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Operational aspects of tritium injection into the JET tokamak

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Abstract
The joint European torus (JET) was the only tokamak capable of deuterium–tritium (D–T) operations in the last 30 years. The first D–T operations were in the 1990s and again in 2004. In 2020/2021/2023, JET operated a much larger D–T and pure T campaigns aimed at sustained high fusion power, requiring a much higher tritium throughput. This paper presents operational aspects of the recent tritium injections into the JET tokamak. Tritium injection into the JET tokamak involves transfer of tritium between the Active Gas Handling System (AGHS) and the tritium gas injection modules (TIMs) and neutral beam injectors (NBIs), the control of TIMs, and NBI, gas inventory (pre-pulse estimate, post-pulse usage), gas limits (explosive, tritium) etc. Operations require close collaboration of staff in the JET Control Room,), AGHS, vacuum, and cryogenic groups.

Keywords: tokamak, tritium, gas injection, operations

1. Introduction

The joint European torus (JET) was the only tokamak capable of deuterium–tritium (D–T) operations in the last 30 years. As of 2023, JET has finished its operational life and is now being decommissioned. The first D–T operations were in the 1990s and again in 2004. In 2020/2021/2023, JET operated much larger campaigns (dueterium–tritium-2 DTE2, pure tritium TT, dueterium–tritium-3 DTE3), aimed at sustained high sustained fusion power, requiring a much higher tritium throughput [1]. Tritium injection into the JET tokamak involves transfer of tritium between the Active Gas Handling System (AGHS) and the tritium gas injection modules (TIMs) and neutral beam injectors (NBIs), the control of TIMs, and NBI, gas inventory (pre-pulse estimate, post-pulse usage), gas limits (explosive, tritium) etc.

This paper describes some of the operational aspects of injecting tritium in JET. The first section presents the machine context—the supply of tritium from the AGHS, the TIMs, and the JET vacuum vessel. The second section covers operational boundaries—budgets, inventories, and operating instructions. The third section describes a TIM, its basic operations and control system. The fourth section covers tritium operations planning and monitoring.

An overview of the DTE scientific results can be found in [2].

1.1. Context

The DTE1 experiments in the 1990s [3, 4] achieved record fusion powers, but the machine could not sustain them for many confinement times. Since then, JET has upgraded the

[1] See King *et al* 2024 (https://doi.org/10.1088/1741-4326/ad6ce5) for the JET Operations Team.
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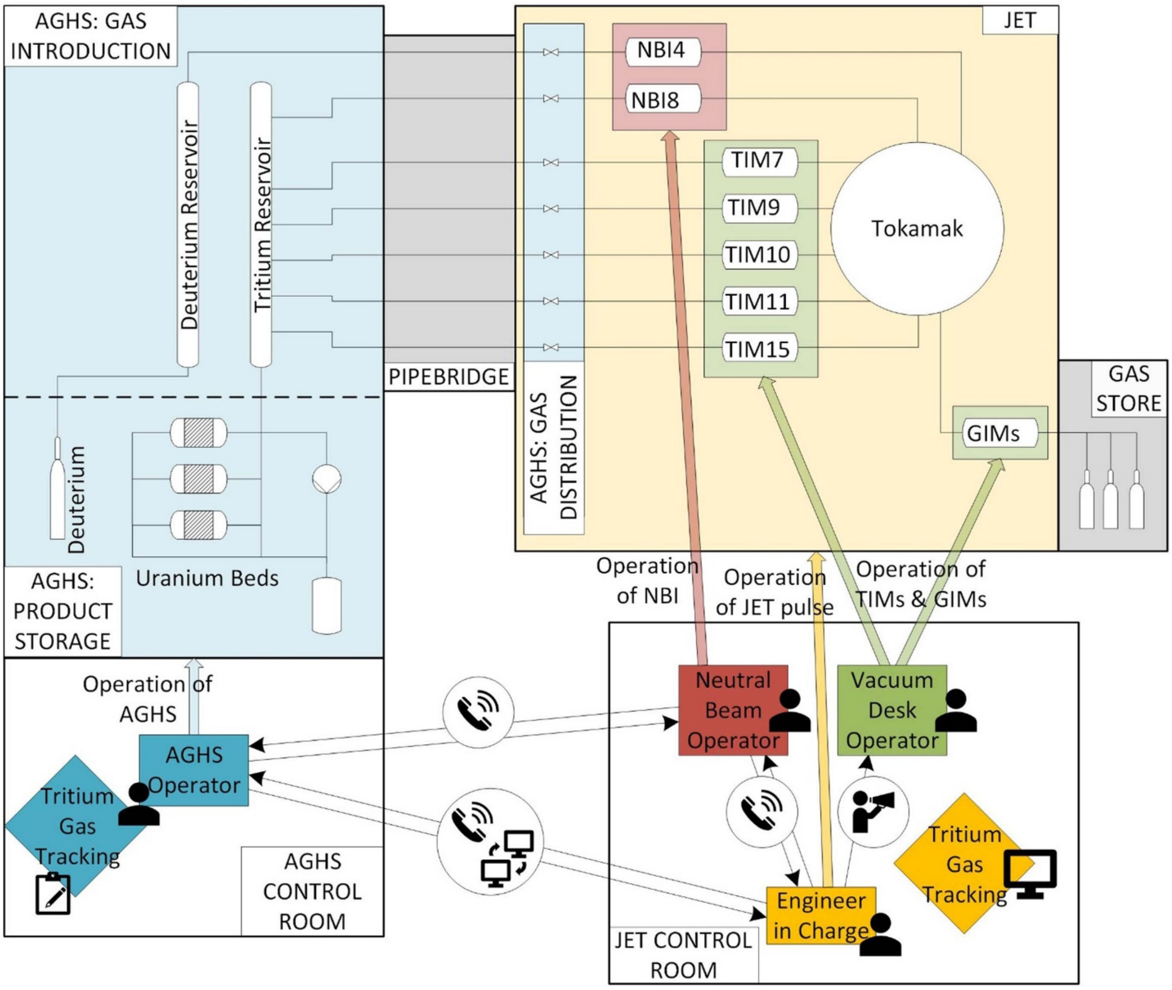

