EVALUATION OF A NONEVAPORABLE GETTER PUMP FOR TRITIUM HANDLING IN THE TOKAMAK FUSION TEST REACTOR

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ABSTRACT

Lawrence Livermore Laboratory has tested and evaluated a commercially available getter pump for use with tritium in the Tokamak Fusion Test Reactor (TFTR). The pump contains Zr (84%)-Al in cartridge form with a concentric heating unit. It performed well in all tests, except for frequent heater failures.

INTRODUCTION

Fusion test facilities that will use tritium as a fuel are now being built. This development adds a new dimension to the operation of a fusion test facility; the safe and economical handling of a highly volatile radioactive gas. Although the problems of tritium technology for fusion reactors have been anticipated for some time,[1,2] the actual building and testing of components are now urgent concerns.

We have evaluated a commercially available nonevaporable getter pump for use in the Tokamak Fusion Test Reactor (TFTR) being built at Princeton Plasma Physics Laboratory. These pumps will back up the turbomolecular pumps that remove residual deuterium and tritium from the torus after each burn. They are dead-end pumps designed to trap and hold the pumped gases by absorption on Zr(84%)-Al powder. Getters are generally defined as metals or other materials that absorb gases to form stable compounds. The pumping speed must be fast enough to reduce system pressure from 1×10^{-3} to 2×10^{-6} Torr between each 5-min pulse of the tokamak. About 95% of the gas injected into the torus will be absorbed by the getter pumps. When the pumps are filled to their rated capacity with hydrogen isotopes, they will be sent off-site for tritium and deuterium recovery. They will be recycled until their rated capacity for active gases such as O_2, CO, and N_2, which are permanently retained on the Zr-Al, has been reached.

The purpose of our evaluation was to determine if these pumps will perform as expected in the TFTR operating mode and if any unexpected failures might occur with tritium use. Tritium is the radioactive isotope of hydrogen and decays into He^3 plus a 5.7 MeV beta particle. We also investigated the effect of active gas contaminants on the pumping speed and the base pressure of hydrogen isotopes at anticipated TFTR operating levels.

The performance of the pumps with hydrogen and deuterium has been previously measured,[3] and the expected isotope effect on pumping speed has been observed; i.e., pumping speeds are inversely proportional to the square root of the masses. However, the pumps had not been tested previously with tritium, and tritium pumping speeds had not been measured.

The getter pumps are manufactured by Societa Apparecchi Elettrici e Scientifici (SAES), an Italian company, and are distributed in the U.S. by Westinghouse Electric Corporation and SAES Getters/ U.S.A. All cartridges containing the Zr-Al getter material are produced by SAES in Italy. We made some initial tests with pumps manufactured completely by SAES, but the majority of the tests were made on pumps with Westinghouse heaters and jackets. The designs are very similar and in all cases the dimensions are the same. The pumps are composed of a Zr-Al cartridge, a heater, and an outer case or jacket with water cooling (Fig. 1). There are no moving parts. An enclosed pump has a water-cooled jacket and a nude pump is simply a cartridge and heater mounted on a flange.

The SAES trade name for Zr(84%)-Al is St101 alloy. This mixture of intermetallic compounds is powdered and pressed onto an iron substrate by a proprietary process (Fig. 2). The folded strips of powder on the substrate are arranged in concertina style at approximately 4-deg angles to form a circular cartridge with maximum surface area and trapping efficiency. This cartridge fits around the rod-shaped heating element mounted on a Conflat-style flange with electrical feed-throughs (Fig. 3). The heater activates the Zr-Al at 750°C *in vacuo* and maintains an operating temperature of 400°C. The pumps operate in the 10^{-2}- to 10^{-10}-Torr range.
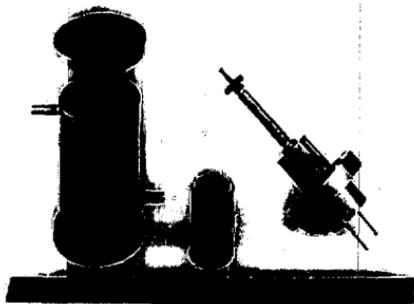
Fig. 1. Three components of SAES getter pump: jacket, cartridge, and heater mounted on flange.

Fig. 2. Photomicrograph of Zr-Al powder pressed onto substrate for SAES cartridges (500X).

