EUV IMPURITY STUDY OF THE ALCATOR TOKAMAK

Technical Report

J. L. Terry, K. I. Chen, and H. W. Moos

The Johns Hopkins University
Department of Physics
Baltimore, Maryland 21218

and

E. S. Marmar

Francis Bitter National Magnet Laboratory
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

June 1977

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PREPARED FOR THE U. S. ENERGY RESEARCH AND DEVELOPMENT

ADMINISTRATION UNDER CONTRACT EY-76-S-02-2711

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ABSTRACT

The intensity of resonance line radiation from oxygen, nitrogen, carbon and molybdenum impurities has been measured in the high field (80 kG), high density ($6 \times 10^{14} \text{ cm}^{-3}$) discharges of the Alcator tokamak, using a 0.4 m normal incidence monochromator (300 - 1300 Å) with its line of sight fixed along a major radius. The total light impurity concentrations were 2×10^{-3} , 7×10^{-4} , and 3×10^{-3} at central electron densities of $4.5 \times 10^{13} \text{ cm}^{-3}$ (burnout), 4.0×10^{13} (low density plateau) and 6.0×10^{14} (high density plateau). Both a simple model and a computer code which included Pfirsch-Schlüter impurity diffusion were used to estimate oxygen influxes of $1.6 \times 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$ and $1.5 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$ at the plasma edge in the low and high density emission plateaus. The resulting values of Z_{eff} , including the contributions due to both the light impurities and molybdenum, were close to one. The power lost through the impurity line radiation accounted for $\approx 7\%$ of the total ohmic input power at high densities.

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I. INTRODUCTION

It is well known that impurities can have an important influence on magnetically confined plasmas, in some cases determining the major characteristics of the discharge. The most obvious effects are the increase in plasma resistivity and the decrease in energy confinement time through radiation losses; however, other changes such as peaking of the temperature profile also occur [1]. It is also a common observation that impurity dominated discharges often show other undesirable features such as an increase in disruptive instabilities [2].

Most tokamaks have reported values of Z_{eff} , ($Z_{\text{eff}} \equiv \sum_{\text{ion}} n_i Z_i^2 / n_e$), between 2.5 and 6; light impurities in amounts on the order of a few percent of the electron density were present [3,4,5,6,7]. On the TFR tokamak a Z_{eff} of 6 resulted in a power loss due to impurity line radiation which was 30-40% of the input power averaged over the plasma volume [3]. Energy balance measurements made with relatively clean helium plasmas ($Z_{\text{eff}} \sim 2.4$) in the ST tokamak indicated that in the developed discharge approximately 30% of the total input power was being lost through radiation [4].

One distinguishing feature of the Alcator tokamak has been a plasma purity high enough that Z_{eff} was consistently close to 1 [2,8]. The value has been obtained from measurements of the plasma resistance and the electron temperature, and from soft x-ray bremsstrahlung measurements. A more direct measure of Z_{eff} may be obtained with spectroscopic techniques, in which the actual impurity densities are found from measured resonance line intensities. We report here a spectroscopic study primarily of the light impurities, oxygen, nitrogen, and carbon, utilizing line emissions in the extreme ultraviolet (EUV) from 300 to 1300 Å.

In Section II we discuss the range of Alcator discharge parameters and describe the spectrometer. The characteristics of the observed emissions are described in Section III. In Section IV, the computation of impurity fluxes and concentrations from these measurements is described; this was done first by relatively simple straightforward arguments, and then by using a computer code which included ionization, recombination and transport. (In both cases measurements of line emissions were used to deduce the role of the metastable populations). The fluxes, impurity concentrations and effective Z for a particular date deduced from the

analysis are presented in Section V and their variation with plasma parameters is discussed in Section VI.

Section VII describes the molybdenum impurity emissions and their contribution to the effective Z . A summary and conclusions are presented in Section VIII.

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II. EXPERIMENTAL DETAILS

A. Alcator Parameters. The toroidal field, plasma current, electron density and electron temperature, were varied over a wide range during the time of the study (December, 1976 through February, 1977). Discharges were obtained at fields of 40, 60, 70 and 80 kG. Average electron densities as measured by a 2 mm microwave interferometer and an alcohol laser interferometer [9] ($\lambda = 0.119$ mm) varied from 2.0 to $3.5 \times 10^{13} \text{ cm}^{-3}$ in the low density phase and from 2.0 to $5.5 \times 10^{14} \text{ cm}^{-3}$ in the high density phase; the interferometer positions are shown in Fig.

II-1. Electron temperature was measured on a shot to shot basis by Thomson scattering ruby laser radiation at the plasma center and at 3 other fixed points along a major radius. Profiles constructed in this manner were well fitted by a gaussian for $r \leq 7.5$ cm. After calibration by one of the electron density interferometers, the Thomson scattering system was also used to construct density profiles which were well fitted by a parabola. The plasma current (I_p) time history, indicated in Fig. III-1 of Section III was consistently flat topped; the values

II-2

FIGURE II-1 Schematic of selected Alcator diagnostics, including EUV spectrometer system.

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at the plateau varied from about 100 kA to about 170 kA. Peak central temperatures in the low and high density plateaus were between 700 eV and 1.1 keV.

B. Instrumentation.

1. Spectrometer System. The instrument used for the EUV measurements was a 0.4 m, normal incidence, scanning monochromator covering the spectral range from 300 to 1300 Å. The 20 mm by 20 mm, 2400 lines mm^{-1} concave grating produced a linear dispersion of 10 Å mm^{-1} in first order. The short wavelength limit to the wavelength coverage was determined by the reflectivity of the platinum grating overcoat. The best experimental resolution was 0.20 Å (resolutions from 0.7 Å to 5.5 Å were used for the study), and the wavelength reproducibility was ~ 0.35 Å. Incident intensity was controlled by adjusting slit widths and heights and by using an adjustable preslit parallel to the entrance slit (see Fig. II-1) which controlled the field of view. The spectrometer, designed by Wm. G. Fastie of the Johns Hopkins University, was intended specifically for use on and compatibility with high

temperature plasma devices. For this reason the design stressed portability (size 14 x 35 x 80 cm, weight - 25 kgm), ruggedness, and good vacuum quality (stainless steel construction with copper gasket seals and ion pumping).

The dispersed radiation was detected at the exit slit by a windowless photomultiplier (EMR 510W) whose first CuBe dynode served as the photocathode; the loss of sensitivity of the CuBe at wavelengths greater than 1300 Å determined the upper bound on the instrument's usable spectral range. Detector pickup due to X-rays and magnetic fields in the tokamak environment was eliminated by incorporating shields into the detector package. The magnetic shielding was shown in laboratory tests to effectively eliminate magnetic field penetration of pulsed fields up to 100 gauss in the transverse direction and penetration of fields up to 25 gauss in the longitudinal (PM tube axis) dimension. Stray magnetic fields on Alcator at the detector location (about 2.5 m from the torus center in the torus plane) were measured to be ± 40 gauss maximum in the transverse dimension ($\hat{Z}$ direction) and less than 1 gauss in the longitudinal dimension ($\hat{r}$ direction). To minimize electrical noise,

the high voltage supply and fast electrometer were an integral part of the detector package. The electrometer had a response time of 70 μ sec and a limiting sensitivity 10^{-10} amp; the three low impedance 0-10 volt outputs corresponding to 1.0, 0.1 and 0.01 μ amp full scale were measured in the control room by a digital oscilloscope and then recorded on magnetic tape.