Figure 1. Overview of tritium systems. In normal operation, EIC interacts with AGHS operator and NB operator. In the event of a fault, EIC interacts with vacuum operator. Colour coding is used to indicate activities grouped by operations personnel. AGHS (plant areas and control room), JET control room and JET are all physically located in separate buildings. Reproduced from [5]. © The Author(s). Published by IOP Publishing Ltd. CC BY 4.0.

first wall to minimise tritium retention in the vessel and the magnet power supplies, neutral beam systems, neutron diagnostics and active gas handling to deliver the goal of 10 MW fusion power for more than 5 s. Figure 1 shows the whole system—tritium storage and distribution to the injectors, and the roles of AGHS and JET operators. Many thanks to S Bickerton *et al* for permission to use the figure from their paper [5].

During the recent JET D–T and T experiments, tritium gas (T_2) was injected into the torus by Neutral Beam injection and by TIMs [5, 6]. Other gasses (e.g. D_2, H_2, Ne) were injected from the existing gas injection modules (GIMs). In DTE2 and TT, the NBI used tritium from AGHS. In DTE3, NBI used deuterium from the JET gas store. Experiments compared different isotopic mixtures—tritium from the TIMs and deuterium from the GIMs at the same location, but not at the same time. Figure 2 illustrates the location of the GIMs and TIMs in vessel pipework. The gas injection pipes opened in the upper and midplane main chambers and the inner and outer diverter chambers. To avoid in-vessel work, the TIMs shared outlet pipes with some existing GIMs, so that either a TIM or a GIM could be used, but not both.

The Authority To Operate Holders (ATOH) for AGHS and JET had formal responsibilities either side of the supply valves on TIM or NB reservoirs.

AGHS stored tritium in cold uranium beds (U-bed) in the product storage (PS) zone. When required, AGHS warmed the U-beds and transferred gas from the hot U-bed to a 15 l reservoir in gas introduction (GI) subsystem. GI then transferred the gas up to the TIM or NB supply valve via the ~100 m transmission lines between the AGHS building and the JET building. And then to the reservoirs in the TIMs or NBIs figure 3 illustrates the processes. Bickerton *et al* [5] describes the AGHS operation in more detail. King *et al* [6] describes the NB operations.

The transfer lines and injectors were all enclosed within secondary containment filled with flowing nitrogen. AGHS received the nitrogen and monitored ionising radiation to

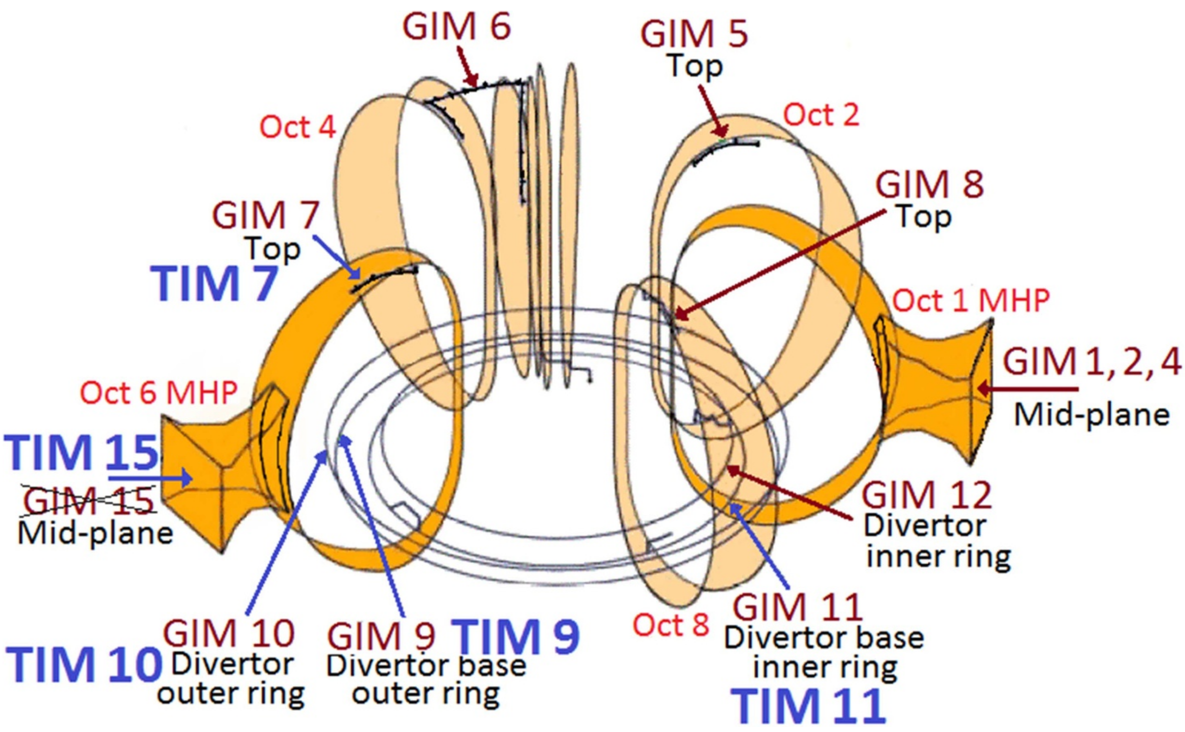

Figure 2. Locations of TIMs and GIMs—The JET vessel has eight sections, hence 'octants'. In the vessel the injection lines, shown in black, have simple holes through which the gas is injected. Outside the vessel, the lines are fed from GIM or TIM.

check that no tritium has passed from primary to secondary containment, as shown in figure 1.

