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Operational Experience with the JET AGHS Cryodistillation System during and after DTE1

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ABSTRACT

The JET Active Gas Handling (AGH) Cryodistillation System (CD) was designed to separate a mixture of hydrogen isotopes into individual isotopic components, discharging low activity protium gas directly to stack, and storing the deuterium and tritium product for re-use. Following successful trace tritium commissioning the system became fully operational for the JET DTE1 experimental campaign which commenced in 1997. This paper describes the operating performance of the CD system during and after this period. This includes an assessment of the total amount of gas processed and the operating conditions which were implemented to achieve optimum process conditions. Note that the original design specification of the system assumed a large proportion of process gas would be protium from the fast pellet injection system. This system was not used during the campaign and consequently the feed gas was mainly a deuterium mix requiring the discharge of large amounts of detritiated deuterium to stack. Hence operating parameters had to be changed to suit these new conditions, which led to a need to keep the tritium inventory in the system to a minimum. Despite this, the overall tritium enrichment in the system with a feed of low activity hydrogen input was up to 35% thus providing an effective pre-enrichment level for introduction to the preparative gas chromatograph (GC) hydrogen isotope separation system used in the AGHS. In this respect even though the operational requirements of CD had changed from the original design specification, the system was successfully adapted to its revised role, providing an important contribution in the tritium reprocessing cycle during the DTE1 campaign.

1. INTRODUCTION

The Active Gas Handling System (AGHS) at JET is used to supply tritium (T_2) and deuterium (D_2) to the JET Torus and Neutral Injector Systems and process gas mixtures pumped from the torus and connected systems. The gases are separated into hydrogenic and impurity streams. Impurities are detritiated to regain tritium. Hydrogen gas mixtures are isotopically separated into pure tritium, deuterium and protium components. Tritium and deuterium can then be re-supplied to the various users. The gas processing is done in various subsystems which are described in a companion paper [1]. The specific task of hydrogen isotope separation is undertaken by two Isotopic Separation Systems (ISS) of the AGHS: the Gas Chromatograph (GC) system and the Cryodistillation (CD) system. The GC system has been associated with high purity tritium enrichment from an initial few per cent tritium in hydrogen under batch process conditions [2]. CD on the other hand was designed to operate as a continuous separation process with large volume throughput, producing a stream of enriched tritium for further supply to users. In reality the on-site tritium inventory has to date at JET not been large enough to satisfy the original design capacity of the CD system. Hence during the DTE1 experimental campaign [3], it was found that the CD system could be more favourably employed in processing low tritiated

hydrogen components for pre-enrichment of tritium and subsequent transfer to the GC system with the detritiated hydrogen gas discharged to ambient under controlled conditions.

2. CRYODISTILLATION TECHNIQUE

In distillation the principal mechanism in the separation process is the difference in vapour pressure between the individual component liquids. The order of volatility of the hydrogenic species is H₂, HD, HT, D₂, DT and T₂, with H₂ the most volatile. The liquefaction of these components requires operating temperatures of between 20 – 30 K and a desired process pressure of 0.10 - 0.12 MPa. The distillation columns are designed to provide a specified separation between any two species adjacent to each other on the volatility scale. In this respect the number of columns required will reflect the number of separate pure product components required. The hybrid species HT is normally removed by a strategically placed equilibrator to promote the equilibrium $HT + D_2 \rightarrow HD + DT$ after which HD is a harmless discharge product. The species DT can be processed further in the tritium product recycle stream with an additional equilibrator to promote its dissociation, although the effectiveness of this promotion depends on the tritium inventory in the system.

The design of a cryodistillation system is normally preceded by a number of simulation exercises which establish basic design parameters required for the optimum separation of hydrogen components into their respective product streams. These exercises require specified feed streams and target product purities, thus yielding a set of design parameters which fix the column diameters, height equivalent to theoretical stage (HETP), reflux and liquid hold-up. In operational conditions certain parameters may be altered depending on the inventory composition, typically condensor power and reboiler duty which can change the reflux and gas load respectively within a column. In order to promote effective component separation it is of crucial importance to maintain mass and energy balance in each of the separation columns. Automatic control sequences are often employed to achieve such conditions, although the method of control can vary with each system.

