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HELIUM PUMPING BY ARGON FROSTING ON A 4.5 K SURFACE

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Helium Pumping by Argon Frosting on a 4.5 K Surface

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Pumping of helium gas by means of argon frosting on a bare copper surface cooled to ~4.5 K has been investigated in one of the neutral beamlines of the DIII–D tokamak. The beamline is designed to handle high power hydrogen and deuterium beams and corresponding high gas feed rates. By prefrosting the cryo panels with argon in an actual beamline, multi-second helium gas pulses have been handled at a background gas pressure low enough for formation and transport of helium beams. Appreciable pumping of helium gas was observed even at an argon-to-helium ratio as low as 20.

I. INTRODUCTION

In tokamaks, auxiliary heating of the plasma is most effectively accomplished by injection of energetic neutral hydrogen isotopes. High energy helium neutral beam injection (NBI) was considered as early as the mid 1970's for its advantages in ion-to-neutral conversion efficiency and its monoenergetic nature.[1] Helium NBI is also used occasionally to produce experimental variations, such as, He° into He^{++} plasma and $_3He^{\circ}$ into D^+ plasma. Only short-pulse (~0.5 sec) He° NBI has been tried on He^{++} plasmas in the DIII–D tokamak, relying on the beamline's volume to keep the helium gas pressure low enough for short-pulse operation.[2] Helium beam operation in the existing hydrogen neutral injectors is also proposed as a simulation of future tritium beam operation in TFTR[3] and JET.[4]

It is known that gases can be trapped on a surface at a higher temperature than their condensation temperatures by using a technique called cryosorption or cryotrapping. Cryosorption of hydrogen has been studied for beamline pumping as an alternative to cryocondensation pumping, in an effort to relax the refrigeration requirements by running the cryosurface at 15 to 20 K instead of 4.2 K.[5,6] For helium gas, in particular, heavy molecules such as argon[3,4,7-12] or SF_6[13] have been used to form a frosted cryotrapping surface at liquid helium temperatures (~ 4.2 K).

Helium pumping experiments by argon frosting were carried out in one of the four beamlines in use for hydrogen NBI in the DIII–D tokamak.[14] The beamline pumping system[15] consists of two separate LN_2-shielded, liquid-helium-cooled cryopanels and a 1500 ℓs^{-1} turbomolecular pump (TMP) as shown in Fig. 1. The volume of the beamline (V) is 1.3×10^4 liters. The "front" liquid-helium panel is a flat copper sheet with a total area of 69 m^2 and employs LN_2 chevron baffles with a calculated transmission probability of 0.22. The "rear" panel (8 m^2) consists of copper strips arranged into a cylindrical geometry using a "modified Santeler type" LN_2 shield[16] with a calculated transmission probability of 0.19. The estimated pumping speed for H_2 is about 10^5 ℓs^{-1} m^{-2}. The forced-flow liquid helium line runs in series for the two panels and operates at pressures slightly above atmospheric pressure, the liquid temperature corresponding to ~4.5 K.

In this paper, we report a series of experiments, primarily aimed for demonstrating the feasibility of an argon-cryotrapping technique for pumping helium gas, adequate for helium-beam operation in the DIII–D beamline. Instrumentation and experimental setup was not ideally suitable for investigating the fundamental properties of helium trapping on argon frost. Some interesting properties and observations, however, were obtained from the experiments as presented in Section 3.

II. EXPERIMENTAL CONDITIONS

Argon and helium gas were fed into the DIII–D beamline through the existing gas feed system as shown in Fig 1. Argon gas was introduced through the neutralizer duct gas puff system, and helium gas through the usual ion source gas puff system. The gas pressure was monitored by an ionization gauge (Bayard-Alpert type), identified as BG2 in Fig. 1. Since the puffed helium gas has to fill the ion source chamber and the neutralizer duct before it reaches the cyropanels or the pressure gauge, the pressure signal is somewhat delayed. Including a delay caused by instrumentation, the pressure waveform typically exhibits a time delay of about 200 ms. Because the decay tail of the waveform is likely to have a time delay of similar magnitude, the use of pressure decay to determine the pumping speed is not applicable.

