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COMPATIBILITY OF THE Zr-Al ALLOY WITH A TOKAMAK PLASMA ENVIRONMENT

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We have investigated the compatibility of the Zr-Al alloy bulk getter with a tokamak plasma environment, where the hydrogenic fluxes are sufficient to cause embrittlement in relatively short times. Under normal operating conditions with the getters activated, it is necessary to regenerate the absorbed hydrogenic species before the embrittlement limit is reached. We present a method for determining the loading under tokamak conditions where the Zr-Al surface characteristics can change. During glow discharge cleaning and pulse discharge cleaning, it is not convenient to regenerate. We find, however, that during the cleaning operations the getter self-inerts, thus limiting the loading. We present data and a model which accounts for this behavior in terms of impurity adsorption on the room temperature getter surface during the cleaning operations.

DISCLAIMER

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1. INTRODUCTION

The tokamak fusion devices of the next generation (JET, JT-60, TFTR) are intended to achieve reactor-like plasma conditions. TFTR, in particular, will be the first machine to use deuterium and tritium to demonstrate scientific fusion energy breakeven [1]. A crucial element in realizing the high temperatures and fuel densities required for these objectives is the control of plasma impurities. Additionally, to maximize the fusion power output of TFTR, the deuterium and tritium density ratio must be optimized by controlling fuel recycling in conjunction with selective gas or pellet injection [2]. A number of present and past tokamak experiments have utilized Ti sublimated on the vacuum vessel walls to effect the control of both hydrogen recycling and impurities [3]; however, the feasibility of its use in future devices is questionable, owing to the problems of flaking and the necessity of limiting the tritium inventory. A more promising alternative is the Zr-Al non-evaporable bulk getter [4], which pumps hydrogen isotopes reversibly and impurities (C,N,O) irreversibly. This getter utilizes the alloy St'01® in the form of a powder bonded to a constantan heating substrate. The alloy is a near equal mixture of the two compounds Zr_5Al_3 and Zr_3Al_2 [5]. At low concentrations, each of these components absorbs hydrogen in dilute solution. At concentrations greater than ~ 20 Torr-1/g (18 at. %), flaking of the getter material can occur, presumably due to embrittlement resulting from hydride precipitation [4]. Such flaking would be deleterious to plasma operation, since it can cause contamination, disruptions, and potential reservoirs of tritium which cannot be desorbed easily.

In this paper we explore the embrittlement problem for tokamak operation. Under normal pulsed conditions when the getters would be activated

and pumping, it is necessary to regenerate the hydrogen isotopes before the embrittlement limit is reached. In Sec. 2. we present a method for determining the loading under tokamak operating conditions. Due to the low duty cycle for H_2 exposure during normal operation, the time required to reach embrittlement is relatively long.

During glow discharge cleaning (GDC) and pulse discharge cleaning (PDC) operations [3], the hydrogenic fluxes to the getter are in principle, sufficient to exceed the embrittlement limit in a short time. Furthermore, it would not be desirable to interrupt the cleaning for frequent getter regeneration. Previous measurements [6] indicate, however, that during GDC, a much smaller hydrogenic uptake is realized in comparison to the expected equivalent thermal hydrogenic exposure. In Sec. 3 we examine the getter loading during PDC. In this case the loading is also less than expected. To explore further this apparent "self-inerting" of the getter, we have measured the dependence of the hydrogenic pumping speed on O_2 and N_2 adsorption. These data are presented in Sec. 4. In Sec. 5 a model of the self-inerting is described. Our results are summarized in Sec. 6.

2. TOKAMAK OPERATION

A key element in avoiding embrittlement is a reliable means for determining the hydrogen loading. Under usual conditions the loading may be determined from the equilibrium pressure P which will be a function of the temperature T and hydrogen concentration q . This relationship is shown in Fig. 1 and was measured using the laboratory apparatus shown schematically in Fig. 2. These data can be fit with the usual Sievert's expression [7]:

$$P = Kq^2, \quad (1)$$

with Sievert's constant K ($\text{Torr}/(\text{Torr-l/g})^2$) given by

$$K = (4.68 \times 10^4) \exp (-1.65 \times 10^4/T), \quad (2)$$

where T is the temperature in $^{\circ}\text{K}$. This expression for K is in good agreement with previous measurements [8]. The graph also indicates how the desorption of hydrogen is accomplished. After some period of operation at the normal temperature of 400°C , the temperature of the getter is raised to $\sim 700^{\circ}\text{C}$. This causes a large rise in the equilibrium pressure and the resulting outflux of hydrogen is pumped by the associated back up pumping system.

