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JET Active Gas Handling System–operating experience and lessons learned from recent D-T campaigns

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Abstract

The Active Gas Handling System (AGHS) stores, supplies and re-processes tritium for the JET fusion experiment. The plant had not operated in this capacity in recent years and required upgrade and recommissioning to enable use during the latest JET tritium campaigns. Thousands of tritium transfers and operations have now been performed with over 1 kg tritium in total supplied to JET and subsequently recovered and reprocessed. This paper summarises AGHS plant operations providing examples from the recent campaigns, and presents the knowledge gained and lessons learnt. A summary of AGHS sub-system upgrades and usage during campaigns is presented. This paper includes data captured from those operations, which have been extracted from the control system as part of a wider AGHS data capture project. Findings are presented from an initiative to capture operator knowledge from AGHS, which brings together operational team input in working groups, a targeted survey and an ideas repository. Key operations are discussed with reference to plant data presented graphically. Operational challenges and lessons learnt are presented from which improvements to design and operations have been proposed. Topics discussed include system design and limitations, process control and automation, tritium accountancy, operating instructions, and ergonomics. Many of the lessons learnt and improvements presented here are relevant to the wider fusion community planning to design and operate tritium plants.

Keywords: fusion fuel cycle, tritium operations, Joint European Torus

[5] See King et al 2024 (https://doi.org/10.1088/1741-4326/ad6ce5) for JET Contributors.
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1. Introduction

The most viable route to energy production from nuclear fusion requires use of a deuterium-tritium fuel mix [1]. The Joint European Torus (JET) was a magnetic confinement fusion reactor capable of operating with tritium. Recently two major tritium campaigns were performed at JET [2, 3]. Due to the radioactive nature of tritium as well as its scarcity, JET has an Active Gas Handling System (AGHS) to safely store, supply, recover and process tritium.

The AGHS is one of a small handful of tritium fuel cycle facilities in the world. As such the opportunity to share operating experience and lessons learnt is *a priority* for UKAEA. Operating experience of the AGHS [4] and its sub-systems have been reported previously following the first major JET tritium campaign, DTE1, conducted in 1997. Since many years separated DTE1 and DTE2 (which commenced in 2020), an intensive programme of upgrading and recommissioning of the AGHS was necessary and took place between 2016 and 2020. During this time the Exhaust Detritiation System (EDS) also required replacement [5].

AGHS was staffed almost continuously, 24/7, between October 2020 and November 2023, in support of the JET tritium campaigns. There were four, five-person shift teams, and each shift duration was 12 h. Collectively the team completed approximately 2000 shifts. Throughout the campaigns, over 1 kg of tritium has been supplied to JET, and subsequently recovered and isotopically separated from deuterium and protium. This was substantially more than the 100 g of tritium supplied and reprocessed during DTE1 [4]. Accountancy of tritium inventories at numerous locations was also paramount, with over 5000 tritium transfer operations logged to and from JET and between the various AGHS sub-systems.

Operating experiences, learnings and proposed system and process improvements are presented in this paper and have been broken down into a range of topics including: individual AGHS sub-systems, human factors, and engineering principles. This information was successfully used to improve processes for the AGHS in preparation for DTE3 (September to October 2023), and is of wider interest for tritium fuel cycle facilities being designed and built for future fusion machines and power stations.

2. System overview: layout and operation

The AGHS stores, supplies, and recovers tritium for re-use. An overview of and experiences from AGHS operations have been reported previously for the first D-T experiment [4, 6, 7]. Detailed descriptions of the systems and technologies used are not repeated here. However, the systems and their usage evolved over time, therefore a summary of sub-systems, upgrades made, and typical duties during the latest D-T campaigns is presented in section 3. Some general information, including system limitations, and where the latest operating philosophy deviates from the original design intent, is covered in later sections 4 and 5. One of the key underlying principles that guided the design and operation of the systems is that tritium shall be contained within AGHS, the JET vessel and transfer systems.

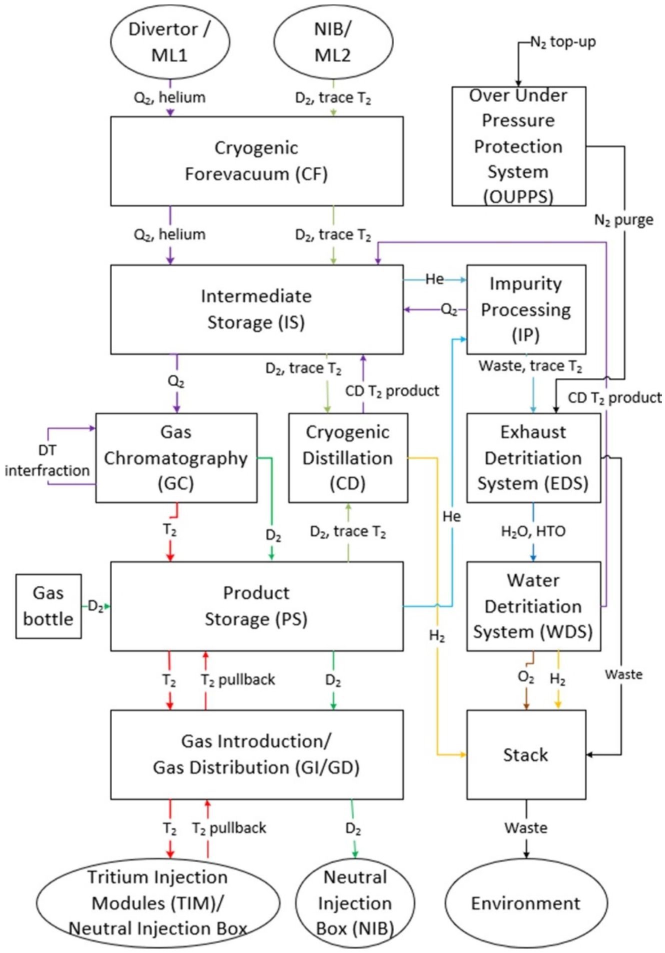

Figure 1. AGHS gas movements between sub-systems typical for recent tritium campaigns. Notes: T_2 Pullback refers to pumping unused tritium back to product storage uranium beds at the end of JET operational day. Over Under Pressure Protection System (OUPPS) refers to the nitrogen-filled secondary containments and sub-system used to maintain a correct amount of depression relative to atmosphere in each case. More detailed system flow diagrams may be found later in section 3.

Figure 1 shows the sub-systems and the routes along which the gas was transferred through the AGHS during the recent D-T campaigns.

At the end of JET operational days, the gases pumped in the divertor and neutral injection box (NIB) cryopumps were released into the matrix lines (ML) 1 and 2 respectively. The divertor gas routed through ML1 was deuterium and tritium, plus helium, resulting from pulses. Note, some of the JET experiments used He-3 for ion cyclotron range of frequencies heating schemes. Others used neon, and in some cases argon, for divertor heat load control. Since these gases are inert, AGHS processing of the exhaust from JET torus and

NIBs was not affected. No further reference to these gas species are made in this paper.

The NIB gas routed through ML2 was essentially deuterium, although trace tritium was usually present. The cryogenic forevacuum (CF) system [8] contains several liquid helium (LHe) cooled cryopumps available to pump the MLs; separate CF modules were used for ML1 and ML2 respectively.

Once the gases were fully collected into CF, the MLs were isolated and transfer of gas to the intermediate storage (IS) [9] system was initiated. There are four uranium beds in IS, allowing for the D-T mix in one CF module and deuterium in another CF module to be pumped on to separate U-beds. Helium had to be removed from the U-bed to enable effective pumping (see section 3.1), this helium was collected in one of two small tanks within IS.

The priority during these operations was to recover tritium at a sufficient purity to be made available for re-use the next day. The D-T isotope mix was therefore transferred to the gas chromatography (GC) system [10]. A portion of the gas was injected onto three separate palladium filled columns to approximately 1/3 capacity each. Then, protium eluent was injected into each column in turn; the protium preferentially displaced tritium, and then deuterium, yielding tritium and deuterium products. Mixed isotopes, referred to as interfractions, were recirculated within GC for future processing.

The tritium and deuterium streams from GC separations were collected in dedicated tanks within the product storage (PS) system [9]. The tritium and deuterium were transferred to one of several dedicated tritium and deuterium U-beds respectively. Any helium present was extracted to a dedicated helium holding tank. The tritium U-bed was heated, and a sample transferred to the analytical system (AN) [11] to confirm suitable tritium purity. All contents of this heated U-bed were then transferred to a separate U-bed. The tritium was then available for re-use.

On a new JET operational day, tritium was metered into the gas introduction/gas distribution (GI/GD) system [12], and on to the NIB [13] or into five tritium injection modules (TIMs) [14] as requested. Periodic top-ups were provided throughout the day. At the end of the day, tritium remaining in these feed system (NIB, TIM and GI/GD) reservoirs was returned to a cold PS tritium U-bed.

Deuterium supplied for JET was provided fresh from a gas bottle. The deuterium subsequently recovered from JET operations was processed in the cryogenic distillation (CD) system [15], which performed isotopic separation to produce an enriched tritium in deuterium mix, which was sent to IS, pending further isotopic separation in GC. The CD protium and deuterium product was monitored using ionisation chamber and would be periodically discharged to stack only once tritium concentration was indicated to be lower than the discharge limit.

In fusion fuel cycle design, several process loops are typically defined to help minimise tritium inventory and reprocessing time. In AGHS, GC performs the inner loop isotopic separation of predominately 50:50 deuterium: tritium exhaust gas. CD performs the outer loop isotopic separation which simultaneously acts to maximise trace-tritium recovery for re-use and produce a protium, deuterium stream that is sufficiently tritium-free to safely discharge from the facility.

Helium (and other impurities) collected in IS and PS was transferred to the impurity processing (IP) system [16, 17]. This system cycles gas through a loop including a nickel catalyst bed and palladium-silver permeator. Any tritium-bearing impurities (hydrocarbons, water) were broken down in the catalyst, producing hydrogen isotopes which were separated from the gas mix via the permeator, and routed into an IP U-bed. This Q_2 mix was sent to IS, ultimately for isotopic separation in GC. Detritiated impurity and helium mix was periodically discharged to the EDS [5].

EDS contains catalytic recombiners which convert any tritium into water form, and a molecular sieve bed which then traps the water, with detritiated gas sent to the building stack. All gases discharged to stack are monitored for tritium contamination. EDS processes several feed gases depending on JET or AGHS operating modes, but the bulk of gas processed during D-T operations was nitrogen from AGHS secondary containments which were purged daily by the OUPPS. The lightly tritiated water is recovered via regeneration of the molsieve and drained to a storage tank.

The water detritiation system (WDS) is designed to process the water arising from EDS. The water is split into hydrogen isotopes and oxygen, via electrolysis; oxygen is discharged to stack. The hydrogen isotopes feed into a dedicated CD column [18], which produces a tritium enriched bottom product routed to IS, and clean protium product discharged to stack. Note, WDS was not operational during the recent JET tritium campaigns.

Indicative timings for reprocessing of tritium are shown in figure 2.

Note that this is considering the route of a given portion of the tritium, not the entire stock, to indicate how long it took from being pumped from JET divertor to being put back into JET. In practise, parallel processing was being undertaken, e.g. whilst one portion of the total tritium stock was being transferred from CF to IS, another portion could have been undergoing isotopic separation in GC, and yet another portion of the stock would be in a hot U-bed being fed to the JET NIBs and TIMs via GI/GD. Because the total processing time was more than 24 h and the total system tritium inventory was finite, AGHS could supply tritium to JET for two consecutive days before requiring a day to catch-up on reprocessing.

3. Sub-systems

3.1. Storage systems—uranium beds

Uranium beds are used for storage of tritium, deuterium and hydrogen isotope mixtures [9]. Pure tritium was stored in PS, whilst mixed isotopes were stored in IS as well as within the GC and IP sub-systems. Tritium import was managed using the upgraded tritium decanting facility [19].

