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Technical Rehearsal of Tritium Operation at JET

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The final phase of the JET Programme in Support of ITER plans to operate with 100% tritium (TT) followed by deuterium-tritium (DT) operation, to help minimise risks and delays in the execution of the ITER Research Plan and the achievement of Q~10. In preparation for Tritium operation, an 8-week technical rehearsal of the procedures and systems is being executed in 2015-16. The aim is to commission (in deuterium or hydrogen) and characterise the NBI performance with a tritium-like gas feed configuration, test the prototype tritium introduction module, commission the torus hall depression and depletion system, carry out emergency exercises, train personnel and to test and optimise operational procedures. The rehearsal demonstrated that JET is still capable of operating with tritium in a safe and reliable manner, and most importantly, provided operational experience and lead to recommendations for the preparation of these future tritium campaigns on JET.

Keywords: tokamak, tritium operation

1. Introduction

Deuterium-tritium is the foreseen fuel mixture for ITER and future fusion power plants, providing the best fusion performance at the achievable operating temperatures. JET is presently the only tokamak capable of tritium operation and is currently preparing for the next two tritium campaigns, the 100% Tritium (TT in 2018) and the second Deuterium-Tritium experiment (DTE2 in 2019) as shown in the timeline presented in Figure 1.

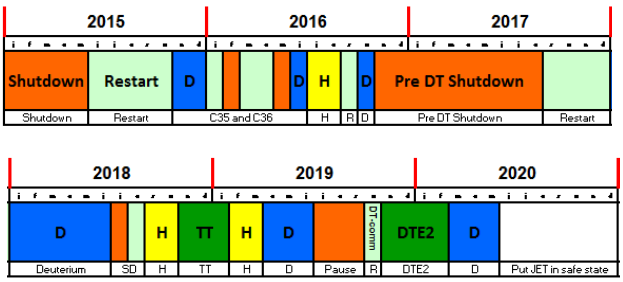

Fig. 1. JET timeline until 2020

1.1 Tritium operation at JET

The preparations are based on the experience of the previous campaigns, the Preliminary Tritium Experiment (PTE) in 1991, the first Deuterium-Tritium Experiment (DTE1) in 1997 and the Trace Tritium Experiment (TTE) in 2003. The new campaigns will explore some of JET's unique features such as the ITER-like first wall (beryllium, tungsten), substantial upgrade of the heating systems (neutral beam upgrade, ITER-like ICRH antenna), extensive remote handling capabilities and the improvements in diagnostics since 2003.

There are a number of additional technical requirements (compared to deuterium and hydrogen) to operate with tritium gas, a high DT neutron flux and neutron activation.

a) Tritium is stored in uranium beds and will be supplied by the tritium plant to one or two neutral beam boxes and five new tritium introduction modules. Other gases (e.g. deuterium, hydrogen, neon, argon) are provided from local gas cylinders or the gas store in the JET building to the standard gas introduction modules, disruption mitigation valves and pellet systems.
b) The torus hall atmosphere is under depression to limit the spread of tritium in case of accidential tritium release. In addition oxygen content of the torus hall is reduced to 15% as a fire suppression measure.
c) Access is restricted to key operational areas of the JET building for prolonged duration due to increased neutron activation and gamma radiation, risk of tritium release and low oxygen level of the torus hall.
d) Tightened access restrictions are applied to computer networks.
e) The divertor and neutral beam cryo-pumps are regenerated after every operational day using cryo-forevacuum pumps to limit and monitor the tritium inventory outside the tritium plant.
f) Additional tritium operational procedures are used in the JET and the tritium plant control rooms.
g) More detailed experiment preparation and monitoring of the tritium inventory and neutron activation is required pulse by pulse.

The key safety requirements and safety measures are described in the DT safety case. The JET operating

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instructions and the local rules provide the relevant procedures.

1.2 DT rehearsal

As part of the preparation for the TT and DT campaigns at JET, an 8-week technical rehearsal of the procedures and systems to be used in tritium operation is being perfomed (without use of tritium) in 2015-16 as shown in Table 1.

Table 1. Structure of the DT rehearsal in 2015-2016.

Campaign	Date	Aim
Restart	2015, 2016	Commissioning of technical systems
C37	July-August 2016	5 week rehearsal in hydrogen
C36B	October 2016	3 week rehearsal in deuterium

The aim of the DT rehearsal is to check if appropriate arrangements are in place for operation, monitoring and maintenance of selected technical systems under the restrictions imposed by tritium operation. The operating procedures follow those proposed for the TT and DT campaigns as closely as reasonable. An integral part of the rehearsal is the training of operational personnel.

