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SURFACE EROSION AND TRITIUM INVENTORY ANALYSIS FOR CIT*

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ABSTRACT

The expected buildup of co-deposited tritium on the CIT carbon divertor and first wall surfaces and operational methods of minimizing the inventory have been examined. The analysis uses impurity transport computer codes, and associated plasma and tritium retention models, to compute the thickness of redeposited sputtered carbon and the resulting co-deposited tritium inventory on the divertor plates and first wall. Predicted erosion/growth rates are dominated by the effect of gaps between carbon tiles. The overall results appear favorable, showing stable operation (finite self-sputtering) and acceptably low (~25 Ci/pulse) co-deposited tritium rates, at high surface temperature (1700°C) design conditions. These results, however, are highly speculative due to serious model inadequacies at the high sputtering rates predicted. If stable operation is obtainable, the prospects appear good for adequate tritium inventory control via helium-oxygen glow discharge cleaning.

I. INTRODUCTION

The proposed Compact Ignition Tokamak (CIT)[1,2] will involve intense plasma surface interactions, with the potential for high carbon erosion/growth rates and high tritium buildup via co-deposition. Minimizing the tritium inventory is important for safety, cost, and siting considerations. Accordingly, we have examined erosion and tritium co-deposition for typical CIT divertor design conditions. Key issues addressed in this study are the effect of high surface temperatures on erosion, the effect of numerous gaps between divertor tiles, and possible means of surface tritium removal between plasma shots.

For the conditions examined, it was found that peak values of sputtered carbon flux are very high, actually exceeding the incoming D-T ion flux. This clearly invalidates plasma models dependent on a trace impurity content; in particular, sheath models and plasma transport code results depending on D-T sheath parameters (e.g., heat transmission factor) for boundary conditions. Also, the properties of carbon surfaces subject to high erosion/redeposition rates (>2000 Å/s) are uncertain. In spite of these deficiencies, we have proceeded with the analysis in order to identify basic trends and define future research needs. The results are encouraging but should be regarded as preliminary, and subject to substantial change as new models and data become available.

II. TRITIUM INVENTORY REQUIREMENTS

The CIT tritium inventory requirements are based on analysis of accidental release scenarios. Calculations, benchmarked by atmospheric tracer analysis[3] indicate that the release and oxidation of 1 g (10^4 curies) of tritium from the CIT torus would result in the maximum permissible radiation dose at the boundary fence.

There are two mechanisms for in-vessel tritium retention: surface co-deposition and bulk graphite trapping.[4] In the case of surface retention, carbon eroded from plasma interactive components can co-deposit with deuterium and tritium on the plasma-facing surfaces, producing a highly tritiated surface film. Laboratory measurements[5,6] have shown that these films are unstable to air exposure, and will completely decompose in air at temperatures of only 500 K. Therefore, co-deposited tritium-carbon films are considered at risk in the accident scenario analysis.

Bulk retention of tritium in graphite can occur at elevated temperatures (>1000 K), where tritium becomes mobile in the graphite lattice and can become trapped at intrinsic or neutron-damage produced defects.[7,8] Tritium retained in the bulk graphite is not viewed as releasable from any credible accident scenario

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because of the high (>4 eV) defect binding energy of tritium.[7]

Based on these considerations, the in-vessel co-deposited tritium limit is set at 10,000 curies. This limit is combined with the results of the following erosion and co-deposition analysis to develop an operational plan to periodically remove the surface tritium.

III. DIVERTOR MODEL

The design point examined is a double null, carbon tile, passively cooled divertor. Graphite tile segments of typical dimensions, ~1 cm along the plate poloidally, ~80 cm toroidally, 4 cm in depth, with gaps of ~1 mm between tiles poloidally, are employed.[9] The gaps thus comprise on the order of 10% of the divertor surface area.

Plasma parameters for the analysis are taken from B2 plasma transport and DEGAS neutral code runs for typical full power CIT conditions.[10] These codes indicate a peak (strike point) heat flux of $q_o \approx 50$ MW/m^2 and peak plasma temperature (at the sheath) of $T_{e_o} = 60$ eV. At the plate the poloidal field lines are approximately perpendicular. The plasma strike point is swept with an approximately linear single sweep of 20 cm in a 5 s plasma flat-top period.

