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ABSTRACT

The installation of all AGHS subsystems in compliance with a strict Quality Assurance Programme^[1] was completed in 1993. Installation was followed by end-to-end commissioning of signal and control loop connections to the Distributed Control System (DCS)^[2]. Plant layout and function are described and results of process tests with hydrogen, deuterium and other test gases are presented. These tests have revealed some minor deficiencies on the subsystems for Cryogenic Distillation, Exhaust Detritiation and Impurity Processing which have been or are in the process of being resolved prior to commissioning with tritium, initially 3g of T₂, due to start in 1994.

Some recent developments are presented:

- adiabatic calorimetry on Uranium Beds (U-beds) in the AGHS Hydrogen Isotope Storage Assemblies (HISA) permitting *in situ* measurement of tritium inventory;
- isothermal calorimetry for accurate input and tritium purity measurement with high resolution and repeatability;
- a novel regeneration method for the molecular sieve dryers of the Exhaust Detritiation System together with a method to demonstrate the expected improved performance by reliable humidity measurement to dewpoints of -100°C or lower.

INTRODUCTION

The JET AGHS was designed for the JET tritium operations phase to handle a daily throughput of up to 5 moles of T₂ together with 15 moles of D₂ and 150 moles of H₂. JET torus operation will result in a variety of mixtures of these hydrogen isotopes together with additions of ⁴He as the main D-T fusion reaction product and impurities resulting from plasma-wall interaction. The impurities consist mainly of tritiated water Q₂O and tritiated hydrocarbons C_xQ_y, in particular methane CQ₄, where Q_y stands for any combination of the hydrogen isotopes HDT. The AGHS receives these mixtures and produces pure T₂ and D₂ for recycling to the torus. The main aim of these operations is to minimise the release of tritium to the environment and to avoid production of tritiated waste.

I AGHS CONFIGURATION AND COMMISSIONING STATUS

Fig 1 presents the AGHS plant layout with the main interconnections between subsystems. The present status of each subsystem is indicated by percentage numbers:

- the left hand number indicates the degree of completion of installation, including the completion of statutory leak and pressure tests;
- the middle number indicates the state of completion of end-to-end signal and control loop tests;
- the right hand number indicates the state of process commissioning without tritium.

A more detailed account is given in the following.

A Cryogenic Forevacuum (CF)

The CF system^[3] uses a combination of 77K coldtraps, 77K adsorbers, 4K cryocondensation, 4K cryosorption and 20K distillation to pump all gases arising from torus operations and to separate them into pure Q₂ mixtures and impurities (Q₂O, C_xQ_y, ⁴He). Process installation and control connections are complete. First cryogenics tests with LN₂ and LHe have been successfully completed, process tests with gas mixtures to measure pumping speeds and separation efficiency are in progress.

B Impurity Processing (IP)

The IP system^[4] receives impurity mixtures (Q₂O, C_xQ_y, ⁴He) mainly from CF with occasional inputs from the Mechanical Forevacuum system (MF) during torus wall conditioning by glow discharge cleaning with ⁴He and gas samples after analysis in the analytical glove box (AN). IP processes impurity mixtures in ⁴He carrier gas with O₂ addition by catalytic recombination to Q₂O, collection of Q₂O on a 160K coldtrap, subsequent reduction of Q₂O on hot iron beds and collection of Q₂ on U-beds. Q₂ is transferred to Intermediate Storage (IS) for subsequent isotopic separation, detritiated impurities (mainly CO₂ in ⁴He carrier) are vented to stack via MF and Exhaust Detritiation (ED). The IP system is fully installed and tested. A deficiency in processing speed (only 20% of the intended mass flow rate through the catalytic

