305
8-9-78

Sh. 335

ORNL/TM-6446

CONF-780431--4

Plasma-Wall Impurity Experiments in ISX-A

R. J. Colchin
C. E. Bush
P. H. Edmonds
A. C. England
K. W. Hill
R. C. Isler
T. C. Jernigan
P. W. King
R. A. Langley
D. H. McNeill
M. Murakami
R. V. Neidigh
G. H. Neilson
J. E. Simpkins
J. B. Wilgen
J. C. DeBoo
K. H. Burrell
E. S. Ensberg

MASTER

OAK RIDGE NATIONAL LABORATORY
OPERATED BY UNION CARBIDE CORPORATION · FOR THE DEPARTMENT OF ENERGY

BLANK PAGE

ORNL/TM-6446
Dist. Category UC-20 a, c, f

Contract No. W-7405-eng-26

FUSION ENERGY DIVISION

PLASMA-WALL IMPURITY EXPERIMENTS IN ISX-A

R. J. Colchin, C. E. Bush, P. H. Edmonds, A. C. England,
K. W. Hill, R. C. Isler, T. C. Jernigan, P. W. King, R. A. Langley,
D. H. McNeill, M. Murakami, R. V. Neidigh, G. H. Neilson,
J. E. Simpkins, and J. B. Wilgen
Oak Ridge National Laboratory
Oak Ridge, Tennessee
and
J. C. DeBoo, K. H. Burrell, and E. S. Ensberg
General Atomic Company
San Diego, California

Date Published: August 1978

Prepared by the
OAK RIDGE NATIONAL LABORATORY
Oak Ridge, Tennessee 37830
operated by
UNION CARBIDE CORPORATION
for the
DEPARTMENT OF ENERGY

CONTENTS

ABSTRACT v

1. INTRODUCTION 1

2. DESCRIPTION OF EXPERIMENTAL CONDITIONS 2

3. VACUUM CONDITIONS, Z_{eff}, AND RECYCLING 2

4. LIMITER EXPERIMENTS 9

5. CONCLUSIONS 12

ACKNOWLEDGMENTS 12

REFERENCES 13

ABSTRACT

The ISX-A was a tokamak designed for studying plasma-wall interactions and plasma impurities. It fulfilled this role quite well, producing reliable and reproducible plasmas which had currents up to 175 kA and energy containment times up to 30 msec. With discharge precleaning, Z_{eff} was as low as 1.6; with titanium evaporation, Z_{eff} approached 1.0. Values of $Z_{eff} \gtrsim 2.0$ were found to be proportional to residual impurity gases in the vacuum system immediately following a discharge. However, there was no clear dependence of Z_{eff} on base pressure. Stainless steel limiters were used in most of the ISX-A experiments. When carbon limiters were introduced into the vacuum system, Z_{eff} increased to 5.6. After twelve days of cleanup with tokamak discharges, during which time Z_{eff} steadily decreased, the carbon limiters tended to give slightly higher values of Z_{eff} than stainless steel limiters. Injection of $<10^{16}$ atoms of tungsten into discharges caused the power incident on the wall to double and the electron temperature profile to become hollow.

1. INTRODUCTION

ISX-A (Impurity Study Experiment)[1] was an iron core tokamak with a major radius of 92 cm and a minor radius of 26 cm. This machine was designed for the study of plasma-wall interactions and plasma impurities. The bulk of the data taken from ISX-A was recorded during a 12-week period between December 12, 1977 and March 5, 1978. Stainless steel limiters were used except during the last two weeks of operation, when retractable molybdenum and carbon limiters were added. Upon completion of the experimental program, ISX-A was converted to ISX-B with the addition of neutral beams, a new vacuum vessel, and a new poloidal field system.

The principal experiments carried out during the lifetime of ISX-A can be broadly classified as the impurity flow reversal experiment,[2] confinement studies, and surface physics studies.[3] The confinement studies were conducted under a broad range of impurity and limiter conditions. In addition, tungsten limiters were simulated by using a laser blowoff system to puff tungsten into the plasma. The results of the confinement experiments, which are described in Sects. 3 and 4, are related to studies in several other tokamaks.[4–9]

Typical values of several plasma parameters are listed in Table 1 for sequences employing stainless steel and carbon limiters. The optimum plasma parameters achieved are given in the last column of Table 1, but these parameters were not all achieved during the same discharge sequence.

