STUDIES OF IMPURITY BEHAVIOR IN TFTR

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ABSTRACT

Central medium- and low-Z impurity concentrations and Z_{eff} have been measured by x-ray spectrometry in Tokamak Fusion Test Reactor discharges during three periods of operation. These were the (1) start-up period, (2) ohmic heating, and (3) ohmic heating portion of the two neutral beam periods, distinguished mainly by different vacuum vessel internal hardware and increasing plasma current and toroidal field capability. Plasma parameters spanned minor radius $a = 0.41 - 0.83$ m, major radius $R = 2.1 - 3.1$ m, current $I_p = 0.25 - 2.0$ MA, line-averaged electron density $\bar{n}_e = 0.9 - 4.0 \times 10^{19} \text{ m}^{-3}$, and toroidal magnetic field $B_T = 1.8 - 4.0$ T. The metal impurities came mostly from the limiter. At low densities titanium or nickel approached 1% of n_e during operation on a TiC-coated graphite or Inconel limiter, respectively. Lower levels of Cr, Fe, and Ni ($< 0.1\%$) were observed with a graphite limiter at similarly low densities; these elements were removed mainly from stainless steel or Inconel hardware within the vacuum vessel during pulse discharge cleaning or plasma operation on an Inconel limiter and then deposited on the graphite limiter. Hardware closest to the graphite limiter contributed most to the deposits. Subsequent discharges slowly eroded

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the deposits from the limiter and reduced the metal impurity levels in the plasma. Both total low-Z and metal impurity concentrations, relative to n_e , decreased approximately exponentially with n_e and increased with I_p . The metals showed much larger variations than did low-Z elements, dropping to $5 \cdot 10^{-5} n_e$ at high density. Low-Z impurities, mainly carbon and oxygen, ranged from 10% of n_e at low n_e to 3% at high n_e and usually dominated Z_{eff} and power loss. In low density plasmas with a TiC-coated graphite or Inconel limiter, the respective metals contributed 30-50% of Z_{eff} and ~ 10 -20% of the central input power. The metal contributions to Z_{eff} and radiated power were much lower with the graphite limiter.

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INTRODUCTION

Information on the behavior of impurities in tokamaks is important for several reasons. Impurity radiation can be a major source of power loss in tokamaks and can induce or exacerbate instabilities (e.g., by altering current profiles) or otherwise detract from achieving favorable fusion plasma parameters.^{1,2} (e.g., by depletion of the fuel ion density). Certain impurities can also have beneficial effects, e.g., by cooling the plasma periphery and thereby reducing the production of more deleterious impurities,^{3,4} or by enhancing energy confinement,⁵ although the latter effect has not been observed in TFTR. The plasma-surface interactions and mechanisms of impurity release are of interest in the field of basic surface physics. Many of these effects have been discussed in detail previously.¹ Quantitative information and scaling with different plasma parameters and geometrical configurations should lead to improved models for predicting the behavior and control of impurities in fusion reactors. Experiments on the Tokamak Fusion Test Reactor (TFTR) have provided an opportunity to study intrinsic and artificially introduced impurities in a machine with near-reactor size and plasma parameters. This paper emphasizes the basic observations. More detailed analyses involving impurity production mechanisms and correlation of observations with theoretical models will be created in forthcoming publications.

Since December 1982, TFTR has experienced three major operational periods.⁶⁻⁸ These consisted of a start-up phase, an ohmic-heating (OH) phase, and a "2-neutral-beam" (2NB) phase. Between operational phases major changes have been made in hardware internal to the vacuum vessel.⁹⁻¹¹ These hardware changes have been accompanied by marked changes in intrinsic metal impurities in the plasma. In general, the plasma impurity reflects qualitatively and

quantitatively the chemical composition of internal hardware and the proximity of various components to the plasma.¹² The results presented in this paper involve the start-up period, the OH period, and mostly the ohmic-heating portion of the 2NB period. Only a few data points from neutral-beam-heated discharges are included to extend the results to higher electron density.

Soft x-ray spectrometry using the x-ray Pulse Height Analysis (PHA) diagnostic¹³ has been used to document quantitatively the changes in metal and low-Z impurities in the center of TFTR as a function of plasma parameters, limiter configuration, limiter material, and other hardware components protruding from the vacuum vessel. Also correlations have been made between the impurity levels and the number of the high power discharges since pulse discharge cleaning.⁹ The values of Z_{eff} calculated from the impurity content have been compared with values inferred from the visible bremsstrahlung brightness.

