CONF-831011--8

CONF-831011--8

DE85 001258

Performance of Zr-Al Getter Pumps Under Transient Load Conditions*

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ABSTRACT

Testing of the pump limiter concept in the Impurity Study Experiment (ISX-B) tokamak will involve the use of Zr-Al nonevaporable getter pumps capable of handling intermittent pulses of hydrogen and/or deuterium in the presence of carbon and oxygen impurity concentrations of several percent. To study the pumping characteristics under these conditions we have installed a Zr-Al cartridge pump in a vacuum chamber equipped with a fast gas puff feed system, a quadrupole residual gas analyzer, and a high speed ion gauge for transient pressure measurements. In this paper we report on the performance of the pump over a wide range of gas loads up to that sufficient to provide tens of monolayers coverage of the getter surface. With flow rates up to 13 torr·L/s, pumping speeds for hydrogen were measured to be 1200-1500 L/s at pressures up to 10 mtorr. The measurements were carried out with gas pulses ranging in length from 50 ms to over 1 s and under conditions that provided a constant pumping speed for impurity species.

*Research sponsored by the Office of Fusion Energy, U.S. Department of Energy, under Contract No. DE-AC05-840R21400 with Martin Marietta Energy Systems, Inc.

I. INTRODUCTION

The use of nonevaporable getter pumps in magnetic fusion devices has, within recent years, expanded such that now these pumps serve as both a viable supplement to the common appendage pumps and an alternative to the widely used evaporated getter films.[1-4] There are a number of features of commercially available Zr-Al getter pump[5] that make them particularly attractive for application in hydrogen plasma devices; chief among these is the ability to pump the hydrogen isotopes reversibly and the common gaseous plasma impurities irreversibly. This attribute will take on added importance during fueling operations in the next generation of tokamak devices where large quantities of tritium will be involved. The Zr-Al getter pumps combine high hydrogen pumping speeds with small physical size, which makes it possible to position the nonmagnetic version of the pump physically within the main vacuum chamber. Since the getter material is not evaporated, there is no subsequent problem with flaking, nor is there the problem of coating viewports and sensitive diagnostics. These features make the Zr-Al getter pump an attractive candidate for use in pump limiter experiments. The main disadvantages are that the pumps must be operated at high temperatures (400-700°C) and their lifetime is limited by impurity buildup.

II. USE ON THE ISX-B TOKAMAK

Use of pump limiters on magnetic fusion devices for particle and impurity control is being actively considered as an alternative concept for the inherently more complex and costly magnetic divertor.[6] A comprehensive review of the concepts as well as of the early experimental results has recently been published by Mioduszewski.[7]

Although performance data on the Zr-Al pumps are readily available,[8] most of the published measurements were carried out under steady-state gas conditions. In tokamak operations the pumps will be subject to intermittent gas loads, that is, short bursts of gas at relatively high pressures. More specifically, when used in pump limiter service, the pumps must operate satisfactorily at pressures up to 10 mtorr of hydrogen in the presence

of impurity levels of several percent and for periods of time ranging from 0.1 s to several seconds. The work described here was undertaken to provide detailed information about the pump under these conditions as well as additional information about regeneration cycling and anticipated lifetimes in tokamak operations.

The initial pump limiter experiment on the Impurity Study Experiment (ISX-B) tokamak yielded encouraging results and led to a decision to further examine the concept by means of a pair of full-size pump limiters on the same device.[9] As shown in Fig. 1, these are installed on bellows with a 25-cm stroke. They may either be withdrawn to allow plasma operation with the usual ISX limiters or inserted into the plasma edge to serve as the main limiters. One of the limiters will be used in connection with plasma fueling studies and is, therefore, equipped with a gas feed system, details of which are shown in Fig. 2. Both limiters are equipped with embedded thermocouples for bulk temperature measurements during and between plasma discharges and with a fast Shultz-Phelps ion gauge mounted near the outer end of each pump module for transient pressure measurements. A special ion gauge controller was fabricated for use with these gauges that provided a high-frequency, chopped dc filament current to permit use of the tubes in magnetic fields up to 0.1 T.[10]

III. EXPERIMENTAL APPARATUS

Prior to the installation of the modules on ISX-B a series of laboratory experiments was carried out to determine the operating characteristics of the Zr-Al getter pumps under the transient load conditions anticipated in the tokamak. One of the pump limiter modules was installed in a vacuum system equipped with both high-vacuum and low-vacuum pressure gauges, a quadrupole mass spectrometer, and a gas feed system with a gas manifold and separate pumping system. The apparatus is shown schematically in Fig. 3. The main chamber was pumped by a turbomolecular pump through a gate valve fitted with a calibrated orifice to provide a known pumping speed. Following bakeout the base pressure was $\sim 4 \times 10^{-10}$ torr.

