INITIAL TESTING OF COATED LIMITERS IN ISX-B

CONF-800455--8

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Abstract

Low-Z coatings on graphite substrates have been developed for testing as limiters in the Impurity Study Experiment (ISX-B) tokamak. Laboratory and tokamak testings have been accomplished. The laboratory tests included thermal shock experiments by means of pulsed e-beam irradiation, arcing experiments, and hydrogen and xenon ion erosion experiments. The tokamak testing consisted of ohmically heated plasma exposures with energy depositions up to 10 kJ/discharge on the limiters.

The coatings, applied by chemical vapor deposition, consisted of TiB_2 and TiC deposited on POCO graphite substrates. The limiter samples were interchanged through the use of a transfer chamber without atmospheric exposure of the ISX-B tokamak. Limiter samples were baked out in the transfer chamber before use in the tokamak. Provisions for both heating and cooling the limiter during tokamak discharges were made.

*Operated by Union Carbide Corporation for the Office of Fusion Energy, U.S. Department of Energy, under contract W-7405-eng-26.

†Operated by Sandia Laboratories under contract DE-AC04-76-DP0789 with the U.S. Department of Energy.

Initial testing of the limiter samples consisted of exposure to only ohmically heated plasmas; subsequent testing will be performed in neutral-beam-heated plasmas having up to 3 MW of injected power. Bulk and surface temperatures of the samples were measured to allow the determination of energy deposition. Extensive plasma and edge diagnostics were used to evaluate the effect of the limiter on the plasma (e.g., vacuum ultraviolet spectrometry to determine plasma impurity concentrations, Thomson scattering to determine Z effective, IR camera to measure limiter surface temperature, and laser fluorescence spectrometry to determine neutral impurity concentration and velocity distribution in the limiter region).

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Introduction

The objectives of this experiment were to compare the performance of TiC and TiB_2 coated limiters with that of stainless steel limiters in an ohmically heated tokamak environment and to gain operational experience in using coated limiters. The Oak Ridge National Laboratory (ORNL) Impurity Study Experiment (ISX-B) tokamak was used for testing; its diagnostic capabilities are described in Ref. [1]. These comparisons between the coated limiters and the stainless steel limiters were made with ohmically heated plasmas centered between the inner and outer limiter. For these studies only the outer limiter was changed; the inner limiter remained stainless steel. For the centered plasma configuration the energy deposited on the outer limiter was small, ∿2 kJ per discharge; therefore, in order to attain maximum, but controllable, heat loads on the outer limiter, the plasma position was moved out by 3 cm after establishing

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the discharge at the geometrical center and this limiter was set 1 cm inside its normal position. For these plasma-shifted conditions, energy deposition to the outer limiter was increased to 10 kJ per discharge and comparisons were made with measurements using centered plasmas.

In the next section the limiter development program is briefly described; a description of the limiter transfer system follows. The effects of the limiters on tokamak operation are presented along with results of several plasma and limiter diagnostics. Results of post-test analysis of the limiters are given, followed by some general conclusions and a summary of future plans.

Limiter Development

The limiter development program and laboratory testing procedures and results are discussed in detail in Refs. [2] and [3].

The limiters were mushroom shaped with a 14-cm diameter, a 14-cm radius of curvature at the center, and a 3.8-cm-deep head on a 5.1-cm-diam stem and were threaded into a copper support cup. Figure 1 shows both the front and rear view of the TiC-coated limiter and the support cup.

Four limiter types were fabricated for the testing program: a 304L stainless steel limiter and three graphite (POCO AXF-FQ) limiters with 10-15 μm coatings of TiC, TiB_2, and B, respectively. These coatings have been developed, characterized, and tested for ion and arc erosion and thermal fatigue resistance in a materials program described in Ref. [3], which provides the deposition parameters and test results. Coating thicknesses were measured at nine positions on the TiC and TiB_2 limiter surfaces by 5-MeV proton backscattering analysis [4] prior to tokamak testing. The TiC mean coating thickness was quite uniform: 8.6-9.2 μm with local variations of ±1.4 μm. The TiB_2 mean coating thickness varied from 5.8-12.5 μm with local variations averaging ±2.9 μm.