Based on thermal analysis results,[9,11] the plate can be modeled, for the present purposes, as having "cold" regions, of surface temperature 400°C and hot regions which reach a uniform peak temperature, T_s. The cold regions are subject to a high plasma particle flux but a low peak heat flux (< 1 MW/m^2). The remainder of the plate is subject to a high heat flux during the sweeping. For purposes of estimating the co-deposition of tritium on the first wall (resulting from the transport of divertor sputtered carbon and charge exchange tritium to the wall) it is assumed that the first wall is at a constant temperature of 400°C.

IV. KINETIC ANALYSIS OF RES CARBON

CIT is designed for divertor surface temperatures where radiation enhanced sublimation (RES) is significant. A recent study [12] computed an upper limit for carbon surface temperatures, based on the requirement for finite self-sputtering (from both RES and physical sputtering). This limit depends on the plasma edge temperature and on several parameters of the redeposited ions. To assess the limit for CIT, as well as to compute RES parameters for use in the overall erosion analysis, the WBC Monte Carlo code[13] was used to analyze RES sputtered particle transport for CIT conditions. In the code 1000 carbon atoms were launched with random thermal energies corresponding to a surface temperature of 1700°C. Such thermal emission of RES carbon is observed experimentally.[14] The sheath potential was modeled with the dual exponential structure described in Ref. 12. The code computes the transport and ionization of sputtered neutrals and the sub-gyroorbit carbon ion motion via collisions with the background D-T plasma and sheath electric field acceleration. The WBC results for CIT are summarized in Table 1.

Table 1
WBC Code Results for CIT/RES Carbon Transport, for T_e = 60 eV, N_{e_o} = 3 × 10^{20} m^{-3}, Trace Impurity Content, other Parameters and Symbol Definition per Ref. 13.

Parameter	Value
1. Fraction of sputtered particles redeposited	100%
2. Mean free path for ionization (normal-to-surface), $\bar{Z}_o$	1.4×10^{-4} m
3. Average redeposited charge state, $\bar{K}$	1.02
4. Average elevation angle of incidence, $\bar{\theta}$	9.0°
5. Average normalized redeposited energy, $\bar{U}/3kT_e$	0.5

The RES carbon atoms tend to be ionized outside of the Debye sheath but within the magnetic sheath. They acquire, on the average, only one half of the sheath potential. The corresponding surface temperature limit from Ref. 12 is ~2000°C -- this is confirmed by detailed erosion code predictions (see next section). This is an encouraging result because it implies that although there may be high rates of RES sputtering, the carbon will be locally redeposited with acceptably low resulting self-sputtering. This calculation, however, is based on a trace impurity content plasma and sheath model and the results may differ for a carbon dominated plasma sheath.

V. REDEP ANALYSIS

A. Erosion/Redeposition

The REDEP erosion/redeposition code[15,16] was used for analysis of an outer (worst case) divertor plate. Tritium retention rates are than scaled for all four divertor surfaces.

The analysis is toroidally symmetric. The REDEP3 code used employs a new capability for computation of RES transport. Both physical, chemical, and RES sputtering are treated. (Due to a number of model deficiencies, the transport of chemically sputtered carbon is treated in a relatively crude manner.) Sputtering properties of original-surface pure carbon are assumed; a discussion of this issue is given in Appendix A.

Figures 1 and 2 show the B2 code plasma profiles used as input to REDEP. A 20 cm wide region (before sweeping) is modeled (not all points are shown). The strike point is at pt. 61. The plate surface temperature is modeled as being at a uniform temperature T_s for the high heat flux region (pts 37-136) and at a temperature of 400°C otherwise. Figure 2 shows the instantaneous (i.e., at any time during the 5s swept flat-top period) sputtering results, assuming no tile gaps and for several different surface temperatures. The sputtered flux includes the effects of D-T ions and neutrals, helium (3%), and carbon self-sputtering.