In section I the internal vacuum vessel hardware for different operational phases of TFTR is reviewed briefly. Section II outlines the experimental technique. The main experimental observations are presented in sections III-V. Sections VI and VII finish with a discussion of uncertainties and a summary of observed results.

I. TFTR INTERNAL VACUUM VESSEL HARDWARE

The time periods encompassed by the present measurements are (1) start-up phase, April - July 1983, (2) OH phase, October 1983 - January 1984, and (3) ohmic-heating portion of the 2NB phase, June - December 1984.

During the start-up phase the limiter consisted of upper and lower graphite plates and inner and outer graphite plates supported at one toroidal location by stainless steel bars.⁶ An additional graphite limiter supported

by stainless steel bars was installed inboard of the plasma at a location displaced 180 degrees toroidally from the main limiter to protect the thin Inconel vacuum vessel bellows sections from plasmas collapsing on the inner wall. The vacuum vessel itself is stainless steel. The total projected surface area in view of the plasma is approximately 120 m^2 , of which ~ 82% was stainless steel and ~ 18% was Inconel during the start-up phase. For the OH and 2NB phases, a preliminary inner bumper limiter was installed, consisting of rows of Inconel X750 slats covering the bellows sections for $\pm 60^\circ$ measured poloidally from the horizontal midplane at the inside of the torus.¹⁰ In addition, Inconel slats were installed at $\pm 30^\circ$ over the bellows at the large major radius side, and arrays of ZrAl bulk getter surface pumping panels were installed near the vacuum vessel wall. For these phases the fraction of Inconel surface area exposed to the plasma was increased to 30%. The Inconel bellows cover plates are, in addition, ~ 12 cm closer to the plasma than are the Inconel bellows. The fixed graphite limiter of the start-up phase was replaced by a limiter consisting of an upper and a lower movable blade and an outboard vertical movable blade at one toroidal location. The blades were covered by graphite tiles which, for the OH phase, were coated with an approximately 20- μm -thick layer of titanium carbide (TiC). This TiC coating was chemically removed between the OH phase and the 2NB run because of severe damage to the coating and associated problems with intense bursts of radiation due to titanium-carbide flakes entering the plasma.

II. EXPERIMENTAL TECHNIQUE

For the measurement of impurity concentrations soft x-ray spectrometry with the x-ray PHA diagnostic was used.¹³ The instrument views the central chord of TFTR horizontally and generates spectra such as those graphed in Fig. 1.

1. Metal impurity concentrations are inferred from the $K\alpha$ line intensities using excitation rates averaged over a coronal equilibrium distribution of emitting charge states. Low-Z impurity concentrations are calculated from the residual enhancement of the continuum portion of the spectrum (relative to pure hydrogen bremsstrahlung), after subtraction of the enhancement contributed by the known metal concentrations. Total Z_{eff} is then the sum of contributions from the fuel ions and the impurities. The PHA instrument and the analysis technique have been described in detail elsewhere.¹³⁻¹⁵ Variations in electron density and temperature across the PHA line of sight were accounted for by a chordal integration of the expression for the bremsstrahlung spectrum and the impurity $K\alpha$ emission rate, using analytic approximations to the $n_e(r)$ and $T_e(r)$ profile shapes taken from the Thomson scattering diagnostic. Values of Z_{eff} calculated from the PHA impurity concentrations were compared with those measured from visible bremsstrahlung. Line emission intensities from vacuum ultraviolet spectroscopic measurements verified the general trends in metal impurity concentration and roughly confirmed the assumption of relative carbon-to-oxygen concentration used for the PHA analysis. Variations in PHA metal content were correlated with bolometric measurements of central radiated power.