Limiter Transfer System

In order to test limiters efficiently, it was necessary to design a transfer system that would allow for changing limiters while maintaining good vacuum conditions in the tokamak and for baking and cleaning a new limiter before insertion into the tokamak. Figure 2 shows a schematic drawing of the transfer system that meets the above requirements and provides the following capabilities:

(1) high vacuum (10^{-6} Pa),

(2) bake-out to 400°C,

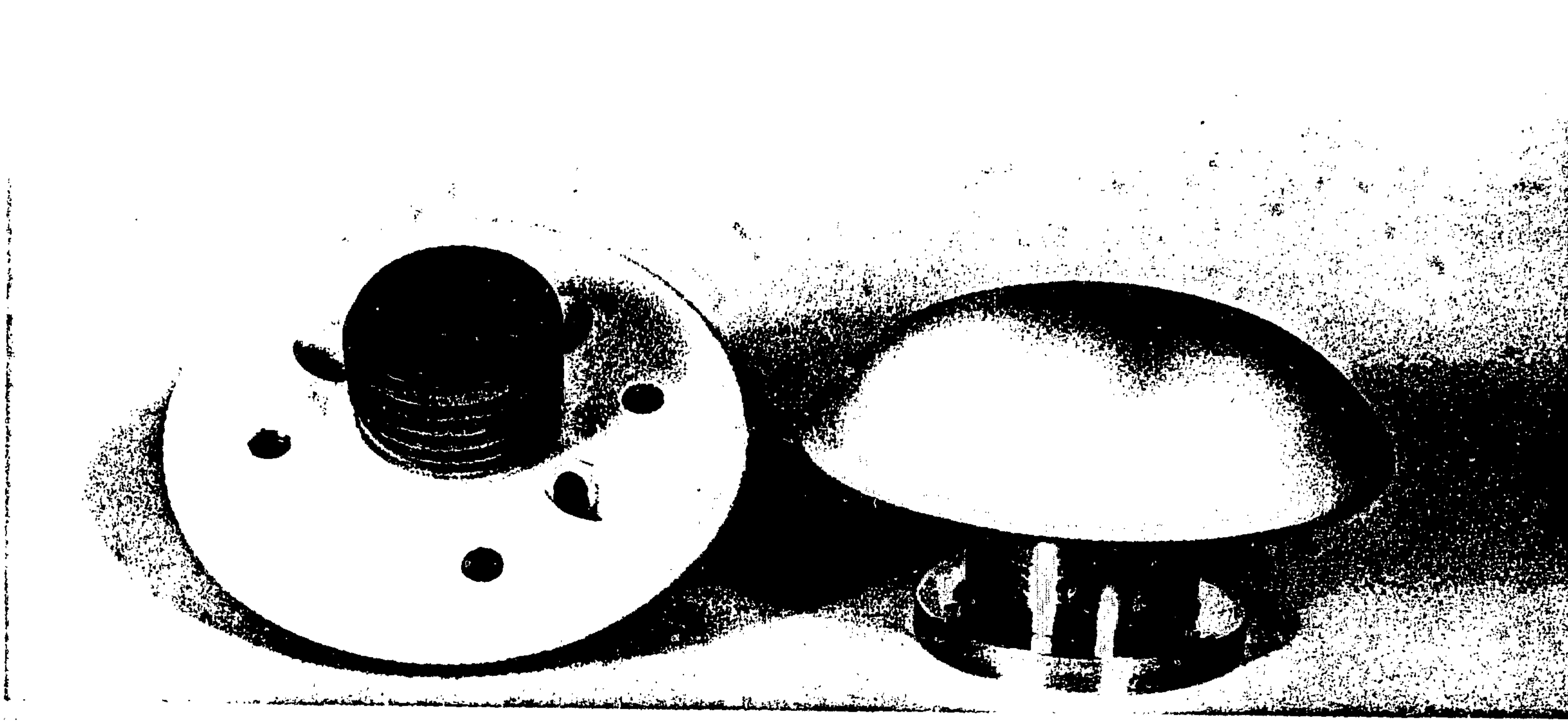
(3) glow discharge cleaning,

(4) precise position control,

(5) temperature measurement of limiter, and

(6) power deposition measurement.

Figure 3 is a photograph of the limiter mounted on the transfer rod with the heater and thermocouples installed. The stainless steel shield, which is used to protect the heater and thermocouples from damage by the plasma, was removed for this photograph.



