# Observations of Flaking of Co-Deposited layers in TFTR

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*Abstract*-Flaking of co-deposited layers in the Tokamak Fusion Test Reactor (TFTR) has been observed after the termination of plasma operations. This unexpected flaking affects approximately 15% of the tiles and appears on isotropic graphite tiles but not on carbon fiber composite tiles. Samples of tiles, flakes and dust were recently collected from the inside of the vacuum vessel and will be analyzed to better characterize the behavior of tritium on plasma facing components in DT fusion devices.

## INTRODUCTION

Carbon is favored as a plasma facing material as it has excellent thermal properties and carbon impurities in the plasma lead to only small increases in radiated power. Unlike metals, it does not melt under the impact of a plasma disruption (it sublimes) and carbon plasma facing components do not change shape under the most extreme temperature excursions. However carbon atoms, sputtered from plasma facing surfaces by a hydrogenic plasma, are likely to be co-deposited along with the hydrogenic atoms on the surrounding surfaces. Tritium accumulates with carbon in co-deposited layers on plasma facing components exposed to DT plasmas. This phenomena is the dominant route for tritium retention in tokamaks and may severely impact the operational schedule for future long pulse machines with carbon plasma facing components[1].

The mobilizability of tritium is an important factor in safety analyses of future DT reactors. Tritium implanted or tenaciously attached to solid objects is considered to be less hazardous than tritium that could be released in potential accident scenarios. Dust generated by plasma operations is an emerging area of concern[2,3]. Studies of metal tritide dust[4] indicate that tritiated graphite dust may be significantly more hazardous than HTO (tritiated water) because of a longer biological half-life. Biological studies of tritiated tokamak dust are needed to establish appropriate occupational limits. A technical basis for predicting and diagnosing the amount of flakes and dust in future reactors needs to be established to quantify the radiological hazards associated with mobilizable tritium or activation products. Deposited layers on plasma facing surfaces have different chemical composition and physical structure from manufactured plasma facing components. The analysis of plasma facing components from tokamaks that have been operated with tritium plasmas is uniquely valuable in understanding the behavior of tritium in these devices.

During 15 years of plasma operations on TFTR co-deposited layers formed a hard 'crusty' layer some tens of microns thick on carbon and stainless steel components inside the TFTR vacuum vessel[5]. In tritium plasma operations, over the period 1993 - 1997, approximately 51% of the tritium supplied to the plasma was retained in the vessel[6-8]. TFTR plasma operations were terminated on 4th April 1997. A program to obtain and analyze samples of plasma facing components commenced as part of a PPPL/JAERI collaboration on tritium issues. Unexpectedly, observation of the surface of the TFTR bumper limiter a year after the termination of operations showed that some areas of the co-deposited layers were beginning to flake off[9]. This paper reports these observations and the status of the continuing program of collection and analysis of tritiated plasma facing materials from the vacuum vessel.

Tritium fuel has also been used on JET and the fraction of tritium retained was unexpectedly high (40%) [10]. The internal geometry of TFTR and JET are quite different as JET has a divertor, but interestingly, the long term retention fraction in both machines was similar at approximately 16%. Flaking has also been observed in the inner divertor leg in JET[11]. Flaking of carbon deposits on a molybdenum liner was observed in JT-60 in 1987[12] and thick carbon flakes have recently been observed in TEXTOR[13]. More information on the experience of tritium in large tokamaks may be found in the summary of a recent workshop[14].

## TFTR PLASMA FACING COMPONENTS

TFTR operated with toroidal plasmas with a circular cross section that were in contact with an inner toroidal 'bumper' limiter. The total area of the bumper limiter was 22 $m^2$ and it is divided into 20 bays (labeled A-T) each composed of 24 rows of tiles, 4 tiles wide. Each bay is curved in both toroidal and poloidal directions and the center extends out 5mm from a true toroidal surface. The midplane tiles are 125 mm wide and 81 mm high. Tile material was initially 100% Union Carbide AXF-5Q isotropic graphite. In 1993 some damage was noted on the top and bottom rows of tiles[15]. In areas of heavy damage, the tiles were replaced with Fiber Materials Inc. 4D coarse weave carbon fiber composite (CFC) tiles and Hercules 3-D fine weave CFC tiles. CFC tiles were installed on the bottom row of the limiter, the less damaged top row was replaced with redesigned isotropic graphite tiles and the limiter was realigned to reduce hot spots. Approximately 45% of tiles are now CFC. The outer vacuum vessel is protected by graphite tiles arranged in poloidal rings and tiles also protect high heat flux locations on the edge of RF antennas and surfaces in the line of sight of the neutral heating beams.