The flow rates are measured by a Hastings flowmeter for steady state flow, a Kurz anemometer-type flowmeter with a fast time response (~30 ms), and also by monitoring the fill pressure by a capacitance manometer. These measurements agreed within 10% of each other. Argon gas was introduced into the beamline (500 to 3000 Torr-liters), while it was isolated from the torus and the turbopump, and then several helium gas pulses were made. When the pressure of untrapped helium in the vessel became too high, another layer of argon frost was deposited without defrosting the previously captured argon and helium. The argon-to-helium atom ratios discussed below were computed from the total number of torr-liters of each gas admitted to the beamline between defrost cycles.

The pressure distribution in the beamline is inherently nonuniform and highly differential even at steady state. The pressure gauges, located on the periphery and being heavily baffled, hardly represent the average gas pressure. Consequently, if the gauge pressure (P) is used to estimate the pumping speed ($S = Q/P$), where Q is the flow rate, a large error is likely to result. In a previous report,[15] for instance, the same pressure gauge yielded a pumping speed (Q/P) that was about twice the one theoretically possible.

Since the argon gas is puffed through the neutralizer rather than sprayed onto the LHe-cooled surface, coverage of argon snow on the LHe panels is not well controlled. However, it is reasonable to assume that helium gas particles reach the cryopanels in a similar pattern as the argon gas particles. Also the downstream-side surface of the disk-shape front cryopanel (area of 3 m^2) was not easily accessible for gas particles because the beam dump hampered downstream flow in the present test. This results in a total effective 4.5 K surface area of about 11 m^2 out of a total 14 m^2.

The overall helium trapping probability (η) can be expressed in terms of the sticking coefficient of helium on the argon frost (f_s) and the LN_2-baffle transmission probability of (η_b) as

$$\frac{1}{\eta} = \frac{1}{f_s} + \frac{1}{\eta_b} - 1 \quad .$$

For $\eta_b = 0.2$ and $f_s = 0.15$,[8] we obtain $\eta = 0.1$; for $\eta_b = 0.2$ and $f_s = 1$, $\eta = 0.2$. The overall trapping probability would improve only by a factor of 2 even if f_s increased by a factor of 6 ($0.15 \rightarrow 1.0$). The volumetric molecular flow rate of helium at room temperature is $Q_0 \simeq 31\ \ell s^{-1}\ cm^{-2}$. For $\eta = 0.1$, the estimated pumping speed would be $A\eta Q_0 = 3.4 \times 10^5\ \ \ell s^{-1}$, where $A = 1.1 \times 10^5\ cm^2$. The "pumping time constant," V/S, is then in the vicinity of 40 ms, which is short compared with the pressure gauge "time delay."

Thermal accommodation of gases to cold surfaces in a cryopumped vessel will lower the actual gas pressure from the one indicated by a pressure gauge. In an earlier work,[16] an effective hydrogen gas temperature in a Doublet–III beamline was measured as a function of LN_2-panel temperature. At 80 K, the effective temperature was determined to be about 150 K, in which case the true gas pressure would be $\sqrt{\frac{150}{300}}$ times the pressure monitored by an ion gauge. Just for simplicity, however, we do not attempt to correct the gauge pressure in this paper.

III. RESULTS

Properties of helium cryotrapping on argon frost were studied by observing the gas pressure monitored by an ion gauge (BG2 in Fig. 1). For the series of shots shown in Fig. 2, the helium pulse length was 5 sec with a flowrate of 27 Torr-ℓs, which would simulate the condition of an actual helium beam operation. The valves to the turbomolecular pump (TPV) and to the DIII–D vessel (TIV) were both open, again for the purpose of proper simulation. A correction multiplier for helium gas of 5.6 has already been applied.

The sequence of events is as follows. Shot (a) is a helium puff prior to the introduction of argon into the system. Little pumping is exhibited. The pressure rises monotonically during the puff duration and then decreases slowly after the pulse as a result of turbopumping and downstream flow into the torus vessel. Shots (b) and (c) are helium puffs with argon frost on the cryopanels. Just prior to (b), an argon gas of 1300 Torr-ℓ was frosted. A 5-sec helium puff was admitted and pressure remained relatively flat throughout the pulse, exhibiting adequate pumping required for safe beam operation. In this setup where both TIV and TPV remain open, unadsorbed gaseous helium is pumped out of the beamline vessel. The pressure runs away on the next shot (c), however, implying that the argon-to-helium ratio at the beginning of the shot (very roughly about 10) is insufficient.