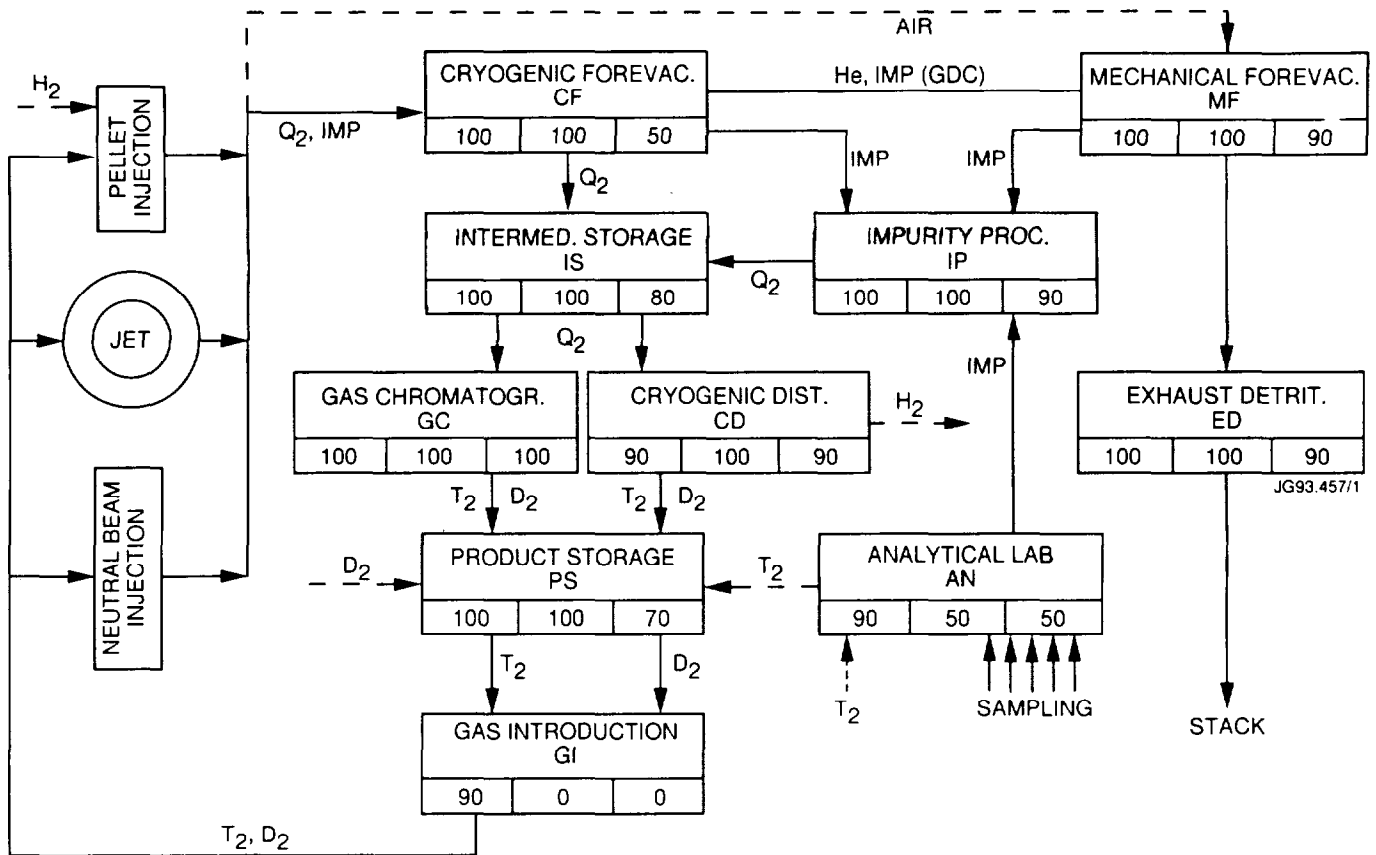


Fig 1 Overall AGHS flow diagram. The numbers indicate (in percent from left to right) the completion status of installation, control system connection and process testing with H₂ and D₂.

recombiner) can either be accommodated due to the fact that the actual amount of impurities produced in torus operation is now expected to be only 10 to 20% of the original design value or by replacing the recombiner module with a design comprising sinter filters of larger surface area.