Heating element

Zr-Al on substrate

Cooling coil

Fig. 3. SAES getter pump in stainless steel container with cooling coils.

The Zr-Al absorbs hydrogen isotopes and active gases including CO, N_2, and O_2. The mechanism of pumping is different for the two types of gases. Hydrogen forms a solid solution and is released when the Zr-Al is heated *in vacuo* to the activation temperature of 750° C. The active gases chemically combine with Zr-Al and activation enhances the rate of diffusion of these gases into the bulk of the getter material.[4] Thus, activation of the getter increases its surface area and exposes fresh surface by diffusion of adsorbed active gases into the bulk and by removal of hydrogen isotopes. Activation is described in more detail in the SAES literature.[5] Bulk material of the St101 alloy has been tested with tritium but its performance was not satisfactory for hydrogen isotope pumping.[6]
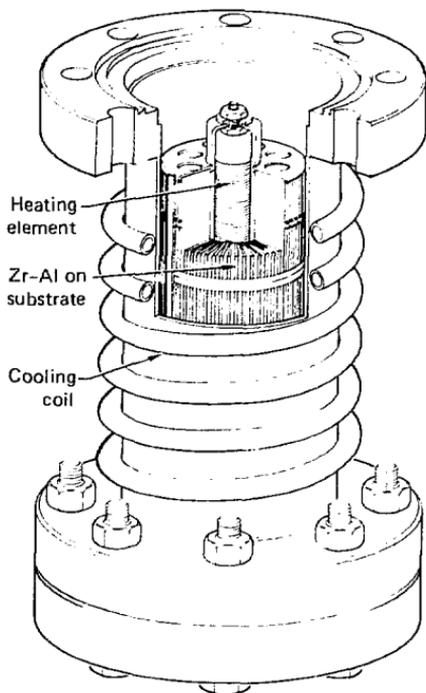
The optimum operating temperature of the pump depends on its particular application. Temperature affects not only the diffusion rate of active gases into the bulk, but also the capacity of the Zr-Al for hydrogen.[7] Hydrogen capacity is a function of temperature and equilibrium partial pressure of hydrogen (Fig. 4). Above 400°C, this capacity rapidly becomes too low for practical use. Temperatures as low as 150°C are recommended by the manufacturer for pumping pure hydrogen in small amounts. The recommended temperature range for pumping large loads of hydrogen is between 200 and 400°C.

At 400°C, water vapor dissociates into hydrogen and oxygen at the getter surface, and the two components are pumped separately. The hydrogen can be removed by reactivation of the cartridge.

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Methane is absorbed at a slower rate than the active gases, but the operating temperature is high enough to crack and pump methane and higher hydrocarbons.

As the amount of active gases increases in the cartridge, the pumping speed decreases. Pumping speed can be increased by reactivation which partially restores the pump to its previous speed level. This is the typical method of operation and requires an auxiliary pumping system for reactivation. The active gases stay in the Zr-Al during this process and continue to accumulate while the hydrogen is removed. Pumping speed drops off more quickly after each reactivation as the result of the build-up of active gases in the getter To maintain a fairly constant pumping speed, a maximum recommended capacity of the cartridge for active gases per reactivation has been established. The total recommended capacity for active gases, which is only 2 to 3% of the stoichiometric capacity of the getter material in the cartridge, is reached in 10 to 20 reactivations. The capacity for N_2 and CO is rated at 0.3 Pa m³ g at 300 to 400 C, and O_2 capacity is approximately five times as much.[5]
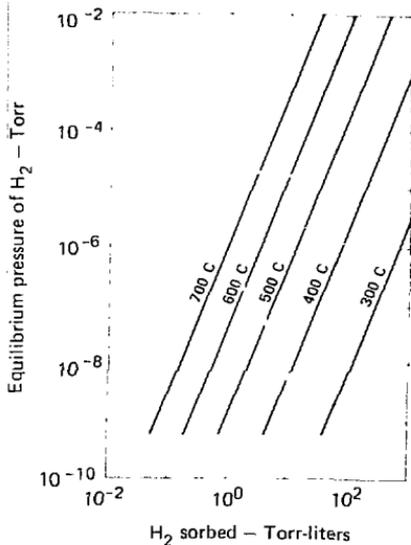

Fig. 4. Pressure-composition isotherms for a C-100 cartridge of Zr-Al.

