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Tritium Retention and Removal on TFTR*

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Abstract — Tritium retention and removal are critical issues for the success of ITER or any DT fusion reactor. The Tokamak Fusion Test Reactor, TFTR, is the first fusion facility to afford the opportunity to study the tritium retention and removal over an extended period. In TFTR, tritium accumulates on all surfaces with line of sight to the plasma by codeposition of tritium with carbon. Measurements of both deuterium and tritium retention fractions have yielded retention between 0.2 and 0.6 of the injected fuel in the torus. Tritium has been successfully removed from TFTR by glow discharge cleaning and by air purges. The in-vessel inventory was reduced by a factor of 2, facilitating machine maintenance. In TFTR, the amount of dust recovered from the TFTR vacuum vessel has varied from several grams to a few kilograms.

I. INTRODUCTION

The results of ex-situ measurements of the deuterium and impurity concentrations found on the various internal surfaces of TFTR following a two-year deuterium run period that had 9922 discharges, including 2756 with neutral beam injection have been reported[1-5]. For ITER, the carbon surfaces of the divertor strike points and start-up limiters will provide a source of carbon whose erosion and redeposition will provide a potential trap of tritium. This represents both a tritium inventory problem and a potential safety issue in case of loss of vacuum events for ITER. For ITER a means of tritium removal will be essential to successful long term operation. Dust has been observed in tokamaks with graphite internal hardware following operational periods[6,7]. This dust may present explosive and radiological hazards in the event of a sudden vent to air for ITER.

The main components of TFTR's internal surfaces are: a stainless steel vacuum vessel, a toroidally-symmetric inner bumper limiter extending ± 60 degrees poloidally and consisting of graphite and carbon fiber composite (CFC) tiles backed by water-cooled inconel plates, CFC poloidal limiters designed to protect the ion-cyclotron radio frequency (ICRF) antennas and partial CFC poloidal limiters designed to limit the power incident on the leading edges of the bumper limiter. All surfaces in TFTR that are expected to be areas of high heat flux are protected by carbon tiles. Much of the vacuum vessel has a direct line-of-sight to the plasma, but is typically more than 10 cm from the last closed flux surface of the plasma. The surface of the ICRF antennas are an exception to this general rule. The measurements of deuterium retention in the vacuum vessel components were made by nuclear reaction analysis (NRA) with a 700 keV ^{3}He beam which is able to probe a depth of about 1 micron. The pattern of metal deposition was measured by beta backscattering [8], proton induced X-ray emission (PIXE) and Rutherford backscattering spectroscopy (RBS). As viewed from the inside of the vacuum vessel each bay (1/20) of the bumper limiter, exhibited a pattern of high metal deposition on the upper right and lower left of each bay and lower metal deposition on the upper left and lower right. It was found that the regions of high metal deposition also had high D concentration and low metal concentrations had low D concentration. On the bumper limiter, about 1/2 of the front surface had low deuterium deposition (($3x10^{17}$ D/cm^2 in the top 1 micron) and about 1/2 has high deposition ($6x10^{18}$ D/cm^2). The thickness of the deposited layers on the limiter's front surface was inferred from PIXE and RBS to be 10 microns. The edges of the limiter tiles had D codeposited in a carbon layer several microns thick. The thickness of this film decreased with increasing distance from the plasma-facing surface with a characteristic length of 5 mm. The bulk of the limiter tiles was found to have a low concentration of D (0.4+/-0.2 atomic ppm). Measurement of D on wall coupons found $6x10^{17}$ D/cm^2 on average. Using the ex situ measurements summarized above, it was found that the fraction of deuterium retained in the vessel was 0.22[1]. A subset of the ex-situ deuterium measurements have been performed after several run periods. The results for global deuterium retention for each run period are summarized in Fig. 1. It can be seen that the fraction of D retained increases with the average beam power for each run period. The distribution of the in-vessel deuterium is 44% on the walls, 41 % on the bumper limiter tile front faces and 15% on the bumper limiter tile edges.