During a JET pulse, the JET CODAS Plasma Pulse Control system controlled the TIMs, closing supply-side isolation valves, opening delivery-side valves, and driving the voltage controlled Piezo valves. The NBI control system drove the injector valves during the pulse.

After the plasma pulse, the gas was captured on the diverter cryo-panels. The panels would be regenerated when the tritium quantity approached the Operating Limit set by Safety Case, or (more usually) regenerated when near the AGHS system handling limits for hydrogenic species, or, occasionally, when access to the Torus Hall was required. Then the diverter and Neutral Beam panels were warmed up and AGHS would collect gasses on their cryogenic fore-vacuum panels and then transfer the gas to impurity processing (IP), separating the gas species and then transferring tritium to PS and transfer other gases to exhaust detritiation system (EDS).

AGHS had a finite capacity to process the regenerated gas and had a regulatory obligation to collect and measure all the T_2. So, the campaigns were organised in cycles of three weeks D–T or T plasma and 1–2 weeks tritium reprocessing and accounting with no plasma. On each day of tritium operation, AGHS collected the regenerated gas and reprocessed it so that as much T_2 as possible was available for the next week. In the accounting week, AGHS collected all the T_2 into reservoirs for precise pressure–volume–temperature (PVT) measurements and estimate gas quantity using the gas law.

2. Tritium operational boundaries

2.1. Safety case

The JET Safety Case estimated the safe maximum of T_2 potentially releasable (in the event of loss of vacuum accident) in the JET vessel was 15 g. They estimated that 4 g could be trapped in the vessel by the end of the campaigns and therefore the maximum injected T_2 should be 11 g before regenerating the cryo panels. The m_mol of tritium is ∼6 and normalised volume is 22.4 l this is equivalent to 41 bar.l; the tritium Working Group with Safety Case added a margin and set the practical limit 44 bar.l. This was formalised in a JET operating instruction and enforced by pre- and post- pulse checks in the live pulse management system supervisory level (PM Level1).

The PM Level1 system tracked the gas injections during the sessions and checked the next pulse's estimate of gas added to the current inventory against the limits. It would warn the engineer in charge (EIC) not to proceed if the estimated gas inventory would exceed the limit.

The Safety Case is described in [7].

2.2. AGHS limits

AGHS has a finite capacity for processing gas regenerated from JET cryo panels, separating hydrogenic isotopes and experimental gasses such as neon. Therefore, experimental sessions were interleaved with non-operational days to give AGHS the time to process the regenerated gasses.

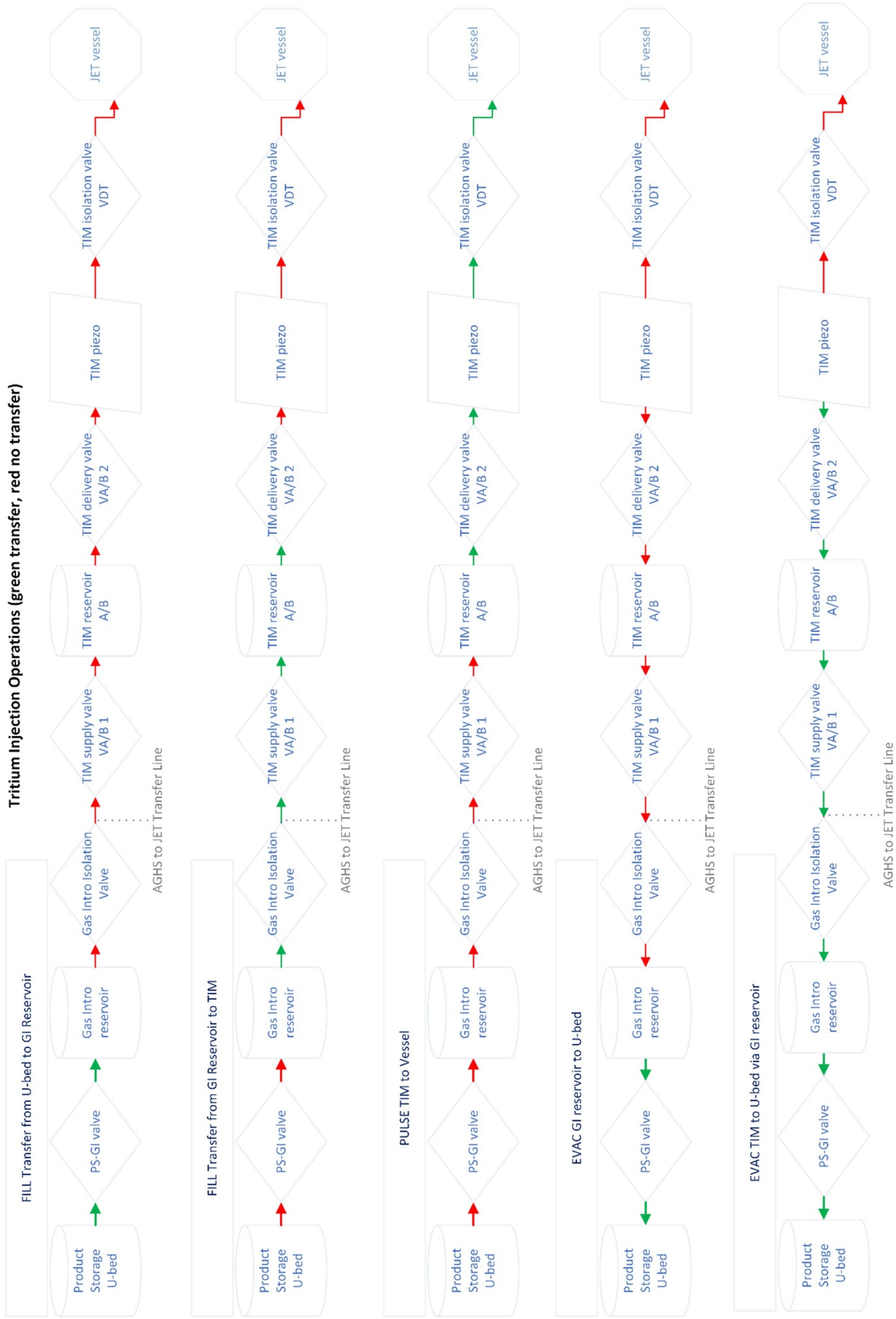

Figure 3. Illustration of tritium transfers—FILL: product storage to U bed and U bed to GI reservoir; FILL: GI reservoir to TIM /NB; PULSE: TIM/NB to vessel; EVAC: GI reservoir to U bed; EVAC TIM/NB to U bed via GI reservoir.