PROCEDURES AND RESULTS

The C-50 and C-100 SAES cartridges used for these evaluation studies contained a minimum of 25 and 80 g of Zr-Al, respectively. The manufacturer's rated capacities and pumping speeds are listed in Table 1. Some cartridges arrived in sealed cans and others were open to the atmosphere in shipping. These two methods of handling did not cause any observable difference in cartridge appearance or performance. The C-50 cartridges were used for pumping speed measurements and the C-100 cartridges were used for base pressure determinations. All tests were run with the enclosed-type pump.

The pumps were attached to a diffusion-pumped vacuum system and the electrical feedthroughs were wired to variable transformers to regulate power to the heaters. The pumps were activated for 15 min at the suggested power setting *in vacuo.* Because there are no thermocouples in the pumps, we relied on these power settings to produce the correct cartridge temperatures. We added two thermocouples to a C-100 pump located

between the cartridge and the inside wall. We still could not read the actual temperature of the cartridge because the temperature gradient from the heater to the thermocouples was more than 200°C.

Except for base pressure evaluations, during activation the pumps were evacuated with a diffusion pump. The base pressure of the diffusion-pumped systems was 10^{-6} Torr or less at the SAES pumps. During activation of a new cartridge, pressure rose to 10^{-2} Torr as the heat increased, and then fell to 10^{-4} Torr or less before the 15-min activation was complete. Base pressure at the SAES pumps was about 10^{-6} Torr and held steady after the diffusion pump was isolated and the pump was set for operating temperature of 400°C. After activation, the pumps were allowed to stabilize at 400°C for at least 30 min before testing.

Gas mixtures were prepared in a manifold that had been calibrated using a portable volume-calibration system. The manifold volume was approximately 2 liters. Before each run, the mixture

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Table 1. Cartridge performances.[a]

Cartridge	Active surface, cm^2	Getter weight, g	Pumping speeds			Permanent sorption capacity per reactivation, Torr-liters		Reversible sorption capacity of H_2, Torr-liters	Power settings[b]			
			CO	N_2	H_2	CO	N_2		750°C		400°C	
									A	V	A	V
C-50	600	25	–	–	–	17	15	35	4.7	~60	2.3	~35
Nude	–	–	150	55	260	–	–		..	..	..	..
Enclosed	–	–	50	25	130	..	..	–	–	–	–	–
C-100	1100	80	–	–	–	30	25	90	10.0	40	5.0	18
Nude	–	–	340	110	580	–	–	–	..	..	..	..
Enclosed	–	–	100	50	250	..	..	..	–	–	–	–

[a]Data taken from *Westinghouse Data Sheet B-439, Westinghouse Electric Corporation (1978).*
[b]Used at LLL.

was analyzed with a residual gas analyzer (UTI 100-C) connected to the manifold through a variable leak valve. Pressure in the manifold was measured with MKS Baratron gages (1- and 1000-Torr heads).

The entire system was designed and built using ultra-high vacuum techniques and all-metal construction, predominantly 316 stainless steel (see Fig. 5).

PUMPING SPEED

To determine pumping speed, two C-50 SAES pumps were attached through 10-cm-o.d. gate-valves to the ends of a large-diameter, 40-liter stainless steel tank (Fig. 6). This configuration allows the pump inlet, a 4.4-cm-diam opening, to be the conductance-limiting path during pumping. The calculated conductance of the inlet is 130 liters/s.[8] The 40-liter tank was connected to an approximately 2-liter manifold through a Granville-Phillips motor-driven leak valve (Series 216) controlled by an MKS pressure controller (Model 99A). During pumping speed determinations the controller maintained a constant pressure at the SAES pump by regulating flow from the high-pressure manifold side to the tank side. The tank was also connected to a portable diffusion pump system for activation and pump-down.

New cartridges were used to determine pumping speeds of deuterium and hydrogen. The cartridges used for tritium pumping speed determinations had seen only a trace amount of active gases and had been used for several deuterium and inert gas pumping speed determinations. After use with tritium, all cartridges were removed and stored in containers in an argon-filled glove-box. The tritium was left on the cartridges so that aging effects can be studied if the interest arises.

We measured pumping speeds at constant pressures of about 10^{-3} Torr. The 40-liter tank was

filled to the test pressure and the controller was set on automatic before opening the gate valve to one of the SAES pumps. The test pressure was detected with a Varian dual-range ion gage mounted on the 40-liter tank and corrections were made for the ionization probability of each test gas. The pressure drop in the manifold was measured with a 1000-Torr MKS Baratron gage.

