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Tritium removal from TFTR

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Abstract

Continued operation of the tokamak fusion test reactor (TFFR) with a mixture of deuterium and tritium fueling has permitted the opportunity to measure the retention of tritium in the graphite limiter and to investigate the use of discharge cleaning techniques and venting to remove the tritium. The tritium was introduced into TFTR by neutral beam injection and by gas puffing. The limiter is subject to erosion and codeposition. While short term retention was high, the retention averaged over the 1993–1995 D–T campaign was $52 \pm 15\%$. The tritium removal techniques resulted in lowering the in-vessel inventory from 16.4 kCi (1 Ci = 2.076×10^{19} tritium atoms and 10 kCi = 1.04 g) at the end of 1995 operation to 7.2 kCi at the start of the 1996 experimental program.

Keywords: TFTR; Erosion and particle deposition; Tritium inventory and economy; Tokamak; Fusion; Technology

1. Introduction

TFTR has been run successfully using a mixture of deuterium and tritium fueling since 1993. An important issue for continued operation of TFTR, for JET in its D–T phase and for ITER is the retention and removal of tritium from internal components. TFTR operates under low site and in-vessel tritium inventory limits of 50 kCi and 20 kCi, respectively. After two years of continued D–T operation, the in-vessel tritium inventory was beginning to constrain experimental operations. It became necessary to reduce the in-vessel tritium inventory to permit continued D–T operations throughout 1996. A two-pronged approach was taken. First glow discharge cleaning techniques were used to remove tritium from internal hardware and then the vessel was purged with air in order to further remove tritium and to determine the maximum amount of tritium that would be released in a credible accident. It was expected, and found to be the case, that the release of tritium in the event of a vent to air would not be complete.

Tritium is injected into TFTR primarily by tritium neutral beam injection. However, significant tritium gas puffing was employed in a series of L-mode species scaling experiments. The methods of measuring the quantity of tritium injected into TFTR and the methods used to measure the tritium recovered from TFTR are discussed below. This is followed by a short discussion of the results of the retention measurements. Finally, the tritium removal techniques and their effectiveness are discussed.

2. Tritium use and measurement in TFTR

Since the start of TFTR DT operations in 1993 more than 400k Ci of tritium have been processed through the vacuum vessel and neutral beams. LaMarche [1] and Nagy [2] have described the tritium handling and accounting systems on TFTR in detail. Briefly, TFTR is configured with fourteen tritium gas injection (TGI) systems of which twelve are used to puff into the neutral beamlines and two are used to deliver tritium directly into the vacuum vessel. Each TGI system consists of a piezo-electric pulse valve, a plenum of a precisely known volume, a pressure gauge and a thermocouple. PVT measurements of the appropriate TGI systems are taken before and after each tritium pulse and the amount delivered is derived from the difference of these measurements. Of the tritium that has been processed through TFTR, the majority has been puffed into the

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neutral beams. Summation of the energetic tritons injected during tritium neutral beam injection (T-NBI) [3] yields 19.4 kCi of tritium injected from September 1993 through September 1995. This summation is based on measurement of the tritium source current, the known species mix, the neutralization efficiency and transport efficiency. It is estimated that about 1.2 kCi of tritium (6% of the energetic tritium) entered the torus as cold streaming gas from the tritium neutral beams during this period. In addition, 10.8 kCi of tritium was used to fuel plasmas in the form of gas puffing. The majority of the tritium delivered to TFTR is pumped by the cryopanels contained in the four neutral beam boxes and a lesser amount ($< 5\%$) is pumped by the torus vacuum pumping system. Periodically the neutral beam cryopanels are warmed and the gas pumped to the gas holding tanks where the tritium is measured by ion chambers and a quadrupole mass spectrometer.

The amount of tritium retained in TFTR and its internal components is taken to be the difference between the delivered values from the TGI systems and the amount recovered in the gas holding tanks [2]. At the end of August, 1995, prior to extensive tritium gas puffing into the torus, these measurements indicated the in-vessel tritium inventory was 6.8 kCi. At that time, 18.4 kCi of tritium had been injected into the torus so the retained fraction was 37%. Based upon past measurements of deuterium retention in TFTR, we expected that $40 \pm 20\%$ [4] of the injected tritium would be retained in the limiter and vacuum vessel walls. Because the difference between the amount of tritium consumed and that recovered into the gas holding tanks is on the order of 2%, small errors in either the input or recovered quantities result in a large percentage error on the measurement of the amount of tritium retained in TFTR.