III. QUALITATIVE OVERVIEW OF EXPERIMENTAL OBSERVATIONS

The variation of metals in the plasma with hardware internal to the vacuum vessel is illustrated in Fig. 1. Figures 1(a), 1(b), and 1(c) were measured during the start-up, OH, and 2NB phases, respectively. The measured chromium (Cr), iron (Fe), and nickel (Ni) ratios during the start-up phase approximate the ratios found in stainless steel (SS), ~ 18:70:10%. During the OH and 2NB phases the Cr:Fe:Ni ratios are closer to those expected for Inconel ~ 17:7:73%. Although the Fe and Ni lines in Fig. 1(b) are much weaker than those in Fig. 1(c), the Cr:Fe:Ni ratios are similar. The higher intensities and concentrations in Fig. 1(c) compared with Fig. 1(b) are due partly to the lower electron density and partly to operation of the plasma directly on the Inconel preliminary bumper limiter. The plasma was more typically operated against the movable graphite limiter during the 2NB phase (1c), in which case the metal lines were weaker. In Fig. 1(c) the Ti K α peak remaining after removal of the TiC layer from the limiter is presumably due to either the 2% Ti in Inconel, or residual titanium from the TiC coating used in the OH phase. The strong Ti K α line in Fig. 1(b) is due to operation of the plasma against the TiC - coated limiter. The Cr K α line in this figure is overwhelmed by the intense, broad, blended Ti K β and K γ peaks. The same spectral features show up in Fig. 1(c) for Ni.

The central Fe concentration relative to line-averaged electron density $\bar{n}_e$ was higher during the start-up phase than during the 2NB phase. This is illustrated in Fig. 2 $\bar{n}_e$ for discharges with a major radius $R = 2.50 - 2.55$ m and minor radius $a = 0.68 - 0.69$ m. The top curve was measured during the start-up phase and the lower two curves during the 2NB phase. The decrease in the magnitude of the slope of these curves with increasing plasma current agrees with the behavior of Ti and Ni shown in later figures. The reason for

this behavior is not understood. The two OH curves for the 2NB phase can be roughly extrapolated down to $I_p = 0.8$ MA; the resulting curve would be a factor of approximately 10 lower than the $I_p = 0.8$ MA curve for the start-up phase. The higher Fe concentration during start-up has several explanations, each of which probably contributes.

To explain these possibilities we must first make some general remarks about how the impurities get into the plasma. It can be presumed from previous experience with tokamaks that during glow and pulse discharge cleaning, as well as during tokamak discharges, metals are removed from the vacuum vessel and other structures and redeposited on all surfaces, including the (graphite) limiter. The plasma then dislodges metal particles from the limiter through sputtering by charge-exchange neutrals or ions, evaporation, or unipolar arcs.¹ Thus the impurity concentration in the plasma depends on the amount of that metal previously deposited on the limiter. The inference of higher Fe concentration on the limiter in start-up plasmas than in 2NB plasmas is consistent with the fact that during start-up (1) an auxiliary limiter consisting of graphite plates supported by stainless steel (72% Fe) bars existed a few centimeters from the plasma edge and that (2) a larger area of the stainless steel vacuum vessel wall was in view of the plasma. Indeed, it was observed from the spatial distribution of hard x-ray emission around the machine that runaway electrons frequently struck the auxiliary limiter. It is possible that the runaway electrons caused melting and sputtering of the stainless steel bars, and that traces of this metal entered the discharge and were deposited around the machine and onto the main limiter. A complication is that the metal impurity concentration in the plasma depends on the degree of conditioning of the limiter. By conditioning we mean a gradual erosion of metal particles from the limiter during normal plasma operation. This effect,

which will be demonstrated later for Ni, can also cause a factor of 2-20 variation in observed concentration for similar discharges.

Oxygen was assumed to be the dominant low-Z impurity during the start-up phase of operation, although no calibrated spectrometer was operable to confirm that carbon was present in smaller quantities. The central concentration of oxygen for discharges with $R = 2.5$ m, $a = 0.68$ m, and $I_p = 0.6$ or 0.8 MA was inferred from the PHA to be between 3 and 4% of n_e , and Z_{eff} ranged from 3 to 4. These parameters showed no clear trend with either n_e or I_p .

IV. THE OH PHASE OF OPERATION

Titanium was the dominant metallic impurity during the OH phase. The scaling of central relative titanium concentration for operation on the TiC-coated graphite limiter is summarized in Figs. 3 and 4. In Fig. 3 we see that the Ti concentration was high, approaching 1% at low density and high current, keeping minor radius $a = 0.83$ m, the major radius $R = 2.5$ m, and the toroidal magnetic field $B_T = 2.7$ T fixed. The concentration increased sharply with current I_p at fixed density n_e , and decreased markedly with n_e for fixed current. At the lowest densities the Ti could account for half of the central Z_{eff} , and could radiate up to 20 kW/m^3 , or approximately 10-20% of the input OH power. However, at the higher values of n_e both the Z_{eff} and radiated power contribution from Ti were negligible.