We calculated pumping speeds as an average value over a designated time period.[9] When pumping speeds decreased with time, we compared identical time intervals. Most pumping speeds were compared over a 3-min interval. We used the following pumping speed formula:

$$\text{pumping speed} = \frac{|\Delta P| \, |Vol|}{|T.P.| \, |\Delta t|} .$$

where ΔP is pressure drop in the manifold in Torr, Vol is calibrated volume of manifold in liters, T.P. is test pressure at the SAES pump in Torr, and Δt is length of time of test in seconds.

If inert gases are present in the mixture, they are not absorbed by the SAES pumps and accumulate in the tank during pumping speed measurements. The amount of inert gas rapidly builds up in the tank so that the automatic controller shuts off completely and the run is terminated. Helium-3 was an inert gas
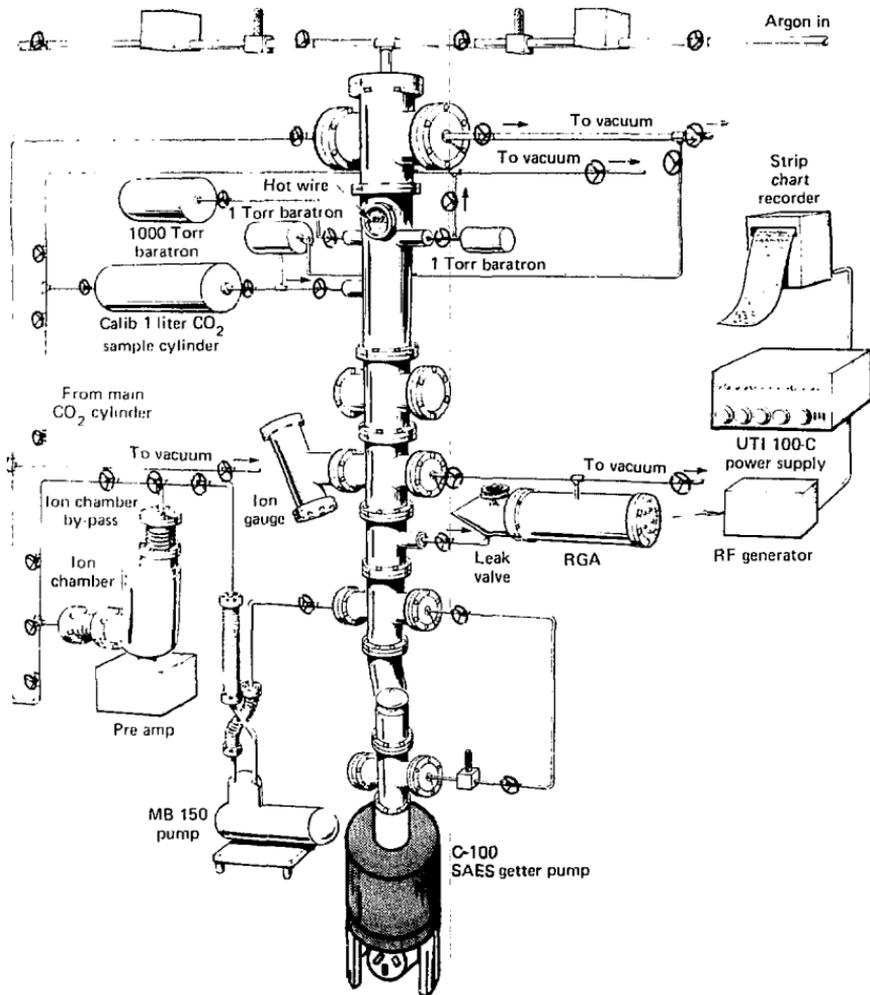
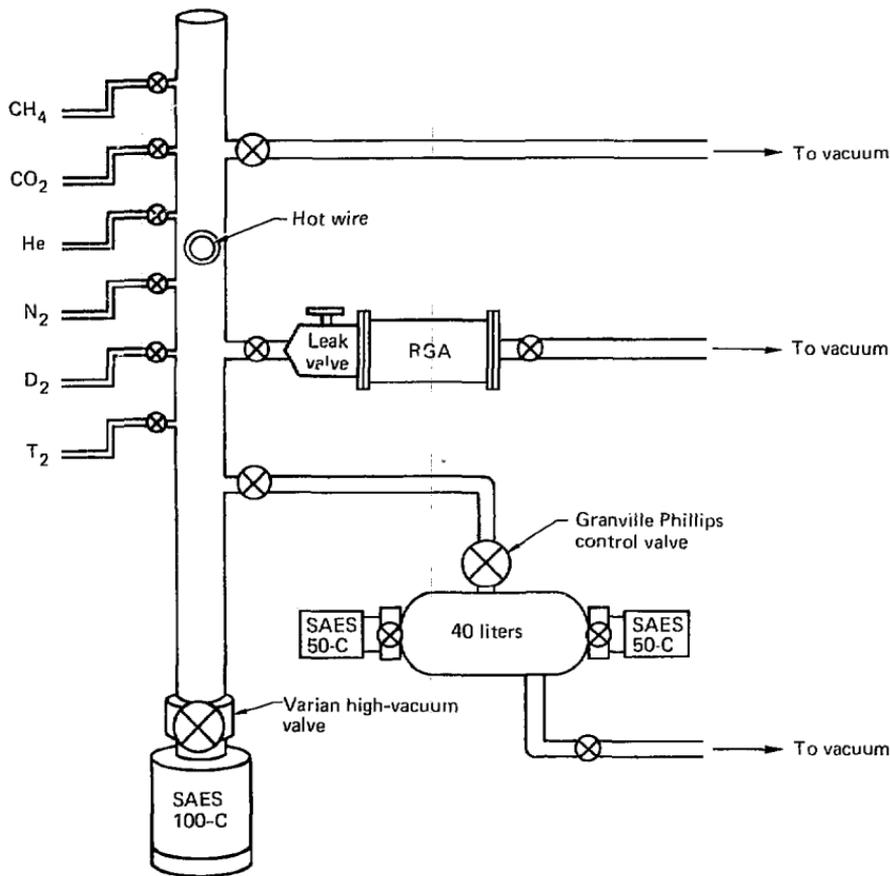Fig. 5. Calibrated manifold with SAES pump.