In Fig. 3, we show a beamline pressure history throughout a series of successive shots. The argon-to-helium ratio is also shown for each shot on the upper scale. For this run, the beamline was isolated, *i.e.*, both TPV and TIV were closed. The first shot was an argon puff onto a virgin cryosurface. After frosting 300 Torr-ℓ of argon on the cryosurface, the background pressure was 2×10^{-8} Torr. Condensation pumping of argon by the LHe-cooled surface appeared to be about 4.5 times slower than the hydrogen pumping. The next five helium puffs each had a 1-sec pulse duration and a flow rate of 12 Torr-ℓs^{-1}. It can be seen that the residual helium pressure increased with each additional puff, almost exponentially with the helium-to-argon ratio. After shot #5, the beamline pressure is high enough to cause a thermal runaway of the cryopanels. The subsequent series of argon shots (5-sec duration, 70 Torr-ℓ per shot) exhibits the effect of cryotrapping again as more argon is added into the system. For this argon shot series, the atomic ratio was calculated based on the inventory of gaseous helium remaining untrapped prior to shot #6 and the accumulated argon counting from shot #6 and on. The trend of the equilibrium helium pressure versus the atomic ratio is more or less the same for the two "opposite" runs.

Actual pressure waveforms in successive helium puffs are illustrated in Fig. 4, where four 2-s-long helium pulses are injected approximately every 8 minutes. The rising slope of the pressure during a pulse tends to increase with the successive shots. At the end of each pulse, the vessel pressure initially decays sharply (with a time constant of about 200 ms). A further slow pressure decrease is seen during the interpulse period, presumably due to redistribution of gas within the beamline and/or due to helium atom diffusion into the argon layers.

The time behavior of the gauge pressure of helium plus argon is shown in Fig. 5. A 5-sec injection of argon is made into the beamline which was previously "flooded" with helium (Region a). The pressure initially rises as a result of the argon influx for about one second (Region b), then actually decreases as the argon flow continues, since helium cryotrapping begins (Region c). The pressure decays sharply at the end of argon puff (Region d) and settles at a new equilibrium pressure.

IV. CONCLUSIONS

The above experiments have demonstrated the feasibility of pumping helium by cryotrapping in a complicated beamline by means of preloading the cryopanels with argon gas. The argon is condensed on the ~4.5 K surface with a pumping speed (*i.e.*, $\sim 2 \times 10^4$ ℓs^{-1} m^{-2}) scalable from that for hydrogen according to the inverse square root of mass. It appears that previously cryotrapped helium molecules can be buried under subsequent argon frost layers, thus playing little role in cryotrapping of a new helium pulse.

Long-pulse helium beam operation can be carried out in the following scenario: (1) prior to a helium beam shot, close the TIV and admit argon gas of sufficient quantity into a beamline to maintain the argon-to-helium ratio greater than ~20. (2) Open TIV and operate an helium beam injection shot. (3) Close the TIV and repeat the sequence for the next shot. The argon vapor pressure within the beamline seems to be low enough to ignore argon contamination of the torus vessel.

Although the pumping speed of helium trapping could not be determined because of the highly differential pressure in the beamline and the deviation of gas flow from the perfect square pulse, the theoretically expected pumping speed per area of 3×10^4 ℓs^{-1} m^{-2} seems to be consistent with our observations. A rising pressure is frequently seen as the helium pulse proceeds, implying that the capture probability (and hence pumping speed) is changing with time as the argon-to-helium ratio decreases.