AGHS set limits on gas injections which were enforced by pre- and post- pulse checks in the live pulse management system (PM Level1). The hydrogenic gas limit was 90 bar.l. Level1 would warn the EIC if the estimated accumulated injection for the next pulse would exceed the limits. The EIC would then inform the Operations and Exploitation management teams and stop operations. Plasma operations would resume when AGHS was ready, which could take a few days.

2.3. Programme budgets

In the preparation for the campaign and very aware that tritium would be a scarce resource, the high-level experimental planning required Scientific Coordinators to provide initial estimates for gas and neutron rates on each candidate pulse. During the campaign, the Scientific Coordinators and Session Leaders revised these estimates to optimise the scientific and technical outcomes.

The tritium and neutron budgets were managed closely by the JET Operations & Experimental teams to ensure that they would be enforced in case of changes to the programme due, for example, to tokamak systems unavailability.

The programme budgets were enforced by pre- and post-pulse checks in PM Level 1. Level1 would warn the EIC if the estimated injection would exceed the limits. The EIC would then inform the Operations and Exploitation management teams and revise or even stop operations. The management teams would reconsider the budgets and experimental priorities. The experiment preparation and resourcing are described Bernardo *et al* [8].

3. Tritium gas injector modules

3.1. Components

Design work began with a feasibility study [9] which considered the required throughput and resilience to neutron damage. It proposed that each TIM would have two lines (see figure 4), so that should elements in one fail, the other could be used. Each line has a five-litre reservoir, with dual pressure and temperature gauges, and a voltage controlled piezo valve (0…1000 V, 0…$\sim$ 150 μm) giving a maximum flow rate of $\sim$ 1.5 bar.l s^{-1}. The reservoirs were filled to $\sim$800 mbar from AGHS.

To avoid making new holes and new in-vessel pipes in the vacuum vessel, the TIMs used the existing in-vessel gas injection pipes. The experiments required that in-vessel gas injections could be made by either GIM or TIM but not both. The pipes from GIM or TIM were joined externally to meet the in-vessel pipe and interlocked isolation valves were fitted to prevent T_2 reaching the GIM.

3.2. Control

The TIM valves were pneumatic air operated. The piezo was controlled by high voltage from a voltage-controlled power unit (0…10 V control of 0…1000 V output). The TIM programmable logic controller (PLC) controlled the solenoid air valves. It received commands from AGHS and JET's control and data acquisitions systems (CODAS) and monitored valve states, reservoir pressures and temperatures. The TIM PLC had separate network connections to the independent supervisory control and data acquisition systems (SCADA) in CODAS and in AGHS to keep the systems isolated from unwanted network traffic. Figure 5 illustrates the control network.

Both AGHS and JET Control Room staff operated the TIM valves via user interface software, but the PLC enforced strict rules to prevent a direct line open from U-bed to JET vessel. In FILL or EVAC-uation mode, AGHS staff open the supply side valves of the TIM, while the PLC keeps the delivery side closed. In PULSE mode, JET Plasma Control System opens the delivery side valves and drives the piezo voltage to open the valve, keeping the supply side closed. Figure 3 illustrates the several processes.

To coordinate JET operations with AGHS operations, the EIC sent a REQUEST to FILL or EVAC-uate to the PLC which relayed the request to AGHS and AGHS acknowledged by setting the TIM state accordingly. When AGHS had completed the transfers, they set the TIM state to IDLE GAS or IDLE EMPTY as appropriate. In an IDLE state all valves were closed and disabled.

If the PLC detected a FAULT, e.g. bad N_2 flow, EIC would set COMMISSION mode and the vacuum operator (VCops) investigated—VCops could set/clear faults and set N_2 flow.

3.3. Operations

As required for the experiments, the EIC requested AGHS to fill the reservoir before pulses. This could take some time as AGHS had to estimate how much gas to transfer from PS to GI in order to achieve the 800 mbar in the TIM, given the gas already in GI reservoir, GI/GD lines and TIM reservoir. AGHS would transfer the gas from PS U-bed to GI reservoir and then to the TIM and then finally declare the TIM filled. There were occasions where a TIM FILL 800 mbar was requested, but the AGHS reservoir had 1200 mbar having just filled a NB reservoir. AGHS had to park the excess gas in unused GI lines.

During a pulse, the plasma density and gas control system put the TIMs in a PULSE mode (supply valve closed, delivery valves opened) and set the piezo voltage according to a waveform designed by the Session Leader with optional density feedback control.

At the end of an experiment period (a few days), or when access to Torus Hall was required, the EIC requested the AGHS evacuate all the TIMs. AGHS would then prepare a route to a cold U-bed, evacuate the GI reservoir and transfer line, and then the TIM reservoir. Once the reservoir pressure had reached an agreed low level (10 mBar), AGHS then declared the TIM or NBI as evacuated and EIC could then permit access.

