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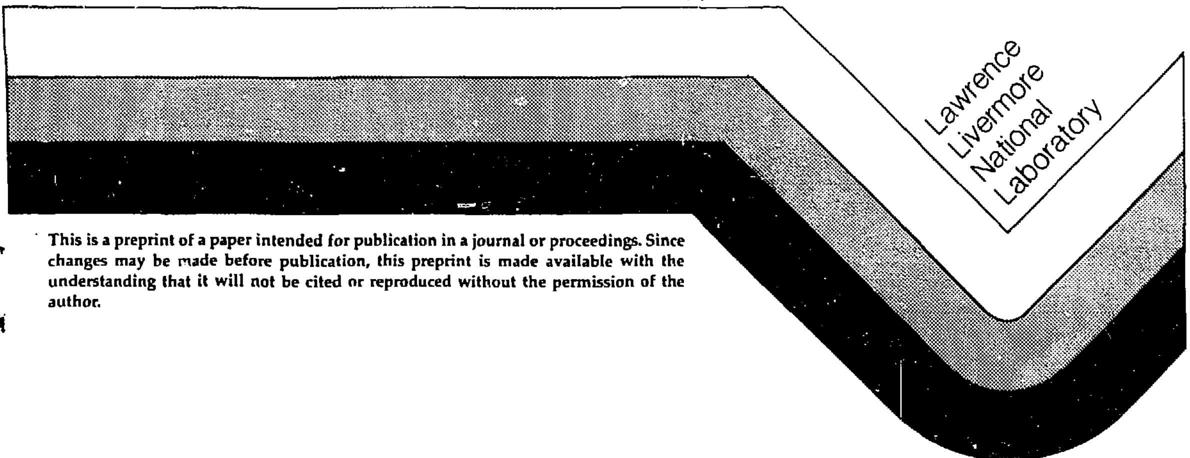

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NEUTRAL BEAM INJECTOR OXYGEN IMPURITY MEASUREMENTS AND CONCENTRATION REDUCTION VIA GETTERING PROCESSES

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ABSTRACT

We have measured the reduction of oxygen impurity levels by means of gettering within the arc chambers of the TMX-U neutral-beam injectors using the TMX-U neutral-beam test stand. Our analysis incorporated silicon surface-probe measurements and optical Doppler-shift measurements of the hydrogen alpha spectra of deuterium atoms with energies appropriate for D_2O parentage. Without gettering, the Auger electron spectroscopy analysis of an exposed silicon sample showed a large oxygen peak below the surface peak with a concentration equivalence of approximately 2% for an accelerated beam. After gettering, with either titanium or chromium getters, optical monochromator data indicated a reduction in the oxygen concentration of at least a factor of 10 whereas Auger spectroscopy data showed at least a factor-of-eight reduction. Other metallic impurities remained below the level of detection even after gettering. Additional effects observed during this study include a change in

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the accelerated deuterium species concentrations, loss of gettering activity, loss of arc operation, and a change in arc performance due to arc chamber gas absorption during operation.

PURPOSE

Neutral beam injector systems are used for heating the magnetically confined fusion plasmas in tokamaks and mirror machines. In these systems hydrogen (H) or deuterium (D) gas is the source of ions to be accelerated through a large negative potential. These ions pass through a region of cold gas and are neutralized by charge exchange before entering the experimental region as a neutral particle beam. One consequence of starting with an ionized gas arc chamber is the acceleration of oxygen (O) along with the desired beam particles. The O content in injectors of this type is generally around 2 to 3% and is the largest impurity component. Trapping of beam-injected impurities can cause undesirably enhanced scattering and trapping of ions in the thermal barrier region.

The idea of using titanium (Ti) metal film evaporated onto the inside of an arc chamber as a getter for O has been discussed previously.[1] This idea formed the basis for our deciding to investigate gettering as a means to reduce the O content in the injectors used on the Tandem Mirror Experiment-Upgrade (TMX-U) at Lawrence Livermore National Laboratory (LLNL). Specifically, the getter is intended to serve as a covering material to prevent O from being liberated from the walls during operation. Our test method, results, and analysis are discussed in this paper.

EXPERIMENTAL MODEL

Sources of arc plasma contamination include oxides on the arc chamber wall, O diffusing from the interior of the walls, arc chamber vacuum seal leaks, and O_2 in the larger vacuum system into which the beam is injected.