2. Calibration. At the beginning and end of the study, the sensitivity of the spectrometer was absolutely calibrated at the Johns Hopkins University. Measurements were made at 12 spaced spectral points with National Bureau of Standards diode detectors as the calibration reference [10]. Calibration was achieved by directing an image formed with a monochromatic beam of light first into the entrance slit of the instrument and then onto a NBS calibrated photodiode. Both were located in the same vacuum chamber so that lamp drifts and pump down effects were minimized. The technique was similar to that described by Fastie and Kerr [11] for wavelengths above 1150 $\text{\AA}$ but utilized a new facility constructed for the windowless spectral region down to 300 $\text{\AA}$ [12]. To reduce sensitivity drifts, the spectrometer was maintained under vacuum from the initial calibration until the calibration check at the end of the study. The uncertainties in the absolute sensitivity are estimated to be

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$\pm 25\%$. This includes the NBS diode calibration uncertainties, the uncertainties due to the calibration transfer to the instrument and the sensitivity drifts over the four month period of the study. Uncertainties in the relative sensitivity calibration between different wavelength regions are estimated to be less than $\pm 10\%$. The spectrometer was calibrated in wavelength at about 110 points from 350 Å to 1300 Å.

3. Alcator Interface. The spectrometer was connected with a flexible bellows to a beam line which ended at a 8.6 cm high x 2.80 cm wide aperture in the torus located below the pulsed gas injection system and 180° away from the limiter. The spectrometer-beamline vacuum was isolated from the torus by a pneumatic gate valve, which was open for a 1 sec period surrounding the time of the shot. A typical pressure in the spectrometer was 4×10^{-7} Torr; the only gas transport between the spectrometer and the beam line was through the open aperture of the entrance slit, typically 0.3 cm by 0.02 cm. To further prevent contamination of the tokamak which had base pressures of $\sim 1 \times 10^{-9}$ Torr, the pressure in the beam line was maintained at 3×10^{-8} Torr by ion pumping when the valve to the tokamak was closed. The hard x-ray signal, voltage-current characteristics and

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plasma stability are qualitative indicators of plasma cleanliness; they showed no evidence that the spectrometer contaminated the tokamak.

The orientation of the instrument with respect to the plasma is indicated in Fig. II-1. The plasma was observed along the major radius in the mid plane of the torus. The field of view at the center of the plasma was typically a 1.75×2.2 cm rectangle ($F_{\text{hor}}=80$, $F_{\text{vert}}=100$). After mechanical alignment, final adjustment of the spectrometer viewing direction was made by a shot to shot mapping of the port in both dimensions using O VI - 1032 Å light.

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III. EUV EMISSION CHARACTERISTICS

This section describes the time behavior of the discharge and the light impurity spectroscopic emissions. The underlying physical mechanisms are discussed qualitatively; the quantitative analysis of the data is given in Sections IV through VI. Molybdenum is covered in Section VII.

Because the energies of the $\Delta n=0$ (n = principle quantum number) transitions are slowly varying functions of ionization state, most of the lighter impurity ions, lithium-like and above, have resonance lines in the spectral region from 400 Å to 1600 Å. Most of this range (300-1300 Å) was covered by the 0.4 m, normal incidence monochromator employed in this study. Within the instrument's spectral range line emission from oxygen, nitrogen, carbon and molybdenum impurities were identified. The observed lines and their atomic transitions are listed in Table III-1. In Figure III-1 time histories of the O VI-0 III emission are shown. For this particular study emission was integrated along a single plasma minor diameter line-of-sight; the plasma was not scanned to provide spatially resolved measurements.

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TABLE III-1

OBSERVED TRANSITIONS AND IONS

ION	WAVELENGTH (Å)	TRANSITION	MEASURED POPULATION RATIO	
			Metastable level	Ground level
O VI	1032	$2s^2 2S-2p^2 2P$ (G)	No metastable level	
O V	630	$2s^2 1S-2s2p^1 1P$ (G)	2.6	
	760	$2s2p^3 3P-2p^2 3P$ (M)		
O IV	554	$2s^2 2p^2 2P-2s2p^2 2P$ (G)	0.5	
	625	$2s2p^2 4P-2p^3 4S$ (M)		
O III	703	$2s^2 2p^2 3P-2s2p^3 3P$ (G)	1.5	
	600	$2s^2 2p^2 1D-2s2p^3 1D$ (M)		
O II	539	$2p^3 4S-2p^2 3s^4 P$ (G)	Not measured	
N V	1239	$2s^2 2S-2p^2 2P$ (G)	No metastable level	
N IV	765	$2s^2 1S-2s2p^1 1P$ (G)	2.2	
	923	$2s2p^3 3P-2p^2 3P$ (M)		
N III	686	$2s^2 2p^2 2P-2s2p^2 2D$ (G)	Not measured	
N II	916	$2s^2 2p^2 3P-2s2p^3 3D$ (G)	Not measured	
C III	977	$2s^2 1S-2s2p^1 1P$ (G)	Not measured	
C II	904	$2s^2 2p^2 2P-2s2p^2 2P$ (G)	Not measured	
Mo XIV	424	$4s^2 S_{1/2}-4p^2 P_{1/2}$ (G)	No metastable level	
Mo XIII	341	$4s^2 1S_0-4s4p^1 P_1$	Not measured	

(G) = The transition between the excited state and the ground state.

(M) = The transition between the excited state and the metastable state.

Figure III-1 Observed oxygen emission with plasma current (I_p) and average electron density ($\bar{n}_e$) in the discharge phases: (1) burnout (0-5 msec), (2) low density plateau (5-15 msec), (3) transition rise (15-80 msec), (4) high density plateau (80-120 msec). The upper value of $\bar{n}_e$ is from the 2 mm microwave interferometer; the lower value is from the 0.119 mm alcohol laser interferometer--1 fringe = 10^{14} cm^{-3} .

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A. Characteristics of the Measured Emissions. It is possible to divide the EUV emissions from a standard, ohmically heated Alcator discharge into four phases occurring consecutively in time. Referring to Figure III-1 we label the phases burnout, low density plateau, transition rise, and high density plateau. The burnout phase is shown by a spike in the emission near the beginning of the discharge; it occurs in the first 5 msec when the plasma current and electron temperature are rising as the loop voltage falls. The average electron density is constant at about $3 \times 10^{13} \text{ cm}^{-3}$, initial gas breakdown having occurred in the first 200 μsec . The term burnout derives from the rapid ionization through the lower ionization states of the impurities until these lower states establish themselves spatially in ring structures. This situation then characterizes the low density plateau phase, in which, although the current and temperature are still rising, the density is still constant. About 15 msec into the discharge more working gas is pulsed into the plasma, increasing the average electron density to between 2 and $5 \times 10^{14} \text{ cm}^{-3}$. At that time the current is constant or slightly rising, as is the central temperature. The temperature profile, however, is narrowed dramatically in going from low to

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high densities as shown in Fig. V-2.

