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The to-be-built beam transport line will carry heavy ions from Tandem to AGS for injection. A simple and inexpensive vacuum system for this line is proposed here. This vacuum system will have the combination of linearly distributed non-evaporable getter pumps and small ion pumps, and will achieve ultra high vacuum.

The Vacuum Requirement

The tandem-AGS beam transport line[1] will transport fully stripped light ions (up to S^{+16} with $\beta = 0.12$) to the AGS ring for injection, or alternatively will carry partially stripped heavy ions (i.e., Au^{+30} with $\beta = 0.046$) to the to-be-built AGS booster for acceleration and stripping before further acceleration in the AGS ring.

The requirements for the residual gas density in the vacuum pipes are determined by three major factors: (a) nuclear scattering of the ions by residual gas atoms; (b) charge exchange through collisions between ions and residual gas molecules; and (c) the pressure bump effect in which the beam ionizes residual gas molecules which are then accelerated to the wall by the beam potential and liberate more gas molecules. The emittance growth caused by nuclear scattering is small for heavy ions ($\sigma_{NS} \sim 4 \times 10^{-25}\ A^{2/3}\ \beta^{-2}\ cm^2$ in nitrogen)[2] and should not be a limiting factor. At the projected 10^8-10^{10} ions per pulse, the energy of the ionized residual gas molecules is too small (a few volts) to have significant desorption, and no pressure bump phenomenon is expected.

The vacuum requirement will be dominated by charge exchange between ions and residual gas molecules. Electron loss and capture cross sections can be estimated by the following formulae[2,3] for $\beta > 0.01$, $q < 30$;

$$\sigma_L \sim 9 \times 10^{-19}\ q^{-2/5}\ \beta^{-2}\ \mathrm{cm}^2$$
$$\sigma_C \sim 3 \times 10^{-28}\ q^{5/2}\ \beta^{-7}\ \mathrm{cm}^2$$

The total cross sections ($\sigma_T = \sigma_L + \sigma_C$) for 8 MeV/A S^{+16} and 1 MeV/A Au^{+30} will be 1×10^{-18} cm^2 and 3×10^{-15} cm^2, respectively, which are in fair agreement with the measured ones.[1,4] The beam loss due to charge exchange can be calculated by

$$d\ln D = -n\ \sigma_T\ dx\ .$$

Here 1-D is the fraction of beam loss after distance x, n number of molecules/cm^3. σ_T is constant for the 700-1000 m Tandem-AGS transport line, and

$$1-D = 1-e^{-n\sigma_T x} = 1-e^{-3.5 \times 10^{16}\ P\sigma_T x} \qquad (1)$$

with P the N_2 equivalent pressure in Torr. For fully stripped light ions ($\sigma_T \sim 1 \times 10^{-18}$ cm^2), the beam loss due to charge exchange will be a mere 0.25% even at a pressure of 1×10^{-6} Torr. However, to have a 1% beam loss for 1 MeV/A Au^{+30}, the vacuum has to be $\leq 1 \times 10^{-9}$ Torr. Of course the beam loss will be smaller if hydrogen is the main residual gas, which has a σ_T one decade lower than nitrogen.

To achieve a vacuum of 1×10^{-9} Torr, the thermal outgassing of the vacuum wall has to be minimized, and high effective pumping speed has to be provided. An outgassing rate of $<1 \times 10^{-11}$ Torr$\cdot\ell$/s$\cdot$cm^2 for Al and SS can be obtained by in situ bakeout at 100-150°C. Two different pumping approaches can be taken; (i) using the conventional lumped pump system (sputter ion pump w or w/o titanium sublimator) distributed along the line; and (ii) using linearly distributed nonevaporable getter (NEG) together with small ion pumps.