Specifically the aims are to: a) characterise the neutral beam performance with a tritium-like gas feed configuration, b) test and characterise a prototype tritium gas introduction module with deuterium, c) rehearse the operation of technical systems (torus hall depletion and depression system, tritium fuel cycle with deuterium), d) clarify, test and optimise operational procedures, e) test and optimise monitoring of gas and neutron budgets, f) train control room and plant staff, and g) gain experience and make recommendations for the preparation of future tritium campaigns on JET.

This paper describes the requirements, preparation and execution of the technical rehearsal of tritium operation at JET in 2015-16.

2 Technical systems

2.1 Tritium fuel cycle

The tritium is stored in uranium beds in the tritium plant (AGHS - Active Gas Handling System) and reprocessed to a purity of 99.4% by gas chromatography. Tritium will be injected into the torus through the Tritium Distribution Gas Introduction System (TDGIS) [1] to one or two neutral beam boxes and 5 new tritium introduction modules. The foreseen quantity of injected tritium will be thus significantly higher compared to previous campaigns using one beam box and one gas introduction module only. In addition, there are 12 standard gas introduction modules, two pellet systems and two disruption mitigation valves injecting other gases. All gases are pumped by neutral beam and divertor cryopumps during the day and after their regeneration by the cryogenic forevacuum pumps in AGHS through an on-site closed circuit as shown in Figure 2.

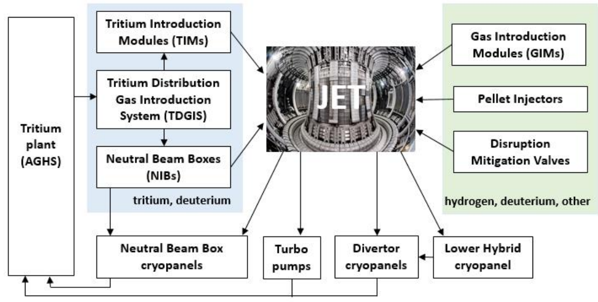

Fig. 2. Tritium fuel cycle at JET

As part of the rehearsal the full fuel cycle was commissioned delivering deuterium gas from the uranium bed through the TDGIS [3] to one neutral beam box and regenerating the cryopanels with the cryogenic forevacuum pumps. The gas was delivered to the neutral beam injectors at the grounded potential of the accelerator (grid gas operation) rather than individually to the ion source and neutraliser due to the engineering challenge of having an insulating high voltage break with secondary containment for the tritium gas.

The neutral beams are expected to provide up to 17.6MW heating power per neutral beam box in tritium (equivalent to 17.3MW in deuterium). It was shown on the neutral beam testbed, that if the grid gas flow rate is sufficiently high, the arc efficiency and other characteristics such as species composition achieved in normal gas operation could be reached [4]. During the rehearsal, two weeks of reliable operation was achieved in grid gas with a single gas flow setting. In this time, 94% of the arc efficiency of standard operation was obtained. Further tests with higher gas flows are planned in the restart period in 2017.

As part of the final design of the new Tritium Introduction Modules (TIMs), a prototype gas introduction module has been assembled and installed at the midplane using a local deuterium/hydrogen bottle. It was operated throughout 2016 gaining experience in its operation both from the technical and the plasma side by providing gas to improve the ICRH coupling in a midplane location. Based on the results, the piezo valves in the TIM design were modified improving their reliability and functionality [1]. The operation of the module provided an opportunity to optimize the related measurements, calibration and control [2].

2.2 Torus hall atmosphere

The JET torus hall, basement and neutral beam test bed are under sub-atmospheric pressure to ensure that any leakage of undesirable air-borne substances will leave the building through a monitored stack where the rate and quantity of any release of activated isotopes can be assessed. In tritium operation, the torus hall depression is increased futher while maintaining at least 100 Pa pressure difference to other areas. The maximum achieved pressure during the rehearsal was 308Pa in the torus hall with the basement at 102Pa. To further improve the depression of the torus hall, and the torus beam seals were repaired and all physical penetration to the torus hall were tested (no major leaks found).

