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By

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# FIRST-WALL CONDITIONING FOR ENHANCED CONFINEMENT DISCHARGES AND THE DT EXPERIMENTS IN TFTR

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## ABSTRACT

The conditioning techniques applied to the TFTR first-wall configuration that will be in place for the DT experiments in 1990-91 are reviewed. Of primary interest is the helium conditioning procedure that was developed to control hydrogenic recycling from the graphite, inner-wall bumper limiter. Operation of TFTR over the plasma density range for gas-fueled ohmic plasmas, $\bar{n}_e = (2 - 5) \times 10^{19}$ m$^{-3}$, typically results in hydrogenic recycling coefficients near unity. The use of the helium conditioning procedure produced recycling coefficients as low as 0.5, and decreased the minimum ohmic plasma density to $\bar{n}_e = 0.5 \times 10^{19}$ m$^{-3}$ at $I_p = 0.8$ MA. Low density ohmic target plasmas with low recycling conditions are prerequisite conditions for the enhanced confinement (e.g., "supershot"), neutral-beam-heated discharges observed in TFTR during 1986-87, which is the primary mode being considered for study in the DT experiments. The recycling changes induced by the helium conditioning procedure are believed to be the result of a plasma pumping effect in the graphite induced by He and C ion desorption of hydrogenic species from the near-surface (< 20 nm) layer of the limiter. The capacity of the conditioned limiter to pump gas-fueled, pellet-fueled, and neutral-beam-fueled discharges is compared. The helium conditioning technique is also beneficial for isotopic exchange and for minimizing the in-vessel tritium inventory.

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## 1.0 Introduction

This paper reviews the conditioning techniques applied to TFTR for impurity and particle control with the first-wall configuration that will be in place for the DT phase of operations (1990-91). A review in 1986 [1] discussed the initial experience with the axisymmetric bumper limiter. As described in Ref. 1, a rather intensive pulse discharge cleaning campaign, in addition to a specially developed impurity conditioning technique involving intentional disruptions, was needed to degas satisfactorily volatile oxygen species from the large area (22 $m^2$) graphite limiter. These conditioning techniques provided excellent impurity control, enabling stable high current ($\lesssim$ 2.5 MA) and high injected power discharges ($\lesssim$ 20 MW) with modest values (1.5 - 3.5) of $Z_{eff}$. However, impurity conditioning techniques left the near-surface region of the limiter saturated with deuterium. Thus, recycling coefficients were near unity and density control was severely limited. Later in 1986 (April-June), a successful particle control method was developed using, He-initiated, low-density discharges [2]. This He conditioning technique which exposes the limiter to a successive series (20 - 30) of conditioning discharges, is capable of reducing the limiter recycling coefficient from near unity to values as low as 0.5 - 0.6. In the course of the conditioning sequence, the minimum density limit of an 0.8 MA gas-fueled ohmic discharge falls a factor of 2 - 3. Low-density, $\bar{n}_e$ = (5 - 8) $\times$ $10^{18}$ $m^{-3}$, ohmic target plasmas with low recycling conditions were found to be prerequisite conditions for the enhanced confinement (so-called "supershot") neutral-beam-fueled discharges discovered in TFTR in June 1986 [3,4].

The "supershot" discharges during 1986 yielded maximum ion temperatures of 22 keV and a Lawson product, $\bar{n}_e(o)\tau T_i$, of 2 $\times$ $10^{20}$ keV $m^{-3}$ s. The achieved energy confinement times were 2-3 times the L-mode [3,4] scaling predictions for the relatively low plasma current (~ 1 MA) discharges which showed the largest enhancements. During 1987, these results were extended to maximum ion temperatures in the range of 30 keV and a $\bar{n}_e(0)\tau T_i$ product of 3 $\times$ $10^{20}$ keV $m^{-3}$ s [5]. The maximum DD fusion reactivity (Q-value) achieved was ~1 $\times$ $10^{-3}$, which transforms to a DT equivalent of ~ 0.2.

During 1988, plasma operations on TFTR will be devoted to optimizing the DD reactivity primarily by exploring the "supershot" at higher, balanced

neutral beam injection power (> 20 MW), and also by investigating means of extending the plasma current limits. The "supershot" is optimized at balanced neutral beam injection, i.e., the toroidal momentum introduced by the injection is near zero. Balanced power was limited to ~ 13.5 MW prior to the reorientation of one neutral beamline late in 1987 to give two co- and two counter-injectors. Modest extensions of the current limit of the "supershot" were achieved by ramping the plasma current from ~ 1.0 to 1.7 MA during injection [5]. However, a detailed understanding of the deterioration of the S-mode with increasing plasma current and MHD effects is lacking. A related issue, the change with current of the ohmic target plasma density and recycling properties, is a topic of the present review.

The "supershot," fueled with two 120 keV deuterium neutral beams and two 120 keV tritium neutral beams, is the primary planned mode of operation for the DT phase. Following the installation of additional neutron shielding and tests of the tritium systems in 1989, a limited series of 200-300 full-power (~30 MW) DT plasma experiments are planned for 1990-91 [6].

The first-wall configuration for the DT configuration is presently complete [7]. A majority of this hardware was installed in 1985, including the 22 $m^2$, inner wall bumper limiter [8] (consisting of 2000 kg of POCO AXF-5Q graphite tiles on water-cooled Inconel 718 backing plates), and the similarly constructed 11 $m^2$ of graphite protective plates which protect the outer wall of the vacuum vessel from neutral beam shinethrough. During the 1987 shutdown, the original movable limiter was removed and replaced by two poloidal, partial-ring (± 120°) limiters constructed of radiatively cooled carbon-carbon composite [9]. Unlike the bumper limiter, which was designed to accommodate the full TFTR input power (> 30 MW for 2 s), these "RF limiters" have very limited power handling capability and are designed only to protect two ICRF antennae.