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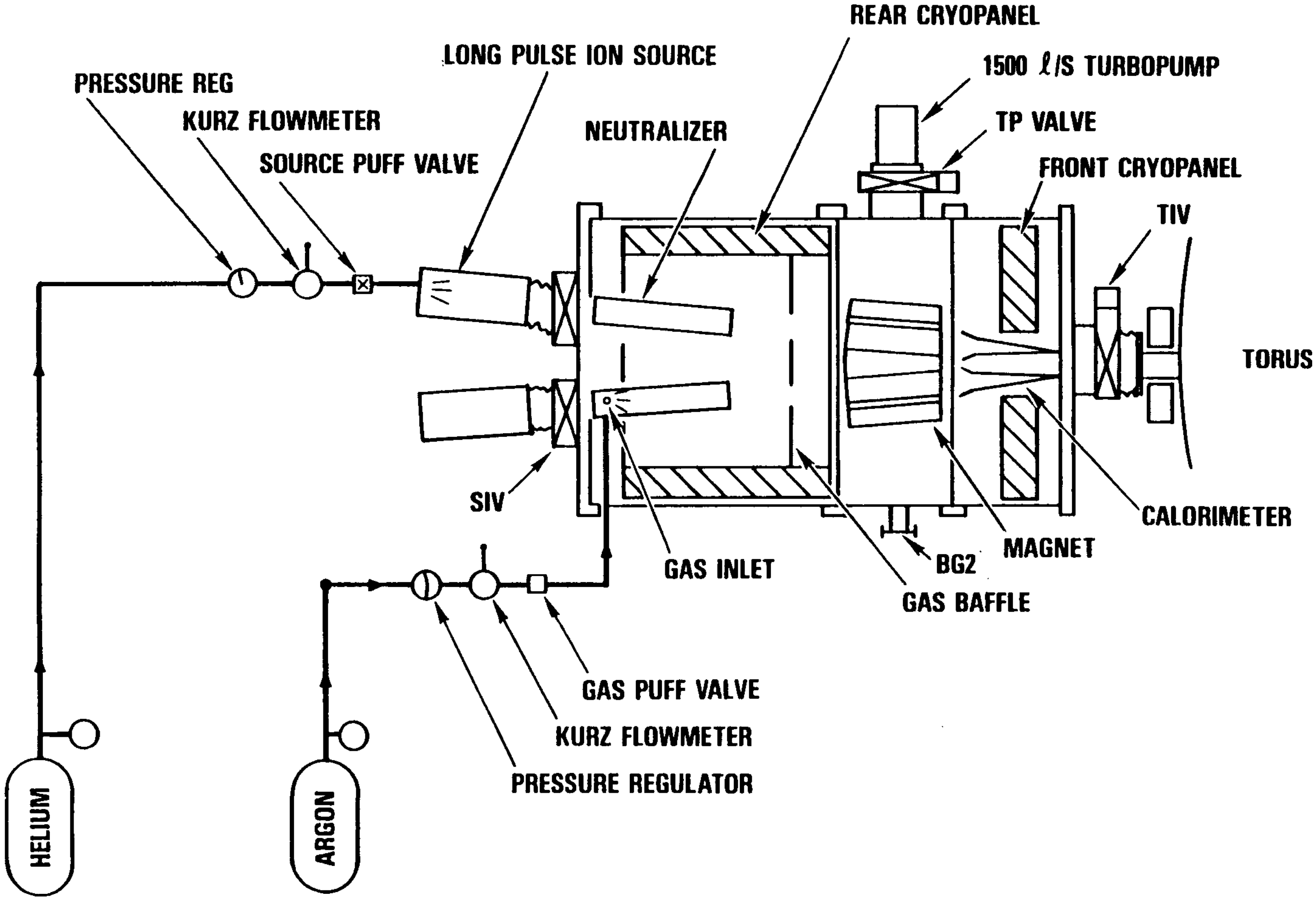

FIG. 1. Schematic of the DIII–D beamline and experimental setup.

