Plasma Physics and
Controlled Fusion

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To cite this article: Sarah Bickerton *et al* 2023 *Plasma Phys. Control. Fusion* **65** 094001

OPEN ACCESS
IOP Publishing
Plasma Physics and Controlled Fusion
Plasma Phys. Control. Fusion **65** (2023) 094001 (12pp)
https://doi.org/10.1088/1361-6587/ace5d5

Operational and engineering experiences of gas injection to JET for TT and DT operational campaigns

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Received 27 January 2023, revised 15 June 2023
Accepted for publication 10 July 2023
Published 3 August 2023

Abstract

Following the first deuterium–tritium experiment (DTE1) at UKAEA, modifications were investigated to the Joint European Torus' (JET) gas introduction (GI) systems to increase the gas feed capabilities of the JET facility to better support future campaigns. The GI systems comprise the GI and gas distribution system in the Active Gas Handling System (AGHS), and neutral beam injection and the tritium injection modules on the torus. During DTE1 about 100 g of tritium was supplied from AGHS to JET users. During the second deuterium–tritium experiment (DTE2) and the tritium–tritium experiment (TT) just over 373 g and 630 g of tritium respectively was supplied to JET users for the campaigns. The tritium and deuterium gas supply systems of the fuel cycle can be underestimated as having fewer technical or scientific challenges based on the mechanical simplicity of equipment that they consist of. However, operational experience has shown these systems have the potential to bottleneck a campaign programme. This publication outlines the upgrade requirements foreseen, following DTE1, for operations in the DTE2 and TT campaigns, how these changes impacted the gas supply operations, and where limitations were encountered. The areas discussed include—challenges of upgrading and maintaining equipment designed for a short operating life; the impact of having differences between user requirements and gas supply capabilities; the logistics of gas supply involving multiple control room locations; communication routes between gas supply systems and teams; and safely controlling and tracking tritium gas movements. The latest JET tritium campaigns highlighted a number of challenges for future facilities looking to operate in both batch and continuous gas injection operational modes. The recommendations from this publication intend to provide a starting point for how to address these challenges and optimise gas supply in support of future fusion programmes. This work has been carried out within the framework of the contract for the operation of the JET Facilities and has received funding from the European Union's Horizon 2020 research and innovation programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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[3] See Mailloux *et al* (https://dx.doi.org/10.1088/1741-4326/ac47b4) for the JET Contributors.
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Keywords: deuterium–tritium experiment, active gas handling system, fuel cycle, human factors, design and operability

(Some figures may appear in colour only in the online journal)

1. Introduction

Following the first deuterium–tritium experiment (DTE1) at UKAEA, modifications were made to the Joint European Torus' (JET) gas introduction (GI) systems to increase the gas feed capabilities of the facility to better support future campaigns.

The tritium and deuterium gas supply systems are made up of reservoirs, pipes and valves, and though simpler than other systems in a tokamak, they are prone to availability and reliability problems. Operation of the gas supply systems are not always smooth and efficient and have caused delays to the campaigns.

During DTE1 about 100 g of tritium was supplied from the Active Gas Handling System (AGHS) to JET users [1]. After DTE1 the changes required to increase plasma power and gas fuelling were identified and implemented. These systems were commissioned in deuterium, followed by trace tritium—a 1% tritium in deuterium mix—and finally in 100% tritium [1]. Once commissioned, tritium and deuterium experimental campaigns from September 2020 to March 2022 saw the facility's 70 g tritium inventory cycled between gas injection, plasma experiments, gas recovery and purification across 500 commissioning and experimental days. During the second deuterium tritium experiment (DTE2) and the tritium–tritium experiment (TT) about 373 g and 630 g of tritium respectively was supplied to JET users for its campaigns.

There are several fusion devices globally that are operating, but without tritium in the fuelling mix. The experiences from JET DTE2 provide a unique opportunity to review the upgrades made and record areas to further improve on gas injection systems (GISs). In the subsequent sections the following will be covered:

- Background to the JET GISs.
- Details of the upgrades required to the GISs between DTE1 and DTE2.
- Observations and findings made during DTE2 and TT on the design and operability of the GISs.
- Discussion on themes identified within the findings and observations.
- Recommendations and learning to be applied to future improvements and designs.

The aim of this publication is to identify the challenges facing tokamak gas injection and investigate how to optimise gas supply in support of future fusion programmes. The key themes identified and discussed in sections 5 and 6 are:

- Engineering and system changes
- Operability
- Human factors
- Tritium tracking and monitoring.

2. Background to JET GISs

2.1. GISs overview

The GISs at JET used in DTE2 include neutral beam injection (NBI) systems for heating the plasma, and tritium injection modules (TIMs) and gas injection modules (GIMs) for fuelling the plasma.