Figure 4 illustrates the dependence of the central titanium relative concentration on the electron density for four different minor radii a at fixed R and fixed safety factor q_a at the limiter. The safety factor is given by

$$q_a = 5 \frac{B_T a^2}{I_p R}$$

where B_T is in Teslas, a and R in meters, and I_p in MA. Except for the case with a very small minor radius ($a = 0.41$ m), the concentrations are relatively similar, suggesting that q_a may be a fundamental parameter on which the metal concentration depends. The $a = 0.41$ m discharges were observed to be poorly behaved and hard to control, with oscillations in n_e and poor confinement, so the more radical departure of Ti concentration for $a = 0.41$ m from the other curves in Fig. 4 should not be so surprising.

A comparison of the low-Z impurities and the metals Ti and Ni for the OH (open points and dashed lines) and 2NB phases (solid points and lines) is shown in Fig. 5. The 2NB phase will be discussed later. The metal concentrations exhibit the usual sharp exponential decrease with density, while the low-Z impurity concentration decreases more modestly, from 7 to 4%. It is evident from Fig. 5 that the TiC coating was not beneficial for impurity control. The low-Z impurity content remained the same with or without the coating. Nickel was only insignificantly lower with TiC, while titanium increased tremendously in the plasma.

Both the low-Z impurities and the metals contribute to the Z_{eff} of the plasma. The dependence of Z_{eff} on $\bar{n}_e$ during the OH phase is illustrated in Fig. 6(a). Figures 6(b) and 6(c) are data from the 2NB phase, which will be discussed in the next section. The curves vary slowly with $\bar{n}_e$ at high density ($\bar{n}_e \geq 3$) because, here, Z_{eff} is due predominately to the low-Z impurities. The sharp increase of Z_{eff} at low densities is due to the metals, mostly Ti, which can contribute up to approximately 50% of total Z_{eff} in this region. The PHA measurements (solid curve) are obtained by adding the Z_{eff} contributions of all the constituent ions. The dashed Z_{eff} curve was measured

by another diagnostic which utilized the bremsstrahlung in the visible wavelength range (VB). The difference between the two curves represents uncertainties in both measurements. However, because of instrumental complexity and assumptions required for measuring low-Z impurity concentrations with the PHA, particularly for discharges with high metal concentration, the visible bremsstrahlung measurement of Z_{eff} probably has a smaller degree of uncertainty.

The results discussed previously for the OH phase pertained to plasmas operated against the TiC-coated graphite movable limiter. Additional (adiabatic compression) experiments were done in which the plasma was established on the movable limiter and then quickly moved radially inward away from the movable limiter to the Inconel preliminary bumper limiter. About 150 ms after the plasma contacted the Inconel limiter the central Ti concentration had dropped a factor of 2, and Ni concentration had increased typically by a factor of 4 even though the electron density was ~ 40% higher. After a day of this type of operation, the amount of Ni on the movable limiter was significantly increased, and additional cleanup shots were required to reduce the nickel in standard operation to previous levels.

In summary, during the OH phase the total concentration of Cr, Fe, and Ni was about the same as during start-up, but Ni replaced Fe as the dominant species of the three. The Ti concentration was typically ten times higher than that of Ni and displayed a strong dependence on both electron density and plasma current. Z_{eff} ranged from 5-7 at the low density range, with about 50% due to Ti and the remainder due to C and O. Z_{eff} was about 2.5-3 at the highest attainable density, where the metal concentration was negligible.

Although the Ti concentration and its contribution to Z_{eff} could be high at low n_e during the OH phase, the plasmas were reasonably well behaved and had good confinement. At $\bar{n}_e = 3 \times 10^{19} \text{ m}^{-3}$, the global energy confinement time was about 0.3 sec. However, because of nonuniform and poor adhesion of the TiC layer to the limiter, TiC particles occasionally entered into the plasma and created large bursts of radiation and poor plasma behavior. Thus the TiC-coated graphite tiles were removed, and the TiC coating was chemically etched away before the tiles were replaced for the 2NF phase of operation.