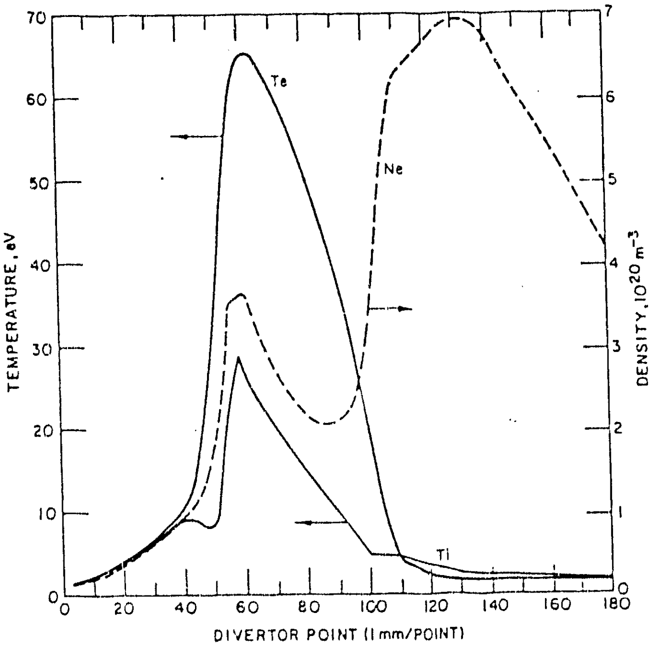

Figure 1. Plasma profiles at CIT outer divertor plate.

At the nominal design value of T_s = 1700°C, the peak sputtered flux is more than twice the value of incident D-T ion flux. This is due primarily to RES. At T_s = 400°C, shown for comparison, the peak sputtering is due primarily to physical sputtering. The sputtered flux for the cold regions are not shown in Fig. 2 but is equal to about 2% of the D-T ion flux and is due primarily to chemical sputtering.

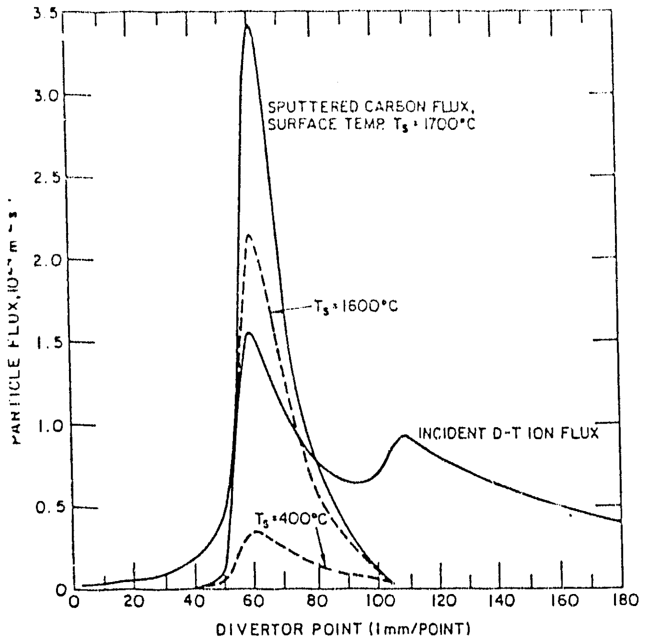

Figure 2. D-T ion flux incident to divertor plate and sputtered carbon flux.

As mentioned, the high rate of carbon sputtering at elevated surface temperatures is not consistent with the present B2 computations which assume trace impurity content. This is true even though most sputtered carbon is predicted to be confined to a small region (< 1 cm) near the plate. In addition, the sheath potential structure, and the resulting angles of incidence, energy etc. used in REDEP are based only on trace impurity models. The B2 and REDEP runs are consistent, however, with the result shown for T_s = 400°C.

Figure 3 shows the instantaneous net erosion flux for the case with tile gaps. The net erosion flux is defined as the sputtered carbon flux minus the redeposited carbon flux. For this computation, the gaps, of width 1 mm, were located at REDEP points 10, 20,...,200. The gap model used assumes the following: 1) gaps do not perturb the plasma, 2) no sputtering within gaps, and 3) no carbon leaves a gap. It is seen by comparing Figs. 2 and 3 that the net erosion is some two orders of magnitude smaller than the gross erosion. This results from high local redeposition, due to the high electron density and the perpendicular poloidal field line geometry. Not surprisingly, erosion tends to occur on either side of a tile gap with the eroded carbon being transferred to the gap.

