Distribution Category:
Magnetic Fusion Energy
(UC-20)

ANL/FPP/TM-191

ANL/FPP/TM--191

DE85 000779

ARGONNE NATIONAL LABORATORY
9700 South Cass Avenue
Argonne, Illinois 60439

SPUTTERING PERFORMANCE OF THE TPCX LIMITER

by

J. N. Brooks

Fusion Power Program

September 1984

SPUTTERING PERFORMANCE OF THE TFCX LIMITER

J. N. Brooks
Fusion Power Program
Argonne National Laboratory
Argonne, Illinois 60439

ABSTRACT

The sputtering performance of the proposed TFCX pumped limiter was analyzed using the REDEP computer code. Erosion, redeposition, surface shape and heat flux changes with time, and plasma contamination issues were examined. A carbon coated limiter was found to give acceptable sputtering performance over the TFCX lifetime if, and only if, acceptable redeposition properties of carbon are obtained.

1.0 INTRODUCTION AND MODEL

The TFCX device, as a near term ignition machine, has different impurity control requirements than either present devices or future advanced devices such as INTOR. Compared to INTOR, the erosion rate due to sputtering is much less of an issue simply because the availability of TFCX is so much lower (1% compared to 50%).

On the other hand, plasma contamination from sputtered material is somewhat more important for TFCX since there is less of an ignition margin than for more advanced machines. Compared to present tokamaks, TFCX would have longer pulse lengths (~100 s) and higher heat particle fluxes, all making the issue of sputtering more important. To evaluate these issues, the sputtering performance of the proposed bottom limiter for TFCX was examined, using the REDEP computer code. This code has been described elsewhere.[1] Briefly, the code models the transport, ionization, and redeposition of sputtered surface material in the scrapeoff zone, plasma, first wall, and limiter/divertor regions of a tokamak. The latest version of the code, REDEP4, follows the time evolution of the limiter surface, and has other improvements in the models.

The input to the REDEP code consisted of plasma profiles (T_e, T_i, N_e, heat and particle fluxes), and charge exchange neutral sputtering fluxes. These were provided[2] by the 1-1/2 dimensional transport code WHIST run in conjunction with the neutral transport code DEGAS. The version of the TFCX design parameters used here are R = 3.25 M, a = 1.31 M, k = 1.6, I_p = 10 MA, and an alpha power of 50 MW. The limiter configuration examined is a flat, toroidally continuous, single-edge design, located at the bottom of the torus. Carbon is the reference coating material.

As will be discussed, it is important for the use of carbon in TFCX that redeposited carbon ions stick to the limiter surface and form a redeposited surface having acceptable properties (adhesion, thermal conductivity, etc.). It is assumed for the calculations that the redeposited carbon layer has the same sputtering coefficients as the original coating. As discussed in Refs. 1 and 3 there is reason to question these assumptions, but relevant data for a better model is lacking. Also, except where otherwise indicated, only physical sputtering was assumed, i.e., chemical sputtering was ignored. This requires adequate control of the carbon coating temperature. The effect of variations in edge conditions and coating materials was also examined.

2.0 RESULTS

For the reference conditions, the limiter shape, net growth rate, and heat flux are shown in Figs. 1 through 3. Except for the leading edge, the limiter results are approximately symmetric about the limiter center, therefore results are shown for the left side only. In Fig. 1, the coordinates x and y denote the major radius and elevation coordinates respectively, with x = y = 0 denoting the center of the tokamak. In Figs. 2 and 3, limiter points 2-21 denote points on the front face initially spaced 1.62 cm apart, and points 22-26 denote leading edge points which are initially spaced 1.00 cm apart. The limiter shape at time t = 0 is prescribed as a flat top surface, with a ~1.5 cm radius leading edge. The bottom side of the limiter is subject to less erosion and was not modeled. As shown, the net growth rate (redeposition minus sputtering) of the carbon surface, at t = 0, varies from ~7 cm/yr at the leading edge to −14 cm/yr on the top surface. The gross erosion rate (hydrogen + helium + self-sputtering) at these two points is 93 cm/yr and 179 cm/yr respectively, thus redeposition is seen to be an important effect in reducing

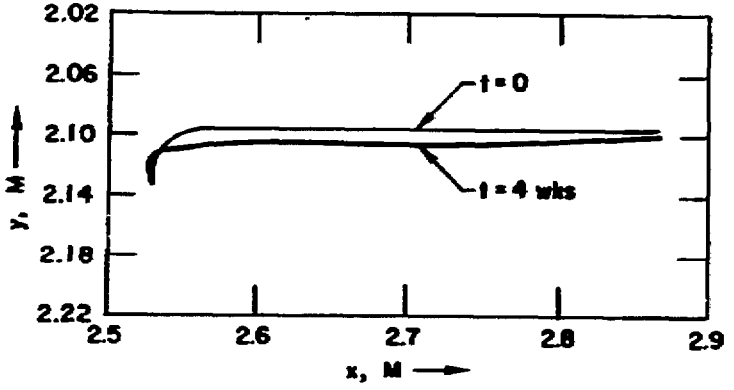

Fig. 1. Limiter shape at initial startup and after four weeks of continuous operation.