3. DESCRIPTION OF THE Jet CRYODISTILLATION SYSTEM

3.1. General Design Description

The JET cryodistillation system (CD) was originally designed to operate at a daily throughput of up to 30g tritium, 60g deuterium and 300g protium. Figure 1 illustrates the column profiles and associated feed, product and recycle streams. Depending on their relative concentration, feed mixtures from AGHS U-beds at a set pressure enter the CD system either into the first column (Feed 1 maximum flow rate 5 l/min) or into the second column (Feed 2 maximum flow rate 1 l/min). In normal operation the driving force for the gas transfer throughout the system is by means of four syphon pumps in combination with the process pressure differences generated across each of the columns. Column 1 allows the lighter non-tritiated hydrogen species to mi-

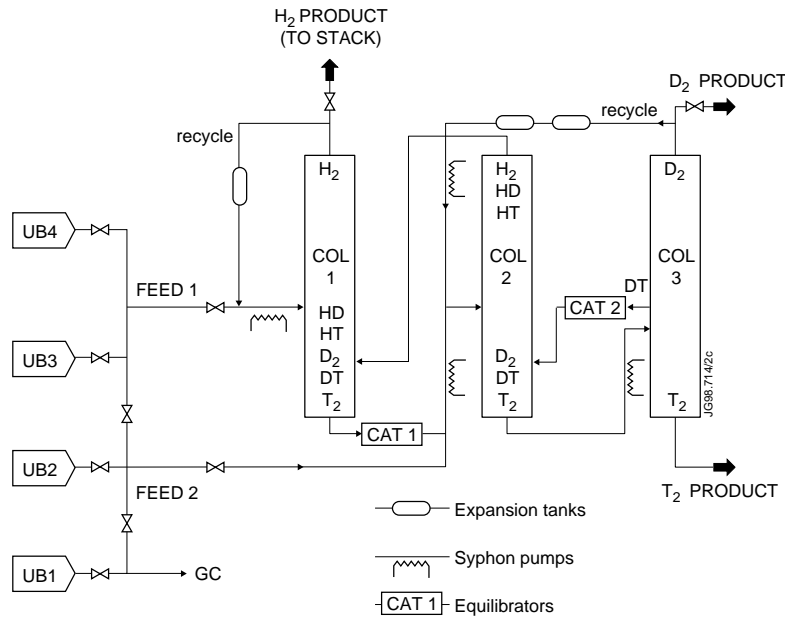


Fig. 1: Schematic Flow Diagram of Cryodistillation (CD) System

grate upwards allowing the top distillate of this column to be discharged directly to stack subject to prescribed discharge limits. Column 2 does not have a product route, but serves as the intermediate separator of the feed 2 stream and dissociated components of the hybrid species passing through the equilibrators, returning a low tritium concentration to column 1 and the heavier tritiated components to column 3. Column 3 provides the two remaining product streams, the top distillate giving pure deuterium product and the bottom product an enriched tritium component, which can be extracted in batch mode or as a continuous stream. Thus the three feed streams can provide pure hydrogen species, with deuterium and tritium returned to AGHS U-beds for use in plasma operation or further reprocessing, and the waste hydrogen safely discharged to stack subject to daily tritium gaseous disposal limits. The purity and composition of the product streams will of course be dependent on the hydrogen inventory distribution in the CD system at the time. Table 1 lists the basic design parameters of the JET CD system.

The three separating columns are housed in a 11 m high bakeable stainless steel vacuum vessel known as the Process Cold Box (PCB). The PCB is maintained at a very low pressure using an accumulation pump (sputter pump) and is actively cooled by circulation of helium at 18K through copper coils surrounding a layer of thermal shielding. Thus the heat load to the process lines from convective and radiative heat transfer processes are minimised.