V. THE β_2 -NEUTRAL-BEAM PHASE OF OPERATION

Removal of the TiC coating from the graphite limiter resulted in a sharp decrease in central Ti concentration as shown in Fig. 5 (solid curve vs dashed curve). This large decrease, a factor of approximately 50, was observed uniformly for all types of plasma operation, $a = 0.41 - 0.83 \text{ m}$, and $I_p = 0.7 - 1.4 \text{ MA}$ for $a = 0.83 \text{ m}$. The remaining titanium in the plasma is presumed to be due to either the 2% titanium in the Inconel preliminary bumper limiter or residual titanium left in the vacuum vessel or on the limiter. The solid curve and points in Fig. 5 for the carbon plus oxygen concentration indicate that removal of the TiC coating did not change the low-Z impurity content.

After removal of the TiC layer from the limiter, the Z_{eff} encountered at low densities was markedly smaller, as illustrated by Figs. 6(a) and 6(b). The metal contribution to Z_{eff} was 15-20% or less at the lowest densities compared to approximately 50% with the TiC. Comparison of Figs. 6(b) and 6(c) illustrates that Z_{eff} depends on current, i.e., is lower for $I_p = 1.0 \text{ MA}$ than for $I_p = 1.4 \text{ MA}$ at the same $\bar{n}_e$. Attendant with removal of the TiC coating, the total radiated power profile shifted toward larger minor radius and dropped by approximately 30% for $I_p = 1.4 \text{ MA}$, $a = 0.83 \text{ m}$.

A very important parameter for the impurity content is the machine conditioning. As discussed earlier, metal is evidently evaporated and/or sputtered from the Inconel and SS hardware within the vacuum vessel during glow or pulse discharge cleaning and deposited on the graphite limiter and elsewhere. This metal deposit is slowly eroded from the limiter by the "high power" or normal tokamak discharges, and the amount available to inject metals into a discharge decreases with time. Thus both metal impurity concentration and Z_{eff} (especially at low $\bar{n}_e$) decreases with time during high power operation. The variation in central Ni concentration in the plasma with machine conditioning is illustrated in Fig. 7. The dashed curves were measured during the OH phase and the solid curves during the 2NB phase. The upper dashed curve was measured nine days after pulse discharge cleaning (PDC), whereas the lower dashed curve was measured after operating the machine for 65 days since the last PDC discharges. The number of days since the last PDC period is marked in Fig. 7. A similar behavior is exhibited by the solid curves measured during the 2NB phase. It is evident that the Ni concentration is higher immediately after PDC, and decreases slowly when the machine is conditioned, or regular tokamak discharges are fired. In fact, the nickel concentration for $\bar{n}_e = 2 \times 10^{19} \text{ m}^{-3}$ can be described to within $\pm 30\%$ by

$$\frac{n_{\text{Ni}}}{n_e} (\bar{n}_e = 2 \times 10^{19} \text{ m}^{-3}) = 1.22 \times 10^{-3} N^{-0.6},$$

where N is the number of tokamak discharges since the last day of PDC or since the last day of plasma operation on the Inconel limiter. Of particular interest are the curves marked 8/2/84 and 6/8/84. The first curve (8/2/84) was measured the first day after PDC. As the discharges proceeded during the day from low n_e to higher n_e , cleanup of the Ni from the limiter resulted in a

more steeply sloped curve than usual. The curve marked 6/8/84 also proceeded in increasing $\bar{n}_e$ steps during the day from $\bar{n}_e = 1$ to $2.5 \times 10^{19} \text{ m}^{-3}$. Then $\bar{n}_e$ was reduced to $2.1 \times 10^{19} \text{ m}^{-3}$ for a "cleanup" shot, and the resulting n_{Ni}/n_e value was 50% lower than previously. As $\bar{n}_e$ was then increased to $2.5 \times 10^{19} \text{ m}^{-3}$, a curve with the same slope but at a lower level ensued. Of course neither the number of days nor the number of discharges since PDC is strictly the appropriate parameter to characterize the rate of limiter cleaning or conditioning. This is because the discharges vary in I_p and n_e , and it is evident that the metal content of the plasma and, hence, to some extent the rate of erosion of the metal from the limiter can vary with I_p and n_e .