II. TRITIUM RETENTION

The TFTR in-vessel components exposed during the DT campaign have only recently become available for analysis of their tritium content and there does not yet exist data that corresponds exactly to the deuterium measurements. However, measurement of the global tritium retention based upon the difference between tritium used in the operation of TFTR and that recovered from the effluent gas does exist. The tritium retention for the first tritium run period on TFTR has been reported [3,4]. The tritium handling and accounting systems on TFTR have also been described in

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detail[9,10]. After receiving a shipment of tritium, the tritium is stored in uranium storage beds. The uranium beds are heated to make the tritium available for injection. From the uranium beds, the tritium is sent to any of the desired fourteen Tritium Gas Injection Systems (TGIS) on TFTR.

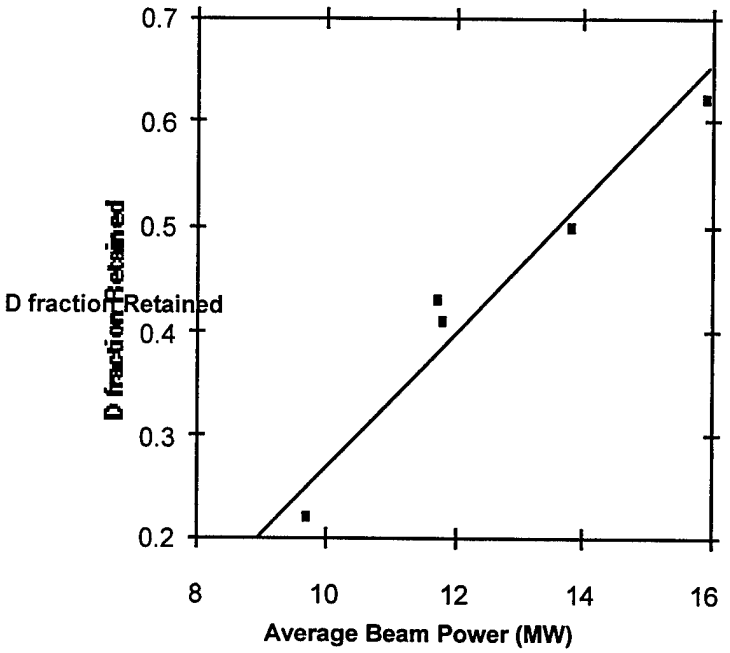

Fig. 1. Deuterium fraction retained in TFTR as a function of beam power averaged over beam heated discharges for several run periods.

Each TGIS has a piezo-electric pulse valve, a plenum of a precisely known volume, a pressure gauge and a thermocouple. Twelve of these are for the tritium neutral beam injectors and two for gas puffing directly into the torus. PVT measurements of the tritium in the TGIS is made before and after each tritium pulse. It should be noted that of the tritium that was injected into the TFTR vacuum vessel, about 2/5 was in the form of gas puffing and 3/5 in the form of energetic neutral beam injection. Of the tritium used for TFTR, the majority has been used to fuel the neutral beam sources. The amount of tritium that is injected into the torus is calculated from measurement of the tritium source voltage and current, the known species mix, the neutralization efficiency (a function of particle energies) and transport efficiency[11]. Most (96.5%) of the tritium used to fuel the tritium neutral beam injectors is trapped on the liquid-He-cooled cryo-panels and never enters the torus. Periodically the neutral beam cryo-panels are warmed and the gas regenerated back to the Tritium Systems via the neutral beam vacuum pumping system. The effluent from the pumping systems is directed to gas holding tanks where the tritium is measured by ion chambers and a quadrupole mass spectrometer. After measurement, the contents of the gas holding tanks are processed through a torus cleanup system (TCS) that oxidizes the hydrogen isotopes. Effluent from the TCS is sent to a disposable molecular sieve bed where the tritiated water is trapped. The beds are then shipped off-site for disposal. For a part of the third tritium run period, the effluent gas was sent to the tritium purification system (TPS) where the tritium was recovered for reuse [12].