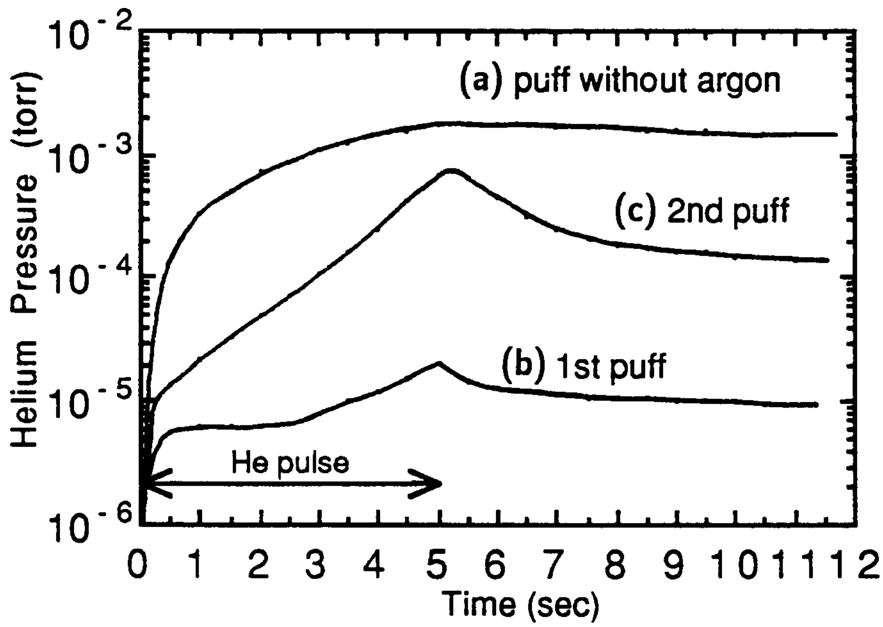

FIG. 2. Helium pressure signal waveforms for 5-s, 27 Torr-ℓs^{-1}, helium gas pulses: (a) Puff system with no argon frost present, (b) puff after an argon layer of 1300 Torr-ℓ was frosted, (c) puff following shot (b).

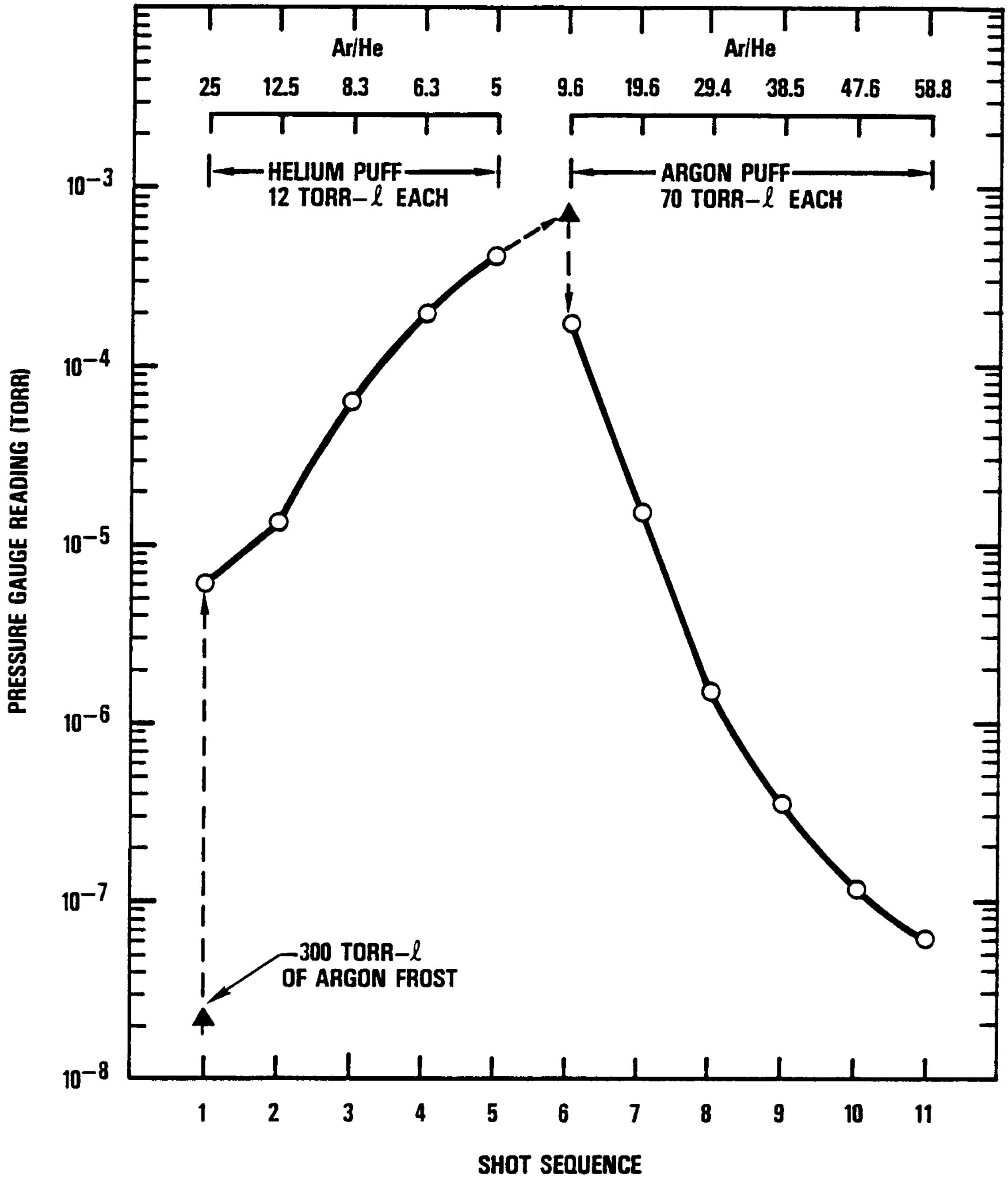

FIG. 3. Equilibrium helium pressures after a series of helium shots and a series of argon shots as a function of the argon-to-helium atom ratio.

