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BY

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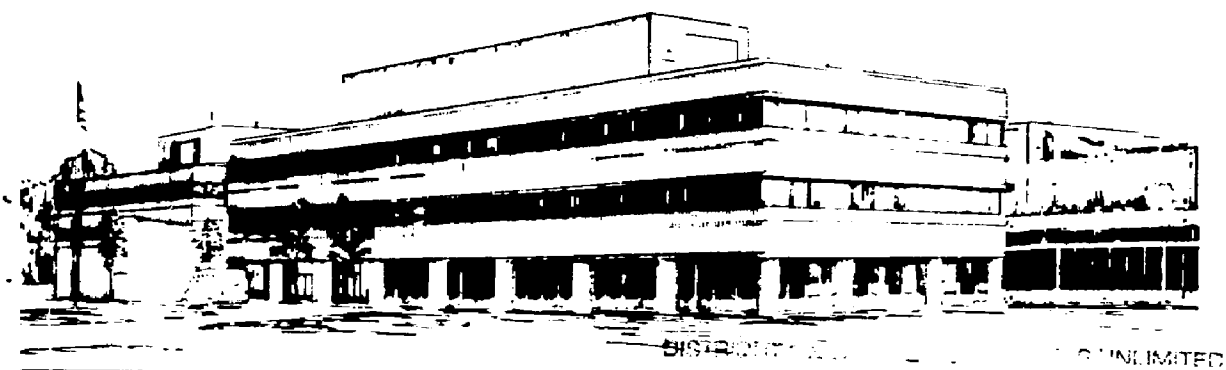

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ABSTRACT

It has been found necessary to perform a series of first-wall conditioning steps prior to successful high power plasma operation in the Tokamak Fusion Test Reactor (TFTR). This series begins with glow discharge cleaning (GDC) and is followed by pulse discharge cleaning (PDC). During machine conditioning, the production of impurities is monitored by a Residual Gas Analyzer (RGA). PDC is made in two distinct modes: 1) Taylor discharge cleaning (TDC), where the plasma current is kept low (15 - 50 kA) and of short duration (50 ms) by means of a relatively high prefill pressure, and 2) aggressive PDC, where lower prefill pressure and higher toroidal field result in higher current (200 - 400 kA) limited by disruptions at $q(a) \approx 3$ at $\approx$ 250 ms. At a constant repetition rate of 12 discharges/minute, the production rate of H_2O, CO, or other impurities has been found to be an unreliable measure of progress in cleaning. However, the ability to produce aggressive PDC with substantial limiter heating, but without the production of X-rays from runaway electrons, is an indication that TDC is no longer necessary after $\approx 10^5$ pulses. During aggressive PDC, the uncooled limiters are heated by the plasma from the bakeout temperature of 150°C to about 250°C over a period of three to eight hours. This limiter heating is important to enhance the rate at which H_2O is removed from the graphite limiter.

INTRODUCTION

We discuss the conditioning techniques used on TFTR during the 1986-1988 operating period. The first-wall environment is dominated by the axisymmetric inner wall bumper limiter, made of 20 m^2 of POCO-AXF-5Q graphite tiles. This conditioning is accomplished by means of successively higher power discharges. Initial conditioning is accomplished by glow discharge cleaning (GDC). This is followed by low current ($\approx$ 2 kA) Taylor discharge cleaning (TDC), higher current ($\approx$ 350 kA) aggressive pulse discharge cleaning (PDC), and is completed by disruptive discharge cleaning (DDC). General remarks on TFTR conditioning with the graphite bumper limiter installed have been reported previously.[1-5] This paper focuses on the indications that signify sufficient PDC has been accomplished to permit high power pulsing (HPP) to commence and some ways in which the efficacy of PDC can be enhanced.