Fig. 6. Assembly for pumping speed measurements.

contaminant in all the tritium pumping speed measurements. The lowest He^3 contamination was less than 1%. For comparison, we measured the pumping speeds of hydrogen and deuterium with less than 1% He^4. The effect of the inert gas accumulation can be seen as a decrease in pumping speed with time (Table 2).

We measured the pumping speeds of pure hydrogen and pure deuterium several times with reproducible results. Several runs were made with deuterium containing from 2 to 9% argon and with tritium having 3% He^3. All of these runs were unsatisfactory because the pressure controller shut off too quickly as a result of inert gas build-up in the 40-liter tank.

The pumping speeds of three active gases were measured on the same cartridge. Measurements were done in duplicate with the two C-50 SAES pumps on the 40-liter tank. The active gases were run in the following order with reactivation of the

Table 2. Pumping speed for C-50-size SAES pump.[a]

Gas	Pumping speed, liters/s	Average time, min	Active gas[b] on cartridge at start, Torr-liters
H_2	134	3	--
H_2(0.8% He)	79	1	--
H_2(0.8% He)	71	2	--
H_2(0.8% He)	63	3	--
D_2	93	3	--
D_2, 0.8% He	59	1	--
D_2, 0.8% He	55	2	--
D_2, 0.8% He	49	3	--
T_2, 0.8% He[3]	51	1	0.02
T_2, 0.8% He[3]	46	2	0.02
T_2, 0.8% He[3]	41	3	0.02
N_2	26	3	--
CO	27	3	3.3
O_2	26	3	10.0

[a]~25 g Zr-Al.

[b]Reactivated before each pumping speed determination.

cartridges between each test (the amount of active gas added to the two cartridges during each test is included in parentheses): N_2 (3.15 and 3.63 Torr-liters), CO (2.91 and 3.09 Torr-liters), and O_2 (2.82 and 1.91 Torr-liters).