There is a strong increase in the EUV emission which has been labelled the transition rise. A substantial part of the increase was due to an increased impurity influx. However, part of it may also be due to the narrowing of the temperature profile and subsequent recombination from higher ionization states [13]. The evidence for this is the fact that the higher the ionization state the sooner the emission increased from its plateau value (consistent for O VI through O II). Figure III-2 shows the O VI and O III emission at this time. Note that when the O VI emission has reached

t=3 msec

t=34 msec

Figure III-2 Onset of the transition rise for O VI-1032 Å (top trace) and O III-703 Å (bottom trace).

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eight times its low density plateau value, the O III emission is only 4.5 times its low density plateau value.

At about 80 msec, after the temperature profile and recombination have stabilized, the emission shows a high density plateau. This phase lasts until near the end of the discharge which is typically 130 msec in length.

B. Relation to Light Impurity Concentrations. The burnout phase is characterized by the rapid peaking of the emission as the impurities in the central discharge region are ionized through their successive charge states. We believe the light impurity emission in this phase is due almost entirely to impurities, loosely bound to the walls (the fraction due to the base pressure, 1×10^{-9} torr, is negligible), which enter before the gas breakdown is complete (within the first 200 μ sec). After the initial peaking of the lower ionization states, emission would drop to zero if there were no impurity flux entering the plasma. That the emission decreases to a small plateau level, a factor of 30 to 130 down from the first peak, is indicative of the small value of this impurity flux. As described in Sections IV and V, the absolute

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brightnesses of the first burnout peaks can be used to infer the initial impurity concentrations, while the absolute brightnesses of the subsequent plateaus yield the impurity fluxes during the low and high density plateaus.

IV. ANALYSIS

The light impurity concentrations and the rates at which impurities enter the plasma were calculated using each of two models. The first was applied only as an order of magnitude estimate. The second utilized a more comprehensive computer simulation of the atomic emission process, in which one dimensional (radial) transport was included. This approach was used only for oxygen as this impurity, which is usually dominant in hydrogen discharges, was the most extensively studied. In both cases the measured quantity in this study, column brightness, was used to infer values for the quantities of interest: absolute ion density and total impurity influx. In both models the brightness at the burnout peak was used to evaluate the initial ion density, while the plateau brightness gave the impurity influx. In this section, the details of the two models, which were used for the results presented in the following section, are discussed.

A. Direct Estimates. To determine the initial impurity density with the first model, we make the assumption that the spatial distribution of an ionization state at the burnout peak is a parabola with the central ion density equaling the total impurity density, i.e.,

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$n_i = n_{oi} (1 - r^2/a^2)$ where a is the limiter radius.

For a spectrometer viewing an optically thin plasma in a narrow pencil along a minor diameter, the column brightness for a resonance transition with a branching ratio of one is

$$B = \frac{2 \int_0^a Q n_i(r) n_e(r) dr}{4\pi}$$

in units of photons per unit time per unit area per unit solid angle. Q is the local electron impact excitation rate coefficient and $n_e(r) = n_{oe}(1 - r^2/a^2)$ is the electron density. Q is relatively insensitive to the spatially varying temperature. Thus, if it is taken outside the integral, the product of n_i and n_e is directly integrable to give n_{oi} .

$$n_{oi} \approx \frac{15}{4} \frac{\pi B}{Q n_{oe} a} \quad (1)$$

To estimate the impurity influx [14], consider a well developed plasma in which the impurity ionization states are distributed in shells of width W_i .

Ions are introduced from a source at the edge of the shell with a flux, Γ , and move through the shell with a diffusion velocity V_d . In that case the column brightness may be expressed as $B \approx \frac{\Gamma(2W_i)Qn_e}{4\pi V_d}$ where n_e ,

IV-3

V_d and Q are taken to be constant over the width of the shell. In order to evaluate Γ we note that the width of the shell may be written as $W_i = V_d / S_i^{i+1} n_e$ where S_i^{i+1} is the ionization rate coefficient for ionization out of that state. Thus

$$\Gamma = \frac{2\pi B S_i^{i+1}}{Q} \quad (2)$$

Another way to view the problem is to rewrite Eq. (2),

$$B = \frac{1}{4\pi} 2\Gamma \frac{n_e Q}{n_e S_i^{i+1}} ; \quad (3)$$

that is, the surface brightness is proportional to twice the flux times the excitation rate times the average time for ionization. Other effects such as temperature variation across the shell have not been considered and make Eq. (2) very approximate. Despite this, Eq. (2) provides a simple way to directly estimate the impurity flux without interposing a code analysis.

B. Code Analysis. In the second model a more complete formalism is used. Here quantitative models for impurity ionization and recombination, excitation, impurity transport and edge injection are used. The

resulting rate equations are solved numerically with a computer code to predict the impurity emission integrated along a line of sight. The validity of the results, of course, depends upon the validity of models assumed for the processes of ionization, excitation, diffusion, and impurity injection. It also depends upon the sensitivity of the results to uncertainties in the code input parameters, mainly electron temperature and density profiles. This aspect will be discussed in Section V.

1. Ionization and Recombination. The distribution of impurities among different ionization states within a homogeneous volume is based upon the following system of rate equations, which are numerically integrated.

$$\begin{aligned}
 \frac{\partial n_1}{\partial t} &= - S_1^2 n_1 n_e + \alpha_2^1 n_2 n_e - \nabla \cdot \vec{r}_1 \\
 \frac{\partial n_2}{\partial t} &= - S_2^3 n_2 n_e + S_1^2 n_1 n_e + \alpha_3^2 n_3 n_e - \alpha_2^1 n_2 n_e - \nabla \cdot \vec{r}_2 \quad (4) \\
 &\vdots \\
 \frac{\partial n_Z}{\partial t} &= S_{Z-1}^Z n_{Z-1} n_e - \alpha_Z^{Z-1} n_Z n_e - \nabla \cdot \vec{r}_Z
 \end{aligned}$$

where n_i and r_i are the density and flux of the i^{th} ionization state, and the S's and α 's are the applicable ionization and recombination rate coefficients. Ionization

was taken to be due solely to electron impact, and the values used are due to Lotz [15]. The recombination rate coefficients include both radiative and dielectronic processes [16]. These coefficients are strong functions of electron temperature which is supplied as a measured parameter.