Gas was injected into the main chamber through a Veco PV-10 piezo valve, which was opened by means of a single, square voltage pulse variable in both amplitude and width. Prior to activation of the pump the throughput of the valve was measured for both hydrogen and carbon monoxide as a function of both the manifold pressure and the magnitude of the voltage pulse. The gate valve to the turbopump was closed and the equilibrium pressure in the chamber was measured with a capacitance manometer. The throughput Q was then obtained from

$$Q = \frac{PV}{\Delta t} , \tag{1}$$

where P is the chamber pressure, V the volume, and Δt the pulse length. The throughput of the valve as a function of the applied voltage exhibited a considerable hysteresis but was found to be reproducible for potentials above about 70 V. Most of the work was carried out using flattop voltage pulses of 100 V, the manufacturer's recommended maximum, for which the gas load $Q\Delta t$ varied linearly with pulse length.

Pump temperatures were monitored by means of a sheathed thermocouple in contact with the gettering alloy. The temperature was controlled by adjusting the current through a resistance heater internal to the pump assembly. The temperature of the St 101 getter alloy was maintained at 400°C during normal operation and raised to 700°C for a short period of time for the regeneration cycle.

IV. RESULTS

Following activation of the getter pump, measurements of the pumping speed were carried out by monitoring the transient pressure in the Shultz-Phelps gauge during the gas puff by means of an oscilloscope triggered by the gating pulse on the valve. During these measurements the gate valve was closed so that the only pumping on the main chamber was that provided by the getter pump.

Two typical oscillograms are shown in Fig. 4. The pressure trace for pure hydrogen is shown for a 200-ms puff in Fig. 4(a). Using the calibrated valve throughput, the pumping speed was determined from the usual relation

$$V\frac{dP}{dt} = Q - PS \ , \tag{2}$$

where S is the pumping speed for hydrogen. In this example the chamber pressure rapidly reached a constant value and S was found to be 1830 L/s simply from the ratio Q/P at 200 ms. The second trace in the oscillogram is that of the 5-V trigger pulse used to gate the high-voltage switch in the piezo valve power supply.

The pressure vs time trace for a gas mixture of 90% H_2 and 10% CO is shown in Fig. 4(b). In this case, the pumping speed for CO is considerably less than that for pure hydrogen with the result that the effective pumping speed for the mixture is not constant throughout the gas puff. Here, the pumping speed can be estimated from a rearranged form of Eq. (2):

$$S = \frac{Q}{P} - \frac{V}{P}\cdot\frac{dP}{dt} \ . \tag{3}$$

The case of the gas mixture is more complicated for two reasons: (1) the composition of the mixture is not constant throughout the puff duration because of the different pumping speeds for the two components, and (2) the gauge factors for the two gases are also different (measured to be 2.0 for H_2 and 1.2 for CO).

A. Pump recovery following deactivation

The pump was deliberately deactivated by exposing the getter surface to the atmosphere at room temperature in order to check the recovery of the pumping speed as the pump was reactivated. The system was then evacuated and baked. Following restoration

of the base pressure the pump temperature was raised at a rate of 5 degrees per minute while the pumping speeds of H_2 and CO were alternately measured. The results are shown in Fig. 5. No pumping was observed until a pump temperature of 400°C was reached. From that temperature the speed for both gases increased monotonically with increasing temperature until the maximum temperature of 750°C was reached, at which S_{H_2} = 1890 L/s and S_{CO} = 480 L/s were measured. At this point the total gas load in the pump was 18.3 torr·L of H_2 and 4.5 torr·L of CO. The pump temperature was then lowered to the normal operating temperature of 400°C and the measured speeds were observed to drop as indicated by the dashed curves in Fig. 5. The duration of the gas puffs throughout this test was initially 100 ms and was increased to 200 ms as the pumping speeds increased. Following activation of the pump the maximum pressure observed in the chamber remained less than 20 mtorr.

B. Pumping speed as a function of impurity loading

In a tokamak environment the pump will be subjected to heavy gas loads of hydrogen isotopes contaminated by significant amounts of those impurities common to high-vacuum systems, such as methane, water vapor, and carbon monoxide. Since methane is not adsorbed on the getter surface, it is not pumped in the molecular form (i.e., as CH_4 molecules), and its presence in the hydrogen working gas will not affect the performance of the pump. A series of tests was carried out using CO, chosen for ease of quantification, as a species with which to provide an impurity load during pump performance tests. Two runs were made, one at room temperature (23°C) and one at the normal operating temperature (400°C). In each case the pumping speed for H_2 and CO was measured after a specified amount of CO had been pumped. The results are shown in Fig. 6(a) for the 23°C case and in Fig. 6(b) for the 400°C case. In both runs the pump was reactivated just before the experiment was initiated.

C. Hydrogen pumping speed at various gas flow rates

From the earlier data it is possible to evaluate the performance of the pump under various transient gas loads. This would be typical of the performance expected during tokamak operation since the gas puff necessary to maintain the plasma density falls within the range of this data. Figure 7 illustrates the essentially constant pumping speed for hydrogen as a function of the throughput up to levels of 13 torr·L/s. Although these data were obtained with 200-ms pulses, similar results were observed for pulses up to 1 s in length. The values along the curve are the equilibrium pressures at the termination of the gas puff.

V. DISCUSSION

The use of the Zr-Al getter pump in tokamak operation is contingent on its compatibility with the plasma, especially with respect to the regeneration cycle and the lifetime of the getter elements. The regeneration cycle is of importance because this procedure can be carried out only during down times and the frequency of regeneration could be a factor in the scheduling of tokamak operations. The lifetime of the getter elements is likewise important because of the problem of replacement. The replacement procedure itself is difficult and, furthermore, would require that ISX be vented.