Figures 8-10 illustrate the variation of the relative Ni concentration, the low-Z impurity content, and the PHA Z_{eff} with density and plasma current. The vertical error bars represent the scattering of several averaged data points. The horizontal bars represent the width of the averaging intervals. In general, all three quantities, n_{Ni}/n_e , $(n_0 + n_C)/n_e$, and Z_{eff} increase monotonically with I_p at a given $\bar{n}_e$. Relatively few data points exist at $I_p = 0.7 \text{ MA}$. Also for $I_p = 1.4 \text{ MA}$ relatively few data points were available for discharges with a well-conditioned limiter, and data from discharges with high Ni concentration (soon after PDC) were included in the average to complete the $\bar{n}_e$ scan. Thus the Ni concentration and Z_{eff} values at the $\bar{n}_e = 1.8 \times 10^{19} \text{ m}^{-3}$ point are abnormally high. For the $I_p = 1.8 \text{ MA}$ data in Fig. 8, the limiter conditioning was evidently better than for the 1.4 MA curve. The data seem abnormally low in the density range $\bar{n}_e = 2.3 - 2.5 \times 10^{19} \text{ m}^{-3}$.

VI. DISCUSSION

The uncertainties in the measurement of central metal concentration by the PHA arise from several factors. First, the x-ray rate coefficients for determining the medium-Z impurity concentration from the measured line intensities are good only to within a factor 2. The x-ray peaks are averaged out by the approximately 220 eV resolution of the detectors and comprise several lines from different charge states. Coronal equilibrium is used to predict the charge-state distribution assumed in calculating the average excitation cross sections. Fortunately, at the electron temperatures relevant to the present measurements ($T_{eo} = 1.5 - 3.5$ keV), the metal ions exist mostly in helium-like and lithium-like states, as determined by high resolution x-ray crystal spectrometry. These states do not differ greatly from the predictions of coronal equilibrium in the center of TFTR for ohmic discharges. Also, the theoretical cross sections are easier to calculate for these simple ions. However, detailed excitation rate calculations have been done only for Fe and, partially, for Ti. Rates for Cr and Ni have been interpolated from the Fe and Ti rates, and consequently, have larger uncertainties. It would be useful to the fusion research diagnosticians to have a thorough review of the existing rates and the best techniques for calculating them, followed by revised, improved calculations (including noncoronal distributions resulting from diffusion and charge exchange with deuterium neutrals) for all the relevant metals, Ti, Cr, Fe, and Ni.

Another uncertainty arises from the lack of multiple chordal views of the plasma. Fortunately, at these temperatures, the metal x-ray lines are weighted strongly toward the hotter, central region of the plasma. The technique for interpreting the measured line intensities is to compare them with simulated line-of-sight intensities predicted by a model which used the

theoretical T_e -dependent excitation rates. The impurity concentration is assumed to be proportional to n_e , which is probably good over the hot central region. Profile shapes for T_e and n_e are taken from the laser Thomson scattering diagnostic or other diagnostics. However, for the present, a constant profile shape is assumed throughout the discharge with $T_e(0)$ taken from the PHA and $\bar{n}_e$ taken from interferometry, so time dependent T_e or n_e profile shape changes will introduce errors. Since concentration relates to n_{eo}^2 , where n_{eo} is the central electron density, an incorrect n_{eo} value in the model will affect the results accordingly. All of the uncertainties together, including the instrumental absolute throughout calibration, combine to yield a global uncertainty of a factor of 2-3 in the metal-fraction determination.

Measurement of low-Z impurity concentrations is further complicated by an incomplete knowledge of the relative concentration of C and O. Since one cannot infer from the continuum enhancement which low-Z ions are contributing, assumptions must be made or information from other diagnostics must be used. As suggested by ultraviolet spectroscopy, C and O in a 2:1 ratio were assumed to be the low-Z impurities for the OH and 2NB phases. In addition, because of spectral statistics, an accurate measurement of the enhancement factor ϵ of the x-ray continuum spectrum is difficult.^{14,15} Adding to the complication is the fact that the continuum enhancement contributions from the measured metal fractions must be subtracted from the total ϵ . Thus uncertainties in the metal fraction add more uncertainty to the low-Z concentrations especially at low n_e where ϵ due to metals can be a significant part of total ϵ . This effect is illustrated by the error bars on C + O in Fig. 5, which derive from an assumed factor of three uncertainty in the metal concentrations. Altogether, the uncertainty in total low-Z impurity concentration can range from 2 to a factor as large as 4.