C Intermediate Storage (IS)

The IS system uses four U-beds^[5] with a maximum of 27 moles each sorption capacity for Q₂ to receive Q₂ mixtures from CF and IP at low pressures and to supply Q₂ at a constant pressure of 140kPa to the subsequent isotope separation system. The U-beds have been activated showing the full expected sorption capacity and reliable control at constant temperature as well as at constant pressure. Operating in the constant pressure mode (feedback control of heater via pressure signal), the bed temperature is monitored simultaneously and, upon reaching a maximum temperature (T_{max} ≈ 800K) with the delivery pressure starting to droop, the U-bed is known to be nearly empty. Another U-bed with sufficient Q₂ inventory is then selected for delivery.

D Cryogenic Distillation (CD)

The CD system^[6] comprises of three distillation columns with the necessary recirculating streams through catalytic equilibrators at room temperature to separate the full AGHS design throughput (see introduction). Difficulties were encountered with the pumps driving the recirculating streams: transpiration pumps proposed by JET^[5] built with metal sinter filters were found to cease operation when pumping H₂/D₂ mixtures rather than pure isotopes. This was found to be due to isotopic enrichment of the less volatile (D₂) species on the high pressure (heated) side of the sinter filter leading to a rise in boiling point and, eventually, to loss of the full heating power by thermal conduction to the low pressure outer side containing liquid at lower D₂ concentration. The problem was resolved by replacing the transpiration pumps with conventional hydrostatic syphon pumps, which however, will lead to a slight increase of T₂ inventory of CD in full operation (from ~30g T₂ to ~33g T₂). The performance for H/D separation was found satisfactory: H₂ purity at top of Column 1 was 99.9995% (with D₂ at or below the detection limit of the analytic equipment used) and D₂ purity at the bottom of Column 3 was 99.97%. A more detailed account of these tests will be given later^[7]. In the meantime, further

tests have shown that use of transpiration pumps built with low thermal conductivity ceramic sinter filters could provide superior performance in pumping isotopic mixtures at minimum liquid inventories^[8].

E Gas Chromatographic Separation (GC)

The GC system is fully installed and commissioned for separation of H/D mixtures. A detailed account on design, function and performance will be given at this conference^[9].

F Product Storage (PS)

The PS system comprises one HISA with 4 U-beds (maximum capacity 7.5 moles Q₂) for T₂ storage and one HISA with 4 U-beds (maximum capacity 27 moles Q₂) for D₂ storage together with assay tanks for T₂ (100ℓ vol) and D₂ (600ℓ vol) for PVT inventory measurements. A recirculating system comprising a 15m³/h Normetex and a metal bellows pump serves to remove ³He arising from T₂ decay which would otherwise prevent T₂ sorption on U-beds due to its blanketing effect.

The system is fully installed, U-beds have been activated with D₂ and tested for temperature/pressure control.

G Gas Introduction (GI)

The GI system distributes T₂ and D₂ from PS to the various users. It contains calibrated volumes permitting to account by the PVT method for gases delivered to eight individual user lines, which are presently terminated in a valve box near the torus.

The system is installed but will not be included in tritium tests pending installation of all final user lines to torus, neutral beam and pellet injectors.

H Analytical Laboratory (AN)

The AN system serves three major purposes:

- analysis of process gases through a variety of sampling lines from several subsystems (IP, IS, GC, CD, MF, GI) using an analytic gas chromatography system^[10] and omegatron^[11] and quadrupole mass spectrometers;
- continuous monitoring of CD product purity, mainly T content in H₂ via an ionisation chamber, H₂ and D₂ purity via comparison to pure H₂ and D₂ reference gases in dedicated thermal conductivity detectors. A method for tritium purity monitoring by a calorimetric method is under development (see chapter "Recent Developments");
- tritium make-up, ie **connection** of and transfer from small transportable U-beds containing up to 5g T₂ to PS or IS depending on the result of a purity measurement. Tritium inventory received will be assessed by the PVT method in the PS-T₂ assay tank and the purity analysed in AN or (see chapter "new developments") by isothermal calorimetry of the transport bed as received.

