CONF-800439--3

SAND79-2105C

TESTING OF LOW Z COATED LIMITERS IN TOKAMAK FUSION DEVICES*

J. B. Whitley, A. W. Mullendore
Sandia National Laboratories**
Albuquerque, New Mexico 87185

and

R. A. Langley
Oak Ridge National Laboratory†
Oak Ridge, Tennessee 37830

MASTER

ABSTRACT

Low Z coatings are being developed for application both in experimental tokamak devices such as ISX and TFTR and for possible use on various components of large power producing controlled thermonuclear reactors (CTR's). A suitable coating has the potential of improving the plasma energy balance by lowering the Z of impurities injected by plasma-wall interactions. This results in a decrease of plasma radiation losses and improved plasma stability. The coatings will be subjected to a severe environment, and must be able to withstand physical erosion, chemical erosion, thermal shock thermal fatigue and arcing without rapid degradation or loss of adhesion.

Extensive testing on a laboratory scale has been used to select those coatings most suitable for this environment. From this testing,

---

*This work is supported by the Office of Fusion Energy, U.S. Department of Energy (DOE), under Contract DE-AC04-76-DP00789.

**A U.S. DOE facility.

† A U.S. DOE facility.

which included pulsed electron beam heating, low energy ion bombardment and arcing, chemical vapor deposited coatings of TiB_2 and TiC on Poco graphite substrates have been selected and tested as limiters in ISX. Both limiter materials gave clean, stable, reproducible tokamak discharges the first day of operation. After one weeks exposure, the TiC limiter showed only superficial damage with no coating failure. The TiB_2 limiter had some small areas of coating failure. TiC coated graphite limiters have also been briefly tested in the tokamaks Alcator and PDX with favorable results.

INTRODUCTION

In the past several years, significant advances have been made in producing fusion power reactor type conditions in tokamak devices. The recent results from the Princeton tokamak PLT indicate that the ion confinement time will not deteriorate at the high ion temperatures necessary for useful fusion power to be generated and that the next generation tokamaks should reach energy breakeven (i.e., output fusion energy greater than the energy supplied for plasma production and heating). These results in PLT were made possible by the use of low Z materials which reduced the plasma radiation losses due to impurity injection. As the plasma physics experiments have reached higher temperatures and densities, the introduction of impurities from plasma-wall interactions has become an important factor in machine performance. In particular the limiters, which serve to define the plasma shape and to protect the first wall from plasma excursions, interact strongly with the plasma and are an important source of plasma impurities. This paper will review the tokamak testing of both low Z limiters and of low Z coated limiters.

THE TOKAMAK

The term tokamak is the generic name for those types of toroidal machines which use the current induced in the plasma to enhance particle confinement and plasma stability.[1,2,3,4] A doughnut shaped plasma can be formed by a set of toroidal field (TF) coils (~18 coils) surrounding the plasma. While this geometry does have closed field lines, plasma confinement is poor due to the instabilities caused by the lower field on the outside of the torus. In a tokamak, this problem is overcome by making the plasma serve as the secondary of a large transformer and inducing a large current (10^5-10^6 A) in the plasma. The magnetic field from this poloidal current make the resultant magnetic field lines form helices, greatly enhancing plasma confinement. In addition, this large current serves to ohmically heat the plasma. With the addition of a few smaller vertical field coils, the plasma can be positioned and controlled during relatively long (>1 sec.) discharges.