In the tokamak environment, the getter will be subjected to bombardment by energetic charge exchange neutral atoms, high particle fluxes and forces due to disruptions, radiative heat loads, runaway electrons, and deposition of limiter and armour plate materials like C and Ti. These interactions may cause modifications to the getter surface. Since the constant K is related to the desorption/absorption kinetic rates, $K = k_o/k_i$ describing the hydrogen metal interaction:

it is possible that the above surface modifications could alter K . For this reason, using a previously measured value of K and equilibrium pressure measurements to determine q can be unreliable.

An alternative method for measuring q which does not require knowledge of K is to measure the pressure as a function of time during desorption. Fig. 3 shows a graph of $p^{-1/2}$ as a function of time t . For outgassing, Eq. 1 is

modified to become [9]:

$$P(t) = \frac{K[q(t)]^2}{S/S_T}, \quad (4)$$

with S being the pumping speed of the backup pump and S_T the effective series pumping speed:

$$\frac{1}{S_T} = \frac{1}{S} + \frac{1}{k_i}. \quad (5)$$

For surface limited desorption the loading can be written as [9]:

$$\alpha(t) = (\alpha t + q_0^{-1})^{-1} \quad (6)$$

with $q_0 = q(0)$ and $\alpha = KS_T/M$ where M is the getter mass. Thus, the slope of $P^{-1/2}$ vs. t will be proportional to $K^{1/2}$ which, when combined with the pressure, can be used to determine the loading. We have verified that this procedure determines the correct loading for a getter loaded with a known quantity of hydrogen. From Fig. 3 it can be seen that the initial outgassing deviates from the prediction of Eqs. 3-5. In this region bulk diffusion is the rate limiting step in desorption [10]. This has little effect on the present method, however, it will affect the transient getter operation described in Ref. [9] especially at lower temperatures where the diffusivity is smaller.

3. LOADING DURING PULSED DISCHARGE CLEANING

During tokamak cleaning operations (GDC and PDC) it would be desirable to limit the hydrogenic loading of the getters without requiring regeneration, which would interrupt cleaning. For this reason the getters are operated

nominally at room temperature. (The radiative heat load on the getter from GDC and the most common type of PDC is small). Nevertheless, since the cleaning operation will usually follow a period when the getters have been activated (45 min. at 700°C), the room temperature hydrogenic pumping speed of a standard getter module (80g of Zr-Al) will be ~ 1000 l/s. At this speed, with a typical PDC H_2 pressure of 1×10^{-4} Torr, the embrittlement limit would be reached in approximately four hours or one half of a typical PDC period.

We have determined the loading during PDC for two arrays of Zr-Al getters installed in the PDX tokamak [11]. The system comprises 16 modules with a pumping speed of $\sim 18,000$ l/s at 400°C . During PDC the H_2 pressure was 1×10^{-4} Torr. In Table I we show the measured H_2 loading as a function of PDC exposure. We also list the projected loading based upon the measured initial (room temperature) H_2 pumping speed of 1000 l/s per standard module.

Table I
Measured and Projected H_2 Loading
for the PDX Zr/Al System

No. of PDC Pulses	Time (Hr.)	Measured (Torr-l/g)	Projected (Torr-l/g)
0	0	≤ 0.1	0
463	0.5	0.6	2.2
3683	4.0	1.6	18.0
6875	8.0	1.6	36.0

Instead of a linear increase in q , the loading saturates at 1.6 Torr-1/g. This apparent self-inerting is similar to the results for GDC exposure reported previously [6]. A possible mechanism for this behavior is discussed in Sec. 4.

4. MECHANISM FOR SELF-INERTING

During both GDC and PDC, impurities containing carbon, nitrogen, and oxygen are liberated from the surfaces of the vacuum vessel [3]. At room temperature, the bulk diffusion rate of these impurities in Zr-Al is small [12]. Consequently, one possible explanation for the observed self-inerting behavior is that the liberated impurities saturate the getter surface causing the hydrogenic pumping speed to go to zero.