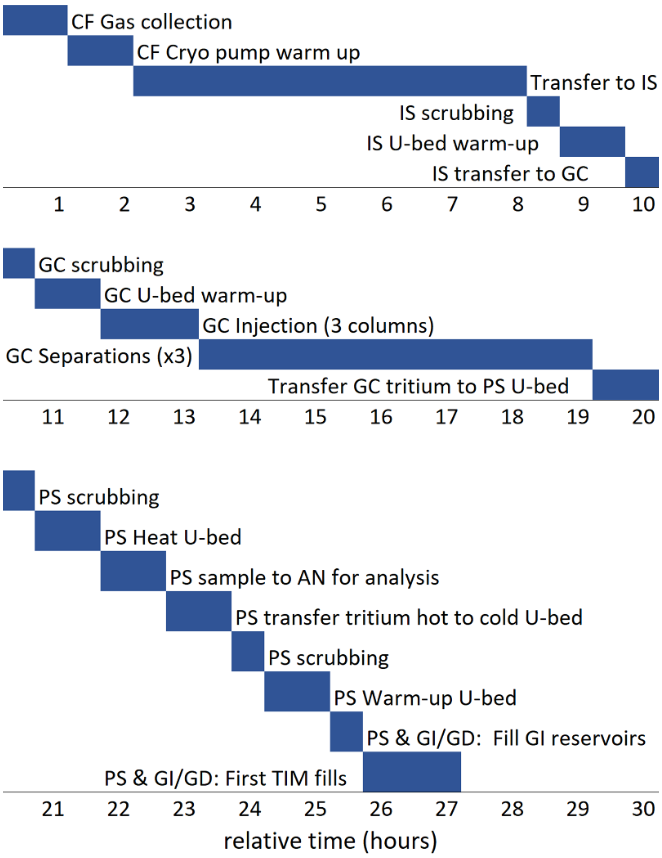

Figure 2. AGHS tritium reprocessing—indicative operation times. It would take typically 24–36 h to make tritium available for use having received it from the JET divertor cryopump. The larger the inventory of helium (He-4 or He-3 resulting from tritium decay) the longer the transfers typically took.

Since DTE1, IS has been enhanced by addition of a bellows and scroll pump-set, plus two small tanks downstream of the pumps. This equipment allows for scrubbing of gas through the U-beds, where uranium hydride is formed, with the helium collected into the tanks as described below. A combined CF and IS schematic is shown later in figure 9. The PS system is functionally the same as reported for DTE1 [9]. A second U-bed outlet manifold, which would have enabled more operational flexibility (see section 3.5) was installed but not commissioned in time for DTE2 or DTE3. A schematic of PS U-beds is shown in figure 3.

When transferring to the bed, the formation of uranium hydride pumps the gas from its source. However, the pumping efficacy is affected by a mechanism known as helium blanketing, where the presence of helium within the U-bed vessel slows down and eventually prevents the formation of further uranium hydride. Whilst this is a known phenomenon [20], it was found that only very small quantities of helium need to be present within the bed to stop the pumping. Even when absorbing deuterium, with what should be trace tritium contamination at most, blanketing would often occur. For reference, the lower threshold for tritium accounting within the AGHS process was 0.1 TBq, so the precise value of tritium and therefore helium in this case is unknown. The helium blanketing effect may be exacerbated by the age and condition of the U-bed, with helium potentially trapped in the U-bed matrix.

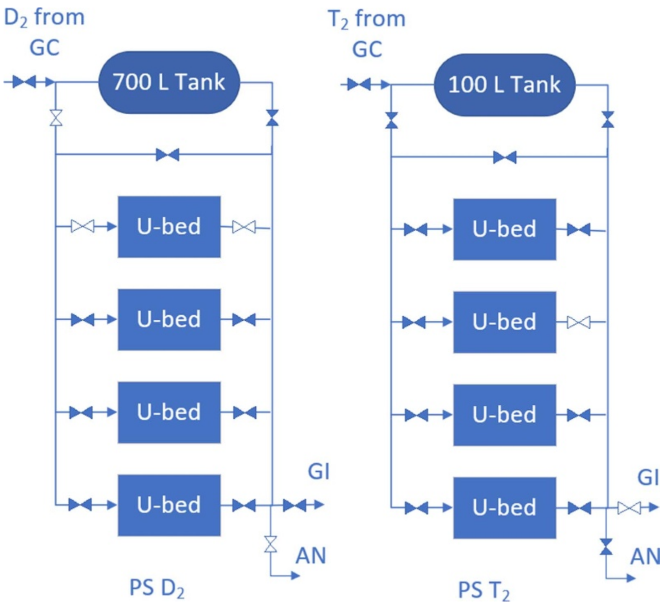

Figure 3. Schematic flow diagram for product storage system. There are four Uranium beds each for deuterium and tritium storage. Deuterium from GC was sent to CD for detritiation prior to discharge. Fresh deuterium from bottle was supplied to JET. Tritium from GC was sampled for purity in AN system prior to being supplied to JET.

Figure 4 shows the deuterium transfer from PS deuterium holding tank to a U-bed.

Figure 5 shows a typical pumpdown from CF to an IS uranium bed. The total transfer time was often excessive (the reasons for which follow in the figure caption and the next paragraph), which had implications for the overall reprocessing duration as shown in figure 2.

One of the limiting factors for the CF to IS transfer was the small size of the helium collection tanks (16 plus 32 L respectively), which necessitated multiple pauses of the CF pumpdown to allow for scrubbing and inventory reduction as the Q_2 from the tank adsorbed onto the U-bed. Additionally, better IS pumping capability would have been achieved if the bellows pump had been in service backing the scroll pump, which would have allowed a much larger discharge pressure into the tank (1000 instead of 150 mbar(a)) and potentially less back pressure upstream of the scroll pump. The bellows pump tripped several times due to an electrical fault so a decision was made early in DTE2 to avoid its use.

An example of uranium bed heating and cooling is shown in figure 6. The pressure and temperature trend is characteristic of all AGHS U-beds, however heat up times varied from bed to bed, dependent on bed capacity, bed loading, and the U-bed condition (heaters, heat transfer, containment vacuum).

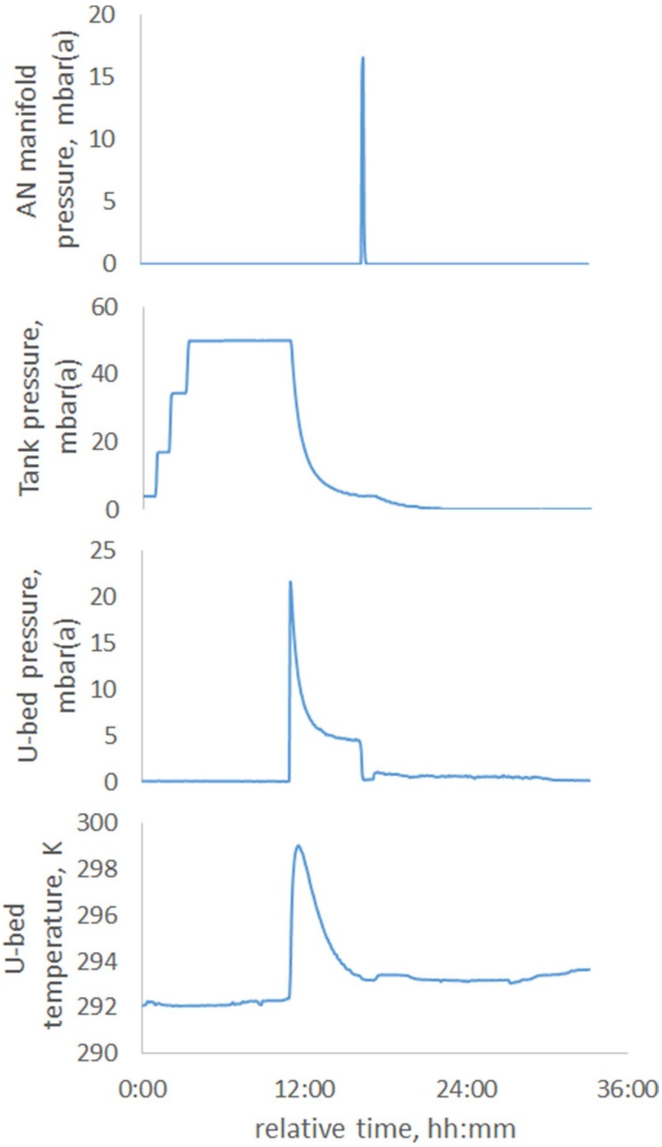

Figure 4. PS Deuterium tank to U-bed transfer, 20–21 October 2023: The U-bed alone cannot fully pump down the tank and requires removal of blanketing gas. This is indicated by the peak in analytical system (AN) manifold pressure, which follows opening of the U-bed outlet and subsequent transfer and pumpdown of helium via AN to the Impurity Processing system. Deuterium continued to be pumped by the U-bed throughout.

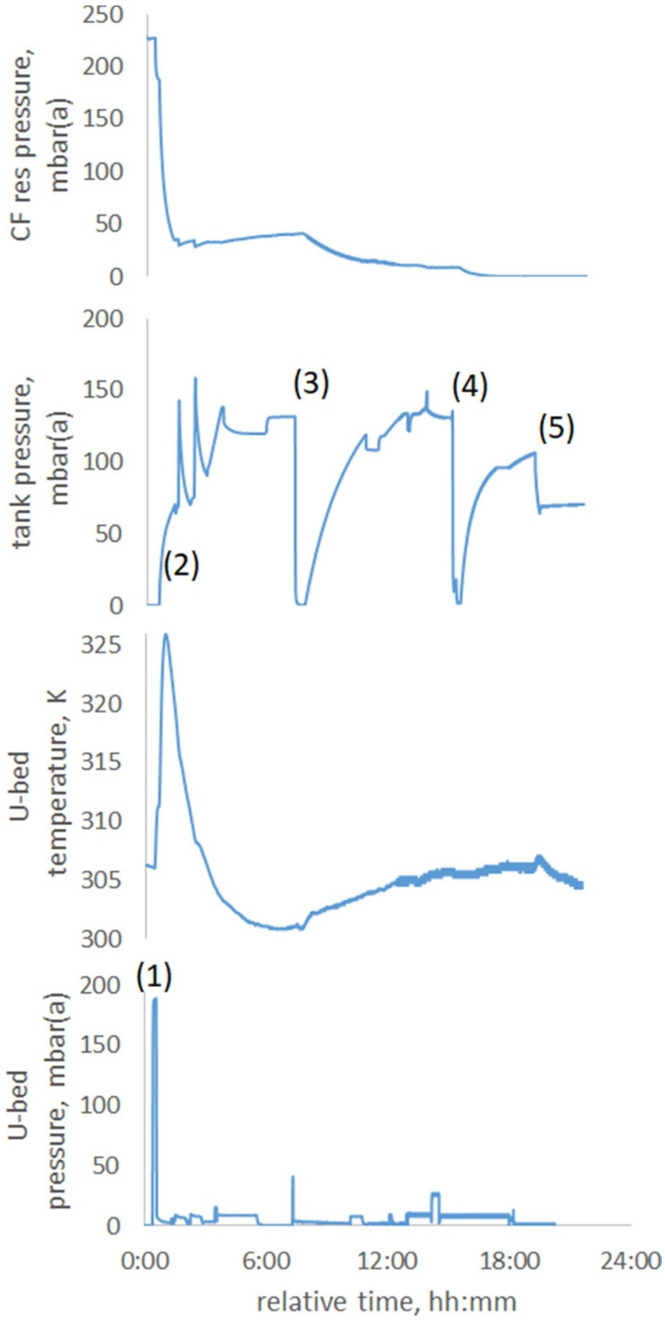

Figure 5. CF transfer to IS U-bed, helium to IS tank, 6th–7th October 2023. The gas was initially pumped directly on the Uranium bed (1). The pumping speed reduced as a result of helium blanketing, so the outlet valve of the U-bed was opened to mechanically back the U-bed pumping into a downstream IS tank (2) as indicated by the rising tank pressure. The fastest way to recover the last portion of gas was to mechanically pump directly to the IS tank, bypassing the U-bed which otherwise introduces a significant pressure drop through the pumping route. Several times the pumpdown of CF was paused to allow scrubbing of gas collection in the IS tank through the U-bed as shown (3)–(5). In this way, hydrogen isotopes were separated from the remaining helium, but each pause and scrub operation added time to the overall transfer duration.

