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High-throughput continuous cryopump*

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Abstract

A cryopump with a unique method of regeneration which allows continuous operation at high throughput has been constructed and tested. Deuterium was pumped continuously at a throughput of 30 Torr·L/s at a speed of 2000 L/s and a compression ratio of 200. Argon was pumped at a throughput of 60 Torr·L/s at a speed of 1275 L/s. To produce continuous operation of the pump, a method of regeneration that does not thermally cycle the pump is employed. A small chamber (the "snail") passes over the pumping surface and removes the frost from it either by mechanical action with a scraper or by local heating. The material removed is topologically in a secondary vacuum system with low conductance into the primary vacuum; thus, the exhaust can be pumped at pressures up to an effective compression ratio determined by the ratio of the pumping speed to the leakage conductance of the snail. The pump, which is all-metal-sealed and dry and which regenerates every 60 s, would be an ideal system for pumping tritium. Potential fusion applications are for pump limiters, for repeating pneumatic pellet injection lines, and for the centrifuge pellet injector spin tank, all of which will require pumping tritium at high throughput. Industrial applications requiring ultraclean pumping of corrosive gases at high throughput, such as the reactive ion etch semiconductor process, may also be feasible.

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I. INTRODUCTION

Cryopumping has been very effective in pumping hydrogen and its isotopes at very high pumping speeds. Typical applications have included pumping space simulation chambers and high-power neutral beam lines. Neutral beam injection line pumps, for example, pump at speeds of 250,000 L/s. These pumps are cooled with liquid helium and typically are surrounded with liquid-nitrogen-cooled thermal radiation shields. The operation of these pumps involves initially pumping the vacuum chamber with an auxiliary pumping system (e.g., a turbopump to a pressure at or below 10^{-4} Torr) and then chilling the pumping surfaces to 4–6 K with liquid helium. The system is then put into operation; the material being pumped is collected on the cold surfaces as a frozen solid. Pumping can continue indefinitely unless so much material is pumped that the frost layer becomes excessively thick and thus limits the thermal conduction to the pumping surface. In many applications the collection of material on the pump is limited by other criteria; for example, when hydrogen is being pumped, it may be desirable, for safety reasons, to limit the total inventory to a value below the explosive limit inside the vacuum chamber. Also, when tritium is being pumped, it is usually desirable to limit the total inventory of the radioactive gas. In all cryopumping systems to date, after one of these limits occurred the pumps would require regeneration. This process involves warming the cryopanels, causing the cryofrost to evaporate. The evaporated frost is then pumped by the auxiliary pumping system, after which the pumps can be recooled and the pumping cycle repeated.

In many applications the cyclical nature of the pumping cannot be tolerated. To pump a chamber continuously, two or more pumps, isolated from the process chamber by gate valves, are operated in tandem. Another technique being developed[1] is to close the liquid nitrogen chevrons of a tandem set of pumps during regeneration and pump the regenerated material with a separate pump that evacuates the volume inside the baffles.

High-speed cryopumps also undergo a thermal instability when the process chamber goes above a certain pressure, usually in the range of 10^{-3} Torr. This occurs because the process vacuum serves as cryogenic insulation for the liquid-helium-cooled pumping surface. Thus, when the pressure in the chamber becomes too high, the heat conducted through the gas overwhelms the cooling capacity, and the panels spontaneously regenerate. Because of this, large cryopumps are usually designed to operate at or below 10^{-4} Torr. This limitation either restricts the throughput of the pump or necessitates very large pumping speeds in the pump chamber. Although this may be irrelevant in many instances, it can impact many potential applications. For example, in a tokamak fusion reactor, the throughput of fuel will be in the range of 100 Torr·L/s, while the conductance of the vacuum lines and gate valves leading to the pumps may be of the order of 10,000 to 100,000 L/s. To handle the throughput, a typical high-speed cryopump operating at 10^{-4} Torr at a pumping speed of 1 million L/s would be required, 10 to 100 times as great as the conductance.