Table I
Tritium inventory in TFTR

Description	Run Period		
	'93-95	96	'97
Total Number of discharges	14724	5324	3619
Discharges with NBI	6134	2167	1609
Discharges with tritium NBI	500	124	107
Tritium processed (kCi)	700	161	140
Tritium Injected (kCi)	31.4	8.1	10.3
Tritium T retained in TFTR (kCi)	16.4	15.0	17.6
Increment of T inventory in TFTR (kCi)	16.4	7.8	7.3
Fraction of T retained	0.52	0.96	0.68
Tritium Removed at end of Run (kCi)	9.2	4.7	8.1

The amount of tritium injected into TFTR is only a small fraction of the total tritium processed. Because the tritium inventory in TFTR is accounted for by taking the difference between the tritium used for fueling and the tritium recovered in the gas holding tanks, even a 1% error in the tritium accounting results in about a 50% error in the difference. Table 1 summarizes the tritium retention measurement made for all three tritium run periods. While the deuterium retention measurements focused only on the D in the torus, the tritium retention measurements include the tritium trapped in the neutral beam injectors and in the various vacuum appendages. It is expected that the tritium trapped in the vacuum systems' hardware is only a small fraction of the total retained in TFTR, but the neutral beams can be a more substantive part of the retained tritium[13, 14]. In fact, about 6 kCi were recovered from the neutral beam injectors when they were warmed and purged with air between after operational periods. The average tritium retention fraction in the vacuum vessel over the 3 run periods was about 0.5. This fraction excludes the 6 kCi of tritium that was recovered from the neutral beam boxes to allow for easy comparison with the deuterium results. During the tritium run period, the average beam injection power was 14.5 MW and the tritium retention agrees with that expected from the deuterium retention data shown in Fig. 1.

III. TRITIUM REMOVAL

At the end of each tritium run period, tritium removal techniques were employed to reduce the in-vessel tritium inventory. The purpose was three-fold: one reason was to investigate which techniques would be most effective and might have application to ITER, the second was to reduce the tritium inventory in order to permit continued operation within the site inventory limit and the third was to reduce the tritium outgassing during vacuum vessel vents done for maintenance or shutdown. Fig. 2 compares the tritium removed during glow discharge cleaning performed with D_2 as the working gas (D_2 GDC) and with a mixture of 10% oxygen in He (He-O GDC). The D_2 GDC was done before the He-O GDC. It can be seen that the removal rate using D_2 GDC decreases with time and is lower than that for He-O

GDC after only a few hours. This trend persisted over several periods of GDC with the D_2 GDC 's removal rate decreasing with time while that for He-O was nearly constant over the entire 23 hours it was performed. The removal rate of carbon during He-O GDC was found to be about 20 times less than had been reported in laboratory measurements [3,15]. The He-O GDC was discontinued due to concerns of possible effects of oxygen contamination on future operation. and because when He-O GDC was performed in 1992 for 5 days, the limiter was found to have developed a textured surface consisting of small projections that could be easily wiped off the limiter surface. In fact, the entire bumper limiter surface was sanded to remove these projections before further operation was attempted. Therefore, the possible impact of these projections on operation was unknown and it was decided that extensive He-O GDC presented an unacceptable risk to continued operation in the tritium phase of TFTR.

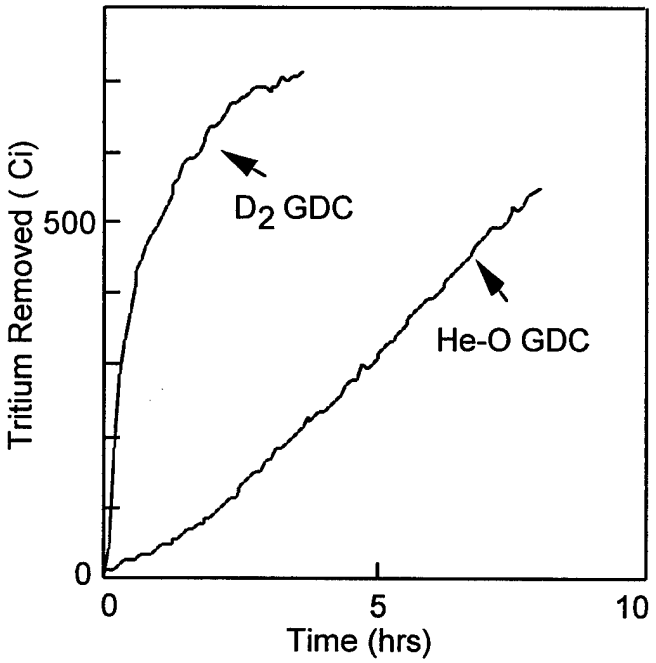

Fig. 2 Tritium removed versus time for the first periods of D_2 GDC and He-O GDC done after the first tritium run period on TFTR.