Although uncertainties in absolute impurity concentration can be relatively large, relative changes in concentration for different plasma conditions are more accurate. Also, it is believed that the absolute determinations are better than the quoted uncertainties would suggest, because the calculated values of Z_{eff} agree quite well with those measured from the visible bremsstrahlung and with Z_{eff} values deduced from neoclassical resistivity. Most discrepancies between the PHA and the visible bremsstrahlung diagnostics in the past have been traced to either incorrect n_e or T_e profiles or to shifts in throughput of either diagnostic due, e.g., to PHA aperture misalignment or darkening of the VB window from metal deposits. A further testament to the accuracy of the PHA absolute measurements is the good agreement at very low density between ζ measured from the continuum and the ζ deduced from the metal $K\alpha$ measurements. At very low density ζ is due mainly to metal impurities, and the two ζ determinations are usually consistent to about 30%.

VII. CONCLUSIONS

The metal impurities in the center of TFTR discharges come predominately from the limiter. In addition to those metals which are part of the limiter's construction, metals from other hardware within the vacuum vessel are deposited on the limiter during pulse discharge cleaning or during normal plasma discharges against, e.g., the Inconel preliminary bumper limiter. The deposited metals are slowly cleaned off the limiter during normal tokamak operation. These facts are supported by (1) metals (Cr, Fe, Ni) characteristic of the stainless steel or Inconel components inside the vacuum vessel appearing in the plasma when the plasma is operated on a graphite limiter or a TiC-coated graphite limiter; (2) much higher levels of deposited

metals immediately after pulse discharge cleaning and after operation against the Inconel bumper limiter; (3) progressive reduction of these deposited metals with normal plasma operation; (4) very high concentrations of titanium during operation on the TiC-coated graphite limiter or of Cr, Fe, and Ni during operation on an Inconel limiter; and (5) similar levels of metals over a range of plasma minor radii and currents when q is kept fixed.

The closer a metal object is to the plasma, the more easily its material is deposited on the limiter. This is documented by the stainless-steel-like mix of impurities in the plasma when the metal in view of the plasma was the predominately stainless steel wall, and an Inconel-like mix when Inconel plates were installed over part of the wall but 12 cm closer to the plasma.

The titanium-carbide coating on the graphite limiter was not beneficial from the point of view of impurities. It neither reduced the total low-Z impurity levels in the plasma nor changed the nickel concentration, but did introduce considerable titanium and produced flakes of TiC and intense radiation bursts.

The impurities, expressed as a fraction of electron density, decrease approximately exponentially with increasing density and increase with plasma current. The rate of decrease of metals with density is much larger than that of the low-Z components. This decrease is faster than a n_e^{-1} dilution effect.

The Z_{eff} and power loss are usually dominated by low-Z impurities. The metals become significant only (a) at low density and (b) when the plasma is operated on a limiter containing high metal concentration, such as an Inconel surface or a TiC coating.

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REFERENCES

- ¹G.M. McCracken, P.E. Stott, Nucl. Fusion 19, 889 (1979).
- ²K.W. Hill, M. Bitter, D. Eames, S. von Goeler, M.A. Goldman, N.R. Sauthoff, and E. Silver, Princeton Plasma Physics Laboratory Report No. PPPL-1887, 1982; in Low Energy X-Ray Diagnostics 1981, AIP Conference Proceedings No. 75, Edited by D.T. Attwood and B.L. Henke (American Institute of Physics, New York, 1981) p. 8.
- ³S. Suckewer, E. Hinnov, D. Hwang, J.F. Schivell, G.L. Schmidt, K. Bol, N.L. Bretz, P.L. Colestock, D. Dimock, H.P. Eubank, R.J. Goldston, R.J. Hawryluk, J.C. Hosea, H. Hsuan, D.W. Johnson, E.B. Meservey, and D.H. McNeill, Nucl. Fusion 21, 981 (1981).
- ⁴C. De Michelis and M. Mattioli, Rep. Prog. Phys. 47, 1233, (1984).
- ⁵E.B. Meservey et al., Nucl. Fusion 24, 3 (1984); M. Murakami et al., Tenth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, London, U.K., 12-19 Sept. 1984.
- ⁶K.M. Young et al., in Plasma Physics and Controlled Fusion, Proc. Int. Conf. Aachen, 1983 (Institute of Physics and Pergamon Press, Oxford, 1984), Vol. 26, p. 11.
- ⁷P.C. Efthimion et al., Phys. Rev. Lett. 52, 1492 (1984).

