.
[16] Institute of Plasma Physics, Academia Sinica, Hefei, Anhui Province, China.
[17] National Institute for Fusion Science, Nagoya, Japan.
[18] Soltan Institute for Nuclear Studies, Otwock/Świerk, Poland.
[19] Plasma Fusion Center, Massachusetts Institute of Technology, Boston, MA, USA.
[20] Nuclear Engineering Laboratory, Lappeenranta University, Finland.
[21] A.F. Ioffe Physico-Technical Institute, St. Petersburg, Russian Federation.
[22] Max-Planck-Institut für Plasmaphysik, Garching, Germany.
[23] Department of Physics, University of Milan, Milan, Italy.
[24] Universidad Complutense de Madrid, Madrid, Spain.
[25] North Carolina State University, Raleigh, NC, USA.
[26] Dartmouth College, Hanover, NH, USA.
[27] Central Research Institute for Physics, Budapest, Hungary.
[28] University of Lund, Lund, Sweden.
[29] Laboratorio Nacional de Engenharia e Tecnologia Industrial, Sacavem, Portugal.
[30] Institute of Mathematics, University of Oxford, Oxford, UK.
[31] Princeton Plasma Physics Laboratory, Princeton University, Princeton, NJ, USA.
[32] RCC Cyfronet, Otwock/Świerk, Poland,
[33] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas, Madrid, Spain.
[34] Freie Universität, Berlin, Germany.
[35] Insitute for Mechanics, Academia Sinica, Beijing, China.