THE ISX-A GRAPHITE LIMITER EXPERIMENT*

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As part of the ISX surface physics program and the TFTR materials research program, ATJS graphite rail limiters were installed in the ISX tokamak in order to compare them with the existing stainless steel limiters and to investigate any deleterious effects arising from operation at elevated temperatures of the graphite. To facilitate the latter experiment, heaters were installed in the graphite limiters since the power deposition on the limiter in ISX was expected to be considerably less than for TFTR. The graphite limiters also contained thermocouples to monitor the bulk temperature. No large systematic differences were observed in the electron temperature profiles, electron density profiles nor Z_{eff} between successive runs with the stainless steel (SS) limiters and graphite (G) limiters. There was, however, a monotonic decrease in Z_{eff} for both cases from ~ 5.6 in the first run following the installation of the graphite limiters to ~ 2.8 after a two week period when the experiment was terminated due to a scheduled shutdown. Normal incidence UV spectroscopic measurements of C, N, O, and H radiation showed a factor of 3-4 greater hydrogen light for the SS case over the G case, but no systematic differences in the impurity light. Arc tracks were observed on the graphite limiters upon removal and SEM analysis was performed so that the amount of material removed could be estimated. In the hot graphite limiter experiment, the temperature of one of the graphite limiters was increased on successive shots. The hydrocarbons formed, as determined by residual gas analysis (RGA), increased monotonically with increasing limiter temperature, e.g. mass 16 (presumed to be CH_4) increased about a factor of two as the temperature was raised from 150°C to 500°C. CO and CO_2 were also found to increase only slightly. The carbon impurity light was also observed to increase by a factor of two as the limiter temperature was raised from 150°C to 500°C. Further experiments using graphite limiters are indicated before their application in beam driven tokamaks.

1. INTRODUCTION

Graphite limiters were installed and tested in the ISX-A tokamak as part of the ISX-A surface physics program and the TFTR materials research program. The purpose of the experiment was to compare plasma performance using graphite limiters as opposed to the standard ISX-A stainless steel limiters. Heaters were installed in the graphite limiters so that the effects of operation at elevated temperatures could be evaluated.

Graphite limiters have been used with some limited success in tokamaks [1,2,3]. TFR used 5890 CL-PT graphite and observed that it behaved well mechanically up to plasma currents of 400 kA for 1000 discharges. Surface erosion and a few microfailures were observed. This was attributed to thermal loads exceeding 10 kW·cm^{-2} with local temperature excursions grater than 3000°C. No appreciable difference in plasma performance was observed between graphite and molybdenum limiters. Carbon radiation from the plasma was observed to increase but the total power radiated and the hard x-ray signal decreased when graphite limiters were used. Hollow profiles were observed for both molybdenum and graphite limiters. In ohmically heated PLT discharges changing from stainless steel limiters to graphite limiters had a negligible effect on the gross plasma parameters such as Z_{eff}, τ_E, and T_e, although the carbon radiation typically increased by a factor of three while the iron radiation decreased by a similar factor [2]. With high-power neutral beam injection, however, decidedly better results were obtained with graphite limiters and Ti gettering than with stainless steel limiters and Ti gettering [3].

2. EXPERIMENTAL CONFIGURATION

ATJ-S [4] graphite was used for this study because of its relatively good thermal shock

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resistance and purity, i.e., ash level of 0.01 wt. %, availability, large size and low cost. ATJ-S is a commercial grade graphite used mostly for rocket reentry nosecones; (see Table 1 for its physical properties).

With stainless steel (SS) limiters in ISX-A, which were permanently mounted, the plasma minor radius was 26 cm and major radius was 92 cm. The graphite limiters which were movable could be inserted 2.5 cm beyond and withdrawn 2 cm behind the SS limiters. A schematic diagram of the configuration is shown in Fig. 1. Only three graphite limiters were used; top, outside and bottom (not shown in Fig. 1). Use of a movable inside limiter was considered too formidable a task for the short time available for the experiment. For graphite limiter experiments, the plasma was positioned so that it did not contact the inner SS limiter. It should be noted that when the graphite limiters were fully inserted the plasma diameter was 2 cm smaller in minor radius. Graphite limiters were used alternatively with SS and Mo limiters during the final 12 days of operation of ISX-A before the scheduled shutdown.