The term "conditioned" has a wide variety of meanings and/or degrees: for the purposes of this study of PDC, conditioned will mean that as a minimum, 1) operation of TFTR at plasma currents up to about 2 MA can be achieved, and 2) recovery from disruptions by producing another discharge in a few attempts is possible. The most common and serious sign of a lack of

conditioning is the inability to establish a discharge. This lack of conditioning is believed to arise from either of two causes: 1) Hydrogenic species outgassing from the limiter surface, which results in high density and increased resistivity early in the discharge, or 2) oxygen contaminating the discharge, which causes a radiative collapse of the discharge.[5] Since it is neither possible nor necessary to remove all oxygen and hydrogen from the machine surfaces, it is important to determine at which point conditioning is sufficient to permit operation.

GLOW DISCHARGE CLEANING

GDC is performed by the introduction of two probes, (both anodes) located about 180° apart toroidally, into the grounded vacuum vessel that acts as the cathode and that is heated to 150°C.[2] The pressure of hydrogen or deuterium in the torus is feedback controlled at 0.7 Pascal by means of a computer controlled piezoelectric valve.[7] The probe current is limited to 7.5 A at a discharge potential of 390 V DC for hydrogenic discharges. The partial pressure of the vacuum constituents are monitored continuously by a differentially pumped RGA.[8] Initially the H_2O peak falls inversely with time, but then the rate of H_2O removal decreases. GDC is terminated after about 48 hours when the partial pressures of complex hydrocarbons (mass 41-43) have been reduced to 10^{-6} Pascal in the vacuum vessel (10^{-9} Pascal in the RGA vacuum), which is the level of detectability. This level of conditioning is insufficient to permit normal operation.

PULSE DISCHARGE CLEANING

PDC is performed in two modes with the vacuum vessel heated to 150°C. In the first mode termed TDC, capacitor banks are employed to provide a one turn loop voltage of about 60 V with a low toroidal field (B_T = 0. 2 Tesla) and a prefill pressure of D_2 (0.05 to 0.2 Pascal), which together produce low current (15 to 50 kA) discharges of short duration (50 ms). In the second mode, termed aggressive PDC, the loop voltage is somewhat lower (35 V), the prefill pressure is about an order of magnitude lower ($\approx 5 \times 10^{-3}$ Pascal), the toroidal field is higher (B_T = 0.7 Tesla), and the ohmic heating (OH) coil rectifiers are utilized to increase I_p to 400 kA and extend the discharge duration up to about 400 ms. The production rate of CO and H_2O as measured by the RGA is two to ten times greater during TDC than that during aggressive PDC, as was observed in previous studies.[1-4] Figure 1 shows the partial pressures inferred from the amplitude of the mass 18 and 28 peaks (H_2O and CO) in the RGA spectrum during TDC. After a rapid fall during the first day of TDC (12,000 discharges), the partial pressures change very slowly with time. Data indicate that the partial pressures do not fall much during aggressive PDC. After 4.5 days of TDC (74,000 discharges) and about 2.75 days of aggressive PDC (28,000 discharges), an attempt to produce high powered discharges was unsuccessful in the sense that, although a 500 kA discharge could be produced, recovery from a single intentional disruption at 500 kA was not possible. An additional day of TDC (14,000 discharges) and 2.75 days of aggressive PDC (34,000 discharges), however, was sufficient to permit successful high power operation. The total H_2O, D_2O, and CO exhausted from the torus during pulse discharge

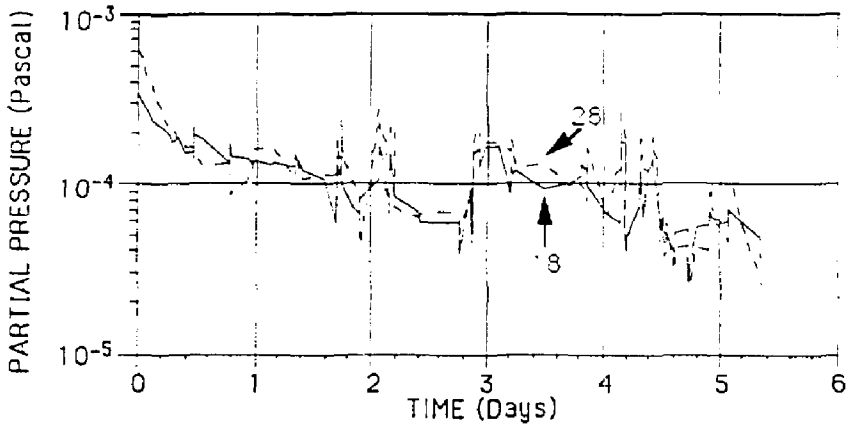

Fig. 1 Partial pressures due to the mass 18 and 28 peaks in the RGA spectra versus run time during TDC. The large variations in pressure are not well understood, although some of the variation is due to changing repetition rate, fill pressure and/or loop voltage. The CO fraction of the total mass 28 peak is ≈ 0.8.

