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Methods For Cryopumping Xenon

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ABSTRACT

Design characteristics of a cryopump optimized for xenon are presented. Single-stage Gifford-McMahon helium cryopumps that provide a cryorefrigeration capability of 105 W at 50 K to chill cold plates are used without baffles to enable large pump speeds on on. Shrouds are used to reduce the thermal load to the cold plate to enable greater xenon pump speeds, but it is not required to operate the shrouds at LN2 temperatures. To maximize pump speed on xenon gases such as nitrogen, neon and helium can not be cryotrapped with these pumps. The cryopumps are 52 cm in length, 16 cm in diameter and weigh 15.4 Kg, however the cold head assembly is only 29 cm long and 8.3 cm in diameter. The cryorefrigerators can be mounted using a 15-cm-dia flange and a 10-cm-dia through-hole in the vacuum chamber. Alternatively, the entire cryopump can be mounted inside the vacuum chamber, although preliminary data indicate that pump efficiency decreases when the pumps are operated in vacuum. Tests indicate that the full theoretical pump speed on xenon is achieved. A pumping system designed for the 1,000 hr NSTAR validation test was operated without shrouds or baffles. A poor] y controlled thermal radiation load to the cryopanels and unexpectedly low cryopanel coefficient of thermal conductivity resulted in pressure spikes and a drop in the xenon pump speed. A cryopumping system utilizing three cryorefrigerators with a chilled shroud but without baffles is being used on the 8,000-hr NSTAR wear lest to better control the thermal environment. Each of these xenon cryopumps provides a pump speed on xenon of approximately 15,000 l./s. The, small size of the pumps, coupled with their ability to be operated in vacuum, provide the user with a great deal of versatility as far as locating the pumps with respect to thrusters, tank walls, shrouds, etc. The cost and complexity of installing and operating these cryopumps is a fraction of the. cost and complexity to install and operate diffusion pumps or cryopumps that deliver similar pump speeds on xenon.

INTRODUCTION

One of the most difficult problems in testing electric thrusters utilizing xenon as the propellant is simulating the space environment. For a number of reasons researchers desire the lowest possible working pressure possible to reduce backflow of xenon into the thrusters, reduce charge-exchange erosion of thruster components, and reduce plasma densities in the vacuum chamber to measure thruster plume effects on solar panels and science instruments.

Charge-exchange erosion of the downstream face of the accelerator grid limits the operating life of an ion thruster; numerous works have reported the relationship between ion engine charge-exchange erosion and vacuum tank pressure [1-3]. Best estimates present] y available indicate that a pump speed on xenon of approximately 50,000 1./s is required to test a 30-cm-dia ion thruster at a charge-exchange erosion rate that does not artificially reduce the operating life of an ion engine [4].

Backflow of xenon into the discharge chamber of ion thrusters and Hall thrusters is a direct function of tank pressure and must be considered in calculating thruster efficiency [5,6]. Backflow can be estimated using a simple mathematical model based on discharge chamber area and tank pressure but the uncertainty in the backflow estimate is considerable, given the unknowns in calculating the backflow [6].

Facility pressure effects on the performance of Hall electric thrusters have been reported [7.8]. In tests performed on a 4.5 kW T-160 stationary plasma thruster, thruster efficiency decreased when the thruster was operated in a vacuum chamber with a higher xenon pump speed [7]. References 7 and 9 report that facility pressure effects I Ian thruster plume characteristics.

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Typically facilities achieve high vacuum using oil diffusion pumps or cryopumps to pump both xenon and residual gases such as nitrogen, neon, hydrogen and helium. Diffusion pumps provide. a pump speed on xenon of approximately 5,000-12,000 1./s per square meter of pump inlet area, depending upon the number of flow restrictions such as elbows and baffles. For example, a large diffusion pump on JPL's 2.4 m x 5.4 m vacuum facility with an inlet area of 0.9 square meters has a measured pump speed on xenon of approximatel y 10,000 1./s. This diffusion pump is 2.6 meters in length and weighs over 455 kg. The cost for a similar pump [10], including installation, would be approximately $50,000 for a total cost of $5 per 1./s of xenon pump speed.

Cryopumps have come into increasing use by researchers studying and testing electric thrusters. Cryocondensation using helium cryopumps offers an attractive alternative to diffusion pumps. Advantages include high pump speeds on water and nitrogen (the most common species in a vacuum chamber) and elimination of backstreaming of diffusion pump oil making it's way into the vacuum chamber. Diffusion pump oil contamination was cited as the likely cause for deterioration in the performance of SPT thrusters tested in Russia [11]. Both Fakel [11] and JPL [12] used cryopumps to perform wear tests of the SPT-100.

Three-stage stage helium cryopumps employ liquid nitrogen-chilled baffles and shrouds as the first stage to cryotrap water and to reduce the heat load to the cryopanels. The second stage of the cryopump consists of a double-stage Gifford-McMahon helium refrigerator that operates between 10-20 K and is used to cool the cryopanel that freezes nitrogen, oxygen, argon, xenon and most other gases. The third stage of the cryopump employs charcoal plates attached to the cold panel to cryosorb gases such as neon, hydrogen and helium that do not freeze at 10-20 K [13].

The pump speed on xenon of a cryocondensation pump is approximately 14,000 1./s per m^2 of pump inlet area, compared to up to 10,000 1./s per m2 for a diffusion pump. Three each, 1.2 m-dia helium cryopumps were installed onto JPL's 3 m x 10 m vacuum chamber to achieve a pump speed on xenon of approximately 48,000 1./s, or 16,000 1./s per large cryopump. This facility will be used to perform an 8,000-hour life test of the NSTAR ion engine, The test specifications require a no-load pressure of 4 x 10-5 Pa (3 x 10-7 Torr) [14], and a pump speed on xenon of approximate] y 90,000 1./s to achieve a pressure in the vacuum chamber with the ion engine on of 6.7 x 1()-4 Pa (5 x 10-6 Torr) [14].

It is difficult to achieve substantial pump speeds on xenon using conventional three-stage cryopumps that are not optimized to pump xenon. For example, to install each 1.2-m-dia cryopump described above a hole 1.4 m in diameter was cut into the vacuum chamber wall, and a spool piece 1.4 m in diameter and 27 cm in length, with an inner open diameter of just over 1.38 m, was welded to the tank walls. Following that a flange 7.6 cm thick and 1.5 m in dia was welded to the spool piece. Then a crane was used to place each cryopump, weighing over 545 kg, onto it's flange.

Each cryopump uses approximately 9.4 gallons of liquid nitrogen per hour, or 225 gallons of liquid nitrogen per day, for a total daily LN2 cost of approximately $80.00. Total cost for purchase and installation of a 1.2 m-dia cryopump today is approximately $90,000. This comes to approximately $5.5 per 1./s of xenon pump speed, excluding LN2 costs 115-17].

JPL's 7.6 m x 25.8 m Space Simulator utilizes 10 ea. 0.9-m-dia cryopumps to provide a pump speed on xenon of approximately 150,000 1/s [1 8]. NASA LeRC's Tank 5 contains 20 each O. 8-m-dia diffusion pumps and a cryopanel with 27 m^2 of pump inlet area, for a total facility pump speed on xenon of approximate y 300,000 1/s [19]. Pump and installation costs for these unique facilities approached several million dollars each,

Six standard 1.2-m-dia cryopumps, occupying approximately 9 m^2 of vacuum chamber area and costing approximately $50(),000 would be required to provide a pump speed on xenon required for the NSTAR program. LN2 costs for six 1.2-m-dia cryopumps, based on JPI .'s experiences with the SPT cyclic endurance test and 1,000-hour wear test, would be approximately $480.00 per day, or $200,000 for the duration of the 8,000-hour wear test. The vacuum chamber space/volume requirements and LN2 costs for six 1.2-m-dia cryopumps were beyond the space limitations of the vacuum chamber and financial resources of the NSTAR program.

Several companies were approached about new pump designs that could provide increased pump speed for the dollar, The cost in dollars per 1./s of xenon pump speed was decided as an appropriate figure of merit for pump system evaluation. Designs included a 2.2 m^2 pump to deliver a pump speed on xenon of 33,000 L/s at a cost of $3.3 per 1./s of xenon pump speed [20], and a large helium refrigerator that delivers 1,000 W at 50 K [21]. None of these options discussed above were within the area/volume constraints of JPL's ion engine life test facility and the budgetary constraints of the NSTAR program,

1.2-m-dia cryopumps have a rated pump speed on xenon of approximately 27,000 L/s [22], however that pump speed rating is measured based on an American Vacuum Society standard that places the pressure measuring gauge inside a test dome with the pump. At JPL the pump speed on xenon of a 1.2-m-dia cryopump was measured using ion gauges and flow meters calibrated on xenon, The ion gauge was located in the vacuum chamber at a distance from the cryopump of at least two meters. The measured pump speed on xenon for a 1.2-m-dia cryopump is 16,000 1./s [23,24].

Radiation baffles which are effective in blocking radiant heat from reaching the cryopanel have a transparency of approximately 50%; of the atoms and molecules that enter the cryopump, 50% are cryotrapped and 50% exit the pump. Therefore only 25% of the xenon that reaches the pump inlet is cryotrapped, and the pump speed of the pump is substantially reduced relative to it's theoretical maximum. Hydrogen, helium and neon, which must be cryosorbed by the third stage charcoal plates, have an even more convoluted path to the charcoal and the effective pump speed for these gases is only approximately 10- 12% of the theoretical maximum. The two-stage GM cryorefrigerators used in 1.2-m-dia cryopumps have a cooling capacity of about 15-20 W at 20 K. Therefore it is not possible to increase the pump speed of these pumps by using baffles with a significantly greater open area fraction, because the increased radiant heat load to the cryopanel would exceed the cryorefrigerator capacity.

Xenon has a vapor pressure at 50 K of 10-8 Torr [25]; if a vacuum tank partial pressure on xenon of 10-7 Torr is acceptable to the user, it is only necessary to chill the cryopanel to a temperature of approximately 54.2 K. Use of cryorefrigerators designed to operate efficiently at a temperature of 50 K and elimination of radiation baffles are the key to reducing the cost of cryopumping of xenon, reducing the pump size and increasing of the pumping speed on xenon.

This paper presents the results of experiments with small cryopumps that operate at a temperature of 50 K. Because of their small size these pumps can be mounted to vacuum chambers at a very low cost, and in some instances the pumps can be mounted inside the vacuum chamber, thus eliminating the need for any holes to be drilled. The pumps do not require liquid nitrogen to operate. The cost and complexity of installing and operating these cryopumps is a fraction of the cost and complexity to install and operate diffusion pumps or cryopumps that deliver similar pump speeds on xenon. Test data for various cryopumping system designs, including pumping system data from the NSTAR 1,00(-hour validation test and 8,000-hour wear test will be presented.

THEORY

The theoretical pumping speed of a cryopanel is, from page 72 of reference 24,

$$S_{th} = \left(\frac{T_i R}{2 \pi M}\right)^{1/2} \left[1 - \frac{P_c}{P_i} \left(\frac{T_i}{T_c}\right)^{1/2} \right. \qquad \text{(Eq. 1)}$$

where

Sth = pump speed
Ti = temperature of the pumped gas
M = molecular weight of the pumped gas
Pc = vapor pressure of the pumped gas at temperature Tc
Pi = vacuum chamber pressure

T_C = cryopanel temperature

The pumping speed (in 1./s per cm^2 of cryopanel surface area) of any gas capable of condensation becomes, from equation 8.9 of reference 24,

$$s_{th} = 3.638\left(\frac{T_i}{M}\right)^{1/2}\left[1 - \frac{P_c}{P_i}\left(\frac{T_i}{T_c}\right)^{1/2}\right] \qquad \text{“ , „2)}$$

For cryopumping xenon the theoretical maximum pumping speed of a cryopanel is (in L/s per cm^2 of cryopanel surface area)

$$s_{th} = 3175\left(T_i\right)^{1/2}\left[1 - \frac{P_c}{P_i}\cdot\left(\frac{T_i}{T_c}\right)^{1/2}\right] \qquad \text{(Eq. 3)}$$

Normally the vapor pressure of the condensated gas is much lower than the working vacuum tank pressure and the term in brackets can be ignored, The above equation means that the cryopumping speed is nearly independent of the vacuum tank pressure, until the working pressure approaches the vapor pressure of the condensate gas.