Two other large containment vessels are used for the CD main process operation. One containment houses the valve units and expansion tanks to accommodate the hydrogen gas at ambient temperature conditions. The other contains non-bakeable equipment such as flowmeters, pressure indicators and ionisation chambers. Both containments are at ambient temperature and are pressurised to 0.18 MPa helium so that during any primary line leakage will result in ingress of non-freezing containment gas into the process line, and minimise egress of tritium into the secondary containment. Note that a development of a leak in the PCB primary lines is unlikely

Table 1: Design Parameters of the JET Cryodistillation System

	COLUMN 1	COLUMN 2	COLUMN 3
no. of stages	80	80	100
feed locations	60/79	40/79	45
sidestream drawoff			42
intermediate boiler location			60
HETP (mm)	60	60	75/60
liquid hold-up (mol/stage)	0.06	0.06	0.08/0.04
packing height (m) + type	4.8 dixon rings	4.8 dixon rings	6.9 dixon/ spiral rings
inner diameter (mm)	16	16	17/13
column top pressure (MPa)	0.10-0.12	COL1 + 0.005	COL1 + 0.010
typical column pressure drop (kPa)	4	5	8
condenser temperature (K)	18-20	20-24	22-25
reboiler temperature (K)	21-24	21-24	23-26
condenser duty (W)	10	13	15
reboiler duty (W)	8.5	9.0	7.0/4.5
reflux ratio	6+	12	35
column vapour velocities (m/s)	0.01+	0.05-0.1	0.05-0.1

as all components are welded and no dismountable fittings are used within the PCB. All three containments have a common transfer line to a 10 m³ vacuum tank to allow for expansion of any combined process and containment gas to create a sub-atmospheric pressure in the event of an internal leak

The operational conditions in the separating columns can vary depending on the inventory composition, although in general an operating pressure of between 0.10 and 0.12 MPa at condenser temperatures of around 20 – 25 K is used which is regarded as an appropriate compromise between separation efficiency and operational safety constraints. These conditions give rise to a He refrigeration power requirement of 200W based on a normal system operating inventory of around 0.175MPa·m³.

The use of the CD system requires a preliminary cooldown period of around 2 days to achieve an operational state. This action is done remotely using an automated control sequence such that operator intervention is only optional. Further automated operational modes are available again to minimise manual intervention, although such interventions are at times convenient for specific feed and product control. This was especially the case with inventories containing little protium component, which restricted the separation capability of the first column and the

permissibility of top product distillate discharge, and also the need to maximise tritium product purity using batch operation. Neither of these operations were fully envisaged in the original plant specification. In this respect manual operation of the system was sometimes necessary.

While the general principles for isotope separation are relatively straightforward, the control philosophy of the system is somewhat more complex. In order to separate the components effectively it is imperative to maintain system stability which manifests itself as an exercise in mass and heat balance in each of the operating columns. The control process of the CD system comprises a set of cascaded closed loop feedback systems operating under a general control strategy which is described below.

3.2. Control Philosophy

During operation the three main purposes of the control system are:

- to maintain separation performance even during process perturbations
- to react quickly to load changes and set point variations initiated by operator
- to establish and maintain preset operational modes to minimise operator input

The columns have several variable inputs (flows, heat loads etc) and consequent variable states (pressure, concentration, internal gas flow etc) that must be maintained within permissible limits. A single change in an input parameter can affect several system parameters in any of the three columns.

The control strategy is therefore based on the need to maintain mass and energy balance in each of the columns under a transparent mode of control which incorporates single and cascaded loops with proportional integral derivative (PID) algorithms. There are different methods of achieving this control regime, however with the JET design the 3 columns are coupled together by their feed and recycle streams thus requiring minimum adjustment between them for stable operation, especially as the flow rates between the columns vary only slightly. Hence feed rates to the columns are maintained at a constant rate using fixed power syphon pumps.

It is the sump level change of each column which indicates the mass balance of that column. As the feed rates to each column are already fixed any change in sump reboiler duty affects primarily the distillate (top) flow and its purity. A direct cascade control of sump level from product flow is not desirable due to the long dynamic response time (the columns are several metres in length). Instead the sump level is controlled directly by the reboiler to a specific set level irrespective of system perturbations. Hence the product flow purity is affected by this process which either increases or reduces the flow depending on the required purity product level.