We used the same pair of cartridges to measure the effect of active gas load on hydrogen pumping speed (which we had measured before any active gases were put on the cartridges). We measured hydrogen pumping speed again after the three active gases were tested and the cartridge was reactivated. We performed a series of 14 more tests alternating hydrogen and nitrogen pumping speed determinations with reactivation of the cartridges after each addition of hydrogen and after each addition of nitrogen. For each test, approximately 18 Torr-liters of nitrogen were added to the pumps and they were still working when the tests were terminated with almost 250 Torr-liters of active gases on each cartridge (Figs. 7 and 8). The cartridges had been reactivated at least 30 times and still appeared to be functioning very well. They did not show any visible signs of deterioration when removed.
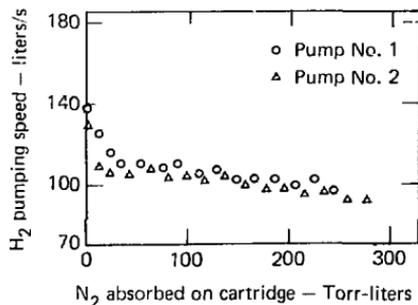

Fig. 7. H_2 pumping speed at 1.2×10^{-3} Torr vs N_2 load on pump. Pumps were reactivated before each measurement.
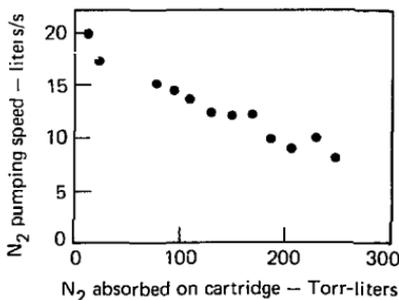

Fig. 8. N_2 pumping speed at 6×10^{-3} Torr vs N_2 load on pump.

BASE PRESSURE

A C-100 SAES pump was connected to the calibrated manifold through a Varian all-metal bakeable vacuum valve. A Varian Millitorr gage was located on the pump side of the valve, so the pressure at the SAES pump could be monitored continuously. This pump was used for base pressure evaluation studies.

The TFTR will operate in a 5-min pulse mode and unused gas must be removed from the torus between each pulse. SAES pumps will be used to back up the turbomolecular pumps that evacuate the torus. The base pressure at the SAES pumps must stay below 10^{-3} Torr for 60 consecutive pulses *according to present design criteria.*

It is anticipated that SAES pumps will be activated at around 10^{-3} Torr in the TFTR. This is considerably higher than we used with the diffusion-pumped systems. To determine the effect of activation on pump performance in this pressure range, we used roughing pumps for activation and reactivation for all base pressure experiments. If the apparatus had not been pumped previously with a diffusion pump, the base pressure of the rough-pumped system was about 10^{-4} Torr. To simulate TFTR conditions, the roughing pump was shut off during activation when the pressure had peaked out and was dropping back through the 10^{-3} Torr range. When the SAES pump stabilized at 400°C, the base pressure was in the 10^{-5} Torr range. This method of activation appears to be satisfactory if 10^{-5} Torr is a low enough base pressure for backing the turbo-molecular pumps.

In the first base pressure experiment, an activated pump at 2×10^{-5} Torr was opened to the manifold which contained deuterium at 81 Torr (150 Torr-liters). The pressure dropped to 2×10^{-4} Torr in 1 min and to 1.5×10^{-4} Torr in 2 h. Without reactivation, a second addition of deuterium at 390 Torr (722 Torr-liters) caused the pressure drop outlined in Table 3. We observed that single additions of large amounts of hydrogen to the SAES pumps result in much slower returns to stable base pressure. The calibrated volume of the manifold is 1.852 liters and the C-100 pump volume is 0.691 liters.

The second base pressure experiment simulated, as closely as possible, the TFTR operating mode. A mixture of deuterium with low-level impurities was prepared. The impurity level was based on data from the Princeton Large Torus (PLT) exhaust gas mixtures. The major contaminants by volume were 1% CO and 1% CH₄ (methane) which would result in

Table 3. D_2 pressure vs time after single addition of 722 Torr-liters.

Time, min	Pressure, Torr
0	390
1	6×10^{-3}
2	1.8×10^{-3}
12	6.4×10^{-4}
120	5.8×10^{-4}
2160	4.2×10^{-4}

tritiated methanes in TFTR.[10] Table 4 lists the quantity of each component of exhaust gas that could be pumped onto an array of twelve C-500 SAES cartridges as proposed for use in TFTR. The twelve cartridges contain approximately 4600 g of Zr-Al. Table 4 also lists the percent of each component in a similar gas mixture prepared for the SAES pump evaluations.