The average pressure $\bar{P}$ in the beam pipe with the lumped pumps can be calculated by

$$\bar{P} = P_o + \frac{q\pi D}{2C}\left(\frac{CL}{S} + \frac{2}{3}\left(\frac{L}{2}\right)^2\right) . \quad (2)$$

Here P_o is the background pressure of lumped pump; D, diameter of pipe; C, linear conductance of pipe; S, pumping speed of lumped pump; and L, distance between lumped pumps. The results are listed in Table I. When linearly ditributed NEG and small ion pumps are used, the pumping speed is no longer conductance limited and the average pressure of active gases along the line is

$$\bar{P} = P_o + q\pi D/S . \quad (3)$$

Here S is the unit length pumping speed of NEG. The pressure of nongettable gases (<1% in a baked system) can be treated by equation (2). The results are compared with those of the lumped pump system in Table I.

Nonevaporable Getter (NEG)

Any materials which pump gases in a vacuum system without sublimation can be called nonevaporable getter (NEG). Among them, two, with tradenames St101 and St707, have been proven suitable for particle accelerator and ultrahigh vacuum (UHV) application.[5-7] Both were developed by SAES Getters Inc. The St101 is a Zr84-Al 16 alloy and has been widely used in fusion devices (i.e., TFTR) in the last 10 years. The newly developed lower temperature St707 is a Zr70-V24.6-Fe5.4 alloy with a biphasic structure of Zr and Zr(V0.83F0.17)2. The alloys are heat treated in inert atmosphere into powder form (125-150 μm grain size) and deposited on both sides of a constantan support strip 0.2 mm thick and 3 cm wide (√28 mg/cm^2 or 16 gm per linear meter).

NEG pumps gases with two different mechanisms. It forms a solid solution with hydrogen atom, the hydrogen molecules are adsorbed on the surface, dissociated into atomic form, and diffused into the bulk. At low gas load, pumping speed is proportional to rate of diffusion. The equilibrium pressure of H_2 can be predicted by Sievert's law

$$\log P\ (\text{Torr}) = 2 \log Q\ (\text{Torr}\cdot\ell/\text{gm}) + A - B/T\ (^{\circ}\text{K})$$

with A = 5.26, B = 6250 for St101, and A = 4.4, B = 7000 for St707. The equilibrium pressure of H_2 without gas flow will be immeasurably low (i.e., $<10^{-10}$ Torr at 100 Torr•ℓ/m). The adsorption process is also reversible. At high temperature P will increase and can be removed by auxiliary pump (regeneration).

NEG pumps other active gases (CO, O_2, N_2, H_2O) by forming a stable compound on the surface. With a surface roughness factor (ratio of real surface area of NEG powder over the geometry surface area of support strip) of ≤ 100 and assuming one monolayer of CO, up to 1 Torr•ℓ/m gas can be coated on the surface. In reality, the pumping speed will diminish to a useless level at ~ 0.3 monolayer. At this stage, NEG has to be activated at high temperatures which enhance the diffusion of the active gases into the bulk and create a fresh surface for subsequent pumping. The activation at high temperatures (i.e., 400°C x 1 hr for St707, 700°C x 30' for St101) is done by resistive heating of constantan support strip. At 400°C, current of 70A and 500 watts/m power will be required. The St101 requires higher temperatures not only for activation, but also for optimum pumping (≥ 200°C) of active gases. The high current and thermal stress are undesirable, therefore we will only consider St707 NEG for our application.

At room temperature, NEG does not pump inert gases (He, CH_4, Ar hydrocarbon); methane will be cracked into C and H at high temperature and pumped accordingly; however, the speed is <1 ℓ/s•m.

The pumping speeds of St707 NEG for H_2 and CO (the most common residual gases in a baked system) were studied in detail[6] and are shown in Fig. 1. With speeds of >100 ℓ/s·m for H_2 and active gases, and outgassing of $<1 \times 10^{-7}$ Torr·ℓ/s·m, pressure of 10^{-10} Torr can be achieved. At gas loads of ~100 and ~0.4 Torr·ℓ/m for H_2 and CO, respectively (equivalent to ~100 days' pumping), NEG has to be activated to restore the pumping speeds. Lifetime capacity of the active gases is ~50-100 Torr·ℓ/m, which represents hundreds of activation. The NEG will retain half of its pumping speeds even after 40-50 exposures to atmosphere pressure.