On several occasions during bulk (>300 bar.L) transfers of hydrogen isotopes between U-beds, particularly in the absence of blanketing impurities, the exothermic formation of uranium hydride generated sufficient heat to overcome the U-bed's nitrogen cooling. This caused the U-bed to warm sufficiently that the absorption slowed and stalled. As this heating effect could raise the U-bed temperature beyond the high temperature shut-off point for the nitrogen cooling circuit (450 K), operational delays resulted waiting for the U-bed to cool back down before the transfer operation could be resumed.

During the DTE2 campaign, a PS U-bed nitrogen cooling system leak was identified, with slightly elevated tritium levels detected in the PS room. Although tritium concentrations were still low (typically below 0.3 MBq m^{-3}), this resulted in restricted access to the PS room. To minimise the leak

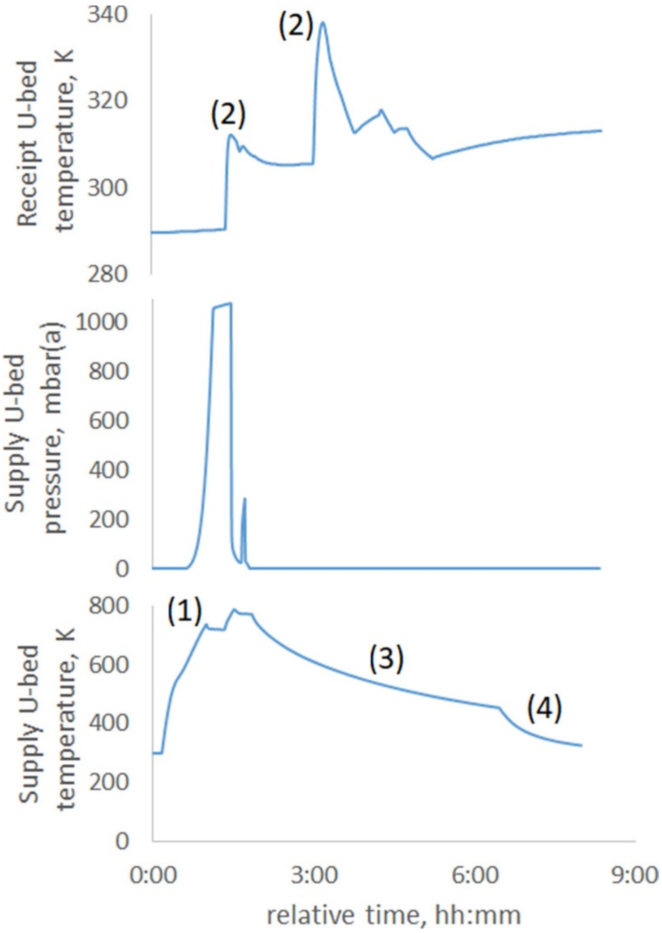

Figure 6. U-Bed to U-Bed transfer in GC, 18–19 October 2023. The heating phase is shown (1), followed by transfer to a second U-bed (2) where temperature rise due to exothermic formation of UQ_3 can be seen. The source U-bed cooldown is split into two phases: natural (3) and with addition of gaseous nitrogen cooling (4). For reference, this was an internal GC transfer, of approximately 56 bar.L of mixed hydrogen isotopes.

rate, the allowable operating pressure in the affected tritium U-bed was reduced, which added additional complexity to GI feeding, accountancy, and management of inventory in PS. It became more difficult to do AN testing, and also resulted in additional scheduling complexity with operators having to ensure all gases were in the correct U-bed at the correct time.

3.1.1. Recommendations. Learning from these experiences, using uranium beds as a sole means to pump hydrogen isotopes must be avoided, instead a hybrid system including sufficient mechanical pumps and tanks, must be included within designs to ensure that transfers to uranium beds are performed efficiently. This includes U-beds used for hydrogen or deuterium, based on the operating experience with helium blanketing. It is recognised this would add more cost and complexity to the plant, but would be very beneficial for operations.

Further, some automation of the process could be implemented, to identify U-bed blanketing and switch pumping route, isolate source, and automatically scrub. Note, scrubbing here refers to circulating mixed gas through the U-bed until all detectable hydrogen isotopes have been captured on the U-bed.

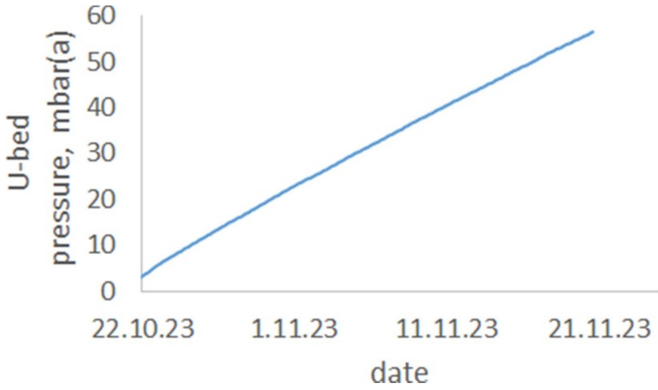

Figure 7. Helium generation and pressure build-up during tritium storage on U-bed, 22nd October–21st November 2023. This corresponds to 10 000 TBq of tritium in the U-bed with an internal volume of 2.38 L.

The mechanical design of U-beds should be optimised to improve cooling capability and resilience to helium blanketing. During transfer to a U-bed, software could automatically isolate the bed if the temperature became too high, and re-open once it has reduced, under the condition that this automation does not give rise to any safety implications.

It should be ensured that services such as nitrogen or water cooling, particularly in contact with high temperature tritium equipment such as U-beds, are designed, maintained and tested to reduce the likelihood of a leak occurring. Codes and standards should be conservatively applied and with tritium compatibility considered.

Plenty of redundancy of uranium beds is required. Several beds in AGHS are out of service or operate at reduced capacity due to failures, irreversible poisoning, heater faults, or the mentioned nitrogen cooling leak. Redundancy here refers to the U-beds themselves, as well as spare or redundant instruments and heaters for each bed.

Volumes and hardware also need to be able to accommodate He-3 generation from decay of tritium stored on U-beds. An example showing pressure increase within a PS U-bed containment is shown in figure 7.

3.2. Cryogenic Forevacuum

The cryo pumps of CF [8] were used for providing backing of the evacuated matrix (exhaust) lines connected to the torus and NIBs, and pump down of the exhaust and unused gases at the end of each operating day, when the torus and NIB cryopumps were warmed up. Since DTE1, the system remains functionally the same, with the exception of the addition of an ITER-like prototype cryosorption pump in one CF module [21]. This new equipment was not used during the recent campaigns.

One of the main issues encountered with the system was that during the pump down (also referred to as gas collection), the loading of gas on the accumulation cryo panel (ACP) would sometimes result in loss of cooling at the panel. Quick intervention was often required to isolate the cryo-pump, allowing the cooling to stabilise before opening back up to the ML to collect any remaining gas. Failure to intervene could result in the entire inventory being released from the cryopump back into the ML, with a risk to damage the JET turbo pumps. It is postulated that warming of panel could cause vaporisation of the liquid helium coolant, which in turn led to further localised warming and re-vaporisation of the process gas.

Cold systems like CF should not be used to hold gases from regenerations for any extended periods of time. A loss of cooling would lead to rapid expansion (expansion coefficient of 1:848 for protium [22]) resulting in over-pressurisation of the ACP or cryogenic transfer panel (CTP) in question, rupture of bursting discs and safe relief of gas to the large (10 m^3) buffer tank, and then subsequent recovery and bursting disc replacement.

The CF modules' design included the ability to separate helium from hydrogen isotopes as described in figure 8.

In practice, separation of the gases was never effective and a different process was adopted to pump all gases to IS, scrubbing over the recipient U-bed and mechanically pumping the helium to a pair of small tanks, prior to sending to IP. The operating instructions (OIs) were not updated during DTE2 to reflect this however, and so cooling of both parts of the cryo module continued to be performed which was not an efficient use of liquid helium cooling. For the DTE3 campaign in 2023, the OIs were updated, and cooldown of the CTP was no longer performed, instead gas was expanded directly from the ACP to the cryopump reservoir and on to IS.

A schematic of one CF module and interfacing systems is shown in figure 9.

An example of ACP cooldown is shown in figure 10. The cooldown from LN_2 to LHe temperature (77–4 K) typically took 40 min.

An example of a gas collection and pumpdown to IS is shown in figure 11.

An issue that was encountered, that was not unique to the CF system, were sticking pneumatic process valves. These did not change state when instructed by the operator, with the control system feedback incorrectly showing a valve as open when in reality it was closed. A work around to manually open the valves in question was adopted (using a mechanical pump to suck air out of the solenoid).

Valves on the cooling circuit also suffered sealing issues: Although leak tight at ambient temperature, some valves were failing to seal properly at 4 K. This translated to difficulties in warming up the cryo pumps and resulted in an extended time to transfer gas out of CF, since the helium cooling was still partially going to cryo-panels where no longer needed. It is shown in figure 11 that warm up and pump out took approximately 24 h in this example. Transfers of ML2 gas to IS were especially long since they were lower priority than ML1 gas transfers, with mechanical pumping of helium mostly dedicated to the ML1 transfer.

It was also noted that the shared helium return design, common to all CF modules, was not optimal; the boil-off had the effect of cooling modules that should have been warming.

3.2.1. Recommendations. For similar systems, careful attention during the design of the system must be taken, to ensure the cryo panels and especially the cooling systems are sized to receive the quantity of gas, and rate of delivery of gas be managed to avoid the coolant vaporisation issues encountered in CF. Means to monitor how much gas is on the panel in real-time would also help.

Reliance on isolation valves opening or closing should be considered in the system design, and systems which operate continuously should avoid the need to routinely switch routes if possible. The risk of valves failing to open or close and seal must be assessed throughout the design. Specification of valves must consider the risk of sticking in position, or failing to seal, particularly for valves operating at cryogenic temperatures.

Note, these issues may be attributed to the AGHS maintenance philosophy. Most production plants would periodically replace valves if their effective performance and seating was critical to production (according to the principles of reliability centred maintenance). By contrast, the AGHS mostly followed 'run to failure' maintenance, since it was rarely cost effective to replace equipment in a seldom used asset. The radiological risk to people and the environment from invasive maintenance to replace components 'just in case' was also often not ALARA (as low as reasonably achievable). The maintenance philosophy for fusion power plants will require careful assessment of the balance of risk.

The liquid helium distribution could be automated to optimise liquid helium consumption versus keeping the cryopanel suitably cold to prevent the release of gas. This would be a sequence linking the cryopanel's vapour pressure indicator and LHe flow control valves to adjust the vapour pressure automatically.

It is also recommended to implement a built-in residual gas analyser (RGA) in any helium return line to the cryoplant to identify any contamination issues.

3.3. Impurity Processing

The IP system as operated during DTE1 [16], underwent a major upgrade [17] and now works by pumping waste gases through a nickel catalyst and palladium permeator in series, to liberate hydrogen isotopes from compounds such as methane or water, and then pull out the hydrogen isotopes by permeation against vacuum. Additionally, one of the two IP scroll pumps failed and was replaced by a pair of small bellows pumps to provide pumping capability in the event of the remaining scroll pump failing.

The intent was to use an IP uranium bed to pump and store the hydrogen gases from the permeator, however, the pumping speed was very slow. This may have been caused by helium blanketing, although helium would only be present in trace amounts due to tritium decay. The large volume of IP processing tank meant a low feed pressure into the permeator, also limiting permeation rate.