At the beginning of the TFTR DT experiments, a short clean-up experiment was undertaken by Caorlin et al. [5]. They investigated tritium removal following the injection of 360 Ci over a series of 21 D–T and 50 D–D discharges and found that in the subsequent 34 discharges only 8% of the injected tritium was removed.

During September 1–12 of 1995 a series of experiments were undertaken in which one of the neutral beam lines was used with only deuterium [6]. Any tritium found when regenerating this beamline then must have come from the torus effluent and would represent 1/4 of the total tritium exhaust. During this run period, a mixture of L-mode species scaling and ICRF heating experiments were performed. Tritium gas puffing (10.61 kCi total) was used to fuel the plasma in an attempt to change the DT recycling mixture and hence, the plasma composition from deuterium to tritium during the ICRF and L-mode experiments. Previously, tritium gas puffing had been used only for perturbation experiments that employed small puffs (203 Ci total). Also, 0.90 kCi were injected by the neutral beams. Of the total tritium injected in this period, only about 0.9 kCi were recovered, this gives a short term retention $> 90\%$. The tritium to hydrogen + deuterium + tritium Balmer-alpha emission ratio is measured during TFTR discharges [7]. During the L-mode gas puffing experiments, this ratio rose as high as 42%, while during a series of T-NBI experiments with no tritium gas puffs, this ratio rose to only 7.5% [8].

During the remainder of plasma operations from September 13–16, 1995, no further tritium gas puffing was employed, but all four beamlines were used in various supershot experiments to inject another 1.36 kCi of tritium into the torus. The total tritium injected in September was 12.9 kCi of which 3.53 kCi was recovered giving a retention of 73% for the month. At the end of plasma operations in September 1995, the in-vessel tritium inventory was 16.2 kCi, approaching the in-vessel tritium inventory limit of 20 kCi.

The distribution of tritium in the vacuum vessel has not yet been measured. For discussions of the deuterium and tritium distributions observed in the past see Wampler et al. [9], Ulrickson et al. [10], Pontau et al. [11] and Dylla and Wilson [4].

3. Tritium removal techniques

The techniques investigated to measure their effectiveness in tritium removal were, a D_2 soak, glow discharge cleaning (GDC) with working gasses of helium, deuterium or a 9:1 mixture of He:O_2 (He–O) and a vessel vent with air. As discussed below, tritium was also removed during the normal start-up procedure [12] after a vent on TFTR.

In the eight day period between the end of plasma operation and initiation of the tritium removal experiments, only 36 Ci of tritium were recovered due to outgassing of the torus under vacuum. A D_2 soak at a pressure of 124 Pa for one hour resulted in 5 ± 9 Ci of tritium removed. This is in contrast to the results of Andrew et al. [13] on JET who found that a D_2 soak was an effective tritium removal technique. Presumably this is due to the fact that JET was heated to 300°C while TFTR was at room temperature.

The GDC system at TFTR [14] consists of two Innotec Model PP57920 Power Supplies with the jumpers and taps set for 660 V at 20 A. These provide a controlled current to either of two pairs of GDC Probes. The pressure of the selected gas is maintained, at a value determined by the desired glow characteristics, by the non-tritium gas injection system via a piezo-electric valve. Typically, the total probe current is 14 A, the working pressure is 267 Pa and the probe voltage is 200 V.

A He-GDC performed to aid in disruption recovery during the September 1995 resulted in the removal of only 13 Ci of tritium in 0.8 hours, too little for He-GDC to be considered an effective tritium removal technique at room temperature.

The top half of Fig. 1 shows the amount of tritium recovered versus time for both D_2 and He–O GDC per-

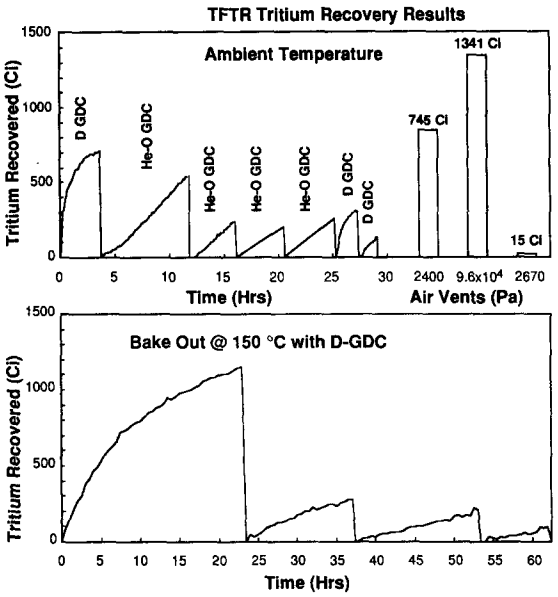

Fig. 1. The tritium removed versus time for each of the D and He–O GDC periods. The time dependent data during the third and fourth He–O GDC periods is unavailable, only the total tritium removed for these periods is available and the data is represented as a constant removal rate for these two periods.