The reboiler compensates for a change in sump level by changing the boil-up rate and gasload in the packing. If the sump level has to be reduced then a higher gasload ensues, giving a cleaner product at the top and so the top valve will open more to produce more distillate, and so the column mass storage will fall. The response for such a perturbation is dependant on the

PID values for the cascade control and also for the gasload migration to the column top. Typically a response time of several minutes can be expected before a new column equilibrium is achieved. These response times do not pose a restriction for system operation.

Energy balance within each column is reflected by individual pressure rises. A steady pressure in each column is essential for establishing a steady separation profile and equilibrium composition of the 6 hydrogen species. In normal operation the pressure is set at one physical location only, in this case at the top of column 1 as governed by its condenser power. A higher pressure in the column induces a higher helium cooling flow by valve control, which condenses more vapour and so returns the column pressure to its prescribed set point. No direct pressure control occurs with columns 2 and 3 and so a designed imbalance exists between the reboiler and condenser duties which creates the distillate cycle.

4. PREPARATION OF CD FOR DTE1 PHASE

Before significant amounts of tritium could be admitted into the CD system an extensive commissioning program was required to demonstrate its safety and reliability during separation operations. The bulk of this work is described elsewhere [4] but the salient conclusions are briefly discussed below.

4.1. Non-Active Commissioning

An extensive campaign of inactive commissioning was undertaken with the aim of evaluating the separation capabilities of the system using various mixes of protium/deuterium gas [5]. Experience in the operation of the CD system was gained and the assessment of design parameters such as pressure levels, flow rates, reflux etc. were undertaken. Purity analyses of the column products were checked with high resolution mass spectrometry to demonstrate that deuterium transport through the distillation columns was effective and the equilibrators were working satisfactorily. It was found that from the top of column 1 protium purity of > 99.9996% and from column 3 deuterium purity of >99.998% could be established. Note these purity values exceed nominal values of hydrogen purities in commercial gas bottles.

4.2. Trace Tritium Commissioning

After the evaluation of performance of the CD system using non-active hydrogen gases, a small amount of tritium gas (40 TBq) present from the JET PTE [6] experiment in 1992 was processed in CD in May of 1996 [4]. The aim of the tests was to demonstrate that the CD system was able to process this small tritium mix and produce a tritium enriched product at the bottom of column 3 which could be successfully removed and analysed. Additionally it was crucial to check the response of the in-line ionisation chambers and demonstrate that the discharge route to stack from the top of column 1 could be used within designated discharge limits. .

At this time it was known that the hydrogen gases to be separated would be mostly deuterium from tritium as the fast pellet injector [7] (the main source of protium) would no longer be

used in the DTE1 phase. Also the need to provide pure deuterium for subsequent re-use in the torus and neutral injectors would not be of importance. In this respect the operation of the CD system had changed to deal with the following requirements:

- 1) detritiation of mainly deuterium feed for direct discharge to stack from column 1
- 2) enrichment of tritium in deuterium (DT) for further separation with GC columns

It was found that with a total of 40 TBq present in the system a maximum tritium purity of 4% could be achieved from the bottom of column 3 with a single batch product. This represents probably the maximum purity that could be achieved for the trace inventory level. Hence the operating parameters set for the system proved to be effective in promoting optimum separation.

In addition trial discharges of deuterium from the top of column 1 into the environment were carefully undertaken over a 4 day period. The results showed that for the given tritium inventory a maximum measured activity of 8.5 GBq in 50kPa·m³ was discharged over this 4 day period. This value is well below the permitted discharge limit of 40GBq/day. This value corresponded to tritium contamination of around 1 ppm. Hence the experiment demonstrated that detritiation of deuterium could also be performed satisfactorily to allow discharge to atmosphere. The original design specification called for a target discharge level of 5 ppb. However in practice this was not achievable due to the residual contamination of the ionisation chamber and process lines. A more realistic target level was taken as < 1 ppm to allow discharges well within JET's daily limits. A lower level of 0.2 ppm was recorded on the top column ionisation chamber (IC) and this value represented the background level throughout the DTE1 phase.