- ⁸R.J. Hawryluk et al., in Proceedings of the 4th International Symposium on Heating in Toroidal Plasmas, Rome, Edited by H. Knoepfel and E. Sindoni, Vol. II, 1012 (March 1984).
- ⁹H.F. Dylla, W.R. Blanchard, R.J. Hawryluk, K.W. Hill, R.B. Krawchuk, D. Mueller, D.K. Owens, A.T. Ramsey, S. Sesnic, and F.H. Tenney, J. Nucl. Mater. 128 and 129, 851 (1984).
- ¹⁰J.L. Cecchi et al., Ibid., 1.
- ¹¹M. Ulrickson et al., in Proceedings of the First International Conference on Fusion Reactor Materials, Tokyo, (December, 1984); to be published in J. Nucl. Mater.
- ¹²K.W. Hill, M. Bitter, M. Diesso, S. von Goeler, A.T. Ramsey, N.R. Sauthoff, J.F. Schivell, S. Sesnic, and F.H. Tenney, Bull. Am. Phys. Soc. 29, 1303 (1984).
- ¹³K.W. Hill, M. Bitter, M. Diesso, L.E. Dudek, S. von Goeler, S. Hayes, L.C. Johnson, G. Renda, S. Sesnic, N.R. Sauthoff, F.H. Tenney, and K.M. Young, Rev. Sci. Instrum. 56, 840 (1985).
- ¹⁴S. von Goeler, Diagnostics for Fusion Experiments (Pergamon, New York, 1979).
- ¹⁵E.H. Silver, M. Bitter, K. Brau, D. Eames, A. Greenberger, K.W. Hill, D.M. Meade, W. Roney, N.R. Sauthoff, and S. von Goeler, Rev. Sci. Instrum. 53, 1198 (1982).

FIGURE CAPTIONS

Fig. 1 Soft x-ray spectra from TFTR measured during the three different operational phases (a) start-up phase, (b) ohmic-heating phase and (c) 2-neutral-beam phase. The impurity lines illustrate qualitatively the change in dominant metal impurities as the limiter and intra-vacuum-vessel hardware was changed.

Fig. 2 Dependence of relative iron (Fe) concentration (iron density divided by electron density) in the center of TFTR plasmas on line-averaged electron density for different plasma currents and limiter/intra-vacuum-vessel material. The top curve was measured during the start-up phase, the lower curves during the 2NB phase.

Fig. 3 Density dependence of central relative titanium (Ti) concentration for different values of plasma current with the plasma operated on the TiC-coated graphite limiter. Other parameters are $R = 2.5$ m, $a = 0.83$ m, and $B_T = 2.7$ T.

Fig. 4 Density dependence of central relative titanium concentration for different minor radii with safety factor q approximately constant.

Fig. 5 Density dependence of relative concentration of low-Z impurities and metal impurities in the center of TFTR plasmas for operation with (OH phase) and without (2NB phase) TiC coating on the graphite movable limiter blades. The error bars represent an assumed factor of 3 uncertainty in determination of the metal fractions.

Fig. 6 Density dependence of Z_{eff} as measured by the x-ray pulse height analyzer (PHA) and from the visible bremsstrahlung (VB) intensity. (a) With TiC coating on limiter and $I_p = 1.4$ MA; (b) Without TiC coating, $I_p = 1.4$ MA; (c) Without TiC, $I_p = 1$ MA.

Fig. 7 Density dependence of central Ni relative concentration for different degrees of conditioning of the graphite or TiC-coated graphite limiter. The Ni concentration at fixed n_e decreased with the number N of shots since pulse discharge cleaning (PDC) as $N^{-0.6}$.

Fig. 8 Density dependence of central Ni concentration for four different plasma currents. Each point is an average of several measurements. The error bars indicate the scatter in these measurements.

Fig. 9 Density dependence of central low-Z impurity concentration for different plasma currents. The impurities were assumed to be C and O in a 2:1 proportion. The error bars represent the scatter in several measurements.

Fig. 10 Density dependence of Z_{eff} as measured by the PHA for different plasma currents.

Fig. 1

#85X0134

Fig. 2

Fig. 3

#85X0125

Fig. 4

Fig. 5

Fig. 6

Fig. 7

Fig. 8

LOW-Z DENSITY/ELECTRON DENSITY

Fig. 9

#85X0130

Fig. 10

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