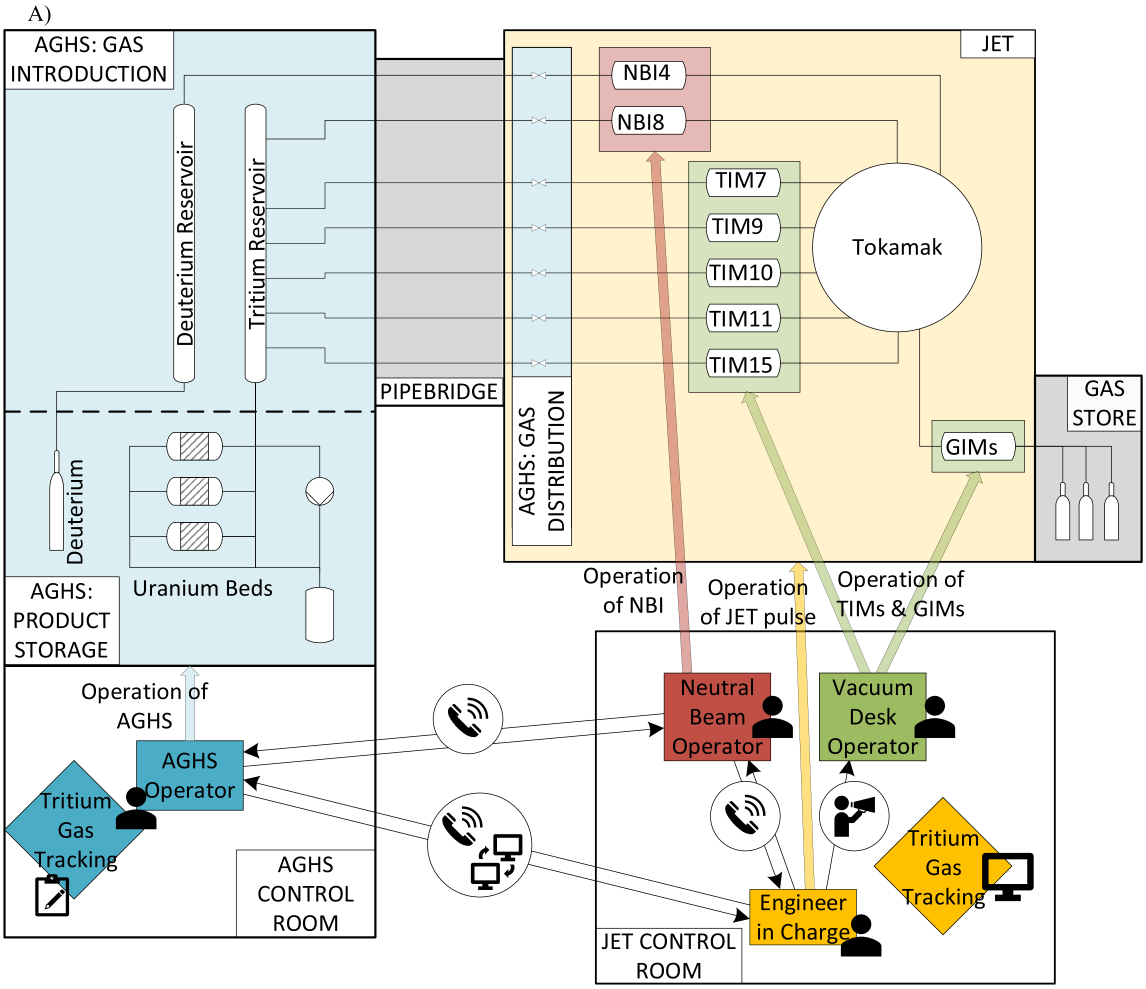
The GIMs are supplied with non-radiological gases selected specifically to meet the requirements of each experiment from a gas store. The GIMs are topped up automatically as they are non-radiotoxic gases that have fewer controls required for safe operation. The TIMs are supplied with tritium from AGHS, as tritium is radioactive greater operational oversight is required for transfers of this gas. The TIMs are described in more detail in [2]. The GIMs and TIMs are mounted onto the tokamak exterior, with the equipment located in the main JET hall or the basement depending on their gas injection point.

Two NBI are installed on the JET torus, one is located on octant 4 of the machine (NBI4), the other is on octant 8 (NBI8). The NBIs can be supplied with either tritium or deuterium, with both gases being supplied from AGHS. The NBIs require very high purity gas—a minimum of 99% purity tritium [1]—to ensure that the positive ion neutral injection modules can be calibrated to direct the high-power ion beams in the correct direction. The NBIs are described in more detail in [3]. The NBIs are in the JET basement, and feed gas to the positive ion neutral injectors (PINIs) above them in the main JET hall.

The gases from AGHS are supplied from the product storage (PS) system via the GI and gas distribution (GD) system to the NBIs and TIMs. Tritium is stored in uranium getter beds in the PS system, and deuterium is supplied from a gas cylinder. Deuterium and tritium are transferred from PS to the GI system which provides the expansion volume allowing tritium leaving AGHS to be monitored. The GD system is in the JET basement and acts as an isolation point between NBIs and TIMs, and the AGHS. The AGHS systems are described in more detail in [1]. For commissioning TIMs and NBIs were supplied with deuterium and then trace tritium from AGHS [1].

A simplified arrangement of the equipment described above is shown in figure 1.

All equipment that contains tritium is held within a secondary containment. If there is a leak of tritium from the primary system, it is captured in the secondary containment. From the secondary containment the tritium can be recovered and returned to the primary system for continued use. Ionisation chambers (ICs) are installed within the secondary containment to monitor for the presence of tritium. These work by



B)

System	Acronym	Description
Active Gas Handling System	AGHS	Facility for supplying, processing, and recycling gases including tritium to the JET tokamak.
Product Storage	PS	Storage and supply system for tritium using uranium getter beds. Part of AGHS.
Gas Introduction	GI	Gas supply system providing monitoring of tritium being transferred from AGHS to JET. Part of AGHS.
Gas Distribution	GD	Gas supply system providing isolation between AGHS and TIMs and NBIs. Part of AGHS but located in the basement of JET.
Neutral Beam Injector at Octant 4 and Octant 8	NBI4 & NBI8	Gas injection to the JET tokamak providing plasma heating.
Tritium Injection Module at Octants 7, 9, 10, 11 and 15	TIM7, TIM9, TIM 10, TIM11 & TIM15	Tritium injection to the JET tokamak providing fuelling for the plasma.
Gas Injection Modules	GIMs	Non-radiological gas injection to the JET tokamak providing fuelling for the plasma.

Figure 1. (A) Interactions between plant and operations teams to enable gas supply to the JET tokamak. Colour coding is used to indicate activities grouped by operations personnel. AGHS (plant areas and control room), JET control room and JET are all physically located in separate buildings. (B) Descriptions of systems shown in the figure 1(A).

the energy from a beta particle released during the decay of tritium to helium-3 generating an electrical current within the instrument which is then output as a reading.

The AGHS subsystems are controlled by a team of operators, managed by the Operations Engineer. The NBI has a dedicated operations team, and TIMs and GIMs are controlled via the Vacuum Desk Operator in the JET control room. The JET control room operations are managed by the Engineer in charge. The coordination of gas supply requires communication between all these operational groups.

2.2. Outline of operation

At room temperature and ambient pressure tritium will react with depleted uranium to form a uranium hydride in a reversible reaction. In AGHS, depleted uranium beds are used to safely store the facility's tritium inventory when it is not in use. The uranium beds for high purity tritium storage contain approximately 1 kg of depleted uranium [1] and have a maximum operational limit to hold 146.6 bar-litres, or 39 g, of tritium. When required for experiments the uranium bed is heated to approximately 500 °C which releases the tritium from its hydride form into a high purity gas [4].

For DTE2, the tritium from the uranium bed was used to fill reservoirs in the GI to a pressure between 800 and 1200 millibar absolute (mbara). The pressure required in these reservoirs was calculated by the operations team and was dependant on the downstream volumes that were required to be supplied. The standard unit for pressure used in JET operations is bar absolute (bara), or mbara. The use of absolute pressure indicates the pressures are measured relative to a perfect vacuum. The conversion to SI is that 1 bar is equal to 100 kPa.

The quantity of gas in the reservoir was expanded to the AGHS boundary and then expanded to either a TIM or NBI reservoir. This was repeated until all TIM and NBI reservoirs were at the pressure required for the JET pulse.

Deuterium was supplied from a gas cylinder via PS, GI/GD to the NBI reservoir. No gas tracking was carried out on deuterium by the AGHS operations team, but it was tracked by the automated JET accountancy system.