The AN glovebox is fully installed, the omegatron mass spectrometer has been extensively tested with H₂, HD, D₂, ³He and ⁴He, the GC system has been extensively tested with all specified test gas mixtures including small amounts of tritiated species^[10]. Integrated system tests are in progress.

I Mechanical Forevacuum (MF)

The MF system comprises one Normetex pump of 600m³h⁻¹ and two Normetex pumps of 150m³h⁻¹ nominal pumping speed. This system will be used for torus roughing, discharging to Exhaust Detritiation (ED) and for ⁴He pumping (including tritiated impurities) during torus glow discharge cleaning, discharging to IP for recovery of tritium. The system has been fully installed and tested with ⁴He and N₂. Another part of the MF system, an on-line analytical station, is foreseen to measure tritium concentration (based on the experience gained in the JET First Tritium Experiment^[12]) in gas batches arriving from the torus systems and to detect the pressure of combustible mixtures by a PVT method prior to compression by CF to exclude the hazard of explosive mixtures. The method employed measures the pressure of a gas sample at 77K in a 1ℓ volume at the (low) delivery pressure before and after heating an internal platinum filament to 600°C. Due to the negligible vapour pressure of Q₂O at 77K, each O₂ molecule recombining with 2Q₂ molecules will lead to a pressure drop after recombination, eg for 1% O₂ in Q₂ the pressure will drop by 3%. Mixtures with excessive O₂ content can then be processed differently using activated charcoal adsorbers in CF^[3]. This detection system is installed and ready for testing.

J Exhaust Detritiation (ED)

The main purpose of ED^[13, 14] is to prevent major tritium emissions in case of torus systems up-to-air accidents and during torus maintenance operations which require venting to atmospheric pressure and opening for access. Its throughput of 500m³h⁻¹ was designed to maintain air inflow at a speed of ≥1ms⁻¹ into a torus main horizontal port (remote handling access) at continuous duty. The system comprises a catalytic recombiner for Q₂ at 150°C, CQ₄ at 500°C and three subsequent molecular sieve dryers collecting the resulting Q₂O, alternating in adsorption, regeneration and standby. Q₂O is collected in a 5m³ holding tank, the disposal route depending on tritium concentration. The system was installed and commissioned in 1991/92^[14] including tests for CH₄ combustion efficiency: recombiner temperatures were gradually raised in steps of 10°C. At each step a 1 minute pulse of 1% methane was added to the once-through air flow of 500m³h⁻¹ and the ED outlet analysed by gas chromatography^[10] immediately after the methane pulse. CH₄ combustion started at ~270°C recombiner temperature. At 350°C recombiner temperature combustion was virtually complete (99.7%). At the design recombiner temperature of 500°C, the design value (detritiation factor DF ≥1000) is well achieved (CH₄ below detection limit of ~100ppm). Only tritiated methane with its much lower detection limit would allow accurate measurements at design conditions.