2. Excitation. The coronal model is used to describe the excitation and emission process. It assumes 1) collisional excitation rates are much larger than photo-excitation rates, 2) spontaneous radiative decay rates are much larger than collisional de-excitation rates, and 3) characteristic ionization and excitation times are much longer than characteristic decay times. The working result of these assumptions is that the volume emission rate of photons due to the transition from level p to level q is given by $E_{pq} = B_{pq} Q_{\text{gnd} \rightarrow p} n_i n_e$, where n_i is the ion density, $Q_{\text{gnd} \rightarrow p}$ is the electron excitation rate from the ground state to the upper level p , n_e is the electron density, and B_{pq} is the branching ratio to the lower level q . This is valid for ions with no metastable levels, so that in the lithium-like ions (O VI and N V) the ion density is simply related to the volume emission rate. For ions with metastable levels the situation is more complicated; here the metastable level may be populated directly by ionization from the next lower charge

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state or by collisional excitation from the ion's ground state. In this case, since there may be a significant metastable population, the ion density is no longer given by the ground state density, and $E_{pq} = B_{pq} Q_{gnd \rightarrow p} n_i n_e$ no longer holds. To see how to derive an ion density from volume emission rates consider how a given excited state in an ion with a metastable level is populated. A simplified energy level diagram for a beryllium-like ion is shown in Fig. IV-1. The ratio of volume emission rates for the $1P^0 \rightarrow 1S$ and $2p^2 \ 3P \rightarrow 2s2p \ 3P^0$ transitions is given by

$$\frac{E(1P^0 \rightarrow 1S)}{E(3P \rightarrow 3P^0)} = \frac{[n(1S)Q(1S \rightarrow 1P^0) + n(3P^0)Q(3P^0 \rightarrow 1P^0)]}{[n(3P^0)Q(3P^0 \rightarrow 3P) + n(1S)Q(1S \rightarrow 3P)]} \quad (5)$$

FIGURE IV-1

Partial term diagram for beryllium-like ions. Dashed lines indicate possible populating processes; solid lines indicate the allowed radiative decay channels with wavelengths given for the observed O V lines. The level diagram is not to scale.

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where the n's are the densities of the specified level (ground or metastable) and where population from any other level is negligible, since radiative decay from those levels is allowed. Solving equation (5) for $\frac{n(^1S)}{n(^3P^o)}$ yields

$$\frac{n(^1S)}{n(^3P^o)} = \frac{Q(^3P^o \rightarrow ^3P)E(^1P^o \rightarrow ^1S) - Q(^3P^o \rightarrow ^1P^o)E(^3P \rightarrow ^3P^o)}{Q(^1S \rightarrow ^1P^o)E(^3P \rightarrow ^3P^o) - Q(^1S \rightarrow ^3P)E(^1P^o \rightarrow ^1S)}. \quad (6)$$

If the emission rates are comparable, this reduces to

$$\frac{n(^1S)}{n(^3P^o)} \approx \frac{E(^1P^o \rightarrow ^1S)Q(^3P^o \rightarrow ^3P)}{E(^3P \rightarrow ^3P^o)Q(^1S \rightarrow ^1P^o)} \quad (7)$$

since the excitation rates to levels of a different system are much smaller than those to levels of the same system [17]. Thus the total ion density becomes

$$n_i = n(^1S) + n(^3P^o) \approx \left\{ \frac{E(^1P^o \rightarrow ^1S)}{Q(^1S \rightarrow ^1P^o)n_e} + \frac{E(^3P \rightarrow ^3P^o)}{Q(^3P^o \rightarrow ^3P)n_e} \right\} \quad (8)$$

and one is forced to measure 2 lines to determine the density of a given ion. For boron-like ions similar considerations apply, this time for doublets and quartets.

In using the computer code these metastable considerations are taken into account. For the resonant transitions considered all branching ratios are one; the excitation rate coefficients used are due to Davis [18,19,20].

3. Transport and Injection. Transport and impurity injection in the computer code are treated in the same manner as in ref. [21], where the code predictions compared well with experimental measurements of Al impurity injection on the ATC tokamak. A detailed description is contained in ref. [22]; so the treatment will be discussed only briefly here.

Transport has been included in the system of rate equations (Eq. (4)) through the $\nabla \cdot \Gamma_j = \frac{1}{r} \frac{\partial}{\partial r}(r \Gamma_j)$ terms. The flux, Γ_j , is taken to be described by Pfrisch-Schlüter impurity diffusion. Not including classical diffusion, the flux is [23]

$$\Gamma_j = \frac{q^2 \rho_p^2 v_{pj}}{Z_j T_p} \left[\alpha \left(T_p \frac{\partial n_p}{\partial r} - \frac{n_p T_j}{n_j Z_j} \frac{\partial n_j}{\partial r} + n_p \frac{\partial T_p}{\partial r} - \frac{n_p}{Z_j} \frac{\partial T_j}{\partial r} \right) - \beta n_p \frac{\partial T_p}{\partial r} \right] \quad (9)$$

where ρ_p is the proton gyroradius, $v_{pj} =$

$$\frac{4\sqrt{2}\pi n_j Z_j^2 e^4 \ln \Lambda}{3\sqrt{m_p} T_p^{3/2}} \quad \text{is the impurity - proton collision}$$

frequency, Z_j is the impurity ion charge, q is the safety factor, T_p (T_j) the proton (ion impurity) temperature, and n_p (n_j) is the proton (ion impurity) density. α and β are given by

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$$\alpha = 0.47 + 0.35/[0.66 + n_j Z_j^2/n_p]$$

$$\beta = 0.3 + 0.41/[0.58 + n_j Z_j^2/n_p]$$

and result from deviations from a pure Maxwellian ion distribution function caused by collisions with other ion species (note for $n_j Z_j^2 < n_p, \alpha = \beta = 1$).

If

$$T_p = T_j = T,$$

$$\frac{n_p}{Z_j} \left| \frac{\partial T}{\partial r} \right| < T \left| \frac{\partial n_p}{\partial r} \right|,$$

and $n_j/n_p \ll 10^{-2},$

then for the ions considered (O VI - O III) Eq. (9) may be closely approximated

$$r_j \approx \frac{\alpha q^2 \rho_p^2 v_{pj}}{Z_j} \left[\frac{\partial n_p}{\partial r} - \frac{n_p}{Z_j n_j} \frac{\partial n_j}{\partial r} \right]$$

With the inclusion of the classical terms

$$r_j \approx \frac{\rho_p^2 v_{pj}}{Z_j} (1 + \alpha q^2) \left[\frac{\partial n_p}{\partial r} - \frac{n_p}{Z_j n_j} \frac{\partial n_j}{\partial r} \right]$$

For $\frac{\partial n_p}{\partial r} < 0$ this form of the flux predicts both

"inward" and "spreading" diffusion. Experimental evidence for the inward impurity transport has been sought on the ST, TM-3, and TFR tokamaks [6,5,3] using intrinsic impurities with inconclusive results. The injected impurity study on ATC [21, 22], as mentioned previously, gave good agreement with this Pfrisch-Schlüter diffusion model. We have applied it to Alcator because of its high collisionality.