The tritium and deuterium gases, and other experimental gases were then pulsed into the tokamak via NBIs, TIMs and GIMs.

Tritium cannot be left in the GIS reservoirs for extended periods. This control forms part of the mitigation of tritium hazards defined in the safety case [5]. At the end of an operational day, if no further operations were to take place in the following 36 h, the tritium would be absorbed back onto a cold uranium bed in PS for safe storage.

For each tritium gas transfer the gas quantities were recorded before and after the transfer by AGHS staff for tritium tracking and each gas injection was recorded for JET operation tracking. The amount of tritium transferred into the tokamak had to be tracked to ensure the total tritium inventory in the tokamak did not exceed the JET DT safety case limits [6]. The tokamak tritium inventory includes tritium injected during pulses (limit of 11 g) and tritium retained in the vessel walls (limit of 4 g). The tritium retention in the vessel is covered in detail covered in [7, 8].

Throughout all the operational activities using tritium the secondary containment ICs would be monitored to ensure that there was no loss of tritium into the secondary containment.

The operation of the JET tritium fuel cycle is by fundamental design a batch operation, this mode of operation slowed down the gas supply but was necessary for operations safety reasons. With the large storage capacity of the uranium beds, it was critical to ensure multiple barriers were in place to prevent the direct connection of a uranium bed filled with 39 g of tritium to the tokamak. If this were to occur, it was considered likely that the tokamak safety limits for tritium would be quickly exceeded. The use of reservoirs facilitates tritium gas tracking across the boundary between AGHS and JET and ensures the safety limits are maintained. JET has a safety limit for tritium of 11 g, whereas AGHS had up to 70 g of tritium stored within the system. This meant it was feasible for AGHS to supply significantly more tritium to JET than it was allowed, and tracking was required to ensure this did not happen. Details of setting tritium safety limits is described in [5].

3. Identifying changes required for DTE2 following on from DTE1 experience

3.1. Neutral beam injectors

During DTE1 the highest power sustained pulse achieved approximately 4 MW level for 5 s providing 21.7 MJ. For DTE2 there was an experimental aim for repeating and exceeding this pulse performance but with the ITER-like metal wall. The record breaking pulse came in December 2021 and achieved 59 MJ over 5 s [9]. Following DTE1 it was recognised that achieving a pulse duration of 10 s would only be possible if the NBI beam power was reduced significantly due to the quantity of gas that could be stored in the gas supply systems.

The available reservoir and pipework volume for storing deuterium or tritium for a beam pulse using the NBIs to feed gas to the PINIs was limited. The gas available could support high power operation up to 5 or 6 s for a single NBI operation and ∼2.5 s with both NBI being used.

The most effective way of achieving a full power, 10 s beam pulse was to increase the gas quantity available by installing new reservoirs for gas storage in each NBI.

A minimum reservoir volume of 3 l would be required but it was agreed that the volume should be a large as could practicably be fitted into the NBI secondary containment. As such, 5 l reservoirs were installed on each deuterium and tritium gas line on both NBI4 and NBI8.

The pressure instruments in the GD system on the NBI supply lines were also replaced. Instruments connected to the primary tritium system are usually replaced rather than maintained due to tritium contamination of the equipment.

The operational boundary between AGHS and NBI operator responsibility was re-used from the original system. This consisted of a software level handshake procedure on specific valves on the connecting lines, that allowed the AGHS operator to hand over control of the boundary valve to the NBI operator.

3.2. TIMs

The review of DTE1 pulse data showed that, to meet the desired experimental programme of DTE2, the total peak gas fuelling requirement was going to be almost 14.8 bar-litres of tritium. Using 293.15 K, as a room temperature reference value, this is approximately 1310 TBq or 3.7 g of tritium.

TIMs were designed and built to provide the additional functionality required. Each TIM consists of two connected 5 l reservoirs, with redundancy on pressure and temperature instruments. Each reservoir has a piezo valve to allow operational flexibility and potential redundancy. If the valve on one reservoir failed, both reservoirs could be connected, and the alternative reservoir valve used.

The supply of tritium to the injection modules was provided via five lines that had been installed between GI in AGHS and GD in the JET basement, for spare expansion capacity. These lines were repurposed and allowed for five TIMs to be installed around the tokamak.

The TIMs, being new equipment, were designed to have a software-based handshake system to ensure that only one set of operators could be in control of the system at one time. These handshake systems had to be designed to communicate between software and hardware control systems. Further details of the TIMs are described in [2] and [10].

3.3. AGHS—GI & PS

The extra volumes in NBI and TIMs needed to be filled with tritium in the same amount of time that was taken to fill the old GIM lines during DTE1. Calculations were performed to estimate the amount of time that would be required to fill the 10 l TIM reservoirs if the original DTE1 fuelling procedure were used. If no changes were made it would take approximately 75 min to fill a single 10 l reservoir to 0.7 bara and over 120 min to fill the reservoir to 1 bara. This was considered to be too long and would have created a constraint on the number of experimental pulses that could be achieved in the daily JET operational window.

To prevent tritium supply creating a bottleneck on the experimental schedule, more capacity for tritium had to be installed in GI. The secondary containment in GI was very confined so additional vessels could not be added, but two pre-existing reservoirs were identified as being suitable for repurposing. Modifications to the pipework and valve connections meant that the two additional reservoirs could be connected directly to the original tritium reservoir and allowed the tritium supply capacity to be increased from 5 l to 15 l. By retaining the valves between the three reservoirs, the capacity used to supply tritium from could be changed from 5 l to 10 l to 15 l depending on the operational requirement. The new volumes did not have pressure instrumentation installed so this configuration required pressure instrumentation to be shared between the new vessels and the original vessel.

With the pressure instrumentation being a potential single source of failure, and without the option to add redundancy due to space constraints, the critical instruments were replaced with new like-for-like calibrated instrumentation. Faulty instruments were also identified and replaced.

Upgrades were planned in the PS system to install an additional manifold on the tritium storage uranium beds. This upgrade would have provided greater operational flexibility to supply and receive tritium onto different uranium beds simultaneously. These planned upgrades had to be cancelled due to schedule constraints as it was considered non-critical.

4. Findings observed

The following section describes observations on the design and operation of the GIS on JET. It has been split between into observations specifically on the AGHS, on the NBIs and TIMs, and finally on the overall system where issues impacted across all three subsystems.

4.1. AGHS

4.1.1. Equipment congestion. The arrangement of equipment within the AGHS secondary containments is very compact—see figure 2. Installation of additional equipment is very challenging, and in the case of GI was not possible. Existing equipment had to be modified rather than installing new vessels due to space constraints.

