MATERIALS EXPERIENCE WITH TOKAMAK PLASMAS*

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The primary effects of using various wall and limiter materials have been in the amount and kind of impurities they introduce into the plasma. Only a limited number of materials have been employed to date. These include gold, stainless steel, inconel, glass, alumina, and titanium for first walls and carbon, stainless steel, inconel, alumina, silicon carbide, boron carbide, molybdenum, tantalum, titanium, and tungsten for limiters and divertors. Limiter surfaces bear the brunt of the plasma bombardment and so typically introduce impurities far out of proportion to their relative size. The ratio of the bombarded limiter area to that of the first wall is of order 1 to 10^3.

The effect of first wall materials *per se* on the plasma is often largely masked by coatings of foreign substances. Such layers are deposited on walls either by the plasma or by residual gases and often persist in spite of discharge cleaning because of the low rate of bombardment of the first wall. Carbon and oxygen compounds are the most abundant impurities observed on walls with surface analysis techniques, and this correlates well with plasma spectroscopic observations which show carbon and oxygen levels of 1-6% in typical tokamak plasmas. Metals with intermediate atomic numbers such as Fe, Ni, Cr, and Ti usually constitute less than 1% of the plasma density.

Because of the heavy ion bombardment they receive, limiters are normally stripped of surface layers so that their bulk constituents are exposed. This results in the heavy metal contamination observed in many plasmas. Plasma impurities act to reduce the energy stored in the plasma through line, bremsstrahlung, and recombination radiation. Heavy metals are particularly bad since the radiated power is a strong function of the atomic number, $\sim Z^{3.7}$. Tungsten and molybdenum radiation is responsible for the "hollow" temperature profiles observed in DITE, ORMAK, and PLT, and as a consequence most tokamaks now employ either carbon or stainless steel limiters. Thermal shock, another limiter problem, led to the breakup of a B_4C limiter in the TFR 400 tokamak.

1. INTRODUCTION

In a general sense, a tokamak consists of a toroidal vacuum structure surrounded by electrical circuits. The vacuum structure is usually constructed of materials which are easy to fabricate and have good vacuum properties. In welded structures which have no electrical break, large currents can be induced, and as a consequence electrical conductivity is also an important consideration.

Limiters are usually placed inside the vacuum vessel to intercept particle and energy fluxes leaving the plasma, thereby protecting the vacuum vessel wall. In a general sense, limiters also include divertor surfaces, which are really limiters connected to the main plasma region by extended magnetic field lines. In this paper the terms limiter and divertor are used interchangeably. The materials used for limiters are sometimes the same as, but are more often different from, those used for the vacuum vessel. The reason for this difference is that limiters withstand more thermal shock, higher heat loads, and greater particle bombardment than the vacuum vessel walls.

Limiters define the plasma edge only in a fuzzy way. In the first place, there is always a warm plasma present between the limiter and the vacuum wall. The density of this warm plasma is 10^9-10^{12} particles/cm^3, and electron temperatures are in the range 5-100 eV [1-3] and decrease with

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increasing minor radius. Second, although there may be a single set of primary limiters, there are always many secondary limiters located between the primary limiter and the wall. Some secondary limiters are deliberately introduced as backup protection for the vacuum vessel, but most are diagnostic probes.

As might be expected, the closer a limiter is to the wall, the hazier the distinction between the two, while the larger the distance of separation, the more nearly a limiter will serve to decouple the plasma from the wall. This decoupling was nicely demonstrated in a series of experiments on TFR 400 [4], where the limiter was moved radially inward from 19 to 12.5 cm. As the limiter was moved away from the wall, the oxygen impurity level, characteristic of the wall, decreased while the molybdenum from the limiter increased. In present tokamaks the necessity to conserve space results in wall-to-limiter separations of a few centimeters, so that the wall-limiter distinction is not sharply defined.

During the breakdown phase of a discharge, the entire vacuum chamber is filled with cold plasma. Upon termination, the discharge collapses toward one of the walls. This collapse is often rather sudden, and thus is not effectively restricted by the main limiter, leading to surface melting on secondary as well as primary limiters [5].