Several parameters from a typical discharge in the Oak Ridge National Laboratory ISX-B tokamak are shown in Figure 1. At about 50 msec. before the shot, two things happen. The chamber is prefilled with the working gas (~10^{-2} Pa of D_2 in this case) and the TF coils are energized. By t = 0, the TF coil current will be stable and will not change throughout the shot. At t = 0, a current is induced in the iron core and the resultant field ionizes the gas forming a plasma. The plasma current is then set by controlling the current in the iron core. At t = 50 msec, a puff of gas is introduced to raise the plasma density and to quench some plasma instabilities which often occur at this time. A slow gas fill throughout the discharge then leads to a continual increase in density, with the central electron density in this discharge reaching 5 x 10^{13} cm^{-3}. At t = 130 msec, the plasma current is ramped down and the discharge is usually completely gone by 200 msec. The magnetohydrodynamic (MHD) level is a measure of the plasma stability where a high MHD level indicates gross plasma oscillations. The MHD level is high during the plasma formation, and even a good discharge eventually ends by a sudden disruption. Even under the best operating conditions, at least 10% of the tokamak discharges develop instabilities which disrupt the discharge before the current is ramped down. When a disruption occurs, the energy contained in the plasma (>6 kJ) is deposited onto the walls or limiters over an unspecified area and time interval.

The determination of the actual plasma conditions achieved is made by the various diagnostic devices surrounding the tokamak.[5] Due to the large energy content of the plasma, it is impossible to physically insert probes into the plasma and hence the plasma conditions must be inferred from indirect measurements. On ISX, some of these include Rogowski coils to measure plasma current, diamagnetic loops and internal coils to monitor plasma shape, position and MHD activity, a Thompson scattering system to measure electron density and temperature, radiometers to measure radiated power, spectrometers to determine plasma purity, residual gas analysers to measure background gases, and an infrared camera to measure limiter surface temperatures. The large number of diagnostics placed on these machines severely limits the number and size of ports available for materials studies. In addition, most of the emphasis on plasma diagnostics has been placed on the bulk plasma properties and not on the plasma conditions in the difficult to measure edge region. As of now, the environment seen by the limiters in tokamaks is very poorly defined (for a review of plasma wall interactions, see Ref. 6).

The plasma energy balance is shown schematically in Figure 2. While the plasma is initially heated by ohmic heating, the maximum temperature achievable by this method alone is about 1 keV due to the decreasing plasma resistance at high temperatures. To reach the 10 keV ion temperature necessary for ignition, some type of auxiliary heating is necessary. The method used at present is to inject large amounts (>1 MW) of high energy (50-200 keV) neutrals of deutrium into the plasma. Being neutrals, the particles can penetrate the high magnetic fields and reach the plasma, where they are ionized and give their energy to the plasma particles.

The plasma loses energy by several paths. Any neutrals that are formed in the plasma will no longer be confined by the magnetic field, and unless they are reionized, they will escape and impinge on the walls. Ions and electrons can diffuse across the field lines and those near the edge will be removed by the limiters. The plasma particles will also radiate energy to the walls, and it is here that the choice of materials can strongly affect plasma performance. The types of radiation in order of increasing importance are Bremsstrahlung, line, and recombination. Low Z particles are fully ionized in the plasma core and hence do not give off line or recombination radiation.

These particles only radiate strongly when they are in the plasma edge region. High Z particles, such as tungsten, are not fully ionized in the plasma core and strongly cool the plasma by emitting line radiation. Since it will be very difficult to keep from introducing some structural material into the plasma from plasma-wall interactions, it seems clearly advantageous to keep the wall materials of as low a Z as possible.

The final contribution to the plasma energy balance comes from the fusion products themselves. While the bulk of the fusion energy release is carried off as high energy neutrons, the 4 MeV alpha particle products will be trapped by the magnetic field and will heat the plasma as they slow down. If the radiation losses are not too large, the energy gain from the alpha particles can equal the power losses, at which time the plasma temperature can be maintained without external heating and the plasma is said to be ignited. An ignited plasma is the ultimate goal of the magnetic fusion program and the control of high Z impurities in the plasma is essential to obtaining this goal.