4.1.2. Access to equipment. In addition to the subsystems being congested within the containment, the locations of equipment within the AGHS and JET buildings were also very restricted. When accessing tritium containing equipment for maintenance or upgrade work, a controlled area must be set up around the equipment being worked on to safely control any potential leak of tritium and manage the handling of equipment and tools used to the work.

Respiratory protective equipment and physical barriers were required to carry out maintenance on equipment that had contained tritium, this included air-fed hoods and isolators. These are bulky pieces of equipment that needed space for change areas and for storing.

The GI and GD subsystems are both located at the top of vertical ladders with very limited space to work comfortably and to have a change barrier. The GD system also has very restricted head room. These are shown in the photographs in figure 2.

4.1.3. Tritium recovery. The use of uranium getter beds for safe storage and recovery of tritium and the challenges of inert gas blanketing are described in [1]. Tritium decays into Helium-3 (^{3}He), an inert gas, over time. The tritium supplied to GIS and held in the pipework and volumes during operations will incur a small, but not insignificant, amount of tritium decay.

The tritium is removed from GIS by absorbing it back onto a uranium bed in PS. The rate of tritium absorption slows as the ^{3}He forms an inert layer across the uranium that the tritium needs to diffuse through [1]. To remove this ^{3}He blanket from the PS uranium bed the tritium recovery process has to be paused and the uranium bed has to be isolated from GIS. A vacuum pump can then be used to pump ^{3}He away. Once all residual ^{3}He has been removed, the uranium bed can be reconnected to the GIS system to continue tritium recovery.

Figure 3 shows the pressure of the GI vessel over time during tritium recovery from all GIS volumes onto a uranium bed. The first drop in pressure is the tritium being recovered from the GI vessel, and each subsequent spike is a NBI or TIM volume being opened up to have the tritium recovered. The

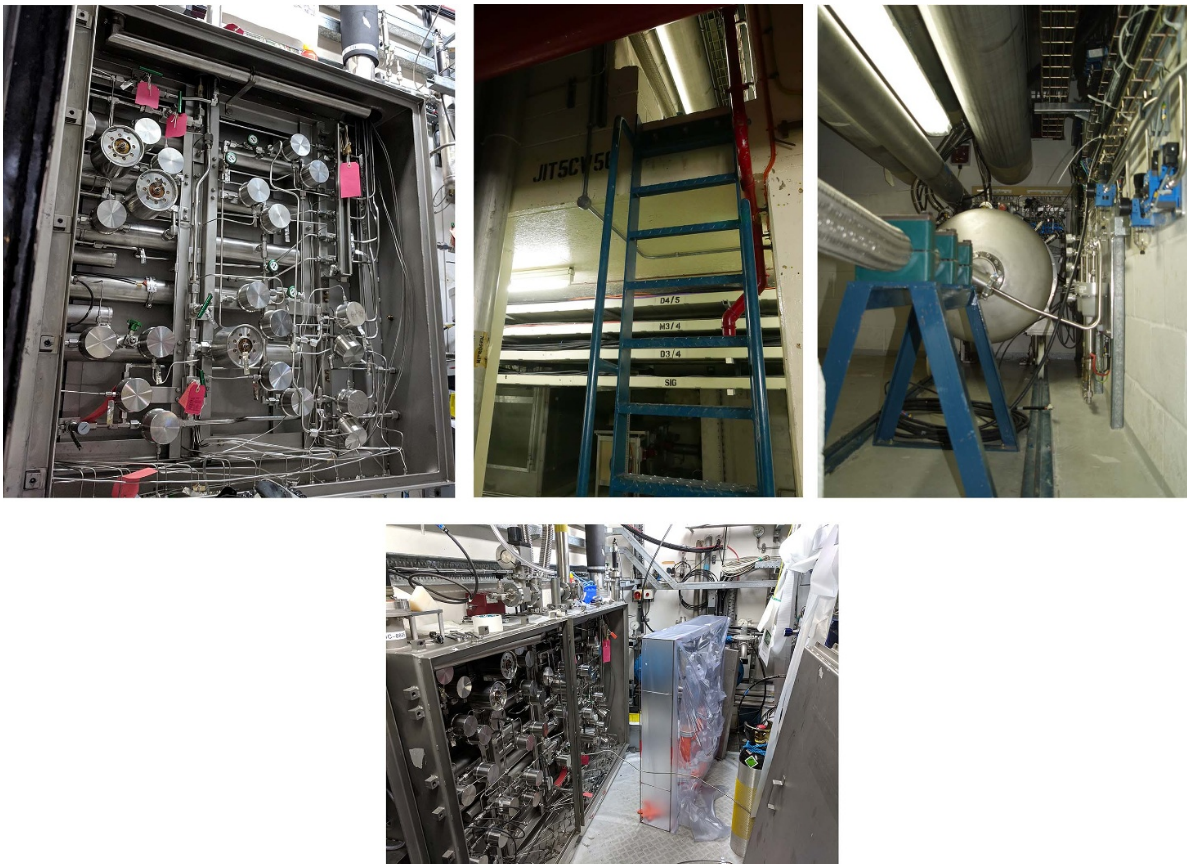


Figure 2. (Clockwise from top left): photographs of inside GI showing equipment congestion; access ladder to GD; area around GD containment available for carrying out modification work; the controlled area around GI whilst preparing for modification work to be carried out.

pressure very rapidly drops as the tritium hydride forms but would plateau with a few mbar of tritium remaining due to the ^{3}He layer forming between the tritium and the uranium. The times between each spike are when the ^{3}He is being removed from the uranium bed. To recover tritium from the full GIS system this process would be repeated many times and added large delays to the operation.

4.1.4. Task repetition. The operation of gas supply from AGHS to NBIs and TIMs was a very manual and repetitive task. Every gas movement had to be recorded so that the location of the tritium inventory was known as it was moved from storage to the tokamak. Each gas movement required starting and finishing pressures to be recorded on paper, and then 4–6 operator actions to be completed on the control system. To fill all TIMs and NBI at the start of a day's operation could require 34 gas movements, this required 170 temperature or pressure values to be written by hand and 166 valve positions to be changed on the control system.

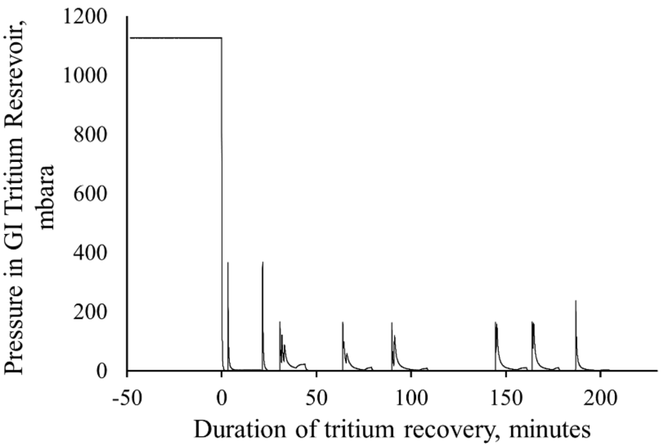


Figure 3. Pressure reading in the gas introduction (GI) tritium reservoir over the course of the tritium recovery activity. Instrument reading shows the time taken to pull tritium back onto a uranium storage bed from the various gas injection reservoirs. The declining rate at which the pressure drops indicates where the uranium bed is becoming 'blanketed' by the helium-3 present in the tritium. Time zero is when the tritium recovery activity is started.