With this form of diffusion, ions "injected" at the plasma edge will be carried inward. These "injected" ions are the code counterparts of the impurity flux responsible for the plateau brightnesses discussed in Section III. To relate these brightnesses to an impurity flux, one provides as an initial condition in the code a gaussian distribution of O II ions (full width half maximum ≈ 0.5 cm) with a peak at 9.0 cm in minor radius. (Alcator limiter radius is 10.0 cm). This is arrived at by assuming that neutral oxygen impinges on the edge of the plasma with an energy of several eV/atom and is subsequently ionized in the plasma. Ions are then added at a constant rate until a steady state in emission is reached. The rate of ion injection is then varied until the predicted steady state brightnesses match those measured. In burnout the situation is changed.

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Here the initial impurity density is of interest, and in this case the initial condition is a parabolic O II ion distribution across the plasma cross-section; these ions are then ionized through the higher charge states as the discharge is "turned on". The initial O II density is varied until the predicted and measured peak brightnesses agree.

V. RESULTS

The oxygen concentrations and fluxes given in this section are based on data taken February 4, 1977 in a deuterium plasma. Other relevant plasma parameters for this day are shown in Fig. III-1. Note that the peak line average density was $4.0 \times 10^{14} \text{ cm}^{-3}$ and the current plateau was 175 kA. The toroidal field for these discharges was 80 kG, and $n_{oe}\tau_E$ at the density peak was $8 \times 10^{12} \text{ sec cm}^{-3}$, where τ_E was the global energy replacement time. Each phase of the discharge had different values of the electron temperature, and they will be discussed separately in the following subsections. Only oxygen is discussed in subsections A, B and C. In subsection D the other light impurities, measured in other runs, are covered; these values with the results for molybdenum from Section VII are then used to estimate the values of Z_{eff} . (All quoted values of Z_{eff} are at the center and assume nuclear O, N and C, and Mo XXXI.) See Table V-2 on page V-14 for a summary of the results. Possible causes of the oxygen flux are discussed briefly in subsection C. The degree to which these results are representative, and the long term behavior of the impurity concentrations are discussed in Section VI.

A. Burnout. Transcribed curves of the measured column brightnesses of O VI - O III lines are shown in Fig. V-1(a) for the first 2 msec after breakdown. A direct

estimate of the initial impurity density was made using Eq. (1) of Section IV and the brightness of the O VI line emission. For $B = 1.0 \times 10^{16} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$, $Q = 1.7 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$, $n_{oe} = 4.5 \times 10^{13} \text{ cm}^{-3}$ and $a = 10 \text{ cm}$, it yielded $n_{oi} = 1.5 \times 10^{10} \text{ cm}^{-3}$.

In the computer simulation, the value for the temperature as a function of time was needed because of the temperature dependence of the various rate coefficients. Temperature measurements this early in time were lacking, so the temperature rise in the code simulation was varied until a satisfactory match in the predicted burnout times was achieved. The code predictions for the burnout phase are shown in Fig. V-1(b), using a temperature rise and profile, $T_e(r,t) = [40t + 10][1 - r^2/(9.5)^2] \text{ eV}$, t in msec. The initial density in the code was chosen so that the predicted and measured O VI - 1032 Å peaks agreed. With this choice, the other brightnesses were fixed. As shown, the agreement for the other states was good; the worst case was in the O IV - 554 Å line where the prediction was a factor of 2.6 high. The metastable populations were considered in these predictions; the fact that their inclusion was significant can be seen in Table III-1, where the ratio of ground to metastable level population is listed. The

Figure V-1(a) Measured oxygen emissions at burnout with average electron density ($\bar{n}_e$ at 0.5 msec = $3.0 \times 10^{13} \text{ cm}^{-3}$).

Figure V-1(b) Oxygen emissions at burnout as predicted by the computer simulation with an initial oxygen distribution $n_i = 3.2 \times 10^{10} [1-r^2/(9.5)^2] \text{ cm}^{-3}$ ($\bar{n}_e = 3.0 \times 10^{13} \text{ cm}^{-3}$).

initial oxygen density derived from the code comparison was $3.2 \times 10^{10} \text{ cm}^{-3}$ for a peak electron density of $4.5 \times 10^{13} \text{ cm}^{-3}$, implying an oxygen concentration of 0.07% and a contribution to Z_{eff} of 0.05.

B. Low Density Plateau. After 10 msec, the O VI emission decreased to a low density plateau lasting 5 msec, at which time gas (H_2 or D_2) was introduced to increase the density. The average column brightness of the O VI - 1032 Å line at that plateau was $3.6 \times 10^{14} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$ as listed in Table V-1. The electron temperature computed for the center of the O VI shell (by the code) was 58 eV implying $Q = 1.7 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$ and $S_5^6 = 9 \times 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$. The impurity influx was then estimated directly using Eq. (2) of Section IV: $r = 1.2 \times 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$.

Before evaluating the low density plateau flux with the computer simulation, it was necessary to check the influence of the density at burnout on the signal at 10 msec. In the code no oxygen was lost. The code predicted brightness at this time due to the initial oxygen was $3.4 \times 10^{13} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$; the measured value, an order of magnitude larger, was thus attributable to an entering impurity flux. Matching the O VI plateau brightness predicted by the code to the measured value gave $r = 1.6 \times 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$. The

measured brightnesses and those predicted for this flux are listed in Table V-1.

The oxygen density was estimated by accounting for particle loss. The density was sensitive to the confinement time; this can be seen by noting that if there were no loss, the low density plateau concentration calculated below would have to be increased by a factor of 8, while the high density plateau value would increase a factor of 2. The total concentration of oxygen ions was assumed to obey the equation:

$$\frac{dn_{oi}}{dt} = \frac{\Gamma A}{V} - \frac{n_{oi}}{\tau_p},$$

where Γ was assumed independent of time, τ_p was the average oxygen particle confinement time also assumed to be time independent, and A and V were the plasma surface area and volume. For the initial condition $n_{oi}(t=0) = 3.2 \times 10^{10} \text{ cm}^{-3}$ and for $\tau_p = 2.7 \text{ msec}$ [24], this equation yielded $n_{oi}(t = 12 \text{ msec}) = 8.9 \times 10^9 \text{ cm}^{-3}$, implying a contribution to Z_{eff} of 0.01.

The major source of uncertainty in the value for the impurity flux at low densities was the uncertainty in the spatial profile of the temperature. The low density profile was not measured in this particular run, but was constructed from data available for

TABLE V-1

PREDICTED AND MEASURED PLATEAU BRIGHTNESSES

	MEASURED LOW DENSITY PLATEAU BRIGHTNESS	BRIGHTNESS PREDICTED FOR FLUX OF $1.6 \times 10^{13} \text{cm}^{-2} \text{sec}^{-1}$
O VI 1032 Å	$3.6 \times 10^{14} \text{ B}$	$3.6 \times 10^{14} \text{ B}$
O V 630 Å	$1.1 \times 10^{14} \text{ B}$	$0.85 \times 10^{14} \text{ B}$
O IV 554 Å	$3.5 \times 10^{13} \text{ B}$	$4.0 \times 10^{13} \text{ B}$
O III 703 Å	$1.0 \times 10^{13} \text{ B}$	$0.45 \times 10^{13} \text{ B}$