<u>NEG for Tandem-AGS beam transport line</u>

To incorporate NEG strips into synchrotron, the size of the vacuum chambers and the magnet pole gap have to be larger, which will drastically increase the cost of magnets. No limitations of these sorts exist in the beam transport line. The maximum vertical and horizontal beam excursions for all the heavy ions from Tandem are about one inch.[1,8] The NEG strips with insulators will have a vertical dimension of ~1" and can lay comfortably inside a pipe of ≥3" diameter.

The St707 NEG strips come from manufacture with a 10 m standard length. Within vacuum sectors of 200 feet in length, six strips will be required. They can be powered in series or in parallel with AC or DC during 400°C activation with a maximum load of ~500 watts/m (70 amps). The residual gas composition in a modestly baked (<150°C) vacuum chamber is ~70% H_2, ~30% active gases (CO, CO_2, H_2O) and ~1% inert gases (CH_4, He, Ar). The inert gases not pumped by NEG will be removed by small sputter ion pumps (i.e., 20 ℓ/s) stationed every 100-200 feet. The average pressures (N_2 equivalent) based on NEG and small sputter ion pumps are given in Table I in comparison with those pumped by large sputter ion pumps alone.

Tests were done on a prototype vacuum pipe for transport line. A 2.7 m long NEG strip was installed in a 3 m long 8.8 cm I.D. stainless steel pipe with a 20 ℓ/s sputter ion pump mounted at one end and a BA gauge at the other end. In these test runs, the NEG strip was also used as an internal heater for in situ bakeout. No thermal insulation and external heaters were wrapped on the pipe. The pipe was roughed down by turbomolecular pump and baked by heating the NEG strip to $\sim$300°C with 50 A current ($\sim$250 w/m). Little activation of NEG will occur at 300°C, which preserves the capacity of getter for UHV. Within 2 hrs, temperatures of $\sim$100°C was reached on the pipe. After bakeout at $\sim$100°C for 6 hours, the NEG was activated at 400°C (70 A, 500 watts/m) for 30 min. At the end of activation, the 20 ℓ/s SIP was turned on and the turbo was valved off. Pressure of 10^{-10} Torr was reached in one day. The pump down curve is shown in Fig 2. The effect of inert gases was also studied by turning off the ion pump for 3 days; pressure of 10^{-8} Torr was maintained. In the beam transport line, the inert gases will be removed by the next ion pump and pressure rise due to one ion pump failure will be negligible (Table I).

A 200 ft. vacuum system simulating the vacuum sector of beam transport line is under design and construction. The isolation of NEG strip, the thermal expansion and other operational procedures will be studied in detail by this test line.

Conclusion

A vacuum system using a linearly distributed NEG/ion pump combination will offer simplicity in operation, rapid pump down (10^{-10} Torr in one day), better average pressure and low cost in construction, and should be applied to the vacuum systems of Tandem-AGS beam transport line and other similar systems (i.e., U-line).

Table I. Comparison of Average Pressure and Cost of Pumps, Using Sputter Ion Pump With or Without NEG.

	ℓ(ft)[a]	d(inch)[b]	$\bar{P}_{H_2}$[c]	$\bar{P}_{CO,CO_2,H_2O}$[c]	$\bar{P}_{CH_4,Ar}$[c]	$\bar{P}_{total}$	Cost/200'[d]
NEG	50	3.5	6.5-11	8.3-11	1.6-10	3-10	7.2K
SIP(20ℓ/s)	100	3.5	6.5-11	8.3-11	4.5-10	6-10	5.6K
	200	3.5	6.5-11	8.3-11	1.4-9	1.5-9	4.8K
	50	6	1.1-10	1.4-10	3.9-10	6.4-10	7.2K
	100	6	1.1-10	1.4-10	8.6-10	1.1-9	5.6K
	200	6	1.1-10	1.4-10	1-9	1.3-9	4.8K
SIP (200ℓ/s)	50	3.5	1.5-9	2.2-9	7-11	3.8-9	20K
	100	3.5	5.4-9	8-9	2.7-10	1.4-8	10K
	50	6	1-9	1.1-9	4-11	2.2-9	20K
	100	6	2.8-9	3.5-9	1.2-10	6.4-9	10K

[a]Distance between sputter ion pumps.
[b]Inner diameter of vacuum pipes.
[c]Partial pressures based on outgassing rate of 1 x 10^{-11} Torr•ℓ/s•cm^2 with 70% H_2, 30% active gases and 1% inert gases.
[d]Does not include power supply.