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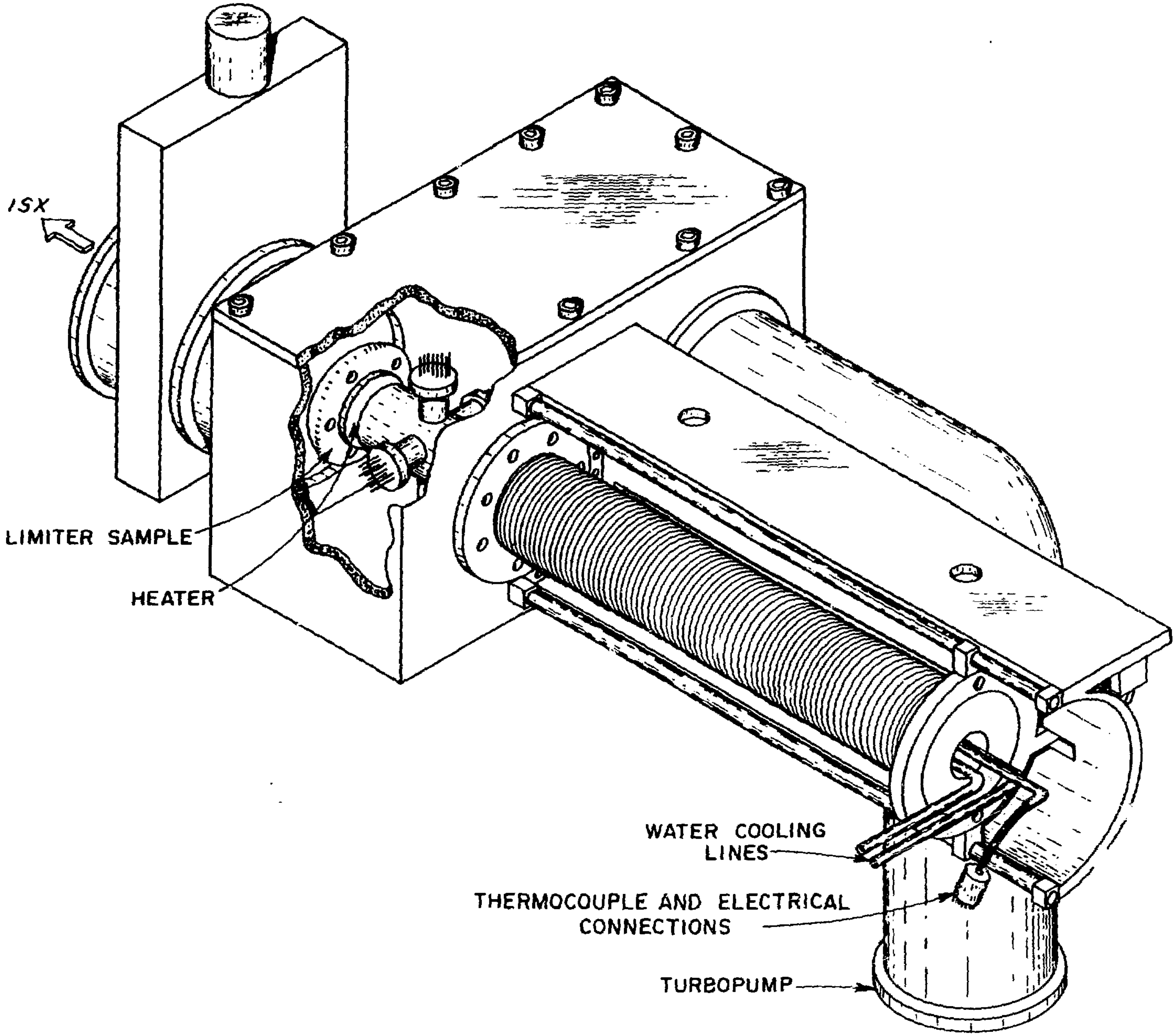