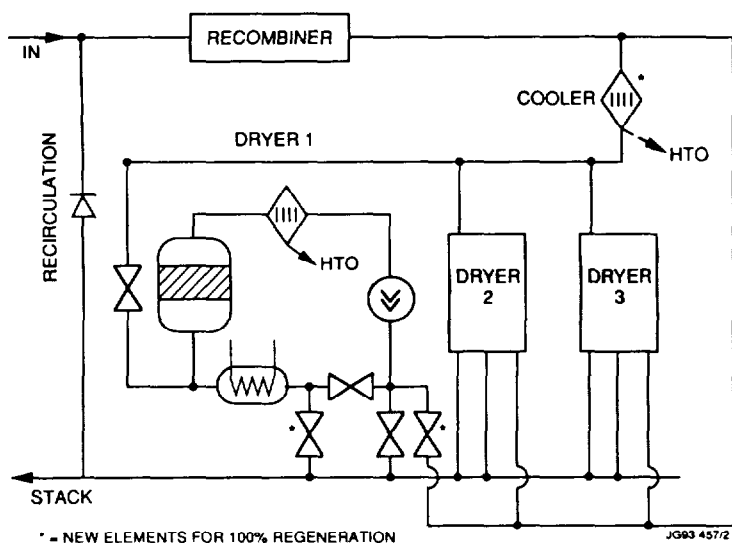


Fig 2 Exhaust Detritiation system after addition of new components.

The molecular sieve dryers reached their design value of outlet dewpoint -60°C , corresponding to a humidity concentration of $\leq 10\text{ppm}$ (vol), again to achieve $\text{DF} \geq 1000$ for inlet humidities in the order of 10000ppm (vol).

A subsequent analysis^[15] showed that a major improvement in dryer performance is possible: the present regeneration method leaves $\sim 3\%$ Q_2O (by weight) on the molecular sieve; by "borrowing" a flow of dry air from the systems outlet manifold during the final phase of regeneration, this residual humidity can be shifted to an additional cooler and the adsorbing dryer to produce a fully regenerated molecular sieve with a potential outlet dewpoint $\leq -100^{\circ}\text{C}$, ie outlet humidity $\leq 0.01\text{ppm}$ (vol). These modifications have recently been implemented and recommissioning of the system is in progress. The flow diagram of the modified system is shown in Fig 2, the additional components (valves, lines, cooler) are highlighted by asterisks.

II RECENT DEVELOPMENTS

A Hygrometry

The demonstration of the expected enhanced performance of the modified ED system will require reliable measurements of dewpoints to $\leq -100^{\circ}\text{C}$ (apart from using undesirably large amounts of tritium). Our experience has shown that manufacturers' claims for sensitivity and accuracy of humidity sensors in this very low dewpoint range have to be treated with caution. To overcome this problem, we have developed a humidity generator ("Hygostat"^[16]) permitting sensor calibration *in situ*. This device is based on the principle that air or other gases are recirculated through a counterflow heat exchanger and a heavy isothermal copper block with large internal surface area -copper wool- saturated with H_2O in form of ice. The recirculated air contains humidity in equilibrium with the surface temperature, the dewpoint is directly obtained by measuring the block temperature. This device is schematically shown in Fig 3. The humidity sensor is either connected to the process, measuring its humidity with valves

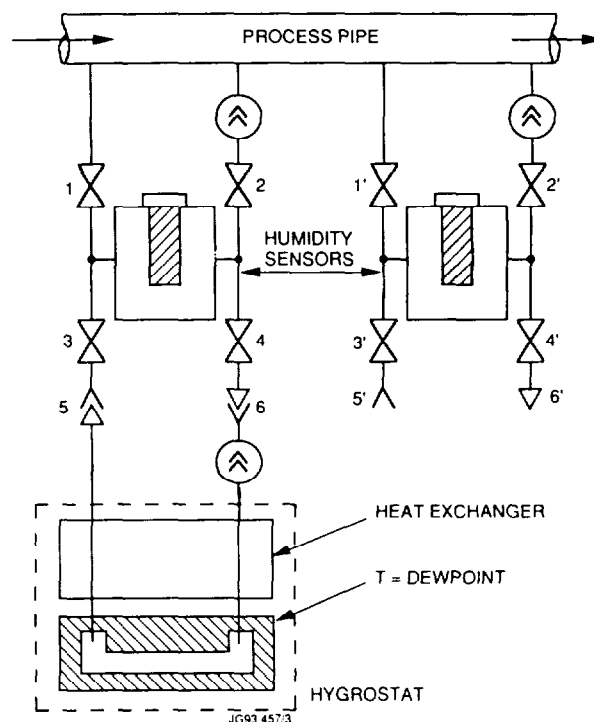


Fig 3 Schematic of humidity sensors in the Exhaust Detritiation system with on-line calibration facility.