In addition to GDC, air purges were an effective method to remove tritium from TFTR. The experience from the first opening after tritium operation showed that the initial vent to air removed significant tritium, that the effectiveness of the vent in removing tritium increased with pressure and that subsequent vents were less effective[3]. Also when the normal start-up procedure was followed, it was discovered the pulse discharge cleaning (PDC) with the vacuum vessel at 150 C removed additional tritium.

During the most recent opening, the vacuum vessel was heated to 150 C and D_2 GDC and PDC were performed. These activities removed 746 Ci and 911 Ci respectively. Then, after the vessel was vented to 100 Torr of air at room temperature and 148 Ci were removed. Following this, an air vent at 150 C removed 301 Ci, twice that of the room temperature vent. Had the second vent been at room temperature, we expect that less than 148 Ci would have been removed. After this initial success, the vessel was heated to 150 C again, and a pressure of 160 Torr of air was maintained for 3 days. Measurement of the tritium content of the vessel indicated that 239 Ci were present in the air inside the vessel. The air pressure in the vessel was raised to 600 Torr for one day and the tritium content of the air removed from the vessel was 639 Ci. Most of the change in tritium content of the air occurred in both cases within 12 hours of changing the pressure or temperature and little additional evolution of tritium from the walls was observed after that. A third vent was performed at 150 C, this time at 600 Torr, and 433 Ci were removed. After these activities, the vessel pressure was raised to about 650 Torr of room temperature air and was maintained for 2.5 months. During this period, tritium continued to evolve from the wall at a rate of about 10 Ci /day and was removed from the vessel by a mixture of pump/purges and continuos flow at 4 CFM.

Twenty-two kCi of tritium were removed from TFTR by active means (D_2 GDC, He-O GDC, PDC and air vents at both ambient temperature and 150 C) and only 9.5 kCi of the 49 kCi of the tritium injected remain inside TFTR. About 6 of the 22 kCi were removed from the neutral beams by warming the cryogenic panels and room temperature air vents.

IV. IN-VESSEL TRITIUM MEASUREMENT

A method of in-situ measurement of tritium would be valuable for ITER as a tool to manage the tritium inventory. A method that can be useful for measuring the tritium trapped in the top micron of surfaces is detection of the beta particles from the radioactive decay of tritium. The same principle used in an ionization chamber was employed in TFTR[16]. One of the glow probes was used to collect secondary electrons produced by betas from tritium decay by biasing the probe to 15 V and measuring the current. This was done with the vacuum vessel at 20 Torr of nitrogen. Separate scans of the voltage and gas pressure were done to ensure that the dependence of the collected current on these variables was small. Fig. 3 shows the results for measurements performed on 5 different dates. The tritium inventory in TFTR at the time of the last 3 probe measurements is also shown. These times were at the end of the last tritium run period and at two times during the tritium removal efforts. Between the point labeled 4/5/97 and the next time, about 1.9 kCi were removed from TFTR, 373 Ci during D_2 GDC, 610 Ci during PDC, 756 Ci during air purges and 189 Ci from the neutral beams. Between the last two points, 1200 Ci were removed from the vacuum vessel by air purges at 150 C and 22 Ci were removed from the neutral beams. The collected current tracks the estimated tritium inventory; however, absolute measurement of the in-vessel inventory using this technique can not yet be made due to uncertainty in the effective area of current collection.

IV. TRITIATED DUST

Graphite dust produced during plasma operation or during disruptions may present explosive or radioactive hazards in the event of a sudden vessel vent. A wide variation in the amount of dust found in the vessel following operational periods on TFTR has been reported[6,7]. The amount of debris has varied from several grams[6] to a few kg[7]. There was a correlation with the amount of damage seen on the limiter tiles with more damage corresponding to more dust.