To remedy this, a new procedure was devised to mechanically pump the permeate into a small (16 L) tank, using part of the system originally designated for vacuum containment

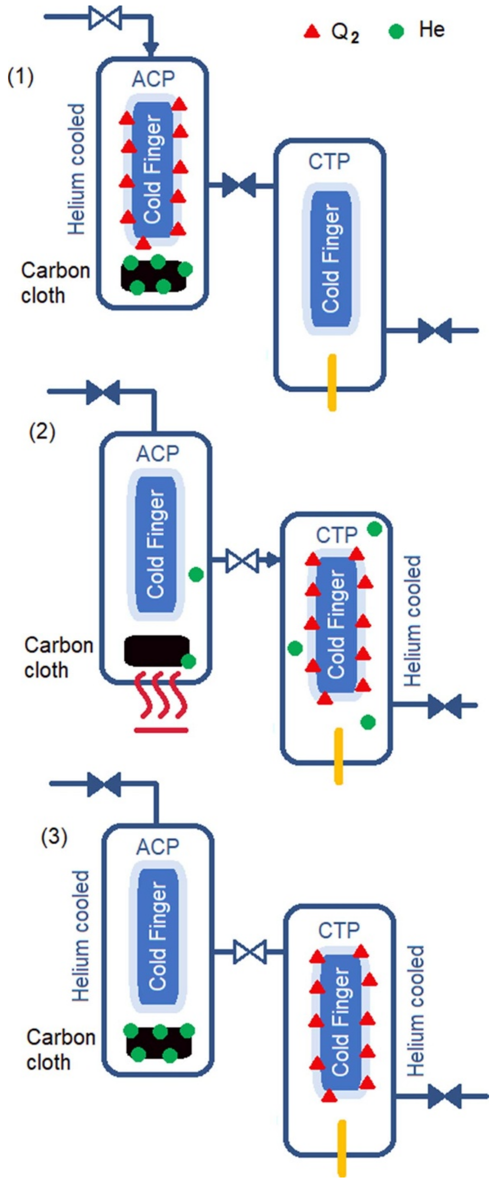

Figure 8. CF cryopumping with helium separation from hydrogen isotopes. Isotopes of hydrogen (Q_2) and helium are represented by red triangles and green circles respectively. Protium, deuterium and tritium are pumped onto ACP or CTP cold fingers whilst helium adsorbs onto the carbon cloth when cold. Gas is first cryo-pumped into a volume including charcoal beds (the ACP), stage (1). The cryo panel would be warmed to 77 K, releasing all gas onto a second, cold cryopanel (the CTP—cryogenic transfer panel), stage (2). The ACP would then be re-cooled resulting in capture of the helium into the carbon cloth, stage (3) and the CTP isolated from the ACP. The hydrogen steam would then be sent from CTP for isotopic separation, whilst helium sent from the ACP to impurity processing for clean-up prior to discharge via EDS.

pumping only (see also section 4.3 on ergonomics—manual valve operations). There were several issues doing this. First, due to isolation valves passing whilst closed, gas pumped into this part of IP was reaching the sputter and getter pump-set used for maintaining high vacuum in IP and IS uranium bed vacuum containments. Pressure spikes could cause a hard-wired trip of IP, so ultimately the sputter and getter pump-set had to be carefully isolated during IP processing, and conversely IP processing had to be paused during heating of IS U-beds as the sputter and getter pump-set required reinstating. The next issue was when the tank collecting permeate pressure was over ∼150 mbar. This scroll pump back pressure at the permeator could cause a hard wired trip of the permeator module, a turbo pump between the permeator and scroll pump would have remedied this. Finally, once the tank was filled (recovering only a couple of bar.L each time), the IP processing had to be paused, with all gas pulled back to the main IP process tank to evacuate the process lines. This was necessary to transfer collected hydrogen isotopes to an IP U-bed without contaminating it with other waste gases.

A schematic of IP is shown in figure 12.

Figure 13 shows the IP process adopted, with permeate collected in the 16 l tank, subsequent processing pause and transfer of the tank gas to U-bed.

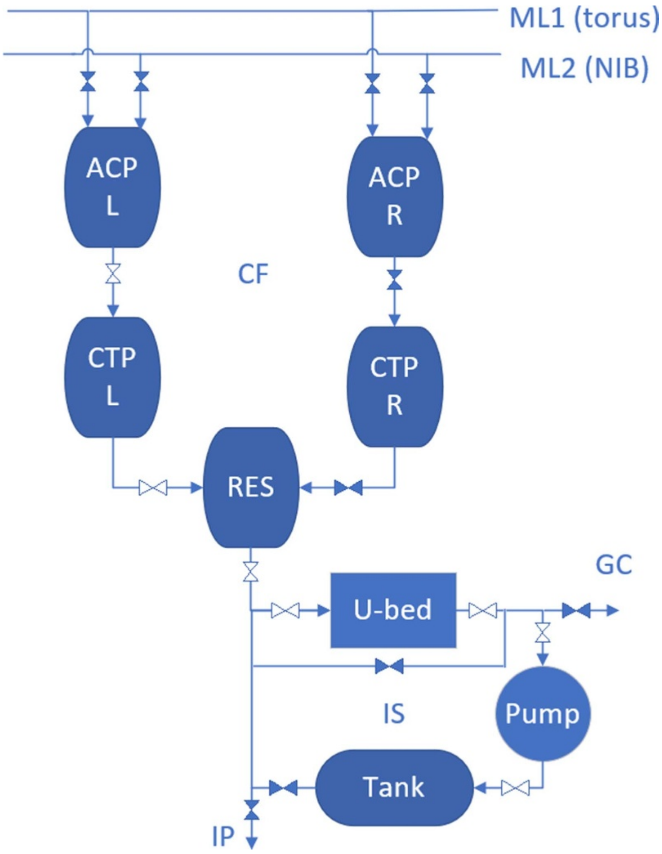

Figure 9. Schematic flow diagram of a CF module and interfaces. A single CF Module is shown for simplicity. In DT operation, gas was collected in either left or right hand side cold ACP, the ACP was then warmed allowing gas expansion into the CTP and 100 l reservoir. It was next pumped onto an IS U-bed, with helium mechanically pumped into one of two small tanks. The helium was then sent to IP and hydrogen isotopes transferred from U-bed to GC.

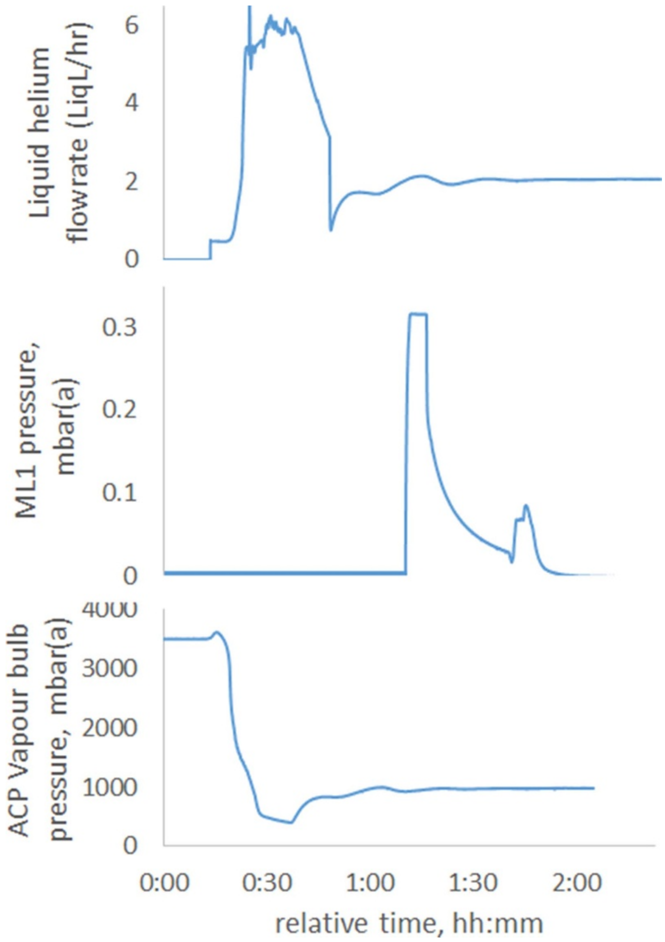

Figure 10. Cooling of CF cryo-panel and gas collection, 24 October 2023. The temperature was inferred by observing the drop in pressure of the ACP helium vapour bulb. Cooling demand is indicated by the liquid helium flowrate. The ML1 pressure change represented the gas being transferred from JET into the matrix line and subsequent pump down onto the CF ACP.

The palladium permeator operates at 400 °C and is at risk of mechanical damage if it contains hydrogen isotopes when cooling down. The hardwired trip for the module would lead to exactly this condition if it occurs during processing.

3.3.1. Recommendations. As can be seen, operating IP in this new regime created several challenges and risks, as well as operator time to access the plant to manually operate valves each time a tank to U-Bed transfer was required. Plant modifications (both to plant and to process) must be assessed to understand all implications.

Primary (process) containment and secondary vacuum containment, and associated pumps should not be mixed; certainly not for routine operations. Use of sputter and getter pump sets can be replaced by ability to turbo pump permeated gas from secondary vacuum containment as required, this is how the future H3AT facility being constructed at Culham [23], will be operated. The permeation rate through primary containment must be assessed however, to determine how frequently the secondary containment will need to be pumped down to avoid the vacuum spoiling.

Safe shutdown of permeators must be considered. In the event of a fault they should either be isolated but with the heater still on, or evacuated and allowed to cool. In practice, this means ensuring power remains available to the heater, or ensuring a fail-safe evacuation route remains available depending on the fault.

When IP was required for tritiated water processing, carbon was required on the catalyst bed which is achieved by first processing methane injected into the circuit. There was however no direct visibility of how much carbon was deposited on the catalyst.

Trace heating on the IP pipework (i.e. increasing the pipe surface temperature by using electrical cable heater) would have reduced internal water condensation and therefore would have meant shorter pump-down times, and more efficient impurity processing overall.

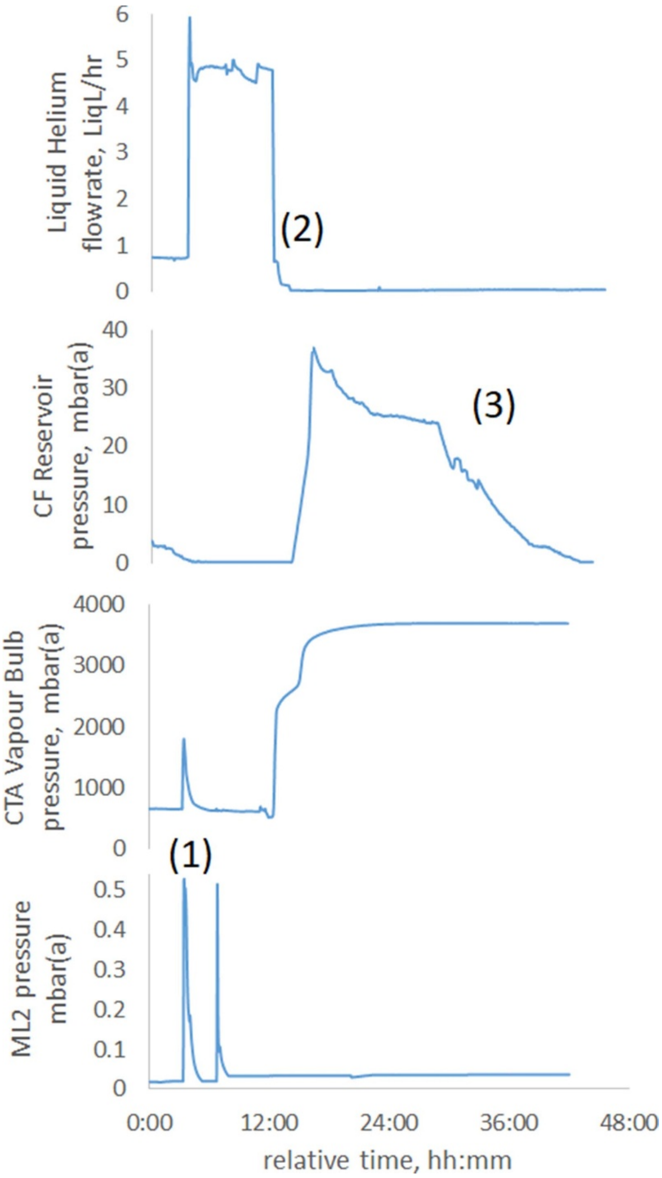

Figure 11. NIB regeneration gas collection on CF cryo-panel and evacuation to IS, 11–12 October 2023. The gas was released into ML2 (matrix line 2) from the JET neutral beam cryopumps, isolation valve opened and pumpdown commenced (1). Next the ML2 isolation valve is closed and LHe cooling to the cryo-panel was then turned off allowing warm up and expansion (2) into the dedicated CF module expansion reservoir. Finally the route to IS was opened and pumping to an IS U-bed commenced (3).