In Fig. 1 the theoretical maximum pump speed of a cryopump using a cryopanel of area 1 m^2 at 50 K is plotted as a function of xenon temperature. Room-temperature xenon condensing on a 50 K cryopanel has a theoretical pump speed of approximately 55,000 1./s per square meter of cryopanel area. If the term in the brackets in Eq. 1 is included, then assuming a tank pressure of 7.5 x 10-9 Pa (10-6 Torr) the pump speed per square meter is reduced 53650 L/s. Pump speed decreases with temperature; for example, if the xenon thermalized completely with an LN2-cooled radiation baffle and shroud at a temperature of 80 K, the pump speed of the cryopump would decrease to approximately 27,500 L/s per square meter of cryopanel surface area. A cryopanel with a surface area of 0.2 m^2 will have a pump speed on xenon of approximately 10,500 1./s if the xenon being cryotrapped is at room temperature.

From page 242 of reference 26, the radiant heat flow between two concentric cylinders or spheres is

$$\frac{H}{A} = \frac{\sigma\varepsilon_1\varepsilon_2\left(T_2^4 - T_1^4\right)}{\varepsilon_2 + \frac{A_1}{A_2}\left(1 - \varepsilon_2\right)\varepsilon_1} \qquad \text{(E'. 4)}$$

where

$\varepsilon 1$ = cryopanel emissivity
$T1$ = cropanel temperature, K
$A 1$ = cryopanel area, m^2

In the case where the emissivities of both the cryopump and the shroud or vacuum chamber are unity, Eq. 4 simplifies to

$$\frac{H}{A} = \sigma\left(T_2^4 - T_1^4\right) \qquad \text{(Eq. 5)}$$

The heat load to a cryopanel of area 1 m^2, temperature 50 K and emissivity of unity is plotted as a function of shroud or vacuum chamber temperature (emissivity = 1) in Fig. 2. From Eq. 5, if both the cryopanel and shroud (or vacuum chamber) have an emissivity of unity, the heat load radiated by a surface at room temperature to a cryopanel with a surface area of 1 m^2 is 460 W, The heat load is reduced by 50% if the radiating surface temperature is reduced to 250 K, and increased by 37% if the radiating surface temperature is increased to 325 K.

The heat load to a cryopanel of area 1 m^2, temperature 50 K and emissivity of unity is plotted as a function of radiating surface temperature in Fig. 3. In Fig. 3 the cryopanel area to radiating surface area ratio is varied from 0.01 to 1, and the radiating surface temperature is fixed at 300 K. The data indicate that if the cryopanel faces a surface at room temperature, the heat load to the cryopanel can be reduced only when the radiating surface emissivity is less than 0.5 and the cryopanel surface area is approximately equal to the radiating surface area,

In the case where the cryopanel surface area is much less than the radiator surface area Eq. 4 simplifies to

$$\frac{H}{A} = \sigma \varepsilon_1 \left(T_2^4 - T_1^4 \right) \qquad \text{(Eq. 6)}$$

In other words, the emissivity of the vacuum chamber or shroud is not a contributing factor to the heat load to the cryopanel; what matters is the emissivity of the cryopanel and the temperatures of the cryopanel and radiator surface. To decrease the heat load to the cryopanel the radiating surface temperature must be decreased.

The vapor pressure of xenon is plotted as a function of temperature in Fig. 4. The data indicate that the vapor pressure of xenon is 1.3 x 10-5 Pa (10-7 Torr) at a cryopanel temperature of 54.2 K. This temperature and vapor pressure are a reasonable goal when designing a cryopumping system to pump xenon. If any part of the cryopanel exceeds a temperature of approximately 54 K the pump speed of the pump will decrease noticeably.

RESULTS AND DISCUSSION

A. Refrigerator Design Features

A schematic diagram of the refrigerator used in the cryopumping experiments reported in this paper is shown in Fig. 5. The refrigerator, called the AL-200, consists of a compressor system and a single-stage helium cryopump utilizing a Gifford-McMahon (GM) refrigeration cycle [27]. "The compressors purchased by JPL are air-cooled and utilize 6 kW of 480V three-phase power. The AL-200 is connected to the compressor by high-pressure helium lines. The AL-200 is warrantied for three years or 6,000 hours of operation.

The AL-200 is 52 cm in length, 16 cm in diameter and weighs 13.6 Kg, however the cold head assembly that must be placed inside the vacuum chamber for cryopumping is only 29 cm long and 8,3 cm in diameter. Another version of the AL-200 can be purchased with a cold head length from flange to heat exchanger of almost 46 cm (18 in).

The pump is installed by mating the 15.9-cm-dia flange to a mating flange and o-ring on the vacuum chamber. A 9-cm-dia clearance hole is required to allow the cold head assembly entry into the vacuum chamber. Alternatively, the entire cryopump can be mounted inside the vacuum chamber, but this requires two welded pipes for connecting high-pressure helium hoses and one 110 VAC electrical connection. Preliminary indications are that pump efficiency decreases when the pumps are operated in vacuum.

The pump can be mounted in any orientation with respect to the horizon; the recommended orientation is pump axis vertical with the heat exchanger down, The cryopanels are mounted to the AL-

200 using six brass screws that screw into threaded holes in the heat exchanger (Fig. 5). Indium washers or low-temperature grease are placed between the heat exchanger and the cryopanel to increase the thermal conductivity the between these two parts of the cryopumping system.

Cooling capacity of the AL-200 is plotted in Fig. 6 as a function of cold head temperature.. The cooling capacity of the AL-2(IO increases with cold head temperature and provides a cryorefrigeration capability of 105 W at 50 K [28] at the cold head, if the Al .-200 motor assembly is mounted in air at room temperature. Five AL-200 pumps were received at JPL. (holing capacity data measured at the factory for one of the AL-200 pumps is also shown in Fig. 6. The data indicate that the cooling capacities of the pumps purchased by JPL meet or exceed the manufacturer specifications.

B. Cryopump System Design Features

Tests were conducted in JPL's 2.4 m x 5.4 m vacuum chamber which is pumped by one oil diffusion pump with an inlet area of 0.9 m^2, and two each 0.8-m-dia diffusion pumps, An ion gauge calibrated on nitrogen was used to measure the no-load tank pressure, and an ion gauge calibrated on xenon was used to determine the facility pressure with xenon flowing into the vacuum tank. Xenon was flowed through a flow meter calibrated on xenon into the end of the vacuum chamber nearest to the large diffusion pump and to the cryopump. Solid-state diodes were placed at the center and edge of the cryopanels to measure cryopanel temperature. A schematic diagram of the test set-up is shown in Fig. 7.

Cryopanels were fabricated from high-purity Al.-1100 aluminum and attached to the heat exchangers with brass screws. A low-temperature vacuum grease was applied between the cryopanels and heat exchangers to increase the thermal conductivity y bet ween these two components, The AI.- 100 was not annealed or treated in any way to increase the thermal conductivity.

C. Xenon Cryopump Experiments

Tests were performed in a 2.4 m x 5.4 m vacuum facility utilizing three oil diffusion pumps. An ion gauge calibrated on nitrogen was used to measure. the no-load tank pressure, and an ion gauge calibrated on xenon was used to measure tank pressure with xenon flow. Pump speed was calculated from the formula in Eq. 7:

$$S = Q/(P - Po) \qquad \text{(Eq. 7)}$$

where
Q = gas throughput
P = working gas pressure (xe flow on)
Po = no-load chamber pressure

Pump speed of the diffusion pumps alone was measured first, then the total pump speed with both diffusion pumps and cryopump in operation was measured. The pump speed of the cryopump was determined by subtracting the pump speed of the diffusion pumps from the total pump speed. Cryopump pumping speeds were then compared to the pump speeds calculated using Eq. 3.

A cryopanel with a diameter of 0.48 m (19 in) and surface area of 0.18 m^2 was attached to the heat exchanger as shown in Fig. 7. Multi-layer insulation (MLI) blankets were placed on the side of the cryopanel nearest to the chamber wall to reduce the heat load. Xenon was flowed into the vacuum chamber and the tank pressure and flow rate were noted. The cryopump was operated for 90 minutes before data was taken. Results are shown in Table 1 under the heading of Test #l. 1 and 1.2.

Table. 1. Cryopump Tests. All pump speeds are for xenon in 1./s. Theoretical cryopump speeds are calculated using the cryopanel area and Eq. 3. Measured cryopump speeds are calculated by subtracting the diffusion pump speed from the total pump speed.

Test #	Flow Rate (seem)	D-pump Speed (L/s)	No-Load Pressure ('I'err)	Pressure With Flow (1'err)	Total Pump Speed ('1'err)	Measured Cryopump Speed (Torr)	Cryopanel Area (m^2)	Cryopump Speed From Eq. 3 (1./s)	Center Diode (K)	Edge Diode (K)
1.1	13.4	14,200	4.6c-7	7.4c-6	24,400	10,200	,18	10,000	38	42
1.2	12.8	nm	4.6c-7	7.0c-6	24,900	10,700	.18	10,000	38	42
2.1	10.1	9,200	9.0c-7	1.0c-5	13,600	4,400	.13	7,200	26.5	26.5
2.2	10.1	9,700	1.1c-6	7.0c-6	21,700	12,000	.26	14,300	29.2	29.5
3.1	10.1	10,000	1.8c-6	6.2c-6	29,000	19,000	.43	23,600	40.6	40.8
3,2	16.1	10,000	1.8c-6	9.4c-6	26,800	16,800	,43	23,600	40.8	47.3

From Eq. 3 the theoretical maximum pump speed for a cryopanel with a surface area of 0.18 m^2 and a xenon temperature of 300 K is 10,000 1./s. The test data from Test #1.1 and 1,2 indicate that the full pump speed on xenon was achieved, It should be noted here that some cryorefrigeration experts believe that it is not possible to cryocondensate xenon if the cryopanel is radiated by surfaces at 300 K; it is theorized that once an ice layer of xenon builds up, direct room-temperature radiation will cause xenon to vaporize, resulting in pressure spikes [29]. No pressure spikes or decrease in pump speed over time were observed in this test, The significance of this test is that xenon can be cryocondensated near the theoretical maximum rate of 55,000 L/s per square meter of cryopanel surface area, provided a proper thermal load to the cryopanel is provided. This is a factor of four greater than the pump speed per 1./s per m^2 using conventional diffusion pumps or cryopumps.

The Al .-200 required 45 minutes to completely chill the cryopanel to a temperature below 50 K. Based on the AL-200 performance data shown in Fig. 6 the heat load to the cryopanel was approximately 65 W. Based on Eq. 6 the heat load to a panel of area 0.18 m^2 due to room-temperature radiation should be 83 W; it is likely that in Test #1 the surface emissivity of the cryopanel was closer to 0.6.

Unfortunately the emissivity of a cryopanel will increase as water or xenon ice accumulates onto the pump. Moore [30] demonstrated that water, carbon dioxide and nitrogen ice layers increase the surface emissivity of cryopanels up to approximately 0.9 ± .05. Caren et al. [31] showed that as little as ().02 mm of water ice on the surface of a polished aluminum substrate at 77 K causes the emissivity to increase from 0.03 to 0.8. Therefore a cryopanel with a surface area of 0.18 m^2 will ultimately transfer a heat load of 83 W to the heat exchanger, If the thermal conductivity of the panel is too low a large temperature gradient across the cryopanel can develop, with a subsequent loss of pump speed. Long-term xenon cryopump operation requires a careful thermal analysis of the pump system, but for short-term operation aggressive thermal strategies can be used to obtain large pump speeds. A discussion about the 1,(K)O-hour NSTAR test, which used 0.48 -m-dia cryopanels without shrouds or baffles, will follow.