Oxygen from the surfaces of the walls of the arc chamber is removed fairly rapidly during neutral beam injector operation and after tens of shots the O concentration drops to approximately 2% of the extracted beam current. Very low concentrations are achievable following large numbers (thousands) of shots or long pulses. However, conditioning an injector assembly for long times on the main experimental apparatus is not feasible. We operate 24 injector systems on TMX-U with about 10 spare injector assemblies. Newly installed injectors need to be fired many times to reduce O concentration. Assemblies are replaced as they fail so it is highly probable that at least one injector would be accelerating large concentrations of O into the target plasma were it not for the fact that the injectors can be gettered.

A gettered injector has trapped much of the O, bringing the concentration far below the value it would have even after many shots on the conventional system. Because gettering buries any O on the walls and absorbs free O in the arc chamber, newly installed assemblies can be prevented from injecting large quantities of O. As the getter layer becomes saturated, it can be re-covered by evaporating a new layer of the metal film.

The TMX-U neutral beam test stand (Fig. 1) was used in our experiment for the operation of the injectors and the acquisition of necessary data. The test stand is normally used for the characterization and the conditioning of injector assemblies. Silicon (Si) targets were provided by Sandia Laboratories (Livermore) to estimate the impurity levels as a function of depth by Auger spectroscopy analysis.

The T_i gettering film is deposited by heating a titanium-tantalum (Ti-Ta) alloy wire (strung around the periphery of the arc chamber) to incandescence. Each cycle deposits 1 to 2 Å of Ti. The evaporated metal film covers all metal surfaces but not the insulating regions because of shadowing. The presence of Ti on these surfaces was not considered to be a problem because the arc chamber filaments evaporate tungsten (W) as a result of their normal operation onto the same surfaces.

Chromium (Cr) was flame sprayed to deposit a very thick surface layer on the Ti-Ta wire. It was heated to incandescence so the evaportion rate is thought to be approximately the same as that for Ti. The actual Cr thickness was not measured however.

OBSERVATIONS

Optical spectroscopy showed that the O component related to D_2O was reduced from about 2% before to approximately 0.2% or less after a gettering film had been deposited. Figures 2(a) and 2(b) show the optical spectra for hydrogen alpha transitions before and after gettering. The accelerated beam had a 16-kV peak voltage component and a power supply current of about 45 A for 75 ms. The gettering became less effective on successive shots. The trend toward the non-gettered state is shown in Fig. 3(a) and 3(b) for Ti and chromium (Cr) gettering, respectively.

The effect on the accelerated ion concentration is significant. When Ti film is used, the full- (D^+) and half-energy (D_2^+) components increase at the expense of the third-energy (D_3^+) and impurity (D_2O^+) components, thereby increasing the mean velocity of the ion beam. Chromium causes the third-energy component to be enhanced with respect to the full-energy component

and reduces the percentage of the higher speed components. In addition, the arc density varies as a function of time during a shot due to enhanced arc chamber pressure changes caused by the presence of a gettering film. The arc density also varies shot-to-shot as the Ti-film becomes saturated with deuterium.

We found that for experimental operations, a getter-film deposition every fourth shot would be adequate for TMX-U. Increased deposition frequency could be implemented when studying the effects of impurities on the plasmas. A regular cycle (i.e., after every fourth beam shot) of gettering stabilizes the operation of the injector during experimentation because it limits the variation in the effect of gettering on arc chamber performance . Thus, short regular getter cycles would aid in minimizing the variation from one shot to the next.

Figures 4(a) and 4(b) are photographs of the power supply waveforms before and after gettering with Ti. The parameter n_i provides a measure of the arc chamber ion-saturation current as detected by a Langmuir probe in the arc chamber. Note the rapid decline in n_i and subsequent recovery when the Ti film is used. This behavior may be caused by the ion pump action at the walls, which is enhanced when Ti is present. This effect is normally visible during non-gettered operation.