4.2. NBIs and TIMs

4.2.1. Equipment failure or error. On the TIMs pressure instrumentation drift was seen on several the vessels. This was monitored as part of the gas tracking process, where each TIM and NBI volume would, as part of the tritium supply operation, be connected to a vessel with independent pressure readings—one on the TIM or NBI, the other was the

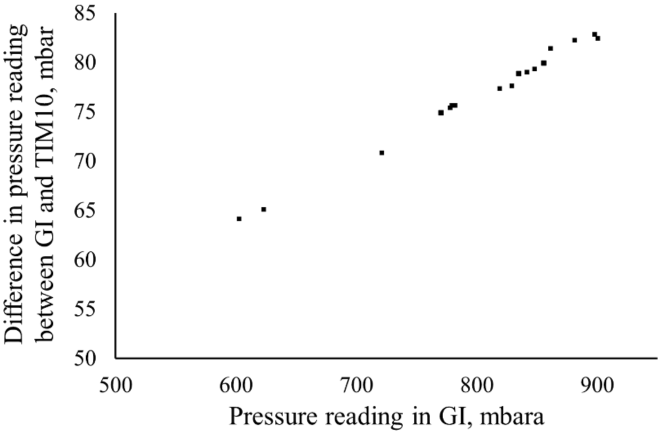


Figure 4. Difference in pressure reading on the gas introduction (GI) tritium reservoir and the TIM10A local pressure reading against the GI pressure gauge. This indicates a 10% discrepancy of the TIM10A pressure reading, with it reading lower than the common gauge in GI.

GI pressure. These checks showed significant instrument drift was occurring in one of the TIM pressures with a 10% discrepancy developing—see figure 4. When checks against the other instrument on the TIM vessel and on the connected vessel were carried out, and showed it was single equipment failure, the secondary instrument could be brought online to replace the faulty one.

None of the TIM piezo valves failed catastrophically, as had been a concern during design, but they did not respond as required during the experiments. The dual reservoir and piezo lines installed allowed operations to use the line with the best flow, with both TIM reservoirs connected, to achieve the smaller pressure changes required and achieve a more consistent flow than with single reservoir.

4.2.2. Tritium monitoring. The secondary containment around the NBIs, TIMs, GD and transfer line between GI and GD are continuously purged with nitrogen which is monitored for tritium presence using an IC. During operations a very minor and transient leak path developed on an item in the primary tritium system. The IC on the secondary containment was able to detect leaks of less than 0.5 picogram of tritium very clearly. This is shown in figure 5.

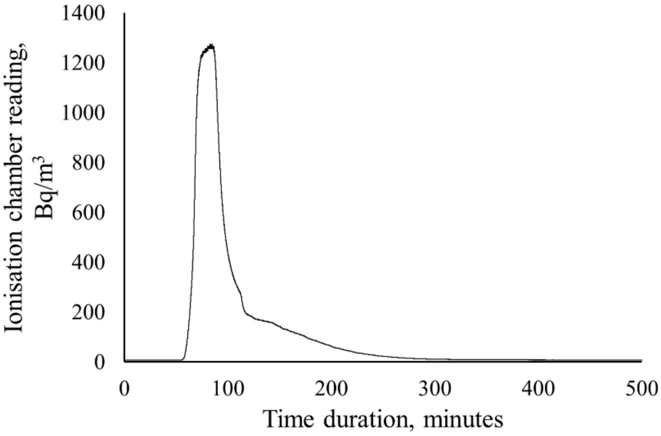


Figure 5. Ionisation chamber output over time. The spike in the instrument reading indicates the presence of a small quantity of tritium in the purge gas stream that is being monitored. This was seen following a small transient tritium leak from the primary system, into the secondary containment system.

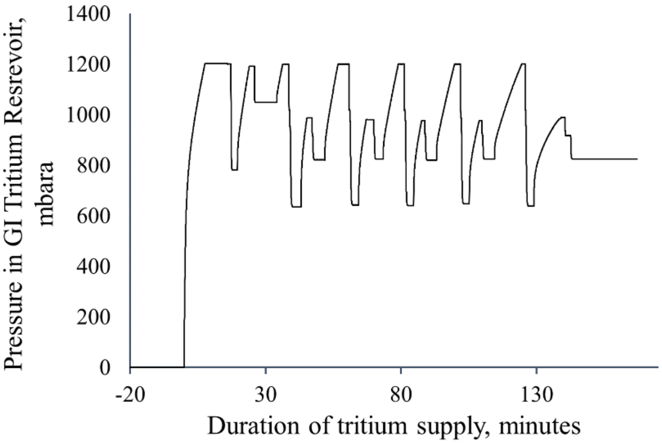


Figure 6. Pressure reading in the gas introduction (GI) tritium reservoir over the course of the tritium supply activity. Instrument reading shows the gas expansions into and out of the GI tritium reservoir through the pressure changes. A rise or fall in pressure indicates an expansion into or out. Time zero is when the tritium supply activity is started.

4.3. GIS

4.3.1. Volume filling duration. Despite the increased volumes to increase the rate at which all volumes in GIS could be filled to their required operating pressure, this process was still slow. As shown in figure 6, to fill all volumes 25 gas expansions were required to prepare NBI and TIMs for a day's operation, and this could take up to 2.5 h to complete.

4.3.2. Increased capacity. The increased volumetric capacity of the GIS resulted in needing more tritium to fill all of the GIS volumes than could be injected into the tokamak for the experiments each day. For example, in the tritium–tritium campaign where both NBI were using tritium, the limit for tritium that could be injected into the tokamak was 11 g, but 22.7 g of tritium was required to fill of the GIS volumes to supply this.

The need for three times the amount of tritium to be available as could be used in the JET experiments, increased the reprocessing demands on the other AGHS sub-systems. It also created large 'dead' volume of tritium that remained in the reservoirs after the pulses had been carried out and could not be used, see table 1. These dead volumes occurred because a minimum back pressure in a reservoir was required to drive tritium into the tokamak at the rate required for the experiments. In NBI the minimum backpressure was around 700 mbara, and in the TIMs it was about 500 mbara.