formed at room temperature. It can be seen that the initial release rate of the D-GDC is quite high (1600 Ci/h), but that this rate declined to less than 50 Ci/h in the course of only 3 h. The total tritium removal during the first D-GDC period of 4 h was 686 Ci. Wampler et al. [9] used nuclear reaction analysis to measure the deuterium concentration in the top 1 μm of TFTR bumper limiter tiles following the 1985–1987 deuterium experimental mn and found values less than $2 \times 10^{22}/m^2$. They also found that the deuterium containing layer ranged from 0.5 to several μm deep. Using the geometric area of 100 m^2, we expect about 2×10^{20} hydrogenic atoms/m^2 in the top 10 nm, which is the range of 200 eV deuterons in carbon. During the last seven days of operation before the cleanup campaign, 2.8×10^{23} deuterons and 1.8×10^{22} tritons were injected into TFTR (T/D = 0.066) and the measured $T_\alpha/(T_\alpha + D_\alpha + H_\alpha)$ emission was < 0.05. Assuming mixing of the deuterium and tritium in the surface and an area of 100 m^2, only about 10^{21} tritons (50 Ci) should be trapped in the top 10 nm. The amount of tritium released is too large by a factor of about 14 to come from only the top 10 nm unless the surface greatly exceeds 100 m^2. A similar, but less pronounced time dependence of tritium removal was seen in the D-GDC that followed the He–O GDC possibly indicating that erosion by the He–O GDC excavated enough graphite to permit fresh surfaces to participate in tritium release, or that tritium had diffused to sites from which it was more easily releasable.

In contrast to the D-GDC, the He–O GDC has a tritium

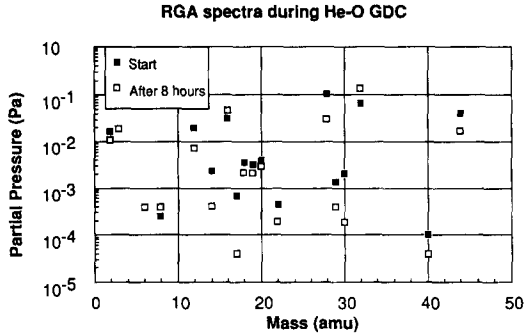

Fig. 2. RGA spectra taken during He–O GDC 30 min after the start and after 8 h of GDC.

removal rate that is nearly constant in time as can be seen in Fig. 1. From Fig. 2 it can be seen that the dominant non-hydrogen peaks in addition to He are masses 44, 32, 28 and 16. These are CO_2, O_2, CO and O respectively. The methane peaks are more than an order of magnitude lower. Tritium release during a He–O glow is expected to occur primarily by removal of the carbon that is trapping the tritium. Fig. 3 shows the time evolution of the CO, CO_2 and O_2 peaks during the four periods of He–O GDC concatenated to remove the non-glow periods. From this, one sees $(CO + CO_2)/(CO + 2 \times CO_2 + 2 \times O_2) = 0.2$. The total gas used during the He–O GDC was 1.6×10^8 Pa liters which corresponds to 225 g of oxygen. Under the assumption that only a small fraction of the oxygen used was trapped inside the torus, this implies removal of 33.8 g of carbon from the torus walls. Using a surface area of 100 m^2 and a graphite density of 1.1 g/cm^3, this corresponds to a depth of 0.34 μm and a removal rate of 0.004 nm/s compared to 0.064 nm/s found by Hsu [15] in laboratory experiments. It should be noted that when the He–O pressure was varied in the fourth period of He–O GDC, the ratio of CO pressure to O_2 pressure varied only slightly indicating a higher removal rate at higher pressure.

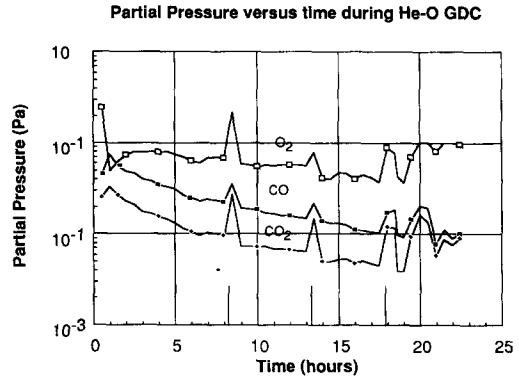

Fig. 3. Partial pressures during He–O GDC. The data has been concatenated to remove the non-glow periods. The start times of the periods are indicated at the bottom of the graph.