Table 1. ISX-A plasma parameters

	Stainless steel limiter	Carbon limiter	Optimum
B_T (kG)	13.2	13.2	14.8
I_p (kA)	120	116	175
$q(a_\ell)$	4	4	2.5
$n_e(0)$ (10^{13} cm^{-3})	5.2	4.8	9
V (v)	1.5	1.5	0.9
$T_e(0)$ (keV)	0.69	0.82	1.5
$T_i(0)$ (keV)	0.42	0.39	0.55
τ_E (msec)	22	20	30
Z_{eff}	1.8	3	1

2. DESCRIPTION OF EXPERIMENTAL CONDITIONS

The vacuum vessel of ISX-A was constructed of welded 304L stainless steel with no insulating break. Metal vacuum seals were used throughout, except for Viton seals in several gate valves and on several laser windows. All Viton seals were prebaked in a vacuum oven. The vacuum vessel consisted of nine rectangular box-shaped sections connected by circular bellows. Each of the box (or diagnostic) sections contained diagnostic ports on the top, bottom, and outside. Figure 1 shows the location of a titanium evaporator, gas puffer, and bottom movable toroidal limiter, which were located in each of the nine diagnostic sections. Note that the titanium evaporators were shielded so that titanium was deposited mainly on the top of the vessel, as required by the impurity flow reversal experiment. Except for the last two weeks of operation, all nine bottom limiters were made of stainless steel and were oriented along the toroidal magnetic field. In addition to the bottom limiters, three 1-in.-diam poloidal stainless steel bar limiters, insulated from the vacuum liner, were located in one diagnostic section.

Among the diagnostics[10] on ISX-A were a scanable Thomson scattering system, a single-channel microwave interferometer, a multichord visual spectrometer, both normal- and grazing-incidence ultraviolet spectrometers, soft x-ray detectors, PIN diode x-ray monitors, a mass-selectable charge exchange analyzer, and a Langmuir probe. A quadrupole mass analyzer, operated by a small computer via CAMAC, was used for gas analysis. A sample transfer system was also attached, which allowed small specimens to be positioned inside ISX-A and withdrawn under vacuum for Auger analysis.[3]

3. VACUUM CONDITIONS, Z_{eff}, AND RECYCLING

Residual gas analysis (RGA) scans of particles with charge-to-mass ratios of 1–50 were routinely made several times each day using a quadrupole mass analyzer. These scans were taken starting 15 sec after a shot. The data were processed in a small computer and plotted on a logarithmic scale in units of partial pressure above background. After several weeks of operation, it became evident from viewing these scans

