A Transient Getter Scheme for the
Tokamak Fusion Test Reactor

J. L. Cecchi, S. A. Cohen

Princeton University, Plasma Physics Laboratory
Princeton, New Jersey 08544

J. J. Sredniawski

Grumman Aerospace Corporation
Bethpage, New York 11714

The ability of the Tokamak Fusion Test Reactor (TFTR) to attain the largest fusion power gain depends critically on minimizing plasma contamination and controlling the densities of the reacting deuterium and tritium. Experiments on a number of tokamaks have demonstrated that gettering over an appreciable surface area ($\geq 10\%$) of the vacuum vessel greatly facilitates both of these objectives. One particular problem in implementing a surface pumping system in TFTR, however, is a restriction on the maximum allowable tritium content of the getter. This restriction could require regeneration of the absorbed tritium after as few as 50 machine pulses. We have developed a scheme utilizing SAES Zr/Al getter modules which obviates the need for such frequent interruptions of machine operation by taking advantage of the pulsed operation of TFTR. With the Zr/Al getter at temperatures between 500°C - 600°C it is possible to achieve a quasi-steady state in the tritium loading where the quantity of tritium desorbed between pulses is equal to the quantity which is absorbed during a pulse. Since frequent thermal cycling is not required, this scheme also reduces the possibility of Zr/Al getter material fatigue.

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1. Introduction

The Tokamak Fusion Test Reactor¹ is a magnetic confinement plasma device which is presently under construction and scheduled for initial operation in 1981. A unique feature of the device is its ability to operate with both deuterium and tritium and thus exploit the large deuterium-tritium fusion cross section for energetic neutron production. Among the major objectives of TFTR is the demonstration of a fusion power gain (fusion power output/neutral beam heating power input) exceeding unity. This requires plasmas of high purity, since radiative losses due to plasma contaminants constitute a formidable barrier to reaching the required high temperatures.² The influx of impurities also causes a depletion of the reacting deuterium and tritium with an associated decrease in fusion power output. In addition, to optimize the fusion power output it is necessary to control the deuterium/tritium density ratio³ which in turn requires control of the recycling⁴ of these species. Experiments on a number of present and past tokamaks have demonstrated that gettering over an appreciable fraction of the surface area ($\geq 10\%$) of the vacuum vessel greatly facilitates the desired reduction of plasma impurities as well as control of hydrogenic species recycling.^{5,6}

The use of tritium in TFTR complicates the implementation of a gettering system since the allowable tritium inventory absorbed in the getter will be limited. The exact limitation, which will be determined from on-site meteorological data, is unlikely to be substantially more than the equivalent of 50 machine pulses. Thus frequent regeneration of getter would

be necessary. For a Zr/Al getter this would entail raising the getter temperature to $\sim 650^{\circ}\text{C}$ for typically 5-10 hours.^{7,8} Not only is this an inconvenience, but also, frequent thermal cycling can lead to mechanical fatigue of the getter material.⁹

We have developed a scheme utilizing modified SAES Zr/Al getter modules¹⁰ which obviates the need for such frequent regeneration by taking advantage of the pulsed operation of TFTR. The device will produce a plasma for 1.5 seconds with at least a 300 second interval between pulses. By adjusting the temperature of the Zr/Al getter, it is possible to achieve a quasi-steady state in the hydrogenic gas loading levels, where the quantity of tritium (and deuterium) desorbed between pulses is equal to the quantity which is absorbed during a pulse. Since the average outgassing rate is only $\sim (1.5/300)$ times the influx rate during the pulse, there is net pumping of the deuterium and tritium during the pulse. Plasma density control can be achieved by selective D/T gas puffing and/or pellet injection. Plasma impurities, such as O_2 and CO are pumped continuously since these are chemisorbed by the getter.⁷ In the quasi-steady state where the gas load from one pulse, L , is pumped by the torus vacuum pumping system (TVPS) with pumping speed S in the time between pulses t_p , the average partial pressure of deuterium and tritium in the vacuum vessel, $\bar{P}$, is approximately given by

$$\bar{P} \approx L / (S t_p) \quad (1)$$

Taking the typical values of $L = 172 \text{ Torr-l}$, $S = 9 \times 10^3 \text{ l/s}$, and $t_p = 300\text{s}$, $\bar{P} \approx 6.4 \times 10^{-5} \text{ Torr}$. Thus the temperature and loading of the getter

must be adjusted to produce an equilibrium pressure which is roughly equal to $\bar{P}$. For any given temperature, since the equilibrium pressure is an increasing function of loading, the quasi-steady state is stable.