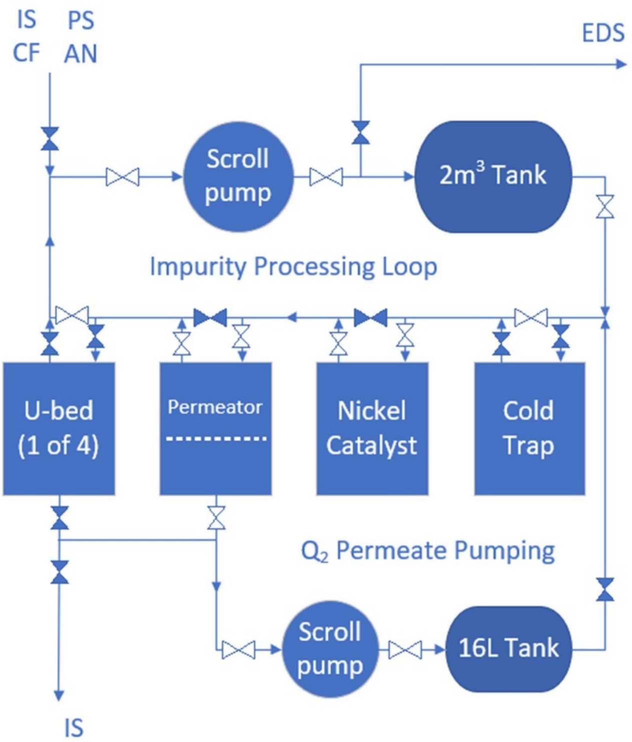

Figure 12. Schematic flow diagram of IP system. Gas was collected in 2 m^3 buffer tank and circulated through nickel catalyst and permeator. Recovered hydrogen isotopes were pumped into 16 L tank. Each time a transfer of hydrogen isotopes to U-bed was required, the main process gas had to be returned to the 2 m^3 buffer tank and lines evacuated.

3.4. Gas Chromatography isotope separation system

Hydrogen isotopes were separated successfully by displacement gas chromatography during the DTE campaigns. The system is functionally the same as previously reported [10]. A schematic flow diagram is shown in figure 14.

The system requires an operator to monitor relevant instrumentation to identify the transition between different isotopes and manually select the target route accordingly. This method requires good attention over the course of several hours and it poses a risk to the operational programme if a mistake is made, resulting in diluting the recovered tritium stream with deuterium or protium.

The key operations of GC are shown in the following figures.

Figure 15 shows the injection of mixed hydrogen isotopes (transferred earlier from IS).

Figure 16 is an example of a GC separation. The most critical step was during sending tritium to the PS tritium holding tank, as high purity (>99.5%) tritium was required and contamination with deuterium would occur quickly if the operator did not react swiftly to re-route the evolving gas from the tank to the interfraction U-bed (point 2 in the figure).

Accountancy for this operation was arguably most complex, involving calculating the quantities of gas through the various stages, identifying destination locations and working out the overall isotopic breakdowns of each of these gas mixtures.

Column inlet mass flow meters were monitored to manually control flow rate and integrate for the quantity of gas loaded into the GC columns. These flowmeters suffered reliability and calibration issues, resulting in incorrect readings and difficulty operating the system.

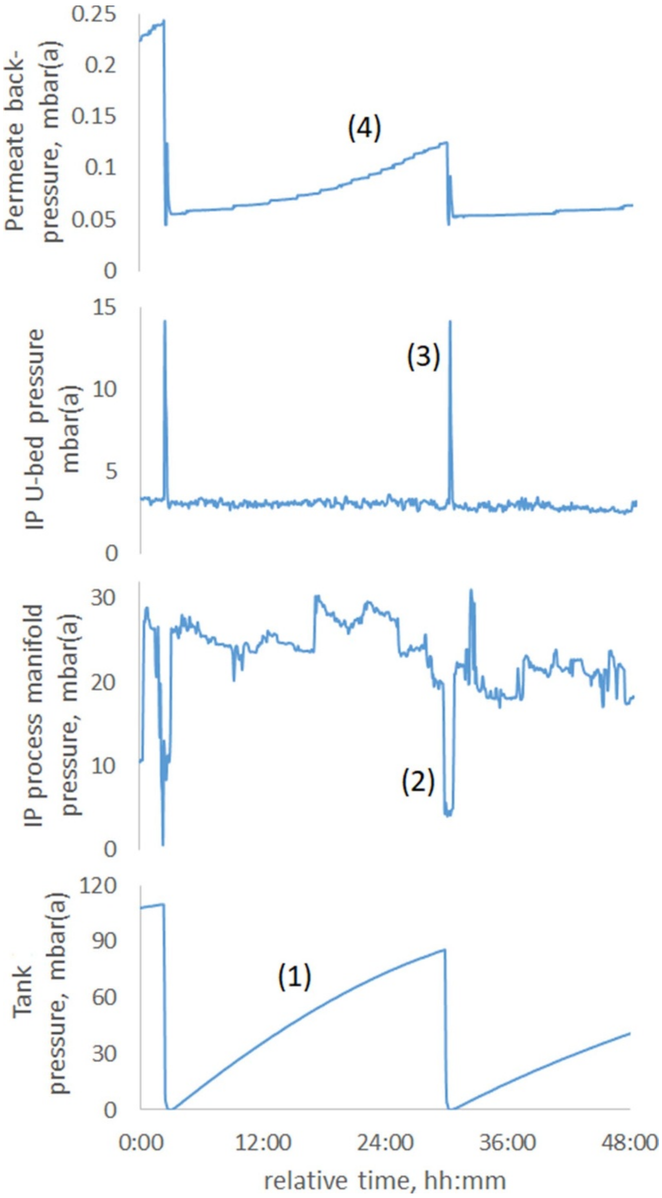

Figure 13. IP processing, 21st–22nd October 2023. The recovery of hydrogen isotopes into the 16 L tank (1), then subsequent pause of IP processing, pumpdown of IP lines (2) and transfer of the 16 L tank gas into IP U-bed (3). Steps 2 and 3 result in a pause to processing typically 60–90 min each time, as well as requiring the operator intervention to perform them. The rising back-pressure mentioned earlier is also shown (4).

Finally, figure 17 shows the GC regeneration, to make the columns available for the next injection and separation operations.

The batch nature of GC operation results in hold-up of tritium inventory as well as an operator intensive process. Whilst not optimal, it is noted that GC does share some of the principles of operation with TCAP (Thermal Cycling Absorption Process [24]).

3.4.1. Recommendations. Should this type of separation system be used for future fuel cycles, then automation of the process is recommended. It is recognised that both the instrumentation and software would need to be very reliable in order to perform the duty without fault, however it should be achievable given some investment.

Instrumentation choices must assess the advantages and disadvantages for different gases and operating conditions. For example, the choice of mass flowmeter for mixed Q (Q = H, D or T) in GC: these thermal conductivity instruments were calibrated for protium, which are inaccurate for mixed Q. An alternative solution would be a means to compensate the measured flow for hydrogen species by using another instrument in tandem such as a katharometer to identify the isotope.

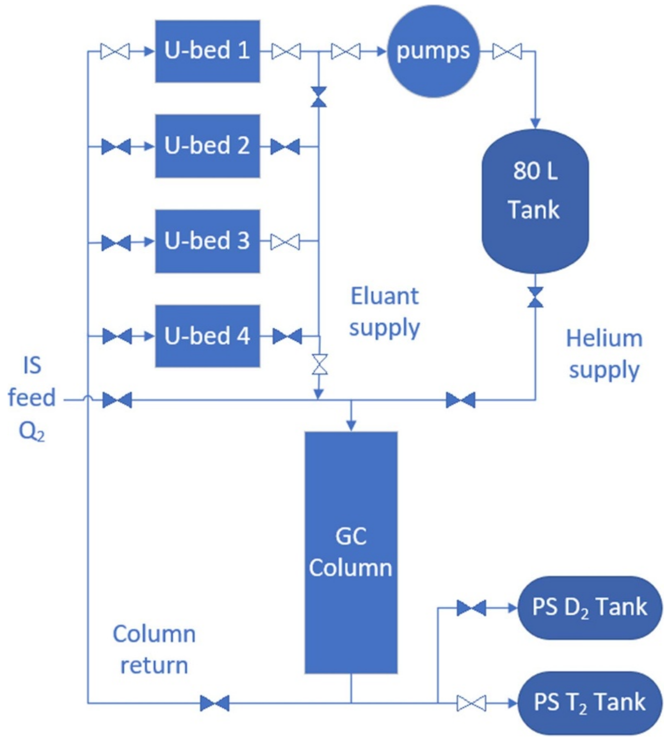

Figure 14. Schematic flow diagram of GC system. Only one GC column is shown. Hydrogen isotopes were injected into the column from U-bed 2 or direct from IS. Next protium was fed into the column from either U-bed 3 or 4. Once saturated, protium would displace tritium preferentially, followed by deuterium. By changing the outlet routing, tritium, deuterium and DT Interfractions were separated. After separation operation, the column was regenerated by heating and protium returned to U-bed 3 or 4. Helium was used to aid regeneration and back-fill the column.

3.5. Product Storage and Gas introduction/ distribution systems

To feed tritium to JET, the PS and GI/GD systems were used in conjunction. In the PS system, tritium was expanded from a hot U-bed into the PS U-bed outlet manifold (see figure 3) and metered into GI tanks. The target NIB or TIM was then selected and the appropriate matrix valve opened to expand the tritium across into the receiving NIB or TIM feed vessel.

There was only a single outlet manifold from the tritium U-Beds. A second one was work-in-progress but unfortunately

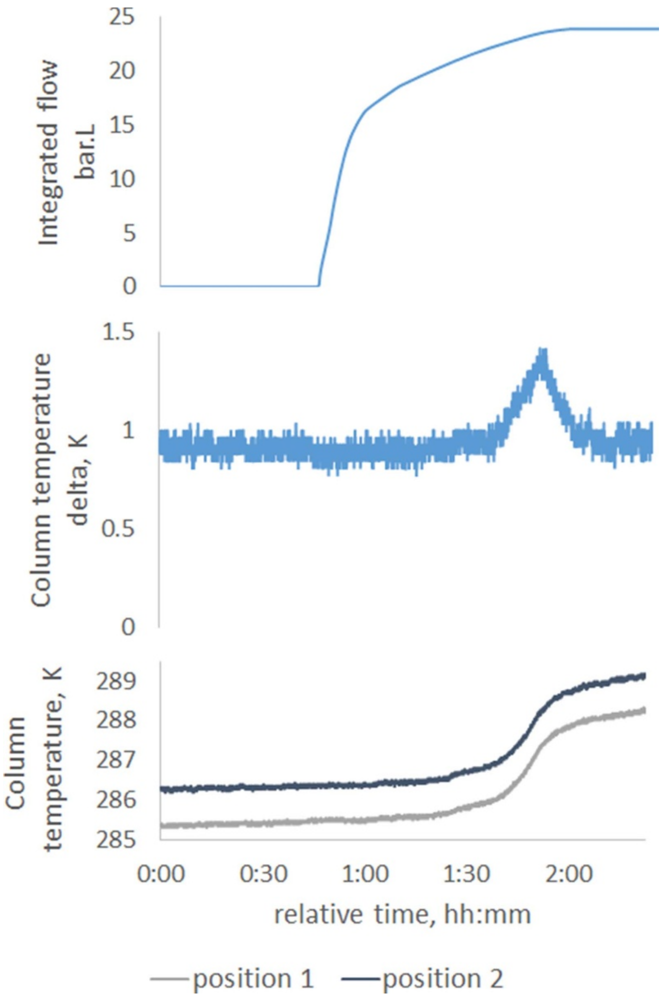

Figure 15. GC Column injection, 15 October 2023. The GC column was filled to approximately 1/3 capacity. The thermopile response (column temperature delta) was used to indicate this quantity of gas had been injected.