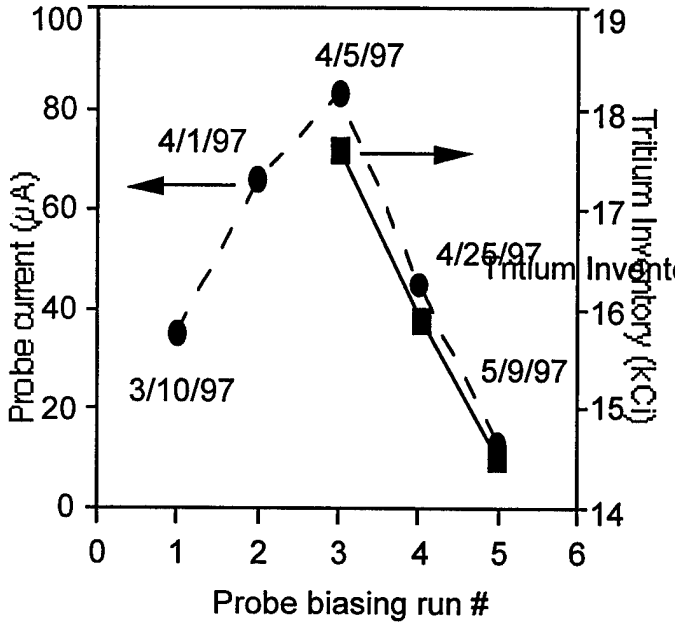

Fig. 3. Probe current for data taken using the TFTR vessel as an ionization chamber. The vessel pressure was 20 Torr of nitrogen and the probe voltage was 15 V.

The average particle size has ranged from 10 microns to 1 cm with an average of 100 microns[7]. After the second tritium run period, a total of 1.43 g of dust was removed from the ten MIRI diagnostic windows on the end of organ pipes extending below TFTR. Observation of the vacuum vessel by a remotely manipulated TV camera indicated that there was little or no dust was visible on the vacuum vessel floor, indicating that the amount of dust in the vessel is less than a kg. In fact the area immediately surrounding the MIRI organ pipes represents about 1/40 of the vessel floor, thus it is reasonable to expect that about 60 g of dust is in the vessel. The dust samples have been sent to Idaho National Engineering Laboratory for particle size analysis. The measured tritium content of the dust was 7 mCi/g. Given the fueling fraction during the first two run periods, T/(T+D) = 0.032, this implies an atomic fraction of $4X10^{-5}$ D or T per carbon atom. This is many orders of magnitude smaller than the D/C fraction found by [1] on the surface of the limiter (0.01 to 0.3) and two orders of magnitude higher than that found in the bulk of the limiter tiles.

V. CONCLUSIONS

Tritium retention in TFTR agrees with that found in past measurements of deuterium retention. The implications for tritium retention in ITER is not simple because of the differing geometry of ITER and TFTR, but the high retention and low removal rate of tritium raise concern about in-vessel tritium inventory control in ITER. The in-vessel retention fraction averaged over all the tritium run periods is 50% if the efforts at active tritium removal are discounted. After all the removal efforts, only 9.5 of the 49 kCi injected into TFTR remain. This does not count the effect of tritium decay which is calculated to lower the tritium inventory by 1.4 kCi. The tritium removal techniques were successful in reducing the inventory and allowing maintenance activities to take place but had removal rates that are too low for ITER. A technique to measure tritium in the near surface by detecting the betas appears promising, but further work is required to make this a quantitative measurement of the tritium content. The small amount of dust seen during a remote in-vessel inspection and recovered in diagnostic ports is consistent with tens of grams of dust, not kg, being created inside TFTR during the first two tritium run periods. The amount of dust found in TFTR correlates with the extent of damage to the graphite armor and indicates that careful design and alignment of internal hardware will reduce the production of dust in ITER. Work is in progress to measure the tritium content of several limiter tiles that were recently removed and to measure the particle size distribution of dust removed from TFTR.

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