A. Regeneration cycling

Each Zr-Al pump module has a maximum capacity for hydrogen, beyond which there is a possibility of hydrogen embrittlement of the getter material. For the C-500 pump elements to be used in ISX this limit is 6.6×10^3 torr·L.[11] To reduce the likelihood of embrittlement and the resulting disintegration of the pump elements, it is necessary to reactivate the pumps to remove the sorbed hydrogen well before this limit is reached. The number of tokamak discharges required to reach the embrittlement limit may be estimated from

$$N = \frac{6.6 \times 10^3}{P \cdot S \cdot \tau} \quad , \tag{4}$$

where P is the pressure to which the pump is exposed, S the pumping speed, and τ the length of the pressure pulse. For pressures of 10 mtorr and discharge lengths of 300 ms the value of N is approximately 1500, which represents two to three weeks or more of normal operation.

B. Element lifetime

Reactivation can be repeated as frequently as necessary up to the point where the getter material is essentially saturated with impurities. This limit is approximately 2.2 torr·L of impurity gases per gram of getter material or 725 torr·L for the ISX pump modules.[11] In terms of the number of discharges the lifetime is estimated from

$$N = \frac{725}{f \cdot P \cdot S \cdot \tau} \quad , \tag{5}$$

where f is the impurity fraction in the working gas. With estimated impurity levels of 2%, approximately 4×10^4 discharges would be necessary to saturate the pumps.

C. Rate limiting process

A comparison between the flux at the pump due to adsorption at the surface and that due to diffusion is of interest in a consideration of the rate limiting process. Such information is necessary in understanding the performance of the pump under transient load conditions.

The adsorption flux, Γ_{ads}, can be obtained from the product of the sticking fraction, α, and the flux at the surface, that is,

$$\Gamma_{ads} = \alpha \cdot \frac{n\bar{v}}{4} \quad . \tag{6}$$

The value of α may be obtained from the standard speed equation:

$$S = 3.64\alpha A(T/M)^{1/2} \quad , \tag{7}$$

where A is the getter surface area, T the temperature, and M the molecular weight of the sorbed gas.[12] Rewriting the flux at the surface as

$$\frac{n\bar{v}}{4} = 3.5 \times 10^{22} P \cdot (T \cdot M)^{-1/2} \tag{8}$$

and combining Eqs. (6) and (7) we obtain

$$\Gamma_{ads} = 1 \times 10^{22} \frac{P \cdot S}{A \cdot T} \text{molecules/cm}^2\text{·s}$$

$$= 0.1P \frac{\text{torr} \cdot \text{L}}{\text{s} \cdot \text{cm}^2} \quad . \tag{9}$$

The diffusion flux at the surface of the pump is

$$\Gamma_{diff} = D \cdot \frac{dc}{dx} \quad . \tag{10}$$

In this equation D is the diffusion coefficient and dc/dx is the concentration gradient at the surface, the product of the quantity of gas sorbed and the getter density, $q \cdot \rho$. The value of q may be obtained from Sievert's law:

$$q = (P/K)^{1/2} \ , \tag{11}$$

where K is Sieverts constant. Equation (10) then becomes

$$\Gamma_{\text{diff}} = D \cdot \frac{\rho(P/K)^{1/2}}{\bar{x}} \ , \tag{12}$$

where ρ is the alloy density and the characteristic diffusion length $\bar{x}$ is given by

$$\bar{x} \sim (D \cdot \tau)^{1/2} \ , \tag{13}$$

which is the average distance a particle diffuses in time τ. Equation (10) may now be written as

$$\Gamma_{\text{diff}} \simeq \rho \left(\frac{D \cdot P}{K\tau} \right)^{1/2} \ . \tag{14}$$

Using $D \sim 2 \times 10^{-8}$ cm^2/s (Ref. 13), $K \sim 8 \times 10^{-7}$ torr/(torr·L/g)^2 (Ref. 14), and taking ρ to be 3.0 g/cm^3, the diffusion flux is approximately

$$\Gamma_{\text{diff}} \simeq (P)^{1/2} \ \frac{\text{torr} \cdot \text{L}}{\text{s} \cdot \text{cm}^2} \ . \tag{15}$$

From this we observe that for pressures of <150 mtorr and pulse lengths of 0.3 s the adsorption process is rate limiting.

VI. CONCLUSIONS

From laboratory studies of the Zr-Al getter pump performance under transient gas loads of hydrogen and carbon monoxide, we have measured the pumping speed over a range of pulse lengths, pressures, and impurity levels. These ranges of parameters were chosen to bracket the conditions to be expected in the ISX-B tokamak. We found the pump to operate satisfactorily under transient loads from 0.05 to >1 s with gas pressures up to 10 mtorr and impurity levels ranging up to 10%. The operating characteristics of the pumps are compatible with normal tokamak operation in that the infrequent regeneration cycle can be performed without interrupting the operating schedule. The lifetime of the getter elements should extend beyond that anticipated for ISX-B.

Finally, the rate-limiting process for the Zr-Al pumps is the adsorption at the surface rather than diffusion into the bulk. This is a direct result of the transient gas load, which leads to steep concentration gradients and, thus, higher diffusion rates.