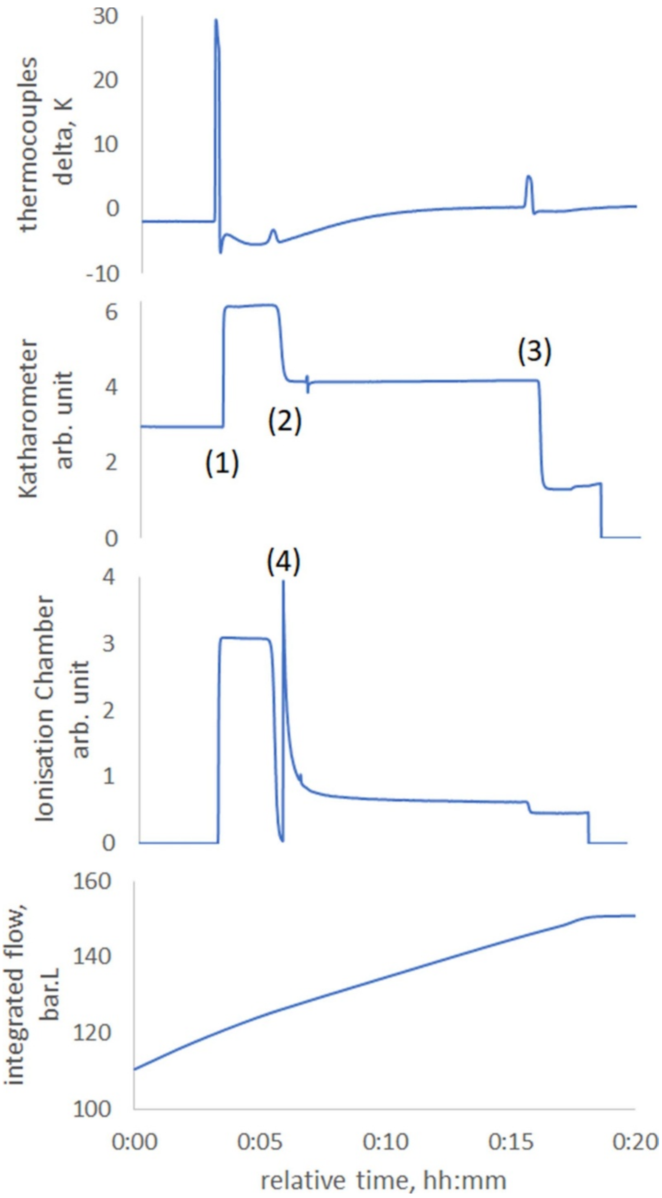

Figure 16. GC Separation run, 13 July 2023. The operator was reliant on responses from thermocouples, a katharometer and an ionisation chamber to identify the arrival of different hydrogen isotopes (1) tritium, (2) deuterium, and (3) protium. Note, the sharp peak in ionisation chamber signal (4) reflects switching the displayed range to 100 times more sensitive.

not ready in time for the campaign, due to the challenge of breaching the heavily contaminated system without the EDS (section 3.7) available to safely vent to. This would have allowed for operations using PS U-beds to occur in parallel (e.g. feeding tritium to NIBs via first outlet manifold, whilst performing transfer—including scrubbing—to a different U-bed using the second outlet manifold). This would have cut down the overall processing time to have tritium available for re-use.

As noted, feeding of tritium to the JET NIBs and TIMs was performed by filling small reservoirs from a U-bed, then isolating the U-bed and expanding the gas into the NIB or TIM vessels [12]. This method required several iterations in order to reach the target quantities of tritium in each NIB or TIM. A larger buffer volume in GI would have meant fewer fill and expansion operations to meet the target pressures in the NIB and TIM reservoirs.

Figure 18 is an example of TIMs supply with tritium.

The subsystem was very operator intensive to use and very inefficient in terms of shift resources—requiring at least one full-time operator for the whole day. The feeding process was also susceptible to errors—it was possible to open the wrong valve or write down the wrong value in a long process with lots of steps and actions that need to be taken quickly in a specific order. Multiple accountancy forms were necessary throughout each operational day, to track each expansion of gas from the supplying U-bed to its target location.

Since not all the tritium fed into the NIB or TIM reservoirs could be utilised for operations, this gas, as well as gas in the GI reservoirs, would be recovered onto a cold PS U-bed at the end of the operational day.

It is noted that the D_2 pumped from JET and processed through GC was not re-used to supply JET. Instead JET NIBs

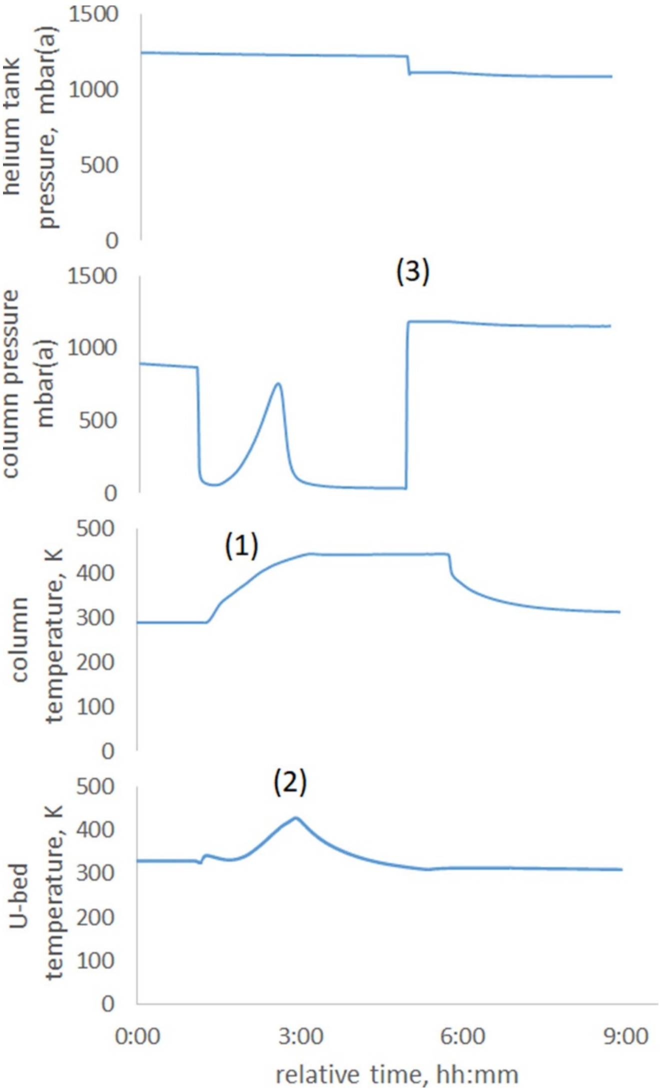

Figure 17. GC regeneration, 30 September 2023. The columns were heated (1) to release the adsorbed protium, which was absorbed onto a cold receiving U-bed (2) followed by filling (3) and circulation of helium through the columns to drive out any remaining Q_2 and make the columns available for the next injection and separation operations.

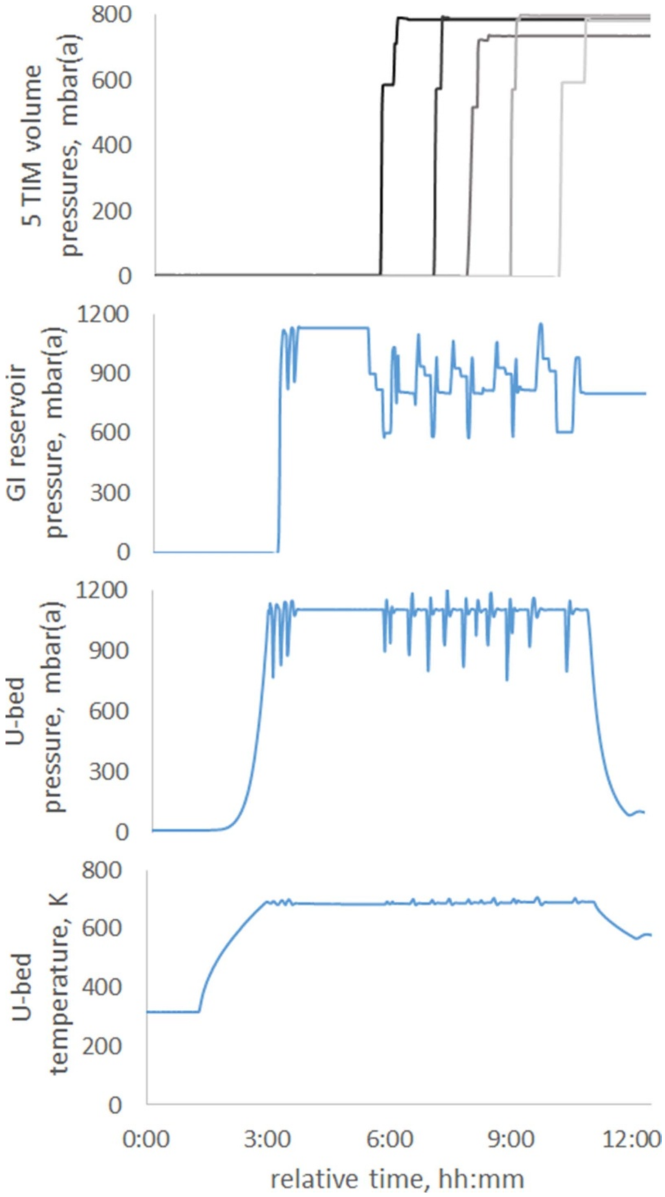

Figure 18. TIM supply with tritium, 30 August 2023. The heating and pressure rise of the U-bed can be seen, along with the pressure changes as gas filled the GI reservoirs, then was expanded into the 5 TIMs in turn. Once done, the temperature of the U-bed was lowered to reduce the pressure, to balance availability time to warm the U-bed back up versus permeation losses into secondary containment (not shown).

were fed with fresh D_2 for each supply. This simplified the D_2 feed process, but the downside was accumulation of D_2—with a minor T_2 content—which then required processing. This gas was injected into the CD system, to recover tritium and allow safe discharge of detritiated protium and deuterium to stack.

3.5.1. Recommendations. Sufficient flexibility must be ensured on PS, or equivalent systems with U-beds, to allow transfers in and out of the system in parallel, including ability to scrub gas over a cold U-bed.

Optimisation of GI/GD operations, along with its associated accounting functions by adding automation, is recommended. This could be achieved by carefully thought-through sequencing of the valves to open and shut in the right order for a chosen source and target. It would also output accountancy values calculated from the instrument & control system data. Automation of this type would greatly cut down the risk of errors. An operator would need to supervise the process (and likely operate the U-bed for refilling the system) but reducing the specific actions they need to perform would be invaluable.

Future fusion fuel cycles should avoid use of ongoing D_2 injection from gas bottles as the plant D_2 inventory would swiftly build up and become challenging to manage.

3.6. Analytical laboratory (AN)

The analytical laboratory [25], which centres around an analytical gas chromatogaphy system, was upgraded prior to the JET DT campaign [11].

One of the GC columns requires liquid nitrogen to function. However, the liquid nitrogen supply is not through installed pipework, instead relying on filling and transporting a portable dewar and then filling the AN dewar from this. Appropriate safety precautions and controls helped ensure no incidents involving handling of cryogens occurred, but it would save operator time and reduce the safety risk if the liquid nitrogen supply was fully plumbed in.