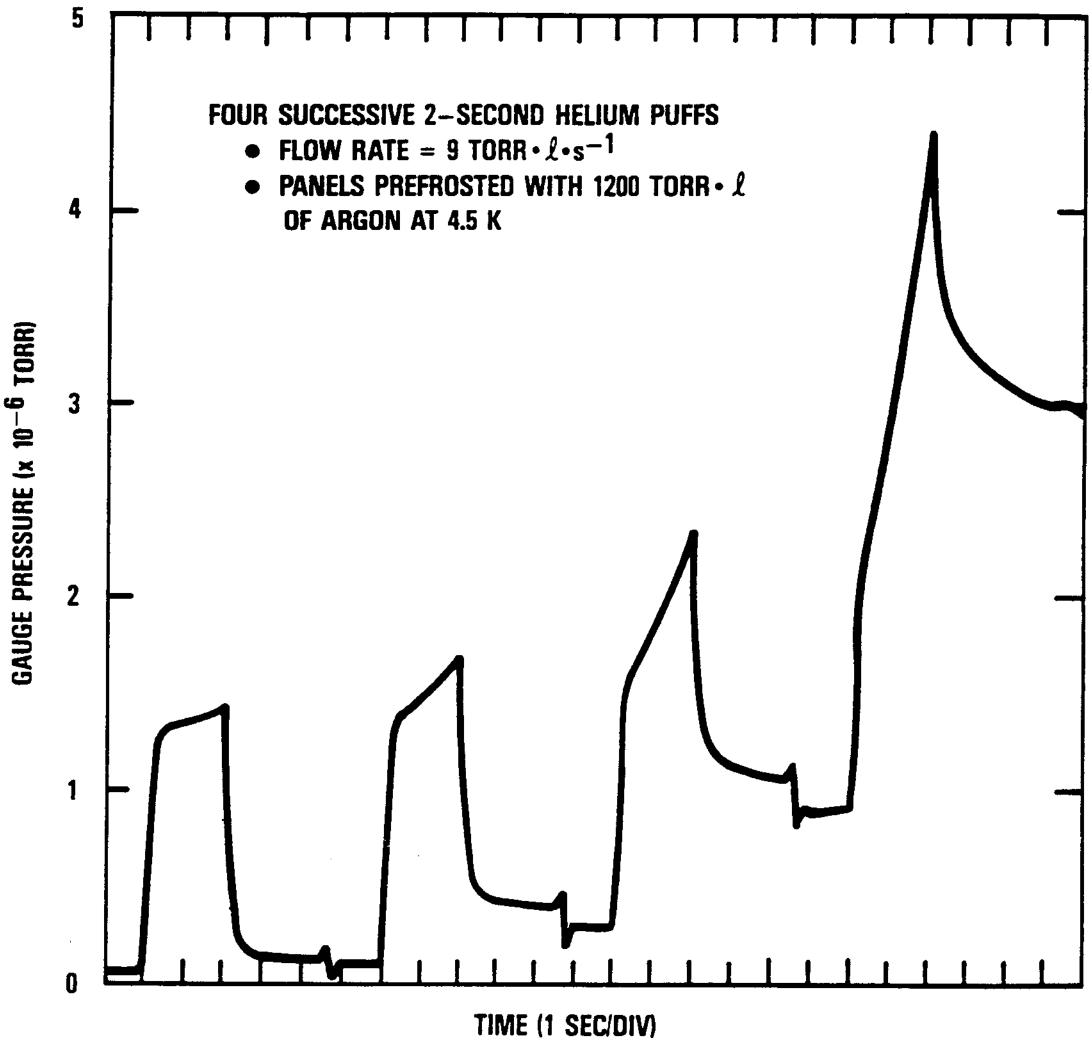

FIG. 4. Ion gauge waveforms of four successive helium puffs of 2-sec duration with 9 Torr-ℓs^{-1} flow rate. Multiply 5.6 for helium pressure.