5. DTE1 OPERATION

The JET CD system was designed for processing up to 33g of tritium daily. At the start of DTE1 operations on 15th May 1997 the total amount of tritium on site was 20g [1]. It was therefore clear that the separation duties of the system would not reach its potential capacity. Furthermore the distribution of tritium throughout the closed loop of the DTE1 operation cycle meant that the inventory of tritium in the CD system would always be a small fraction of the site inventory. In fact the maximum inventory in the system did not exceed 1g at any time .

As discussed in the introduction, even though the two ISS's in the plant (CD and GC) were originally expected to operate in parallel, the development of the experimental program meant that the CD system became important as a detritiation system for large amounts of lightly tritiated deuterium for direct discharge to stack and as tritium pre-enricher for subsequent processing in the GC system to produce pure tritium. Hence the ISS's were operated in series where appropriate.

5.1. Initial Filling and System Cooling

The DTE1 phase officially started with the supply of a 1% tritium in deuterium mix to the Neutral Beam Injector Box at Octant 8 (NIB8) in May 1997 [8]. The return of the gas from the

torus systems came from two sources - the Torus vessel (plasma pulse exhaust gas and regeneration of in-vessel cryopumps), mostly containing hydrogen with wall impurities, and NIB cryopumps, which mainly comprised pure hydrogen of tritium composition similar to the day's supply [8].

Following adsorption of these gases on the AGHS cryopump modules [1], the gases were again regenerated and absorbed onto the four Intermediate Storage (IS) U-beds, with non-hydrogenic and tritiated impurity gases directed to Impurity Processing (IP). Depending on the degree of tritium component in the hydrogen as estimated from IC measurements and more detailed analysis using the Analytic Laboratory Gas Chromatograph (GC) the IS U-beds were earmarked for use in the following way:

UB-4110 tritium mix > 0.2% direct to GC with CD bypassed

UB-4220 heavier hydrogen isotopes < 0.2% tritium mix for CD transfer via Feed 2 line

UB-4330 lighter hydrogen isotopes < 0.2% tritium mix for CD transfer via Feed 1 line

UB-4440 as above.

The volume of the CD system is 0.8 m^3 , most of which represents the capacity of the warm expansion tanks located in the column recycle lines. An operating inventory of about $0.175 \text{ MPa}\cdot\text{m}^3$ litres is required, which means that the system must be filled to about 0.22 MPa prior to cool-down. In this respect the CD system could be treated as a storage volume until the optimum cooldown inventory had been reached. Feed 1 was generally used for this process as the maximum flow rate through this line is 5.5 l/min compared with feed 2 flow of 1 l/min . Since in the absence of significant protium component there was no real advantage in using feed 2 as a supply line for the heavier isotopes during separation.

During the first stage of DTE1 operations to the end of June 1997 CD received at warm conditions a total of $0.1723 \text{ MPa}\cdot\text{m}^3$ with a measured tritium content of $0.1887 \text{ kPa}\cdot\text{m}^3$ (0.468 g).

With the above initial inventory the CD system was cooled down on 20 June 1997 to a normal operational status of about 20 K at 0.11 MPa . The cooling process to operational conditions took approximately two days, although the system was allowed to operate for some days more to allow for optimum separation of the hydrogen isotopes.

5.2. Product Purity Analysis

With the inventory composition stated above tritium component analyses were made of the three product lines at 2 July 1997. Up to this point no further gas had been added to the system other than the initial starting inventory.

As shown in Fig 1, two product lines exit from the tops of column 1 and column 3, although nominally referred to as the protium and deuterium product lines respectively, the prod-

ucts will be mainly deuterium due to the negligible protium feed component. The bottom of column 3 supplies the enriched tritium, which is taken as a batch sample with a volume capacity of 2.3 litres. Table 2 shows typical tritium contents measured from in-line ionisation chambers and where applicable a gas chromatograph result for each product.