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FIGURE CAPTIONS

Fig 1. Diagram showing the arrangement of the two pump limiters on ISX-B.

Fig. 2. Details of the gas puff limiter showing placement of the various components.

Fig. 3. Schematic diagram of the experimental apparatus.

Fig. 4. Oscillograms of the (a) pressure vs time traces for hydrogen and (b) hydrogen plus 10% CO. Q for each case was 7.5 torr·L/s. The vertical sensitivity was 1 mtorr/div (see text).

Fig. 5. Recovery of pumping speed for H_2 and CO following deactivation of the pump.

Fig. 6. Pumping speeds for H_2 Hand CO as a function of the total CO load. The room temperature (23°C) case is shown in Fig. 6(a) and the 400°C case in Fig. 6(b).

Fig. 7. Pumping speed for H_2 as a function of the pulsed gas flow rate.

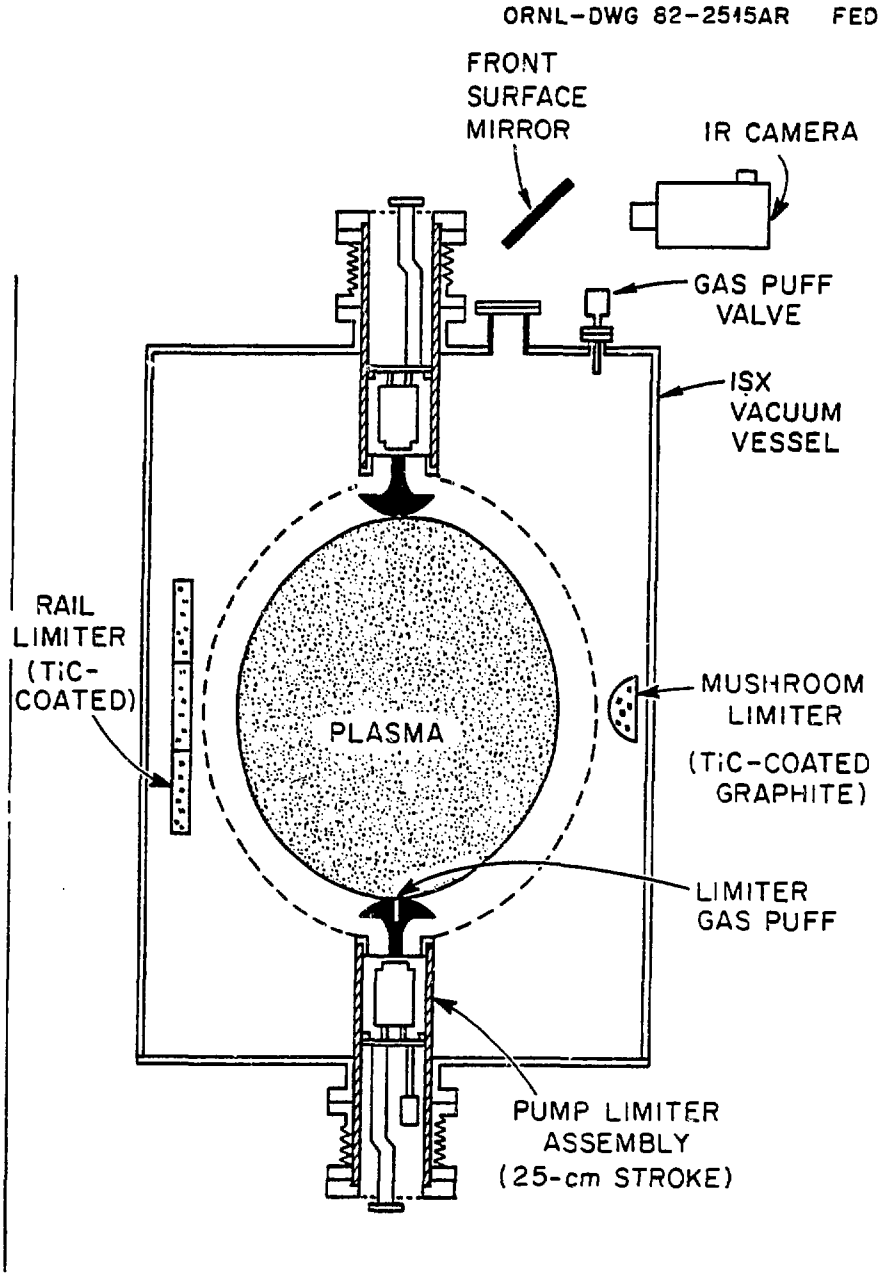
ORNL-DWG 82-2515AR FED
FRONT SURFACE MIRROR
IR CAMERA
GAS PUFF VALVE
ISX VACUUM VESSEL
RAIL LIMITER (TiC-COATED)
PLASMA
MUSHROOM LIMITER (TiC-COATED GRAPHITE)
LIMITER GAS PUFF
PUMP LIMITER ASSEMBLY (25-cm STROKE)