The effects of sweeping were computed by convolving the instantaneous erosion solution, i.e., Fig. 3, with a sweep function representing a 20 cm strike point motion in 5 s. (The effects of the startup and shutdown period, if any, are not included.) The resulting net erosion profile is shown in Fig. 4. This profile is approximately the same for each 1 cm wide tile in the high heat flux region. The predicted erosion rate is high but should not pose a lifetime issue for CIT where the number of pulses is limited. For example, for 3000 full power shots the predicted peak erosion would be only ~1 mm.

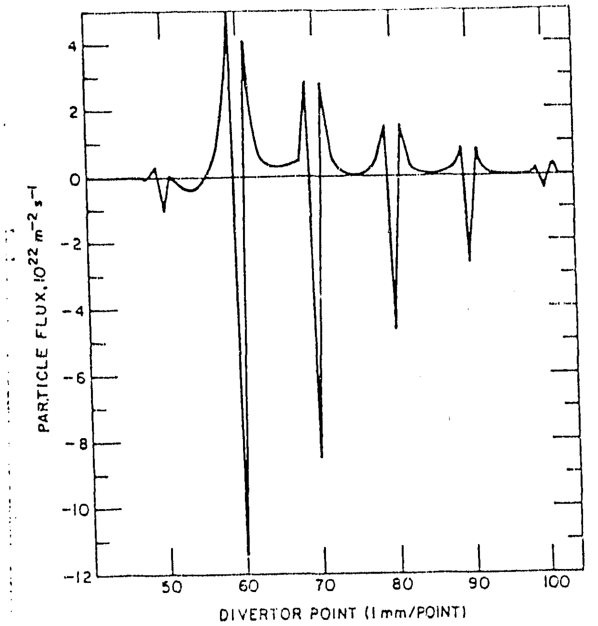

Figure 3. Net erosion flux across divertor plate with 1 mm wide tile gaps.

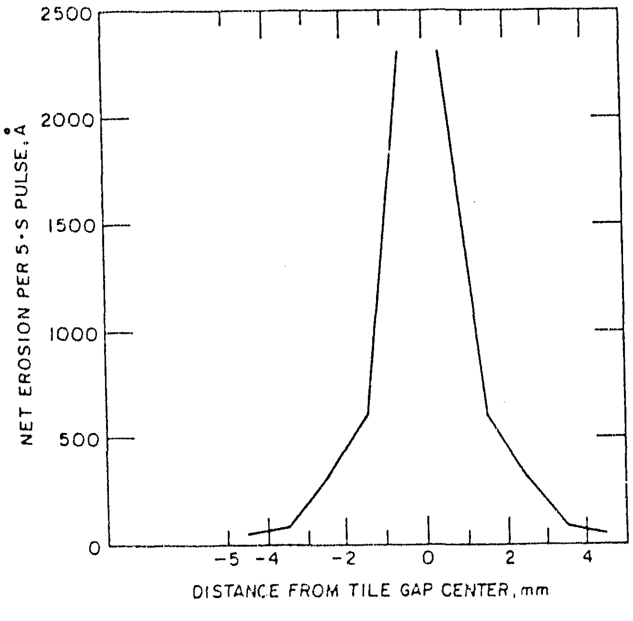

Figure 4. Net erosion profile across 1 cm wide carbon tiles; for a five second pulse with sweeping (growth not shown for gap region).

B. Co-Deposited Tritium

The REDEP code, incorporating the tritium retention model described in Appendix B, was used to compute the co-deposited tritium on the divertor and first wall surfaces. The erosion and tritium results are summarized in Table 2, for a range of peak divertor surface temperatures. To compute overall inventories, an equal division of power between upper and lower divertors and a two to one split between outer and inner plates was assumed.

Table 2.
CIT/REDEP Analysis:
Erosion and Tritium Co-Deposition Summary

Peak Divertor Surface Temp. °C	Carbon Deposition in Gaps[a] g·/5 s Pulse	Peak Net Erosion, Å/5·s Pulse	Co-Deposited Tritium,[b] Ci/5·s Pulse
400	.59	974	89
700	.62	1045	38
1000	.59	978	25
1600	.95	1821	23
1700	1.2	2300	23
1800	1.5	3147	23
2000[c]			

a- Total for all divertor plates.

b- Total for all divertor plates, and adjacent first wall at 400°C.

c- Does not converge.