In the discussion which follows, only general conditions during the well-controlled portion of the plasma discharge of operating tokamaks are considered. And, in spite of the often hazy distinction between walls and limiters, they are treated as separate entities in Sections 2 and 3, respectively. Conclusions are presented in Section 4.

2. WALL MATERIALS

The earliest USSR tokamaks were constructed with glass walls. During the last decade, stainless steel has been the most commonly used material, although there have been a number of exceptions. Inconel was employed in constructing TFR 400 [6], TFR 600 [7], and DOUBLET III [8]. Gold-coated walls were used for the inner vacuum wall in T-6 [9], ORMAK [10], and DIVA [11] because gold is a good vacuum material. The PDX divertor experiment has an inner liner of titanium, and in PETULA [12], 80% of the wall facing the plasma is alumina. Titanium coatings have been used inside ATC [13], PLT [3], DITE [14], MACROTOR [15], and ISX [16] for vacuum pumping and impurity suppression.

During plasma discharges the surfaces of the walls are coated by a mixture of wall, limiter, and probe materials. Metal coatings as large as a monolayer per discharge have been measured in TFR 600 [17]. If vacuum systems are not clean, carbon tends to dominate the surface composition and discoloration occurs.

From the foregoing discussion it is evident that the surface layers on the walls of present tokamaks are much more important than the bulk properties of the materials from which the walls are constructed. This is because of their large area relative to limiters and the resulting low energy flux intercepted. This low energy flux, coupled with the relatively low duty cycle of today's devices, results in the walls remaining near room temperature.

Since it is only the top micron of wall material that is important, residual gas and surface analytical techniques have been employed to determine the condition of the wall surfaces. Auger electron spectroscopy has successfully been applied to determine the surface conditions in the ATC [18], PLT [19], DOUBLET III [20], ISX [16], PULSATOR [21], TFR 400, TFR 600 [17], ALCATOR [22], and T-12 [20] tokamaks. The principal findings resulting from this work are that for devices with clean vacuum systems, the main surface contaminants are carbon, oxygen, and materials from the limiter. The flux of these impurities to the wall peaks at the beginning and at the end of a discharge, coinciding with those times when the plasma is least well confined.

In retrospect, these results should have been expected. Oxygen arises from the oxide layer normally present on stainless steel. Carbon is ubiquitous in vacuum systems, emanating from cleaning fluids, from vacuum pump oils, and from within stainless steel. Limiter materials result from plasma erosion and redistribution of limiter surfaces.

To combat the buildup of both carbon and oxygen layers, the walls are cleaned by plasma discharges. During this discharge cleaning cold H^+ is formed and reacts chemically with carbon and oxygen wall impurities to form gaseous hydrocarbons and H_2O, which are subsequently pumped from the system [23]. This treatment can be quite effective: in the ISX tokamak, discharge cleaning removed loosely bound oxides, reducing the surface oxygen to substoichiometric levels [24,25]. Loosely bound carbon atoms were also removed, leaving only the more tightly bound metallic carbides. The main residual gases present in a clean stainless steel tokamak vacuum system are H_2, H_2O, CO_2, and CH_4 [16,26-28]. The elements in these gaseous compounds are well correlated with the carbon and oxygen observed by surface analysis.

Trace amounts of almost every material present in the vacuum system can be detected spectroscopically in the plasma. Since tokamaks are generally heavily laden with ports, windows, and diagnostics, this list can be fairly long. For example, Table I lists the elements detected spectroscopically in ORMAK [29] along with their likely sources. Oxygen and carbon are the principal contaminants present in all tokamaks, usually constituting 1 to 6% of the plasma density.

Table 1.

Plasma impurities in ORMAK.

Element	Likely origin
He	diagnostics
Be	x-ray window
C	vacuum pumps, cleaning fluids
N	air
O	metal surfaces
Na, Cl, Ca	windows, fingerprints
Si	quartz window
S	stainless steel
Cr, Mn, Ni, Fe	stainless steel
Cu, Ag	neutral beam injectors
Au, Pt	walls
W	limiter

Oxygen and carbon are also the principal contributors to Z_{eff}, the effective nuclear charge of he plasma ions. Iron, nickel, and chromium from stainless steel walls are also observed spectroscopically, but at lower levels (<1%). These results, combined with the surface and gas analyses described previously, emphasize the relative importance of surface rather than bulk wall materials properties in tokamaks.