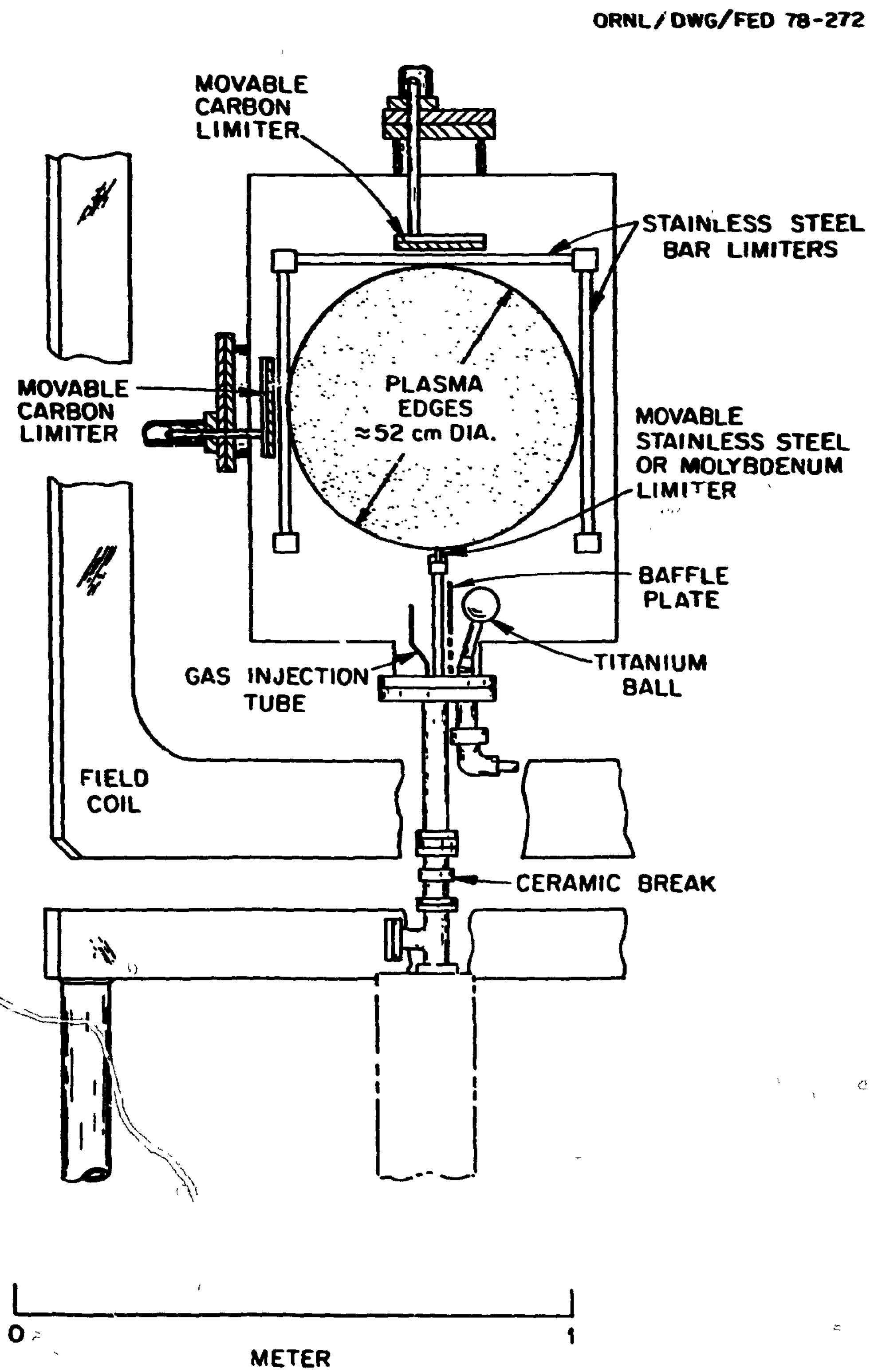

Fig. 1. Cross section of the ISX-A vacuum chamber showing the position of several limiters.

that the measured values of Z_{eff} were proportional to the total partial pressure of contaminant gases. This relationship is shown quantitatively in Fig. 2, where Z_{eff} values, as determined by the plasma conductivity and $T_e(r)$ profiles, are plotted against N_I/N_H (N_I is the number of impurity atoms in the residual gas scan, and N_H is the number of hydrogen atoms). It is not clear, *a priori*, that such a proportionality should exist. However, because the low Z impurities carbon, oxygen, and nitrogen were the principal contributors to Z_{eff} in ISX-A, and because these impurities formed gases (such as CH_4, C_2H_4, CO, H_2O) which remained after each discharge, this result is perhaps not too surprising. For $Z_{eff} < 2$, the relationship between RGA scans and Z_{eff} is not totally clear. This

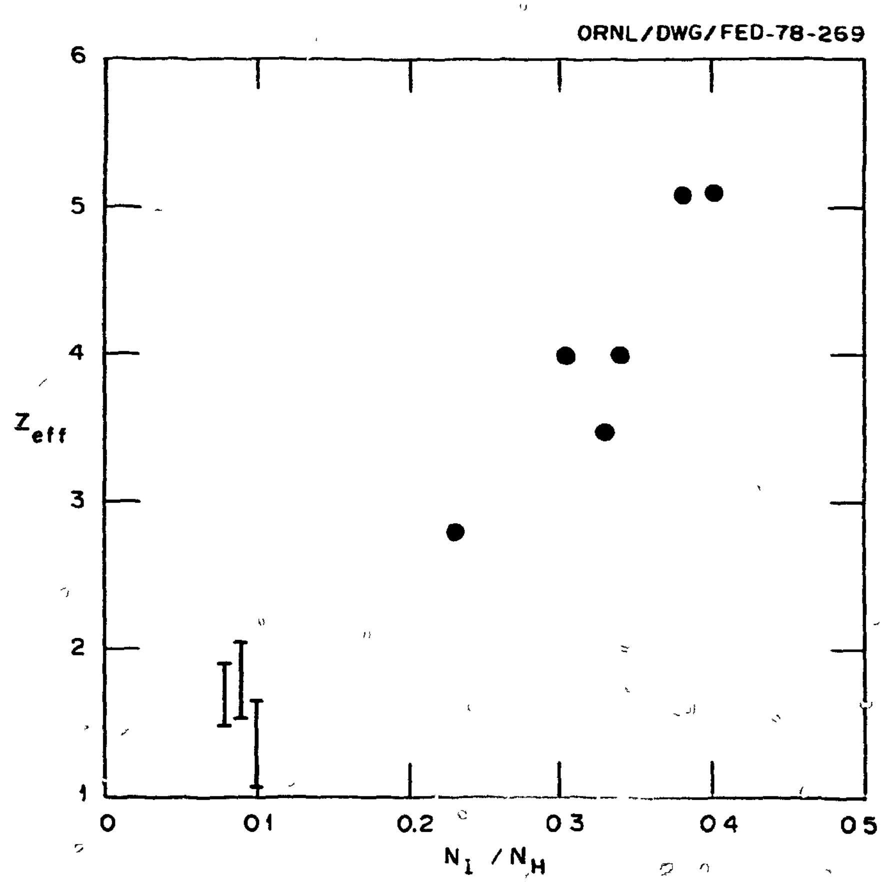

Fig. 2. A comparison of Z_{eff}, as determined from conductivity and $T_e(r)$ profiles, with N_I/N_H. The Z_{eff} values in the lower three points have an indicated range as a result of Z_{eff} variations during a discharge.