Cryopumps are not alone in the inability to pump high throughputs at pressures greater than 10^{-3} Torr. The other potential high-speed pumps, turbomolecular pumps and diffusion pumps, both lose effective pumping above 10^{-3} Torr. The most effective pumps in this region of pressure are Roots blowers, which have significant difficulty in tritium applications because of the need for oil lubrication. This article describes a pump which has the potential of pumping 100 Torr·L/s at a speed of 10,000 L/s, which is tritium compatible, and which can operate continuously.

The pump described here is different from the conventional cryopumps in two areas. First, to pump at high pressures and to limit the cryopumping to surfaces cleaned by the "snail" (the mechanism that travels over the cryopump to remove frost), the cold surfaces were vacuum-insulated by using a separate vacuum chamber and a metal bellows between the pump inlet and the cryosurfaces (Fig. 1). The second difference is in the method of regeneration. In a small pump operating at high throughputs, the material buildup on the chamber walls occurs rapidly; frost buildups of 0.1 to 1 mm/min occur. A system that thermally regenerates so frequently would be extremely inefficient. However, the finite thickness of the frost layer makes it possible to remove the frost layer without thermally cycling the pump. Much in the same manner as one can remove the frost from an automobile windshield, either thermally by defrosting or mechanically by scraping, a method of removing the frost mechanically was devised. However, scraping the frost from the panels is not really sufficient since ultimately the frost must be removed from the pumping chamber. To accomplish frost removal, the scraper is surrounded by a secondary chamber that slides over the primary pumping surface. Thus, the frost removed is physically trapped inside the smaller chamber. With proper orientation and with the secondary chamber kept at a slightly elevated temperature, the frost can be made either to evaporate or to slide away from the cryosurface. Subsequently, the frost will either evaporate or be collected as a solid and will then be pumped at a higher pressure with another pump. The compression ratio of such an arrangement is limited only by the leakage conductance between the secondary chamber and the primary chamber. The vacuum equations for this configuration (shown in Fig. 1) are as follows:

$$P_{\text{in}} = Q_{\text{in}} + P_{\text{ex}} C \ ,$$

$$Q_{ex} = P_{ex} S_{ex} ,$$

where P_{in} and P_{ex} are the inlet and exhaust pressures in Torr; Q_{in} and Q_{ex} are the input and exhaust gas flows in Torr·liters per second; S_{ex} is the forepump pumping speed in liters per second; and C is the leakage conductance, in liters per second, between the snail chamber and the cryopump chamber.

In equilibrium, $Q_{in} = Q_{ex}$, yielding

$$Q = P_{in} S/(1 + C/S_{ex}) ,$$

where S is the cryopump pumping speed in liters per second, so that the effective speed of the pump is lowered by the ratio of the leakage conductance to the exhaust pump speed. Also, the compression ratio of the system is

$$P_{ex}/P_{in} = S/(S_{ex} + C) .$$

A very high compression ratio should be obtainable by making the snail small and by using thin metal curtains that allow the frost layer to pass into the snail while closing off the leakage paths to the primary chamber.

II. PUMP CONFIGURATION

The cryopumping surfaces of the pump are the inside surface of an 18-cm-ID stainless steel tube with 1.5-mm-thick walls. The outside of the cryosurface tube is wrapped with square copper tubing that is soldered to the tube. Liquid helium from a storage dewar is continuously transferred through a transfer line to cool the pump. The cryopump itself is contained inside a separately pumped vacuum chamber (Fig. 1). The internal cryopumping surfaces are connected to a room-temperature duct through a pair of metal bellows with a helium exhaust tracer that intercepts heat flow up the bellows. A chevron could also be placed midway up the bellows but was not used in this experimental arrangement so that we could observe the snail scraping the frost through a TV camera, looking up from the bottom of the pump through a window. The use of the bellows enables a high-conductance path to the cryopump with a low heat leak. This configuration is cryostable since the thermal conduction through the gas is negligible. Typically, high-speed cryopumps attempt to maximize both the cryopumping surface area and the conductance into the pump; this leads to an open geometry which, with operation at high pressure, causes a severe heat leak to the pumps. Therefore, the speed of the pump was compromised to achieve a cryostable configuration.