Fig. 1

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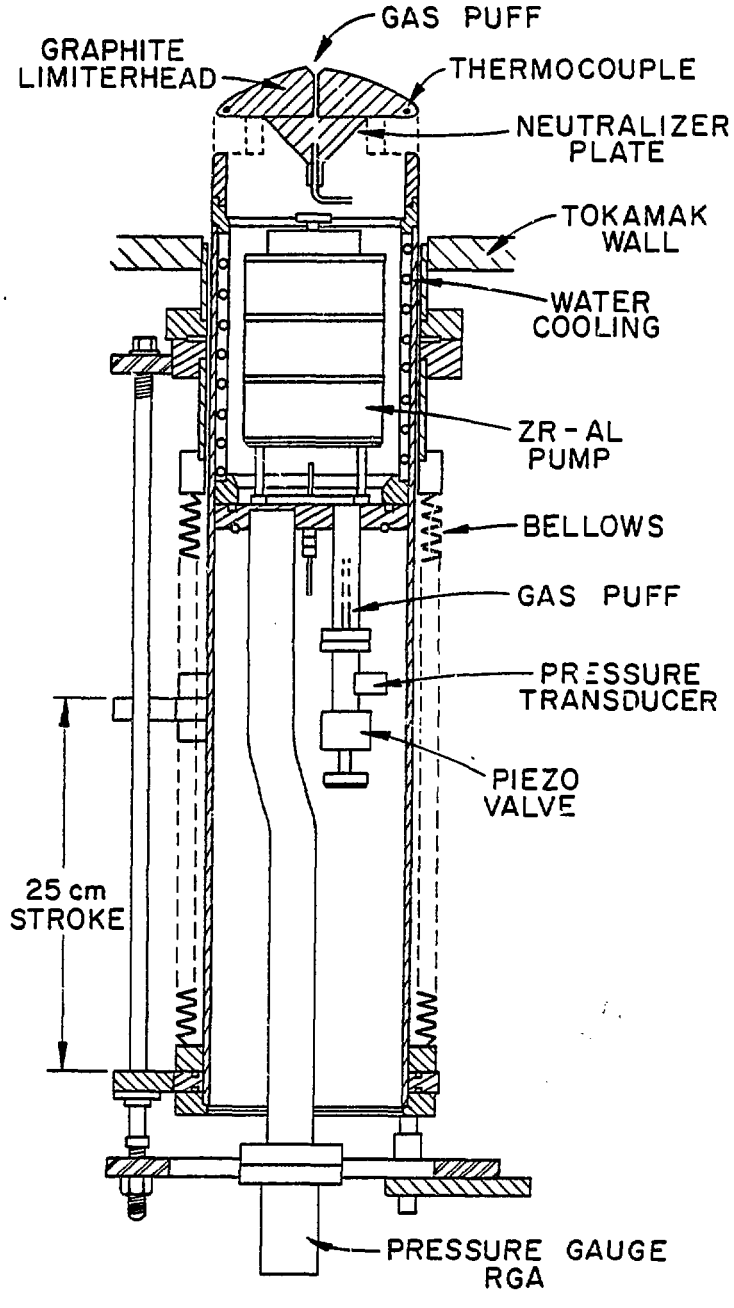
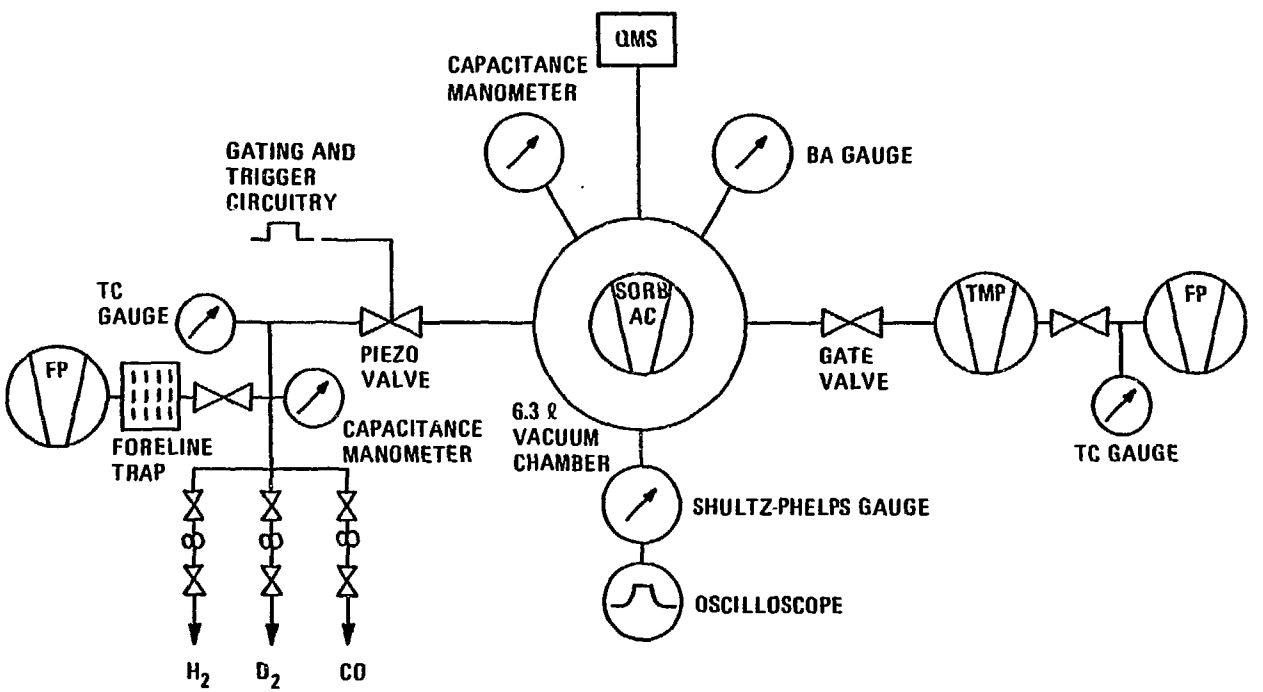