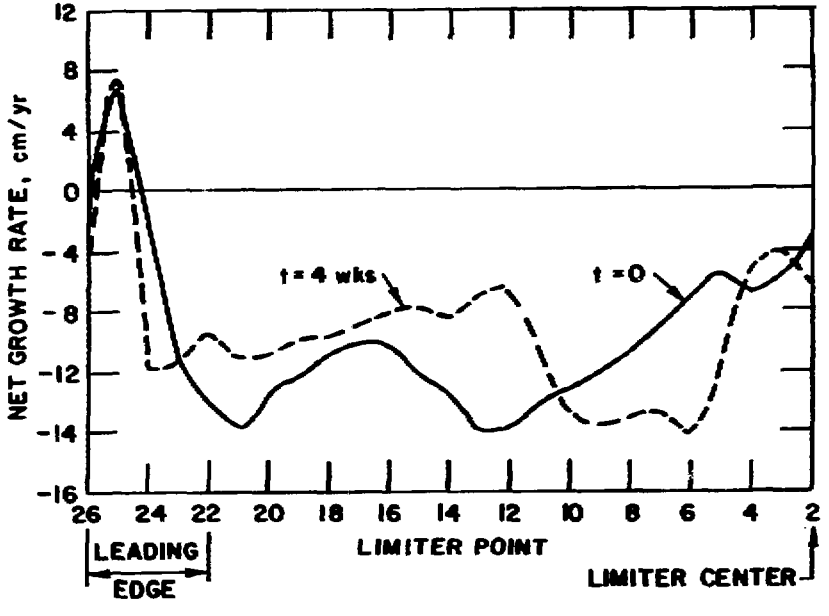

Fig. 2. Net growth rate of the limiter carbon coating at initial startup and after four weeks of continuous operatior.

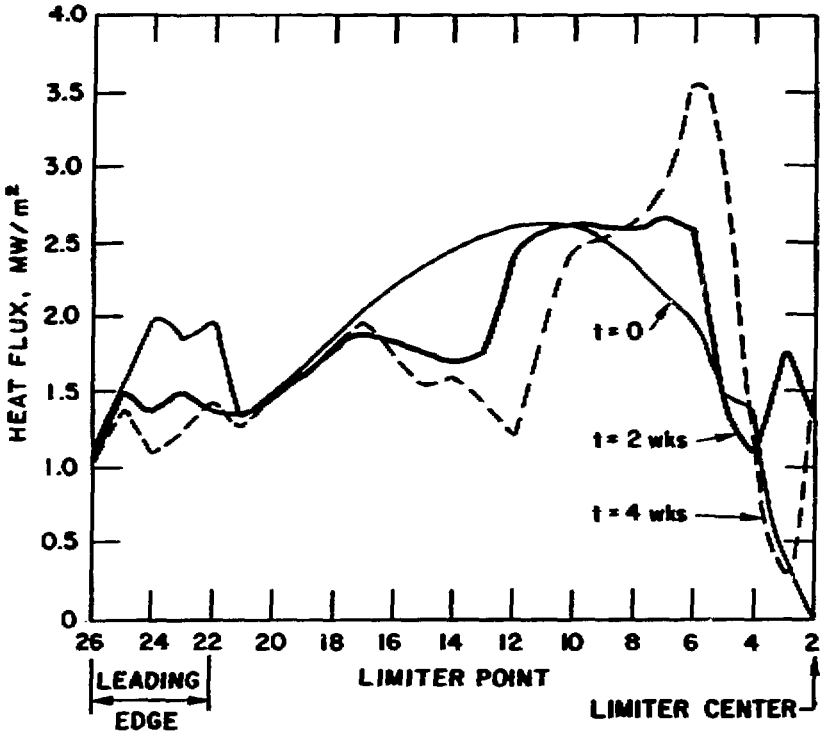

Fig. 3. Limiter heat flux at initial startup and after two and four weeks of continuous operation.

erosion. (All erosion rates quoted are for continuous operation; for a device like TFCX having a ~1% availability, one week of continuous operation is equivalent to about two calendar years.) The positive net growth rate over some of the leading edge is due to transfer of material from the front face. Since the net erosion rate is determined by the difference between two fairly large terms (erosion and redeposition) the net rate is model dependent and can change with variations in such parameters as edge density, e-folding distances and magnetic field line structure.