In Sec. II, we present the general formalism for transient getter operation, with typical TFTR applications discussed in Sec. III. In Sec. IV, we discuss additional details including the effects of impurity saturation of the getters and thermal fluctuations during the machine pulse.

II. General Solution

During a plasma discharge, there are two major sources of particles incident on the getter. The first is an energetic neutral flux from plasma ions which have undergone charge exchange. In TFTR this is expected to have a magnitude of $\sim 3 \times 10^{15} \text{ cm}^{-2} \text{ sec}^{-1}$ with a most probable energy of 300 eV, and will consist roughly of a 50:50 mixture of D and T.¹¹ A flux of D^+ and T^+ ions of similar magnitude but of lower energy (~ 10 eV) will also be incident on the getter. This flux comes from the edge plasma which is formed beyond the tokamak limiter. It is expected that these atomic and ionic species will have high sticking probabilities, and we assume for the present calculation that the entire gas load which is pulsed into the vacuum vessel during each pulse is absorbed by the getter. This is an overestimate, since some of the gas load is pumped by the TVPS both during and just after a

pulse; however, the essential features of the present calculation are not adversely affected by this simplifying assumption.

Following the pulse we assume that the system quickly relaxes to where the only non-negligible source of gas is from the getter which is outgassing with a flux Γ . Then if S is the TVPS pumping speed (taken to be the average of the D_2 and T_2 pumping speeds), and V is the vacuum vessel volume, the pressure P evolves according to the usual expression:¹²

$$V \frac{dP}{dt} = \Gamma - PS. \quad (2)$$

The VdP/dt term in Eq. (2) gives rise to transient terms in the solution which, if Γ is slowly varying in time, die away with the TVPS time constant $\tau_T = V/S$. For TFTR, with $V \sim 8 \times 10^4$ l and $S \sim 9 \times 10^3$ l/s, $\tau_T \sim 9$ seconds. This is small compared to the 300 seconds between pulses, and we will therefore neglect the term in Eq. (2). Comparisons between the present model and detailed numerical solutions show that this assumption is justified. We may therefore rewrite Eq. (2) as

$$\Gamma = PS, \quad (3)$$

The flux of particles into the getter Γ_i is given by

$$\Gamma_i = \sigma P, \quad (4)$$

where σ is the pumping speed of the getter and P is the pressure at the surface. Since the hydrogenic species are in dilute solution in the Zr/Al

getter we may use Sieverts Law¹³ with constant K to write the expression for the flux out of the getter Γ_0 as

$$\Gamma_0 = \sigma K q^2 \quad (5)$$

here q is the hydrogenic concentration at the surface which, assuming that surface desorption is the rate-limiting step, we take to be constant throughout the getter material. The validity of this assumption is discussed in Sec. IV. In writing Eq. (5) we have used Eq. (4) and the definition of equilibrium ($\Gamma_0 = \Gamma_i$) which underlies Sieverts Law. The net flux out of the getter $\Gamma_0 - \Gamma_i \equiv \Gamma$ is

$$\Gamma = \sigma(Kq^2 - p) \quad (6)$$

We can also write that

$$\Gamma = - \frac{dq}{dt} M, \quad (7)$$

where M is the mass of the getter material and q is expressed in units of Torr-l/g. Then combining Eqs. (3), (6) and (7) we arrive at a differential equation for $q(t)$:

$$\frac{dq}{dt} = - \alpha q^2, \quad (8)$$

where $\alpha = KS_T/M$ and S_T is the effective pumping speed:

$$\frac{1}{S_T} = \frac{1}{S} + \frac{1}{\sigma} \quad (9)$$

The solution of Eq. (8) is

$$q(t) = \left(\alpha t + \frac{1}{q_0} \right)^{-1} \quad (10)$$

where $q_0 \equiv q(0)$. If $\sigma \gg S$, the pumping speed of the TVPS is rate-limiting and the getter is close to equilibrium ($r_0 \approx r_i$). Equation (10) then agrees with Eq. (2) from Ref. 8. We will be concerned with one possible application where $S \approx \sigma$, hence we have developed the general solution here.