Fig. 2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QMS
CAPACITANCE MANOMETER
BA GAUGE
GATING AND TRIGGER CIRCUITRY
TC GAUGE
SORB AC
TMP
FP
FP
PIEZO VALVE
GATE VALVE
FORELINE TRAP
CAPACITANCE MANOMETER
6.3 ℓ VACUUM CHAMBER
TC GAUGE
SHULTZ-PHELPS GAUGE
OSCILLOSCOPE
H_2
D_2
CO

Fig. 3

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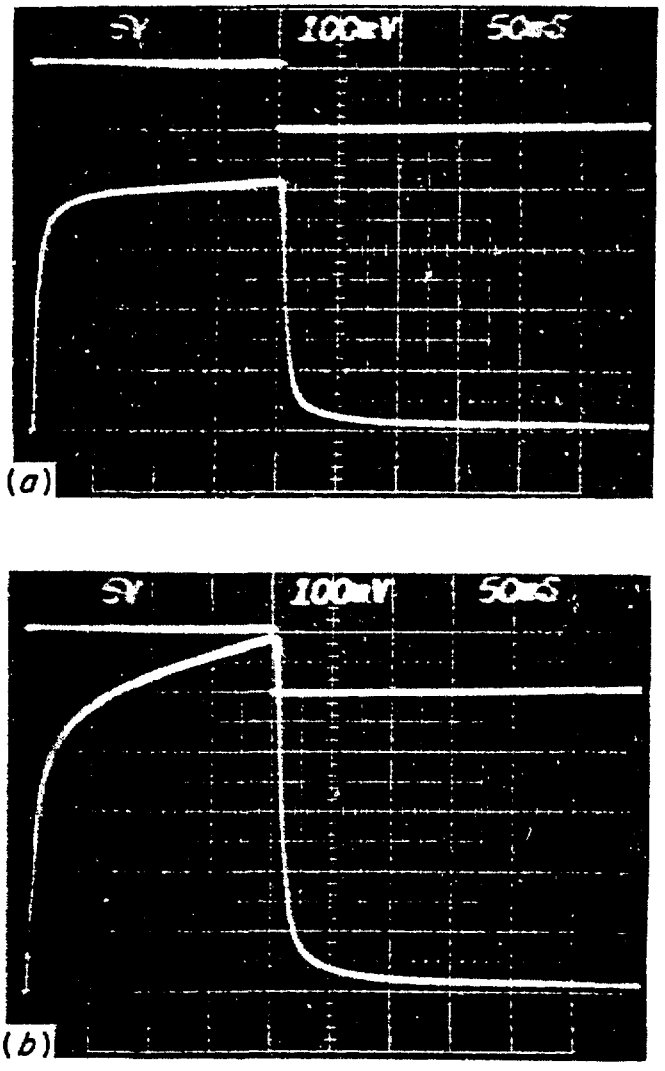
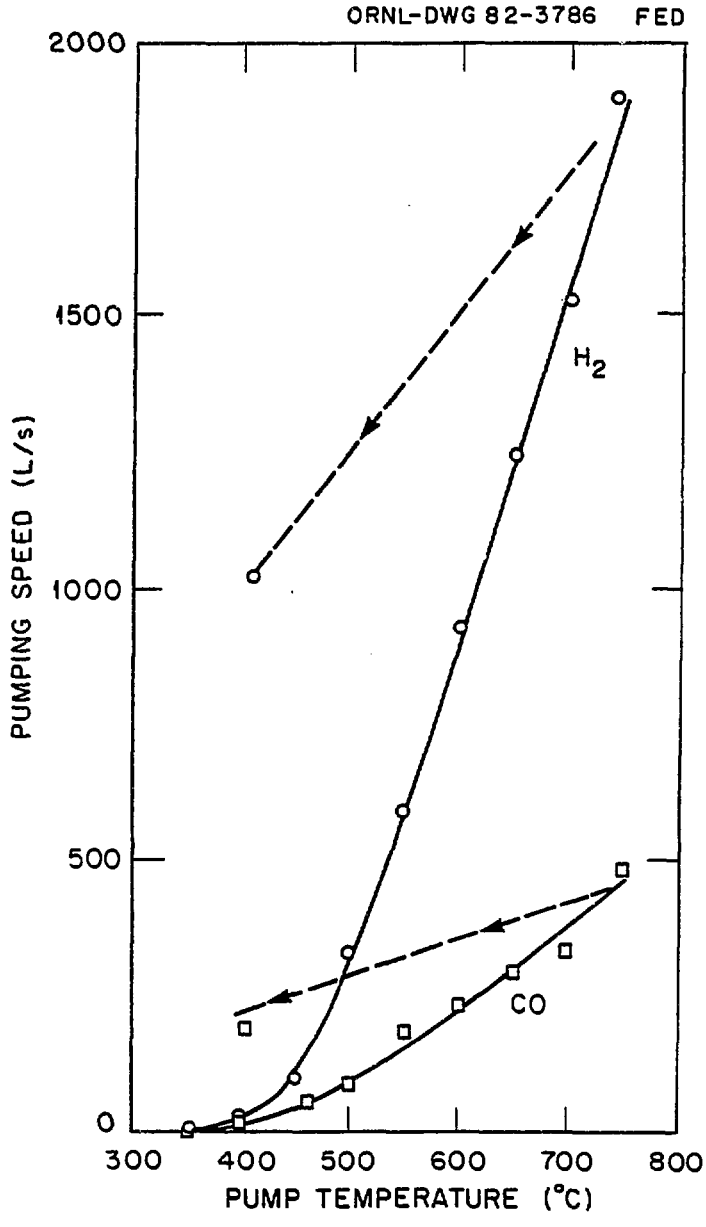