3.4. Calibrations

The piezo valves have a non-linear relationship with control voltage and the pulse control systems have calibration tables mapping the requested opening (0…100%) to control

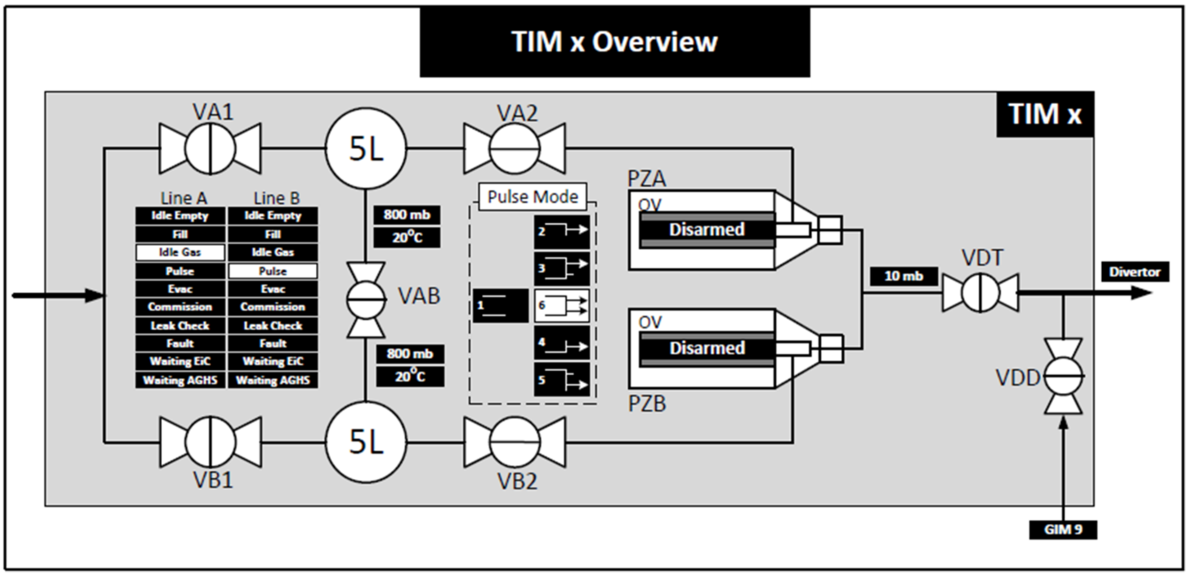

Figure 4. TIM schematic—Each TIM has two lines, each with a 5-litre reservoir and a piezoelectric valve. The reservoirs have duplicated pressure and temperature gauges; VA1, VB1 supply side isolation pneumatic valves; VA2, VB2 delivery side isolation pneumatic valves; VD–T, VD–T TIM/GIM isolation pneumatic valves; VAB link reservoirs for 10 l operation; PZA, PZB voltage controlled piezo valves. The TIMs could be used in several pulse modes—line A 5 l (with VAB closed); line A 10 l (with VAB open); line B 5 l (with VAB closed); line B 10 l (with VAB open); line A and B (with VAB closed); line A and B (with VAB open). For use in tritium pulse, the CODA Pulse Control Software would close the VDD valve and open the VDT valve.

voltage (0…10 V). Each TIM's piezo valve was initially calibrated using deuterium supplied from a gas bottle attached to the AGHS GI (i.e. not from the U-bed). The procedure used a series of short duration blips, increasing control voltage and hence valve opening. Figure 6 shows a calibration pulse. Each blip decreases the reservoir pressure, and the outflow gauge sees a short burst. The calibration curve of Fraction Opening vs Control Voltage was derived from the pressure drops scaled to a reference pressure 800 mbar and then to the maximum flow, i.e. fully open. The maximum gas flow and opening point was different for each TIM due to variations in the mechanical setting. Variations in operating point for a single TIM were also observed on different days—this correlated with the TIM temperature. The piezo had a significant thermal expansion, which the mechanical design did not account for.

Unfortunately, the competing demands of the campaign, the conditioning plant systems (especially NB), and AGHS processes restricted the number of such calibrations, in particular the number of blips, and the voltage range and resolution, so the accuracy of the dependence of flow on reservoir pressure, piezo hysteresis and piezo temperature was limited.

In AGHS, TIM11 does not have a connection to the D2 supply, so TIM11 calibration had to wait until the tritium boundary had reached the TIMs, and then the calibrations were repeated for all TIMs.

The quality and accuracy were just enough to get through the Campaign, though Session Leaders had to be quite inventive at times to get the low flow they sometimes required and to deal with the hysteresis of the piezos.

3.5. Performance

In the initial commissioning with D_2, it was found that the isolation valves did not close properly and passed gas. The TIMs had to be taken off the machine, stripped down, then clean and rebuilt. Fortunately, it was possible to do this as the tritium boundary had not been expanded up to the TIMs at the time. Small grains of swarf were found in the valve seats, including the piezos. The piezos were returned to manufacturer for a strip down/clean/rebuild/retest. This delayed the commissioning by two months.

After re-installation and calibration, the TIMs performed reliably with no faults. It was found that the pipework between the TIMs, and the vessel caused a significant delay in delivery of gas, of the order of 300 ms. Session Leaders adapted their schedules which had been developed using GIMs before the TIMs were installed. They would preload a feedforward waveform to get gas to plasma as quickly as possible. Also, the piezo valves showed significant hysteresis with an opening control waveform going from low ($\sim$20%) to high ($\sim$7%) and back to low. The flow did not return to the first flow rate and was significantly higher. A work around was found—setting the control waveform to zero for $\sim$ 100 ms after a wide opening reset the piezo and did not perturb the plasma.

Models were developed to predict gas flow, but these were based on very limited data and so were not very accurate. Session Leaders were able to adapt their schedules and the plasma pulses mostly worked as expected.