## CHRONOLOGY OF FLAKING

A video inspection of the inside of the TFTR vacuum vessel in October 1996 showed that the co-deposited layers on the bumper limiter were tenaciously attached with no sign of flaking. Samples of dust were removed from the bottom of vertical diagnostic viewing pipes at that time and a small amount of millimeter scale flakes was observed with the dust. Plasma operations were terminated in April 1997 and no evidence of flaking was visible at the next vessel opening in October 1997. However, at the subsequent opening in August 1998 the technicians reported that the tiles showed signs of scarring - this was initially believed to be due to abrasion during the removal of some tiles the previous year. Photographic inspection in November 1998 however clearly showed flaking of tiles

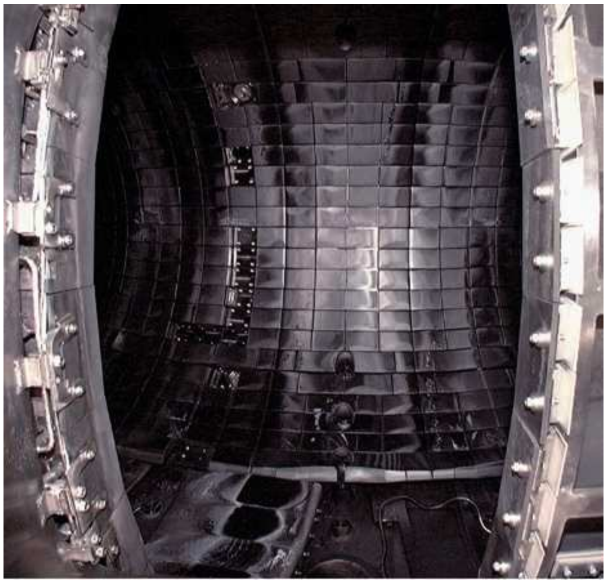

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Fig. 1 Overview of bumper limiter bays L, K, J. Some tiles have been removed from Bay L on the left.

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Fig. 3 Flaking at the top of Bay K. Note the CFC tiles on the left do not show flaking.

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Fig. 2 Close up of blistering at lower part of Bay K. The vertical height of a tile is 81 mm.

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Fig. 4 White deposits on the bumper limiter near a diagnostic penetration (upper right) and on the poloidal limiter tiles on the floor.

on the lower part of the bumper limiter and some unflaked areas showed blistering and corrugation (see Figs. 1 and 2). At the next opening in January 1999 the upper part of the limiter also showed flaking (Fig. 3). The flaking affects approximately 15% of the tiles and appears to occur only on isotropic AXF-Q tiles and not on carbon fiber composite tiles. White deposits are evident near diagnostic penetrations on the lower Bay K bumper limiter and heavy deposits are apparent on the poloidal limiter tiles at the floor of the vessel (Fig. 4) [16].

Flakes were collected from Bay J by a specialized device on the end of a long pole and baked to release tritium and assay the tritium content of the flakes. On baking 0.24 g of flakes at 500°C for 1 hour, 0.72 Ci of tritium was released. This amount is similar to the tritium released on baking other tiles removed from the vessel and confirms that the flakes are detached co-deposited layers that contain most of the tritium. The bake out measurements show levels of tritium that are consistent with estimates of the in-vessel tritium inventory derived from the difference between tritium fueling and tritium exhaust over the whole DT campaign and are an important confirmation of the difference inventory methodology used for tritium inventory control.

