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Tritium Introduction Module Design for the JET Tokamak

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In support of ITER, two experimental campaigns are foreseen to take place at JET, the first with tritium only and a second with deuterium plus tritium to explore the machine fusion potential. To support the tritium operation, a total of five Tritium Introduction Modules (TIMs) are expected to be installed at JET, one on top of the machine, another in the mid-plane and three in the divertor region.

Since no human intervention or serviceability to the TIMs is foreseen during the tritium experimental campaigns, their design needs to incorporate redundancy, reliability, secure operation and conform to JET specific design, inspection, testing and safety case requirements. The challenges to the design in complying with operational requirements, connection to the Active Gas Handling System (AGHS), predicted neutron and gamma levels, were taken into account and shaped the design choices presented in this paper.

Keywords: JET tokamak, Tritium, Nuclear fusion, Tritium safety, piezoelectric valves.

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1. Introduction

In previous JET tritium experiments (Deuterium-Tritium Experiment 1 (DTE1) [1] and the Trace Tritium Experiment [2], the tritium fuelling capability was provided by the Octant 8 Neutral Beam Injection system and one dedicated Tritium Gas Introduction Module GIM 15 (located at the mid-plane of Octant 6). The fuelling rates and quantities from these two sources are insufficient to carry out the objectives of the planned DTE2 campaign [3,4]. The proposed solution is to provide five new tritium modules at three divertor and two main vessel locations (one mid-plane and one on the top of the machine [5], providing a total maximum delivery of ~4g of tritium, for the 4.5MA worst case pulse. This is approximately 16 bar litres in total (or 4 bar litres per TIM, based on 4 operational modules at any given point in time). In order to reproduce in tritium recent deuterium experiments a maximum flow rate from each module of at least 1.6 bar.l/s, is also required [5].

Control of the amount of delivered gas on all Gas Introduction Modules (GIMs) [6] (both active and non-active gases), pre DTE2, relies on VAT piezo-crystal actuated valves, operating with gases pressures at up to 2.4 bar. For tritium delivery using gas supplied at sub-atmospheric pressure (~800 mbar), new piezo-valves capable of delivering three times the present flow rates had to be developed. Prototype testing of the piezo-valves is underway with significant improvements to the VAT design being implemented for the production valves which will be included within the TIMs.

Physical access to these modules will not be possible during the DTE2 campaign (due to very high personal dose levels), so that redundancy within the design to cater for sub-component failure has had to be considered.

The TIMs are scheduled to be installed within the next JET shutdown period, which starts Nov 2016 with restart around Aug 2017.

2. Functional & Operational Requirements

The original GIM 15 depicted in figure 1 provided a single delivery point at the Main Horizontal Port of Octant 6. The physical size of GIM15 is 220 mm outside diameter by 550mm high.

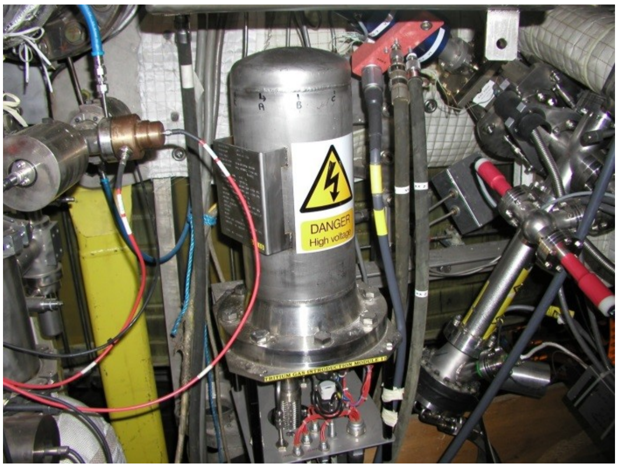


Fig. 1. GIM 15, the tritium delivery module for the DTE1 campaign (to be replaced by the TIMs).

The positions selected have been based on available space, proximity of torus entry and most importantly lowest total radiation dose [6]. No shielding has been included in the design, on the basis that gamma and neutrons dose levels will be below those already experienced by existing surviving Baratrons (with > 20 years survival on the JET Torus) as detailed in table 1.

Simulations were performed to access the level of radiation at several potential TIM locations that aimed to minimise the distance between the TIM location and the corresponding machine tritium injection point. As an example one of the selected locations to install the TIMs is depicted in figure 2. The results of this simulation is detailed in table 2 and summarised in figure 3 where it can be seen that the expected radiation levels at the chosen TIM locations, are below the historical values. It is therefore expected that the TIM Baratrons are able to survive during the foreseen DT campaign.