Table 2: Tritium Concentrations in CD Product Lines after First DTE1 Fill

Product Line	Tritium Content
Column 1 Top	0.3 ppm
Column 3 Top	30 ppb
Column 3 Bottom	35% peak - see figure 2

In the case of the two top column products, it is seen that the tritium levels were low enough to permit large volume discharge to the stack while remaining well within the daily discharge limits. However it would be expected from design calculations and basic distillation physics that the lower tritium level would occur at the top of column 1. The results show that the top of column 3 is the cleaner product. This effect was confirmed by additional checks with ionisation chambers external to CD. This result became a consistent feature throughout the DTE1 campaign in the absence of significant protium product. However on the few occasions where an appreciable amount of protium was transferred to the system, the column 1 top product became much cleaner.

The purity of the tritium product was very good, although it should be emphasised that the above figure of 35% represented the maximum for one sample volume. Over the period 1-2 July 1997 successive samples were taken at 3-4 hour intervals to extract as much tritium as possible from the system. Figure 2 shows the tritium concentration for each sample taken, and as would be expected the amount extracted decreased as the total tritium inventory in the system was progressively reduced. Note that the first sample is low due to a dead volume in the tritium transfer line which does not have the representative composition of the bottom of column 3.

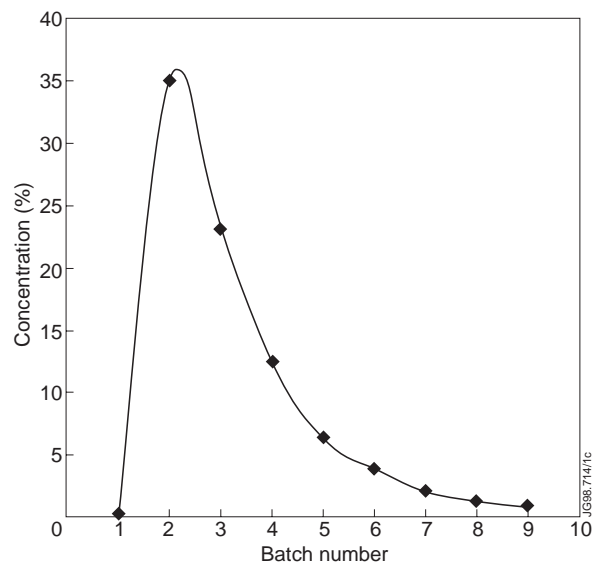


Fig 2: Variation of Tritium Concentration with Batch No. from bottom of Column 3

The total amount of tritium extracted from the system over the two day period was $0.162\text{kPa}\cdot\text{m}^3$ (0.402g) compared with an initial fill of $0.1887\text{kPa}\cdot\text{m}^3$ (0.468g). The difference

between the tritium feed and extraction is probably due to a small retention load within the packing of the columns. In addition some of the measurements of the extracted tritium were made only by the outlet ionisation chamber. More accurate measurements could be made using the Analytical Gas Chromatography system (AN-GC) [9], but this was sometimes not available due to other plant requirements. The equivalent analysis using the more accurate AN-GC systematically showed a higher tritium content of 10 - 20% in comparison with the IC, and so the measured tritium output would probably be higher if all results were based exclusively on AN-GC analyses. The tritium product was transferred to a GC U-bed for final enrichment to almost pure tritium.

5.3. Combined Feed and Discharge Operations

Over the period 3 July to 19 July 1997 a number of operations were carried out involving the supply of further hydrogen feed to the system while at the same time discharging gas either to the Exhaust Detritiation (ED) system or directly to stack, and further minor extractions of tritium from column 3. A key factor in these tests were to establish that the CD system could be operated over an extended period of time under controlled conditions (i.e. continuous equilibrium conditions in the columns) without excessive perturbations arising from feed and discharge operations. In addition the amount of feed and discharge quantities had to be carefully measured using integral values of in-line flowmeters in order to maintain system inventory at the correct level of around $0.175\text{MPa}\cdot\text{m}^3$. Any significant deviation from this amount would result in instability and so inefficient separation. Any serious overfilling of the system could result if high warm-up pressures occurring in the event of an unscheduled shutdown.