Table 1. Quantity of tritium required to fill GIS systems for the TT and DTE2 campaigns prior to starting each days experiments, and quantity of tritium stuck as 'dead' volume in the GIS systems.

Campaign	TT	DTE2
GIS volumes in use	GI (15 l), NBI4 & NBI8 (7.5 l each), TIM7/9/10/11/15 (approx. 14 l each)	GI (15 l), NBI8 (7.5 l), TIM7/9/10/11/15 (approx. 14 l each)
Quantity of tritium required to prepare all volumes to operating pressure at 293.15 K, bar.l (g)	90.5 (22.4)	81.9 (20.3)
'Dead' volume trapped in GIS at 293.15 K, bar.l (g)	63.1 (15.6)	57.8 (14.3)

4.3.3. Operational limits and flexibility. The GI tritium reservoir was a single point from which all downstream volumes—NBIs and TIMS—had tritium expanded from. The NBI required filling to a pressure greater than 1100 mbara. TIMs required filling to a pressure of 800 mbara. This led to conflicts where GI had expanded to NBI leaving 1100 mbara of tritium in its reservoir, which, if expanded directly to a TIM would result in the TIM being taken above its maximum operating pressure. AGHS operators would have to calculate the amount of gas required for the TIM top-up and then find the optimal combination of the three GI reservoirs to achieve the expansion that would not result in exceeding the TIM maximum operating pressure. This was time consuming and had a high risk of human error.

4.3.4. Operational expectations. Prior to the TT and DTE2 JET had only required gases supplied from gas cylinders. These gas top-ups were achieved quickly and, in the case of the GIMs automatically, from gas cylinders on the completion of each pulse. This required very little planning consideration around gas supplies during non-tritium experimental campaigns. In TT and DTE2 campaigns tritium was supplied from uranium beds that required heating up in advance to release the tritium and supply it to the TIMs and NBI. Heating a uranium bed to the temperatures required for gas supply could take 2 h depending on uranium bed loading and the heater efficiency. This had a knock-on impact on the experimental schedule and experiments planned in a shift.

4.3.5. Communication channels. The task of ensuring the correct gases were supplied for each JET TT and DTE2 pulse required several groups of operations staff, split between three different control rooms. These operational teams had different ways of communication between each other—communications lines varied between telephone conversations, in person discussion and software system requests, as indicated in figure 1—but it was very difficult to have all operations teams involved in a single discussion. This led to confusion over priorities and timings of gas movements and could lead to gas supply requests being missed or completed incorrectly.

COVID-19 control measures included limiting the control room staff to only those who needed to be on-site to carry out their roles. This meant that the scientific team directing the experimental schedule were participating remotely. At times this added further delay in the communications needed for decisions on operations, such as which TIMs to fill, while the JET control room staff interacted with the scientific team.

4.3.6. Tritium tracking. In the JET tritium fuel cycle, there were two separate tritium tracking systems in place. On the JET side of the cycle this system was embedded into the software, on the AGHS side this was a manual process carried out by the operations teams. In the JET system the tracking software was programmed to handle specific scenarios and an operator opening valves in the wrong order by accident would create errors in the results. On the AGHS side the whole gas tracking process was dependant on operators recording values, carrying out calculations and transcribing values into the record tables correctly. Whilst there were processes to follow and some of these tracking forms were partially automated, there were still many opportunities for errors to be made and carried forward through a shift's activities.

The different tritium tracking systems used—JET's software embedded system and AGHS's manual process—not only used different methods, but different volumes and instrumentation to calculate the gas quantities.

Due to location of the gas tracking boundary between AGHS and JET and the instrumentation available to support the gas tracking, the final tracking process became very complex and operator intensive.

4.3.7. Interfaces. The work to upgrade and operate the GIS had many interfaces—design team interfaces between departments and disciplines; physical equipment interfaces; control system interfaces.

The upgrades to equipment discussed were carried out with different project teams responsible for different areas. It was recognised that co-ordination between these different teams was essential to the overall success. To aid this cross functional teams were set up with representatives for the equipment areas and different disciplines working together. These teams work effectively however often remained high-level due to constraints of timing and resource.

When carrying out the upgrades to individual areas of equipment there were risks of conflicting tasks creating hazards for each other. Careful planning and coordination was required to keep all personnel safe. It also highlighted challenges when coordinating work between areas using different permit to work or work authorisation systems.

A risk of error at the operational interfaces between equipment controlled by different operations teams was identified. Between AGHS and NBI there was an existing software level handshake procedure, on specific valves on the connecting lines, that was deemed adequate, so no changes were implemented. The TIMs, being new equipment, were designed to have a software-based handshake system to ensure that only one set of operators could be in control of the system at one time. These handshake systems had to be designed to communicate between software and hardware control systems.

5. Lessons learnt & discussion of findings

The following section takes the finding observed across the operational areas and reviews them in line with common themes. The themes identified are engineering and system changes, operability, human factors, and tritium tracking and monitoring.

5.1. Engineering and system changes

5.1.1. Equipment congestion. On conception, the AGHS was deemed a short-term installation and as such future proofing for maintainability or upgrade was not incorporated into the design intent. This resulted in equipment installations that are very compact but lack flexibility for expansion or modification. The upgrades required to increase the operational life of the facility, even if simple, were constrained by the physical limitations of the space, meaning compromises on functionality had to be made to fit within a space—such as reducing the number of new pressure instruments that were installed—or upgrades impacted more items of equipment and had a much greater complexity than was necessary—such as the installation of the TIMs onto the tokamak vessel.

These issues add time and cost to completing work, and ease of maintainability and upgrade should be considered in the design of future facilities, both within and around the secondary containment.

5.1.2. Equipment failure or error. The importance of instrument and equipment redundancy was realised during the campaign. Fortunately, the high-risk areas had been correctly identified and redundancy was available where equipment failure or error was seen. The planned monitoring of drift meant errors could be identified and addressed in a timely manner. Although it could not be guaranteed that the GI pressure instrument remained error free, it provided a consistent point of reference to the instruments that were in the more challenging environment near the tokamak. If the checks had not been carried out and action taken on the worst performing instruments, it could have resulted in unidentified errors in the experimental results.

With the undesirable piezo valve responses on TIMs, the functionality designed in to allow both reservoirs to be injected via a single piezo valve, meant the full tritium capability to meet experimental needs was maintained.

The tritium contamination of systems makes maintenance of instruments very difficult. They cannot be calibrated *in-situ* without contaminating the calibration equipment. Removing instruments from the primary systems for external calibration requires the spread of contamination to be controlled and monitored. Installation of equipment redundancy is a good way to extend the operational life span but is expensive and does not guarantee that both instruments will not fail if they are in a harsh environment. Designing in the ability to compare and monitor instruments for deterioration of output allows for any errors to be accounted for. The amount of investment on maintaining good instrument output should be linked to the criticality of the information to continue safe operation.