The available cryopumping surface in the prototype pump is 320 cm^2. A throughput of 100 Torr·L/s would result in a frost accumulation of 0.3 mm/min, assuming that the frost is a dense-packed solid. This rapid accumulation of frost could lead to a saturation of the pumping speed because of the poor thermal conduction of solid hydrogen.

The snail is attached to and driven by a mechanism designed to allow it to scrape the inside surface of the cylindrical cryocondensation surface. A lead screw, driven through a rotary vacuum feedthrough by a fractional-horsepower dc gear motor, moves the snail in a helical motion around and up the walls of the chamber. The motion reverses at the top, and the snail returns down the surface. A complete cycle requires approximately 2 min.

Two different types of snail have been tested, a mechanical snail that scrapes the frost from the cryosurface and a thermal snail that sublimes the frost from the surface. The mechanical snail, shown in Fig. 2(a), consists of two knife edges to scrape the frost and a pair of thin, metal curtains that ride over the cryosurface to seal off the snail chamber from the process chamber. A heater and a silicon diode cryogenic thermometer are attached to the snail so that the scraped frost can be sublimed inside the snail. The thermal snail, shown in Fig. 2(b), consists of a copper "box" with a surface contoured to fit flush with the cryosurface. When heated, the metal plate, which is pressed against the cryosurface, warms the surface of the cryofrost, causing the frost to sublime. Holes drilled through the plate allow the evaporated cryofrost to vent into the exhaust duct. The edges of the box serve the same function as the metal curtains, limiting the backflow of sublimed gas from the snail chamber into the process chamber. The snail heads are attached to the drive tube with a bellows with springs added to force the snail to press against the cryosurface with 15 N (3 lb) of force.

Since this cryopump is a true throughput pump as opposed to a collector pump, a forepump is used to back the pump. Several rather conventional pumps could be employed. For tritium applications an all-metal scroll pump or bellows pump could be used. Alternatively, the scraped solids and evaporated gases could be collected in a solid hydrogen extruder and pumped as a cryogenic solid directly to high pressure (100 atm) or be fabricated into fusion fueling applications. For the tests reported, a conventional two-stage rotary vane pump with an inlet molecular sieve trap was used as the forepump. The effective speed of the forepump, including the trap and the vacuum lines, was measured to be 11.7 L/s for deuterium amd 10.7 L/s for argon.

Several other components are shown in Fig. 1. A 2-in. diffusion pump was used to evacuate the cryogenic insulation vacuum space surrounding the pump. A gas flow controller (0 to 100 Torr·L/s) was used to admit and measure the flow of test gas to the pump. A second flowmeter was installed on the rotary vane pump to measure the exhaust flow from the pump. Capacitance manometers were used to measure the process chamber vacuum (0 to 1 Torr) and the exhaust pressure (0 to 10 Torr). Silicon diode cryogenic thermometers were used to measure the temperature of the snail head and the cryopump surface.