We used the 1987 shutdown of TFTR to advantage by also removing a subset (33) of the bumper limiter tiles and numerous wall samples to analyze carbon and impurity redeposition from the 1985-87 plasma operations [10,11]. Some of the results of these analyses have important implications for wall conditioning and hydrogenic recycling and retention [11], as discussed below.

The main portion of this paper updates plasma-material interaction studies on TFTR which have been performed since the 7th PSI Conference [1].

The primary topic is the development of the He conditioning technique and its success in affecting the "supershot." In addition, the technique holds promise as an efficient means of affecting isotopic changeover with graphite limiters, including the removal of tritium in order to minimize the in-vessel inventory during the DT phase [12]. A related topic is the impurity conditioning techniques applied to TFTR, which are coupled to hydrogenic recycling and retention through the observed redeposition processes.

## 2.0 Impurity Conditioning

The various conditioning discharge techniques applied to TFTR are summarized in Table I. Impurity conditioning techniques are usually applied to TFTR only after exposure of the vacuum vessel to atmospheric conditions or (in one case) to $H_2O$ leaks from internal piping. Following major installations of internal hardware (which occurred with the original installation of the bumper limiter in 1985, and the recent RF antennae/limiter installation in 1987), rather heroic applications of the standard glow discharge cleaning (GDC) and pulse discharge cleaning (PDC) were required. Glow discharge exposures of 100 - 150 hrs and over $10^5$ PDC pulses were required in both the 1985 and 1988 initial conditioning periods. Minor vents of the vessel (duration $\leq$1 week with little or no disturbance of the in-vessel hardware) required considerably less GDC (~10 hr) and PDC ($\sim 2.5 \cdot 10^4$ of pulses). However, we discovered in 1985 following exposures to high current disruptions that these techniques, when applied with the TFTR vessel/limiter temperature limits (150/250°C), provided insufficient conditioning of the large area graphite limiters. A new procedure, dubbed disruptive discharge cleaning (DDC), was developed [1]. DDC requires forced disruptions to flash desorb impurity species (primarily $H_2O$ and CO) from the limiter surface. The procedure involves increasing the plasma current from 0.4 MA to 2.5 MA in 0.2 MA increments. The increases were applied only after clean, stable discharges were achieved subsequent to a forced disruption at a given current level.

Bumper limiter temperature measurements during a disruption with a fast infrared array [7] show the bumper limiter surface temperature rising above 1000°C over a large poloidal extent (±30°) with reasonable toroidal symmetry. We estimate that the affected depth of the flash heating is of the order of 1 mm. DDC is apparently not necessary for the other large tokamaks.

JET [13] and JT-60 [14], which have the capability of in-situ bakeout at temperatures above the optimal water desorption temperatures [15] for graphite (T > 300°C).

## 2.1 He GDC for Impurity Control

During the initial vessel conditioning for 1988 operations, the use of brief (0.5 - 1 h) periods of He glow discharge cleaning was found to be beneficial on the subsequent evolution of PDC and DDC shot sequences. During the PDC campaign our usual procedure [16,17] involved switching to high current (0.2 - 0.4 MA) pulse discharge cleaning pulses for limiter heating after sufficient low-current (0.05 MA), Taylor-type (TDC) pulses were performed to produce stable, runaway-free, high-current pulses. The transition time between TDC and PDC was usually determined by trial and error. At several points during the $1.2 \times 10^5$ pulse PDC/TDC campaign in 1988, a successful transition from TDC to PDC could be affected by a modest He GDC exposure (15A $He^+$ dc glow discharge for less than 1 hr). The beneficial effect appears to be related to enhanced desorption of $H_2O$, CO, and $CO_2$ (Fig. 1) during the He GDC exposure when a monolayer of oxygen-containing molecules is removed from the first-wall. A similar benefit of He-GDC was observed during the start of the April 1988 DDC campaign. A difficulty in recovering from the effects of the initial 0.5 - 1.0 MA disruptions was alleviated with a 1 hr He GDC exposure.

## 2.2 Redeposition Effects and the Long-Term Evolution of First-Wall Surfaces

The removal of a subset of bumper limiter tiles and numerous wall samples during the 1987 shutdown allowed us to evaluate the evolution of first-wall surfaces during the 1985-87 operations period [7,10]. Surface analysis of these samples showed the cumulative effects of exposure to the 1985 initial conditioning (GDC, PDC, DDC) and subsequent exposure to 9,922 high power discharges (including 2756 discharges with $D^0 \rightarrow D^+$ neutral beam injection). Examination of the bumper limiter tiles showed that a redeposited, amorphous carbon film was built up on the plasma-facing surfaces and on the tile sides. The film varied in thickness from 10 - 50 μm; with the thinnest films occurring on high flux areas of the limiter and the thicker films on the low-

flux areas. The toroidal and poloidal variations of the redeposited film was mapped in-situ on the entire bumper limiter using a beta-backscattering technique [10,11] and the ~1% metallic (Fe, Ni) content of the film as a tracer. The redeposit thickness variations are in good agreement with the expected plasma flux deposition pattern as calculated from the plasma magnetic geometry [18].

The redeposited film on the limiter surface is of interest because it is this material, rather than the original tile graphite, that becomes the primary plasma-material interface soon after initiation of plasma operations. We determined [10,11] that a significant fraction (~30%) of the deuterium throughout during the 1985-87 operations period was retained in this redeposited film. Also, by partially depleting the H-isotope inventory in high plasma flux areas of the limiter, the plasma recycling properties could be substantially altered (see Sec. 3.0). The relatively small metallic content (~1%) of the films reflected the evolution of the metal impurity levels in the plasma. Therefore, it is prudent to pursue laboratory measurements of the basic physical properties of these redeposited films, such as film density, H-retention, implantation parameters, and sputtering coefficients. These studies are underway for the TFTR samples [11]. Some preliminary analyses indicate that the H-retention saturation levels are similar to bulk graphite H/C $\leq$ 0.4. However, ion ranges in the material may be extended because microscopic analyses of the films show significant voids, which would lower the effective carbon density.