A cryopanel with a diameter of 0.41 m(16 in) and surface area of (), 13 m^2 was attached to the heat exchanger as shown in Fig. 8. An LN2 shroud was placed as shown in Fig. 8 to reduce the heat load radiated to the cryopanel. The distance between the cryopanel and shroud was approximate] y 12 cm, The shroud temperature was approximate] y 120 K. An (M 1.1) blanket were placed on the side of the cryopanel facing the vacuum chamber. Results are shown in Table 1 under the heading of Tests #2.1 and 2.2.

Based on Eq. 3 the expected pump speed on xenon for this cryopump is 7,200 1./s; the measured pump speed of this pump was approximately 4,400 L/s. The pump speed reduction may be due to: xenon thermalizing on the shroud surface resulting in a decrease in pump speed per Eq. 3, geometric decrease in pump inlet area due to the location of the cryopanel, and spacing between the cryopanel and shroud . The pump speed reduction is approximately 40% for this test.

The AL-200 required just 30 minutes to completely chill the cryopanel to a temperature below 50 K. Based on the AL-200 performance data shown in Fig. 6 the heat load to the cryopanel was just a few W, With this configuration the AL-200 can be operated indefinitely without overheating the cryopump due to radiation to the cryopanel.

Next, the MI.] blanket on the O. 13-m-dia cryopanel was removed and the experiment was repeated. Data are shown in Table 1 under the heading of Test #2.2. Based on Eq. 3 the expected pump speed on xenon for this cryopump is 14,300 L/s; the measured pump speed of this pump was approximately 12,000 1./s. These data are consistent with a pump speed of 4,400 1./son the cryopanel side facing the shroud and 7,600 1./s on the side facing the vacuum chamber. 'l'he data imp] y that the full theoretical pump speed limit of approximate y 55,000 L/s per m^2 of cryopanel area was achieved.

A cryopanel with a total surface area of 0.43 m^2 (0.5-m or 20.6 in -dia) was installed as shown in Fig. 8, except no MLI blankets were attached to the cryopump. Two different flow rates were tested with this pump configuration. Based on Eq. 3 the expected pump speed on xenon for this cryopump is 23,600 1./s; the measured pump speed of this pump was approximate] y 18,000 1,/s. These data are consistent with a pump speed of about 6,000 L/s on the cryopanel side facing the shroud and 12,000 1./s on the side facing the vacuum chamber. The data imply that the full theoretical pump speed limit of approximately 55,000 1./s per m^2 of cryopanel area was achieved,

The significance of this testis that this small cryopump, using a small bathtub-shaped shroud, has a pump speed on xenon similar to the pump speed of a 1.2-m-dia cryopump. In terms of xenon pumping speed per 1./s per dollar, the AL-200" costs are approximately a factor of five lower compared to using large cryopumps.

The pump was operated at or below 50 K for approximately two hours after xenon flow was started, A layer of white xenon ice was visible on the side of the cryopanel facing the vacuum chamber. The data reported in Table 1 were taken after over two hours of operating time with the cryopump below 50 K and with xenon flow through into the vacuum chamber. A maximum radiation load to this pump of approximately 100 W is estimated from Eq. 6. Long-term operation using this configuration would be determined by the heat conduction between the heat exchanger and cryopanels, and by the thermal conductivity of the cryopanels. Assuming a 0.53 -m-dia cryopanel with a thermal conductivity of 1000 W/ m^2 and a temperature at the center of 50 K, a temperature at the edge of the cryopanel of 53.6 K is calculated.

I). 1000 -Hour-NSTAR Validation Test_

The NSTAR technology validation program includes several long-duration tests to identify unexpected failure modes and validate design changes to the ion engine. Following a 2,000-hour test at LeRC a 1,000-hour test was conducted at JPL to test and verify modifications made to the 30-cm-dia NSTAR ion engine.

The 1,000-hour wear test was performed in a 3 m x 10 m stainless steel vacuum chamber pumped by three each, 1.22 m-dia cryopumps with a pumping speed on xenon of about 48,000 1./s. The validation test requirements specify a facility pump speed on xenon of approximately 90,000 1./s.

A cryopumping system consisting of four each, AL-200 cryorefrigerators with 0.48 m-dia (19 in) aluminum cryopanels was fabricated and installed into the vacuum chamber. The AL-200 cold head assemblies were inserted into the chamber through 9-cm-dia holes such that the heat exchangers were positioned approximately three inches from the chamber walls. The cryopanel sides facing the vacuum chamber walls were covered in multi-layer insulation to reduce the heat load to this surface. Cryopumping was performed on the sides of the panels facing the vacuum chamber interior. No shrouds or baffles were used in the 1,000-hour validation test.

The cryopanels were sized for a total thermal radiation load of 84 W and a pump speed on xenon of approximate] y 10,000 L/s each. 'l'he expected temperature at the center of the cryopanels based on the heat load and AL-200 performance characteristics was 44 K. High-purity aluminum was used for the cryopanels.

Thermal conductivity for aluminum at 50 K ranges from a high of 1,000 W/m-K for high-purity aluminum to a low of 150 W/m-K for moderately pure aluminum [32]. A thermal model was used to predict the temperature gradient across the cryopanels based on a temperature at the center of 44 K. Cryopanel edge temperature is plotted as a function of thermal conductivity in Fig. 9. The model indicates that the panels designed for the 1,000-hour NSTAR test should be adequate for a heat load of 84 W if the coefficient of thermal conductivity for the cryopanel is above 400 W/m-K,

Facility pump speed on xenon is plotted as a function of flow rate in Fig. 10, A pump speed of approximately 90,000 L/s was achieved using three 1.2-m-dia helium cryopumps and smaller cryopumps using the AL-200 refrigerator. The pump speed of the four AL-200 pumps in the 1,000-hour test configuration is estimated to be approximately 40,000 L/s, or 10,000 L/s per AL-200. Diode temperatures at the beginning of the 1,000-hour test for the AL-200 pumps are shown in Table 2. No AL-200 cryopanel temperature data after the wear test was started are available.

Table 2. Diode temperatures for the AL-200 pumps.

Pump A		Pump B		Pump C		Pump D	
Center (K)	Edge (K)	Center (K)	Edge (K)	Center (K)	Edge (K)	Center (K)	Edge (K)
38	39	36	38	28	30	29	35

Pumping system performance data for the 1,000-hour test are shown in Figs. 11-13. In Fig. 11 the vacuum tank pressure is plotted vs. elapsed time after start of the wear test. Tank pressure varied with a period of approximately 24 hours. Total facility pump speed is plotted against wear test hours in Fig. 12. Pump speed initially decreased to approximately 70,000 L/s, then increased for reasons which will be discussed subsequently. An AL-200 pump failed at approximately 550 hours due an accidental electrical short, and the pump speed decreased by about 10, 000 L/s. The test was continued with only three AL-200 pumps operating. At 900 hours into the wear test the damaged AL-200 was repaired without opening the vacuum chamber and the pump speed increased back to about 90,000 L/s, Pressure spikes, defined as when the vacuum tank pressure exceeded 5.5 x 10-5 Torr, are plotted in Fig. 13 as a function of wear test hours. Over the course of the wear test there were approximately 12 computer-commanded shutdowns due to pressure spikes that exceeded 8 x 10-6 Torr.

The cyclical variations in tank pressure, pressure spikes and decline in pump speed of the AL-200 pumps are related to two causes: a poorly-controlled thermal environment and apparent low thermal conductivity in the aluminum cryopanels.

The aluminum cryopanels were designed to operate with a tank wall temperature of 300 K, The vacuum facility is located outdoors, and thermocouples placed on the tank walls measured wall temperatures as high as 350 K. As illustrated in Fig. 2 even small changes in the environmental temperature can have significant effects on the thermal load to the cryopanels. Cyclical variations in tank pressure shown in Fig. 11 are likely due to day/night heating and cooling of the vacuum tank walls. Since the heat load to the cryopanels was already near the maximum allowable, it is likely that the increased radiation load to the panels due to hot tank walls resulted in increased cryopanel temperatures, especially at the edges.

The other design aspect that strongly affects panel temperature is thermal conductivity. As shown in Fig. 9, thermal conductivity has a significant effect on temperature gradients across the cryopanels. Experiments performed after the 1,000-hour test was initiated” indicated” that the coefficient of thermal conductivity of the aluminum used to make the cryopanels was approximately 200 W/m-K. Such a thermal conductivity would result in large temperature gradients across the cryopanel and temperatures near the edges that could exceed 65 K.

E. 8000-Hour-NSTAR Validation Test

System description

Initially a pump gas loading test was performed. The goal of this test was to quickly form a layer of xenon ice on the cryopumps and determine pump performance characteristics such as pressure spikes. The pump system was tested by flowing xenon into the vacuum chamber for 71 hours such that the tank pressure (8 x 10-5 Torr) was approximately 20 times the nominal NSTAR tank. One 1.2-m-dia cryopump and one AL-200 cryopump were used in this test; the other cryopumps were turned off. The shroud temperature was 120 K in the actively-cooled portion, and 230-270 K at the sidewalls.

Results from this test are shown in Fig. 14. Tank pressure during this period varied between 7-9.4 x 10-5 Torr. Large pressure variations during pump loading shown in Fig. 14 were due to variations in the xenon flow rate. The xenon flow was stopped for 24 hours and then restarted at a flow rate resulting in a tank pressure 150% of the nominal NSTAR working pressure of 4 x 10-6 Torr. There were no pressure spikes observed for 2.5 days,

AL-20() cryopanel temperatures after completion of the pump loading experiment are shown in Fig. 15. The data indicate that cryopump temperatures are less than 56 K and are stable several days after pump loading. The data imply that the NSTAR test can be performed for at least 700 hours before pump loading will result in pressure spikes.

The pump speed on xenon of the 8,000-hour test configuration is plotted as a function of flow rate in Fig. 16. The data indicate that the pump speed of the three AL-200 cryopumps is approximately 95,000 L/s -48,000 L/s = 47,000 1./s, or 15,700 1./s per AL-200. Tank pressure and total facility pump speed are plotted vs. time in Figs. 17-18. No significant pressure spikes or changes in facility pump speed have been observed with the 8,000-hour test pump configuration, even though the temperatures of the shroud sidewalls at certain locations are nearly room temperature.

F. Discussion

It has been demonstrated that cryorefrigerators optimized at 50 K can provide large pump speeds on xenon without the use of baffles and shrouds. However, to make the most advantage of these pumps a shroud is necessary to reduce the heat load to the cryopanels. From Fig. 2 the heat load radiated by a 170 K shroud to the cryopanels is 60 W/ m^2 of cryopanel area, The shrouds used in tests of the AL-200 all operated at temperatures substantially higher than convent ional LN2 shrouds. The best wa y to do reduce heat loading to the cryopanels is to chill a shroud using a powerful freon refrigerator. For example, a large freon refrigerator offered by Pol ycold Systems, Inc. can provide 3.6 kW of cooling at a temperature of 170 K [33].

There are some disadvantages in using the particular type of cryopump tested at JPL. To design a cryopumping system that maximizes the pump speed on xenon, the Al .-2.00 can not be used for pumping gases that require low temperatures such as neon, nitrogen and helium, Therefore the vacuum facility will require separate pumps to remove light gases and maintain a good base vacuum. However, most vacuum facilities already have good pumps for removing these gases.

The AL-200 is quite noisy and transmits a strong vibration pulse when bolted to the vacuum tank. Preliminary thrust stand data from the 8,000-hour NSTAR test indicate that the vibration generated by the AL-200 does not deleteriously effect thrust measurements.