The post-pulse analysis codes to calculate gas flow and electron flow were adapted to use the TIMs as well as the GIMs. They use simple approximations, e.g. flow proportional to pressure and aperture, and did not consider second order

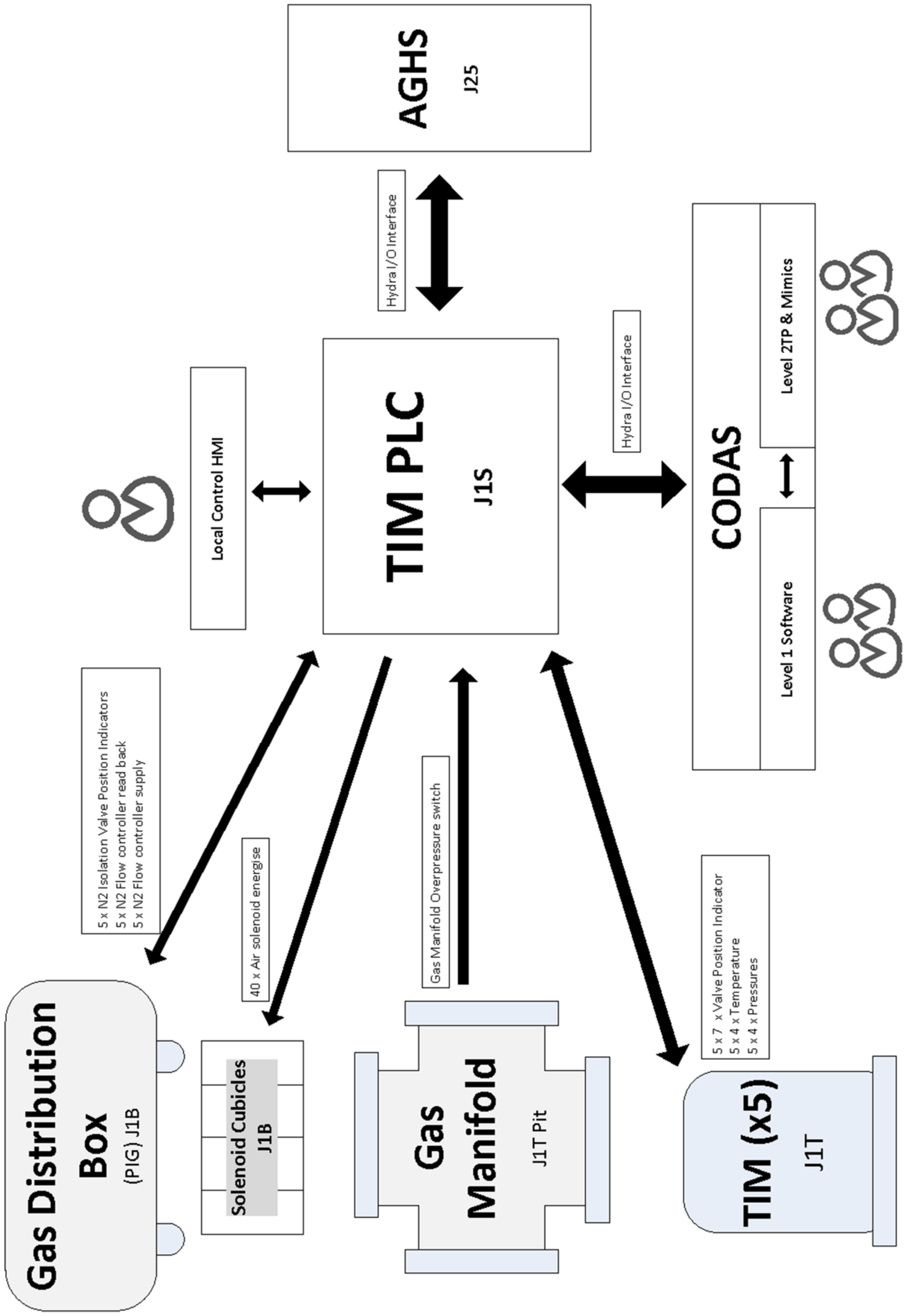

Figure 5. TIM control paths. The PLC relays AGHS plant data to JET control room and JET plant data to AGHS control room via separate networks. EIC sends requests FILL/EVAC to PLC which relays the request to AGHS. AGHS acknowledge via the PLC. EIC also interacts with AGHS over telephone and video links. In PULSE mode, CODAS sets the supply and delivery valve states and drives the piezo valve If the PLC detects a FAULT, EIC requests COMMISSION mode to allow vacuum operator to investigate. They can set/clear faults, can set N2 flow. J1S is the JET is the gas store. J1T is the torus Hall. J1B is the basement below J1T. J25 is the AGHS building.

effects (e.g. dynamic pressure). One code attempted to correct for hysteresis but only had hysteresis data for one TIM. The hysteresis was thought to be similar in all the TIMs, so the same correction factors were used for all TIMs. Another code uses gas flow fitted to the outflow pressure gauges, but the fitting is not accurate as the data set is limited. We did not have opportunities to further develop gas flow models experimentally.