In addition, the torus hall atmosphere is depleted to 15% oxygen content by circulating increased amounts of nitrogen for fire suppression as access to the torus hall can be delayed by several hours during tritium operation. A two day test carried out in 2015 was successful in reaching the required 15% oxygen level in 6 hours. It was maintained it for a day then the standard 21% oxygen level was recovered within 3 hours. The test identified a number of issues including strong interaction between the depression and depletion system (corrected during the test) and issues with the torus hall oxygen monitors (new oxygen monitors installed in 2016) and icing of the Nitrogen evaporators (solution under discussion). Following the rectification of most of these issues, additional two day test of the depletion system is planned in October 2016.

2.3 Cryopanel regenerations

The divertor and neutral beam cryogenic pumps at JET will be regenerated daily to limit and monitor the amount of tritium outside the tritium plant. The regenerations of all cryopanels were tested and optimized to fit into a single night by cooling down the divertor and one neutral beam cryopanel at the same time. The regenerations were tested with both the standard mechanical pumps and the cryogenic forevacuum pumps to be used in tritium operation. In addition, a modified regeneration sequence was tested for the reduced amounts of gas expected in a TT campaign.

3 Procedures

3.1 Safety

The safety case includes a comprehensive review of JET accident scenarios and prescribes the required (key) safety related equipment and management systems. The DD Safety Case for deuterium & hydrogen operation was modified prior to the rehearsal to include the technical tests foreseen for the rehearsal. The provisional DT Safety Case for tritium operation has been approved. The final version will include lessons learned from the DT rehearsal.

The site emergency plan is routinely tested with table-top exercises. In addition, a site-wide emergency exercise was carried out in August 2016 to test the response to a possible tritium release.

The security of the computer network was tightened in preparation for tritium operation including changes to the firewall, tunnel policy and document access. A security exercise was performed to evaluate whether there is any dependency of JET operations on availability of non-operational related networks. Although the operation of JET is independent of the external firewall, some services related to session preparation and software licenses required access to the internal firewall. These issues will be addressed for the next rehearsal in 2017.

3.2 Access restrictions to the JET building

Access to several areas in the JET building, shown in red & blue in Figure 3, will be restricted during tritium operation due to increased neutron activation and gamma radiation (activation of circulating fluids), risk of tritium release and low oxygen level of the torus hall. These areas include diagnostics, power supplies, vacuum, cryogenic and heating systems and thus are required for the morning start-up of the plant system, the evening shutdown of these systems, maintenance, repairs and setting of diagnostics. Efficient access management is essential for a future tritium campaign. The access requirements were clarified and the approval, management and monitoring procedures were tested with/without a turnstyle entry system and chaperon for 3 weeks. The information collected complemented and confirmed the list of access requirements for for both routine and fault scenarios. Over 900 entries to the JET building were registered during the three week period, identifying the diagnostic hall as the main entry point. An optimized limited access scheme for the diagnostic hall will be tested in October 2016.

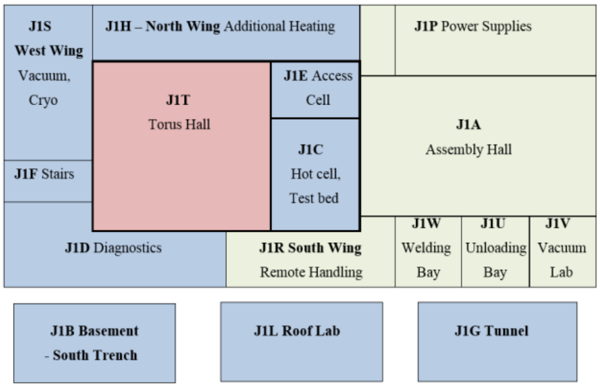

Fig. 3. Access restictions of operational areas of the JET building: red – no access, blue – restricted access, green – no restriction.

3.3 Diagnostic requirements

The diagnostic procedures for tritium operation were reviewed and updated with the diagnostics foreseen to be operational in the TT and DTE2 campaigns. The additional data validation and analysis required between pulses are under assessment and will be tested in October 2016. The rehearsal will aim to define the additional diagnostic manning requirements and test the technical requirements, analysis tools and procedures for the control room.

3.4 Experiment preparation

The preparation of a tritium campaign will be similar to deuterium operation with the campaign planned in task forces, programmatic and scarce resource approval at the JET Programme Executive Committee and final approval of the weekly plan at the JET Coordination meeting. In addition increased preparation of each pulse will be required with known reference pulses and detailed pulse by pulse gas and neutron estimates will be provided in advance. A rough estimate of the required gas and neutrons are already routinely provided per session and specific tools are being developed for a more accurate estimate of these quantities.