Fig. 4


ORNL-DWG 82-3786 FED
2000
1500
1000
500
0
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H_2
CO
300
400
500
600
700
800
PUMP TEMPERATURE (°C)

Fig. 5

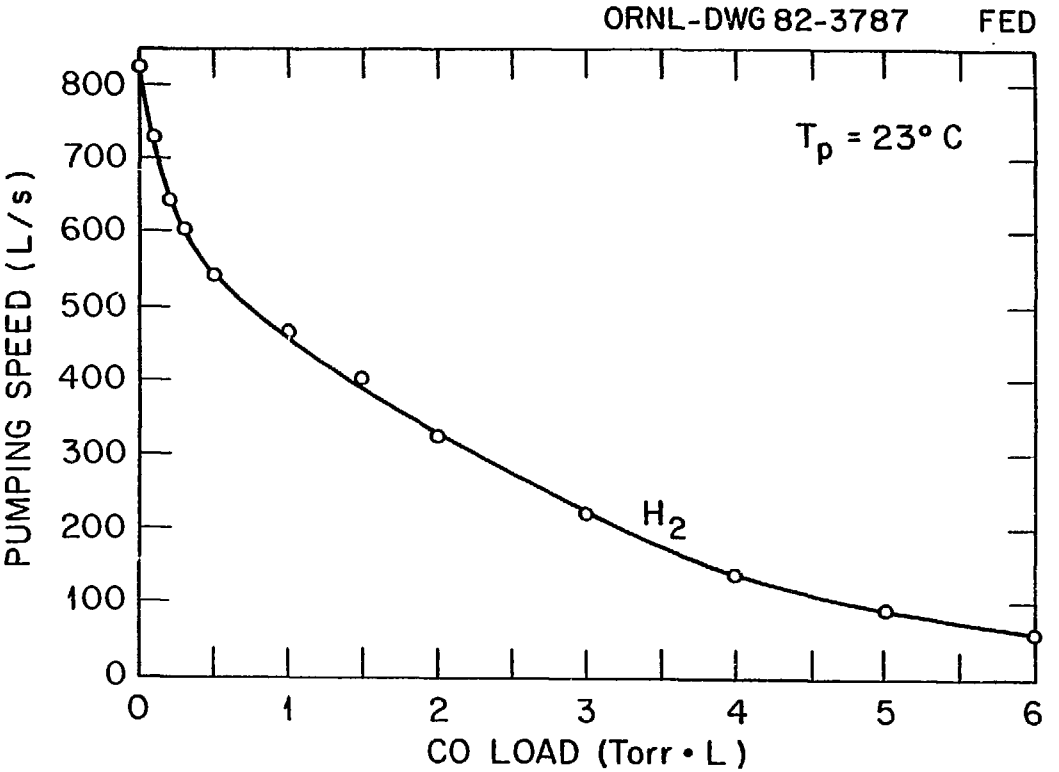
ORNL-DWG 82-3787 FED
T_p = 23° C
H_2
PUMPING SPEED (L/s)
800
700
600
500
400
300
200
100
0
0
1
2
3
4
5
6
CO LOAD (Torr • L)

Fig 6(a)