Examination of a poloidally and toroidally distributed array of wall coupons gave reasonable indication of redeposition effects on the vacuum vessel wall. An average deuterium retention of $6 \times 10^{17}$ cm$^{-2}$ was observed on the wall coupons with the partial deuterium content varying from D/C = 0.1 to 0.3. Analysis of a small subset of these samples partway through the 1985-87 operations (after 1770 discharges) showed that the deuterium-deposition is roughly proportional to the number of discharges. This result has important implications for estimating the tritium inventory in the DT phase [10,12]. A brief summary of the limiter and wall sample analysis after the 1985-87 operations is given in Table 2 and a more complete summary is given in References 10 and 11.

## 3.0 He Conditioning for Particle Control

The first particle control effects seen on TFTR, in the form of density decay times shorter than the discharge length, were observed after exposure of the bumper limiter to a series of low density, He-fueled discharges [1]. Prior attempts to affect the particle recycling with gettering techniques, ZrAl [19] and Cr [20], were unsuccessful. Since the first observations of the particle control effects of He conditioning in 1986, the technique was developed as a routine procedure [2] for producing the low recycling and low target density plasmas, which are prerequisite for the "supershot" discharges [3,4].

The discharges used for this type of conditioning are fueled with the minimal amount of gas necessary to ensure plasma breakdown, typically $\lesssim$3 torr-liters of He (although $D_2$ also has been used). Plasma currents for the conditioning discharges have spanned 0.8 - 1.8 MA, with most of TFTR conditioning employing 1.4 MA He-fueled discharges at a 5 - 7 min repetition period. The first extended study of He conditioning involved a discharge sequence spanning approximately 100 shots with the measured recycling coefficient falling from near unity to $\lesssim$ 0.5 [2]. As a routine procedure, conditioning sequences involved exposures of 5 - 30 shots, depending on the initial conditions and the desired endpoint.

We have used several diagnostic signals as monitors of the conditioning process. Figure 2 shows how the plasma density, edge neutral pressure, $D_\delta$ emission, and integrated outgassing from the conditioning discharges decrease with shot number during the conditioning sequence. Typically, the density (Fig. 2a) of a conditioning discharge decreases by a factor of 2 - 3 during the sequence with the same gas input. This indicates that less gas is liberated from the limiter as the sequence progresses, as shown directly by the decrease in integrated outgassing (2d). Correspondingly, the $D_\delta$ emission (Fig. 2b) and edge neutral pressure (Fig. 2a), which are proportional to the edge neutral deuterium flux and density, respectively, decrease by an order of magnitude during a full conditioning sequence.

After a successful conditioning sequence, the density of deuterium-fueled ohmic discharges (with prefill fueling only) can be as low as $0.5 \cdot 10^{19}$ $m^{-3}$ at plasma currents of $I_p$ = 0.8 MA.

The operational envelope of target plasma densities and currents where we observed the "supershot" discharges (1986-1987) is shown in Fig. 3. The locus of minimum density vs. plasma current is termed the recycling limit because, apart from the minimal prefill gas-fueling necessary to initiate the plasma, the dominant fueling for the discharge is recycling from the limiter. At the recycling limit, measured $Z_{eff}$ values are in the range of 6 ± 1 [21]. Spectroscopic analysis indicates that carbon is the dominant impurity under these conditions with varying minor contributions to $Z_{eff}$ due to metallic impurities (0.1 1.0). Therefore, the dominant impurity ion is carbon for both the target plasmas for the "supershot" discharges and for any of the 0.8 - 1.8 MA discharges used for limiter conditioning. Only a very narrow range of plasma currents 0.8 - 1.1 MA, with minimum average densities of 0.5 - 0.8 × $10^{19}$ $m^{-3}$, have shown the enhanced confinement and plasma reactivity characteristics of supershots. Experiments with transient gas puffs before beam injection indicate that the prerequisite for the enhanced confinement and reactivity is not a low target deuterium density but a low recycling coefficient for deuterium from the limiter.

The above observation of the high carbon content of the minimal density discharges has at least two interesting ramifications. The quiescent nature of these discharges would be difficult to explain if the source of carbon influx to the discharge were $C^+$ self-sputtering. The $C^+/C$ self-sputtering coefficient above 1 keV is energy-independent, and does not exceed 0.6 as quoted in laboratory measurements [22]. However, recent calculations by Brooks et al. [23] have shown with the inclusion of a more realistic incident particle geometry characteristic of the TFTR bumper limiter, and the effects of partial H-isotope saturation of the carbon near-surface region, that the self-sputtering coefficient approaches unity. These refinements qualitatively explain the observed steady-state density behavior of the recycling-limited discharges.

Secondly, the carbon content of the conditioning discharges plays an important role in our model of the conditioning process. We assume that the hydrogenic degassing of the limiter observed during the conditioning process (through the $D_\delta$ emission and the integrated gas output) is caused by ion-induced desorption of ydrogen isotopes from the near-surface region of the limiter [2]. Laboratory measurements of the ion-induced desorption

coefficients for desorbing deuterium from deuterium-saturated carbon have been measured for $He^+$, $C^+$, and $H^+$ ions by Wampler and Doyle [24]. For energies characteristic of the impacting ion energy of $C^{4+}$ (~1.2 keV) and $He^{++}$ (0.6 keV), the desorption coefficients (desorbed deuterium/incident ion) are five and two, respectively, i.e., much larger than the $C^+$, $He^+$, and $D^+$ sputtering coefficients. Thus, ion-induced desorption of deuterium should be the dominant surface process during a conditioning discharge. By using measured ion-induced desorption cross sections for $He^+$ and $C^+$, and including the possibility of deuterium-retrapping, Wampler and Doyle [24] were able to model degassing data from laboratory samples of deuterium-saturated graphite. These data appear similar to the observed $D_\beta$ data during a TFTR conditioning sequence (Fig. 2b)