The noise problem can be mitigated by operating the Al .-200 in the vacuum chamber. This was performed at JPL by hanging the AL-200 pump assembly from the roof of the vacuum tank with cables. The pumps can not be heard in this configuration, but preliminary data from these tests suggest that the efficiency of the Al .-200 operated in vacuum decreased by over 60% relative to when the pump is operated in air. Additional tests will be performed to verify these data and determine engineering solutions to the pump efficiency problem.

Several other manufacturers now offer cryorefrigerators that work efficiently at 50 K. Some of these cryorefrigerators drive the pump displacers using a different technique than the AL-2(IO that may result in substantially reduced noise levels when the pumps are mounted to the vacuum chamber. Several of these pumps will be investigated for performance, noise and vibration levels, and ease of installation.

CONCLUSIONS

Single-stage Gifford-McMahon helium cryopumps that provide a cryorefrigeration capability of 105 W at 50 K to chill cold plates were used without baffles to enable large pump speeds on xenon. The cryopanels do not require a surrounding shroud if the cryopanel surface area is sized appropriately with the thermal environment. Chilled shrouds reduce the thermal load to the cold plate to enable greater xenon pump speeds, but it is not required to operate the shrouds at 1.N2 temperatures. If high-capacity cryorefrigerators are used shrouds can be chilled to temperatures of 150 K or more without thermally overloading the cryopump. To maximize pump speed on xenon gases such as nitrogen, neon and helium can not be cryotrapped with these pumps.

The cryorefrigerators are 52 cm in length, 16 cm in diameter and weigh 15.4 Kg, however the cold head assembly is only 29 cm long and 8.3 cm in diameter. The cryorefrigerators can be mounted using a 15-cm-dia flange and a 10-cm-dia through-hole in the vacuum chamber. Alternatively, the entire cryopump can be mounted inside the vacuum chamber, although preliminary data indicatate that pump efficiency decreases when the pumps are operated in vacuum. Tests indicate that the full theoretical pump speed on xenon is achieved.

A pumping system designed for the 1,000-hr NSTAR validation test was operated without shrouds or baffles. A poorly controlled thermal radiation load to the cryopanels and unexpectedly low cryopanel coefficient of thermal conductivity y resulted in pressure spikes and a drop in the xenon pump speed. A cryopumping system utilizing three cryorefrigerators with a chilled shroud but without baffles is being used on the 8,000-hr NSTAR wear test to better control the thermal environment. Each of these xenon cryopumps provides a pump speed on xenon of approximately 15,000 1./s.

The small size of the pumps, coupled with their ability to be operated in vacuum, provide the user with a great deal of versatility as far as heating the pumps with respect to thrusters, tank walls, shrouds, etc. The cost and complexity of installing and operating these cryopumps is a fraction of the cost and complexity to install and operate diffusion pumps or cryopumps that deliver similar pump speeds on xenon.

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3.