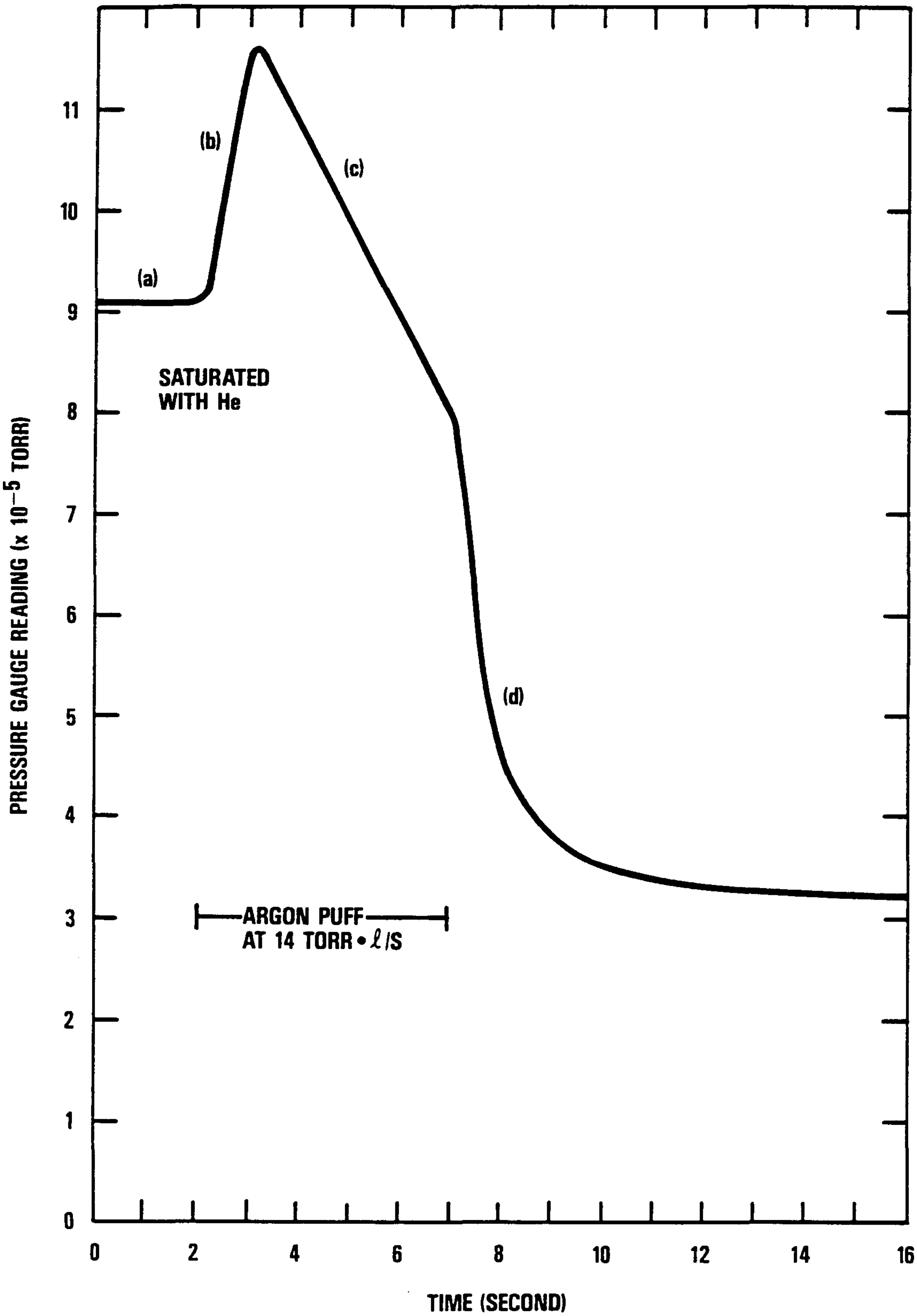

FIG. 5. An ion gauge pressure waveform for an argon shot into a helium flooded vessel. Gauge factors are 5.6 for helium and 0.77 for argon, respectively.