A cross-check on the O concentration and a check for other impurities during gettering were made using Si surface samples and Auger electron depth profiling analysis. This method was capable of analyzing the total O content whereas the optical technique was sensitive to only the D_2O^+ component. Silicon disc samples, 7.7 mm in diameter and 0.6 mm thick, were exposed to the beam current in the vacuum tank in front of the calorimeter. Each sample was inserted in a probe and held in thermal contact to provide inertial cooling before being exposed to 20 beam shots. Each beam shot lasted 30 ms. The

injector produced about 15 atomic A, at 16 kV with a cross-sectional area of approximately 200 cm^2. A gettering film was deposited in the arc chamber after every fourth beam shot. Following exposure, the samples were removed and transported to the surface analysis chamber. The carbon (C) and O depth profiles were determined, using Auger depth profiling on the Si discs. A 5-kV, approximately 10-uA electron beam and a 1-keV Ar ion beam were employed. The ion beam was rastered across the sample with an amplitude that produced a current density of 25 uA/cm^2, resulting in a Si sputter rate of approximately 2.3 nm/min.

The near-surface O and C concentration profiles in atomic percentages appear in Fig. 5 as solid and dashed lines, respectively. Cases (a), (b), and (c) correspond to samples exposed when the arc chamber was gettered with Ti, ungettered, and gettered with Cr, respectively. At depths less than a few nm all the samples show similar contamination caused by atmospheric exposure when the samples were transported. Case (d) corresponds to the O and C profiles taken on a control sample.

The reduction of O by gettering is immediately evident. In the ungettered case (b), there is an O peak below the surface peak. The peak is centered near 17 nm, which corresponds to O having approximately ten keV of energy. With either Ti or Cr getter films, shown in cases (a) and (c), the O peak disappears with the result that the overall O concentration is reduced by at least a factor of 8. The results of the gettering process are consistent with a model in which oxygen is trapped on the walls by the metal film. The good agreement between the optical and the Auger spectroscopy analyses is due to the impurities being dominated by the D_2O^+ and DO^+ components.[1,2] Note the increased concentrations of C and O in the gettering cases compared to the residual concentrations in unexposed Si [Fig. 5(d)]. These may be due to the knock-on of surface contaminants by the high flux of deuterium.

Integrating the O profile in case (b) gives a total implanted O concentration of 3×10^{15} atoms/cm^2. The total number of injected hydrogen beam atoms over 20 exposures was estimated to be 2.8×10^{17} atoms/cm^2. Taking the ratio of these numbers gives an impurity concentration in the beam of 1.1%, which agrees with earlier independent estimates.[1,3] The heating of the sample by the incident beam is not expected to cause diffusion of O into the sample.[4] In any case, this effect would not reduce the total number of O atoms trapped in the sample.

The C depth profiles also shown in Fig. 5 do not indicate a substantial change from one case to the next. Auger electron spectra were examined for the surface of each sample, and showed no detectable levels of either Ti or Cr. The effect of gettering therefore reduced the level of O without noticeably increasing the impurity levels of other elements. Titanium and Cr performed equally well in this regard.

REALIABILITY

The reliability of the gettering process was of concern. Changing an injector assembly requires considerable time (4 hours) and must be performed when the machine is not operating. Our experimentation included a 500-getter-shot life test for the getter wire under conditions similar to those we expected in use of the machine. No significant degradation was detected in the performance of the getter wire, and the buildup of Ti caused no noticeable effects in the arc performance. Flaking of the material from the walls was not observed either during operation or during a visual examination after the life test.

Chromium was also used for a short time, but some tendency to flake was noticed after 30 to 50 getter shots. Because we had no prior experience with Cr in this application, we chose to abandon it in favor of Ti.

If used to excess, the lifetime of a Ti getter wire may set the limit on the entire getter system. At present, the Ti wire is not used unless required so our present failure mode, the thermal overload of other parts of the injector assembly, remains the primary mode of failure. Nevertheless, a staggered maintenance cycle was planned to prevent getter failures from occurring within a short time and to reduce the number of injectors in the shop for getter replacement.

CONCLUSIONS

Gettering reduces D_2O^+ impurities in ion beams by approximately a factor of 10, and the total O impurity concentration may be reduced by a factor of eight. Experimentation with plasma impurities appears possible with gettering as a means of controlling the impurity level. Surface analysis and optical spectra agreed in the level of improvement. Although getter materials other than Ti and Cr may improve performance, we prefer to use Ti because of our ongoing experience with it.