A new, activated cartridge pumped a total of 170 Torr-liters of this gas mixture in 60 consecutive 5-min pulses. The manifold was filled to a pressure of 1.5 Torr containing approximately 2.8 Torr-liters of the mixture per pulse. The initial base pressure at the SAES pump was 1.2×10^{-5} Torr and the final pressure after 60 pulses was 6.1×10^{-5} Torr. Within seconds after opening the pump to the manifold, base pressure was established for each pulse. Adding this quantity of the gas mixture in small increments at 400°C did not appreciably affect the pumping speed or equilibrium base pressures.

Table 4. Projected gas loading for a TFTR getter pump[a] (using 12, C-500 cartridges).

Gas	Load, Torr-liters	Volume, %	Experimental volume,[b] %
H_2	3	0.03	—
D_2	1400	15.4	97.99
T_2	7500	82.5	—
CO	90	1.0	0.99
CH_4	90	1.0	0.99
N_2	1	0.01	0.0097
O_2	1	0.01	0.0092
CO_2	1	0.01	0.010

[a]Based on PLT data.

[b]Used at LLL.

We conducted a similar base-pressure experiment using tritium in the first and last pulses. Between the two tritium pulses, deuterium with 1% CO and 1% CH₄ was added in one large amount equal to 58 pulses of the previous run. The extra-high-purity tritium had a He³ content of less than 0.10%. The starting base pressure of the SAES pump was 1.1×10^{-5} Torr.

For the first pulse, the manifold was filled with tritium to a pressure of 1.78 Torr (3.02 Torr-liters) and the Varian valve was opened. The pressure in the manifold immediately dropped to 1.8×10^{-4} Torr and remained steady. This fairly large increase in base pressure was attributed to the He³ in the tritium. We used the RGA to analyze the overpressure gas and found it to be predominantly at 3 amu. The Varian valve was closed and the manifold was evacuated and filled with deuterium plus 1% CO and 1% CH₄ at 94.03 Torr (159.6 Torr-liters) which is equivalent to 58 smaller pulses. The valve was then opened and the pump and manifold based out at 1.6×10^{-4} Torr in 3 min. The pump reached equilibrium more slowly because of the large amount of deuterium added in one pulse. We attributed the slight drop in final pressure from the previous tritium-pulse final pressure to the fact that the He³ in the SAES pump expanded into the extra manifold volume. A final pulse with tritium at 1.83 Torr (3.11 Torr-liters) in the manifold based out at 3×10^{-4} Torr in a few seconds after opening up to the SAES pump. Again, the increase in base pressure can be attributed to the He³ in the tritium.

CONCLUSIONS AND RECOMMENDATIONS

The performance of SAES St101 alloy for pumping hydrogen isotopes was excellent. On a short-term basis, tritium did not appear to adversely affect the pumps. We did not investigate the long-term effects of radiolysis and He³ production in the cartridges.

The He³ overpressure in the pumps is a problem that must be further investigated in the TFTR design. The auxiliary vacuum system used to activate the pumps could remove He³ overpressure and divert it to the molecular-sieve clean-up system. There would be very low levels of tritium in this effluent gas so it could not be released without further processing.

Methane was satisfactorily pumped by the SAES pumps at the level of contamination anticipated for the TFTR. A hot wire, placed in the manifold for cracking hydrocarbons, was not needed for the 1% methane in deuterium pumping experiments. We did not investigate the effect of prolonged or high-level methane absorption on pumping speed.

The SAES pumping speeds for hydrogen isotopes and active gases demonstrated by our tests are more than satisfactory for the TFTR as long as the recommended capacity of active gases is not exceeded. It is the active gas content of the cartridge that limits its usefulness because it affects both pumping speed and base pressure. The pumping speeds of hydrogen and nitrogen are plotted as a function of active gas capacity in Figs. 7 and 8. The manufacturer's total rated capacity for the C-50 cartridge is 140 Torr-liters of active gases and reactivation is required after each addition of 17 Torr-liters. We conducted tests to 250 Torr-liters

of active gases on a C-50 cartridge and found the initial hydrogen pumping speeds after reactivation were still quite satisfactory for the TFTR. A sharp drop in hydrogen pumping speed occurred while adding the first 40 Torr-liters of active gases. After this initial decrease the hydrogen pumping speed leveled off as a function of active gas capacity, but the nitrogen pumping speed continued to drop at a faster rate. However, the pumping speed drops off more quickly after each addition of active gas.