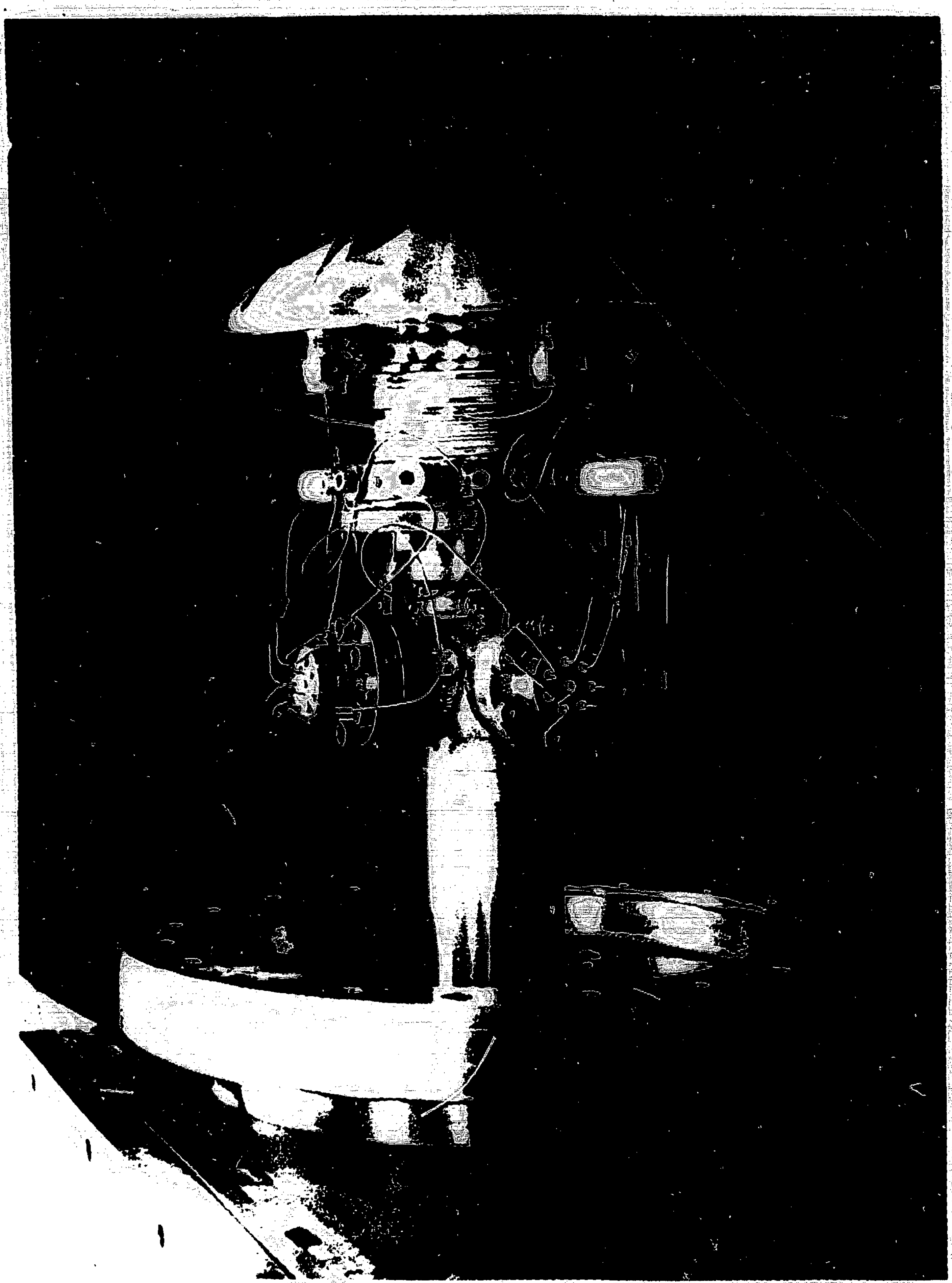
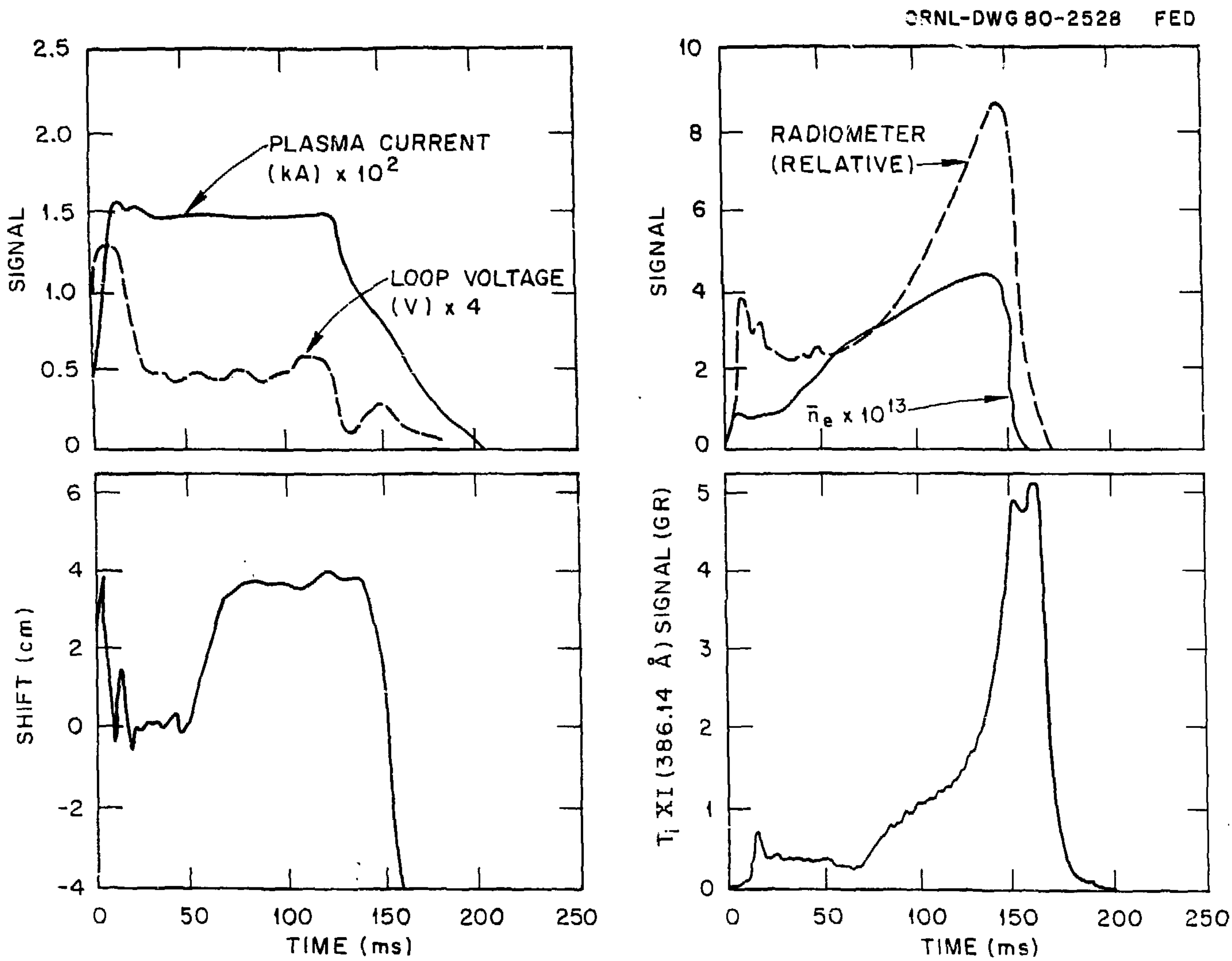




