**Two-Dimensional Toroidal Geometry
Neutral Atom Transport and Material Erosion Rates
in the TEXTOR and TFTR Tokamaks**

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Abstract

The power deposition and wall material erosion rates due to charge-exchange neutral atoms resulting from a recycling source at limiters in the TEXTOR and TFTR tokamaks are reported. The analysis is carried out using a recently developed finite element, two-dimensional toroidal geometry diffusion theory neutral atom transport theory and the computer code, FENAT. The power deposition and material erosion are highest at the limiter. The first wall suffers very little erosion except for the portion near the limiter.

I. Introduction

Limiters are used in TEXTOR [1,2] and TFTR [3] to provide impurity and particle control. As a consequence of its functional requirement, a limiter is subject to an intense bombardment by plasma. One of the key questions is the effect of material erosion by both plasma and charge-exchange-produced neutral atoms, created as a result of recycling at the limiter. We have shown elsewhere [4] that the transport of neutral atoms in fusion plasmas can be accurately described by an energy dependent diffusion theory. A two-dimensional, triangular mesh, finite element code, FENAT, has been developed [5]. FENAT solves the multigroup diffusion equation for the transport of neutral atoms in x-y Cartesian and R-Z cylindrical or toroidal plasma geometries. The code assumes that wall originated thermal neutral atoms are emitted isotropically and includes reflection of neutral atoms at surfaces according to data or models available in the literature [6]. Here, FENAT is applied to compute both the distribution of neutral atoms originating at the limiter and the wall power deposition and material erosion rates in the TEXTOR and TFTR tokamaks. The results are in general agreement with those obtained by Heifetz et al. [7] for the TFTR tokamak, although the calculations reported here require significantly less computer time and storage. The neutral atom distributions, wall power depositions, and erosion rates are presented in Secs. II and III, respectively. Section IV contains a summary and conclusions.

II. Neutral Atom Distribution and Wall Loads in TEXTOR

The experimental tokamak TEXTOR [1] is planned to have a toroidal belt pump limiter, ALT-II [2]. The plasma cross section is circular. Figure 1(a) shows a schematic of the plasma and the location of the toroidal belt

limiter. The intensity of the neutral atom source at the tips of the limiter is about 20 times greater than at other positions on the limiter surface. Machine parameters and reference plasma properties for TEXTOR are given in Table 1. For this experimental tokamak, the duty factor of 9.13×10^{-4} corresponds to a total of 9600 pulses per year, and a pulse length of 3 seconds. The neutral atom energy range is covered by 15 energy groups, with the maximum energy being 3 keV. Neutral atoms originating at the limiter are assumed to have 5 eV of energy as a result of the Franck-Condon process. The same is true of fast neutral atoms not reflected directly from the wall or limiter.

The total neutral atom density at five plasma minor radii are plotted as functions of the poloidal angle in Fig. 2, while a contour plot of the total neutral atom density is given in Fig. 3. The maximum neutral density is normalized to the value of 10^{10} cm^{-3} . In the plasma, the density is attenuated by about 3.3 orders of magnitude. Note that while the maximum density occurs at the limiter tips, the minimum density occurs 180° poloidally across from the limiter but somewhat inside the plasma because of reflection from the wall. Due to the strong poloidal variation in neutral atom density, the wall power deposition and erosion rate are also strong functions of poloidal angle.

Figures 4 and 5 show the wall power deposition and material erosion rate due to the neutral atom bombardment. Both the power deposition and erosion rate are highest at the limiter. The power deposition at the limiter is about 3 W/cm^2 and the erosion rate amounts to $0.1 \text{ }\mu\text{m/pulse}$. Both the power deposition and erosion rate decrease rapidly along the first wall away from the limiter. The minimum values of both these parameters are one percent of their maxima.

III. Neutral Atom Distribution and Wall Loads in TFTR

A schematic of the plasma geometry and the location of the toroidal bumper limiter in TFTR are shown in Fig. 1(b). Table II contains the plasma properties and other parameters used in modeling the TFTR plasma. The plasma properties are taken as those at 0.7 seconds into a beam-heated, 2.2 second discharge as calculated by the one-dimensional transport code BALDUR [8]. These are the same parameters as reported in Ref. [7], and are chosen to facilitate a general comparison between FENAT and Monte Carlo calculations. Here, the energy of the neutral atoms is modeled using 21 energy groups. The highest energy is taken to be 40 keV. The source of a few eV neutral atoms is taken to be uniform over the limiter surface. All fast neutral atoms not reflected directly from the wall are assumed to desorb again at a few eV. Since the neutral distribution is symmetric above and below the midplane, the problem is solved only in the upper half of the plasma [$\theta = 0^\circ$ to 180° in Fig. 1(b)].

Figures 6 and 7 show the total neutral atom density at four plasma minor radii as functions of the poloidal angle and as a density contour plot, respectively. The maximum density is normalized to 10^{10} cm^{-3} . Again the total density is a strong function of poloidal angle. In the plasma, the total density is attenuated by about 3 orders of magnitude. The wall power deposition and erosion rate as functions of the poloidal angle are shown in Fig. 8. Here, as in TEXTOR, the power deposition and erosion rate are maximum at the limiter. The maximum values are about 75 W/cm^2 and $0.05 \text{ } \mu\text{m}/3 \text{ sec.}$ pulse, respectively. The minimum values of power deposition and erosion rate occur on the first wall directly opposite to the limiter, and are smaller than their maximum values at the limiter by more than a factor of 10.