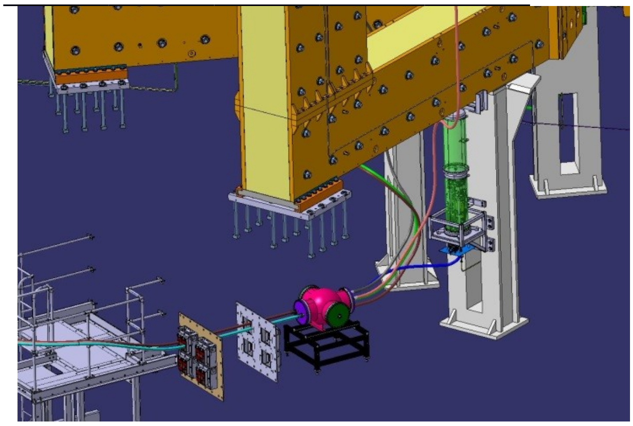


Fig. 2. Proposed machine location for one of the TIMs in a relatively protected area to avoid the need of extra shielding.

The main design requirement is for secure and reliable operation of the TIMs. The new modules need to be integrated into an existing tritium gas system, that includes tritium transfer lines, distribution vessels and the JET Active Gas Handling System (AGHS) [8] that contains the uranium tritium storage beds and systems for handling of the nitrogen purge gas used in all of the secondary containment volumes.

Various operations modes are envisaged to: fill TIMs with tritium or recover tritium back to AGHS, tritium injection for plasma operations, injection using both piezo-valves, system plant commissioning (local control). All these states are to be controlled using a local cubicle Programmable Logic Controller (PLC) unit and are reflected in the proposed control room mimic of figure 4.

Table 1. Aggregate Baratron exposure from 1996 to 2015.

Octant number Baratron	Neutron Silicon Dose, Rad(Si)	Gamma Silicon Dose, Rad(Si)	Total Silicon Dose, Rad(Si)	Neutron Fluence (n/cm^2)	Gamma Fluence (g/cm^2)
1	3.35E+02	7.16E+02	1.05E+03	1.16E+13	1.48E+12
5	2.15E+02	3.78E+02	5.93E+02	9.59E+12	8.30E+11

Table 2. Predicted Radiation for each TIM position.

TIM	Neutron Silicon Dose, Rad(Si)	Gamma Silicon Dose, Rad(Si)	Total Silicon Dose, Rad(Si)	Neutron Fluence (n/cm^2)	Gamma Fluence (g/cm^2)
7	1.24E+02	8.60E+01	2.10E+02	1.30E+12	1.27E+11
9	1.94E+01	4.43E+01	6.36E+01	1.12E+12	6.82E+10
10	2.67E+01	5.82E+01	8.49E+01	1.07E+12	7.01E+10
11	2.76E+01	4.42E+01	7.18E+01	1.09E+12	6.70E+10
15	5.63E+01	9.47E+01	1.51E+02	1.24E+11	2.21E+10

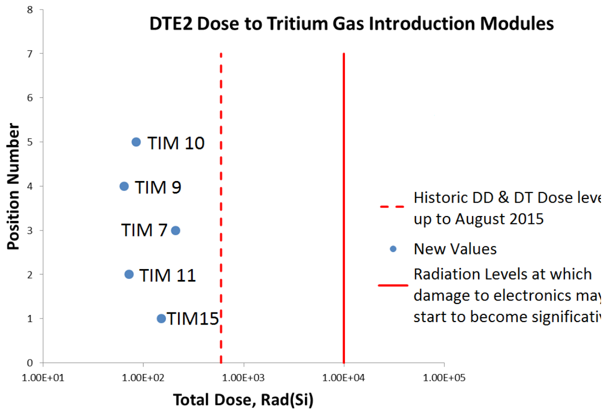


Fig. 3. Expected radiation dose levels for each TIM compared with historical values.

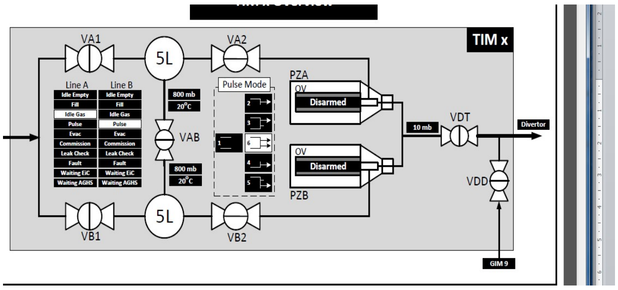


Fig. 4. Proposed control room Mimic for the TIMs

3. Tritium Introduction Modules

TIMs are required to provide controlled tritium injection to the vacuum vessel while avoiding accidental release to the vessel or environment. TIMs consist of a secondary containment vessel, internally filled with a purge gas of recirculating Nitrogen. This container also encloses the primary tritium components, including the piezoelectric valves, the primary tritium reservoirs, and pressure and temperature instrumentation for accurate tritium inventory accounting. Prototype piezo-valves developed by VAT Vacuum Valves AG with a nominal stroke of ~160μm and orifice area of 5.2mm^2, are being tested for T_2 equivalent target flow rates of 1.6 bar.l/s.