At high (>1200°C) peak surface temperatures tritium co-deposition occurs primarily at the first wall with some 20% of the total being due to trapping in the gaps of the colder sections of the divertor plates. No trapping occurs in the high power flux divertor regions since any tritium co-deposited at the beginning of the burn pulse is driven out as sweeping increases the surface temperature above 1200°C. A high surface temperature therefore helps to minimize the tritium surface inventory even though it increases the sputtering rate. A key point in this regard is that, because of the high redeposition, there is little transport of sputtered carbon from hot to cold regions of the CIT divertor. At T_s < 1200°C (corresponding to a hypothetically different divertor design or operating conditions) tritium co-deposition occurs over all of the plate with a resulting increase in buildup rate.

The divertor erosion increases with increasing T_s except near ~700°C where chemical sputtering tends to peak. The peak erosion rates increase exponentially at high T_s due to the RES process. At T_s = 2000°C the REDEP code predicts a runaway erosion process due to high self-sputtering. As mentioned, the predicted limit depends on local plasma parameters and thus may change with a self-consistent analysis.

VI. SURFACE TRITIUM INVENTORY CONTROL

The tritium inventory management scheme for CIT includes both monitoring and control of the in-vessel surface inventory. Careful measurements of tritium fuel input and tritium exhaust will allow for the determination of tritium accumulation in the torus. Control of the inventory is possible by in-situ removal of codeposited films, such as by using a reactive glow-discharge plasma to volatilize the carbon films. In particular, the effectiveness of using a He/O_2 mixture as reactant gases for etching the codeposited film has been demonstrated by Hsu.[17] This work showed removal rates of a carbon surface of 0.65 Å/s. In this technique the trapped hydrogen isotopes are liberated as water molecules, which can be readily removed by vacuum pumping for further processing. In the semiconductor industry, oxygen plasmas with trace amounts of CF_4 are used to etch carbon based photoresists.[18] Adding trace levels of foreign species to oxygen may point to the way of enhancing carbon film etching rate by enhancing the concentrations of reactive neutral oxygen radicals.

It is anticipated that deuterium glow discharge cleaning will be applied following each CIT run shift, to remove readily releasable near surface tritium. When the in-vessel tritium inventory is observed to reach the one gram administrative limit, an aggressive helium-oxygen glow discharge cleaning would be initiated to volatilize and remove the co-deposited hydrogen isotope carbon films. Based on the computed value of ~25 Ci/shot accumulation, a total of 400 full power shots could be run before this was necessary. This represents a substantial fraction of CIT full power operation. (Analysis has not yet been performed for lower power CIT shots.)

VII. CONCLUSION

This paper represents an initial analysis of CIT divertor erosion and tritium co-deposition. The analysis has been performed for full power, 5 s flattop phase, CIT conditions using presently available models for the plasma, materials properties, and sputtered particle transport. Because of the use of trace impurity plasma models the analysis is not self-consistent; in addition the analysis depends critically on as-yet unverified oblique field sheath structure and thermally sputtered carbon transport near a divertor surface. Aside from these qualifications, the analysis shows several encouraging trends. One is that stable and acceptable erosion operation at elevated surface temperature (1700°C) and moderate plasma sheath temperature (60 eV) is possible. Also, in spite of the high sputtering rates at these conditions, most sputtered carbon is locally redeposited, with little consequent plasma contamination. Secondly, there is essentially no co-deposited tritium occurring over most of the swept divertor region, due to the high surface temperature reached. Tritium co-deposition can occur at colder regions of the plate and at the first wall, due primarily to chemically sputtered carbon transport.

The computed tritium co-deposition rate, at ~25 Ci/pulse is small, with respect to the 10,000 Ci inventory limit. Most or all of this co-deposition should be readily removable by glow discharge techniques. Key issues in this area requiring additional work, are the following: (1) properties of high temperature redeposited carbon surfaces, (2) self-consistent scrape-off layer plasma performance, and (3) verification of sheath structure and transport of RES and chemically sputtered carbon. Future analysis on the effects of start-up, shutdown, and disruptions on surface tritium inventory is also in order.