5.1.3. Tritium recovery. An improvement to the tritium recovery process would have been to reduce the time taken to recover tritium onto a uranium bed. This could have been achieved by continuously pumping the ^{3}He away from the uranium to stop the inert gas layer forming, removing the need to repeatedly stop and start the tritium recovery process. With the equipment and line-work installed in PS, continuous removal of ^{3}He was not possible. An upgrade to install a second linework manifold to make this operation possible was considered, but ultimately was not implemented. Modifying the uranium bed system to allow ^{3}He to be continuously pumped away would have brought the tritium recovery time down to a fraction of what was seen in the TT and DTE2 campaigns.

5.1.4. Increased capacity. The increased volumetric capacity of the GIS, and resulting ‘dead’ volume of tritium created, increased the demand on the reprocessing of tritium returned from the torus to AGHS. Any errors in the gas collection or purification had a direct impact on experimental schedule as there was no buffer in the tritium available for supply. The time taken to reprocess any low purity tritium would cause a corresponding delay to the experimental programme.

The design of the gas supply system in future facility needs to consider the volume of supply system in addition to the desired gas injection quantity. Continuous operation alleviates this issue since it should not require large static volumes of tritium to inject from, instead using a constant flow of gas.

5.2. Operability

5.2.1. Operational limits and flexibility. The configuration of GIS with the GI reservoir as a single point from which all downstream volumes had tritium expanded from in the batch expansion process and the different pressure requirements of the downstream volumes, all increased the complexity of the operation of tritium supply to the NBIs and TIMs. In hindsight there are a number of changes that could have been made to reduce the operational demand. Automating simple repetitive tasks in the gas supply and gas tracking would have reduced the risk of human error. Consistent operating pressures across the operational envelope would have reduced the reliance on operating procedures to keep equipment in its limits.

5.2.2. Interfaces. The upgrades to the GIS system focused on the scientific requirements of the next campaign, rather than the operability of the equipment during the campaign. The complexity and number of work packages ongoing made it very difficult to track the nuances and details of individual changes when design and installation teams were working in relative independence of each other, and only communicating high-level design. Whilst operability was considered in the design phase, the details of equipment operation was not fully developed until after the design of upgrades had been fixed.

The operability of the equipment as a whole system would have benefited from the development of a comprehensive concept of operations and operational philosophy early in the design of the system. This process endeavours to capture as many different operating requirements and scenarios as possible and give the maximum operational flexibility.

There are areas within GIS where interfaces have very similar operational requirements but have been approached differently—such as the handshake valves—due to systems being installed at different times through the facility life cycle. All interfaces between subsystems, especially if required for safe operations, should be consistent in appearance and function to reduce the potential for human error. Treating the fuel cycle as a single entity would also give better cohesion for the operation teams.

5.3. Human factors

5.3.1. Operational expectations and communication. Having the operational teams split between different control rooms increased the complexity of the teams communicating effectively. It made managing expectations between teams difficult, as teams do not fully understand the constraints each other face. This can lead to frustration when tasks take longer than expected, or confusion over priorities and timings of gas movements, and could lead to operational errors with gas supply requests being missed or completed incorrectly. Designing facilities to bring operations teams together provides a better environment for good communication, or if this is not possible, standardise communication routes and develop ways of working that promote careful and well-structured communication between teams. Integrating operational teams as much as possible and providing people with the opportunities to meet their counterparts increases the good-will between teams. Where operations team members had developed better interpersonal relationships the communication and planning between control room teams went much smoother.

5.3.2. Tritium tracking. The separate tritium tracking systems in place on JET and AGHS were both impacted by human factors as discussed previously. The methods of tracking were using different raw values meaning there were discrepancies in the quantity of tritium recording leaving AGHS and entering JET due to instrument errors. These discrepancies then had to be identified, justified, and accounted for manually.

5.3.3. Task repetition and volume filling duration. The operation of gas supply from AGHS to NBIs and TIMs was a very manual and repetitive task. The process of batch tritium supply was very labour intensive, albeit a very simple task, making it monotonous for operations which leads to the human factors risks of errors being made or short-cuts being looked for. As well as the operations process, the gas tracking was a very repetitive task which leads to people becoming complacent and less likely to check for errors. Much of the operation of the control system and the gas tracking could have been automated, with operator input reduced to supervision and monitoring. Where possible, automate repetitive processes and reduce the potential for human error to occur.

5.3.4. Design consideration. The impact of human factors was first seen in the design phase where despite significant endeavours to ensure all requirements were captured correctly, the full extent of the design decisions made were not identified. For example, when determining the maximum operating pressures for the TIMs the upstream system was considered which was a correct identification of the stakeholder, but the requirements of the NBIs were not considered in the same design envelope. This led to equipment in the same operating envelope having different maximum operating conditions. This then had to be managed by procedures and operator action.

Insufficient appreciation of human factors also resulted in the decision not to automate the gas supply from AGHS—this would have required significantly more upfront resource to complete but would have removed the need operator involvement in a simple but monotonous operations activity with a high potential for error.

5.4. Tritium tracking and monitoring

5.4.1. Tritium tracking. Tritium tracking is critical for inventory management. Tracking systems should be automated where possible using live data from process instrumentation and have a consistent methodology. The tritium tracking in JET also relies on the process being a batch gas supply, so these methods of tracking would not be suitable for a continuous operation power plant.

To robustly supply a continuous or long pulse plasma, continuous fuelling supply of both tritium and deuterium needs to be achieved. For a continuous process, either the mass balance boundaries need to be more wholistic to cover larger areas of the process, or measurement of the gases being transferred needs to be instrumented to provide continuous online measurements.

5.4.2. Equipment reliability. A significant constraint on the tracking process was instrument availability and confidence in the instrument output. Checks could be carried to cross reference instruments against others within the primary tritium system, but due to the tritium contamination and AGHS not being designed as a long-term facility with ease of maintenance as a requirement, calibration checks on installed instrumentation was not possible. The poor design for maintainability also meant that if an instrument failed, replacement was very difficult, requiring taking entire subsystems out of service to allow for instruments to be replaced or maintained. Preparing these large systems for a maintenance through evacuation of tritium and gas purging to reduce contamination levels, and then conditioning the system to remove the purge gases and any air ingresses after the maintenance, meant a simple instrument change could take weeks to complete. The ability for checking, maintaining and replacing critical instrumentation should also be designed in so that the duration of these activities can be minimised.