In the middle of the DTE1 experimental campaign, a small in vacuo leak was observed on the Neutral Injection System NIB8. An intervention to repair this was necessary and is described in detail in [8], [10]. The period of maintenance associated with this intervention allowed the CD system to be warmed up in order to establish the residual inventory using pressure indicators and compare the calculated inventory derived from the totalisers on each of the feed and product flowmeters. Under warm-up conditions the gas inventory was extracted from the top of columns 1 and 3 for further discharge and storage. Table 3 details the total amount of gas processed and extracted over the operating period 20 June to 19 July 1998 during both the operational phase and warm evacuation. Note that for the tritium enriched bottom product of column 3, the transfer to GC for further enrichment occurred only when the tritium content exceeded 0.2%, otherwise it was directed to the IS U-beds for re-introduction into CD. The total gas process and removed from the system during this operating period is as follows:

Total hydrogen gas fed to system	= $0.2466\text{MPa}\cdot\text{m}^3$ (tritium content 173.9 TBq, 0.489g)
Total gas extracted (from Table 3)	= $0.2487\text{MPa}\cdot\text{m}^3$ (tritium content 156.1 TBq, 0.439g)

Table 3: CD Processing Details First DTE1 Phase (Tritium activities in parentheses)

destination	Column 1 top	Column 3 top	Column 3 bottom
	kPa.m ³	kPa.m ³	kPa.m ³
ED (discharge)	70 (97 Gbq)	32 (214 Gbq)	0
Stack (discharge)	92 (54 Gbq)	0	0
PS U-beds (storage)	0	37 (85 GBq)	0
IS U-beds (recycle)	0	0	13 (14.939 TBq)
GC U-beds (enrichment)	0	0	4.7 (140.9 TBq)

5.4. CD Control Parameters

In order to achieve conditions within the system such that deuterium discharge to stack could be undertaken within the strict activity discharge limits a number of specific parameter setpoints in the system control were investigated. The main aim was to clean the column 1 distillate as quick as possible to permit discharge, otherwise no further feed could occur. The problem centred around the poor separation of the deuterium in column 1. With the original settings determined in the non-active commissioning phase the rate of fall of activity in the top column IC following filling and subsequent feeds was very slow. This resulted in a wait of days before activity levels fell to < 1 ppm to permit discharge. For the second phase of DTE1 from July to November 1997 operations the process demands on the CD system were such that prolonged delays in gas separation could not be tolerated as the capacity of the holding U-beds used for CD feed would then soon be reached. In this respect a number of operating parameters were addressed to alleviate the problem, the following of which proved to be the most effective:

- 1) reduction of operating pressure to maximise separation (ratios of hydrogen vapour pressures increase slightly with falling pressure)
- 2) high reboiler duty in column 1 to promote greater gas load in column 1
- 3) high reflux at the top of column 2 to provide cleaner product for re-introduction into column 1
- 4) low sump level in column 3 to concentrate tritium in liquid phase and maximise tritium purity
- 5) regular tritium extraction to minimise overall tritium inventory of system

Clearly some of the above parameter optimisations were often in conflict. In the case of 1 and 2 a higher boil-up rate tends to increase the system pressure, whilst the column 1 condenser is trying to reduce the pressure. Hence a compromise was always required. The important con-

straint was always the need to maintain column mass and energy balance. Too much change in one parameter could create a perturbation which the system was unable to handle, resulting in excessive fluctuations in column liquid levels which could more than cancel out any gains made in rate of cleaning of the column 1 distillate product. Table 4 lists the chief operating parameters and the values that were used during the separation duties.