We tested the base pressure of a cartridge under the conditions of one complete loading at the TFTR using the active gas contaminants projected from PLT. The base pressure proved very steady and the only problem we anticipate is the He³ overpressure that we mentioned previously. Base pressure only increased from 1.2×10^{-5} to 6.1×10^{-5} Torr with deuterium containing 1% CO and 1% CH₄ during one complete TFTR loading cycle. Variations of this experiment using tritium and/or larger single loadings were all satisfactory. We did not test the cartridges for the recycling that is planned for the TFTR, e.g., tritium removal and repeated use over an extended time period.

We heated a SAES pump loaded with tritium to activation temperatures and did not detect any tritium diffusion through the walls of the pump. This is no doubt caused by the placement of the heater at the center of the pump and the water cooling of the outer jacket. However, we found the heaters to be most unsatisfactory. They failed repeatedly for several reasons; e.g., the heater element shorted out, the circuit opened, the support rod

broke, or insulators cracked. A reliable heater is essential for tritium use because of the difficulties in repairing a tritium-contaminated pump. We spent a great deal of our time during this study repairing heaters or changing pumps with failed heaters. A new SAES pump configuration is now available with panels heated by direct current through the substrate material. We did not test this design but it may eliminate the heater problems we encountered and be a more reliable pump for tritium use.

Some concern has been expressed about the danger of fire should an air leak develop in the SAES pump system. We did not have an opportunity to check this possibility. The manufacturer states that the cartridges will not burn below 500°C and that the only time there is a possibility of a pump catching fire is during the activation process.[11] At the TFTR, only new or recycled cartridges containing no appreciable amounts of tritium will be activated. Tritium will be removed from the cartridges at an off-site location. The cartridges will be returned for reuse several times. We anticipate that detectable levels of tritium would be released from a cartridge if exposed to air after absorption of tritium, but the release would be small and the air would quickly passivate the getter material. The pumps absorb hydrogen quite rapidly even at room temperature, and we demonstrated this was also true for tritium. We loaded a C-100 cartridge to twice-rated capacity with T_2 at room temperature.

The pumping speed determinations of all three hydrogen isotopes make it possible for the first time to compare tritium speeds to hydrogen and deuterium. Pure hydrogen and deuterium pumping speeds measured in our laboratory agreed very closely with the values measured and reported by the manufacturer. Our method of calculating pumping speeds was different, but hydrogen pumping speeds are constant at 400°C over a large-capacity range, so the results were essentially the same. All the duplicate pumping speed measurements agreed within 5% of each other.

The pumping speed of the C-50 model was conductance-limited to 130 liters/s by the area of the inlet. This is the hydrogen pumping speed value reported by the manufacturer for the C-50 pump and

Table 5.

Isotopes of hydrogen	Calculated inverse sq. root ratio	Pumping speed ratio, 3-min runs	SAES literature
H_2 vs D_2	1.41	1.44	1.43
D_2 vs T_2	1.2	1.2	–
H_2 vs T_2	1.7	1.5	–
H_2 vs D_2	1.4	1.3	–

*With 0.8% He.

it is very close to our average measured value of 134 liters/s. The pure deuterium pumping speed measured on this pump was 93 liters s.

The tritium used for pumping speed determinations contained about 0.8% He^3. Inert contaminants cause a decrease in pumping speed with time as previously explained. The tritium pumping speed varied from 51 to 41 liters s for 1- and 3-min intervals. For comparison, we ran deuterium and hydrogen pumping speeds with 0.8% He^4 as an inert gas contaminate. The pumping speeds measured for deuterium with helium were 59 and 49 liters s for 1- and 3-min intervals. For hydrogen with helium, the speeds were 79 and 63 liters s for 1 and 3 min.

The isotope effect on pumping speed is predicted to be proportional to the inverse square root of the ratio of the masses. The SAES pump results are outlined in Table 5. Our hydrogen and deuterium data compare favorably with the SAES values. Tritium and deuterium show excellent agreement with the predicted values.

The results of our studies indicate that St101 alloy in cartridge form is a satisfactory getter for tritium at temperatures between 25 and 400°C, depending on the level of active gas contamination. The measured pumping speeds are more than adequate for the TFTR operating mode. All the cartridges we tested were reliable. The heaters caused several problems and should be redesigned for reliability.

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