may be because heavy metals or plasma turbulence played a role in determining Z_{eff} at low levels. Little correlation between Z_{eff} and base pressure was observed.

Discharge cleaning in hydrogen gas was routinely practiced prior to December 12, 1977 and for five weeks thereafter. The cleaning discharges consisted of 0.5-msec-long pulses, applied at the rate of 120/sec in a toroidal field of 200 G. Breakdown was assisted by a 1-GHz low power (~50 W) microwave source. This procedure produced a cold plasma with electron temperatures estimated spectroscopically to be from 9 to 18 eV. This cleaning procedure was sometimes varied to allow 1-sec or shorter bursts followed by 1-5 sec of pumping. As a by-product of discharge cleaning, the bellows sections were heated to 160°C by currents running through the liner while the box sections remained cool.

The ultimate vacuum attained after hydrogen discharge cleaning was 8×10^{-8} torr (gage pressure), and hydrogen was the principal residual gas. The pumping speed of the system was restricted by conductance limits to about 250 liters/sec. Values of Z_{eff} steadily decreased during the five weeks of discharge cleaning after December 12, 1977, reaching $Z_{eff} = 1.6$. The principal contaminant gases were CH_4, CO, and H_2O, each contributing less than 10^{-8} torr to the background partial pressure. The resulting tokamak discharges exhibited relatively low impurity radiation levels. Table 2 lists preliminary data for the fraction of the ohmic input power radiated by the most abundant plasma impurities. Present uncertainties in analysis of these data imply a 50% possible error in the results.

Titanium gettering was the principal method of wall conditioning used during the last seven weeks of ISX-A experiments. The initial effect of titanium evaporation was that the ultimate base pressure decreased by a factor of ten, and the carbon and oxygen radiation levels decreased by a factor of three. At first titanium was evaporated after each shot. While this titanium decreased the base pressure, RGA scans 15 sec after the next discharge showed that the CH_3 and CH_4 peaks increased by an order of magnitude, but that other impurity gases remained unchanged. Without further titanium evaporation these contamination levels and the value of

Table 2. ISX: power radiated to the wall

Spectroscopic measurements: $Z_{eff} = 2.1$

Source	Percent of ohmic heating input power		
	50 msec	100 msec	150 msec
Hydrogen (Ly-α)	1.7	4.1	1.6
Carbon	1	3.5	1.7
Oxygen	2	16.3	14
Nitrogen	0.5	5.9	3.5
Iron	1	1.9	1.9
Nickel	0.2	0.2	0.5
Chromium	0.2	0.2	0.4
	6.6	32.1	23.6

Z_{eff} remained fairly constant, regardless of the number of shots. Because of this constancy, it became common practice to evaporate titanium only infrequently between shots and at the end of a day's run. The lowest values of Z_{eff} achieved with titanium evaporation approached 1.0, and with deuterium puffing, energy containment times reached 30 msec.

Table 3 lists O VI, H, and C III radiation for several different discharge sequences. The plasma density was not constant during these experiments, so different shot sequences cannot be directly compared. However, the general trend is clear; lower Z_{eff} values imply more hydrogen radiation and relatively less emission from C III and O VI. The increase in the emission of hydrogen light is particularly striking for $Z_{eff} = 1.1$.

The fraction of the total input power reaching the walls for discharges with different Z_{eff} values is shown in Fig. 3. These data were derived from a pyroelectric detector, and each trace represents an average over several shots. In comparison with spectroscopy data, the radiometer measurements show a larger fraction of the ohmic heating power reaching the wall than was indicated by the intensities of impurity lines, as given in Table 2. Typically, half as much power was radiated to the walls as compared to similar ORMAK discharges.[10]