Results of Tokamak Testing

On the first day of testing, tokamak operation with the TiC-coated limiter resulted in reproducible and clean ($Z_{eff} < 3$) discharges. Initial operation with the TiB_2-coated limiter did not result in plasmas as reproducible, but after a short conditioning period, one day, reproducible and clean discharges were obtained. For discharges with the plasma centered, only a small fraction of the ohmic heating power was deposited on the outer limiter; therefore, in order to give the coated limiters as severe a test as possible while maintaining controllable plasmas, the outer limiter was moved in 1 cm and the plasma was shifted out by 3 cm after the discharge at the geometrical center was established. The demand to shift was supplied at 50 ms for the remainder of the discharge; the actual shift was determined from magnetic probes, and the signal is displayed in Fig. 4c. Also displayed in Fig. 4 are the plasma current (4a), loop voltage (4a), average electron density (4b), major fraction of radiated power (4b), and power radiated in the Ti XI (386.14 Å) line (4d). Both the radiated power and the Ti signal increase about a factor of four when the shift is applied. After the termination of the discharge at ∿130 ms the Ti signal rises sharply as disruption occurs. The results of time and spatial measurements of the surface temperature of both the inner and outer limiters are shown in Fig. 5. Both limiters are observed on the same scan by the use of mirrors. A schematic diagram of the inner and outer limiters is shown so as to distinguish the various parts of the system. The angle of viewing is oblique for both limiters and is indicated at the top of the figure. The abscissa is the scan time of the infrared camera. The scans are sequential starting at times into



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PLASMA CURRENT (kA) x 10²
LOOP VOLTAGE (V) x 4
SIGNAL
RADIOMETER (RELATIVE)
n̄e x 10¹³
SHIFT (cm)
Ti XI (386.14 Å) SIGNAL (GR)
TIME (ms)