cleaning increased from 1.5×10^7 to 2.1×10^7 Pascal-liters during the additional conditioning. Averaged over the vessel wall, 2×10^7 Pascal-liters is equivalent to 3×10^{22} molecules/m^2. Based on the RGA measurements alone, there is no clear evidence that sufficient conditioning has occurred or that some threshold has been crossed. However, the evolution of the aggressive PDC discharges discussed below provides additional information on the progress of the conditioning process.

Figure 2 shows the time evolution of three aggressive PDC discharges. The discharge labeled A, produced near the end of the discharge cleaning run, exhibits both radiated power and plasma electron density rising with plasma current and an absence of hard Xrays. A series of discharges like A, called productive discharges, produced over a period of three to four hours at a repetition rate of 12/minute results in the heating of the uncooled graphite bumper limiter from 150° to 250°C. The 250°C limit is due to constraints based on thermal stress. The bumper limiter is thermally isolated from the vacuum vessel and is cooled by radiation to the vessel wall. The discharges labeled B and C were produced in earlier phases of the cleaning. Both of these discharges exhibit initial electron densities three to four times that of the productive discharge. The electron density for the discharge labeled C falls as the plasma current rises. Discharge C exhibits little radiated power after discharge initiation and is accompanied by a large flux of hard Xray. However, the productive discharges exhibit only background levels of Xrays. Discharges with high fluxes of hard Xrays result in local heating of the outboard RF limiters,[9] presumably due to runaway electrons. Early in the discharge cleaning process, the aggressive PDC attempts never result in productive discharges. Instead either low-current, high-density discharges similar to B or runaway discharges similar to C result. It is only when productive PDC discharges can be generated routinely that sufficient discharge cleaning has been accomplished to permit DDC to be performed successfully.

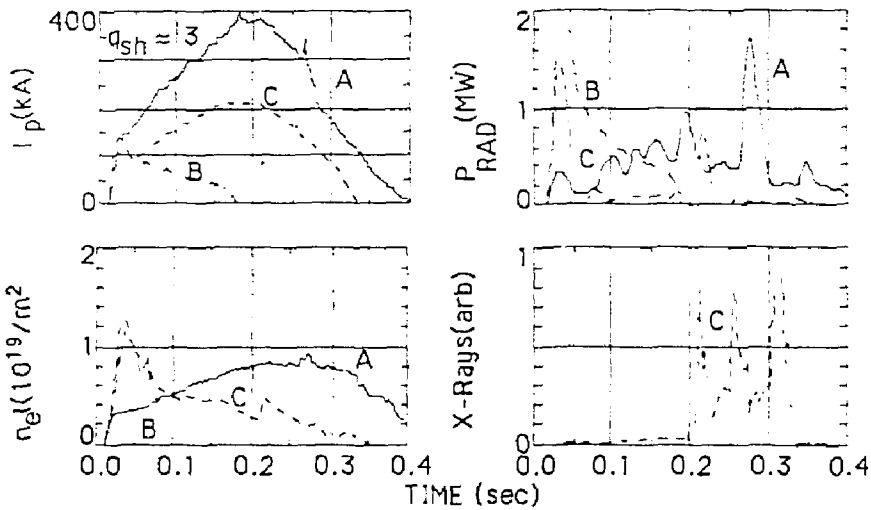

Fig. 2 Time evolution of the plasma current(I_p), radiated power(P_{RAD}), line integral electron density($n_e l$), and hard X-ray flux for three different aggressive PDC pulses. The discharge A, indicated by the solid lines, is the productive type discharge discussed in the text. Discharges B and C indicated by the dashed curves are unproductive PDC. The hard X-ray flux for discharge A is at the background level, while that for B is above background only at breakdown where the level is 10^{-3} of that reached in C.