III. EXPERIMENT

Tests of the mechanical snail pump were performed with deuterium gas. After cool-down of the pump to a temperature below 6 K, deuterium was admitted at various flow rates from 0 to 50 Torr·L/s. With no heat applied to the snail head, the temperature of the head dropped from a value near 90 K during the start of the test to below 20 K. When the temperature dropped below 20 K, the exhaust flow and exhaust pressure dropped, and the snail ceased pumping while the pump continued operation. This is probably due to accumulation of frost inside the snail, causing the exit ports to plug. When heat was added to the snail, the pumping action resumed. The snail temperature was then regulated at 70 K for the remainder of the test. Up to a flow of 30 Torr·L/s, the pumping was stable and continuous. Figure 3 shows a portion of the time history of the inlet and exhaust pressures for an inlet of 20 Torr·L/s. The exhaust pressure at a given moment of time is proportional to the amount of frost being "eaten" by the snail, which is proportional to the frost thickness. The regular variation of the exhaust pressure is due to a combination of two effects. First, the motion of the snail is reciprocal so that, on the start of the return motion, the snail is removing frost from a region of the pump which it has just cleaned; thus, a sawtooth fluctuation of the exhaust would be expected. Second, the accumulation of frost in the pump is probably not uniform from top to bottom. Because of the geometry, more gas is pumped near the bottom (entrance) of the pump than at the top. These two effects combine to account for the variation in exhaust flow with the average exhaust flow equal to the inlet flow. The process chamber pressure can be simulated with a pumping speed of 2000 L/s, a snail conductance of 4 L/s, and an exhaust pumping speed of 11.7 L/s. The variation of the pressure observed in the process chamber is a result of the backflow of gas from the snail into the process chamber. This effect determines the size of backing pump required. At a flow of 50 Torr·L/s, a large fluctuation in the process vacuum occurred which was due to a rise in cryosurface temperature to above 8 K. The heat load on the pump was large enough to raise the cryosurface temperature to a value at which the equilibrium vapor pressure of the frost was higher than the process vacuum. The limit of the throughput was the cooling limit of the liquid helium transfer system, estimated at 20 to 30 L/s of liquid helium. An early version of this pump with a liquid-bath cooling system and a liquid-nitrogen-cooled baffle was capable of much higher instantaneous throughputs. The bath pump was tested to determine if it could pump pressure bursts of hydrogen propellant used in the pneumatic pellet accelerators. Gas bursts of 90 Torr·L/s from a solenoid valve were pumped stably at a rate of 5 s^{-1} for 6 s, a throughput of 450 Torr·L/s.

Test data from the thermal snail are shown in Fig. 4. When deuterium is being pumped, the thermal snail performs in much the same manner as the mechanical snail except that it has a significantly lower leakage conductance, 1 L/s vs 4 L/s for the mechanical snail. This results in smaller pressure fluctuations in the process chamber. The responses of the inlet pressure and the exhaust pressure to a step increase in the inlet flow are also shown. The inlet pressure shows an immediate response that is proportional to the inlet flow, as would be expected for a constant pumping speed. The integrated exhaust flow also responds in proportion to the increased inlet flow but is delayed by one cycle time of the snail.

Another difference between the mechanical and the thermal snail was that the thermal snail could be used in pumping argon. When the mechanical snail was used in pumping argon, the snail head chattered and was generally not built with sufficient mechanical rigidity to shave the stronger argon frost. The thermal snail performed quite well with argon; at a throughput of 60 Torr·L/s the process chamber was maintained at 0.047 to 0.050 Torr, which corresponds to a speed of 1275 L/s. The snail was maintained at 240 K by using 70 W of heater power, the cryosurface was maintained at 30 K, and the helium consumption was estimated at 20 to 30 L/h.

IV. DISCUSSION

The construction of this pump was intended to demonstrate the feasibility of continuously regenerating a high-throughput cryocondensation pump in order to minimize the inventory of material in the pump. The three aspects of this problem, high throughput, low inventory, and continuous regeneration, are interrelated. Without high throughput, the problems of regeneration and inventory are not really severe. Producing a practical cryopump that can handle high throughputs requires a solution to the regeneration problem to prevent the pumps from saturating or acquiring too much inventory in an unreasonably short time. The application of this pump, therefore, will probably be in systems which have high throughputs of gas and which require high-speed, ultraclean pumping.

The very high compression ratio demonstrated in this pump has two important aspects. First, the compression ratio will increase linearly with the pumping speed of the pump. Therefore, the same backing pump can be used for a 10,000-L/s pump as for a 1000-L/s pump. Second, the compression ratio is large enough that an all-metal scroll pump or perhaps a metal bellows pump would be adequate to back the pump.