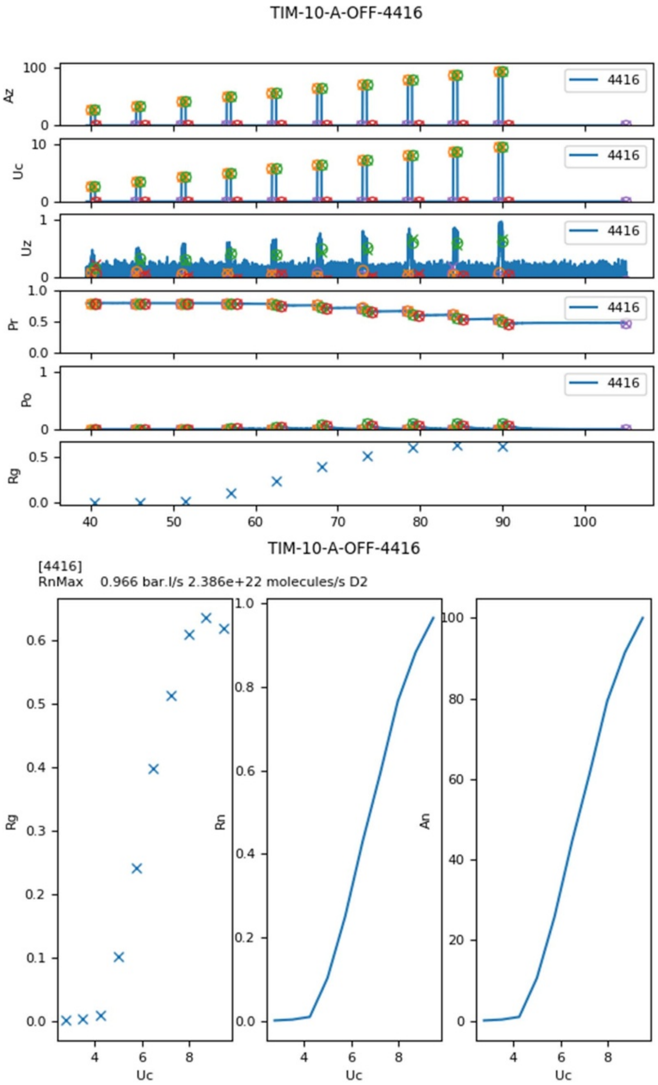

Figure 6. TIM calibration. upper plot: increasing short openings (blips) of valve opening *Az* [%] and Control Voltage *Uc* [V] causing reservoir pressure *Pr* [bar] drops and outflow pressure *Po* [bar] bursts. *Uz* [V] is the piezo voltage, scaled by 0.001. Lower plot: lower: calibration curve is the normalised pressure drop vs control voltage for each blip. *Rg* is Gas flow [bar.l s^{-1}] at the reservoir pressure. *Rn* is Gas flow [bar.l s^{-1}] normalised to 800 mbar, *An* is valve opening [%] normalised to maximum flow. The operator staff transfer the aperture *An* curve to the plant. The GIM Calibration procedure is similar.

4. Tritium operations

4.1. Pulse preparation

The pulses to be used in the DTE2 campaign were first developed with D_2 in the GIM at the same locations as the TIMs would be, and D_2 in the NBI. In this time, budget and inventory software controls were developed.

Once the TIMs were installed, the pulses were repeated but using the TIMs in D_2. The pulses were adapted to deal with the different valve openings to the different flow characteristics and the delays.

Before any tritium was transferred to TIM or NBI for experiments, the integrity of the lines was checked with a procedure called Tritium Boundary Expansion. First, within AGHS, tritium was transferred up to the transmission lines, then and reservoir and line pressures monitored for a day or so. Then tritium was transferred to across each line up to the supply side valves on TIM or NBI and monitored for another day and then tritium was transferred up to the delivery side valves and the pressures monitored. Finally, the tritium was pulled back to AGHS. No significant pressure change was found, and the system deemed ready for operation.

4.2. Weekly, tritium plasma

The JET exploitation committee (exploitation manager, task force leaders, etc) planned the coming weeks experiments, addressing the scientific progress and priorities, and balancing the distribution of tritium across the several scientific programmes. The operations coordination Meeting (including the operations manager, group leaders, etc) planned the machine requirements, addressing machine capabilities, budgets, and resources. The main budgets were determined by the capability of AGHS to process the gas and the Safety Case limit of 11 g (44 bar.l) limit of tritium on the cryo-panels.

4.3. Daily, tritium plasma

AGHS warmed up the U-beds early in the morning for delivery to JET later in the day. The EICs checked the Session Leader's pulse schedules and ran the JET pulses, requesting FILL or EVAC as required.

The vessel diverter and NB cryo-panels were regenerated every night.

If access to Torus Hall or Basement would be required overnight, the EIC would request EVAC of TIMs and NBIs. AGHS would pull back the gas to U-beds via GI and declare that the T_2 had been pulled back and access allowed.

The Daily Tritium Meeting, comprising JET ATOH, AGHS ATOH, JET Chief Engineer (JCE), JET Operations Manager, tritium reporting officer and Safety Case representative) would review the area radiation, tritium transfers, neutron rates, etc. of the previous day and instigate investigations if there were anomalies (see figure 7).

4.4. Weekly, no plasma, accounting

Approximately every fourth week, plasma operations were suspended to allow AGHS to collect all the tritium and estimate the total quantity as precisely as possible from PVT and Radioactive Decay Heat. AGHS transferred all the T_2 into reservoirs with accurate pressure and temperature gauges. Also, the AGHS accounting staff would reconcile the written records of gas transfers with the records of the location stock [10].

The Exploitation (Science Programme) and Operations meetings continued to review progress and plan further work.