IV. Summary

The results for both the TEXTOR and TFTR tokamaks show that both the wall power deposition and the material erosion due to neutral atom bombardment are strong functions of poloidal angle. The wall power deposition and erosion rate are maximum at the limiter, and much smaller at the first wall except near the limiter.

A comparison of the TEXTOR and TFTR results shows that a higher plasma temperature in TFTR has a small effect on material erosion because, after an initial increase with the energy, the sputtering yield *decreases* with further energy increase. The wall power deposition, however, increases with increasing plasma temperature. A higher plasma temperature also reduces the differences between the limiter and first wall power deposition and erosion rates. The reasons are that there exists a greater number of high energy charge-exchange neutrals in a high temperature plasma, and that the plasma is *optically thin* for such high energy neutrals. Thus, the higher energy neutrals are more or less uniformly deposited on the vessel wall.

The TFTR results from FENAT are in general agreement with those in Ref. [7] obtained by Monte Carlo code. Detailed comparison is not possible because of a lack of correspondence in boundary conditions. The main contribution of FENAT to the neutral transport calculation would be a significant reduction in computer time when modeling a complex plasma geometry. A comparison of FENAT with the neutron transport code DOT-4.3 presented in Ref. [5] shows that FENAT provides very good accuracy and, even for medium-sized problems, FENAT is one to two orders of magnitude faster than transport theory calculation. It is expected that the saving in computation time will be even greater in comparison with Monte Carlo codes.

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Figure Captions

- Fig. 1 Schematics of plasma geometry and the location of toroidal limiters (a) for TEXTOR tokamak and (b) for TFTR tokamak (not to scale).
- Fig. 2 Total neutral atom density in TEXTOR at 5 plasma minor radii as functions of the poloidal angle. The maximum density is normalized to 10^{10} cm^{-3} . The limiter is located between $\theta = 297^\circ$ and $\theta = 233^\circ$.
- Fig. 3 A contour plot of $\log_{10}$ of total neutral atom density in TEXTOR plasma. The maximum density is normalized to 10^{10} cm^{-3} . The order of density attenuation is about 3.3.
- Fig. 4 Wall power deposition in TEXTOR. The maximum power deposition is about 3 W/cm^2 at the limiter and the minimum power deposition is about 0.056 W/cm^2 on the first wall at $\theta = 135^\circ$. The limiter is located between $\theta = 297^\circ$ and $\theta = 233^\circ$.
- Fig. 5 Wall material erosion rate in TEXTOR. The duty factor is 9.13×10^{-4} . The maximum erosion rate is about 10^{-3} cm/yr. at the limiter tips. The minimum erosion rate is less than 10^{-5} cm/yr. on the first wall at $\theta = 135^\circ$. The limiter is located between $\theta = 297^\circ$ and $\theta = 233^\circ$.

Fig. 6 Total neutral atom density in TFTR at 4 plasma minor radii as functions of the poloidal angle. The maximum density is normalized to 10^{10} cm^{-3} . The density is symmetric about 180° . The bumper limiter is located between $\theta = 120^\circ$ and $\theta = 240^\circ$ [see Fig. 1(b)].

Fig. 7 A contour plot of $\log_{10}$ of total neutral atom density in TFTR. The maximum density is normalized to 10^{10} cm^{-3} . Total density attenuation in the plasma is about 3 orders of magnitude. The density is symmetric below the midplane.

Fig. 8 The wall power deposition (a) and erosion rate (b) as functions of the poloidal angle, θ , in TFTR. The duty factor is assumed to be one.

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Table I

TEXTOR Parameters and Reference Plasma Properties

Major radius	175 cm
Minor radius	48 cm
Plasma geometry	circular
Limiter material	graphite
First wall material	stainless steel
Central ion temperature	0.773 keV
Edge ion temperature	50 eV
Central electron temperature	0.865 keV
Edge electron temperature	100 eV
Central plasma density	$2.5 \times 10^{13} \text{ cm}^{-3}$
Edge plasma density	$8.4 \times 10^{12} \text{ cm}^{-3}$
Total plasma ion efflux rate	$6 \times 10^{21} \text{ sec}^{-1}$
Plasma ion recycling coefficient	0.9
Duty factor	9.13×10^{-4}

Parabolic profiles are assumed for plasma temperature and density.

Table II

TFTR Parameters and Plasma Properties

(Temperatures and densities are taken from
model calculations reported in Ref. [7])

Major radius	265 cm
Minor radius	85 cm
Plasma geometry	circular
Limiter material	graphite
First wall material	stainless steel
Central plasma temperature	16.46 keV
Edge plasma temperature	111 eV
Central plasma density	$5.44 \times 10^{13} \text{ cm}^{-3}$
Edge plasma density	$1.33 \times 10^{13} \text{ cm}^{-3}$
Total plasma ion efflux rate	10^{22} sec^{-1}
Plasma ion recycling coefficient	0.9

Parabolic profiles are assumed for temperature and density. Ion and electron temperatures are assumed equal.