	MEASURED HIGH DENSITY PLATEAU BRIGHTNESS	BRIGHTNESS PREDICTED FOR FLUX OF $1.5 \times 10^{14} \text{cm}^{-2} \text{sec}^{-1}$
O VI 1032 Å	$6.7 \times 10^{15} \text{ B}$	$6.7 \times 10^{15} \text{ B}$
O V 630 Å	$2.8 \times 10^{15} \text{ B}$	$1.9 \times 10^{15} \text{ B}$
O IV 554 Å	$1.9 \times 10^{15} \text{ B}$	$0.75 \times 10^{15} \text{ B}$

$$\text{B} = \text{ph cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$$

similar discharges on other dates. Temperature profile measurements on Alcator were taken at 4 points along a major radius. Most of the O II - O VI emissions were expected to come from the region $r \gtrsim 8$ cm where no temperature measurements were available. The matter was further complicated by the fact that the peak temperature was still rising during the low density plateau; depending on the current rise in a given run, the values ranged from 500 eV to 1100 eV at 12 msec. The best estimate temperature profile, $T_e(r) = 750 (1 - r^2/9.5^2)^{3/2}$ eV, is plotted in Fig. V-2 with the measured profile points. The code was run with the peak temperature at both extremes as well as at 750 eV and with different profiles allowed by the 4 point measurement. The dependence of the predicted flux upon the form of the temperature profile in the region $r \gtrsim 8$ cm introduced an uncertainty of a factor of 2. In order to estimate the dependence of the code predictions upon the value of the diffusion coefficient, the code was run with coefficients having twice and one half the theoretical value; the predicted flux was 40% higher in the first case and 27% lower in the second case. Finally, note that the direct estimate discussed in the first paragraph gave a result in good agreement with that determined using the code.

Figure V-2 The electron temperature profiles used in the computer simulation of the high and low density emission plateaus. The x's are the measured high density values. The open circle data points indicate a profile determined from low density profiles measured in other runs.

C. High Density Plateau. After starting gas injection to increase the density, the emission stabilized in a second plateau at 80 msec. The oxygen flux during the high density phase of discharge was determined from the value of the brightness at this plateau. Besides the obvious density difference, the second major difference between the low and high density plateaus was a narrowing of the temperature profile. As shown in Fig. V-2, the temperature beyond 5 cm was lower than in the low density phase.

The impurity influx was estimated using Eq. (2) and the O VI - 1032 Å brightness of $6.7 \times 10^{15} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$. The central temperature of the ionization shell decreased with the increased density and change in the temperature profile; 36 eV was predicted by the code. For this value, $Q = 1.7 \times 10^{-8} \text{ cm}^3 \text{ sec}^{-1}$ and $S_5^6 = 2 \times 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$, yielding $\Gamma \approx 5 \times 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$.

The flux inferred from the O VI - 1032 Å brightness using the computer simulation was $1.5 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$. The brightnesses of the other oxygen ion lines predicted for this flux are compared with the measured values in Table V-1. No comparison was made for O III because the radius at which that ion would exist was largely outside of the injection radius (to a lesser extent this was also true for O IV). The concentration was determined at 100 msec by using $\tau_p = 40 \text{ msec}$ [24]. The concentration $n_{oi} =$

$9.9 \times 10^{11} \text{ cm}^{-3}$ implied Z_{eff} (oxygen only) = 1.11 at the center.

At high densities the temperature profile and peak temperature were changing slowly in time. Also, the high density temperature profile was measured in the same run as the oxygen line emissions. Both effects resulted in a temperature profile uncertainty which was smaller at high densities than at low densities. However, when the code was used with different temperature profiles allowed by the measurement, the uncertainty in the predicted flux was still found to be a factor of 2, just as in the low density case. Furthermore, sensitivity of the flux to the value of the diffusion coefficient increased in going to higher densities. Using values which were twice and one half theoretical, the predicted flux was increased by a factor of 2.8 in the first case and decreased by a factor of 2.1 in the second. The increased sensitivity of the flux at high density to both the temperature profile and the diffusion rate was caused by the fact that at higher densities the ionization state shells were located in regions of lower temperature; at lower temperatures the dependence of the ionization rate coefficients (and thus the shell widths) upon temperature is quite strong.

The most striking thing about this high density flux value was the order of magnitude increase over the

low density flux. The increase could not be due to increased oxygen recycling since on Alcator the confinement increases approximately linearly with electron density [24]. EUV radiation to the walls increased by more than an order of magnitude in going from low to high densities, but desorption of oxygen from the walls by 15 eV photons is probably not an efficient process. At high densities, the flux of EUV photons from deuterium, oxygen, nitrogen, and carbon was $\approx 1.9 \times 10^{18} \text{ cm}^{-2} \text{ sec}^{-1}$, and for a desorption efficiency of 10^{-4} [14] a full oxygen monolayer would have been needed for an oxygen flux of $1.5 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$. A process for oxygen desorption which is probably more efficient is impact by charge exchanged neutrals; reference [14] gave an average efficiency for desorption of oxygen by 50-1000 eV neutrals as $\sim 10^{-1}$. In Alcator the charge exchanged neutral flux has been measured for energies $\geq 100 \text{ eV}$ [25]. The flux of 100 eV neutrals rose approximately linearly with the electron density up to about $1 \times 10^{14} \text{ cm}^{-3}$, where the neutral flux was abruptly cut off because the neutrals could no longer penetrate to a region where the ion temperature was $\geq 100 \text{ eV}$. Since the cross section for charge exchange increases as the ion temperature decreases, it is reasonable to expect that there was a substantial total neutral

flux below 100 eV which continued to increase with density. Furthermore, the total neutral flux from 100 to 3000 eV during the low density plateau was enough that 0.01 of a wall monolayer of oxygen could account for the measured oxygen influx. (Only a portion of the energy spectrum is considered, so this estimate is an upper limit.) Therefore, it is quite possible that the increase in the charge exchanged neutral flux with increasing electron density caused the increase of the light impurity fluxes.

D. Z_{eff} and Power Loss. As mentioned in the introduction, a major goal of this study was determination of Z_{eff} . Although no computer analysis similar to that for oxygen was done for the other impurities, nitrogen, carbon, and molybdenum, those impurity concentrations and fluxes have been estimated, and values for Z_{eff} at burnout, 12 msec (low density plateau) and 100 msec (high density plateau) have been obtained.

To evaluate the burnout concentrations, the brightnesses of lines from ions which should exist in the same plasma regions have been compared after account was taken of metastable populations and of differences in excitation rates. In this manner the nitrogen concentration at burnout has been found to be a factor of two larger than that of oxygen, i.e., a

nitrogen concentration at burnout of 0.14%. The carbon concentration was considerably lower, 0.02%. As discussed in Section VII, the concentration of molybdenum at burnout was estimated as 0.005%.