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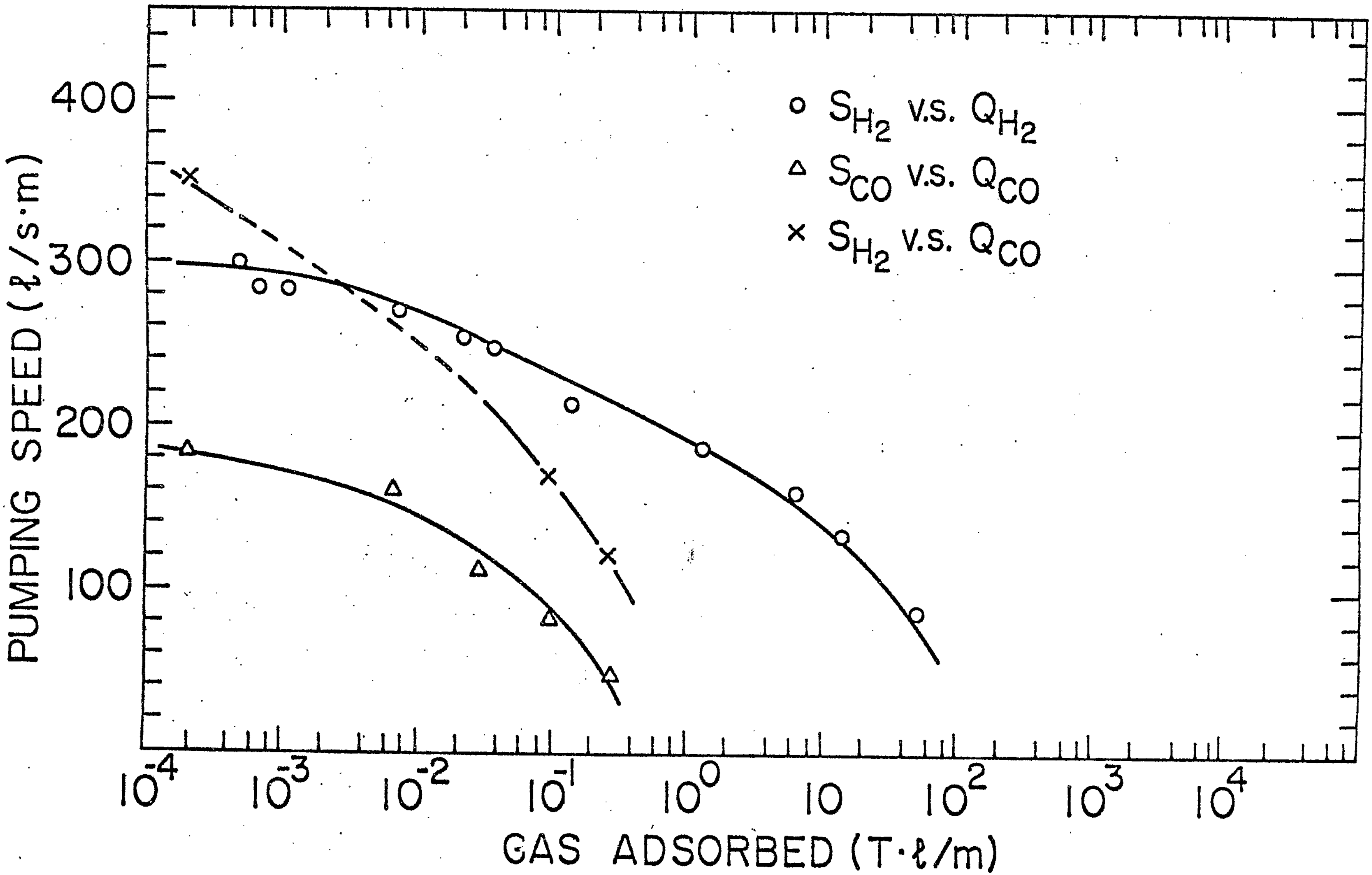

Figure 1. Pumping speeds of St707 getter for H_2 and CO versus gas loads.