Several improvements and refinements in this pump are envisioned. First, changes could be made in the drive mechanism of the snail and in the geometry of the cryosurface to produce a steady exhaust pressure. This would have the effect of increasing further the usable compression ratio while reducing or eliminating the pressure fluctuations in the cryopump. Second, changes could be made so that the snail mechanism would be driven directly through a metal bellows feedthrough, thereby removing the drive mechanisms from the process vacuum chamber. When combined with an all-metal forepump, this would produce a pumping system in which no materials other than stainless steel would be in contact with the process gas. Third, a closed-cycle refrigeration system could be used to replace the liquid helium refrigerant to enhance the practicality of the pump.

Although the demonstration pump was a cryocondensation pump, the basic principle of operation of the pump could be applied to continuously regenerate a cryosorption pump. In such a system, a cryosorption material with a relatively smooth surface would be used so that a low-conductance seal could be made between the surface and the snail. Selective heating of the cryosorption material could be produced by using infrared or microwave power to heat the cryosorption layer directly as it passed through the snail chamber.

REFERENCE

[1] T. H. Batzer and W. R. Call, "A Continuous Cryopump," J. Vac. Sci. Technol. A 1(2), 1315 (April–June 1983).

FIGURE CAPTIONS

FIG. 1. Schematic drawing of the snail high-throughput continuous cryopump.

FIG. 2. (a) Mechanical snail. (b) Thermal snail.

FIG. 3. Partial time history of the inlet and exhaust pressures with the mechanical snail for a throughput 20 Torr·L/s.

FIG. 4. Partial time history of the inlet and exhaust pressures with the thermal snail for a throughput of 15 and 30 Torr·L/s.

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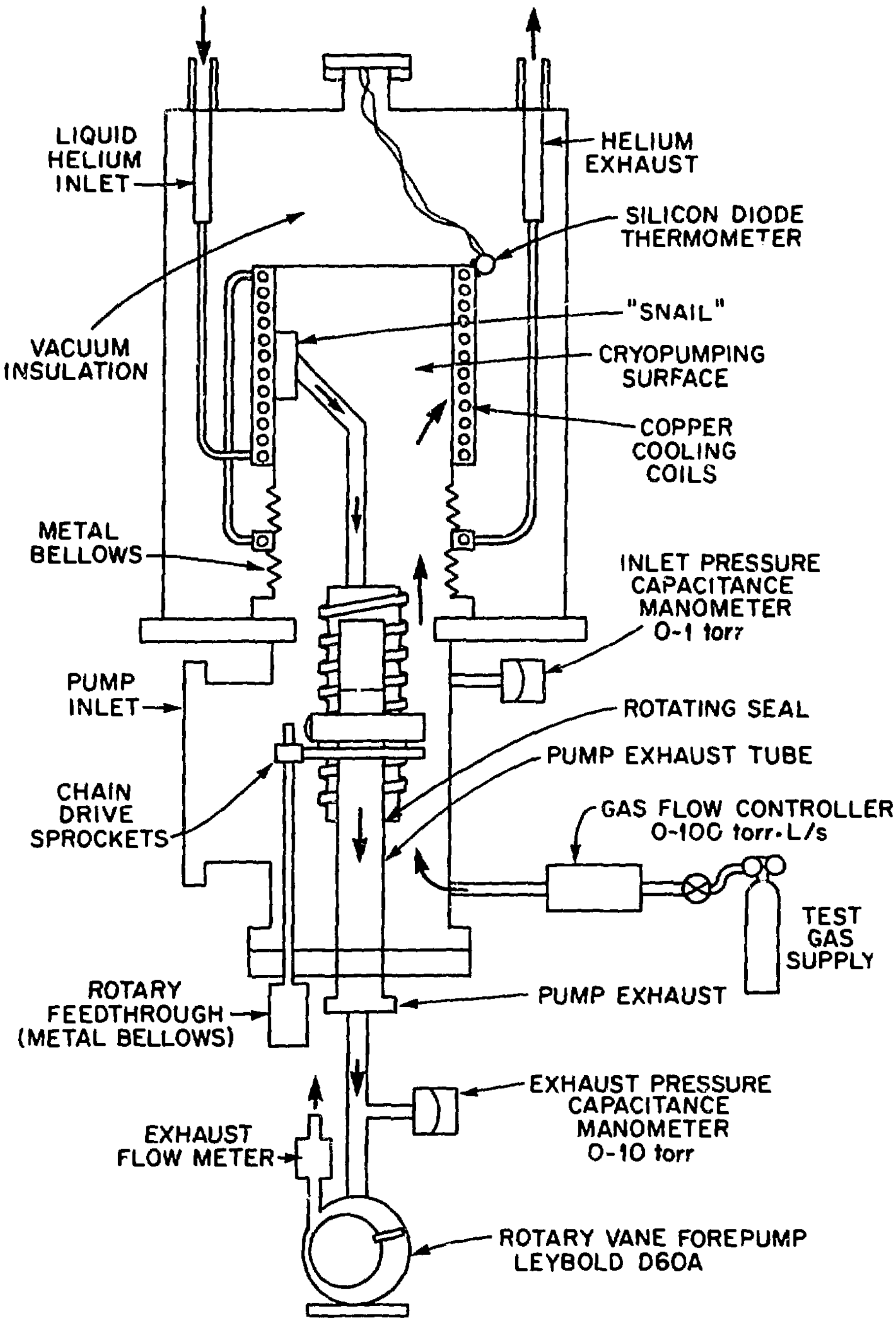