The fluxes of carbon, nitrogen, and molybdenum impurities during the low and high density plateaus were directly estimated using Eq. (2) of Section IV with the following results

for nitrogen:

$$\Gamma_{\text{low density}} \approx 2.7 \times 10^{13} \text{ cm}^{-2} \text{ sec}^{-1}$$

$$\Gamma_{\text{high density}} \approx 1.2 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1}$$

for carbon:

$$\Gamma_{\text{low density}} \approx 4 \times 10^{12} \text{ cm}^{-2} \text{ sec}^{-1}$$

$$\Gamma_{\text{high density}} \approx 8 \times 10^{12} \text{ cm}^{-2} \text{ sec}^{-1}$$

for molybdenum (see Section VII for details):

$$\Gamma_{\text{low density}} \approx 1 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$$

$$\Gamma_{\text{high density}} \approx 1 \times 10^{12} \text{ cm}^{-2} \text{ sec}^{-1}$$

The concentrations were then determined in the same way as for oxygen. These values combined with the code determined results for oxygen of the previous subsection yielded

$$Z_{\text{eff}} (\text{burnout}) = 1.15$$

$$Z_{\text{eff}} (\text{low density}) = 1.04$$

$$Z_{\text{eff}} (\text{high density}) = 1.16$$

The results are summarized in Table V-2.

TABLE V-2

SUMMARY OF IMPURITY DENSITIES AND FLUXES

		<u>Oxygen</u>	<u>Nitrogen</u>	<u>Carbon</u>	<u>Molybdenum</u>
BURNOUT:	Flux ($10^{12} \text{cm}^{-2} \text{sec}^{-1}$)	-	-	-	5
$n_{\text{oe}} = 4.5 \times 10^{13} \text{cm}^{-3}$	Density (10^{10}cm^{-3})	3.2 (1.5)	6.4	1.1	0.2
$Z_{\text{eff}} = 1.15$					
LOW DENSITY PLATEAU:	Flux ($10^{12} \text{cm}^{-2} \text{sec}^{-1}$)	16 (12)	27	4	0.1
$n_{\text{oe}} = 4.0 \times 10^{13} \text{cm}^{-3}$	Density (10^9cm^{-3})	8.9 -	15	2	0.6
$Z_{\text{eff}} = 1.04$					
HIGH DENSITY PLATEAU:	Flux ($10^{13} \text{cm}^{-2} \text{sec}^{-1}$)	15 (5)	12	0.8	0.1
$n_{\text{oe}} = 6.0 \times 10^{14} \text{cm}^{-3}$	Density (10^{11}cm^{-3})	9.9 -	8.0	0.5	0.09
$Z_{\text{eff}} = 1.16$					

The values shown in parentheses for O were determined by direct estimates rather than by a code. The means for determining the values for N, C and Mo are discussed in the text. The values of Z_{eff} are at the center for nuclear O, N and C, and Mo XXXI.

Another goal of this study was determination of the power lost from the plasma through impurity line radiation in the EUV. Only the major lines ($\Delta n=0$) with the ground or metastable level as the lower state were considered. In addition, only radiation from the O VI - O III, N V - N III and C III - C II ions was included, so that the value represents a lower limit, although the actual value is expected to be close to the quoted value. During the low density plateau, the power radiated by impurities was less than 1%. However, at 80 msec in the high density phase, the power radiated by impurities was ≈ 36 kW, 7% of the total ohmic power into the plasma at that time. Inclusion of the radiation lost through the deuterium Ly α , Ly β line emission raised the percentage to $\approx 9\%$. Note that almost all of the power lost through these ions was lost from the spatial region $r \gtrsim 7$ cm, so that although the quoted percentage power loss was calculated using total power into the volume, the loss was from about half the total volume. In this outer region the power lost per unit volume was 0.9 W cm^{-3} , a relatively high value due to Alcator's small plasma volume. For example, in TFR [3] the comparable value was 0.38 W cm^{-3} , lower even though 30-40% of the input power was being lost through radiation. Because the fluxes of nitrogen and oxygen were so low, the power put into impurity ionization and heating of stripped electrons was an insignificant 2.1 kW.

VI-1

VI. VARIATION OF LIGHT IMPURITY CONCENTRATIONS

Fig. VI-1 indicates the changes in the concentrations of oxygen and nitrogen over the period of this study. The plotted value is the brightness at burnout of the O VI - 1032 Å (or N V - 1239 Å) line divided by the average electron density at that time. It is a measure of the number of emitters in the line-of-sight, and for shots with similar temperature profile time histories, it is proportional to the impurity concentration. Two trends are worthy of note: firstly, the oxygen concentration changed with time for reasons that were not always known and showed no correlation with the working gas. The sharp increase on January 14 was due to a vacuum failure which was repaired immediately. Secondly, the nitrogen concentration correlated strongly with the fill gas. It was probable that the nitrogen increase was due to a nitrogen impurity in the deuterium gas itself. The gas purity rating for the H₂ used was much higher than that for the D₂ used. In addition, after this study, a residual gas analyzer was used to measure impurity concentrations in the system after filling with each of the two gases; it was found that for both gas

VI-2

feed systems (the fill system and the pulsed gas system, see Fig. II-1) the residual nitrogen was a factor of two higher in D_2 than it was in H_2 . Rough estimates of the absolute nitrogen/deuterium concentration based on the gas analyzer measurements were of the order of 0.5%, in agreement with the concentration of nitrogen at burnout obtained spectroscopically. Since the purity of the H_2 gas claimed by the manufacturer was at least a factor of 10^2 better than that of the D_2 gas, the fact that the nitrogen increased only a factor of two was indicative that the condition of the gas feed lines may be important.

Note how the concentrations on the 4th (oxygen) and 5th (nitrogen) (the data analyzed in the previous section were taken on those dates) relate to normal Alcator impurity concentrations. They are certainly representative, although the oxygen concentration has at times been higher and the nitrogen concentration lower by factors of 3. This does not change Z_{eff} significantly.

Using the data plotted in Fig. VI-1, impurity concentration was studied for correlations with the plasma parameters; toroidal field, peak current, rate of current rise, and working gas. Aside from the previously mentioned nitrogen increase with deuterium, the only other correlation observed was with the rate

FIGURE VI-1 Long term behavior of the nitrogen and oxygen concentrations. The ordinate is the brightness of 0 VI - 1032 Å (N V - 1239 Å) line at burnout divided by the average electron density at that time; it is proportional to the number of emitters in the line-of-sight and therefore indicates the impurity concentration. The shape of the data point depends on the working gas(es) used in the discharge: • - H₂ fill and pulsed gas, ▲ - H₂ fill gas and D₂ pulsed gas, and + - D₂ fill and pulsed gas. Note that the nitrogen concentration increased when D₂ was the gas present at burnout. The arrows along the abscissa indicate the start of a run after a machine shut down longer than 24 hours.

of current rise; the slower the current (and therefore the temperature) rose, the smaller the value of brightness in the broader burnout peak. At the present time, it is not certain whether this represented an actual change in concentration or was due to the details of the burnout process.

The fact that no correlation with the other parameters was found does not mean that such a correlation did not exist, only that a more systematic study of the impurity concentration vs. plasma parameters may be required for its observation.