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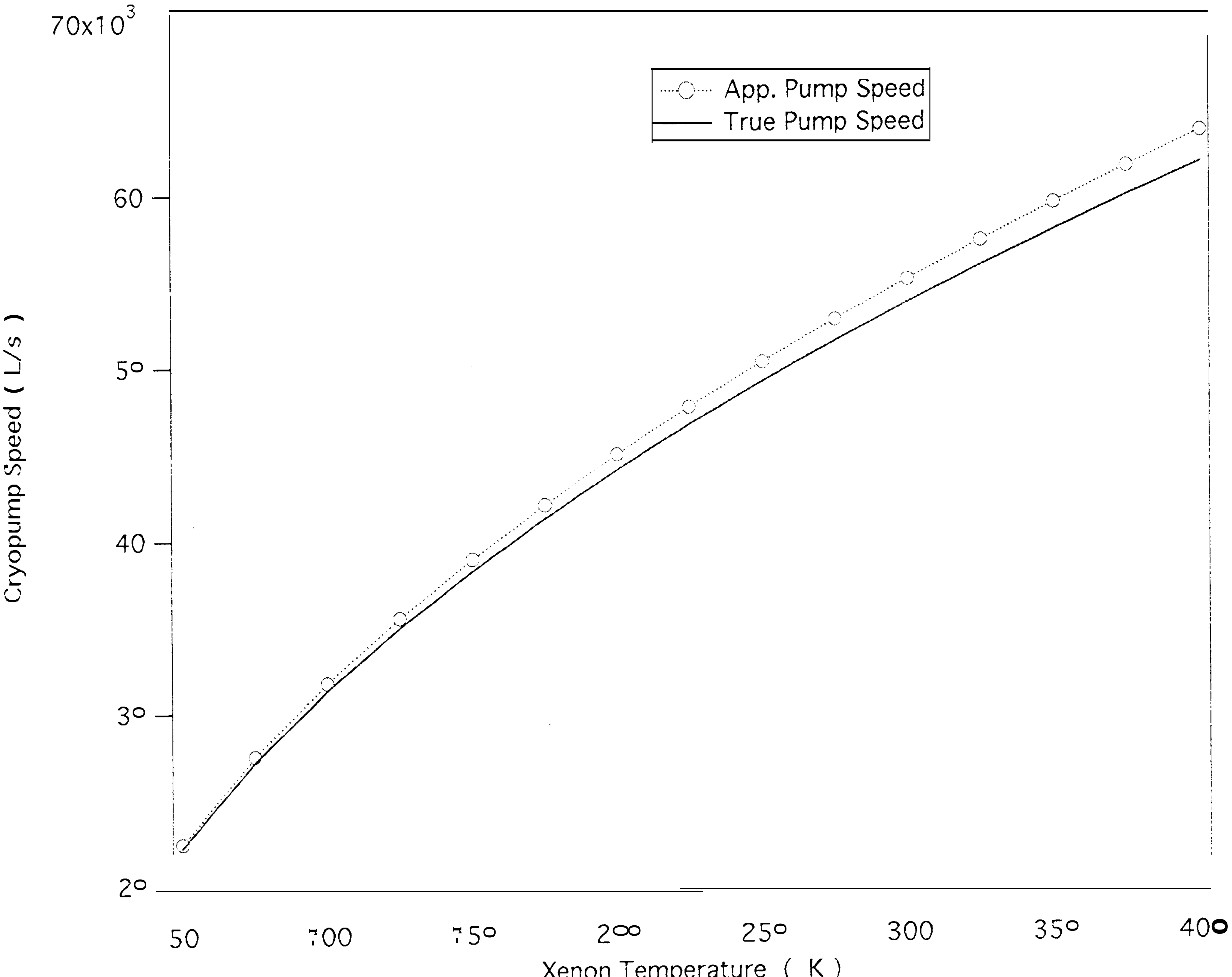
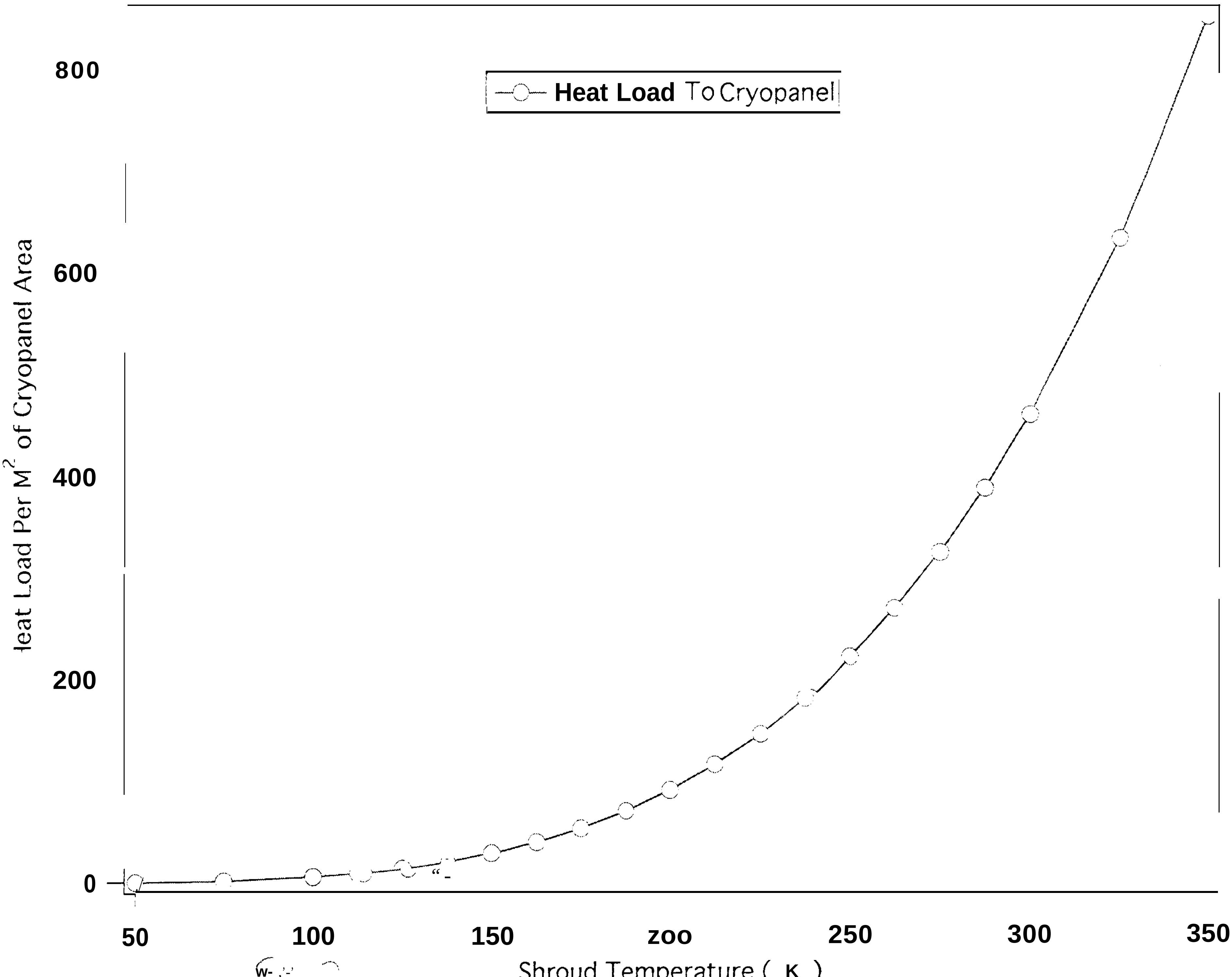
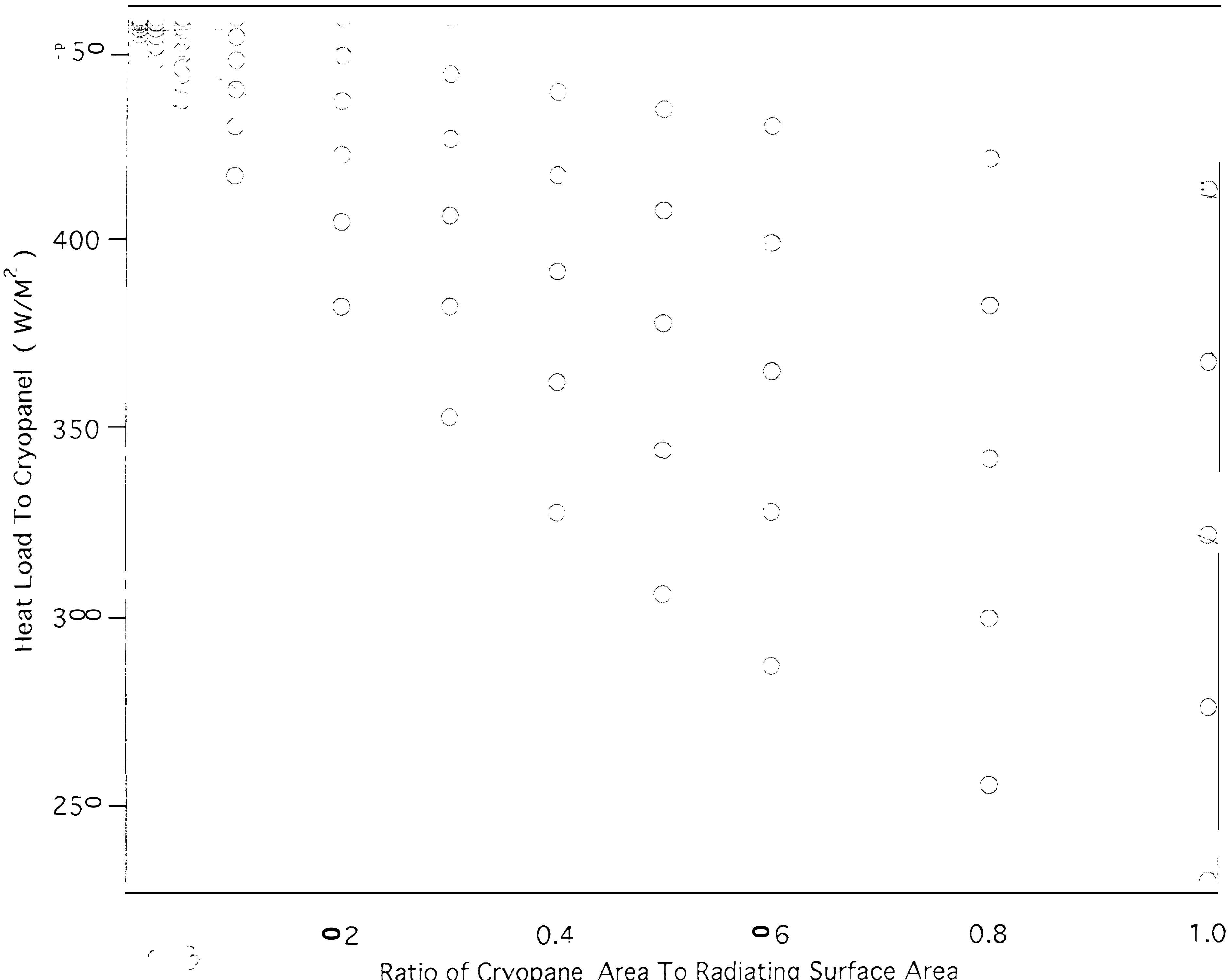
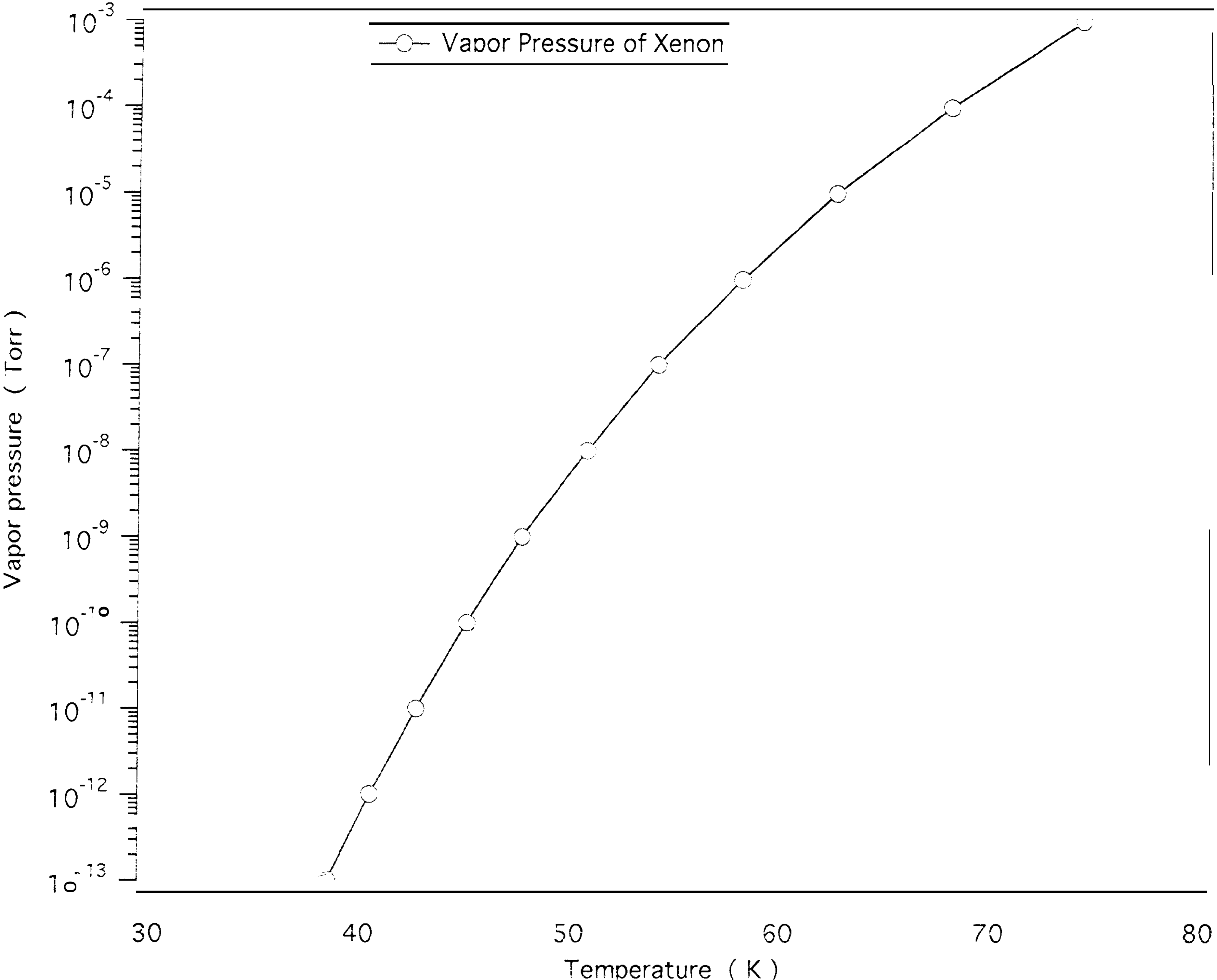
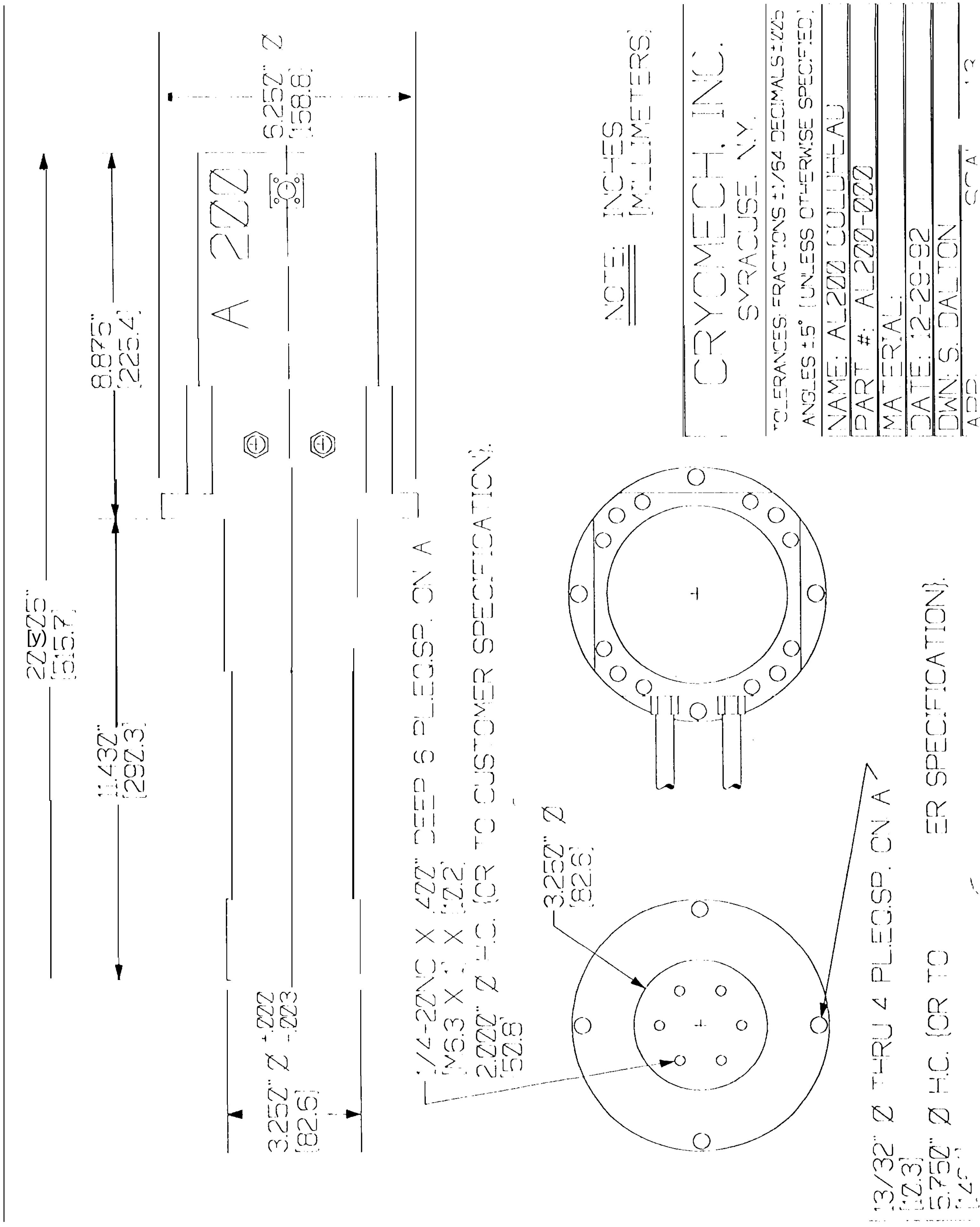

70x10^3
60
50
40
30
20
Cryopump Speed (L/s)
App. Pump Speed
True Pump Speed
50
100
150
200
250
300
350
400
Xenon Temperature (K)