Studies on JET and DIIID[10,11] indicate that GDC in He is effective for impurity conditioning of graphite and for decreasing the recovery time following high power disruptions. He GDC was tried for two one-hour periods during the PDC run.[5] During the He GDC, the oxygen signals fell inversely with time for about 20 minutes, then remained about constant for the remainder of the hour. The results of this conditioning were mixed. After the first one-hour He GDC period, productive PDC discharges could be produced even though this was not possible prior to He GDC. However, the discharges deteriorated to type B and C within 45 minutes. The second He GDC run resulted in no improvement to the PDC pulses being produced.

Not only is the surface condition as reflected in the RGA measurements important for high power operation, but also conditioning of the near subsurface (100°A deep) graphite is critical. Thermal desorption measurements of the POCO-AXF-5Q limiter material indicate that the oxygen (from absorbed H_2O) in the graphite becomes mobile at 300°C.[12,13] The TFTR bakeout temperature of 150°C allows only slow diffusion to the surface from which the oxygen-containing volatile end products (H_2O, CO, and CO_2) are removed. Independent of whether the presence of impurities on the surface or in the bulk of the limiters is important, removal of the impurities from the torus as quickly as possible is important to minimize the time required for conditioning.

TABLE I Partial Pressure of H_2O, D_2O and CO during TDC

D_2 PRESSURE (Pascal)	CAP. VOLTAGE (kV)	PARTIAL PRESSURES (10^{-4} Pascal) H_2O	D_2O	CO	SUM
0.107	24	0.83	0.58	0.68	2.39
0.107	21	0.98	0.88	0.89	2.75
0.123	21	1.15	1.09	0.84	3.08
0.139	21	1.05	0.93	0.52	2.50

We have found two ways in which the production of impurities can be increased. The first method uses high fill pressures during TDC. Table I shows the partial pressures of H_2O, D_2O, and CO during a 40-minute period of TDC in which the fill pressure and capacitor bank voltage were varied slightly. A result of either dropping the capacitor voltage, raising the fill pressure, or lowering the toroidal field (not shown here) is to lower the plasma current. There appears to be an optimum plasma current for maximizing the removal of oxygen. The optimal current is near the limit where further attempts to lower the current result in failure to break down the prefill gas. The second method which increases impurity production is to intentionally force disruptions while performing aggressive PDC. Figure 3 shows the H_2O pressure measured during a four-hour series of productive PDC pulses. Figure 3 indicates the major radius of the discharge, interruptions in PDC, and those periods in which the discharges were intentionally disrupted by forcing the plasma quickly into the inner wall. The plasma contacts different parts of the limiters' surfaces when the major radius is changed. Note that the disruptions produced H_2O at more than 10 times the rate of the non-disrupted discharges. The data shown in Figure 3 were obtained with the neutral beam valves on TFTR open to take advantage of the ten times greater pumping speed $\approx 10^5$ l/s (vacuum vessel pumpout time constant $\tau_v \approx 1.0$s) afforded by the beam cryopanels compared to that of the torus turbo pumps ($\tau_v \approx 10.$s). It should be noted that prior to completion of PDC, use of the neutral beam cryo pumping results in increased incidence of the productive discharges. It is important to remove the impurities from the torus before they condense and may be available to subsequent discharges. Hence, τ_v should be of the order of or less than the period between pulses.