However, a couple of problems were encountered during our testing. The first problem was the change in input power to the experimental plasma due to absorption of the D in the arc chamber by the getter film. Next a variation in arc density in successive shots made it difficult to perform diagnostics on the signals. We find that both problems can be controlled by regular getter operation. We also find that a potential reliability problem can be minimized through system maintenance.

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FIGURE CAPTIONS

Fig. 1. Neutral beam test stand. The equipment shown here, with the exception of the Optical Multichannel Analyzer (OMA), is used for conditioning and characterizing the injector assemblies for TMX-U.

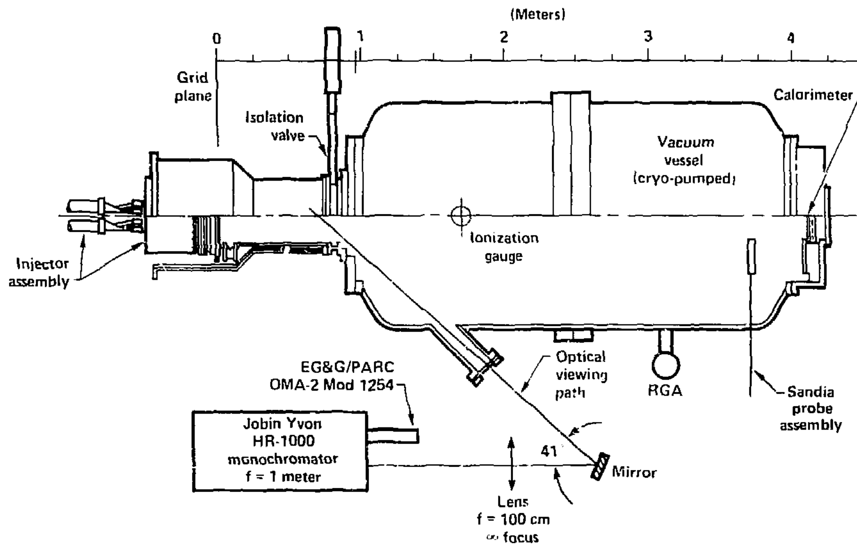
Fig. 2. Optical Doppler-shift spectrum before (a) and after (b) gettering. Increasing wavelength is to the right on the horizontal axis. The large unidentified peak to the right is due to the emission from cold gas in the viewing field and has no doppler shift.

Fig. 3. Comparison of the effects of Ti (a) and Cr (b) gettering on the ion beam for the designated species. Only trends are indicated; statistical fits were not used. The error bars indicate data scatter.

Fig. 4. Effect of gettering on arc voltage v_{arc}, current I_{arc} and chamber density n_i before (a) and after (b) gettering with Ti.

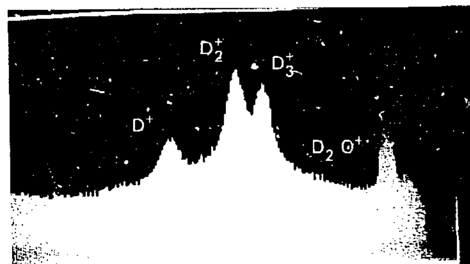
Fig. 5. Auger spectroscopy depth profiles of a beam-illuminated silicon surface for a sample exposed to an arc chamber gettered with Ti(a), ungettered (b), and gettered with Cr (c). The solid and dashed lines represent O and C concentration in atomic %, respectively. Case (d) corresponds to an unexposed sample.