Table 1
Physical Properties of ATJ-S Graphite [5]
$\rho = 1.85\ g \cdot cm^{-3}$

		20°C	1100°C
Tensile strength, psi	wg	5150	6100
	ag	4250	5000
Young's Modulus, 10^6 psi	wg	1.75	
	ag	1.05	
Fracture Strain, %	wg	0.44	0.43
	ag	0.55	0.31
Thermal Conduction	wg	900	380
(BTU·in/hr·ft^3·°F)	ag	650	300

wg = with grain; ag = against grain

The graphite limiters were 30 cm long and machined from a billet 22.5 cm in diameter. The limiter surface which was exposed to the plasma contained machining grooves which were 0.025 mm wide and deep and regularly spaced at 0.25 mm. Heaters were constructed by coiling a tungsten wire on an alumina mandrel. These were placed in a machined groove in the rear side of the limiter. The heaters were used to thermally outgas the limiter and for operation at elevated temperatures. The maximum bulk temperature of the graphite during heating was ~600°C, above this temperature the tungsten filament approached its melting point. In the temperature region higher than 550°C an oxygen producing reaction between the alumina mandrel and tungsten was observed therefore elevated temperature tokamak operation was limited to <550°C. Tokamak operation using Mo limiters has been described previously [6].

3. EXPERIMENTAL PROCEDURE AND RESULTS

After installation of the graphite and Mo

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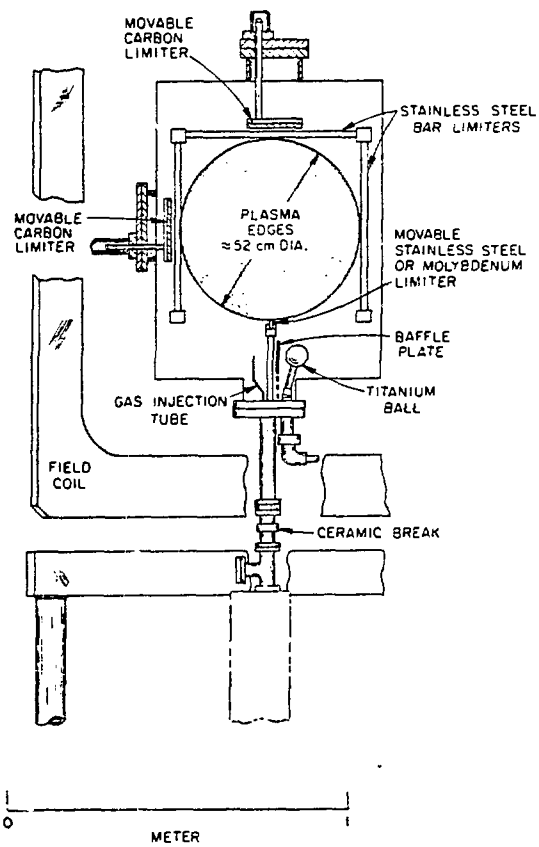

Fig. 1. ISX experimental set up. The axis of toroidal symmetry is to the right. For clarity the bottom carbon limiter is not shown.

limiters, 4 hours of discharge cleaning was run before outgassing the graphite limiters to ~400°C. RGA results indicated that the major contaminants evolved were H_2O, CO and C_3H_6 with the following relative magnitudes 1.0, 0.7 and 0.055. After cooling to ~25°C, tokamak operation was begun using SS limiters followed by operation using graphite limiters. Measurements of various plasma parameters are shown in Fig. 2 for the graphite limiter (C limiter in) and the SS limiter (C limiter out).