LOW Z LIMITER TESTING IN TOKAMAKS

The majority of operating tokamaks have used limiters of refractory metals such as molybdenum or tungsten to withstand the high thermal fluxes. As the tokamak operating conditions were improved and as the level of other impurities was reduced, lower Z materials have been used. One approach has been to choose metals of lower Z, and reasonably good operation has been achieved in ISX-A using stainless steel limiters,[7] in PDX using titanium and in Doublet III using Inconel. Aluminum was tried in the ST tokamak[6] and improved the plasma performance over the usual molybdenum limiter, but the low melting point of aluminum makes it impractical for use in the hot, beam heated discharges of present machines.

Graphite and boron carbide have also been tried as limiter materials. Bulk boron carbide was tried in TFR[8] and found incapable of withstanding the thermal shock. Graphite was also tried in TFR[8] and while it could take the thermal shock, the plasma performance was not improved substantially. Graphite limiters were tested in ISX-A[9] for a two week period. The hydrocarbon contamination increased significantly when the limiter was heated above 400°C during the discharges, indicating enhanced chemical erosion.[10] The primary physical damage observed on the limiter was arcing. By moving the graphite limiters in and out, discharges were run on both graphite and stainless steel limiters with the only significant change in plasma parameters being reduced power radiated to the walls when the graphite limiters were inserted. The most successful use of graphite limiters has been in PLT. The PLT discharges have been significantly improved by replacing the tungsten limiters with graphite limiters[2] which were actively cooled to reduce chemical erosion. The significant advances made in ion and electron temperature in the beam heated discharges of PLT were due largely to the lower radiation losses from the plasma core, and thus the advantages of using low Z limiters have been clearly established.

TESTING OF LOW Z COATINGS IN ISX-B

Materials Selection and Coatings Screening

A joint program is currently being conducted between Sandia National Laboratories and the Fusion Energy Division of Oak Ridge National Laboratory to test low Z coated limiters in the ISX-B tokamak. To allow the greatest flexibility in materials and coating process selection for limiter application, a series of low Z coatings ~~were~~ was screened and evaluated.[10-15] The coating/substrate combinations chosen for extensive evaluation are listed in Table 1. Coatings were applied to the graphite substrates since bare graphite suffers from enhanced chemical erosion at temperatures above 400°C.[10] Several coating techniques capable of depositing relative thick (>10 μm) coatings of refractory materials were studied, with the main emphasis on the chemical vapor deposited coatings of TiC[16] and TiB_2[17,18] on graphite.

The limiter environment in tokamaks is quite severe, and due to the limited time available for limiter testing in tokamaks and to the delays that could be caused by a catastrophic failure of a limiter, it is imperative that only those candidate materials believed capable of acceptable performance actually be tested as limiters. To this end, an extensive laboratory testing program was developed to proof test these materials. The coatings were characterized, their ion and arc erosion rates determined and their thermal fatigue resistance measured in a materials program described in Reference 19 which gives the deposition parameters and test results.

From this testing, chemical vapor deposited coatings of TiC and TiB_2 on a graphite (Poco AXF-5Q) substrate were selected for tokamak testing. The coatings thicknesses were 9 ± 1 μm for the TiC and 9 ± 3 μm for the TiB_2 coating. The TiB_2 coated limiter was vacuum annealed following deposition to reduce the intrinsic stress level and the level of chlorine impurities in the coatings.

A limiter transfer system was designed which allowed the primary outer limiter to be withdrawn and valved off from the tokamak. The limiter could then be changed, the transfer system evacuated and the new limiter baked before insertion into the machine. This system allowed a rapid limiter changeover with no vacuum contamination problems. The limiters were mushrooms (see Fig. 5) with a 14 cm diameter by 3.8 cm deep head supported on a 5.1 cm diameter stem. Thermocouples are embedded directly into the limiter, and the limiter support ring could be either water cooled or resistance heated. The time dependent temperature and stress distributions in the coated mushroom were modeled using a finite element computer code assuming various forms for the heat flux.[15] With a heat flux of 3 kW/cm^2 for 0.2 seconds, the maximum surface temperature was calculated to be 810°C and the maximum coating stress to be 1700 MPa compressive.