Table 3. Impurity emission rates

			$\frac{10^{15}\text{ photons}}{\text{cm}^2\text{-sec-steradian}}$			
			t = 100 msec into the discharge			
Cleaning technique	Limiter material	Z_{eff}	H 1216 Å	C III 977 Å	O VI 1032 Å	Ohmic heating power (kW)
Ti evaporation	Stainless steel	1.1	23.2	0.13	1.05	225
Ti evaporation (D_2 puff into H_2)	Stainless steel	1.7	7.02	0.11	1.79	210
Discharge cleaning	Stainless steel	2.1	8.06	0.36	4.21	213
Discharge cleaning (carbon limiter installed)	Stainless steel	2.8	4.2	0.37	2.25	162
Ti evaporation	Carbon	2.8	0.88	0.36	3.38	203

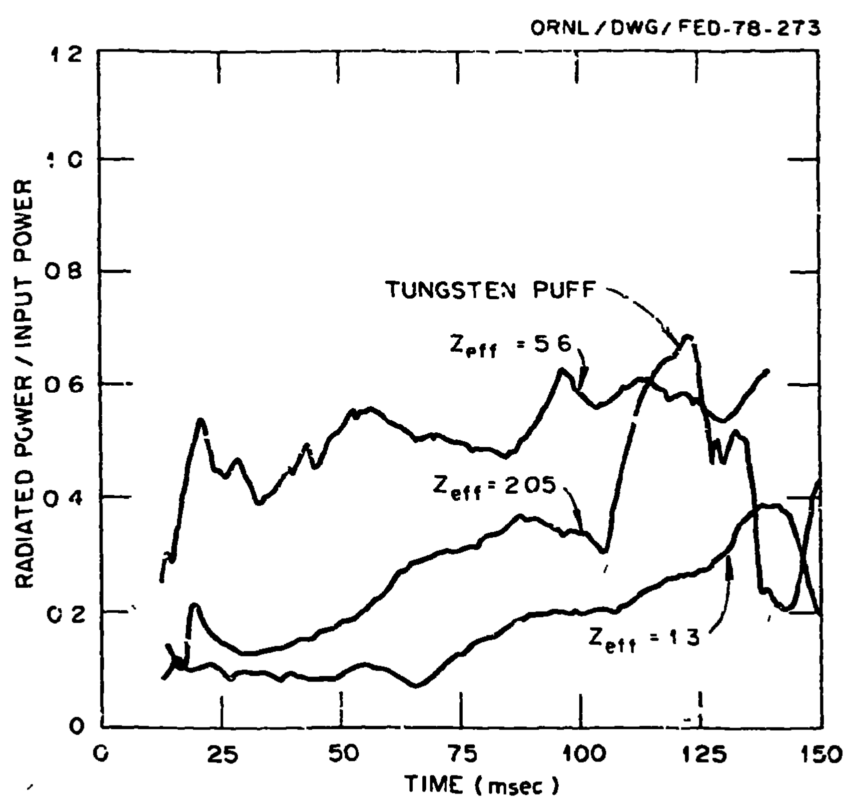

Fig. 3. Fraction of the input power which was radiated to the wall, as observed by a pyroelectric detector. The middle trace shows the result of puffing tungsten atoms into the discharge at t = 100 msec.

Although hydrogen was usually the working gas, deuterium was introduced during three different periods of ISX-A operation. Figure 4 gives data from RGA scans of H_2, HD, and D_2 taken 15 sec after a number of shots. Starting just after a deuterium run the D_2 partial pressure decayed over several hundred shots, reaching a partial pressure of <2% of the total. Much more deuterium was contained in the HD molecule, which never fell below 20% of the total pressure. This implied a considerable wall holdup and recycling of deuterium. A large amount of deuterium was present in the evaporated titanium layers, as indicated by a rise in the D_2 mass peak with each heating of the box sections during titanium evaporation. This accounts for the scatter in the data between shots 400 and 700. Similarly, with the reintroduction of deuterium after several hundred hydrogen shots, a considerable amount of hydrogen remained in the vacuum system.