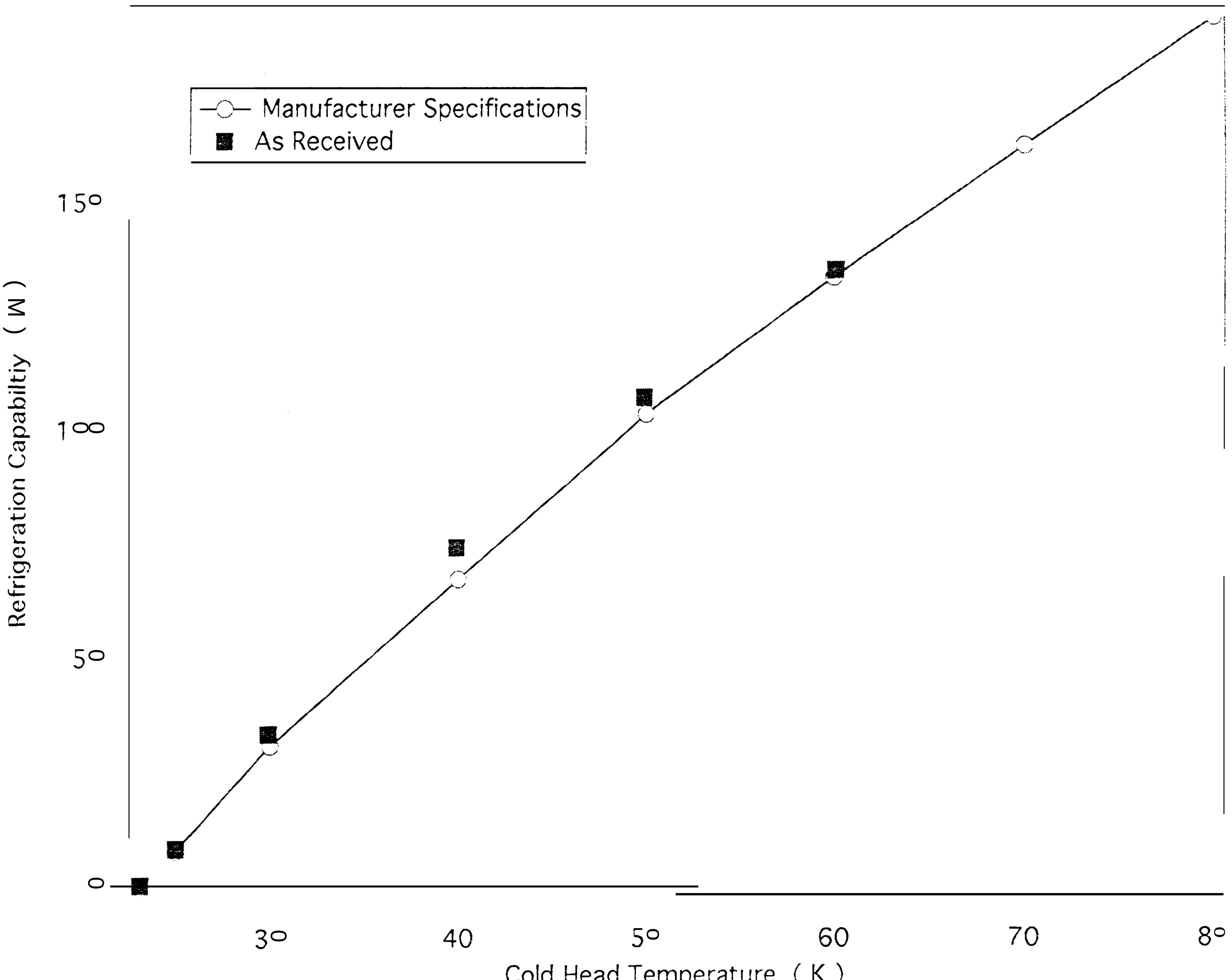

Heat Load To Cryopanel
800
600
400
200
0
leat Load Per M^2 of Cryopanel Area
50
100
150
zoo
250
300
350
Shroud Temperature (K)


Heat Load To Cryopanel (W/M^2)
450
400
350
300
250
0.2
0.4
0.6
0.8
1.0
Ratio of Cryopane Area To Radiating Surface Area


Vapor Pressure of Xenon
Vapor pressure (Torr)
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
30
40
50
60
70
80
Temperature (K)


20[y)05"
[515.7]
11.430"
[290.3]
8.875"
[225.4]
6.250" Ø
[158.8]
A 200
3.250" Ø +.000 -.003
[82.6]
1/4-20NC X .400" DEEP 6 PL.EQ.SP. ON A
[M6.3 X 1 X [10.2]
2.000" Ø H.C. (OR TO CUSTOMER SPECIFICATION).
[50.8]
3.250" Ø
[82.6]
13/32" Ø THRU 4 PL.EQ.SP. ON A
[10.3]
5.750" Ø H.C. (OR TO CUSTOMER SPECIFICATION).
NOTE: INCHES
[MILLIMETERS]
CRYOMECH, INC.
SYRACUSE, N.Y.
TOLERANCES: FRACTIONS ±1/64 DECIMALS ±.005
ANGLES ±.5° (UNLESS OTHERWISE SPECIFIED)
NAME: AL200 COLDHEAD
PART #: AL200-000
MATERIAL:
DATE: 12-29-92
DWN: S. DALTON
APP.
SCA

48 (Figure 1)


Manufacturer Specifications
As Received
Refrigeration Capabiltiy (W)
150
100
50
0
30
40
50
60
70
80
Cold Head Temperature (K)

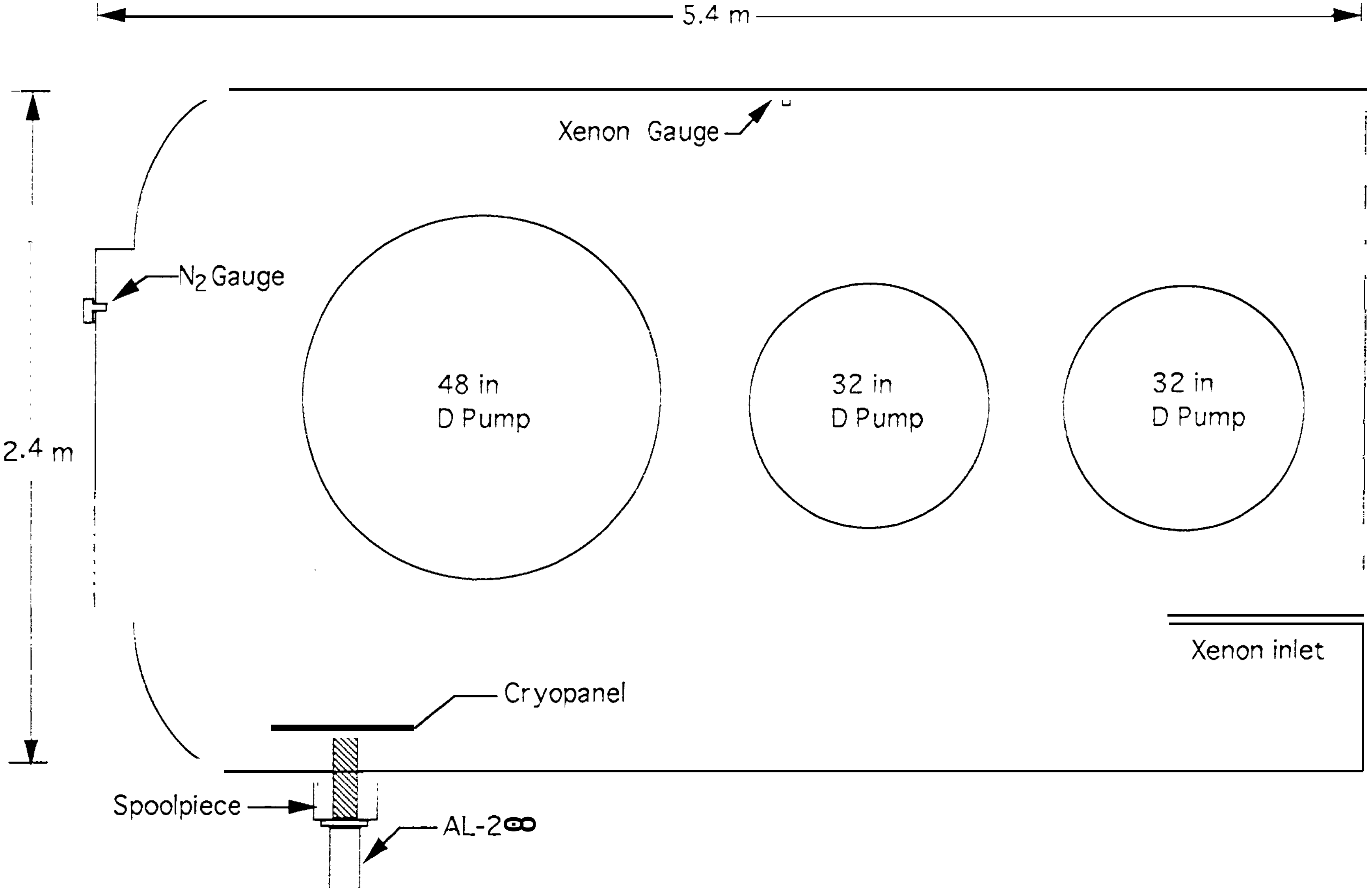


Fig. 7. Test facility to measure pump speed of AL-200 xenon cryopump.

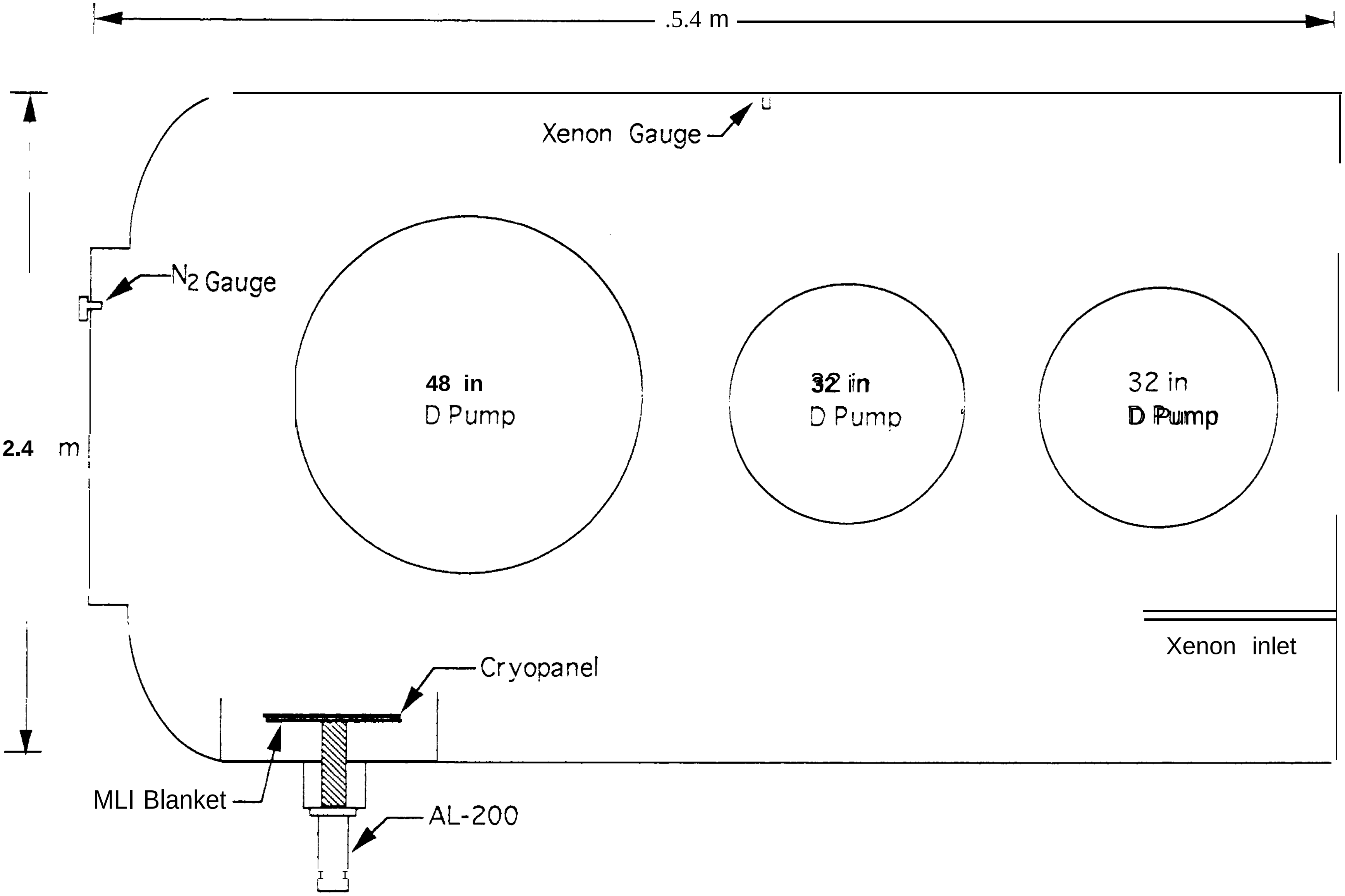
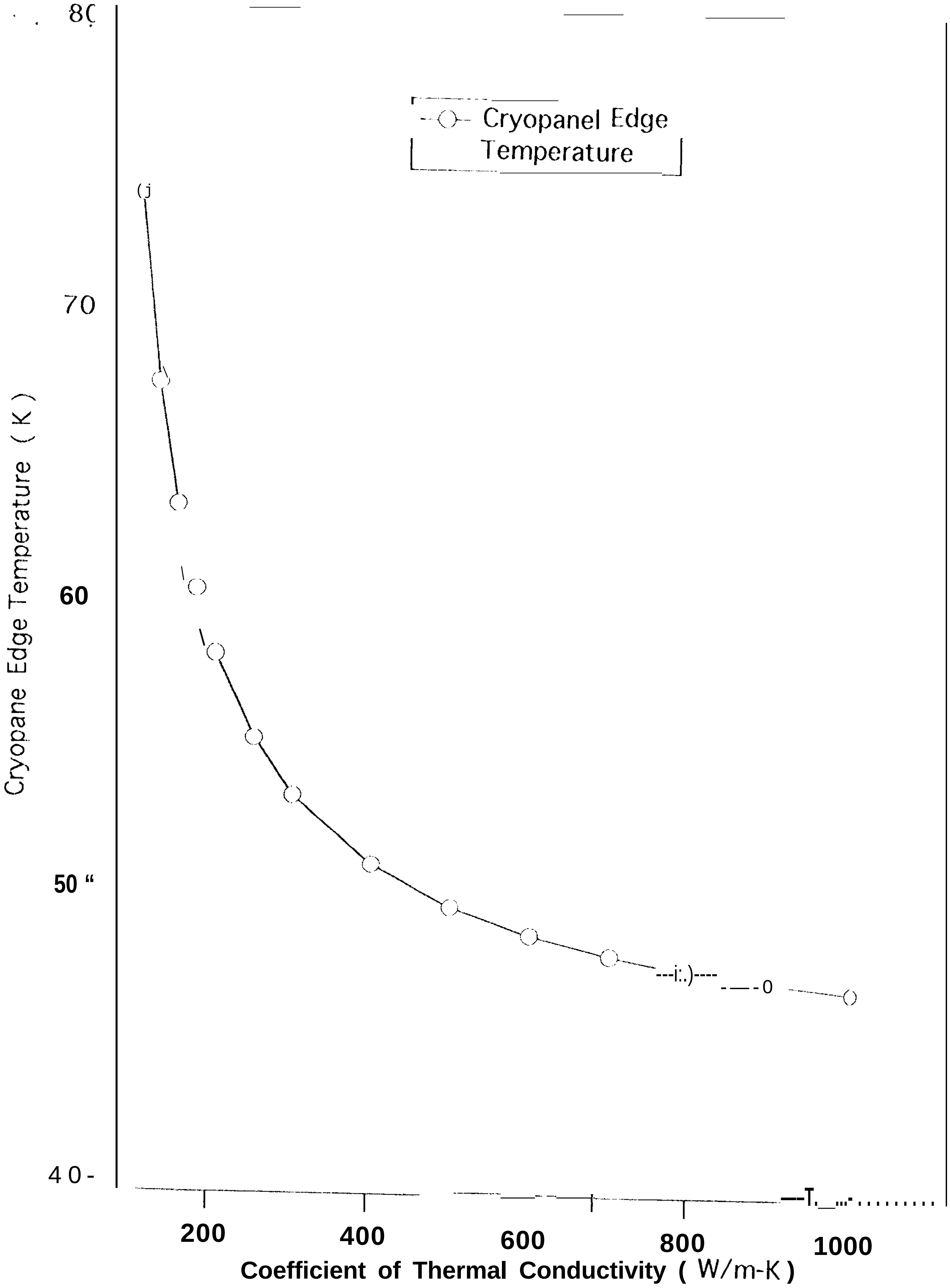