1 & 2 open or to the Hygostat for calibration with valves 3 & 4 open. The mobile calibration device can be connected to other process sensors in different plant locations via couplings 5 & 6. Employing this method will permit us to optimise plant operation prior to tritium commissioning.

B Adiabatic Calorimetry

The JET U-beds^[5] are typically arranged in groups of four in secondary containments under high vacuum^[17] (pressure $\leq 1 \times 10^{-6}\text{mbar}$). As a result, their ideal thermal insulation permits tritium inventory measurement by adiabatic calorimetry. Tests with ohmic heating (10W, corresponding to $\sim 30\text{g T}_2$) have shown that tritium inventories of 30g T_2 can be measured with 1% accuracy. The accuracy and repeatability are typically limited by fluctuations and drift of the ambient temperature. We are presently working on a method to compensate for external temperature fluctuations by suitable data analysis procedures (probably Fourier transform) with the expectation of improving the repeatability by one order of magnitude (30g T_2 to $\pm 0.1\%$). Results will be published after completion of these further tests.

C Isothermal Calorimetry

In 1992 we started to test a commercially available thermoelectric calorimeter^a for the purpose of tritium

^a Model CR.-100-SP, Manufacturer: ITI, Delmar, Ca

inventory measurements on as-received transport U-beds, containing up to 5g T₂. The repeatability limit of this device was found to be $\pm 3\text{mW}$ corresponding to $\pm 3.7\text{TBq}$ ($\pm 100\text{Cie}$). For a 5g T₂ inventory with 1.62W decay heat, this accuracy of $\pm 0.2\%$ is satisfactory in view of the accuracy ($\pm 0.3\%$) to which the decay heat of tritium is known^[18]. The basic elegance and simplicity of this method induced us to consider further applications, for example: given a known amount of gas (by PVT method), its decay heat output measured calorimetrically will give its tritium content and hence could be used to measure tritium concentration in mixtures with other hydrogen isotopes. Ideally, this should enable us to measure on-line tritium purity from isotope separation systems, in particular CD. Clearly, the sample size required is inversely proportional to the repeatability of the calorimeter in absolute terms.

Realising that the repeatability of calorimetric measurements is directly related to the temperature stability of its environment (the originally measured repeatability of $\pm 3\text{mW}$ was achieved by using an industrial thermostat with a temperature stability of $\pm 0.02\text{K h}^{-1}$), we developed a novel temperature stabilisation method^[19], which improved the repeatability of the same calorimeter to $\sim \pm 10\mu\text{W}$. A sample of $\sim 50\text{cm}^3$ at room temperature and atmospheric pressure would be sufficient to measure tritium purity to $\pm 0.3\%$. The further development of this method will be reported after completion of present tests.

The development of calorimetry had the prime aims of improving the accuracy of tritium measurement and of measuring the tritium discharged from U-beds in the configuration used in the first Tritium Experiment. It should be noted that the accuracy of tritium accounting within a fusion fuel cycle is determined by the precision of measurement or assessment of bound tritium, particularly in the tokamak walls. Uncertainties of the order of grams are likely and this, rather than the precision of inventory measurement in individual components, will determine the feasibility and value of "safeguards" accounting.

SUMMARY

The JET AGHS is now fully installed and most subsystems have been or are being commissioned with hydrogen, deuterium and other test gases.

The present phase will be completed by the end of 1993, to be followed by a short assessment of H/D results and subsequent start of commissioning with tritium in 1994. With the major part of tritium-related process monitors (ionisation chambers) already satisfactorily tested and used during the JET First Tritium Experiment^[12], we expect no major problems during tritium commissioning.

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