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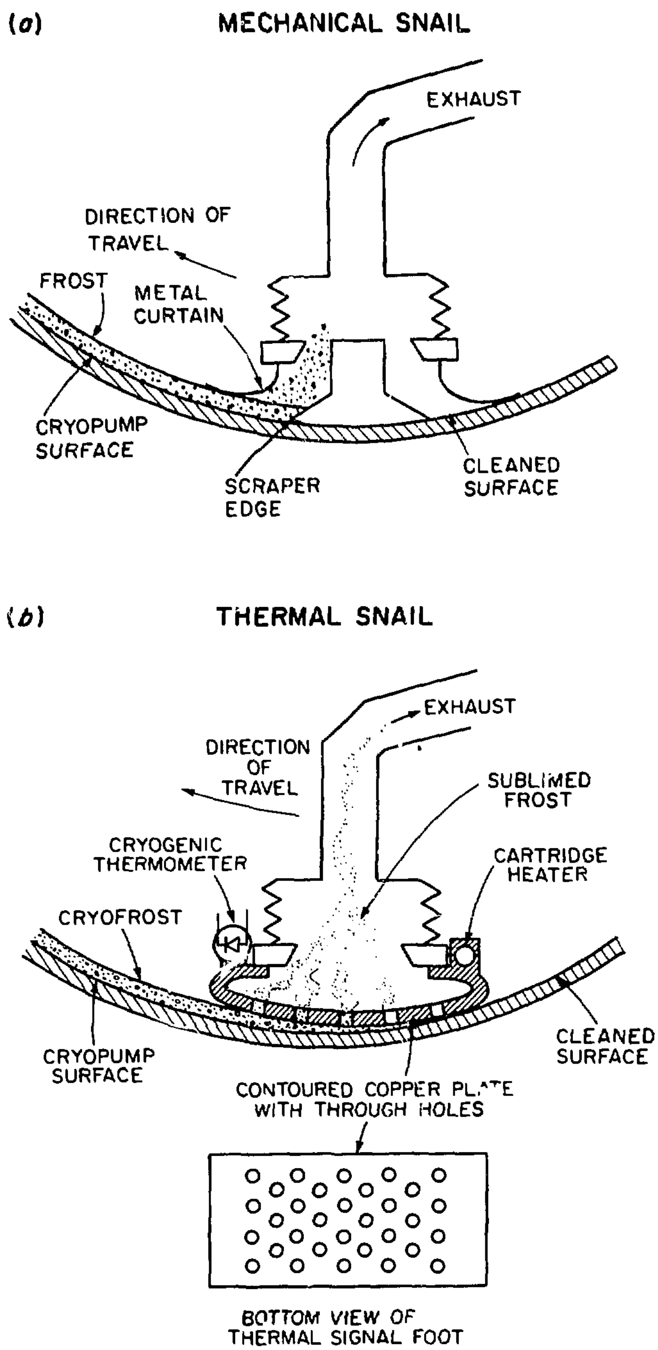