## 3.1 Pumping Capacity of the Conditioned Limiter

A measurement of the capacity of the conditioned bumper limiter to pump incident $D^+$ from a gas-fueled ohmic discharge lends further support for a simple carbon depletion layer model for the He conditioning process. Figure 4 shows particle balance measurements [25,26] for exposure of the limiter in an initially conditioned state (recycling coefficient $R \approx 0.6$) over a sequence of eleven constant-density gas-fueled discharges. The Fig. 4 data show that less gas fueling is required to reach the programmed constant density with each successive shot as the recycling increases. At the end of the sequence, the recycling has increased to $R \approx 0.9$ [25] and the required gas input approaches an asymptotic value of 20 torr-liters. Of this input, 15 torr-liters remains in the vessel after subtracting the integrated outgassing during the period between discharges. We interpret this vessel retention to be the result of redeposition in low flux areas of the torus that do not affect recycling. The larger quantity of retained deuterium indicated by the cross-hatched area in Fig. 4, sums to a retention of 70 torr-liters ($4.9 \times 10^{21}$ D), and represents the saturable capacity of the bumper limiter for pumping $D^+$ plasma with energies characteristic of gas-fueled ohmic plasmas.

Extrapolation of Langmuir probe data for conditioning discharges [27] indicate edge electron temperatures of ~60 eV. Therefore, using a simple sheath model [28], the impacting $D^+$ energy would be 200 - 300 eV. For these energies the implantation depths in carbon at a density of 1.8 $g/cm^{-3}$ (tile

material) is calculated to be 10 - 15 nm [29]. (The range in the redeposited carbon layer, which is the actual first-wall material, is probably larger due to the smaller carbon density.) The above-estimated implantation range multiplied by the scrape-off area of the bumper limiter (~5 $m^2$) and the saturation capacity of carbon (D/C = 0.4) gives a maximum pumping capacity (~100 torr-liters) that is consistent with both the gas-loading (70 torr-liters) in Fig. 4 and the total integrated outgassing (150 torr-liters) observed in the conditioning sequence shown in Fig. 2d. We have observed that this limited pumping capacity for ohmic plasmas is reached through any combination of gas-fueled discharges which sums to a gas input of ~100 torr-liters.

## 3.2 Limiter Pumping Capacity for Neutral Beam and Pellet Fueling

The pumping capacity of the conditioned limiter is significantly larger for neutral-beam (NB)-fueled discharges, or with combined pellet and neutral beam fueling. Figure 5 shows a sequence of 10 NB-fueled discharges with approximately equal power input (~11 MW) and particle input (~6 × $10^{21}$ D) per discharge. At the start of the sequence the limiter was well conditioned, as indicated by the low target density. The significant observation from this sequence is that the conditioning, confinement time, and fusion reactivity during the NB phase remain relatively undisturbed through the 10-shot sequence. During this sequence the total particle input was ~6 × $10^{21}$ D, a quantity which would saturate the pumping effect and drastically increase the recycling if introduced as cold gas. Langmuir probe measurements [27] indicate that the edge electron temperature increases approximately a factor of four [to $T_e(o)$ ~220 eV] during NB heating at power inputs >10 MW. Therefore, the capacity to pump recycling particles from NB-fueled discharges is apparently larger than inferred from a simple extrapolation of the $D^+$ implantation range in proportion to the increased edge temperature.

Figure 6 also illustrates the different pumping capacity of a conditioned limiter for gas-fueled vs. NB-fueled discharges. Figure 6 is a sequence of 24 NB-fueled discharges with approximately constant NB fueling. For discharges 2 - 14 in the sequence, gas-fueling was introduced during the ohmic target phase of the discharge. For the first five discharges into which 4.5 × $10^{21}$ D was injected, no change in energy confinement ($\tau_E$) of the NB phase is noted,

but $\tau_E$ then decreases as the remaining gas ($1.7 \times 10^{22}$ D) is introduced. However, of more interest is the reconditioning which apparently takes place when the gas input is removed for the remaining discharges (15 - 24) in the sequence. We have suspected from long-term observations of the limiter conditioning that NB-fueled discharges have beneficial effects with regard to assisting the degassing process. For the power inputs used in these sequences (~11 MW) the surface heating of the bumper limiter is modest ($\Delta T < 100°C$). Therefore, we assume that both the increased pumping capacity and the limiter-degassing influence of NB-fueled discharges are related to the different plasma-edge conditions. NB-fueled discharges are expected to have hotter edge plasmas because of the increased power input and the deeper fueling, which minimizes the plasma-cooling effects of peripheral cold gas.

Figure 7 shows a sequence of 10 discharges with combined pellet and NB fueling. Pellets with a fueling of $\sim 10^{21}$ D per pellet were introduced in the discharge shortly (0.1 - 1.5 s) after the cessation of the NB pulse with apparently insignificant impact on the confinement properties [30]. Again, a large quantity of deuterium was introduced as a result of the combined pellet and NB fueling ($1.6 \times 10^{22}$ D) with respect to the saturation capacity of the limiter for gas-fueled discharges ($\sim 7 \times 10^{21}$). The combination of the edge heating by the neutral beams and the deep fueling provided by the pellets minimizes deconditioning.

The obvious follow-up studies to the data shown in Figs. 5-7 involve particle balance measurements with longer discharge sequences and concurrent plasma temperature and density measurements of the edge-plasma.

### 3.3 He Conditioning for H-Isotopic Exchange

The changeover of fuel gas from hydrogen to deuterium was observed to be a slow process in TFTR using typical gas-fueled ohmic discharges [31]. The process was accelerated by first using He conditioning discharges to deplete one hydrogen isotope from the active area of the bumper limiter before introducing the second isotope. The changeover from H/H + D = 20% to 80% and then back to 20% was achieved with less than ten medium density ($\bar{n}_e = 1.6 - 3.2 \times 10^{19}$ m$^{-3}$) discharges in the new isotope, when the initial isotope was first depleted with a short (<10) series of He conditioning shots.