In addition to the weekly approval and coordination meetings during a campaign, daily mid-day meetings are foreseen for closer monitoring, coordination and approval of gas and neutron budgets, programme, JET building access and work to be carried out on the JET plant.

3.5 Control room and plasma operation

Operation will be carried out in double shifts from 6.30 to 22.30 for 4 days a week (Monday to Thursday). Additional staff required in the control room of JET and the tritium plant has been assessed and tested. The control room layout has been adjusted for the additional personnel. The readiness of each role for a JET pulse will be recorded electronically instead of the manual signatures used in the past. The monitoring of the neutron and gas budgets are implemented in the JET Level-1 control system.

An extensive review of the JET operating instructions was started to account for the additional requirements from the DT safety case. The modified operating instructions were tested during the rehearsal.

A review of the available and planned real-time networks was also conducted to identify any gaps and prioratise the networks for further development.

4 Accounting

4.1 Neutrons

At JET the 2.45 MeV DD neutron production is monitored and controlled in order to limit the activation of the vacuum vessel for foreseen in-vessel work. In addition JET has a finite lifetime 14 MeV DT neutron budget of $2.0 \cdot 10^{21}$. The previous tritium campaigns used $3 \cdot 10^{20}$ DT neutrons and the TT and DTE2 campaigns are planned to use all remaining neutron budget of $1.7 \cdot 10^{21}$. Careful monitoring and distribution of the neutron budget between campaigns and sessions is thus essential. The neutron yield detectors for the 2.45 MeV DD neutrons were calibrated in 2014 using a ^{252}Cf source [5]. The neutron detector calibration at 14 MeV energy is in progress using a neutron generator [6].

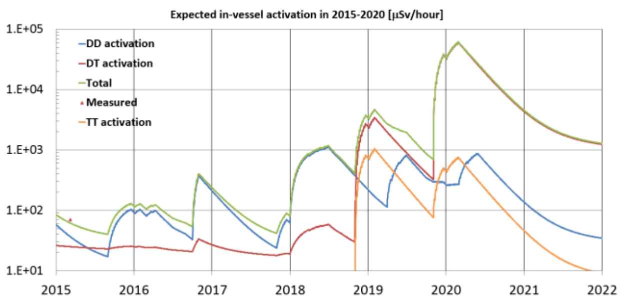

Fig. 4 Prediction of neutron activation of JET

In JET, the 2.45 MeV DD neutrons and 14 MeV DT neutrons produce mainly isotopes of cobalt, chromium and manganese, activating the JET vessel at different levels and with different half lives. The vessel activation for a DT campaign and the decay of the vessel activation can be calculated by estimating the neutron production for each day, taking into account the activation data for 5 isotopes and their respective half lives. Figure 4 shows the in-vessel dose rates due to DD, DT and TT neutron activation estimated for the JET timeline shown in Figure 1 for the period 2015-2020. These predictions have been validated historically by period measurements of the dose rate inside the JET vessel and by sophisticated shutdown dose rate codes [7].

The neutron estimation guidelines were reviewed and will be tested in the final part of the rehearsal during the deuterium campaign in October 2016.

4.2 Tritium and other gas

The DT Safety Case limits the tritium on the torus and neutral beam cryo-panels to 11g (44 barl). Thus tritium accountancy is an essential part of the tritium operation. In addition the total amount of hydrogen isotopes is limited to 330barl per cryopanel to avoid potentially flammable mixtures in case of a loss of vacuum or coolant accident. The following procedure is planned during tritium operation:

1) Tritium and gas estimates are approved per session two weeks in advance and per pulse one day in advance.

2) Gas inventory software routinely monitors each species on each cryopanel. Dedicated tritium inventory software is being developed to monitor the tritium content per location during the day.

3) The JET control system estimates the possible tritium injection (worst case scenario including density control) for the next pulse to ensure maximum allowable tritium inventory is not reached.

4) Weekly measurement and check of the quantity of tritium stored in the tritium plant (accountancy).

Conclusion

In preparation for the future TT and DTE2 campaigns at JET, an 8-week technical rehearsal of the procedures and systems to be used in tritium operation (without use of tritium) is being perfomed, commissioning technical systems, providing essential information and optimisation for operating procedures. The rehearsal demonstrated that JET is still capable of carrying out tritium experiments safely. Further technical rehearsals are planned in the Restart period in 2017.

Acknowledgments

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