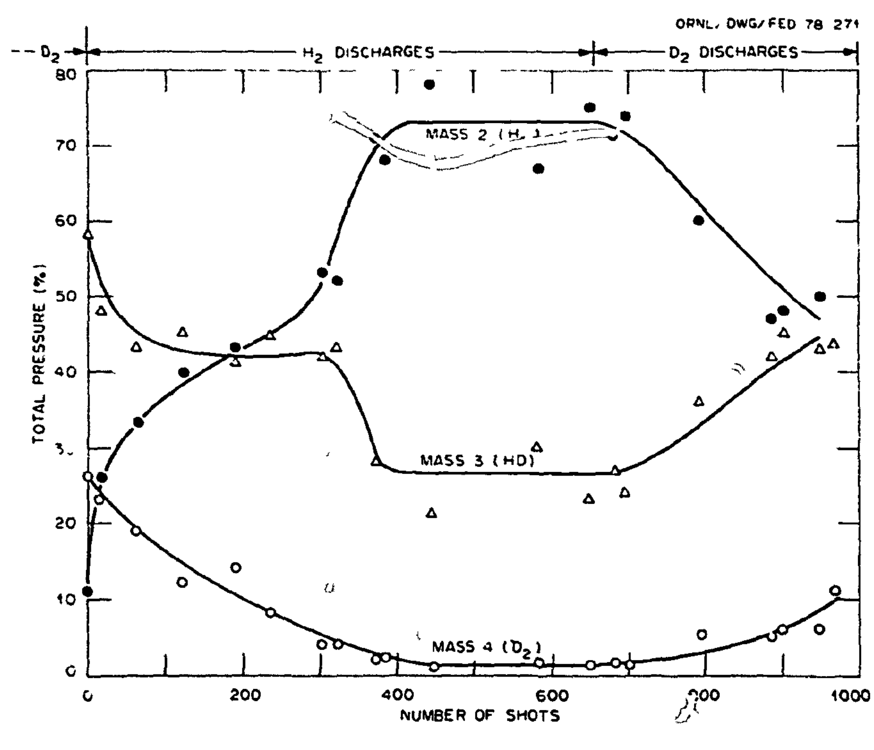

Fig. 4. Variation of the fractional partial pressures of masses 2, 3, and 4 with H_2 and D_2 as the working gases. Titanium evaporation was used during the time period in which these shots were taken. Data were taken starting 15 sec after the completion of tokamak discharges.

4. LIMITER EXPERIMENTS

For all except the last two weeks of operation, stainless steel limiters were used exclusively in ISX-A. With two weeks of experiments remaining, carbon limiters were inserted in a top, bottom, and outside port of one diagnostic section. (Two of these limiters are shown in Fig. 1; a third limiter located in a bottom port is not shown.) All three limiters were adjustable from a distance of 2.5 cm in the shadow of the stainless steel limiter to 5 cm into the plasma. All three carbon limiters were made of ATJ-S graphite and contained tungsten heaters wrapped on alumina spools which were in turn inserted inside the graphite. In addition, a molybdenum limiter was substituted for one of the bottom retractable stainless steel limiters.

The stainless steel limiters performed remarkably well throughout the life of ISX-A. As may be noted from Table 2, metal contamination was not a serious problem. Upon removal of the stainless steel bars, three distinct types of limiter damage were noted (as shown in Fig. 5). The outside limiter experienced some melting at the center. Pitting and melting due to runaway electrons were mainly observed on the sides of the top limiter. Arc tracks were observed on all limiters, particularly the inside limiter. There was ample evidence of arcing near the insulators at the ends of each rod.

The carbon limiters were baked to above 400°C upon installation in ISX-A, having also been previously vacuum baked. Immediately after installation the carbon contamination levels and Z_{eff} increased, and plasma discharges were irreproducible. Values of Z_{eff} slowly decreased with tokamak operation, as shown in Fig. 6. However, plasmas bounded by the carbon limiter never exhibited Z_{eff} below 2.8. A detailed comparison of plasma parameters on the last day of operation (see Table 1) shows only small differences between stainless steel and carbon limiter shots, although the electron temperature and density profiles were somewhat broader using the carbon limiters. Table 3 shows that the emission of hydrogen light was considerably reduced when the carbon limiter was inserted. RGA scans showed an enhancement in hydrocarbon contaminants throughout the time the carbon limiters were in ISX-A. When the bottom