Spectroscopic measurements made with a normal-incidence spectrometer viewing the plasma away from the limiter are listed in Table II. The smaller values of the emission rate normalized to the average electron density $\bar{n}_e$ for the graphite limiter compared to the SS limiter may reflect a decrease in the fraction of recycling of hydrogen and impurities from the vessel wall (as opposed to

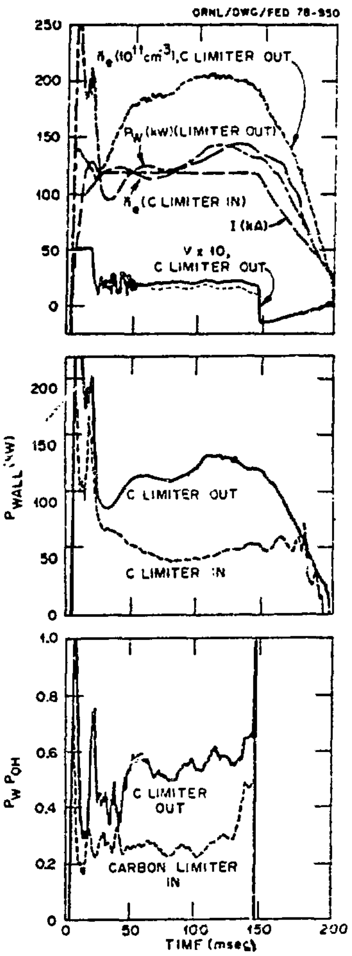

Fig. 2. Comparisons of plasma parameters for discharges with carbon limiter inserted and retracted (stainless steel limiter).

the limiter) due to the smaller plasma minor radius with the graphite limiter in.

On the fifth operational day after graphite limiter installation, one limiter was ramped in temperature to 600°C during tokamak operation. Both spectroscopic and RGA results for this series of discharges are shown in Fig. 3. There is a good correlation for onset of increase and magnitude of increase between the C IV radiation and evolution of CH_4 and CO as a function of limiter temperature; the increase occurring about 450°C. The temperature where the formation of CH_4 increases agrees well with previous laboratory experimental measurements [7,8]. During this run the time between discharges was increased so that the base pressure (predominantly H_2 but with some CH_4 and

Table 2

Comparison of Plasma Parameters

	Stainless Steel	Graphite
I(kA)	120.0	120.0
V(volts)	2.0	1.6
n_e(10^{13}cm^{-3})	2.15	1.25
$\langle Z_{eff} \rangle$	5.6	5.1
Emission Rate/$\bar{n}_e$ (gR/10^{13}cm^{-3})		
1034 Å-CVI	47.0	28.3
629 Å-OV	9.4	5.8
977 Å-CIII	14.5	4.5
1216 Å-HI	14.1	5.8
P_{WALL}/P_{OH}	0.55	0.25

gR = giga RAYLEIGH = 10^{15} photons cm^{-2}·s^{-1}

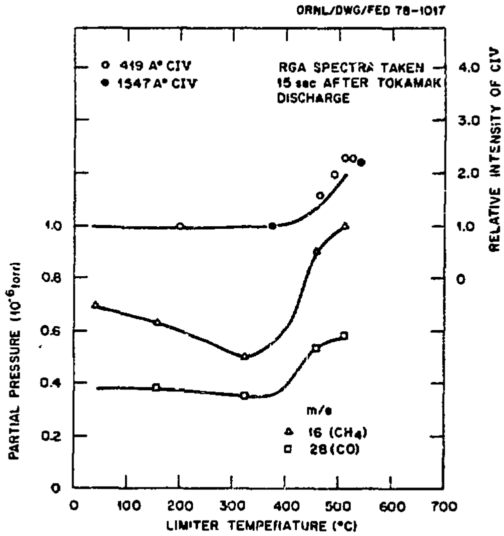

Fig. 3. Impurity partial pressure and carbon radiation as a function of limiter temperature.

CO contamination) at the start of each discharge was approximately the same. The increase in C IV radiation observed above 450°C may be the result of an increased methane partial pressure contribution to the base pressure before a discharge despite the fact that the total pressure was constant before each discharge.