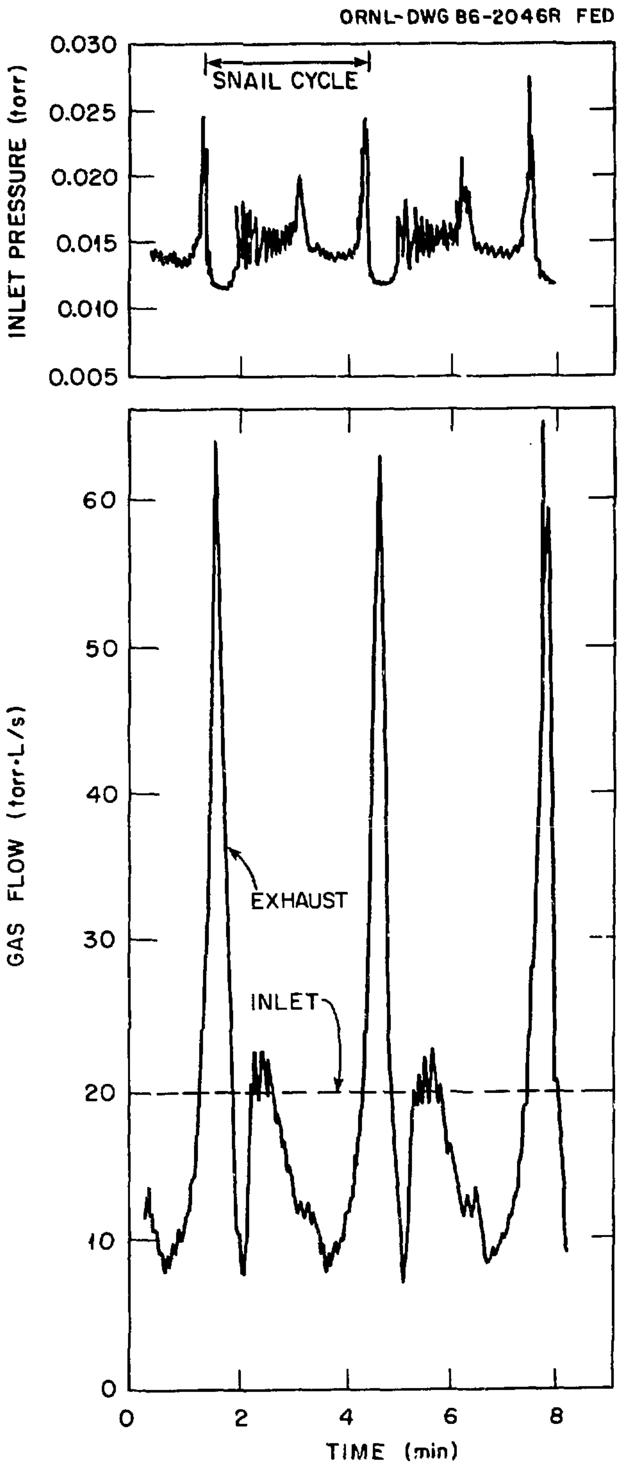
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INLET PRESSURE (torr)
0.030
0.025
0.020
0.015
0.010
0.005
SNAIL CYCLE
GAS FLOW (torr·L/s)
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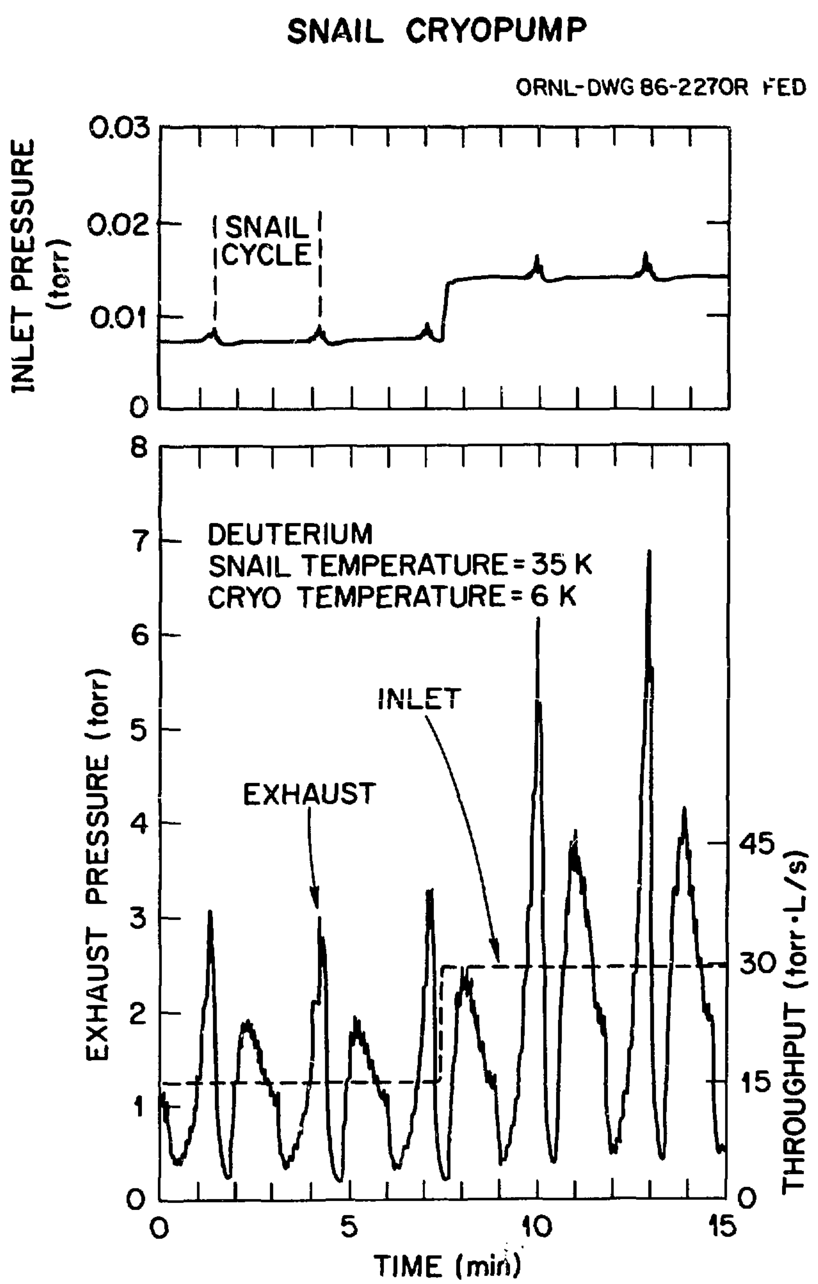
50
40
30
20
10
0
EXHAUST
INLET
0
2
4
6
8
TIME (min)


SNAIL CRYOPUMP
ORNL-DWG 86-2270R FED
INLET PRESSURE (torr)
SNAIL CYCLE
0.03
0.02
0.01
0
EXHAUST PRESSURE (torr)
8
7
6
5
4
3
2
1
0
DEUTERIUM
SNAIL TEMPERATURE = 35 K
CRYO TEMPERATURE = 6 K
INLET
EXHAUST
THROUGHPUT (torr·L/s)
45
30
15
0
5
10
15
TIME (min)