ORNL/DWG/FED 78-607

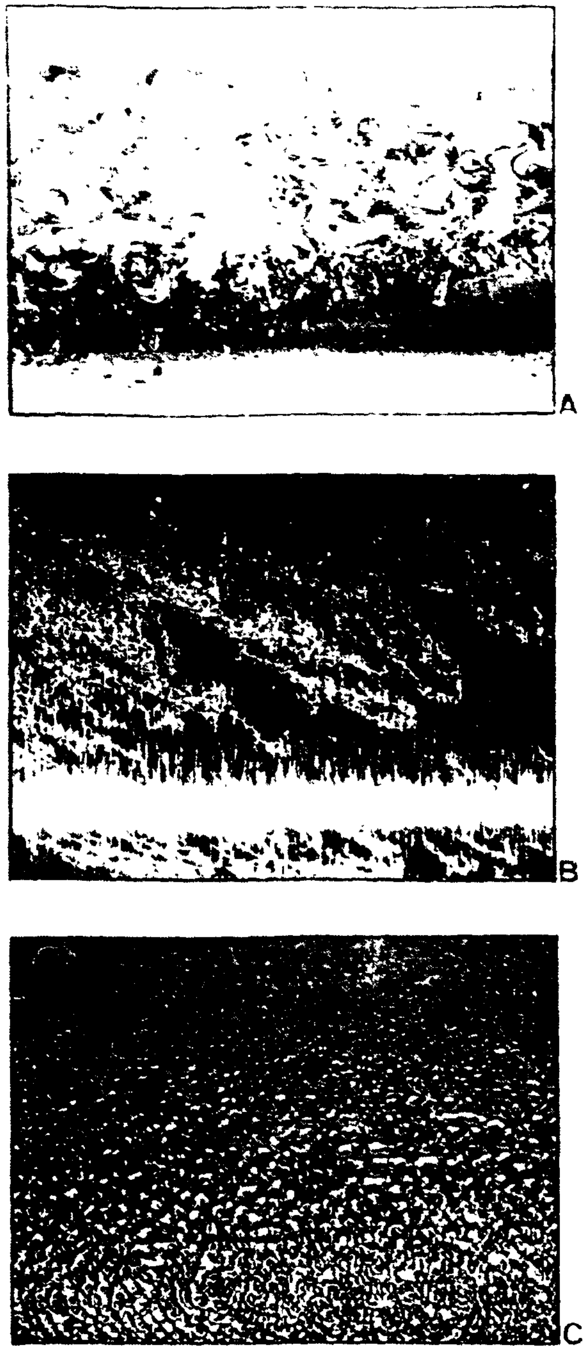

Fig. 5. Three types of limiter damage to the stainless steel bars. (a) Surface melting at the center of the outside bar. (b) Arc tracks, observed generally and particularly on the inner bar. (c) Limiter damage to the side of the top bar caused by runaway electrons melting the surface at localized points. The relative magnifications of (a) to (b) and (c) are 1:4.1:1.7.

BLANK PAGE

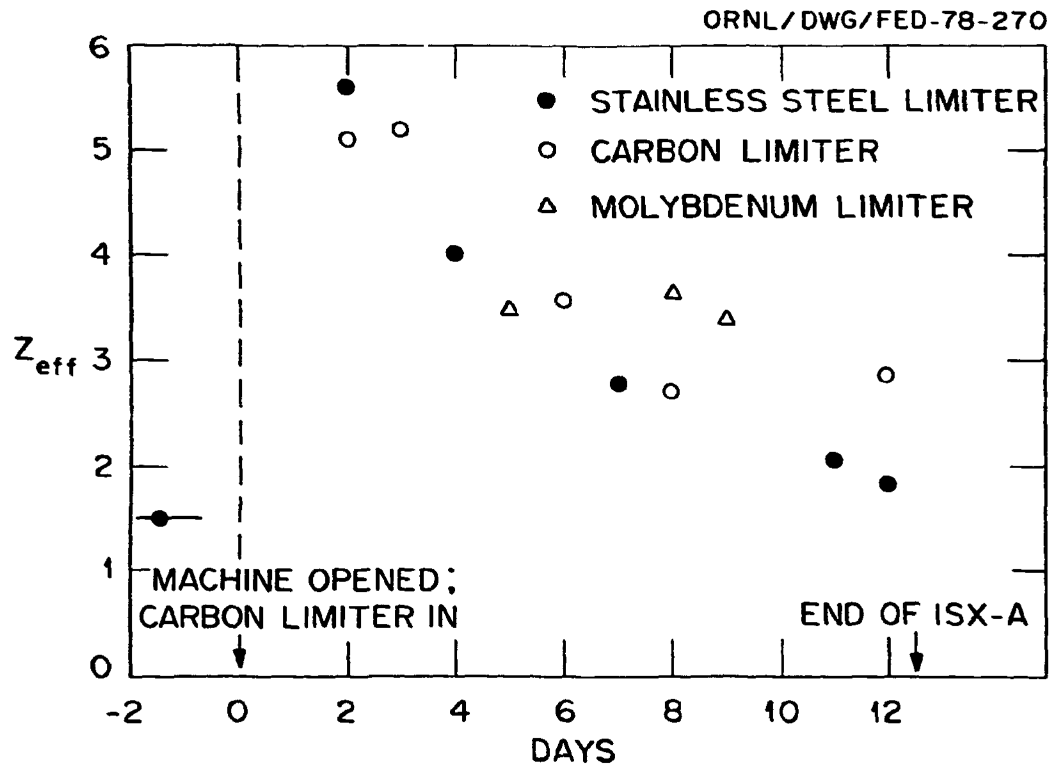

Fig. 6. Z_{eff} as a function of days before and after installation of the carbon and molybdenum limiters. Z_{eff} values are given for stainless steel, molybdenum, and carbon limiters.

carbon limiter was heated to 620°C in the presence of plasma discharges, no increase in the residual methane gas pressure of 9×10^{-7} torr was observed. Considerable evidence of arcing was found on the graphite after removal of the limiters.