RESULTS AND DISCUSSION

A 304 stainless steel limiter of the same design was used to gather baseline data for comparison. All of the tests to date have been run in ohmically heated discharges with the conditions shown in Figure 1. The total energy content of the plasma was about 8 kJ and the ohmic power input 200 kW. The stainless steel limiter was removed after a two week exposure and is shown in Figure 3. The damage consisted of extensive arcing, primarily on the ion side (i.e., the side that intercepts the net ion flux from the plasma current). The arc track density increased near the edge of the limiter and there were a few small melted spots.

The TiC and TiB_2 limiters were each exposed for one week. In both cases, it was possible to obtain clean, stable, reproducible discharges the first day of operation with the new limiter. None of the contamination problems that occurred when the graphite limiters were installed in ISX-A were observed with the use of the limiter transfer system, and hence the practicality of periodically changing the outer limiter was established. The power to the limiter was estimated by measuring the temperature rise of the limiter and by measuring the heat transferred by the cooling water. Under normal operating conditions, the energy deposition on the outer limiter was about 2 kJ per pulse. To increase the power load on the limiter, the limiter was inserted an additional 1 cm into the torus and the plasma, after being generated in the geometric center of the device, was shifted out 3 cm. This procedure increased the energy deposition to ~10 kJ per pulse, or about 0.5 kW/cm^2. With the plasma shifted, the surface temperature of the limiter would rise approximately 100°C while the base temperature rose to 60°C by the end of a days run.

The ultra-violet emission from the titanium and iron atoms in the discharge ~~were~~ was monitored during this testing. With the plasma unshifted, the titanium signal was very low and the iron signal had decreased by about 15% over the signal with the stainless steel limiter. When the plasma was shifted onto the outer limiter, the titanium signal increased by a factor of 7 with the TiC limiter and a factor of 5 with the TiB_2 limiter. Iron was still a major impurity, however, indicating that the plasma was continuing to interact with some stainless steel components.

The TiC coated limiter after removal is shown in Figure 4. There were no areas of coating spall, with the only defect being a crack on the electron side running for about 5 cm along a machining mark of the graphite substrate. The ion side shows evidence of arcing as did the stainless limiter, but the arc tracks did not extend through the coating.

When operating with the TiB_2 limiter, the machine behavior was quite similar to the TiC limiter except for the final operating day. During this day of operation, the discharge stability rather suddenly decreased and it became very difficult to obtain good discharges. On removing the TiB_2 coated limiter, there were several areas of coating failure as is shown in Figure 5. This failure occurred on the ion side and seems to be a failure caused by the heavy arcing. Whether the coating failure was the cause of the poor machine operation is unclear, but the areas of coating failure may have outgassed enough to affect the discharges. There is also an uncertainty as to the actual environment seen by the limiters, and the possibility exists that the TiB_2 could have seen an abnormal environment for a short time that was more damaging than that seen by the TiC. However, from these results, the TiC is clearly the leading candidate material with the TiB_2 coating requiring more testing and development.

OTHER TiC TESTING

In addition to the coating testing program on ISX-B, TiC on Poco graphite limiters have been tested briefly in Alcator[22] and PDX.[23] In Alcator, a small TiC coated limiter segment was inserted beyond the normal molybdenum limiter such that it served as the primary limiter. During the initial operation with this limiter, an arc from the coated limiter to the wall spalled a small area of the coating. The subsequent machine behavior was erratic and poor. The limiter was removed and baked in a separate vacuum chamber, where it outgassed significant amounts of water and hydrocarbons. After baking, the limiter was loaded back in the tokamak where it performed successfully and lowered the molybdenum emission from the plasma a factor of two. A similar experiment was performed in PDX, where a TiC coated limiter was inserted beyond the normal titanium limiters for 30 shots. The PDX discharges were 0.5 sec. in duration and and the heat load to the limiter was estimated to be 500 W/cm^2. The machine behaved well, there was no increase in the emission from either the carbon or titanium lines, and a visual inspection of the limiter revealed no coating failure.