Fig. 8. Liquid nitrogen-cooled shroud surrounding AL-ZOO and cryopanel.


Cryopanel Edge Temperature
80
70
60
50
40
Cryopane Edge Temperature (K)
200
400
600
800
1000
Coefficient of Thermal Conductivity (W/m-K)

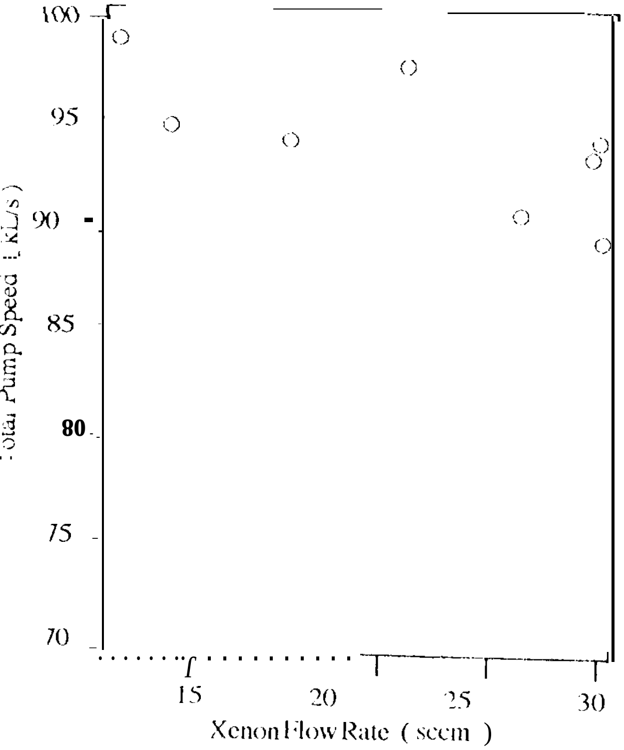


Fig. 10. Total facility pump speed on xenon measured at the start of the wear test.

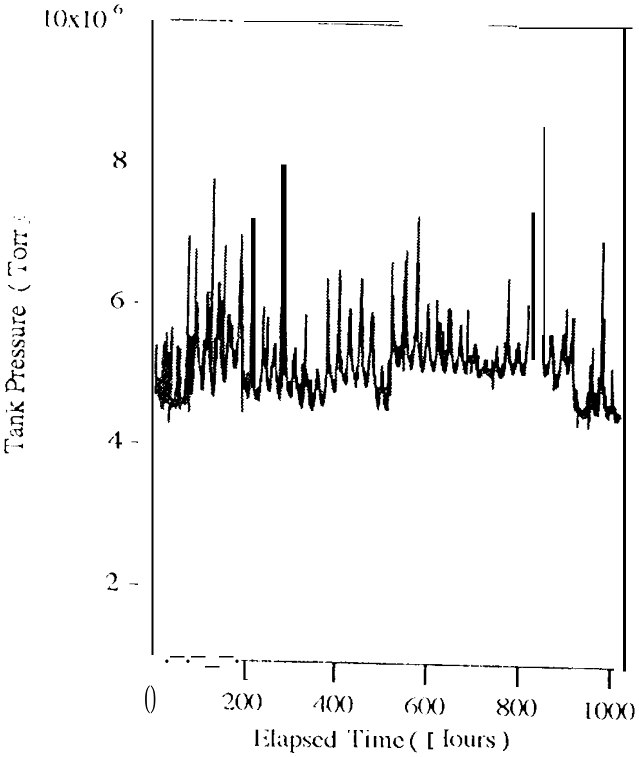


Fig. 11. Tank pressure vs. elapsed time for the 1,000-hour test.

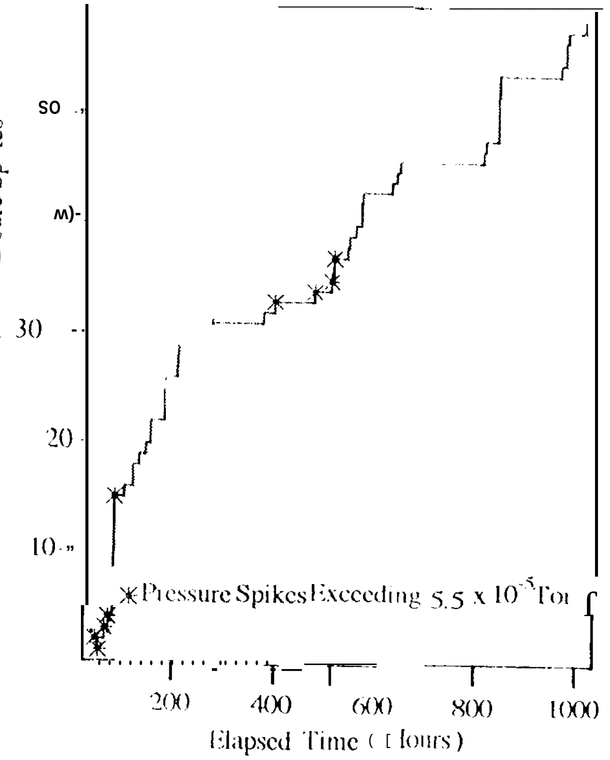


Fig. 12. Total facility pump speed vs. elapsed time.