AN typically requires samples supplied at atmospheric pressure, but in some instances, the source of gas to be sampled was at a lower pressure. The local pump in AN to compress low pressure sample gas to the required pressure was not working, therefore redundancy and maintainability should be considered for future designs. A key example of the sample pump unavailability relates to sampling the purity of tritium produced from GC into PS. The pressure in the tritium receipt tank was below the minimum threshold for AN equipment to perform an analysis. The sequence of operations was therefore to first transfer the tritium from the tritium receipt tank onto a PS U-bed. Then, the U-bed was heated, yielding a sufficiently high pressure sample which was sent to AN. The gas in PS and AN lines then had to be recovered, and because of the U-bed cooldown time, this gas and all the contents of the hot U-bed needed to be transferred to a second receiving U-bed at room temperature. This additional heating and transfer of gas added 3–4 h to the overall tritium reprocessing time (refer to figure 3 for layout of PS tank and U-beds. Figure 6 is an example of a U-bed to U-bed transfer in GC system).

Stratification effects must also be considered when taking samples from tanks with gases of very different masses, with pre-mixing operation recommended to ensure a representative sample is sent for analysis.

3.7. Exhaust Detritiation System

The EDS provides the final clean-up of process waste gases, secondary containment purge gases and maintenance air (local exhaust ventilation, LEV) as well as a route to vent JET when it is open in air during maintenance [5, 26]. The process works by converting tritium gas or tritiated compounds to tritiated water over hot recombiners; the gas then passes through a molecular sieve dryer bed to dehumidify, and hence detritiate, the gas before releasing it to the environment.

There were a few discrete tritium discharges to EDS in the early stages of tritium operations which were unplanned. Gas believed to be free from tritium (e.g. helium from CF) was sent for discharge, and during a CF backing of MLs fault, the route was also manually switched to EDS as a precaution.

A minor leak from a condensate line resulted in elevated tritium-in-air levels during the regeneration of one of the three dryers. The leak occurred into the casemate, a sealed room containing the affected equipment. Attempts to identify the precise location of the leak (by pressurising the relevant plant with helium and doing a leak-search) were unsuccessful, suggesting a very small leak path, yet large enough for tritiated water vapour to pass through.

The molsieve dryers appear to retain tritium preferentially which means they are difficult to fully regenerate. This was evidenced by a previously contaminated dryer effect, where when put into adsorption mode, the EDS outlet ionisation chamber would rise, despite the outlet humidity remaining very low. This effect has been investigated and reported previously [26].

3.7.1. Recommendations. Transferring gas from inner loop systems to the outer loop (EDS and WDS) must be avoided where possible. Whilst the EDS is capable of recovering tritium effectively, it is then stored in water form and costly and time consuming to recover via WDS. Any waste process gases should be cleaned up in IP or an equivalent system to maximise tritium recovery as a gas, thus keeping it available for use within the fuel cycle inner loop.

The containment philosophy for AGHS includes secondary containment around all tritium process lines, except for EDS and WDS. The concentration of tritium is usually much lower in these systems. The tritium in water form however, has a radiotoxicity several thousand times greater, since the body absorbs water far more efficiently than gas. Because of this, and the mobility of tritiated water vapour demonstrated by the condensate line leak, as well as during planned breaches, standards for tritiated water systems must be developed (including appropriate leak testing before service) and secondary containment should be included if tritium concentrations are foreseeably high enough. This learning has been captured in the H3AT Facility ADS (atmosphere detritiation system) and WDS designs and is highly recommended for other future tritium plants to ensure the radiological safety of workers.

Molsieve dryers are an effective technology for detritiation, however, due to tritium retention (as well as other limitations, such as requiring switchovers [27] and regenerations), they may be better suited to back up safety duty rather than continuous process use. Methods to clean up the dryer by isotopic swamping with demineralised water can be investigated, as well as alternative technologies such as wet scrubber columns [28] which would not suffer from this contamination effect.

3.8. Services

Services to AGHS include compressed air, electrical power, chilled water, nitrogen, cryogens, and ventilation.

A fault on compressed air resulted in all AGHS systems going into failsafe shutdown within five minutes of the loss of air. The consequence was an operational delay until the air was restored and the systems were then safely recovered to their correct states to allow operations to resume.

3.8.1. Recommendations. For future plants, redundancy (and potentially diversity and segregation) of services should be provided based on operational as well as safety needs, to provide a plant that is more robust against any single failure of a particular service.

4. Human factors

4.1. Operating Instructions

The OIs were the main documents used by the teams to operate the plant to pre-defined and approved procedures. The OIs were presented as full procedures with sign off for each step. This meant a lot of paper was printed and filled out. For operators familiar with the operation and systems, having to run through such detailed documentation each time took longer than strictly necessary. Such detailed checks and instructions could, in limited cases, create a risk of mistakes being made due to critical steps being missed in the event that an operator deviated (willingly or not, due to time pressure or fatigue).

The OIs each contained a section of pre-checks to be performed prior to commencing the operation. In some cases there were too many; often the assumption was that the operation was being performed as a single 'walk up and do' instead of as part of a continuously running plant. This resulted in a lot of time performing checks which were redundant, duplications of ongoing plant monitoring and daily system health checks. The checks are important and should have been performed, but ways to optimise and avoid duplication should be investigated.

Operations involving scrubbing gases over uranium beds, particularly including PVTs, typically deviated from what was written in the relevant OI. The OI would require a lot of skipping back and forth, whilst these operations are typically too complex and variable to perfectly fit into an OI.

The OI covering action to take in the event of hardwired trips and alarms, was found to not be prescriptive enough, particularly with respect to services plant.

4.1.1. Recommendations. Two sets of instructions could be produced: detailed ones for training on the systems, and check-sheet style for experienced operators. OIs should use visual aids (e.g. marked-up PFD or mimic) to show gas routings instead of listing out all the steps to open valves, start pumps, etc.

Critical steps (non-reversable and safety critical) should be highlighted; and requirement for a peer review (e.g. by shift supervisor) prior to continuing should be considered. Other options include to designate particular sections of the OI as of higher risk, with additional controls for the duration such as supervision, informing the whole shift team, and a request for no distractions or interruptions.

OIs should be reviewed and updated routinely. A mandatory review and update of all OIs should be performed 6 months after start of operations to remedy issues identified by the operations team. Reviews should identify inefficiencies such as unnecessary cycling of valves and pumps, as well as the recording of information which is never actually used.

OIs should not contain a large section of pre-checks, if the overall plant is in operation with many parameters already being tracked from one operation to the next. Instead, a check each shift of relevant plant states (supplementing or replacing the daily plant status and health checks) which would replace the majority of individual OI pre-checks is proposed.

OIs should also avoid having close-out tasks which take a long time to complete. This leads them to be held open for several hours, across different shift teams, after the main operation has been completed (for example, waiting for uranium bed to cool down to remove key when there is no need to remove keys in continuously operating plant).

For performing PVTs, a guidance reference document should be produced, instead of prescriptive steps in individual OIs. Each individual PVT would then be performed and recorded in a log book.

Operators need to understand the context of the safety system alarms. The corresponding OI should list the consequences of taking no action to the alarm. Potential outcomes over time should be included, if other problems compound, e.g. power cuts. The instructions should be shortened to 'must, should, could'. i.e. what must, should, and could be done.

4.2. Control systems

Most AGHS systems used a distributed control system in order to provide a HMI (Human Machine Interface) to the operator and allow them to observe and control the operations, including the ability to trend up to eight parameters simultaneously in real time. The original control system [29] was upgraded to a modern system as part of AGHS upgrades prior to DTE2. It also includes various sequences, software permissives and interlocks.

There were, however, two key exceptions: (1) EDS used a separate (and different) system, to perform the same functions as mentioned above, (2) control and data acquisition system (CODAS), used for radiological protection instrument (RPI) and stack monitoring, access control, and JET interfacing systems, i.e. GD and torus cryopumping. The issue with these systems was that they had far lower interaction with the AGHS operating team and were less intuitive to use. This in turn meant that when interacting with these systems, operators were less proficient.

Most operations carried out in AGHS are manually controlled, and are batch operations. The control system is used in selected cases to run automated sequences, such as the filling of liquid helium dewar and valve box for CF, or operating the CD isotopic separation system (used for trace tritium recovery). General feedback is that automation is desirable, particularly for highly repetitive tasks. However with automation comes a risk that operators are less aware of exactly what is going on and how to control the plant manually if required. The CD system is a good example of this, with many operators not sufficiently familiar with the equipment to develop an intimate knowledge, in turn meaning if a manual intervention would be required, operators would not necessarily be able to take the required action.

There were a lot of alarms and indeed a lot of standing alarms on the control system. This creates a risk of important alarms being acknowledged without action due to human error (alarm fatigue). Many of these were a result of limited foresight at the design and control philosophy stages, to ensure only relevant alarms were included (every instrument can give a high or low alarm, but not every high or low reading requires an alarm to be generated).

4.2.1. Recommendations. Use of a single control system or HMI across all the plant and operations is ideal. This may not be possible, for example a requirement to provide independence between the process control system and safety related systems such as EDS. In this case, enhanced training and exposure of operators to infrequently used systems is necessary to ensure they are able to interact with them in an efficient and competent manner on demand.

Automation of repetitive tasks would reduce operator time and likelihood of human errors in terms of operating wrong valves or making an accounting error. Full automation has advantages and disadvantages, but certainly some improvements could be made, for example automating the pumping out of gas from large tanks—with bypass routes, pump trains, coming into service at the correct pressures.

Another recommendation is to automate operation prechecks on demand for any given OI, i.e. control system would pull-up all relevant instrument readings, valve statuses and present as a dashboard to highlight any non-conformances.

Software permissive and interlocks can help prevent misdirections or accidental mixing of gases, and should be used where possible. However, if any are found to cause unforeseen problems, their need shall be re-evaluated on a case by case basis, to avoid a culture of overriding them being the norm.

Consider including a description of the type of gas in various tanks on the HMI (where useful), as well as the pressure. This would improve visibility of what gas is where and reduce the risk of opening to a tank at an inappropriate time.

Clearer distinction is required, between alerts for operator information, and plant alarms requiring an action. Alarm management should be better considered during early stage of plant design, including the colour coding and what response that would indicate required.

It is also suggested to have automatic logging of operations, instead of having to list everything out in the logbooks. Ideally, each operator would log in, note which OI or transfer is being performed and then all plant state changes would be captured and stored in an electronic log file for that particular job. Further to this, different permissions could be assigned depending on the seniority of the operator.

4.3. Ergonomics

Operations carried out routinely but which required to be performed manually were a concern in some cases. In the IP subsystem, manually operated valves had a fragile coupling which disconnected on more than one occasion; necessitating a secondary containment breach to fix; these valves also had a range of different torque closure settings, which led to some being over-torqued, damaging the seal and causing them to pass gas in the closed position. The original design intent was not to routinely operate these valves but for them to only be used for maintenance, however, the duty of the plant adapted to require their use as described in section 3.3.

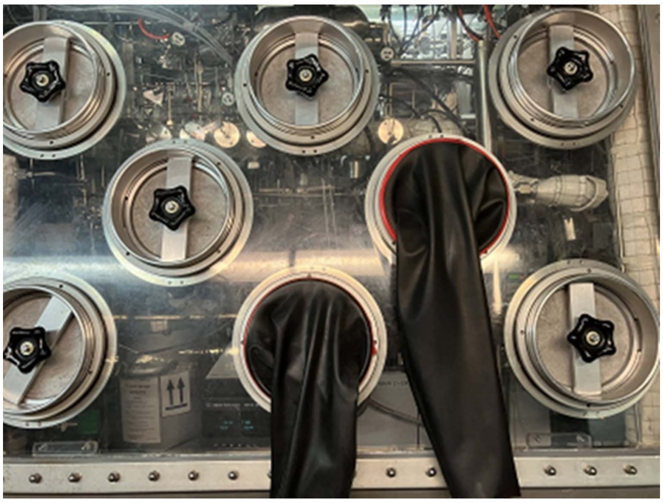

Figure 19. AN Glovebox, with some difficult to reach controls due to the congested layout hampering access.