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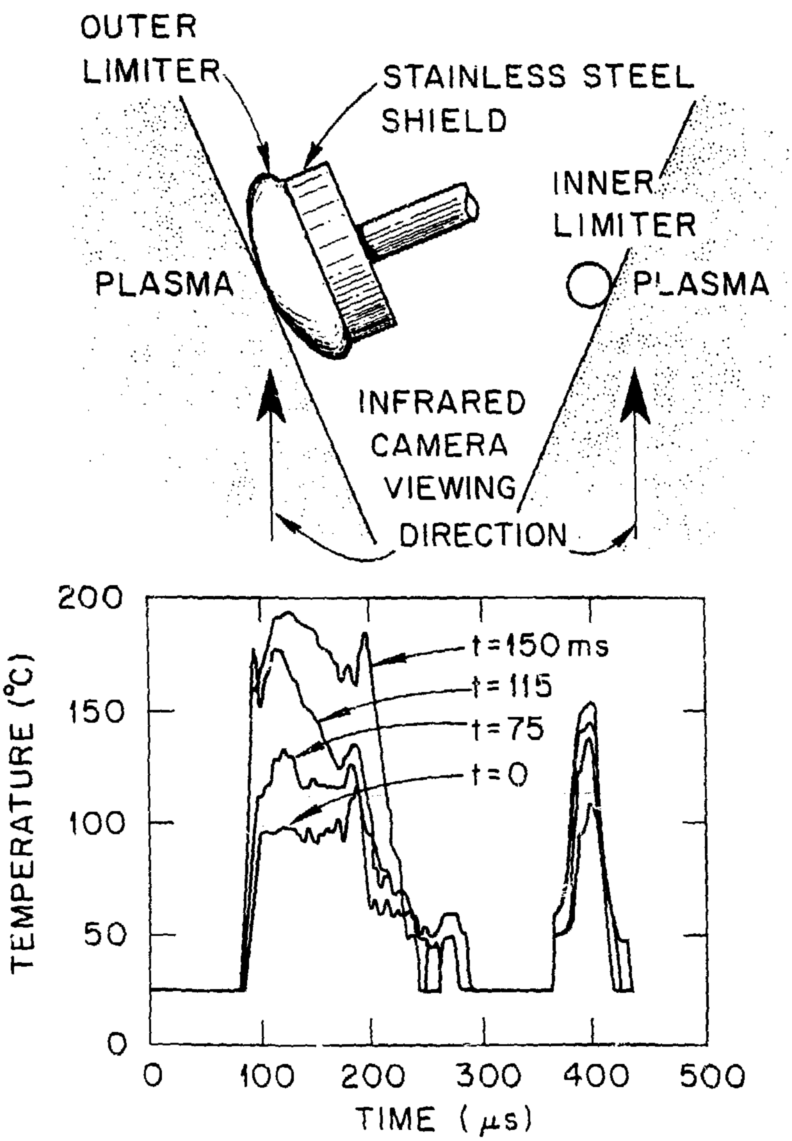
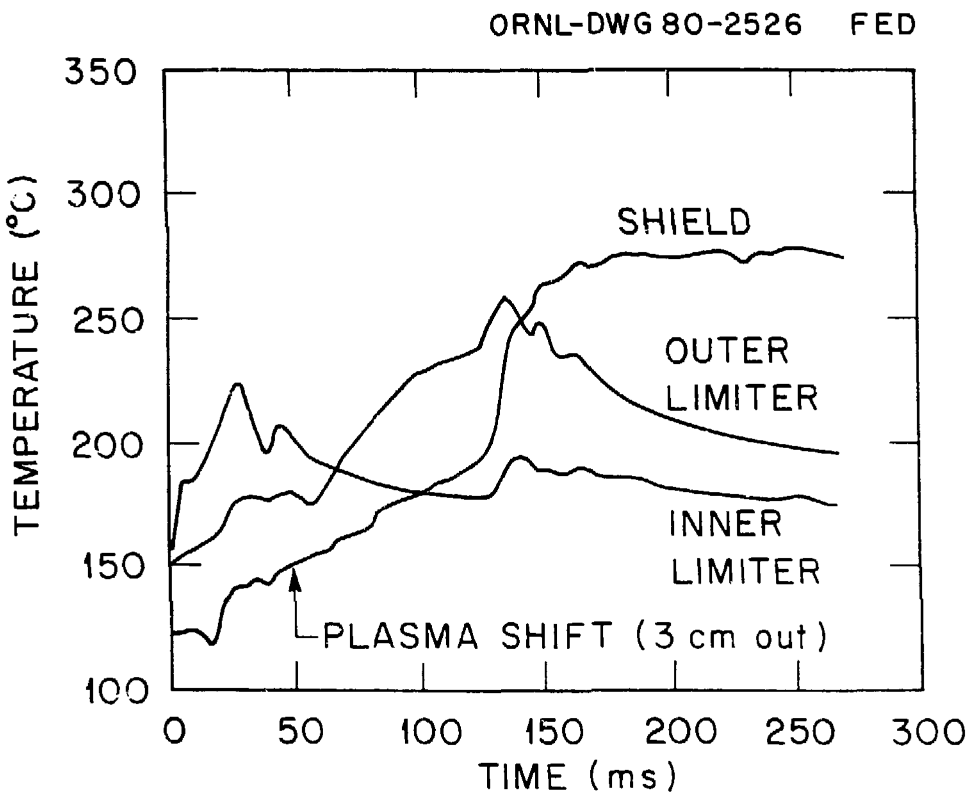