5.4.3. Trace tritium monitoring. The secondary containment around the NBIs, TIMs, GD and transfer line between GI and GD are continuously purged with nitrogen which is monitored for tritium presence using an IC. During operations a very minor and transient leak path developed on an item in the primary tritium system. The amount of tritium passed from primary to secondary containment was so small it could not be identified through pressure or inventory monitoring. However, it was clearly identified using the IC. This demonstrated how efficient this type of instrumentation can be for monitoring for tritium. The IC monitoring the purge nitrogen was able to detect leaks of less than 0.5 picogram of tritium very clearly and meant that investigations could be carried out to identify the source of the leak path and mitigate it. The source of the leak was identified as a small moving part, hence the transient nature. Once located, an assessment determined that operation could be continued safely with the faulty element isolated.

ICs are excellent for monitoring for trace tritium presence. The efficiency of this instrumentation for monitoring for tritium should not be under-estimated as during operations a very minor and transient leak path developed on an item in the primary tritium system. However, it must be designed in to purge or zero correct ICs in case they become saturated with tritium. Once an IC becomes saturated it experiences hysteresis in the reading which can mask the true reading of the system.

6. Recommendations and consideration for future systems

6.1. Engineering and system changes

The design of fusion plant fuel cycles is still being developed and refined. Designing in the capacity and functionality to make changes to equipment will ensure that plants have better future proofing. The key recommendations to be raised from this are:

- Leave additional space in secondary containments to allow for future modifications, include tie-in points in your design that will allow retrofits to be implemented without the need for cutting and welding pipework and vessels.
- Leave space around equipment to allow ease of workers to carry out maintenance and consider the need for controlled areas and change barriers around equipment.
- Design in capability for checking instrument drift, so that operational checks can be carried out to provide early indication of developing problems.
- Identify the critical instrumentation on facility and include redundancy in your design.
- If redundancy is not feasible due to cost, ensure designs allow for ease of equipment replacement.
- Design in capability for continuous removal of ^{3}He from uranium beds to prevent tritium blanketing.

6.2. Operability

Depending on the design of GI systems and locations of facilities that gases are being transferred between, significant proportions of a facility's tritium allowance can become tied-up without adding value. It is important to treat systems as a whole and not to become isolated looking only at a small area. The key recommendations to be raised from this are:

- Develop concept of operations early in the design life and design equipment functionality to meet this.
- Consider how the inventories of line work and storage reservoirs might tie up a facilities tritium inventory.
- Be clear on boundaries of design envelope and have consistent temperatures and pressures.
- Design inherently safe ways to manage different equipment requirements.
- Relying on procedures to protect equipment integrity is not robust engineering practice.
- Design new plant and upgrades with a wide stakeholder group and consideration to how a system fits into its surrounding equipment and operational envelope.
- Ensure the impact of a change has been considered for all connected systems.

6.3. Human factors

Human factors should be considered and incorporated into process and facility design from the start of the design process. Identifying the key stakeholders, including operators and maintenance team will give better final outputs. The key recommendations to be raised from this are:

- Invest in automation of systems to reduce operational delays and the risk of errors occurring.

- Bring operations teams together in a single location to ensure reliable communication of operational priorities and a cohesive operational response.
- Make communication systems simple and consistent.
- In the design phase, bring operational and engineering teams together to develop operational philosophies.

6.4. *Tritium tracking and monitoring*

JET uses batch gas expansions of tritium from uranium beds to an intermediate volume to calculate the quantity of gas, before expanding that volume to either neutral beams or TIMs. The key recommendations to be raised from this are:

- Batch gas tracking processes are time consuming and not suitable for semi-continuous or continuous processes. New methods of continuous gas tracking need to be investigated and tested for use in continuous operation.
- Monitoring containment and ensuring sufficient confidence in equipment integrity needs to be designed in.
- ICs are very effective for identifying very small leaks as long as the instrument is not saturated.
- If an IC is at risk of being saturated it must be possible to purge the instrument to remove as much contamination as possible, and artificial zeroing of the reading may also be required.
- Ensure enough instrumentation is installed to support effective monitoring and troubleshooting. If cost optimisation requires instruments to be removed from design, ensure that functionality for troubleshooting is maintained, and have procedures in place for how a single instrument can be used in place of multiple ones.

6.5. *Limitations*

The recommendations are made in light of only two JET campaigns over two years. Compared to the required life-cycle expectations of a power plant this is a very short timeframe. It is also significant that the JET fuel cycle is a batch process, and future facilities should work towards being continuous or semi-continuous.

The JET fuel cycle and gas injection methods are all batch processes to support short plasma pulses. This is not a system design that is appropriate to replicate for continuous, or even long duration plasmas. Methods for continuous supply and recycling of tritium from the tokamak need to be developed and tested, as do the techniques for tracking and measuring tritium streams.

7. Conclusion

The JET GISs were not designed for a 30 years operational life cycle, and the maintenance and upgrade work have been completed retrospectively to extend its functionality and lifespan. The TT and DTE2 campaigns were very operationally intense, and personnel and equipment preformed excellently.

The campaigns provided a huge amount of learning of which this is only a small part, but in recording these findings it is hoped that future facilities can further improve on the work carried out at JET.

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.

Acknowledgments

This work has been carried out within the framework of the Contract for the Operation of the JET Facilities and has received funding from the European Union's Horizon 2020 research and innovation programme. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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References

[1] Lässer R *et al* 1999 Overview of the performance of the JET Active Gas Handling System during and after DTE1 *Fusion Eng. Des.* **47** 173–203

[2] Carvalho I S *et al* 2017 Operational aspects of the JET tritium introduction modules *Fusion Eng. Des.* **124** 841–5

[3] Jones T T *et al* 1999 Tritium operation of the JET neutral beam systems *Fusion Eng. Des.* **47** 205–31

[4] Stagg R, Hemmerich J L, Lässer R, Laveyry M, Lupo J, Milverton P, Skinner N and Perevezentsev A 1995 The intermediate and product storage systems for the JET active gas handling system—inactive commissioning *Fusion Technol.* **28** 1425–30

[5] Bell A C, Ballantyne P, Gordont C and Wright M A 1999 The safety case for JET D-T operation *Fusion Eng. Des.* **47** 115–30

[6] Perry D and Johnston J An overview of the preparation and implementation of the safety case in support of the 2nd JET deuterium-tritium experiment *Plasma Phys. Control. Fusion* Submitted

[7] Widdowson A *et al* 2021 Evaluation of tritium retention in plasma facing components during JET tritium operations *Phys. Scr.* **96** 124075

[8] Andrew P *et al* 1999 Tritium recycling and retention in JET *J. Nucl. Mater.* **266–269** 153–9

[9] Gibney E 2022 Nuclear-fusion reactor smashes energy record *Nature* **602** 371

[10] Felton R *et al* 2023 Tritium injection into the JET tokamak Submitted