## 4.0 Summary

The introduction of large area carbon limiters in TFTR necessitated the development of new conditioning techniques both for impurity control (Disruptive Discharge Cleaning) and for particle control (He conditioning). The He conditioning technique produces low density target plasmas ($< 8 \times 10^{18}$ $m^{-3}$) with low recycling ($R \approx 0.5$) that are prerequisite conditions for the enhanced confinement "supershot" discharge. The low recycling conditions are produced by degassing the near-surface region of the limiter. The degassing mechanism is most likely ion-induced desorption by helium and carbon ions. The pumping capacity for cold ($D^+$) plasma is the order of $10^{22}$ particles and is consistent with a simple carbon depletion model for the pumping mechanism. The pumping capacity for neutral-beam-fueled or combined neutral-beam- and pellet-fueled discharges is significantly larger ($>10^{23}$ D), presumably because of higher plasma-edge temperatures.

Carbon redeposition onto low flux areas of the limiters and wall appears to have little influence on the recycling, but does impact the hydrogenic inventory. Surface analysis of first-wall components showed that 30% of the total deuterium-fueling was retained in the vessel after exposure to the $\sim 10^4$ DD discharges during the 1985-87 operations period. The He conditioning technique is useful for promoting isotopic exchange and should also be useful for minimizing the in-vessel tritium inventory.

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[31] P. H. LaMarche et al., J. Vac. Sci. Technol. A4 (1986) 1198.

TABLE I

TFTR CONDITIONING DISCHARGE PARAMETERS:

Glow Discharge Cleaning (GDC)

| | |
|---|---|
| $H_2$ Pressure | 5 - 6 mTorr |
| Discharge Current | 15 A |
| Discharge Voltage | 400 V ($D_2$) 300 V (He) |

Pulse Discharge Cleaning (PDC)

| | High Current Mode | Low Current Mode (TDC) |
|---|---|---|
| $H_2$ pressure | $(1 - 2) \times 10^{-5}$ Torr | $(1 - 2) \times 10^{-4}$ Torr |
| Discharge current | 100 - 300 kA | 20 - 40 kA |
| Discharge duration | 40 - 200 ms | < 50 ms |
| Repetition rate | 1/6 - 1/8 $s^{-1}$ | 1/6 - 1/8 $s^{-1}$ |
| Toroidal field | 4 - 6 kG | 1.5 - 2.0 kG |

High Power Plasma (HPP) Conditioning Modes

| | Helium Conditioning | Disruptive Discharge Cleaning (DDC) |
|---|---|---|
| Gas pressure (prefill) | $0.5 \times 10^{-5}$ torr (He) | $(1 - 2) \times 10^{-5}$ torr($D_2$) |
| Discharge current | 0.8 - 1.8 MA | 0.6 - 2.5 MA |
| Discharge duration | 4 - 8 s | 4 - 8 s |
| Repetition rate | 1/5 - 1.8 $min^{-1}$ | 1/5 $min^{-1}$ |
| Toroidal field | 30 - 50 kG | 30 - 50 kG |

TABLE 2

Results from Wall Coupon Analysis[†]

| Sample Set | Number of Discharges | Areal Density ($10^{17}$ atoms/cm$^2$) D | C | O | Cr + Fe + Ni |
|---|---|---|---|---|---|
| Wall Coupons: | | | | | |
| 1 | 1,770 | 1.2 ± 0.3 | 30 ± 20 | 3 ± 2 | 0.9 ± 0.40. |
| 1R | 8,152 | 6.1 ± 0.6 | 12 ± 6 | 1.6 ± 0.8 | 0.45 ± 0.14 |
| 2 | 9,922 | 5.7 ± 2.4 | 33 ± 24 | | 1.50 ± 0.70 |
| Bumper limiter tiles: | | | | | |
| tile face (high plasma flux area) | 9,922 | 3 ± 1 | $\leq 10^2$ | — | < 0.5 |
| -low plasma flux area | | 60 ± 10 | $\sim 10^3$ | — | 10 ± 2 |

[1]Measurements from Ref. 10 and 11.

## Figure Captions

Fig. 1. Partial pressure of mass 18 (primarily $H_2O$) and mass 28 (primarily CO) in the TFTR residual gas analyses during a 30-minute He glow discharge treatment of the vacuum vessel. The discharge potential was 300 V and the discharge current was 15 A.

Fig. 2. Diagnostic signals monitored during a He conditioning sequence involving 1.4 MA and 1.8 MA conditioning discharges: (a) plasma density; (b) $D_\beta$ emission; (c) edge neutral pressure; and (d) integrated outgassing per discharge (for 80 s after discharge termination).

Fig. 3. Plasma density vs. plasma current parameters observed for TFTR ohmic discharges with deuterium gas fueling. The vertical variation in plasma density at a given plasma current level is a measure of the recycling conditions which can be affected by the He conditioning procedure. The observed density-current regime for the "supershot" discharges is indicated.

Fig. 4. Gas loading for a series of 11, constant density ($1.25 \times 10^{19}$ $m^{-3}$), gas-fueled ohmic discharges starting with a well-conditioned limiter. The total gas input per shot ($Q_{in}$) is compared with the integrated outgassing per shot ($Q_{out}$), thus determining the vessel retention per shot. (From Ref. 26 with permission).

Fig. 5. Target plasma density, energy confinement time $\tau_E$ (thermal component), and neutron production rate for a sequence of 10 neutral-beam-fueled discharges. The power (~11 MW) and particle input ($\sim 6 \times 10^{20}$ D) are approximately the same for the entire sequence.

Fig. 6. Energy confinement time ($\tau_E$), neutral beam fueling, and gas fueling for a sequence of 24 neutral beam discharges. The gas fueling was introduced in the ohmic phase preceding the neutral beam input.