the tokamak discharge of 0, 75, 115, and 150 ms. The time evolution of the surface temperatures of the limiters and the shield is shown in Fig. 6. As the plasma position is shifted at 50 ms, the temperature of the outer limiter rises sharply while at the termination of the discharge (∿130 ms), both limiters rise in temperature and then fall; however, the shield rises substantially in temperature and remains at an elevated temperature for a considerable time. Because the shield is only 0.3-mm-thick stainless steel and is thermally isolated, this result is not surprising.

Laser fluorescence spectroscopy, which observed neutral iron in the limiter shadow region, measured a much lower (by a factor of ∿3) Fe signal when coated limiters as opposed to stainless steel limiters were used. Also, measurements of impurity atoms by laser-induced photoluminescence spectroscopy at 1 cm into the plasma from the outer limiter edge showed Fe levels of $10^8/cm^3$ when the stainless steel outer limiter was used and Fe levels of $2 \times 10^7/cm^3$ and titanium levels of $7 \times 10^7/cm^3$ when the TiC- and TiB_2-coated limiters were used. This indicates a strong interaction between the outer limiter and the plasma on shifted discharges.

Post-Tokamak-Test Analysis

Following tokamak testing the TiC- and TiB_2-coated limiters and the stainless steel limiter were inspected for damage. The stainless steel limiter showed extensive arc track damage (Figs. 7a and 7b) primarily on the ion side. Considerable melting and material loss occurred. The TiC-coated limiter (Figs. 8a and 8b) exhibited much less severe arc track



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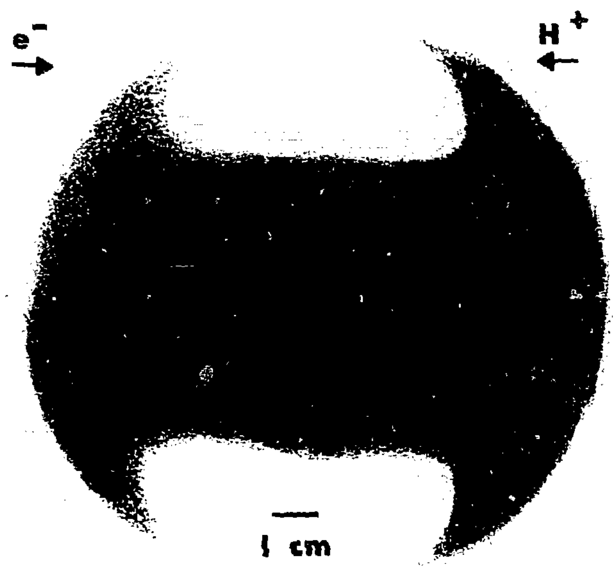
350
300
250
200
150
100
TEMPERATURE (°C)
SHIELD
OUTER
LIMITER
INNER
LIMITER
PLASMA SHIFT (3 cm out)
0
50
100
150
200
250
300
TIME (ms)