Based on the predicted net growth rate, the code computes the change in the surface of the limiter. This was done at two-week (continuous operation) intervals. At each interval, the code computes the new particle flux, sputtering and redeposited distributions. At the end of four weeks the front surface of the limiter had eroded by about 1 cm. As seen from the net growth profiles the limiter erosion is somewhat self-compensating. This is, high

erosion rate areas at t = 0 tend to have lower net erosion at t = 4 weeks, and vice versa.

The heat flux profile across the limiter is sensitive to small changes in shape. As a result, the heat flux profile changes substantially with time, as shown in Fig. 3. The peak heat flux is ~2.5 MW/m^2 initially and rises to ~3.5 MW/m^2 after four weeks. The latter value is still probably acceptable.

Plasma contamination from sputtering depends on the fraction of sputtered carbon ionized in the scrapeoff zone. For the reference case, the contamination fraction, S^{eff}, defined as the ratio of the carbon atom current entering the plasma to the deuterium/tritium ion current leaving the plasma, is 0.018. (S^{eff} can also be thought of as the effective sputtering coefficient.) Ionization and subsequent redeposition in the scrapeoff zone reduce the carbon flux entering the plasma by about a factor of 5. This remains nearly constant through four weeks of operation. The shielding efficiency (see Ref. 1) of the scrapeoff zone is, therefore, ~80%. If the carbon entering the plasma had the same confinement time as the D-T ions, the carbon concentration, in steady state, would be equal to S^{eff}, i.e. 1.8% of the D-T density. However, transport code studies[4] have shown that the core plasma impurity density should be substantially less than this value, due to high impurity recycling in the edge region. Although the transport studies were done for a larger device, a similar result would be expected for TFCX. Based on a predicted factor of 4 difference in the impurity confinement time, the carbon concentration would be ~0.5%. This value is acceptably small.

In the event, however, that redeposited carbon ions do not adequately stick to the limiter surface, the resulting carbon concentration in the plasma would appear to be intolerable. For this case, and in the absence of any other removal mechanism, the buildup of carbon in the plasma can be written as:

$$\frac{d}{dt}\,\frac{N_Z}{N_{DT}} = \frac{S^{eff}}{\tau},$$

where N_Z and N_{DT} are the average carbon and deuterium densities in the plasma, and τ is the D-T particle confinement time. A lower bound on S^{eff} is obtained by ignoring self-sputtering; in this case S^{eff} = 0.043. Based on a value of τ ≈ 60 ms (from Ref. 2 results) the average carbon concentration would reach 72%

in 1 sec. Possible removal mechanisms are carbide formation with a metallic first wall and transport of carbon into the pumping duct. However in TFCX, some 90% of the plasma outflux impinges on the limiter, thus limiting the effect of these removal mechanisms. Information on carbon behavior in present day machines is hard to assess because these machines have colder edges, shorter pulses, and less extensive limiter surfaces than TFCX. An encouraging result however is the observation of redeposited carbon in ASDEX.[5]

Considering the issues of erosion and plasma contamination, the limiter is acceptable under the reference conditions. A 1-cm thick carbon coating (cladding) would last about four weeks of full operation. This translates into about 10 yr of real time operation at 1% availability or about the proposed life of TFCX. The limiter would likely be changed several times for other reasons such as experimentation and damage from disruptions.

3.0 OTHER CASES

Computer runs were made for two different edge temperatures, T_{e_0} = 50 eV, and 300 eV. Other plasma parameters were scaled accordingly. In particular, plasma edge density was scaled as $n_{e_0} \sim T_{e_0}^{-1.5}$, based on the assumption of a constant heat flux. The plasma contamination fraction, and the average net erosion rate for these cases, and the reference case, are compared in Table 1. As shown, contamination and erosion both scale with temperature (in the temperature range shown). The lower temperature regime, T_{e_0} = 50 eV, is significantly better than the reference case, for two reasons: (1) sputtering coefficients are lower; and (2) the higher density results in more scrapeoff zone ionization.

For a beryllium-coated limiter, the contamination results are similar to carbon. The peak erosion, however, which occurs at the leading edge for beryllium is about twice as bad. This is due to higher D-T sputtering coefficients. Beryllium may have the advantage of better redeposition properties than carbon.

For the reference case, average impingement angles for ions on the limiter are taken as 60 deg from the normal. A case (not shown) was run with the average angler set to 0 deg (normal incidence). This reduced the net erosion rate and contamination fraction by about a factor of two.