Consider Eq. (10) applied to the sequence of pulses depicted in Fig. 1a. The time between pulses is t_p , and during each pulse a quantity of gas L is absorbed by the getters producing an additional concentration $Q \equiv L/M$. If $q_{n-1}(t_p)$ is understood to mean $\lim_{\epsilon \rightarrow 0^+} q_{n-1}(t_p - \epsilon)$ then the hydrogenic concentration in the getter during the interval between the n'th and (n + 1)'th pulse, $q_n(t)$, is

$$q_n(t) = \left(\alpha t + \frac{1}{q_{n-1}(t_p) + Q} \right)^{-1} \quad (11)$$

The time $t = 0$ corresponds to the end of the n'th pulse and $q_n(0) = q_{n-1}(t_p) + Q$. (See Fig. 1b). As $n \rightarrow \infty$ $q_n(t)$ approaches equilibrium. The equilibrium concentration just prior to the start of a pulse, q_e , can be obtained from Eq. (11) by setting $q_e = q_n(t_p) = q_{n-1}(t_p)$:

$$q_e = Q \frac{(1 + 4/(\alpha t_p Q))^{1/2} - 1}{2} . \quad (12)$$

The corresponding pressure P_e for $\sigma \gg S$ is, from Eq. (5),

$$P_e = K q_e^2 , \quad (13)$$

and the ratio R of the pressure immediately after a pulse to the pressure just prior to the next pulse (P_e) is

$$R = (1 + Q/q_e)^2 . \quad (14)$$

From Eqs. (12) and (14) it is clear that if the equilibrium loading q_e is the equivalent of many machine pulses, the pressure between pulses is approximately constant in time and is given by Eq. (1).

III. Specific Results

In Fig. 2 we have plotted the normalized concentrations $q_n(t_p)/Q$ as functions of n for various TFTR conditions. Assuming that the modified SAES Zr/Al modules¹⁰ are used to give a projected coverage of $\sim 10^5 \text{ cm}^2$ ($\sim 10\%$ of the vacuum vessel area), M is equal to 10^4 g , and the getter pumping speed $\sigma \approx 4.5 \times 10^5 \text{ l/s}$. The time between pulses, t_p , is 300 s. The gas load/pulse, L , is 172 Torr-l, with an assumed equal D-T mixture. The pumping speed for cases A and C is $9 \times 10^3 \text{ l/s}$ which is the standard TVPS speed.

It is possible to realize a vacuum pumping speed of $\sim 10^5$ l/s by utilizing the pumping systems of the four neutral beam lines on TFTR. This entails allowing the fast operating gate valves between the beam lines and the vacuum vessel to remain open between pulses. Cases B, D, and E represent this condition. Sieverts constant K (in units of Torr/(Torr-l/g)²) is⁸

$$K = 10^{4.4 - 7000/T(^{\circ}\text{K})} \quad , \quad (15)$$

where we have taken the temperature $T = 500^{\circ}\text{C}$ (case B), 550°C (cases A and D), and 600°C (cases C and E). This temperature range is selected because below 500°C there is little advantage to the transient scheme for the anticipated experimental runs of ~ 100 pulses, while above 600°C , the thermal loading on the vacuum vessel becomes prohibitive. The normalized equilibrium loadings, q_e/Q , are shown for each case. The largest equilibrium loading, case A, corresponds to $\sim 9 \times 10^3$ Torr - l which for 10^4 g of Zr/Al is less than 0.5 atomic % while the α -phase boundary for Zr-H in the range $500^{\circ}\text{C} \leq T \leq 600^{\circ}\text{C}$ is ~ 3 atomic %.

Although $q_n(t_p)/Q$ is plotted as a continuous function of n , it should be remembered that n is a discrete variable. The variation of $q_n(t)$ during a pulse will be small for all of these cases, however, since the smallest normalized equilibrium loading (case E) is $q_e/Q \approx 9.5$. For all cases, after a number of pulses approximately equal to the normalized equilibrium loading (q_e/Q), the value of $q_n(t_p)$ is $\sim .75 q_e$, approaching the asymptotic limit with a near-exponential dependence. Except for case A, all of the loadings are less than equivalent of 50 machine pulses, and therefore, even

with the anticipated tritium loading restriction (see Sec. I), the device could be operated for arbitrarily long experimental runs by using the transient scheme. Also, the getter could be kept warm between experimental runs to reduce the frequency of thermal cycling and thus regenerate the residual loading.