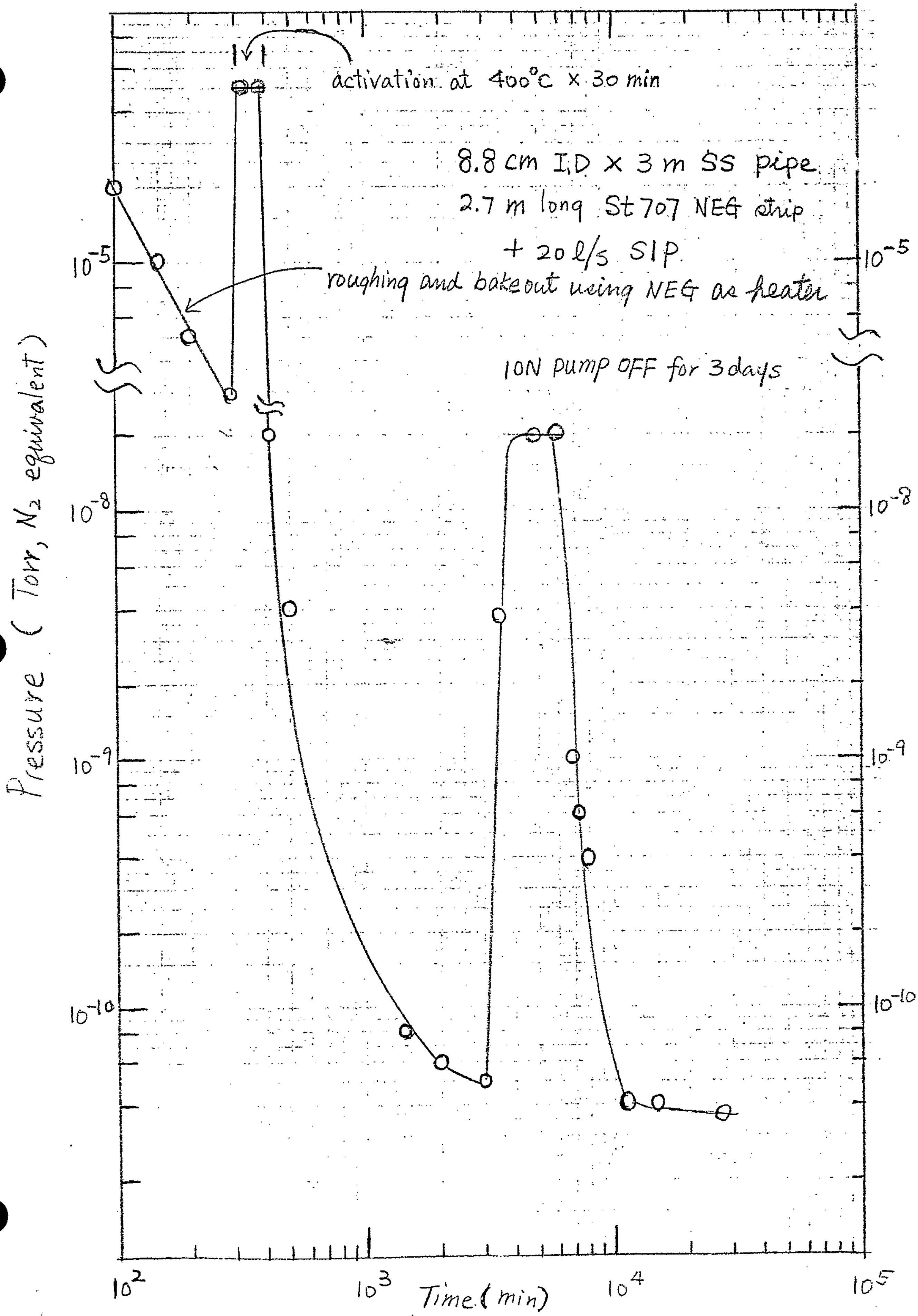

Fig. 2 Pump down curve of prototype vacuum pipe