CONCLUSIONS

The advantages of low Z limiters in present day tokamaks ~~is~~ are becoming clear. Pure graphite can serve well if it is kept below 400°C, but this will be a severe limitation in future tokamaks.

To allow operation at higher temperatures, coatings of TiC and TiB_2 have been tested in a tokamak environment. Both coatings performed well in the tokamak, allowing clear, reproducible discharges to be easily established. The TiC coating survived the exposure contact, while the TiB_2 suffered from some local failures. Future testings will expose the limiters to neutral beam heated discharges where the power loading will be an order of magnitude larger than in these ohmic heated discharges.

ACKNOWLEDGEMENTS

The testing program on ISX-B is being conducted with the cooperation and assistance of all the members of the ISX operating staff and their contribution is gratefully acknowledged. In particular, the UV spectroscopy measurements were made by R. Isler and the surface temperature measurements by C. Bush. The chemical vapor deposition studies of TiB_2 were performed by H. O. Pierson of Sandia National Laboratories and his contribution is also acknowledged.

REFERENCES

1. H. P. Furth, "Progress Towards a Tokamak Fusion Reactor," Scientific American, Vol. 241, No. 2, Aug. (1979), 50.
2. M. Murakami and H. P. Eubank, "Recent Progress in Tokamak Experiments," Physics Today, May 1979, 25.
3. L. A. Artsimovitch, Nuclear Fusion 12, (1972), 215.
4. H. P. Furth, Nuclear Fusion 15, No. 2 (1975), 487.
5. C. B. Wharton, Physics Today, May (1979), 52.
6. G. M. McCracken and P. E. Stott, Nuclear Fusion 19, No. 7 (1979), 889.
7. R. J. Colchin et al., J. of Nuclear Materials 76-77 (1978), 405.
8. TFR Group, in Plasma-Wall Interactions (Proc. Internat'l Sym., Julich, 1976), Pergamon Press (1976), 3.
9. R. A. Langley, R. J. Colchin, R. C. Isler, M. Murakami, and J. E. Simpkins, J. of Nuclear Materials 85-86, (1979), 215.
10. R. Berisch, J. of Nuclear Materials, 85-86, (1979), 1047.
11. M. J. Davis, J. of Nuclear Materials, 85-86, (1979), 1063.
12. D. M. Mattox, A. W. Mullendore, H. O. Pierson and D. J. Sharp, J. of Nuclear Materials, 85-86 (1979), 1127.
13. D. M. Mattox, Thin Solid Films, 63 (1979), 213.
14. A. W. Mullendore, D. M. Mattox, J. B. Whitley and D. J. Sharp, Thin Solid Films, 63, 243.
15. A. W. Mullendore, J. B. Whitley, D. M. Mattox, and R. K. Thomas, Presented to 8th Sym. on Engineering Problems of Fusion Research (IEEE) 13-16 Nov. 1979, San Francisco, to be published in the proceedings.

16. L. Aggom, E. Fitzer and J. Schlichting, "TiC Coatings on Graphite by CVD," Proc. of 5th Internat'l Chemical Vapor Deposition Conf., Princeton, NJ, Electrochemical Society, Published in (1975).

17. H. O. Pierson, E. Randich and D. M. Mattox, J. Less Common Metals 67, (1979), 381.

18. H. O. Pierson and A. W. Mullendore, "The Chemical Vapor Deposition of TiB_2 from Diborane," International Conf. on Metallurgical Coatings, April 21-25, 1980, San Diego, CA.

19. A. W. Mullendore, J. B. Whitley and D. M. Mattox, "The Development and Laboratory Testing of Low Z Refractory Coatings for Fusion Reactor Limiters," Presented at 4th Internat'l Conf. on Plasma Surface Interactions in Controlled Fusion Devices, 21-25 April, 1980, Garmisch-Partenkirchen, FRG.