The mechanisms by which surface atoms are dislodged and enter the plasma include desorption (ion, electron, thermal, and photon desorption), sputtering, arcing, and mechanical shock. It is difficult to determine the principal mechanisms, since neither the reaction rates nor the particle and photon fluxes are well known. Although arc tracks have been observed on walls, wall arcing is not thought to be an important impurity source. Since carbon and oxygen are the most common plasma impurities, regardless of the limiter material, these low-Z impurities must originate at the walls.

Titanium sublimation onto vacuum walls has been very successful in reducing the amount of carbon and oxygen entering tokamak plasmas. Titanium chemisorbs gases such as O_2, H_2O, and CO_2, and effectively reduces most noninert residual gases even though only a fraction of the wall area is overcoated. Titanium itself is not found to be a more significant source of plasma contamination than other wall materials.

Wall surfaces also play a major role in hydrogen and deuterium recycling [30,31] and hence in fueling tokamak plasmas. Hydrogen retention is highly material-dependent and is especially noticeable when titanium is sublimated on vacuum vessel walls.

3. LIMITERS

Limiters withstand measured heat loads as high as several kilowatts per square centimeter [32] and so are often constructed of special materials. In the past, heavy metals have been in favor, but in the last two years low-Z materials have been tried in several tokamaks as well as intermediate-Z metals. Thus at present a variety of high-, intermediate-, and low-Z limiter materials are in use.

A list of limiter materials used includes stainless steel [3,16], inconel [17], alumina [12], silicon carbide [4], boron carbide [4], molybdenum, titanium [33], tantalum [34], tungsten, and various kinds of carbon, as well as no limiter at all [35] in low power tokamaks. Heavier metals such as molybdenum and tungsten have led to "hollow" temperature profiles in the DITE, PLT, and ORMAK tokamaks [36]. "Hollow" profiles have an electron temperature dip at the plasma center as a result of energy loss by heavy metal radiation. Since the radiated power increases as $\sim Z^{3.7}$ for $Z > 6$ [37], heavy metals are capable of radiating away power as fast as it is supplied by ohmic heating.

Carbon limiters have been tested in the T-3 [38], T-10 [39], ISX [16], PLT [3], JFT-2 [28], TFR 400 [4], and PETULA [40] tokamaks by way of attempting to reduce the radiated power. The results of these tests have generally been favorable, although with carbon the impurity level usually increases. In PLT [41] it has been found necessary to water-cool the carbon limiter to reduce the carbon contamination. Carbon has a highly anisotropic heat conductivity, and in tests involving a pyrolytic graphite limiter in JFT-2 [42], surface temperatures of 1900°C were recorded on unfavorably oriented samples.

Various other kinds of low-Z limiters have been tried with varying degrees of success. Alumina has been used to good advantage during two periods of operation in the PETULA [12,40] tokamak. During the earlier period, appreciable limiter damage was noted after 1000 discharges. A boron carbide limiter was placed in TFR 400 [4] and was rapidly damaged by plasma currents of 200 kA due to thermal shock. A limiter made of silicon carbide, vapor deposited onto an isotropic graphite base, was used in JFT-2 [42] with good success.

Finally, intermediate-Z limiters have been recently employed: stainless steel on PLT [3] and ISX [16] and inconel on TFR 600 [43]. Stainless steel limiters have been particularly effective on ISX, leading to low rates of metal influx.

As mentioned above, limiters undergo intense plasma bombardment, and so their bulk composition is important. Indications are that primary and secondary limiters are responsible for most of the metals present in the plasma. Studies conducted on TFR 400 [17,44,45] have shown that erosion is largest near the radius of the limiter and that net material deposition is a maximum just in back of the limiter. The principal mechanisms by which limiter material is released are arcing, melting by runaway electrons, and sputtering, as discussed below. An example of the effects of arcing and sputtering is shown in Fig. 1.