The measured tritium removal during the He–O GDC was 1250 Ci so the atomic ratio of tritium to carbon in the removed layer was 0.011. This is consistent with the assumption of removal of a carbon layer with deuterium at 0.3 D/C and a T/D ratio of 0.036 (the fueling ratio for the entire D–T run period).

Following the periods of GDC, the in-vessel tritium inventory was 14 kCi. Vacuum vessel purges with air were then performed to investigate the amount of tritium that would be released in a credible vacuum accident and the amount tenaciously held in the tokamak walls. The first purge was performed with 2670 Pa of N_2 and 2400 Pa of air. This released 745 Ci. After evacuation, a second purge to 9.6×10^4 Pa released 1341 Ci. After evacuation, a third purge this time to 2670 Pa of air resulted in the removal of only 15 Ci. This together with the further tritium removed during the normal TFTR start-up procedure after a vent has allowed for 5000 Ci of the vessel inventory to be accounted as tenaciously held [16].

The normal start-up of TFTR after a vessel vent is described in detail in Ref. [12]. Briefly, the procedure is to bake the vacuum vessel to 150°C, perform D-GDC for about 60 h to remove complex hydrocarbons, perform a boronization of the walls and perform pulsed discharge cleaning (PDC) to heat the bulk of the bumper limiter tiles to 250°C before allowing the vessel to cool to room temperature. After cool-down, a series of high power disruptions (disruptive discharge cleaning, DDC) [17] are produced to heat the surface of the bumper limiter and desorb gases from the surface. During the D-GDC 1609 Ci of tritium was removed, during the boronization 169 Ci were removed and during PDC 956 Ci were removed. The lower half of Fig. 1 shows the rate of tritium removal for each of the four periods of D-GDC performed during the start-up.

Table 1 summarizes the tritium removal and start-up activities effect on the in-vessel tritium account. Outgassing and purging of miscellaneous volumes removed 524 Ci. Operation including DDC from November 17, 1995 to January 2, 1996 and outgassing removed a further 978 Ci. An air purge of one NB line resulted in the removal of 467 Ci of tritium (this value exceeds by a factor of three the retention expected based on adsorption experiments carried out with room temperature samples [18]). By the beginning of routine experimental operation on TFTR on January 2, 1996, the in-vessel inventory was 7.2 Ci of which 5 kCi is designated as tenaciously held and at present, does not count against the 20 kCi in-vessel limit for releasable tritium [16].

4. Summary

The retention of tritium in TFTR, $52 \pm 15\%$ for the entire D–T run period, is in good agreement with that expected from past measurements of deuterium retention on TFTR, $40\% \pm 20\%$ [4]. The short term retention of tritium puffed into the torus to support L-mode experiments in which a change of the recycling gas from deuterium to tritium was desired was 90%. Tritium removal techniques, summarized in Table 1, were successful in removing half of the tritium that had remained at the end of experimental 1995 operations. The initially high removal rate of DGDC was surprising and indicates that a fraction of the tritium held more than 10 nm inside the geometrical boundary of the graphite is mobile and can rapidly mix with deuterium on the surface and then be released. He–O GDC removes tritium from graphite by simply etching away the graphite at a rate of 0.004 nm/s, an order of magnitude slower than found in laboratory experiments [15].

The air purges released 2.1 kCi or 16% of the retained tritium comparable to the release fraction from thin films found by Causey of 25% [19]. After this release, the

Table 1
The measured tritium removal from TFTR

Activity	Tritium removed (Ci)	In-vessel account (Ci)
End of operation	0	16399
D-GDC	687	15713
He–O GDC	1249	14463
D-GDC	495	13968
Torus vent to 2400 Pa air, 20 Torr N_2	745	13223
Torus vent to 9.6×10^4 Pa air	1341	11882
Torus vent to 2670 Pa air	15	11867
150°C Bake + D-GDC	1609	10258
150°C Bake + boronization	169	10089
150°C Bake + PDC	956	9133
NB vent to 9.6×10^4 Pa air	467	8666
Miscellaneous pumps and purges of volumes and outgassing during the period 10/06/95 to 11/17/95	524	8141
Operations and outgassing from 11/17/95 to 01/02/96	978	7163

continued outgassing of tritium from the vessel was small. That a sizable fraction of the retained tritium was not released upon exposure to air permitted the classification of 5 kCi of the tritium retained in the vessel to be considered tenaciously held and to be removed from the active in-vessel account. This will relieve some of the operational constraints imposed by the higher in-vessel tritium account. The tritium removal techniques succeeded in reducing the in-vessel inventory by 50%.

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