Each time a sample was taken from the AN main manifold for analysis (once a day on average) the TCD calibration module required tuning. This module was located within the AN glovebox (figure 19), and so required entrance with rubber gloves to make the adjustment every time.

4.3.1. Recommendations. To reduce manual operations—and the risks mentioned above—it is recommended to automate all valves which would be used as part of normal operations. The automated valves should be added in series with manual valves (the latter of which will typically only be closed to isolate adjacent equipment for maintenance purposes).

Similarly, to minimise the need to go into plant rooms, all instrument data is recommended to be relayed to HMI.

Any local switches which require regular operation and cannot be operated from the control system, should at least be placed outside of gloveboxes.

Controlling operations remotely as far as reasonably practicable would remove the operator from the (already low) risk of radiological contamination, manual handling injuries, slips, trips and falls, or exposure to hazardous gases or cryogens in the unlikely event of a major fault or accident.

Enough space needs to be allocated around the equipment and instruments in gloveboxes (especially coupled instruments) and equipment needs to be placed at an appropriate distance from the glove ports. This will allow easier and quicker access with more precision to the separate components for troubleshooting, repair or replacement, and adjusting the regulators, detectors, and cables.

5. Engineering principles

5.1. Tritium accountancy and tracking

One of the key aspects of operating the AGHS was tracking of the tritium inventory and whereabouts. It is very important to know how much tritium is in which particular location and to be able to track it as operations are carried out [30]. This is required to ensure radiological safety and to prevent deviation of tritium for proliferation, as well as from an operational point of view. An accountancy and tracking system was therefore created which, whilst fit for purpose, necessitated a lot of paperwork to be completed. This method would not be suitable for fusion fuel cycles, due to the amount of effort and risk of human errors in writing and transposing figures, and performing calculations by hand. Further, the AGHS is operated as a collection of batch processes, whereas future fuel cycles will require to operate continuously and are being designed as such.

A disadvantage of fully automated tracking is that the operator will lose touch with how the calculations are done and will find it very difficult to find faults or investigate anomalies in the tracking system. A fully automated system is also likely to be very rigid and make a manual correction difficult should some factor not allowed for by the automation affect the accuracy of the figures 5.

5.1.1. Recommendations. Tritium tracking systems should be electronic, automated systems, using plant instrument data to determine whereabouts of tritium at any given time. The operator should still have oversight of how the calculations are being performed and ability to check outputs are sensible.

Regular PVTs (when operationally feasible) would still likely be required in order to confirm and account for precise quantities of tritium over time. However, improvement in online monitoring instruments e.g. flow counters, is recommended to support continuous processes, rather than batch transfer of gas and manual accounting at each stage. It is noted there would be a limitation due to the gas mix composition affecting the mass flow meter readings.

Routine calibrations of instruments should be carried out, and so the equipment design must allow for this where feasible without requiring to breach containments.

Different options for static quantity accountancy are recommended to be pursued—feasibility of performing calorimetry on fixed U-beds for example. Indeed this technique for measuring tritium inventory in PS U-beds is mentioned in [4], but has not been performed in recent years.

Accountancy and tracking systems must be designed to meet the national regulations on tritium management, applying international best practise as feasible.

5.2. Line and tank sizing, routing

Having repeated the same operations for many months, it became clear that some gas transfers were taking a very long time compared to others. There were several reasons for this, including issues with helium blanketing of uranium beds discussed elsewhere. However, some cases were related to the sizes (lengths, diameters) of process lines and sizing of tanks, or the inability to bypass tanks.

The AN system is connected to all sub-systems to receive gas samples for chemical and isotopic analysis. However, using the system as a pumping route, either routinely or as a work around was a reoccurring situation, due to original design intent not foreseeing certain routes which were routinely used.

The AN scroll pump and IS bellows pumps failed which caused disruption to operations and required operating teams to use other (not optimal) gas routing.

During transfers of gas from one location to another, recovering the final few percent of total gas inventory often added a lot of time to the transfer.

5.2.1. Recommendations. During design it is important to look at the flow through the plant in and between systems, to identify those transfers which will be performed most of the time. The sizing should be performed accordingly, looking to avoid bottlenecks. Conductance must be considered, particularly for vacuum systems, and sizing must consider the transfer time versus inventory hold-up.

Tanks along a route should have the option to be bypassed, to avoid unnecessary extra volumes requiring pumpdown. Receipt tanks must be adequately sized to take the foreseen quantities of gas, and if the quantity is expected to vary, several smaller tanks in parallel can be adopted.

Additional (normally isolated) interconnections between the various sub-systems should be incorporated in the design to allow flexibility to transfer gases between them. This would avoid using the analytical sub-system as a pumping route as has been performed in AGHS.

Care must also be taken to look at all routine operations and how they may impact on adjacent sub-systems, to avoid, for example, having to pause one operation to allow another to proceed elsewhere.

Where feasible, redundancy should be built into the main pumping routes, i.e. having two pumps in parallel, in case of failure of the first pump. In a similar vein, redundancy must be allowed for with important instruments—many will fail and they are not easy to replace on a tritium plant.

It is suggested to review, for each routine batch transfer, the implications of leaving the last $\sim$1% of gas behind and allowing the next batch of gas to mix with it. Implications could have potential safety, inventory, accountancy, or purity implications, so this would need a suitable assessment in each case; however, where agreed such a strategy would save a lot of operational time pumping those last small gas quantities.

Consider including the capability to heat and bake any lines containing significant amounts of ammonia or water.

5.3. Plant design general

During the high neutron pulses from JET the casemate RPI (an ionisation chamber located within the room) detected spikes in activity. It was later established this was because a gas species in the torus became activated in high neutron pulses with a half life of ∼10 min. Gas pumped by AGHS passed through a pipe close to the casemate RPI. Here the radioactive decay of the activated gas was picked up as it passed through the wall of the pipe.

On another occasion, an unexpectedly high gas load pumped by CF turned out to be the result of a small air leak on the tokamak side. The oxygen component of air poses a flammability risk if ingress into a tritium plant occurs. The exhaust monitoring system in service during DTE1 [4] would likely have detected this, but was not re-commissioned in time for the recent campaigns.

Secondary containments (hard shell boxes, gloveboxes and vacuum containments) were effective in capturing tritium permeation from primary containments. An example is shown in figure 20: Although the PS U-beds are located in a vacuum containment, likely evidence of permeation from hot U-bed outlet pipework into the PS valvebox was observed.

5.3.1. Recommendations. Consider placement of sensitive instruments such as RPIs with respect to lines carrying gamma emitters. Also, avoid putting room ICs near warm vents or right above doors.

Large scale fuel cycle plants will require more shielding, either on the lines and equipment itself, or shielding of the building compartments where they are housed, with strict access control during operations. Such techniques are employed in nuclear power stations and indeed the JET torus hall itself. Work done looking at activation of seeded impurity gases, e.g. [31], would support this recommendation. The radiological hazard will come not only from tritium, but also gamma emitters, and the plant will have to be designed for this.

Sensitive gas detectors are recommended to identify oxygen within the exhaust from the tokamak to tritium plant.

Consider best methods of insulating hot equipment—if tritium is permeating fast, vacuum insulation will lose its effectiveness over time; it needs to be pumped out frequently, or include lagging outside of the containment if not located within a glovebox. Effective insulation is especially important for plant which needs to avoid rapidly cooling following a heater trip (EDS recombiners, palladium permeators).

In a similar vein, cold equipment and pipework requires appropriate insulation—Some CF and IP equipment in AGHS was prone to condensation or ice build-up as demonstrated in figure 21.

For future plants, a single file of issues captured during plant commissioning should be compiled, including small changes to parameters, to aid operational staff in understanding the system evolution and why the intent may have changed.

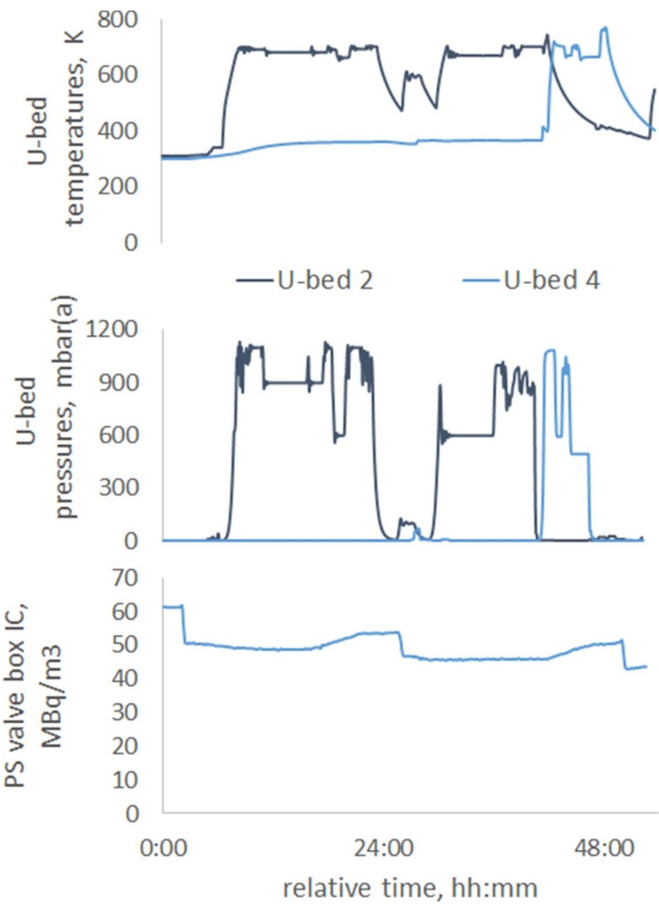

Figure 20. Permeation into PS valvebox during GI filling, 12–14 October 2023. Increases in valvebox activity occurred during the tritium transfers from hot U-bed to GI. The drops in activity correspond to nightly purging of the valvebox nitrogen to EDS.

Figure 21. Build-up of ice around cryogenic plant. Such condensate and ice requires careful management due to the potential for preferential exchange of hydrogen for tritium into the water or ice.

6. Conclusion

The AGHS has been safely and successfully operated for the second and third major JET tritium campaigns.

Although a few small, discrete leaks have been identified and reported, tritium was contained within the facility and potential operator doses were prevented.

It is important to recognise that the facility is over 30 years old, has been subject to numerous minor and major changes and safety case modifications, yet is still operating safely long past its design life, and with much higher throughput than originally foreseen. This is testament to the robustness of the original design and the hard work of the team to implement upgrades, operate and maintain it.

A summary of the system blocks and movement of tritium and other fuel cycle gases has been presented, utilising data captured from the plant operations. The focus of this work was a detailed look at the issues encountered, knowledge gained and lessons learned during operation of the AGHS with tritium.

Key points to takeaway are:

- The impact of helium blanketing on uranium bed adsorption and need for mechanical pumping and scrubbing routes.
- Impact of plant failures and need for increased redundancy for pumps, heaters, and instruments, as well as impact assessment and contingency measures with respect to passing isolation valves.
- Impact of faults or leaks associated with services (coolants) and need to ensure lines and equipment are designed to appropriate codes and standards for tritium service.
- Accountancy of tritium was very labour intensive and at risk from human error. Future systems should be electronic and could be integrated with the plant's data acquisition systems.
- Mobility and radiotoxicity of tritiated water vapour necessitates assessment and provision of secondary containment for the water handling plant.
- Risk of flammable atmosphere, internal and external to the process plant, must be fully assessed and means to detect, protect and mitigate integrated in the design.
- The plant should be designed to avoid bottlenecks and protracted transfer times, considering line sizing, conductance, pumping, and ability to perform parallel operations.

Data availability statement

The data cannot be made publicly available upon publication because they are owned by a third party and the terms of use prevent public distribution. The data that support the findings of this study are available upon reasonable request from the authors.

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