Since flaking occurs on some tiles and not others, it is important to identify the factors leading to flaking. One factor is the tile material - no flaking is observed on carbon fiber composite (CFC) tiles. Possibly the surface texture on CFC tiles facilitates better adhesion of the co-deposited layers. The thickness of the co-deposited layer may be another factor. The source of the co-deposited material is tile erosion that is strongly dependent on tile alignment. Protruding leading edges may have generated above average amount of eroded material that lead to thicker co-deposited layers. To test this hypothesis the tile alignment was measured remotely by a coherent laser rangefinder developed to measure in-vessel geometry with submillimeter accuracy[17]. The results showed that the tiles were well aligned; there was no evidence that tile misalignment was a factor in the flaking[9,18].

## POSSIBLE CAUSES OF FLAKING

Several mechanisms have been proposed for the flaking. Water absorption could promote swelling of the layers leading to detachment when the mechanical stress between the layer and the substrate exceeded the adhesive force. The interior of the vessel has been held slightly below atmospheric pressure (710-735 torr of air with 40% relative humidity) since the end of plasma operations (with the exception of occasional air recirculation to remove tritium when the returned air was dried to 10% humidity). The water absorption could be catalyzed by beta particles emitted by the radiological decay of tritium. Beta particles break chemical bonds along their path in the carbon, which then take up OH. Alternatively lithium could be a potential catalyst. Significant amounts of lithium were introduced into the plasma especially during the final months of operations. Materials analysis is necessary to elucidate the phenomena, however retrieval of the flakes is complicated by their fragile nature and the radiological environment inside the vessel.

## BUBBLE SUIT ENTRY TO THE VACUUM VESSEL

While some tiles were retrieved by specialized tools extended into the vacuum vessel, it became clear that manned entry to the vessel was desirable to efficiently collect samples for subsequent scientific analysis. The radiological and environmental conditions in the vessel were as follows:

i. ~ 1 - 10 million dpm / 100 $cm^2$ removable tritium contamination in vessel.
ii. 1-5 $\mu$Ci / $m^3$ tritium concentration in air in the vacuum vessel during the opening.
iii. ~ 25 mrem/hour direct (gamma) dose to personnel in the vessel.

Manned vessel access would allow a much faster rate of tile removal and avoid disturbing the material surface. It would greatly reduce the time spent on the task and hence the personnel dose. Personnel entering the vessel would be isolated from in-vessel environment by a 'bubble suit' with externally supplied air. During the opening, the contamination was confined to the vessel by a double-stage tent enclosure at the port and by strong air flow (1,600 cubic foot/minute air flow, 40% relative humidity, 65°F) into the vessel. Extensive planning and training in bubble suits in a scale model of the vacuum vessel was undertaken and detailed 'choreography' of the in-vessel tasks laid out.

Manned vessel entry was accomplished safely and successfully on October 7th, 1999 in two 2-hour shifts. The total dose to all persons involved (including safety and support personnel) was less than 0.125 person rem and the stack release 2.2 Ci, all well within administrative limits. Bioassay measurements confirmed that there was no uptake of tritium. The following lists the results:

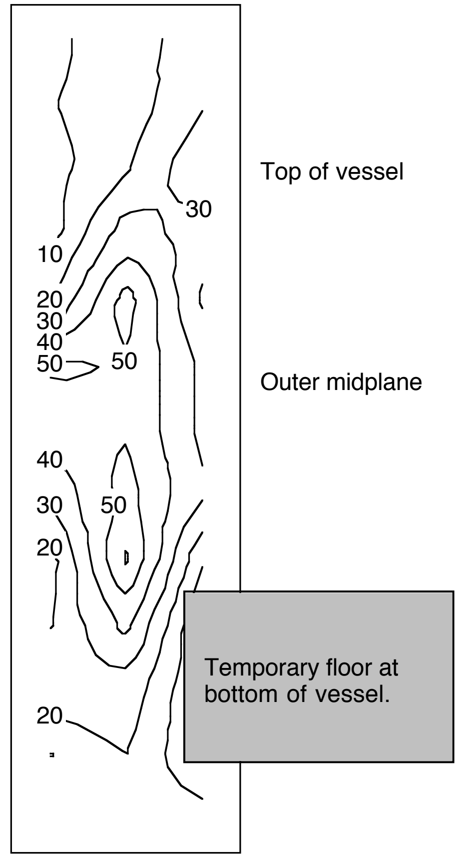


Figure 5. Contour plot of near surface tritium on poloidal limiter between Bays K/L in $\mu Ci/cm^2$. This plot is interpolated from measurements on a 3 x 13 grid.