The major erosion mechanism observed for the graphite limiters was arcing. The arcs consisted of a series of craters which appear to have originated on the edge of the machined grooves noted previously. The craters were about 0.05 mm in diameter and about the same depth, as measured using SEM sterographic techniques. Shown in Fig. 4 is a photograph of the tracks and Fig. 5 is a SEM photograph of a sequence of craters. The arc tracks range in

Fig. 4. Photograph of graphite limiter showing arc tracks

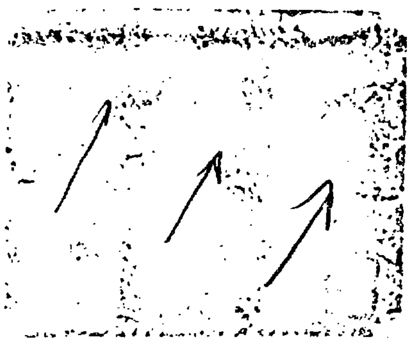

Fig. 5. SEM replica photograph showing arc craters.

length from a few mm's to a few cm's but average about 3 cm. The direction of motion of the arcs appears to be retrograde [9,10]. There was an average of more than one arc per limiter per discharge with an estimated 5×10^{17} atoms released per arc. This amount of eroded material is more than enough to account for the carbon observed in the plasma.

A surface analysis station with an associated sample transfer section was used to measure the amount of impurities deposited on samples exposed to the plasma in the limiter shadow region [11]. This technique yields semiquantitative results on impurity levels in the tokamak and on the effectiveness of various clearing procedures. A summary of these results is given in Fig. 6 along with Z_{eff} results determined by laser Thomson scattering. At the top of the figure is given a sequential description of the operating conditions. The contaminant coverage on a stainless steel sample as measured by AES is shown for both oxygen and carbon/carbide. The oxygen contaminant level remained low, even lower than baseline data with stainless steel limiters. The carbon/carbide contaminant level increased about a factor of 2.5 after each bake out of the graphite limiters but decreased with subsequent discharge cleaning. This indicates that H_2 discharge cleaning is effective in reducing carbon in the ISX-A tokamak. Z_{eff} increased from near 1.0 before installation of the graphite limiters to about 5 immediately after installation. During the 12 operational days succeeding graphite limiter installation Z_{eff} steadily decreased to values near 2. Indications are that with continued operation even lower Z_{eff}'s could probably have been obtained.

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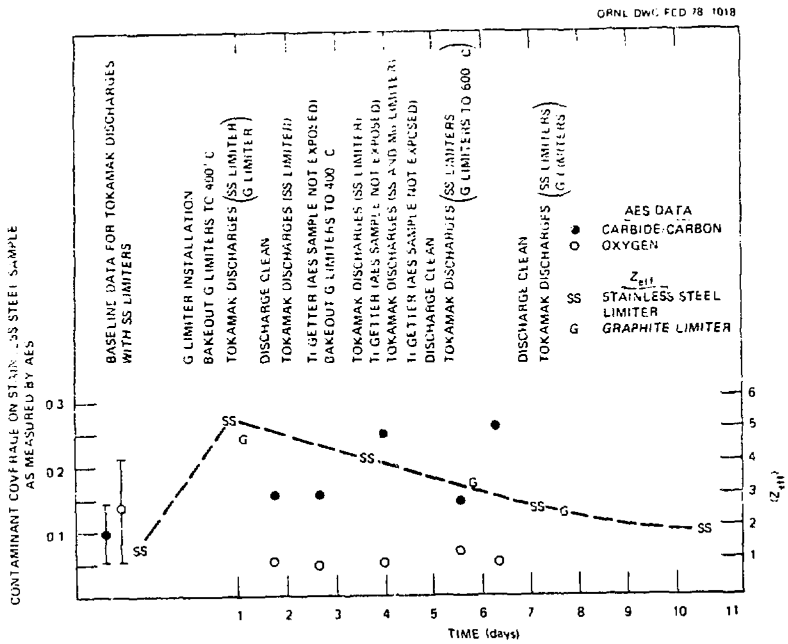

Fig. 6. Time history of graphite limiter experiment.