With the molybdenum limiter extended into the plasma, discharges could not reproducibly be run with densities above 1.5×10^{13} cm^{-3}, and so comparisons with other limiters were inconclusive. Tungsten atoms were puffed into the plasma via a laser blowoff system to simulate the effect of the tungsten limiter in ORMAK.[11] With the introduction of $\lesssim 10^{16}$ tungsten atoms (or less than 0.1% of the total number of electrons), the electron temperature profile became hollow, the voltage increased, and the radiation to the wall increased by 100%. This latter effect is illustrated in Fig. 3.

BLANK PAGE

5. CONCLUSIONS

ISX-A proved to be a very reliable and reproducible tokamak. Using stainless steel limiters, low values of Z_{eff} were achieved both with discharge cleaning (Z_{eff} = 1.6) and titanium evaporation ($Z_{eff} \cong 1.0$). Line radiation and radiometer measurements confirmed that the level of impurity contamination was low. The principal contaminants were carbon, nitrogen, and oxygen, with metals contributing relatively little to the radiated power. Energy containment times were exceptionally long, reaching τ_E = 30 msec at a toroidal field of 13 kG.

Discharge cleaning was the preferred mode of wall conditioning. Using titanium evaporation along with stainless steel limiters, it was possible to open the vacuum system to air one day and to have reproducible discharges the next day. However, there was much hydrogen and deuterium holdup in the titanium, as evidenced by the slow changeover in the residual gases when H_2 was substituted for D_2. As titanium layers became thicker over a several week period, outgassing with titanium evaporation became more and more of a problem.

The introduction of the carbon limiters into ISX-A and their subsequent bake-out caused Z_{eff} to rise to the highest values observed, Z_{eff} = 5.6. During the twelve days of operation after their introduction, Z_{eff} steadily dropped, but Z_{eff} values with carbon limiters were slightly higher than comparable discharges with stainless steel limiters. Considerable evidence of arcing was observed on both the carbon and the stainless steel limiters. When small amounts of tungsten were puffed into the plasma, the radiated power doubled and the temperature profile became hollow.

Values of $Z_{eff} \gtrsim 2.0$ were found to be proportional to the amount of contaminants in residual gases immediately after a discharge, as observed by RGA scans. There was little correlation between Z_{eff} and base pressure.

6. ACKNOWLEDGMENTS

We would like to thank H. E. Ketterer, V. J. Meece, T. F. Rayburn, and W. L. Redmond for operating ISX-A. R. D. Overbey was responsible for computer programming. Design, construction, and experimental assistance with the carbon limiters were provided by R. A. Ellis, Jr., V. Corso, J. L. Cecchi, and M. Nishi of the Princeton Plasma Physics Laboratory. Finally, we would like to thank J. Sheffield, L. A. Berry, and O. B. Morgan for their support of this project.

REFERENCES

1. R. J. Colchin and T. C. Jernigan, J. Nucl. Mater. 63, 83 (1976).
2. K. H. Burrell, Phys. Fluids 19, 401 (1976), and references cited therein.
3. L. C. Emerson, R. E. Clausing, and L. Heatherly, *Proc. 3rd Int. Conf. on Plasma Surface Interactions in Controlled Fusion Devices*, April 1978, Culham, England (to be published).
4. TFR Group, *Proc. Int. Symp. on Plasma Wall Interactions*, p. 3 (1977).
5. P. Ginot et al., *Proc. 3rd Int. Conf. on Plasma Surface Interactions in Controlled Fusion Devices*, April 1978, Culham, England (to be published).
6. T. Hirayama et al., *Proc. 3rd Int. Conf. on Plasma Surface Interactions in Controlled Fusion Devices*, April 1978, Culham, England (to be published).
7. S. Konoshima et al., *Proc. 3rd Int. Conf. on Plasma Surface Interactions in Controlled Fusion Devices*, April 1978, Culham, England (to be published).
8. S. A. Cohen et al., *Proc. 3rd Int. Conf. on Plasma Surface Interactions in Controlled Fusion Devices*, April 1978, Culham, England (to be published).
9. S. A. Cohen, *Proc. 2nd Conf. on Surface Effects in Controlled Fusion Devices*, p. 65 (1976).
10. R. J. Colchin et al., J. Nucl. Mater. 63, 74 (1976).
11. R. C. Isler, R. V. Neidigh, and R. D. Cowen, Phys. Lett. 63A, 295 (1977).