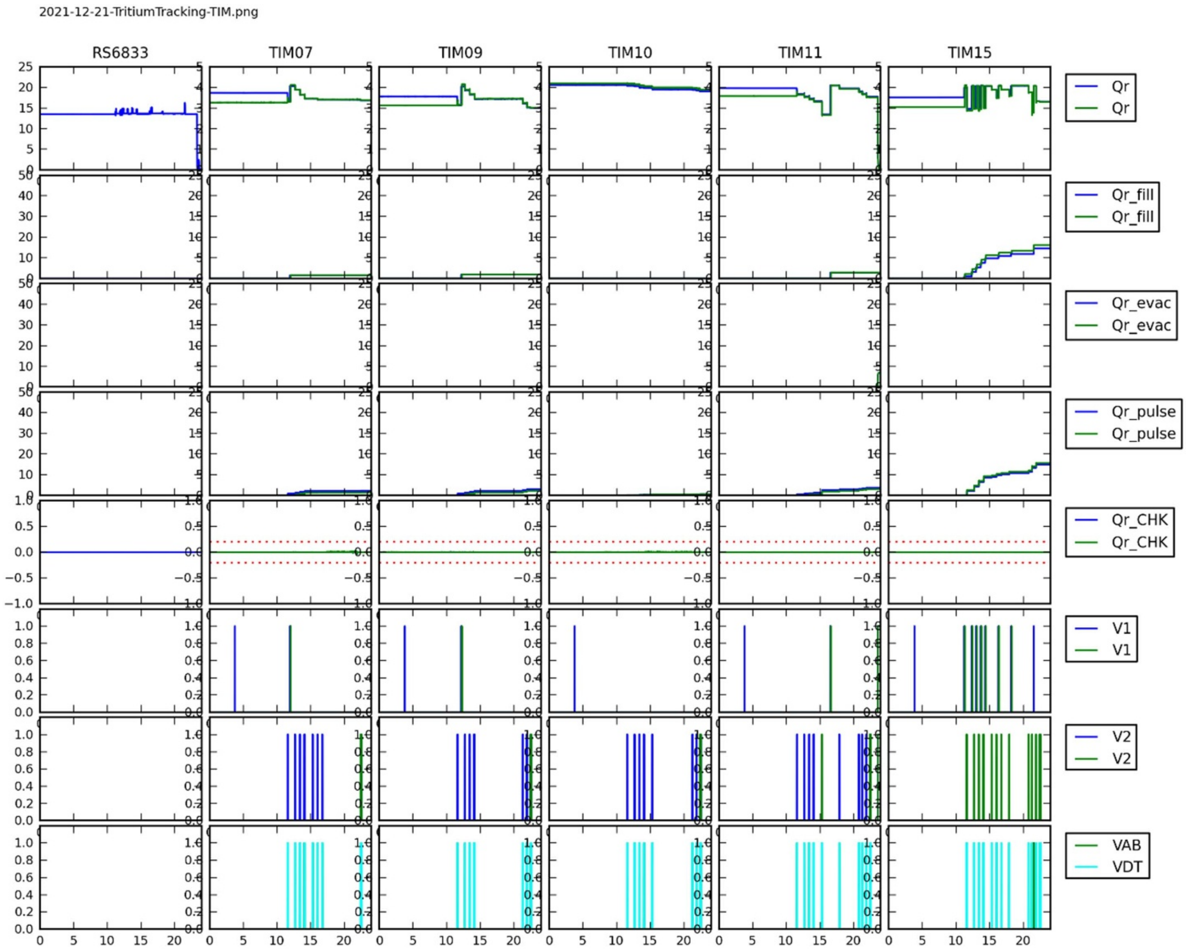

Figure 7. Daily tritium meeting example—tritium transfers inferred from supply/delivery valve state. Line A blue, line B green. *Qfill, Qpulse, Qevac* are T2 quantity transferred, bar.litre *Qr_chk* show gas not assigned to FILL, EVAC or PULSE with limits (red), i.e. when pressure change not consistent with valve state. V1 open, V2 closed indicates FILL V2 open, V12 closed indicates PULSE. V1 open, V2 open indicates EVAC.

4.5. Tracking tritium

For the Daily Meetings, we wanted to know how much tritium was in the AGHS, TIM and NB reservoirs, and how well the transfers were doing.

Software was developed to tracking tritium in JET monitoring pressure changes in TIM and NBI reservoirs and allocating the quantities to FILL/EVAC/PULSE according to valve state. If a supply side valve was open, and the reservoir pressure increased the transfer was recorded as a FILL. If the pressure decreased, the transfer was recorded as an EVAC. If the supply valve was closed and the delivery valve open and the reservoir pressure decreased, the transfer was recorded as a PULSE.

The valve state indication was problematic. Using the valve's internal switch (spring-loaded metal strip) was not reliable and changing to use the pneumatic air indication (when air valve solenoid active assume air-operated valve open) proved sufficiently reliable. Even so, the sampling of the valve states was not synchronised nor very fast, so that a pressure change could be observed but for short time no valves were apparently open.

Tracking was further complicated by AGHS topping up both reservoirs and then equalising the reservoir pressures by opening the link valve VAB. One reservoir pressure would lower and the other would rise, so the tracking had to include a check of the VAB link valve as well as the supply valve VA1/VB1.

The use of so many gauges with no means to cross-calibrate limited the accuracy and self-consistency.

The monitoring of T_2 by the ionisation chamber (IC) in the secondary containment gas return did not trip the safety limits. However, there was an incident where the levels increased to a level large enough to cause concern. Investigations operated the valves one at time and waiting for a response within a few hours on the IC. The whole exercise took days, meanwhile the campaign was suspended. The main suspect was the pressure regulator in NBI4. The tests were repeated, but they were not conclusive, and ATOHs and JCE agreed we could resume the Campaign with caution.

There were no more similar events, and the IC levels have remained low.

5. Concluding remarks

This paper has tried to give an idea of the operational aspects of injecting tritium into JET. It has covered the overall context of the tritium cycle, the Operational Boundaries, the components of the TIMs and their performance, and the management of Operations.

Overall, the Tritium Gas Injection has been successful, re-using the 69 g on site to deliver 1 kg used for DTE2, i.e. 240 g TIMs and 763 g (T-NBI) For comparison, DTE1 used only ~100 g.

The main lessons for future tritium machines are to consider early the operational issues—how to get tritium out of and back into storage, including how to reduce tritium 'lost' in process, how to check gauges, how to track inventories in several locations, and, not least, how to effect repairs.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary files).

Acknowledgments

So many people have worked with the Tritium Gas Injections, and it has been a tremendous collaborative effort, so I would like to thank all and particularly the JET Operations and Exploitation management teams, ATOHs, Office of the Chief Engineer, EICs, the NB operations team, AGHS operations team, the Vacuum group, CODAS, JET Machine Operations Technicians and the designers and constructors of the TIMs and NBIs.

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