IV. Discussion

The derivation in Sec. II is based upon the assumption that surface desorption is the rate limiting step in the out gassing process, i.e., that diffusion of D and T in the bulk is rapid compared to desorption. The diffusivity of Zr/Al has not been measured, however we can infer a lower limit from data which show that the Zr/Al H_2 pumping speed at $400^{\circ}C$ is constant up to pressures of 5×10^{-3} Torr.⁸ Assuming a 3% sticking coefficient, for the getter to accomodate the influx corresponding to this pressure limit requires an inward velocity of -1.0×10^{-4} cm/sec (D/T average), which in turn implies that the time required to traverse the 20 μ m thick layer is ≤ 20 sec. This is an upper limit for a diffusion time, since the pressure limit may be due to surface processes. Also, for the $500^{\circ}C$ - $600^{\circ}C$ range of interest here, the diffusion would be even faster. It is clear that the time for D and T to diffuse through the bulk is short compared to the 300 sec. cycle length of the transient scheme.

For a given temperature, q_e can be decreased by using less getter mass, since from Eq. (13) $q_e \sim M$. This will decrease the overall useful life of the getter, however, since the impurity sorption capacity⁷ will be less by the same factor. The choice of 10^4 g along with the anticipated impurity content of TFTR give a lifetime of $\sim 13,000$ pulses which would represent 6-12 months of operation.¹⁴ Increasing t_p would also lower q_e , although the dependence is weaker than that for $M(q_e \sim t_p^{1/2})$. It is clear, also, that to the extent that the total gas load L does not end up in the getters, q_e is decreased. Therefore, the assumption of total pumping by the getters is conservative insofar as loading is concerned.

For normal (400°C) Zr/Al operation it would be necessary to re-activate the getters every 4000 pulses or so to realize the full 13,000 pulse impurity sorption capacity.⁸ This entails heating them to 700°C for ~ 30 min and serves to diffuse impurities further into the bulk. Since the rate of impurity chemisorption will be greater in the 500°C - 600°C transient operation range,¹⁵ reactivation may be required less frequently or not at all. In either case it would pose no serious limitation.

The maximum thermal loading from the plasma during normal operation will be $\sim 33 \text{ W/cm}^2$ for 1.5s. In addition to a transient temperature rise near the getter surface which will decay ~ 10 seconds after the pulse, the bulk getter temperature will increase $\sim 50^\circ - 75^\circ\text{C}$, returning approximately linearly in time to its nominal value prior to the next pulse.¹⁴ Although the impact of this temperature change on the transient getter scheme is not major, it does reduce the equilibrium loading somewhat. It is possible that the temperature variation could have a deleterious effect by causing mechanical

fatigue. This would require alteration of the getter configuration to minimize the temperature excursions.

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Fig. 1a. Graph of the assumed hydrogenic flux into the getter for a sequence of pulses of duration Δt_p separated by time t_p . The total gas load per pulse is L .

Fig. 1b. Schematic presentation of the functions $q_{n-1}(t)$ and $q_n(t)$ which are the hydrogenic concentrations in the getter at a time t after pulse $(n-1)$ and (n) respectively. These quantities are also shown at specific points in time including $t=0$ and $t=t_p$. Q is the concentration in the getter due to the loading from one pulse and is equal to L/M where L is the gas load/pulse and M is the getter mass.

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Fig. 2. Graph of the normalized getter loading, $q_n(t_p)/Q$ as a function of the pulse number n for five combinations of vacuum pumping speed and getter temperature as indicated. $q_n(t_p)$ is the hydrogenic concentration in the getter at a time t_p after n pulses (i.e., the concentration immediately prior to pulse $(n+1)$). Q is the concentration due to loading from one pulse and is equal to L/M where L is the gas load per pulse and M is the getter mass. n is a discrete variable, but the curves are plotted continuously for convenience. The equilibrium values of $q_n(t_p)/Q$ as $n \rightarrow \infty$, q_e/Q , are listed for each case.

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