DISRUPTIVE DISCHARGE CLEANING

As has been previously reported,[3] after PDC we find that it is important to further condition the machine by producing intentional disruptions at successively higher plasma currents. Beginning at 600 kA, the plasma current is increased by 200 kA increments up to 2 MA after recovery from the previous disruption can be achieved in one or two discharges with low radiated power fraction (≈60%). We discovered that this procedure, termed disruptive discharge cleaning(DDC), was necessary after we were unable to recover from a single 2.2 MA disruption immediately after having completed the first PDC sequence with the graphite bumper limiter. After that first 2.2 MA disruption onto the graphite bumper limiter, the RGA indicated very high levels of H_2O, and it was necessary to perform additional

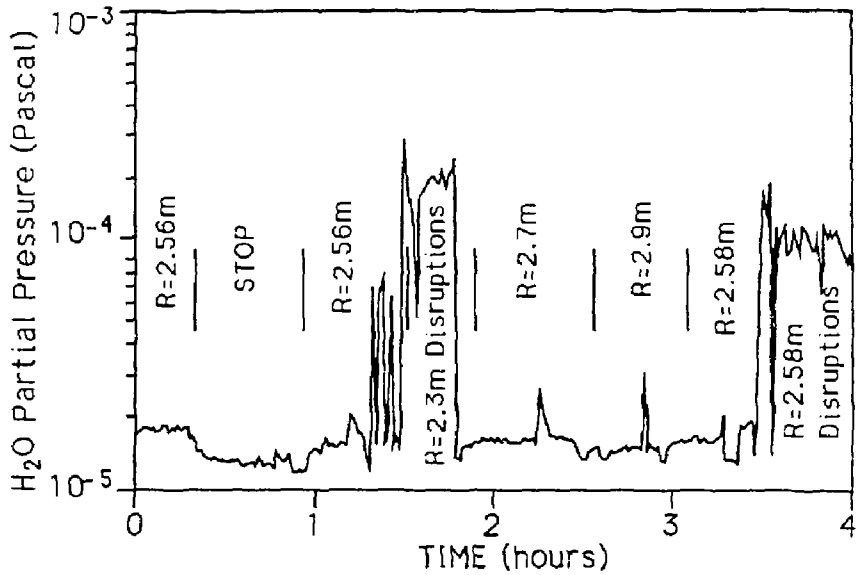

Fig. 3 Partial pressure of H_2O during aggressive PDC. The major radius of the discharges during various times is indicated since different major radii can cause the plasma to contact different first-wall surfaces. The label "Disruptions" indicates when the discharges were forced to disrupt by moving the plasma inward to reduce q(a) to about 2.

TDC and PDC before HPP operation was again possible. Infrared measurements of the surface temperature of the bumper limiter indicate that the temperature reaches 1800°C during a DDC pulse. This flash surface heating causes the temperature in the first 600 μm of the graphite to exceed 300°C. At this temperature the H_2O becomes more mobile and oxygen is available to the next discharge. DDC has been successful in allowing operation of TFTR at high plasma currents with routine recovery from disruptions. At the end of DDC, with a plasma density $\bar{n}_e$ of $1.2 \times 10^{19}/m^3$, Z_{eff} is 6 ± 1, the contribution to Z_{eff} due to metals is 0.15 ± 0.08. This is comparable to that found later at the same density when TFTR is well-conditioned, when Z_{eff} = 4.8 ± 1 and the metal contribution is 0.3 ± 0.1. The carbon to oxygen ratio immediately after DDC is about one. Later this ratio is in the range of five to ten. The recycling coefficient of hydrogenic species remains high (R=1) after DDC indicating that a large reservoir of H or D is still available to the plasma. At this point the He ohmic discharge cleaning technique described in References 5 and 14 is used to decrease the hydrogenic recycling to R ≈ 0.6. This He conditioning technique affects primarily the concentrations of hydrogen isotopes in the near surface region (<20 nm) of graphite.

CONCLUSIONS

The methods discussed in this paper describe the effective, if somewhat lengthy, impurity control procedure used to condition TFTR for high power discharges. GDC followed by TDC is effective in removing oxygen from the machine. The progress of TDC is best evaluated by attempting aggressive PDC. As conditioning progresses, non-productive PDC discharges are gradually replaced by productive PDC discharges as indicated by density control, radiated power proportional to n_e and low levels of hard Xrays. Completion of several hours of PDC heats the limiters to $\approx 250°C$ and is sufficient to permit high power pulsing to proceed. DDC completes the conditioning process by removing oxygen from a greater volume of the carbon first-wall surface than is affected by the PDC process.

ACKNOWLEDGEMENT

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