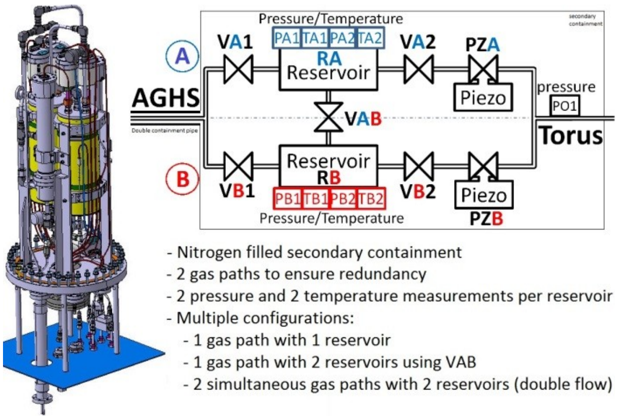
The initial conceptual design proposed using a single 5 litre reservoir located within the TIM (800 mbar within a 5 litre reservoir, equates to 4 bar litres or ~1g of tritium). It was concluded that the actual average flow rate from this configuration would be only ~0.53 bar.l/s over a 5 second period, delivering only 0.65 g per pulse (or 2.6 g from the original 4 off single reservoir TIM design), which is a consequence of the fall-off in pressure within the reservoirs during delivery. This may be further reduced should the actual pressure drops within the delivery lines be higher than expected.

The design is broadly based on the original GIM15 design (first installed in 1994), in that all of the internal tritium containing components are housed inside of a secondary containment vessel, designed to withstand the likely fault conditions, now with a physical size of 350mm outside diameter by 1000mm high.

The design has evolved into a double 5 litre reservoir and piezo-valve configuration, which allows up to twice the single flow rate. A two system A & B approach (see figure 5) provides redundancy as well as allowing operational versatility, so if the tritium demand is less than the maximum, then the tritium inventory external to the uranium beds, can be minimised to meet the safety case limits [8]. Should a piezo-valve fail, then the remaining operational valve, retains access to both of the 5 litre reservoirs (~2g of tritium), if necessary. The total capacity of the 5 off double reservoir TIMs is ~10 g of tritium gas.

Another improvement from the original GIM15 design, is the inclusion of local PVT measurements for accurate tritium accounting at each individual reservoir. The pressure measurement is made using a MKS Baratron absolute pressure transmitter of the capacitance manometer type. The temperature measurement is made using 4 wire PT100s (figure 6).

The tritium containing components are housed inside of a secondary containment vessel that is purged with nitrogen gas at a pressure above atmospheric pressure (up to 2.5 bar gauge), so that the driving force should a leak occur is inwards. Figure 6 shows the internal packaging and how the services are feed through the lower feedthrough flange and are externally supported using a services marshalling plate.



- Nitrogen filled secondary containment
- 2 gas paths to ensure redundancy
- 2 pressure and 2 temperature measurements per reservoir
- Multiple configurations:
  - 1 gas path with 1 reservoir
  - 1 gas path with 2 reservoirs using VAB
  - 2 simultaneous gas paths with 2 reservoirs (double flow)

Fig. 5. Proposed TIM component packaging

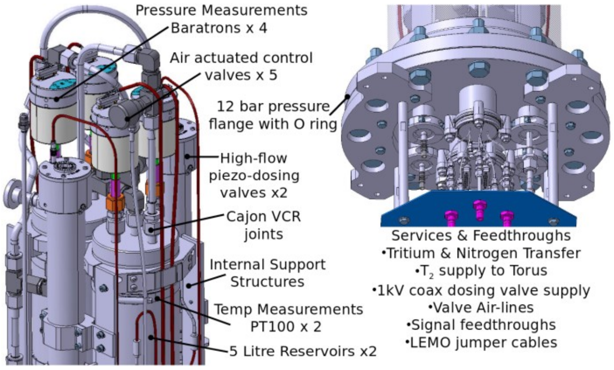


Fig. 6. Details of the TIM internal design.

4. System integration

Since the tritium available on-site for the TT and DT campaigns will be in the order of 60g, the tritium used in the experiments will be recycled through AGHS several times. The exhaust gas will be collected by AGHS and separated first into hydrogen isotopes and then using cryodistillation techniques [10]. The recovered tritium will be stored in the uranium beds.