APPENDIX A: PROPERTIES OF REDEPOSITED CARBON

An important assumption for the calculations of this paper, is that the plasma material interaction behavior of a redeposited carbon layer is identical to that of graphite. We have assessed the plausibility of this hypothesis with reference to the following experimental data.

Causey et al.,[19] have recently compared properties of the hydroger properties of a laboratory prepared saturated carbon layer produced by deuterium ion bombardment with redeposited carbon-deuterium films from the TFTR POCO AXF-5Q graphite bumper limiter. They observed that the saturated layer and TFTR redeposited films displayed virtually identical hydrogen release characteristics in both vacuum and air annealing treatments.

The sputtering characteristics of POCO AXF-5Q graphite redeposited films from the TFTR moveable limiter have been studied by Pontau, Causey, and Bohdansky.[20] They observed that the physical sputtering yield of the TFTR surfaces by 500 eV deuterons was equal to that of published laboratory measurements on virgin graphite samples. They did, however, observe a reduced chemical erosion yield in the 700-1000 K temperature range, but this reduction was attributed to metallic impurities that were incorporated into the redeposited layers. Hirooka et al.,[21] also conducted chemical erosion measurements on different redeposited carbon films from the TFTR bumper limiter; they found the chemical erosion yield was comparable to or slightly (~15%) higher than that for virgin POCO AXF-5Q graphite samples. Recently, Youchison et al.,[22] have reported that redeposited carbon films produced in their laboratory by the collection of sputtered carbon atoms exhibited from 10 to 34 times as much hydrogen and helium sputtering yield as pristine graphites. However these laboratory films may not be representative of redeposited films created in a tokamak under intense plasma bombardment, where extensive carbon recycling and energetic ion beam mixing occurs. In fact, Youchison did not observe any significant increase in sputter yields for redeposited carbon surfaces created by intense plasma bombardment in the PISCES facility.

The hypothesis that redeposited carbon films behave identically to that of graphite is therefore a reasonable interpretation of the present, limited data base for redeposited carbon. However, more measurements are clearly warranted for the properties of tokamak-exposed graphites and of laboratory redeposited films created at high flux rates and/or at elevated substrate temperatures.

APPENDIX B: TRITIUM RETENTION MODEL

The trapping of tritium in codeposited layers is believed to be analogous to deuterium retention in a saturated implant layer.[23] To calculate total retained tritium as a function of implant temperature and anneal time and temperature, we rely on the data of Doyle, Wampler, and Brice[24] recently repeated by Hansah, Biberian, and Bienfait[25] at room temperature. We treat retention phenomenologically by fitting the data in 100°C intervals. We observe in Fig. 4 of Ref. 24 that total tritium retention is less for graphite implanted at elevated temperature than for graphite implanted first and then heated. Retention values are given in Table 3. We incorporate the data into our CIT calculations by invoking a "vanishing bathtub" model. The number of tritons which can be stored at room temperature in each 100°C interval bathtub is derived from the high flux isochronal anneal data; as the temperature rises above 500°C the bathtubs are emptied sequentially. For elevated implant temperatures, as in CIT, unfilled bathtubs (amount of tritium retention possible) decreases, as reflected by the saturation-at-temperature data. We assume that the "rate" that unfilled sites vanish with temperature is independent of the binding energy, and that desorption from sites is first order and not diffusion limited. Thus, we model two processes which occur with rising temperature: (1) filled trapping sites (bathtubs) empty out, and (2) sites which are not yet filled, disappear. We note that while fitting the Doyle et al. data in this manner is not mechanism dependent, we believe that the breadth of the desorption curve is more likely caused by a series of traps rather than the single binding energy site proposed by Hansah et al.

Table 3.
Tritium Retention Model

Surface Temp., °C	(D+T)/C Ratio for Low Temp. Co-Deposition Followed by Heating to Temp.	(D+T)/C Ratio for Co-Deposition at Temp.
RT	0.4	0.4
100	0.4	0.38
200	0.4	0.32
300	0.4	0.24
400	0.4	0.13
500	0.35	0.06
600	0.25	0.03
700	0.16	0.02
800	0.08	0.008
900	0.04	0.004
1000	0.02	0.002
1100	0.01	0.001
1200	0	0

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