R. J. Kane - Figure 1



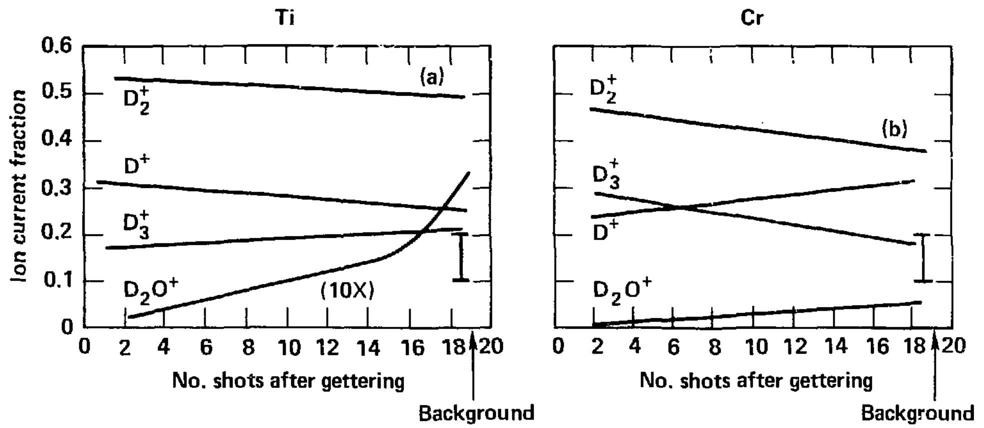
R. J. Kane - Figure 2

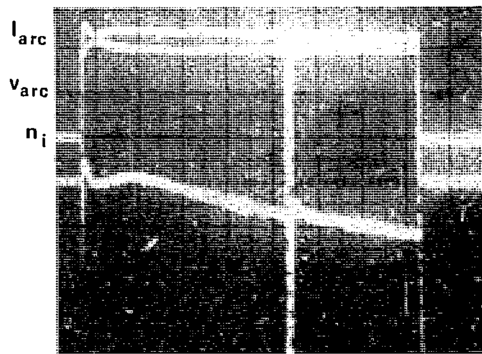
(a)

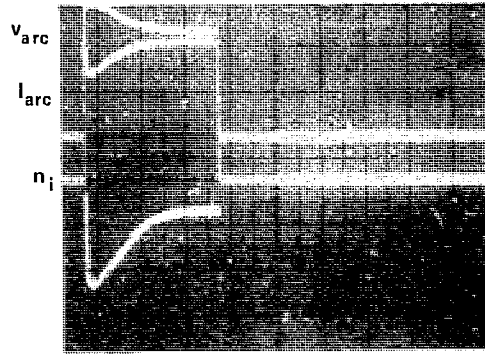


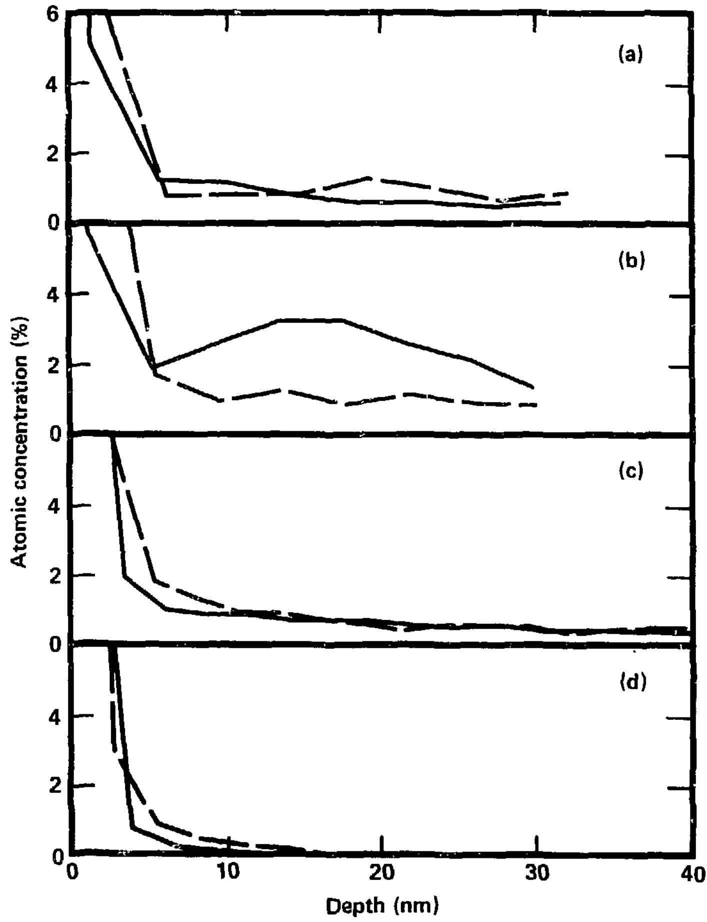
(b)

R. J. Kane - Figure 3




I_{arc}
V_{arc}
n_i
(a)
Time


V_{arc}
I_{arc}
n_i
(b)
Time


(a)
(b)
(c)
(d)
Atomic concentration (%)
Depth (nm)
0
2
4
6
10
20
30
40