Fig. 7. Energy confinement time ($\tau_E$), neutral production rate, target density, and pellet fueling for a sequence of combined neutral-beam- and pellet-fueled-discharges. The pellets were introduced shortly (<0.1 s) after the termination of the neutral beam input.

# 88X0809

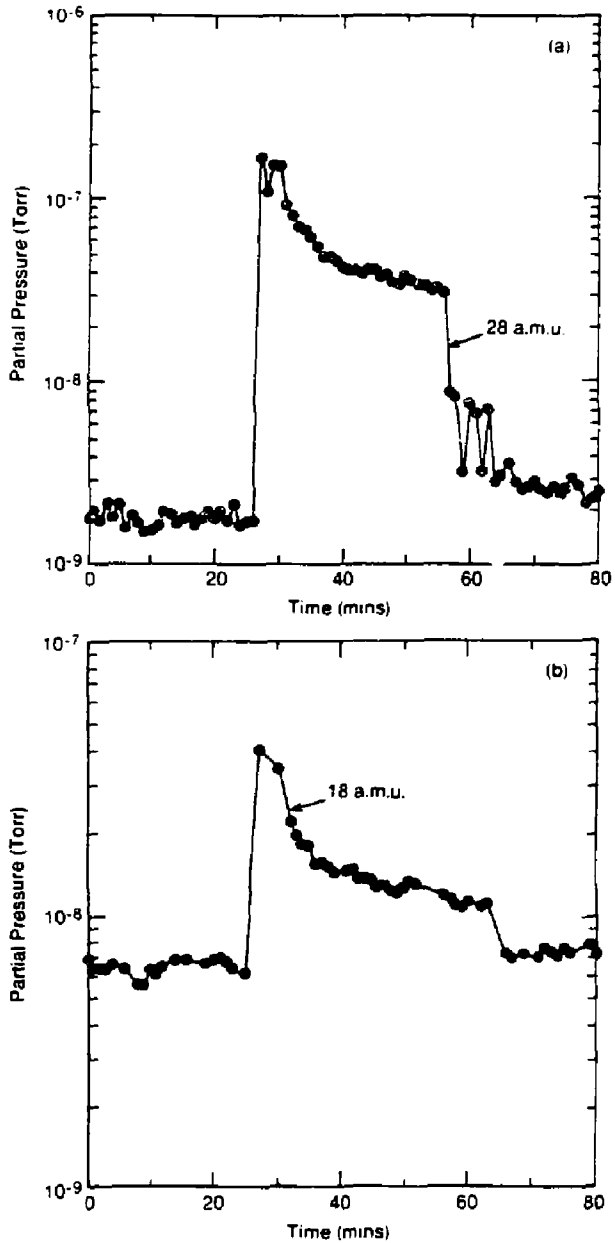


Fig. 1

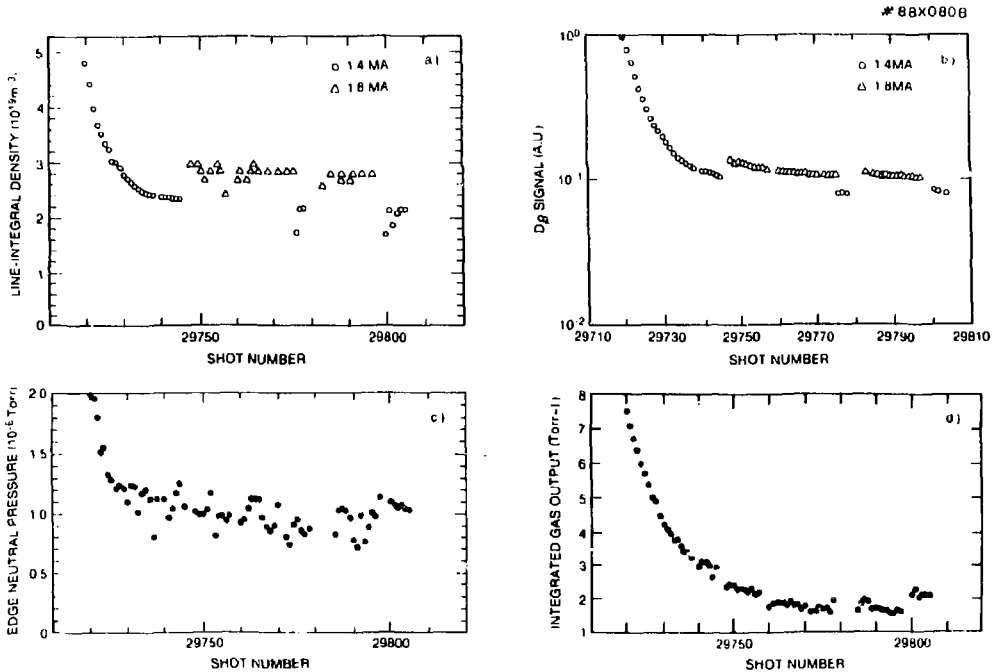
#88X0808
a)
o 1.4 MA
Δ 1.8 MA
LINE-INTEGRAL DENSITY ($10^{19}$m$^{-3}$)
SHOT NUMBER
b)
o 1.4MA
Δ 1.8MA
$D_\beta$ SIGNAL (A.U.)
SHOT NUMBER
c)
EDGE NEUTRAL PRESSURE ($10^{-5}$ Torr)
SHOT NUMBER
d)
INTEGRATED GAS OUTPUT (Torr-l)
SHOT NUMBER