To explore the possibility further we have measured hydrogenic and impurity pumping speeds as functions of the surface impurity loading. Fig. 4 shows the hydrogen and nitrogen pumping speeds, S_H and S_N respectively, as functions of nitrogen loading Q_N . It is apparent that nitrogen coverage has only a limited effect on S_H even when saturation ($S_N=0$) is reached. In Fig. 5 the analogous quantities S_H and S_O are plotted as a function of oxygen loading Q_O . In this case, when $Q_O = 6$ Torr-1, S_H and S_O both approach zero.

The dependence of S_O in Fig. 5 on Q_O is closely approximated by the usual Langmuir isotherm for disassociative adsorption [13]:

$$S_O = S_O^i (1 - Q_O/Q_O^f)^2, \quad (7)$$

where S_O^i is the oxygen pumping speed for $Q_O = 0$ and Q_O^f is the saturation loading. Then Q_O is described by the equation:

$$\frac{dQ_O}{dt} = S_O^i P_O (1 - Q_O/Q_O^f)^2, \quad (8)$$

where P_O is the oxygen partial pressure. Assuming that the hydrogen pumping speed follows the same behavior, the total hydrogen loading Q_H ($Q_i = M q_i$) is given by:

$$Q_H = S_H^i P_O \int_0^t (1 - Q_O/Q_O^f)^2 dt. \quad (9)$$

From the solution to Eq. (8) this becomes:

$$Q_H = Q_H^f \frac{1}{1 + \frac{\tau}{t}}, \quad (10)$$

where Q_H^f is the saturation hydrogen loading given by

$$Q_H^f = \frac{S_H^i P_H}{S_O^i P_O} Q_O^f, \quad (11)$$

and $\tau = Q_O^f / (P_O S_O^i)$.

From Table I, the measured value of q_H^f is 1.6 Torr-l/g. Together with equation 11 this implies a fractional level of oxygen impurities during PDC of $\sim 4\%$ which is in good agreement with residual gas measurements of the oxygen level (predominantly H_2O and CO) during PDC. From Eq. 10 the predicted values of Q_H for 0.5 hr. and 4 hr. are 0.7 Torr-l/g and 1.4 Torr-l/g respectively, which are in reasonable agreement with the measured values in Table I.

5. SUMMARY

We have explored the implications of the embrittlement limit for the tokamak operation of Zr-Al getters. For normal operation, the loading can be determined reliably by the method described in Sec. 2. Since tokamaks are pulsed with a low duty factor, regeneration will be infrequent and can be accomplished before reaching a loading of 20 Torr-l/g. For pulsed and glow discharge cleaning, although the hydrogenic fluxes are sufficient to possibly exceed the embrittlement limit in a short time, the getters appear to self inert such that the saturation loading is well below the embrittlement limit. Measurements of S_H as a function of the surface nitrogen or oxygen loading at room temperature show that nitrogen is only partially effective in inerting the surface but 6 Torr-l of oxygen is sufficient to reduce the hydrogen pump speed close to zero. These measurements in conjunction with a model presented in Sec. 4, predict PDC loadings close to those observed in PDX.

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FIGURE CAPTIONS

Fig. 1. Equilibrium pressure P as a function of the hydrogen concentration q and alloy temperature T . The data follows Sievert's expression $P = Kq^2$.

Fig. 2. Schematic diagram of the apparatus. The 107 liter test chamber contains a Zr-Al getter module and can also be pumped by a nominal 500 l/sec turbomolecular pump whose measured H_2 speed is 300 l/sec. H_2 influx rates are controlled by a piezoelectrical valve (Veeco PV-10) and monitored by measurement of the pressure differential across a molecular flow orifice (MKS Fe 1.0). Total pressure measurements are made using (1) a nude Bayard-Alpert gauge, (2) a nude triode gauge, and (3) a capacitance manometer (MKS-310). Partial pressure measurements are made with a quadrupole residual gas analyzer (RGA).

Fig. 3. Hydrogen pressure ($P^{-1/2}$) as a function of the desorption time t . The initial region is diffusion limited. For $t > \sim L^2/D$, where L is the getter thickness and D is the diffusivity [10], the desorption becomes limited by surface kinetics.

Fig. 4. Hydrogen and nitrogen pumping speeds as functions of nitrogen surface loading.

Fig. 5. Hydrogen and oxygen pumping speeds as functions of oxygen surface loading.

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FIG. 1

Fig. 2

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Fig. 3

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Fig. 4

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Fig. 5