e^-
H^+
1 cm


1 cm
H^+


e^-
H^+
1 cm


1 cm
H^+

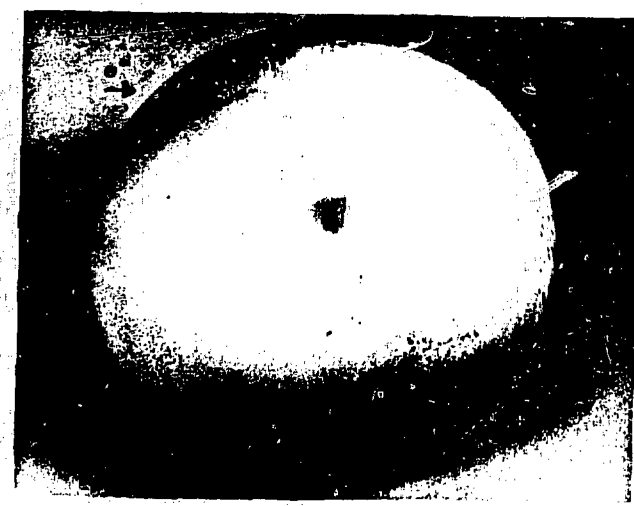
damage; the only other flaw was a thin crack in the coating that follows a machining groove on the electron side of the limiter. The TiB_2-coated limiter (Figs. 9a, 9b, and 9c) also had faintly visible vertical arc tracks but experienced much more arcing damage on the ion side edge (Figs. 9b and 9c). The coating had clearly spalled off, and craters had developed into the graphite substrate. Using a high-magnification microscope it was observed that the coating at the crater's edge exhibited melting. On the electron side (Fig. 9a) the coating was crazed over a 6-cm-wide region. A polished metallographic section of this region showed a degradation of the surface that does not, in general, penetrate through to the graphite substrate; however, scanning microscopy did observe some spots where the graphite was exposed. This degradation is thought to relate to vaporization of coating impurity species (chlorine and oxygen) that causes a disruption in the continuity of the surface layer.

Conclusions and Future Plans

For both TiC- and TiB_2-coated limiters the plasma operation was satisfactory and resulted in reproducible and clean discharges. However, although the TiB_2-coated limiter performed well as a limiter, it did show some damage; the TiC-coated limiter, on the other hand, performed well but showed only minimal evidence of damage. The maximum heat load corresponded to an average power density of about 0.5 kW/cm^2, which is an order of magnitude less than the maximum expected in beam-heated discharges.

Future plans include testing coated limiters in beam-heated plasmas (up to 3 MW of injected power). Both TiC and TiB_2 coatings on POCO graphite and possibly other coating materials and substrates will be


1 cm



tested. Tentative plans call for replacement of the inner limiter with a TiC-coated limiter.

Acknowledgments

The ISX-B operations and plasma physics groups receive our appreciation for a diligent effort in testing the limiters. We would especially like to thank the following persons for use of their data in the paper: C. E. Bush (ORNL) — Infrared camera studies; R. C. Isler (ORNL) — VUV spectrometer studies; B. Schweer (KFA, Jülich) — Laser fluorescence spectroscopy studies; and C. H. Muller (GA) — Laser-induced photoluminescence studies.

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[1] M. J. Saltmarsh, to be published in J. Vac. Sci. Technol.

[2] M. J. Davis, R. A. Langley, and T. S. Prevender, Sandia Laboratories Report SAND77-1027, August 1977.

[3] A. W. Mullendore, J. B. Whitley, and D. M. Mattox, submitted for publication in J. Nucl. Mater.

[4] B. L. Doyle (Sandia Laboratories, Albuquerque), private communication, 1980.

FIGURE CAPTIONS

Fig. 1. Photograph of TiC-coated limiter. Copper support cup is also shown.

Fig. 2. Schematic drawing of limiter transfer system.

Fig. 3. Photograph of limiter mounted on transfer rod. Note coaxial heater installed on copper support cup and thermocouples installed in limiter; stainless steel protective shield is removed.

Fig. 4. Typical plasma parameters for a shifted discharge: (a) plasma current and loop voltage, (b) average electron density $\bar{n}_e$ and major fraction of radiated power to the wall, (c) plasma position, and (d) power radiated in the Ti XI (386.14 Å) line.

Fig. 5. Limiter surface temperatures as determined by infrared camera measurements for times of 0, 75, 115, and 150 ms into tokamak discharge. The various components and the angle of viewing are displayed in the upper section.

Fig. 6. Time-resolved surface temperatures of inner (stainless steel) limiter, outer (TiC-coated) limiter, and stainless steel shield during shifted discharge.

Fig. 7. Photographs of outer stainless steel limiter after 437 centered discharges: (a) photograph taken on axis of limiter and (b) photograph taken about 30° to limiter axis on ion side. Note extensive arcing on the ion side.

Fig. 8. Photographs of outer TiC-coated limiter after 154 centered discharges and 136 shifted discharges: (a) photograph taken on axis of limiter and (b) photograph taken about 30° to limiter axis on ion side. Note small amount of arc damage.

Fig. 9. Photographs of outer TiB_2-coated limiter after 121 centered discharges and 104 shifted discharges: (a) photograph taken about 70° to limiter axis on electron side, (b) photograph taken on axis of limiter, and (c) photograph taken about 120° to limiter axis on ion side. Note large (∿6 cm) crazed area on electron side (a) and arc induced spalling on ion side (b and c).