20. H. O. Pierson and A. W. Mullendore, Thin Solid Films 63, (1979), 257.

21. A. A. Popoff, Mech. Engineering, 100, No. 5 (1978), 28.

22. E. S. Marmar, MIT, Personal Communication.

23. M. Ulrickson, PPPL, Personal Communication.

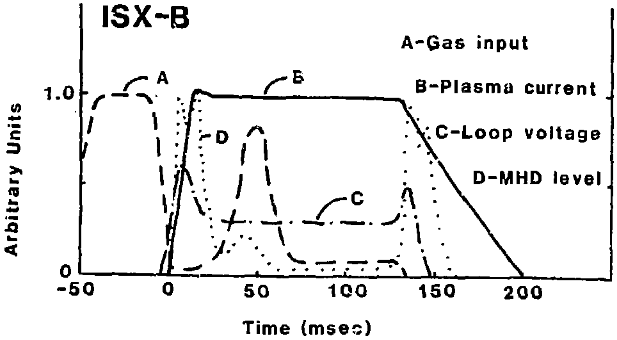

Fig. 1. Several important plasma parameters from a typical tokamak discharge. The plasma current (B) and loop voltage (C) were 150,000 Amps and 2 Volts respectively at 100 msec.

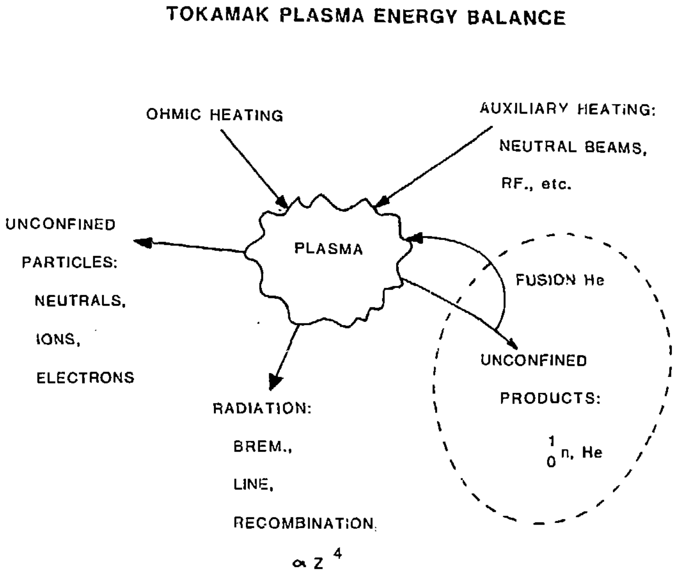

Fig. 2. The energy balance in a tokamak reactor. The section inside the dotted line is the contribution by fusion.

Fig. 3. The ISX-B stainless steel limiter after exposure. The lower picture shows the arc tracks observed on the ion side.

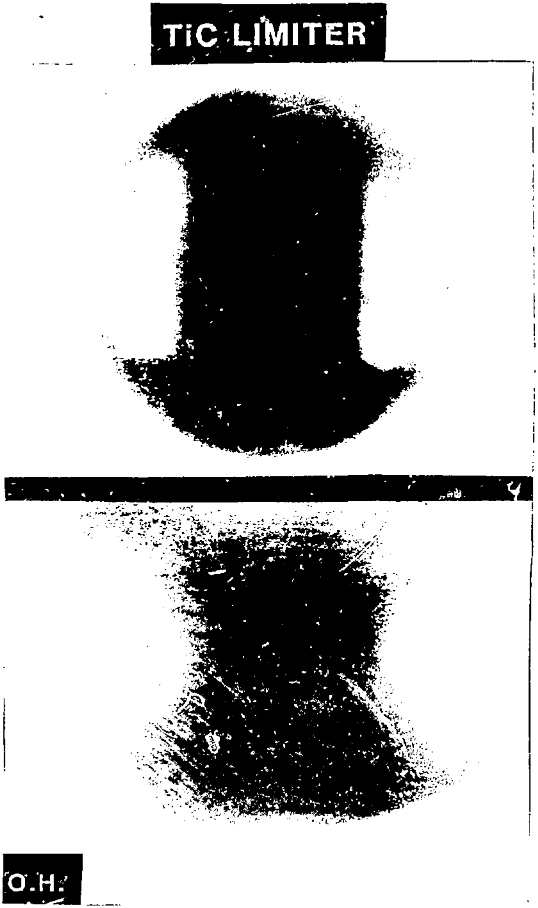

Fig. 4. The TiC coated graphite limiter after a one week exposure. The lower picture is the ion side of the limiter.

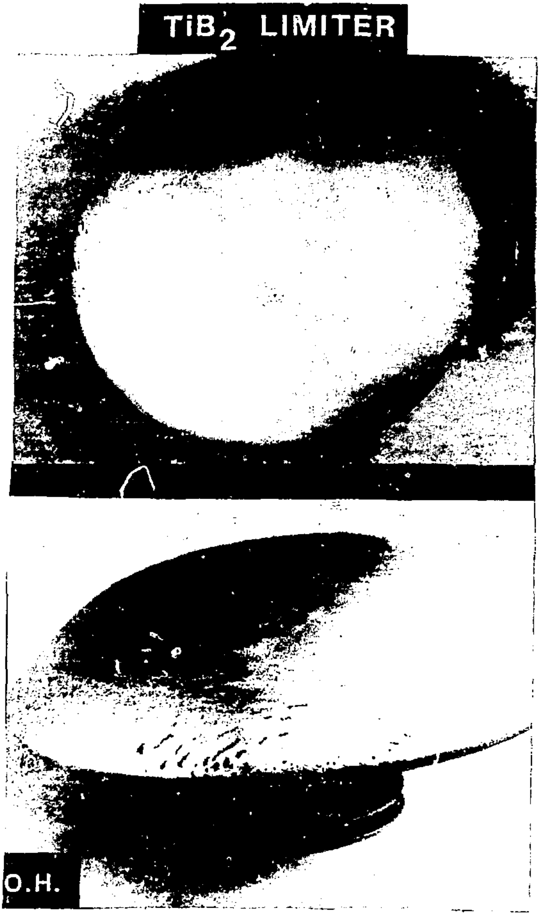

Fig. 5. The TiB_2 coated limiter after exposure. Note the areas of coating failure on the ion side of the limiter.

TABLE I: PRIME LIMITER MATERIALS UNDER ACTIVE DEVELOPMENT

Coating	Substrate	Coating Technique	Supplier	Ref.
TiB_2	Poco[1] AXF-5Q Graphite	CVD - BCl_3 + $TiCl_4$	Sandia Laboratories	17
TiB_2	Poco[1] AXF-5Q Graphite	CVD - B_2H_6 + $TiCl_4$	Sandia Laboratories	18
TiC	Poco[1] AXF-5Q Graphite	CVD - CH_4 + $TiCl_4$	Ultramet[2]	16
TiC	Poco[1] AXF-5Q Graphite	CVD - CH_4 + $TiCl_4$	MTC[3]	16
B	Poco[1] AXF-5Q Graphite	CVD - B_2H_6	Sandia Laboratories	20
TiB_2	Cu	Plasma Spray	UC-Y-12[4]	14
VB_2	V Clad Cu	Chemical Conversion of Explosive Cladding	MRC[5] LASL[6]	21 21

1. Poco Graphite Inc.

2. Ultramet Corp., Pacoima, CA

3. Materials Technology Corp., Dallas, TX

4. Y-12 Division of Union Carbide, Oak Ridge, TN

5. "Borofuze" Process, Materials Research Corp., Medford, MA

6. CMB-6, Los Alamos Scientific Laboratory