The TIMs are connected through a supply network involving distribution vessels and tritium transfer lines connecting directly to the AGHS valve box and ultimately to the primary Uranium bed storage and to a monitored discharge stack for the nitrogen exhaust. AGHS also supplies the neutral beam injector gas [11] (tritium or deuterium) as detailed in figure 7.

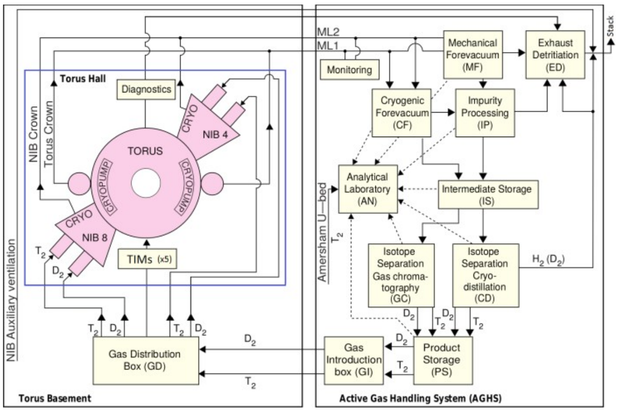


Fig. 7. Detailed schematic of the AGHS operation and connection to the machine.

The TIM control sequence will be controlled via PLC logic with well-defined operational states with the AGHS being responsible for the TIM reservoir top-up/gas evacuation, while CODAS will control the TIM operation during the pulse.

5. JET Specific Design and Safety Requirements

Both general design criteria and safety case requirements [9], apply to the design of all components that make up the Tritium Gas Introduction System (TGIS).

All of the containment vessels and associated piping are designed and pressure tested in accordance with ASME VIII Div1 and ASME B31.3 (2014) Category M respectively. The system acceptance criteria is a helium leak test to $<5\text{x}10^{-10}$ mbar litres per sec, for all components with thermal cycling up to 120°C. The secondary containment vessel and tritium reservoirs are pneumatically pressure tested to 12 bar gauge to satisfy pressure surges, in theory possible during fault conditions.

6. Prototype gas injector (GIM3)

To test and to provide design input, the high flow piezoelectric valve is being tested. A prototype gas injection module (GIM3) was installed in octant six main horizontal port. The results so far show that the maximum flow rate achieved (if scaled to tritium operation at 800 mbar), is approximately1.15 bar.l/s. Since each TIM has two piezo-electric valves it is expected to meet the requirements for DT operations even without further design improvements, which are ongoing. The prototype has only one 5L reservoir and one piezo-electric valve, representing roughly one half of the TIM design (see Figure 8). To further emulate the TIM design, GIM3 has also two reservoir pressure sensors and two temperature sensors as well as a single output gas pressure gauge.

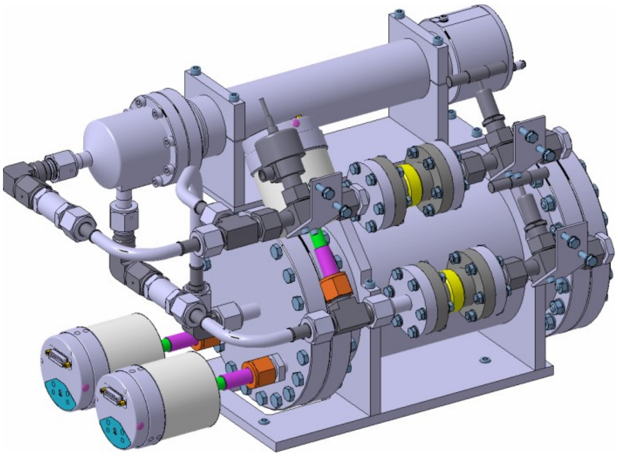


Fig. 8. CAD design of GIM3 installed on octant 6 main horizontal port.

7. Summary and Conclusions

The main design requirement is for secure and reliable operation of the Tritium Introduction Modules. This design was heavily inspired by the DTE1 tritium valve (GIM15) configuration, with respect to the security measures incorporated. Gas flow rates from the old GIM15 were insufficient to meet the demands of the planned TT or DT campaigns, so new modules incorporating high flow piezo-valves with local tritium storage were designed.

Since no serviceability is foreseen during operation, the TIM design has several redundant features in order to continue operation in the event of a part failure, even if it meant increasing the TIM operational space envelope.

A total of five TIM locations were selected after considering the radiation effects on the TIM electronics, and minimising the distance to the machine injection point. Results of simulations show that the TIM electronics are expected to survive the DT campaign.

The TIM prototype piezo-valve is presently under testing during present JET operations and the full TIM system is expected to be installed on the machine by the end of the 2017 shutdown.

Acknowledgments

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