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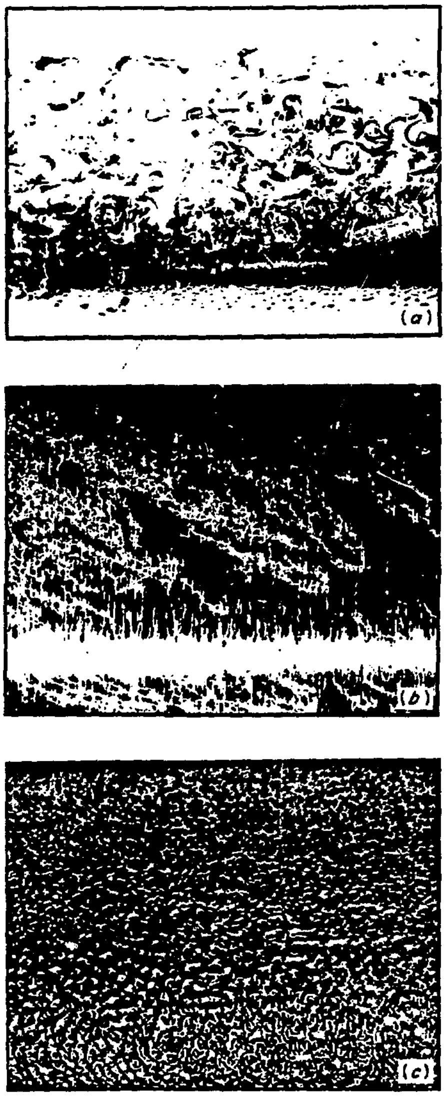

Fig. 1. Three types of damage on stainless steel limiter bars exposed to discharges in the ISX tokamak. (a) Surface melting at the center of the outside bar. (b) Arc tracks, observed generally and particularly on the limiter bar. (c) Limiter damage to the side of the top bar caused by runaway electrons melting the surface at localized points. The relative magnifications of (a) to (b) and (c) are 1:4.1:1.7 (taken from Ref. [16]).

Arc tracks have been observed on the limiters in most tokamaks, i.e., in ISX [16], PULSATOR [21], DITE [33], PLT [19], DIVA [46], and TFR 600 [47]. Measurements show that erosion rates are 10^{16}-10^{18} atoms/arc [19,48], and these rates are adequate to explain the amount of metals deposited in DITE and PLT. However, both laboratory experiments and experiments with probes inserted into the divertor plasma of DIVA [49] indicate that the arcing rate decreases exponentially with exposure time. This is presumably due to patches of surface dielectric contamination being burned off by the arcs [50]. Preliminary evidence from ISX [51] indicates that once this surface conditioning has taken place, arcs only occur during periods of poor plasma control, such as at the beginning or end of a discharge.

Dumps of runaway electrons cause local melting on the limiter. Runaway electrons are usually dumped during periods of poor equilibrium. With proper density and vertical field control, the runaway electron population can be held to innocuous levels.

Sputtering of the limiter by multiply charged impurity atoms poses much more of a threat during the steady portion of the plasma than either arcing or melting. A sheath potential equivalent to about three times the electron temperature will build up around primary and secondary limiters. Multiply charged oxygen atoms may fall through this potential and impinge on the primary limiter with more than a hundred electron volts of energy and thus cause sputtering. This could well account for the metal influx observed in several tokamaks. Cooling the plasma edge, thereby reducing the sheath potential, has been found to lower the influx of metals into PLT plasmas [3].

4. CONCLUSIONS

A number of general conclusions can be reached regarding the behavior of materials in tokamaks, although specific situations can occur which are at variance with these results. A moderate number of materials have been used for vacuum walls and at least ten different kinds of limiter materials have been tested. The principal means of determining how these materials behave is to observe where they go, by making spectroscopic measurements of plasma impurities and by monitoring surface layers on the walls. The general conclusions are that oxygen and carbon are the most abundant plasma impurities and that they originate from the walls. Metals are eroded from primary or secondary limiters and end up both in the plasma and as coatings on walls. Because of the relatively low energy flux that falls on vacuum walls and the low repetition rate of present tokamaks, wall surfaces remain near room temperature. As a consequence, it is the vacuum properties of the walls that are of primary importance. Limiters, on the other hand, represent a more complicated materials problem as incoming energy fluxes and temperature rises can be appreciable. Experience has shown that radiation from heavy metal impurities represents a severe energy drain on the plasma, so the trend has been to low and intermediate atomic number limiter materials.

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