VII-1

VII. HEAVY IMPURITIES

In addition to oxygen, nitrogen and carbon, several metals were expected as significant impurities [26, 27, 3]. Alcator has a stainless steel wall and molybdenum limiter. As a result, the interaction between the hot plasma and the wall or the limiter may lead to introduction of these materials, and in fact, Mo, Fe, and Cr have been detected by the soft x-ray experiment. Mo was the most abundant [28].

All three metals had lines in the short wavelength part ($300 \text{ \AA} - 450 \text{ \AA}$) of the spectral region covered in the study [27, 29]. Although a search for the lines Mo XIII - $341 \text{ \AA}$, Mo XIV - $374 \text{ \AA}$, $424 \text{ \AA}$, Cr XIV - $390 \text{ \AA}$, $412 \text{ \AA}$ and Fe XVI - $335 \text{ \AA}$, $361 \text{ \AA}$ was carried out, only the three Mo lines were positively identified. Presumably the low metal concentrations led to weak emission which was masked by the presence of continua and weak unresolved lines. In addition, the introduction of the metals could be sporadic and uncontrollable both during the discharge (see the discussion of Mo XIV $423.5 \text{ \AA}$ below) and from shot to shot, in contrast to the light impurity emissions which varied smoothly in time and which were much more reproducible.

Of the three Mo lines observed, the Mo XIV $424 \text{ \AA}$ ($4s \text{ } ^2S_{1/2} \rightarrow 4p \text{ } ^2P_{1/2}$), shown in Fig. VII-1, was studied

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most extensively. There were two distinctive features in the molybdenum emission signal. Firstly, instead of one peak at the beginning of the discharge, there were usually four or five peaks at this time. Secondly, during the high density regime, ripples appeared in the signal.

Consider the early part of the discharge first. Fig. VII-2 shows that each peak of the Mo signal corresponded to a negative voltage spike and a small current spike, indicating an unstable plasma. These spikes occurred when the q -value at the limiter was an integer, indicating that an interaction between the plasma and the limiter may have caused the introduction of molybdenum into the system. For a 60 kG toroidal magnetic field q was calculated to be 6, 5, and 4 when I_p was 84 kA, 100 kA, and 125 kA respectively. Fig. VII-2 shows that the Mo spikes occurred when the current was 83, 99, and 127 kA. Thus, there was a correlation between the integral values of q at the limiter and the molybdenum signal peaks.

An estimate of the molybdenum flux during the first part of the discharge was complicated by the fact that the metal was introduced at discreet times into a well developed discharge after the observed oxygen burnout peaks. To make a simple estimate based on the model discussed in Section IV-A, the discreet bursts of flux

FIGURE VII-1(a) Observed Mo XIV-424 Å emission with plasma current (I_p) and average electron density ($\bar{n}_e$). Total current pulse length is 120 msec. The several spikes in the initial peak are unresolved.

FIGURE VII-1(b) Observed Mo XIV burnout with plasma current (note slight bumps indicating integral q at the limiter) and the loop voltage (V_l). The voltage signal is saturated for the initial 8 msec. Note voltage spike just before the last Mo peak (13.3 msec). Other unsaturated voltage signals show large spikes at each Mo peak.

were averaged over a period of time to give an effective constant flux. Between 1 and 8 msec the average brightness was $2.3 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$. (The brightness of the first peak was $8.0 \times 10^{14} \text{ cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$). The temperature at the center of the Mo XIV shell was roughly estimated using coronal equilibrium; for $T_e = 80 \text{ eV}$, $S \approx 10^{-11} \text{ cm}^3 \text{ sec}^{-1}$ and $Q \approx 3.0 \times 10^{-9} \text{ cm}^3 \text{ sec}^{-1}$ [30,31]. For a confinement time of $\tau_p \approx 2.7 \text{ msec}$ [22] the average concentration at 5 msec was $2 \times 10^9 \text{ cm}^{-3}$ and the contribution of molybdenum ionized to Mo XXXI to Z_{eff} at the center was at the most on the order of 0.05.

For the low density plateau regime, the brightness dropped to $6.2 \times 10^{12} \text{ ph cm}^{-2} \text{ sec}^{-1} \text{ ster}^{-1}$. The model of Section IV-A gave an incoming flux of $\Gamma \approx 1 \times 10^{11} \text{ cm}^{-2} \text{ sec}^{-1}$ implying that the concentration of molybdenum at 12 msec ($\tau_p \approx 2.7 \text{ msec}$) was $6 \times 10^8 \text{ cm}^{-3}$. The contribution of molybdenum to Z_{eff} at the center was 0.01.

During the high density part of the discharge, the signal showed a plateau qualitatively similar to the oxygen signal. The ripples in the signal may have been due to the plasma interaction with the wall or limiter. A qualitative comparison between the plasma in-out position monitor and the spectroscopic emission showed that the ripples appeared when the plasma column moved

VII-5

and did not appear when it was stationary. The brightness at the high density plateau was 6.0×10^{13} ph $\text{cm}^{-2}\text{sec}^{-1}\text{ster}^{-1}$ implying $\Gamma \cong 1 \times 10^{12} \text{cm}^{-2}\text{sec}^{-1}$ and $n_{oi} = 9 \times 10^9 \text{cm}^{-3}$ at 100 msec ($\tau_p = 40$ msec). The contribution to Z_{eff} at the center due to molybdenum was 0.02.

VIII-1

VIII. CONCLUSIONS

The major result of this study on the Alcator tokamak was identification of its major impurities and determination of the amounts in which they were present. The high purity implied by voltage-current measurements and soft x-ray studies has been verified. Measurements of impurity line emission have indicated that the total concentration of the light impurities, oxygen, nitrogen, and carbon was 0.24%, 0.07%, and 0.30% at central densities of $4.5 \times 10^{13} \text{ cm}^{-3}$ (burnout), $4.0 \times 10^{13} \text{ cm}^{-3}$ (low density plateau), and $6.0 \times 10^{14} \text{ cm}^{-3}$ (high density plateau) respectively. Including the estimated molybdenum densities, Z_{eff} at the center was 1.15, 1.04 and 1.16 at those times.

This study did not address the question of why the purity of Alcator was so high. A source of significant contamination in deuterium discharges was the impurity in the gas itself as it entered the discharge chamber. If impurity concentrations of a few parts per thousand are unacceptable, higher purity deuterium gas will have to be used.

The power loss due to line radiation from the lower ionization states of the impurities was found to be $\sim 7\%$ of the total ohmic input power at high

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densities and less than 1% at the low density plateau.

In obtaining the impurity densities in the low and high density phases, the entering impurity fluxes were first determined. The oxygen flux was found to increase by an order of magnitude when the electron density increased by a factor of 15. The process causing the incoming flux was postulated to be desorption of oxygen from the walls, and various mechanisms for the desorption were discussed. The most likely candidate was desorption by low energy, charge exchanged neutrals.

ACKNOWLEDGEMENTS

This work was supported by ERDA contracts EY-76-S-02-2711 and EX-76-A-01-2295.

The authors wish to acknowledge the scientific and technical staff of the Alcator tokamak, not only for their direct experimental aid in accomplishing this study but also for numerous illuminating discussions.

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