Fig. 2

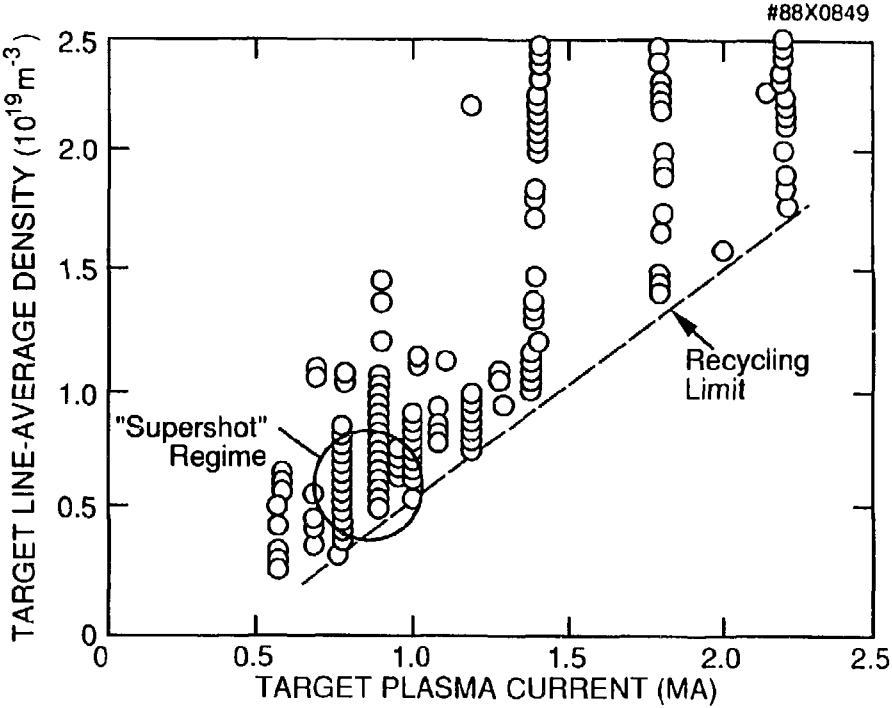
#88X0849
TARGET LINE-AVERAGE DENSITY ($10^{19}m^{-3}$)
2.5
2.0
1.5
1.0
0.5
0
"Supershot" Regime
Recycling Limit
0
0.5
1.0
1.5
2.0
2.5
TARGET PLASMA CURRENT (MA)

Fig. 3

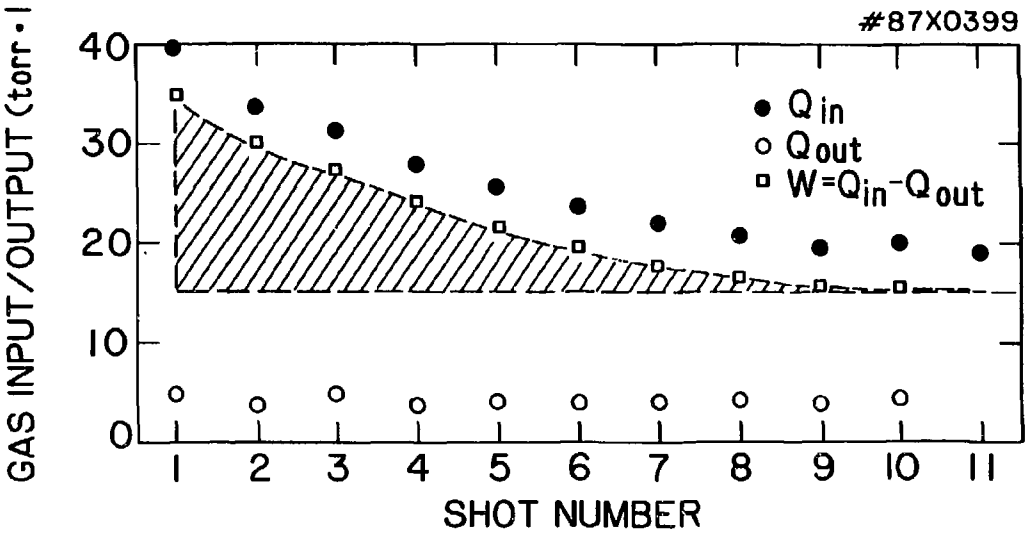
#87X0399
GAS INPUT/OUTPUT (torr • l)
40
30
20
10
0
1
2
3
4
5
6
7
8
9
10
11
SHOT NUMBER
Q in
Q out
W=Q in-Q out

Fig. 4

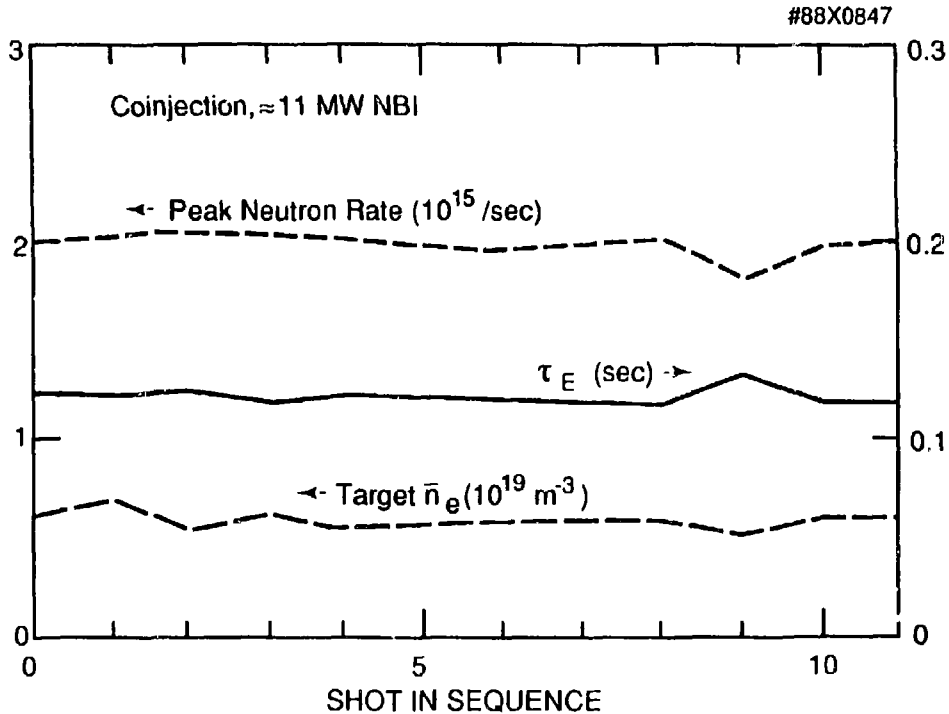
#88X0847
Coinjection, ≈11 MW NBI
Peak Neutron Rate ($10^{15}$ /sec)
$\tau_E$ (sec)
Target $\bar{n}_e$($10^{19}$ $m^{-3}$)
SHOT IN SEQUENCE
0
1
2
3
0
0.1
0.2
0.3
5
10