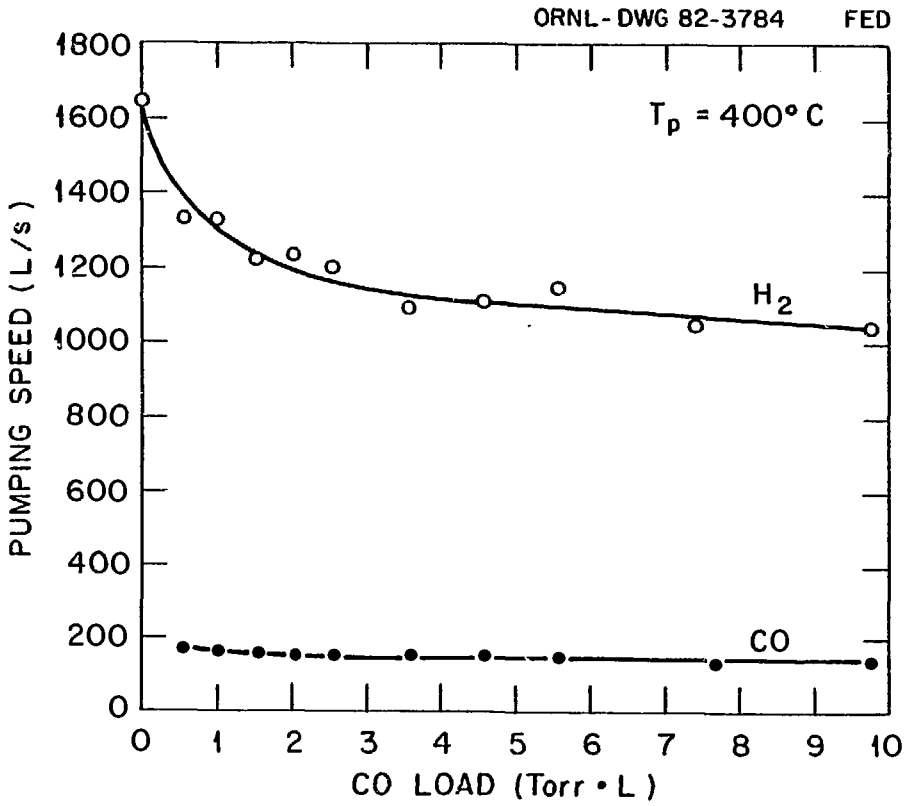
ORNL-DWG 82-3784 FED
1800
1600
1400
1200
1000
800
600
400
200
0
PUMPING SPEED (L/s)
T_p = 400° C
H_2
CO
0 1 2 3 4 5 6 7 8 9 10
CO LOAD (Torr • L)

Fig. 6(b)

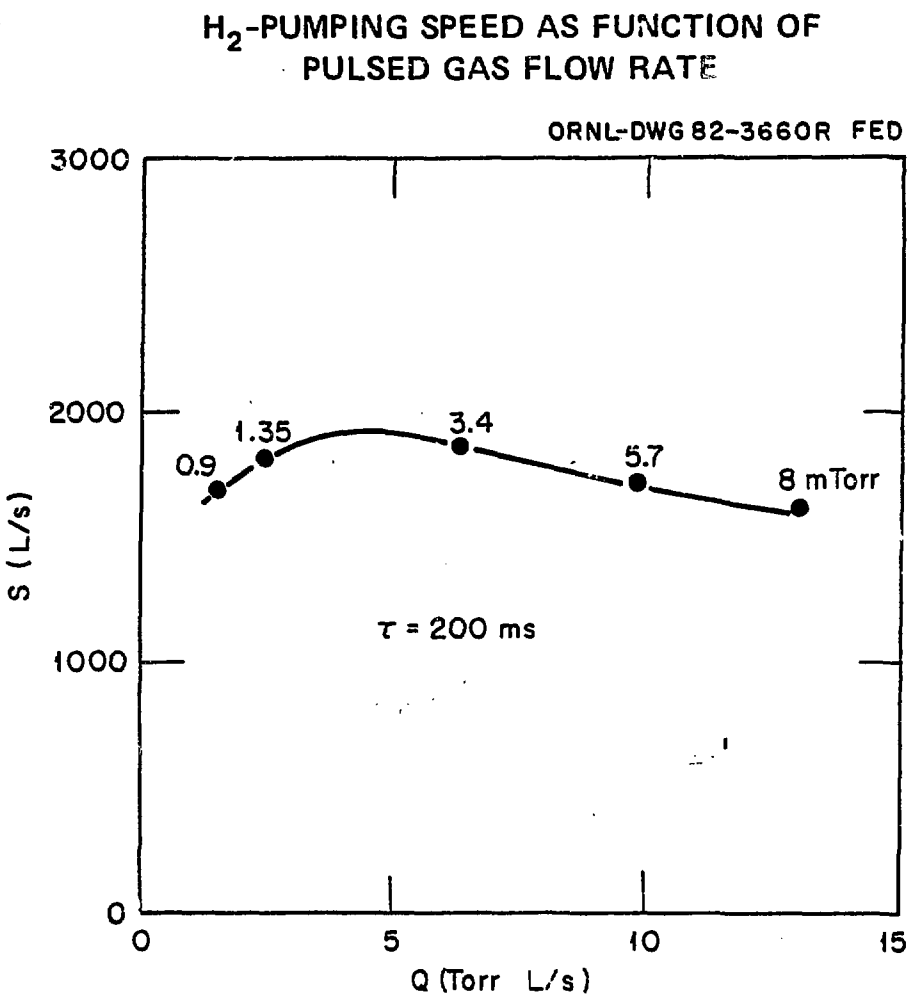
H_2-PUMPING SPEED AS FUNCTION OF PULSED GAS FLOW RATE
ORNL-DWG 82-3660R FED
3000
2000
1000
0
S (L/s)
0.9
1.35
3.4
5.7
8 mTorr
τ = 200 ms
0
5
10
15
Q (Torr L/s)

Fig. 7