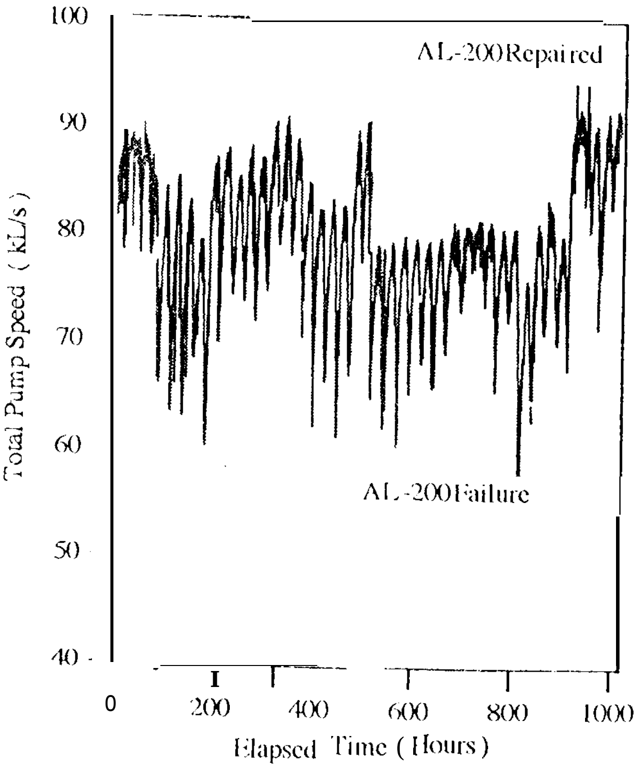
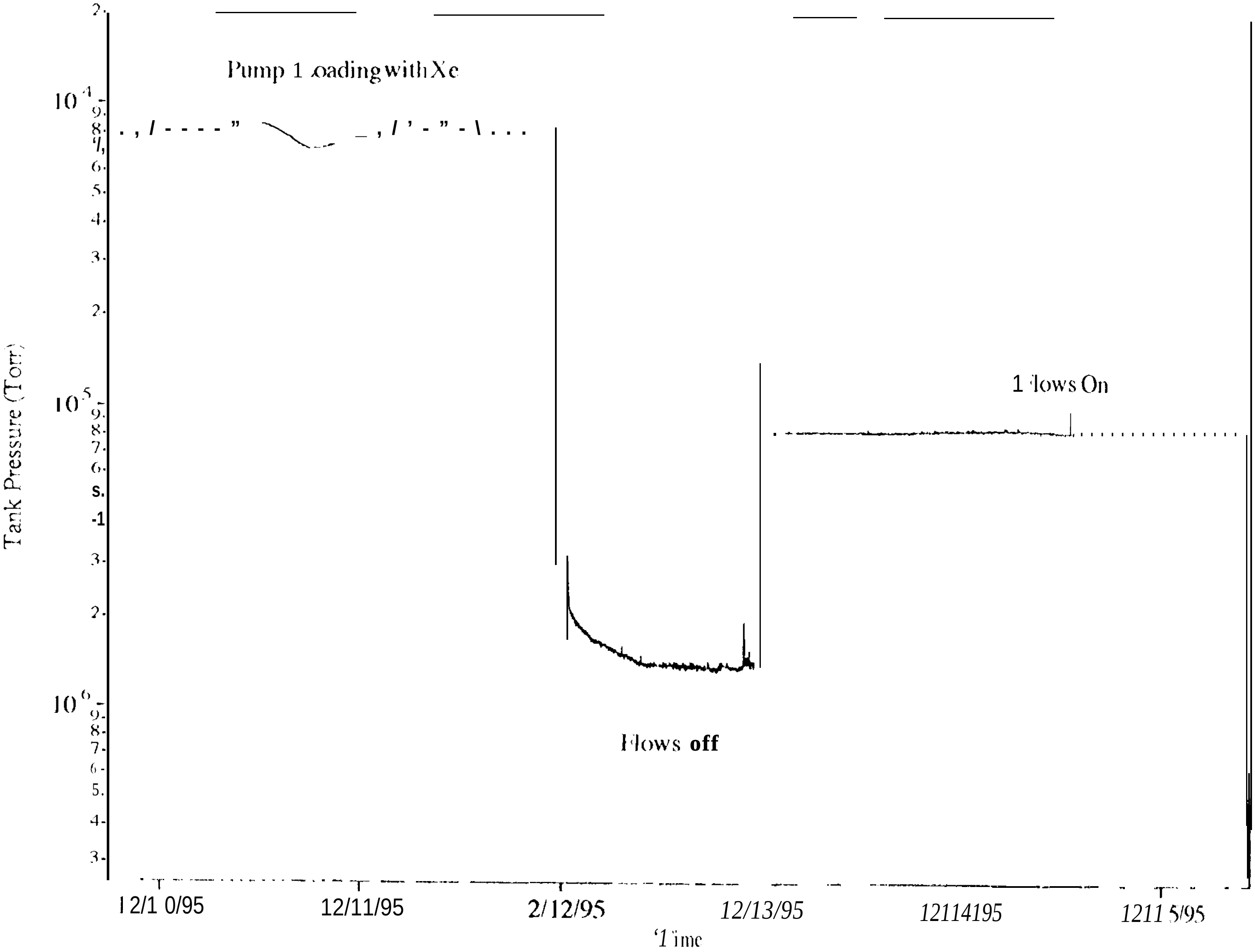
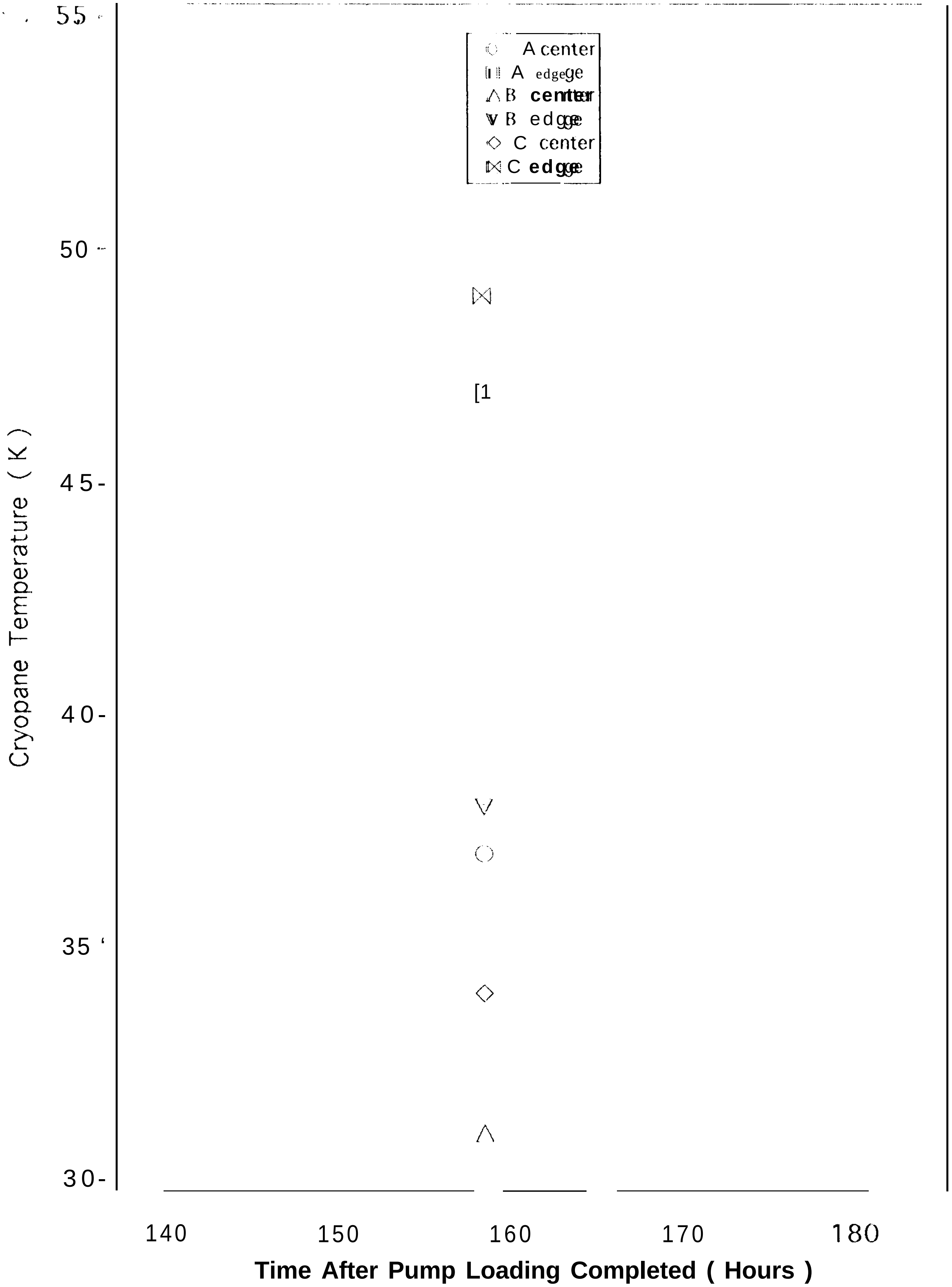
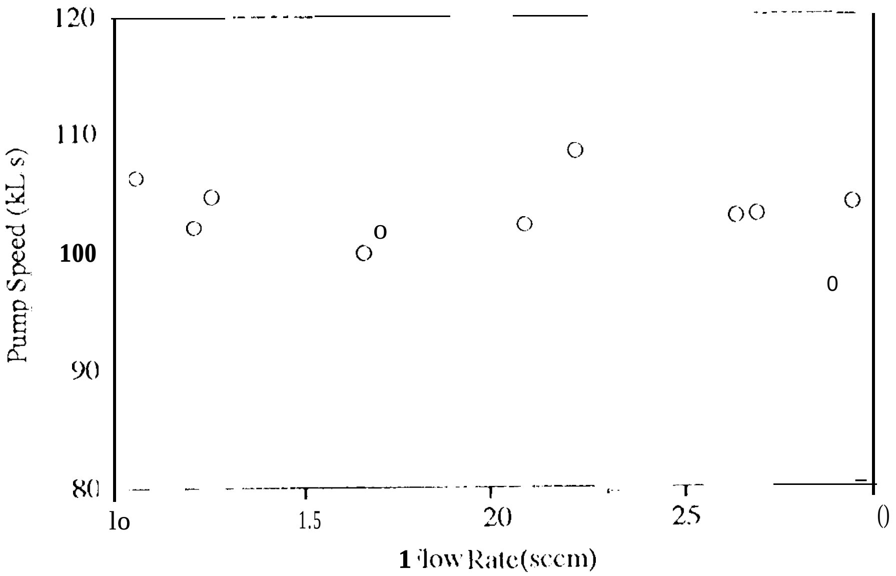


Fig. 13. Cumulative number of pressure spikes vs. elapsed time.



Pump Loading with Xe
Flows On
Flows off
Tank Pressure (Torr)
2
10^-4
9
8
7
6
5
4
3
2
10^-5
9
8
7
6
5
4
3
2
10^-6
9
8
7
6
5
4
3
12/10/95
12/11/95
12/12/95
12/13/95
12/14/95
12/15/95
Time


55
50
45
40
35
30
Cryopane Temperature (K)
A center
A edge
B center
B edge
C center
C edge
140
150
160
170
180
Time After Pump Loading Completed (Hours)



8000 Hr Test
Configuration

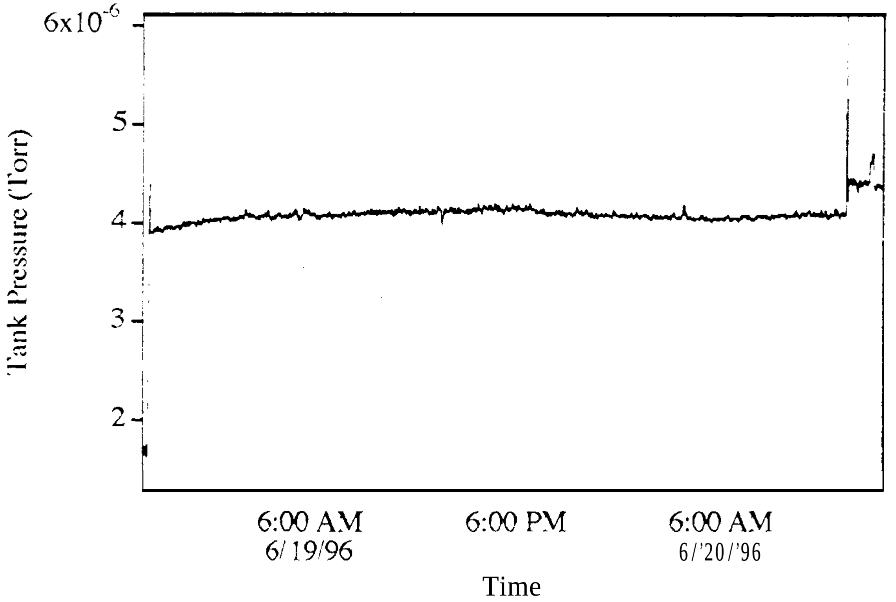


Fig. 18. Total facility pump speed vs. date for 8,000-hour NSTAR test configuration.

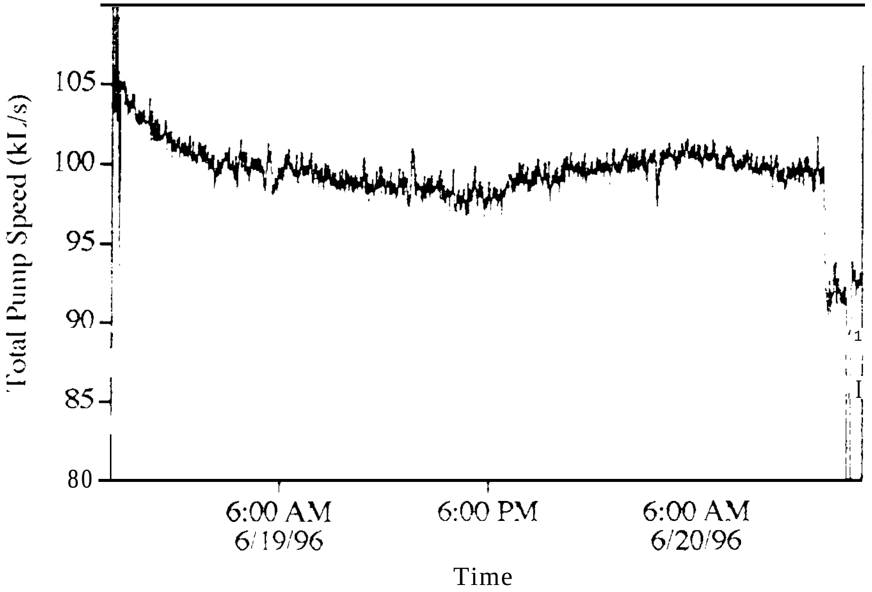


Fig. 17. Tank pressure vs. date for 8,000-hour NSTAR test configuration.