Table 1. Performance Comparison of Different Materials and Edge Conditions

Limiter Coating Material	Edge Electron Temperature[a] T_{e_0}, eV	Peak Net Erosion Rate,[b] cm/yr	Plasma Contamination Fraction[b]	Comments
Carbon	117	16	0.018	Reference case.
Carbon	50	4	0.0043	
Carbon	300	62	0.039	
Beryllium	117	29	0.021	Peak erosion occurs at leading edge.
Carbon - with chemical sputtering	117	42	0.024	Gross sputter rates are very high.
Tungsten	50	4	0.77×10^{-3}	

[a]At start of scrapeoff.

[b]At t = 0.

The effect of chemical sputtering of carbon was also examined. The method described in Ref. 1 was used to model chemical sputtering. Although the contamination fraction shown is reasonable, the results for chemical sputtering are very speculative due to very high gross sputter rates and concerns about sticking properties.

The use of medium and high-Z materials would require lower edge temperatures, $T_{e_0} \leq 50$ eV. Results for a tungsten coating at $T_{e_0} = 50$ eV are shown. The contamination fraction is significant at this temperature but decreases rapidly for lower temperatures.

4.0 CONCLUSIONS

Erosion and plasma contamination calculations were made for the TFCX-pumped limiter. The reference case is a carbon coating with a moderate plasma edge temperature. Based on these results, a pumped limiter will have acceptable sputtering performance for a near term ignition device such as TFCX. Both plasma contamination and erosion appear to be acceptable. An important issue for the use of carbon, however, is to assess the sticking properties of redeposited material. Beryllium provides an important alternative to carbon in the event that chemical sputtering and/or poor redeposition properties are obtained for carbon. Lower edge temperatures than the ~100 eV predicted are not necessary for low-Z coatings but would certainly be beneficial. Medium and high-Z coatings offer another alternative, if edge temperatures of $\lesssim$50 eV are obtainable.

REFERENCES

1. J. N. Brooks, Nucl. Technol./Fusion 4, 33 (1983).

2. C. D. Boley, "Transport of Neutral Atoms and Molecules in TFCX," Sixth International Conf. on Plasma Surface Interactions in Controlled Fusion Devices, Nagoya, Japan (1984), to be published.

3. J. N. Brooks, and M. Kaminsky, "Influence of Erosion and Redeposition Processes on the Lifetime of Impurity Control Components: An Assessment for TiC Coatings," J. Nucl. Mater., to be published.

4. W. K. Terry, et al., "Transport Code Analysis of Some Aspects of Impurity Control in Reactor Grade Tokamak Plasmas," Fusion Technol., to be published.

5. J. B. Roberto, et al., "The Use of Isotopically Enriched Carbon Probes for Erosion/Deposition Measurements in the ASDEX Divertor," Sixth International Conf. on Plasma Surface Interactions in Controlled Fusion Devices, Nagoya, Japan (1984), to be published.

Distribution for ANL/FPP/TM-191

Internal:

C. Baker
C. Boley
J. Brooks (10)
F. Cafasso
Y. Cha
R. Clemmer
D. Ehst
K. Evans
P. Finn
Y. Gohar
L. Greenwood
D. Gruen
A. Hassanein
C. Johnson
J. Jung
M. Kaminsky
S. Kim
R. Kustom
L. LeSage
Y. Liu
B. Loomis
S. Majumdar
V. Maroni
R. Mattas
B. Misra
J. Norem
R. Nygren
W. Praeg
J. Roberts
G. Rosenberg
D. Smith
H. Stevens
D. Sze
L. Turner
ANL Patent Dept.
FP Program (15)
ANL Contract File
ANL Libraries (2)
TIS Files (6)

External:

DOE-TIC, for distribution per UC-20 (107)
Manager, Chicago Operations Office, DOE
Special Committee for the Fusion Program:
S. Baron, Burns & Roe, Inc., Oradell, NJ
H. K. Forsen, Bechtel Group, Inc., San Francisco, CA
J. Maniscalco, TRW, Inc., Redondo Beach, CA
G. H. Miley, University of Illinois, Urbana
P. J. Reardon, Brookhaven National Laboratory
P. H. Rutherford, Princeton Plasma Physics Laboratory
D. Steiner, Rensselaer Polytechnic Institute
K. R. Symon, University of Wisconsin-Madison
K. Thomassen, Lawrence Livermore National Laboratory
J. Cecchi, Princeton Plasma Physics Laboratory
J. Schmidt, Princeton Plasma Physics Laboratory
D. Post, Princeton Plasma Physics Laboratory

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES