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OPERATIONAL HISTORY OF STAINLESS STEEL, TiC, TiB_2, AND BORON LIMITERS IN THE ISX-B TOKAMAK*

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For the past eighteen months a variety of low-Z coatings have been tested for service as limiters in both chmically-heated and beam-heated ISX-B plasmas. To date TiC, TiB_2, and B coatings on a graphite substrate have been examined. The history of these materials in ISX-B is reviewed with particular emphasis and compared with previously used stainless steel limiters on machine performance.

INTRODUCTION

The most commonly used technique to reduce the interactions between the plasma and the first wall in tokamak fusion devices involves the use of mechanical limiters. These devices define the aperture of the plasma and are in intimate contact with it throughout the tokamak discharge. Each successive generation of tokamaks has resulted in hotter and denser plasmas as well as longer pulse lengths, all of which are more demanding on the limiter. Historically, a variety of materials have been used for limiters. These have included, in addition to the refractory metals molybdenum, tungsten, and tantalum, low Z materials, carbon, aluminum, and titanium, and, perhaps most commonly the iron-and nickel-based alloys, stainless steel, and inconel. The use of these materials and their serviceability has been reviewed by McCracken and Stott [1]. For a variety of reasons low Z coatings are under active consideration for service as limiter materials [2–4]. A development program for coatings including extensive laboratory testing has been underway for some time [5–8]. The initial testing of coatings in tokamak environments has been carried out in the Alcator [9], PDX [10,11], ISX-B [9,12–14], and the Doublet-III [15] tokamaks. Although limited testing of TiB_2 and B on graphite substrates has been carried out much more extensive testing was performed using TiC coatings on graphite.

EXPERIMENTAL PROCEDURE

All of the outer limiters tested in ISX-B have been fabricated in the form of a mushroom (Fig. 1) with a head diameter of 13 cm, and a depth of 3.8 cm. A stem with a diameter of

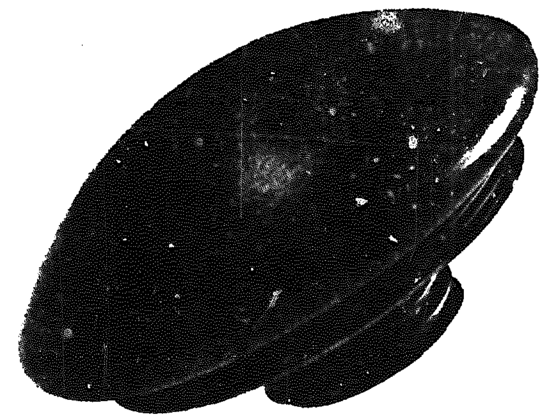

Fig. 1: Photograph of TiC-coated limiter with the skirt removed.

5.1 cm serves as the mounting support. A coated graphite skirt also extends from the rear side and provides shielding for thermocouple connections. The limiter is mounted on a moveable support carriage that permitted control of the radial position within the tokamak. The carriage was equipped with a heater and cooling coils to provide some degree of temperature control of the limiters. Heat was conducted to and from the limiters by means of a copper cylinder machined to fit the stem extending from the rear center of the mushroom head. The carriage was mounted within a separately pumped vacuum chamber and isolated from the ISX vacuum system by means of a pneumatically operated gate valve with a 15 cm aperture. The system was designed to permit changing the limiter without necessitating a vent of the tokamak and has been described previously [13]. Throughout these studies the inner, top, and bottom limiters were stainless steel bars.

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During tokamak operation a variety of diagnostics were available to monitor machine performance and, to a lesser degree, the limiter condition. Most useful in these studies were a number of optical spectrometers used to identify and determine impurity levels in the plasma, various magnetic loops and/or coils to obtain the plasma current and loop voltage from which the resistivity can be obtained, and the Thomson scattering system used to determine the electron temperature, which along with the plasma resistivity, can be used to infer a value for $\langle Z_{eff} \rangle$, the effective atomic number of the plasma. This latter parameter is one measure of the "cleanliness" of the plasma. The usefulness of $\langle Z_{eff} \rangle$ in evaluating limiter materials is open to much doubt as wall impurities, principally oxygen in ISX-B, dominate in determining its value. Thus, a low $\langle Z_{eff} \rangle$ value may not be related to low impurity contributions from the limiter whereas a high value may indicate contributions from the walls or the limiter or both. Limiter diagnostics included thermocouples imbedded within the substrate and a scanning infrared camera to obtain time-resolved surface temperatures. Estimates of the energy deposition in the limiters were obtained from temperature rises and flow rates of the cooling water. Visual and photographic observations were also carried out at various intervals.

RESULTS

In connection with this study a total of seven limiters of four different types have been used throughout the 18 months of operation. This is summarized in Table 1 along with pertinent historical information. The use of several different TiC limiters made possible post-test studies of the condition of the coating and the substrate after various intervals of tokamak exposure. The repeated use of TiC limiters reflects the satisfactory performance of this material in ISX-B. Machine operation with each type of limiter will be summarized in the following discussion.

Table 1

SUMMARY OF OPERATIONAL HISTORY

Limiter	Dates	Number of Shots	Beam Heated Plasmas
Stainless Steel	1/18/80–3/1/80	437	No
TiC#1 on POCO Graphite	3/1/80–3/10/80	301	No
	3/14/80–4/12/80	782	Yes
TiB_2 on POCO Graphite	3/10/80–3/14/80	235	No
TiC#2 on POCO Graphite	4/12/80–7/24/80	3938	Yes
	8/1/80–8/22/80	405	Yes
B on POCO Graphite	7/24/80–8/1/80	257	No
TiC#3 on POCO Graphite	8/22/80–6/6/81	11005	Yes
TiC#4 on POCO Graphite	6/6/81-present	>2300	Yes

Stainless Steel

The initial mushroom shaped limiter used in this study was fabricated from type 304L stainless steel. ISX-B, as well as the earlier ISX-A, operated with stainless steel limiters, and, its use here was intended to provide a baseline against which the performance of other materials could be measured. Typical parameters for tokamak operation were taken to be: $B_T \sim 13.1$ Kg, Ip = 140 ka, $n_e \sim 3 \times 10^{13}$ cm^{-3}. Satisfactory, routine machine operation with ohmically-heated discharges was possible under these typical conditions. Measured Z_{eff} values ranged from 1.10 to 3.06. Some damage to the limiter was observed (extensive arcing and some melting) and has been previously reported [9].

Titanium Carbide on POCO Graphite

To date a total of four TiC coated limiters have been used in ISX-B. The coatings were applied to a POCO graphite substrate by chemical vapor deposition to a thickness of 10–15 µm as measured by ion backscattering. Pre-exposure treatment of the limiters consisted of a vacuum bake-out to remove absorbed gases. Initial testing was performed in ohmically-heated discharges and, from the very first day of operation, clean and reproducible discharges were obtained. Under these conditions limiter surface temperatures remained under 200°C as determined from scanning infrared camera measurements. From these measurements and from independent measurements of the temperature rise in the limiter cooling water the energy deposition in the limiter was estimated to be ~20 Kj/shot. This corresponds to a power density on the limiter of 400 watts/cm^2 when averaged over the full surface area. Except for limited erosion from arcing, TiC coated limiters seem to withstand ohmically-heated ISX-B discharges without significant damage.

Measurements of Z_{eff} were obtained at various times during the interval that the first TiC coated limiter was in ISX-B and values were found to range from 0.88 to 2.80. The initial testing phase included spectroscopic measurements of the iron and titanium concentrations in the plasma as the heat load on the limiter was varied by shifting the plasma from its normal centered position outward against the limiter. The titanium concentration was found to be strongly dependent on the position of the plasma center. The maximum density was estimated to be of the order of 10^9/cm^3 when the shift occurred but dropped to about 10^8/cm^3 when the plasma was centered. As shown in Fig. 2, radiation from the iron is much stronger than that from titanium and is much less dependent on plasma position. The conclusion is that the iron in the plasma comes mainly from the walls [16].

Following the initial testing under low power conditions TiC coated limiters were again put into ISX-B for beam-heated shots. Two neutral

p. 3

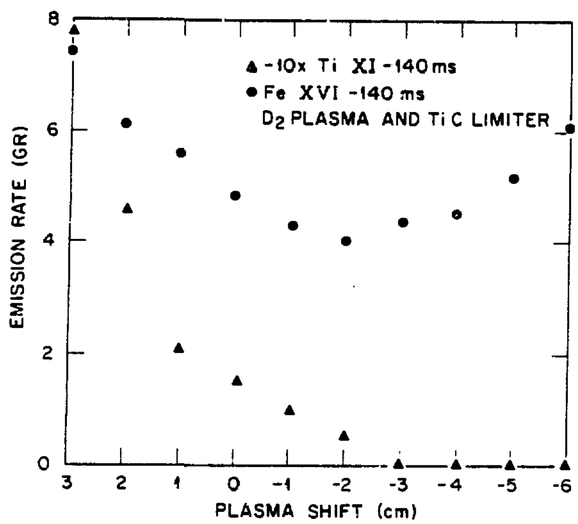

Fig. 2: Spectroscopic observations of iron and titanium radiation in ISX-B plasmas during ohmically-heated discharges as a function of plasma position.

beam injectors are used for auxillary heating, each rated at 40 kV at 100 amps, and capable of an injection power of 1.5 MW. Using the two injectors total power levels of 2.7 MW have been achieved. A typical IR camera scan for a beam heated shot with 2.2 MW of injection is shown in Fig. 3. A mirror arrangement provides a split image so that temperature variations of both the inner and outer limiters can be obtained throughout the shot. As can be seen the temperature spike on the outer limiter exceeds the 3100°C melting point of TiC. As has been observed [15] some areas of the surface of the limiter melted. The energy deposited on the limiter during beam heated shots has been estimated at 70 Kj and results in power densities >10 kW/cm^2. The power density at the nose of the limiter is undoubtedly much higher, and it is in this region that melting has been observed. The sudden temperature rise represents a severe thermal stress on the limiter and is perhaps responsible for a significant amount of the observed damage to the limiter [15]. The temperature spike on the inner limiter at 215 ms occurs at the time of a disruption which terminates the discharge. The loop voltage and plasma current for this shot are shown in Fig. 4. The abrupt rise in the loop voltage and sudden drop in plasma current instead of a normal ramp down are indicative of the disruption.

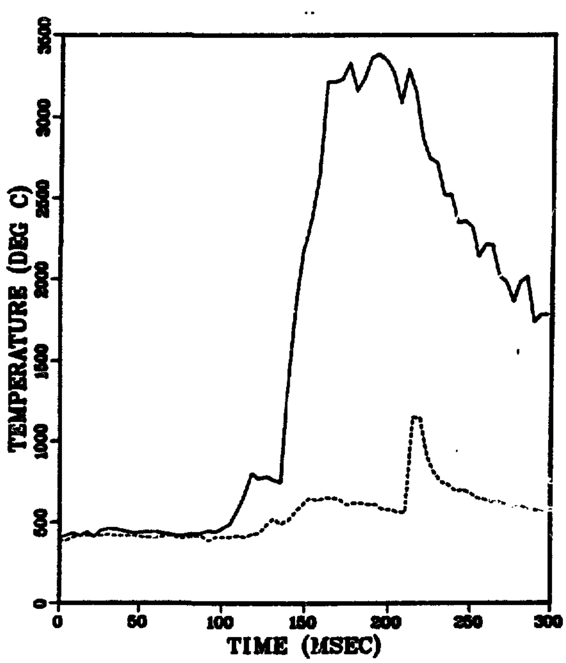

Fig. 3: Limiter surface temperatures as a function of time during a discharge with 2.2 MW of neutral beam injection. (Shot #27064).

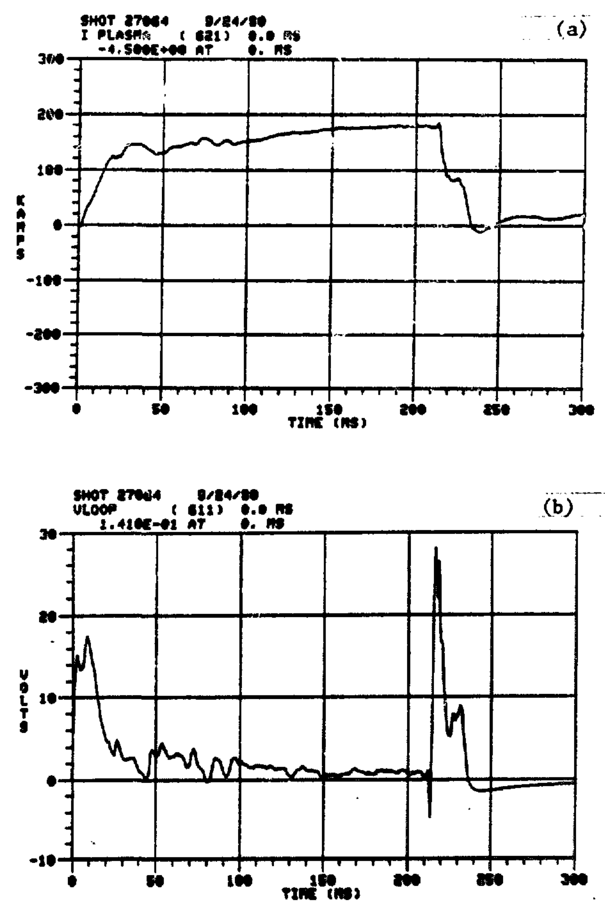

Fig. 4: Plasma parameters for shot #27064, (a) plasma current and (b) loop voltage.

During the testing of the TiC coated limiters operation of ISX-B has been entirely satisfactory. Measurements of the electron temperature and density obtained with the Thomson scattering system yielded values of Z_{eff} which consistently remained <3. This is indicative of relatively clean plasmas. In fact, operation with the TiC limiters has been so satisfactory that there has been some reluctance on the part of the tokamak operations group to remove the limiters in order that other materials could be tested.

<u>Titanium Diboride on POCO Graphite</u>

Operational experience with a TiB_2 coated outer limiter was limited to ohmically-heated discharges early in the limiter study and has been previously reported [13]. For completeness, these results are summarized here. Initially, machine operation was not as satisfactory as was the case with the TiC limiters but after a short conditioning period (~1 day) reproducible and clean discharges were obtained. Significantly more coating damage was observed following the relatively short use in the tokamak.

<u>Boron on POCO Graphite</u>

Limited tokamak operation has also been obtained with a boron coated outer limiter. The limiter was in ISX-B for only a few days during which time 257 ohmically-heated discharges were produced. Machine performance was extremely poor with many disruptions. Machine conditions were so poor that it proved impossible to obtain a laser sequence sufficiently reproducible to obtain a value for Z_{eff}. Figure 5 shows the plasma current, loop voltage, MHD activity, and the output from the PIN monitor for a typical shot during the time the boron limiter was installed. The abnormally high loop voltage and MHD activity and the low output from the PIN monitor are all indicative of a hard disruption. As a direct result the discharge terminated at 90 ms as indicated by the abrupt drop in the plasma current at that time. A normal discharge lasts for 200—250 ms. Because of a vigorous and demanding experimental program involving ISX-B the boron limiter was removed when it became apparent that the machine performance was not improving. Subsequent inspection of the limiter revealed significant damage from arcs that had penetrated the thin boron coating.

CONCLUSIONS

As a result of the limiter studies conducted to date TiC coated graphite has emerged as a leading candidate for service in present day high power tokamaks. This results from experience with over 18,000 discharges in ISX-B many of which were beam injected shots subjecting the limiter to very severe conditions. Even though the limiters sustained damage to both the coating and substrate, machine performance has remained satisfactory. Limited experience using TiB_2 coated limiters indicated

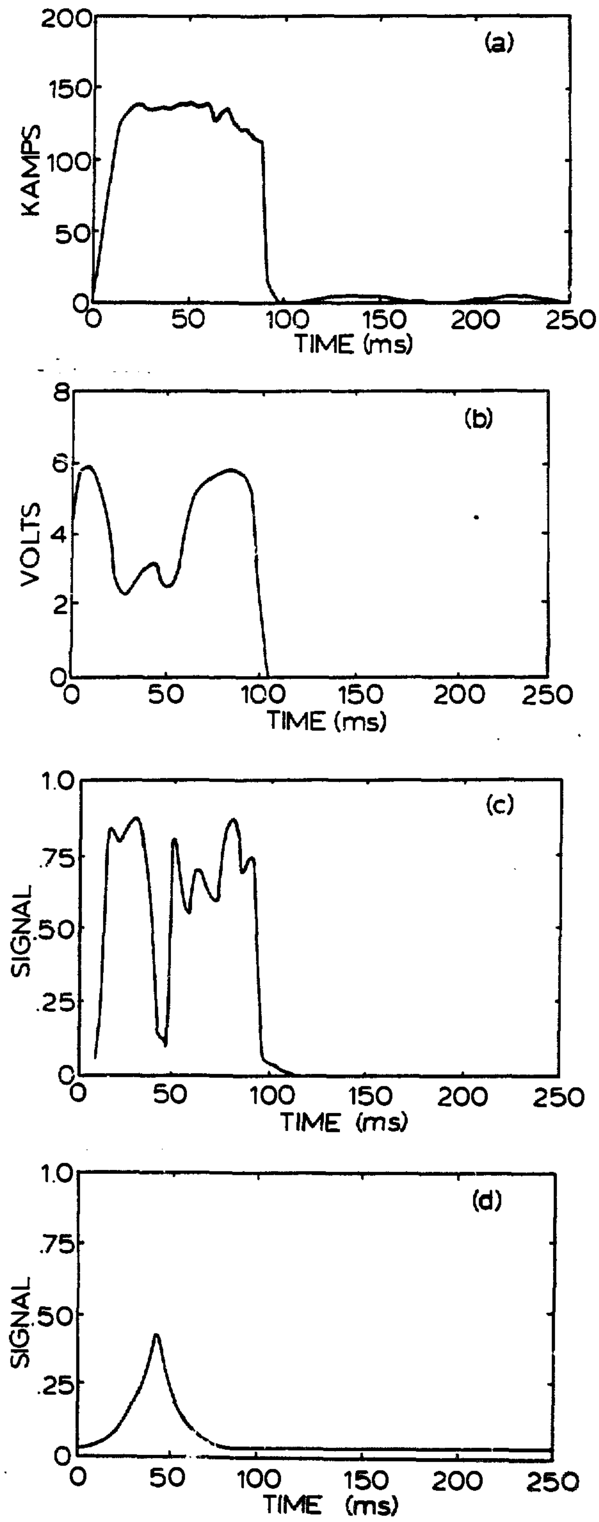

Fig. 5: Typical plasma parameters with boron-coated outer limiter, (a) plasma current, (b) loop voltage, (c) MHD activity, and (d) PIN monitor output.

p. 5

that satisfactory operation was possible with low power ohmically-heated discharges. Operation with boron coated limiters was unsatisfactory indicating that further work with perhaps thicker coatings is necessary. ISX-B will continue to be used as a test stand for coated limiter studies in a continuing effort to develop materials for the coming generation of high power fusion devices.

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