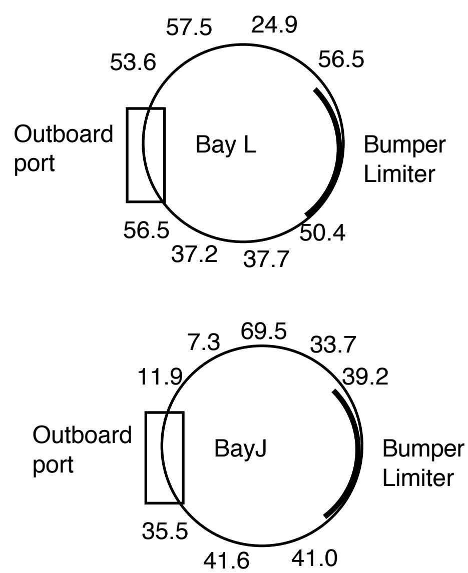


Figure 6. Ion chamber measurements of surface tritium on the vessel wall at Bays L and J in $\mu$Ci/cm2. The approximate location is shown schematically.

1. Collection of 36 tiles (without disturbing of the plasma facing surfaces).
2. Collection of 4 wall coupons
3. Surface tritium on the poloidal limiter and vacuum vessel was measured by an open wall ion chamber and an array of thermoluminescent detectors.
4. Dust samples were collected at five locations.
5. A sample of the white deposit on the poloidal tiles was collected.
6. The outboard vacuum vessel interior was photographed.

The measurements and collected samples will be used as part of a multi-institutional collaboration on tritium issues between PPPL, JAERI, SNL, INEEL, and JET with the following scientific goals:

i. Assaying the total tritium inventory in the bumper limiter by bake out of selected tiles.
ii. Assessment of toroidal symmetry of tritium by comparison of tiles from Bays I, J, K, and L.
iii. Testing models[19] of tritium co-deposition
iv. Information on tritium in the poloidal limiter
v. Information on tritium on vessel wall.
vi. Dust inventory.
vii. Collection of flake and deposit samples for analysis.
viii. Test techniques for in-vessel tritium detection
ix. Test detritiation of tiles via UV exposure.
x. Test detritiation of tiles via laser surface heating[20].
xi. Activation studies of wall coupons

Measurements of the tritium distribution will greatly aid planning of TFTR decommissioning[21]. The poloidal limiter has 24 tiles, each 53 cm by 20 cm, extending poloidally 240° on the top, outboard side and bottom of the vessel and can be partially seen in Fig. 4. Beta particles from the radioactive decay of tritium have a range of approximately one micron in graphite and tritium. Near surface tritium was detected with passive thermoluminescent detectors and an open wall ion chamber[22]. One poloidal tile was sampled twice at 9 locations and every other remaining tile sampled at 3 locations. A contour plot of the ion chamber results is shown in Fig. 5. Ion chamber readings were also taken on the co-deposited layers on the stainless steel vacuum vessel surface and are shown in Fig. 6. The levels of surface tritium on the bumper limiter at Bay L were measured previously by extending the detector into the vessel with a long pole (in this case it was more difficult to ensure that the detector 'landed' correctly on the tile surface). The readings on the bumper limiter were in the range 50-300 $\mu$Ci/cm$^2$. While these readings are higher than those on the outboard part of the vessel, the total wall area (100 m$^2$) is higher and there appears to be a similar total amount of surface tritium on the poloidal tiles and vessel wall as on the bumper limiter. This result is in line with earlier deuterium measurements reported in refs. [5,7].

## SUMMARY

Flaking of co-deposited layers in TFTR has unexpectedly occurred since the end of plasma operations. The flaking occurs on 15% of the tiles and appears on isotropic graphite but not CFC tiles. Manned entry into the vacuum vessel was undertaken to collect samples for materials analysis. A total of 36 tiles, 4 coupons and 5 dust samples were retrieved and surface tritium levels measured on the vacuum vessel interior in a safe and successful operation. The scientific harvesting of the data will aid D&D planning and enable better understanding into the behavior of tritium in fusion machines.

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