Table 4: CD Operating Parameters for Deuterium Detritiation and Discharge

Component	Column 1	Column 2	Column 3
Condenser Duty	8.2 W	12.0 W	11.0 W
Condenser Temp	19.7 K	21.6 K	22.3 K
Reboiler Duty	7.5 W	8.5 W	3.0 + 3.7 W
Sump Level	30%	50%	20%
Recycle flow	5 mol/h	2 mol/h	2 mol/h
Operating Pressure	~ 0.1 MPa	~ 0.1 MPa	~ 0.1 MPa

5.5. Extended DTE1 Operations

From 10 August 1997 the CD system was re-filled and cooled down with the purpose of continuous hydrogen gas processing until the end of DTE1 in November 1997. Processing then continued in continuous fashion during the phase of deuterium-only plasma operation to clean up the Torus [11]. This resulted in an uninterrupted operational phase extending into the end of February 1998. The gas processing as before was mainly deuterium. As discussed above, in the event of large throughput there was on occasions a time delay when the top product of column 1 was too high for direct discharge (typically > 1ppm for large volume discharges). However the capacity of the supply U-beds (about 0.18MPa·m³) was always sufficient to provide a buffer storage while the CD system was cleaning up deuterium gas prior to discharge.

Regular tritium extraction was undertaken with the purpose of minimising the tritium inventory in the system to promote a quicker gas detritiation for discharge. Therefore obtaining maximum purity was not a prime objective and so most extractions were performed where maximum purity levels rarely exceeded 10%. This purity level was still more than adequate for transfer to GC for further enrichment. Any tritium levels < 0.2% were returned to the IS U-beds for further processing with CD.

Table 5 shows the total amounts of gas processed in the CD columns over the 5 month operating period. Note that the initial filling comprised 0.175MPa·m³ of mainly deuterium and a further 0.933MPa·m³ of gas transferred into the system.

Of particular note is the reliability of the system, which remained fully operational without any unscheduled trips. The feed streams were always from U-beds, which reduced the probability of freeze-up in the system as a result of impurities. In addition the transfer lines to the CD

system were always thoroughly pumped down with a turbomolecular pump to remove any impurity gas prior to filling and transfer. As a result no stoppage occurred at any time due to impurity freezing in the CD lines.

Table 5: CD Processing for DTE1 and Clean-up Phase (Tritium activation in parentheses)

	Column 1 Top	Column 3 Top	Column 3 Bottom
	MPa.m ³	MPa.m ³	MPa.m ³
Stack (discharge)	0.856 (356 GBq)	0	0
PS U-beds (storage)	0	0.038 (88 GBq)	0
IS U-beds (recycle)	0	0	0.015 (45.9 TBq)
GC U-beds (Enrichment)	0	0	0.038 (425.0 TBq)

6. CONCLUSIONS

The CD system operated in the JET DTE1 and subsequent clean-up phases from June 1997 to February 1998 with no unscheduled stoppages. The total amount of hydrogen gas processed during this time amounted to 1.364MPa.m³. The predominant component of this gas was deuterium. With careful selection of the CD operating parameters a total of 0.948MPa.m³ of hydrogen gas was discharged to stack with an average tritium concentration of << 1ppm. This represented a small fraction of the JET daily discharge limits.

The production of pure deuterium from the top of column 3 was an easy task in view of the nature of the inventory. Deuterium gas with a tritium content also of << 1ppm was available for use, but generally was not required for use in the experiment.

The total amount of tritium extracted from the system exceeded 2.5g in a deuterium-tritium mix with a typical concentration of 5%, although conditions could be established where the tritium content was 35%. A batch sample purity approaching 100% tritium could have been achieved with a system tritium inventory of > 1g. However the pre-enrichment of tritium in the CD system from hydrogen input of low activity, typically < 0.2% tritium, for subsequent transfer to the GC hydrogen separation system, proved to be of significant value as part of the main AGHS tritium recycling programme.

In the post DTE1 phase, where the return of hydrogenic gas from the torus and neutral beam system was always tritiated, the CD system continued to process gas mainly for discharge to stack and retention of hydrogen gas enriched in tritium. This had the additional advantage of reducing the level of activity which would otherwise have had to pass through the Exhaust Detritiation System, where the tritium is recovered in the form of water.

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