Fig. 5

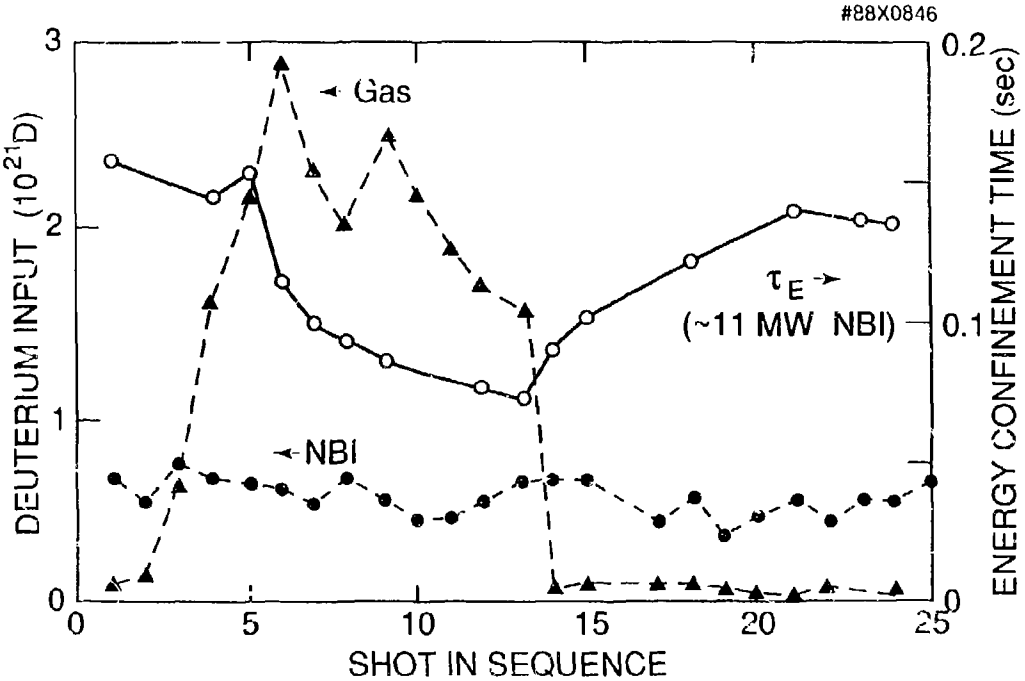
#88X0846
Gas
NBI
$\tau_E$
(~11 MW NBI)
DEUTERIUM INPUT ($10^{21}$D)
ENERGY CONFINEMENT TIME (sec)
SHOT IN SEQUENCE
0
1
2
3
0.1
0.2
5
10
15
20
25

Fig. 6

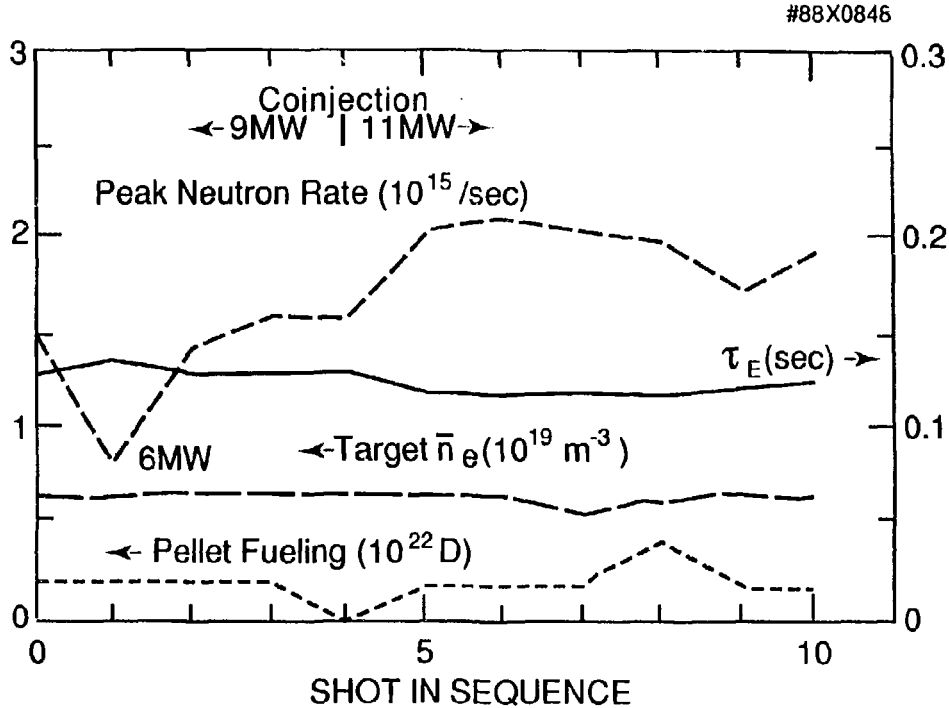
#88X0846
Coinjection
9MW | 11MW
Peak Neutron Rate ($10^{15}$/sec)
$\tau_E$(sec)
6MW
Target $\bar{n}_e$($10^{19}$ $m^{-3}$)
Pellet Fueling ($10^{22}$ D)
SHOT IN SEQUENCE
0
1
2
3
0
0.1
0.2
0.3
0
5
10

Fig. 7

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