Fermilab

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Mechanical Department Engineering Note

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Title: LBNE Cryostat Vacuum Pump Sizing

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Abstract Summary: The following note determines the size of the vacuum pump that will be necessary for the cryostat system as part of the Long Baseline Neutrino Experiment (LBNE).

Applicable Codes:

The cryostat that the vacuum pump is being used to evacuate is 16m x 16m x 70m. This volume is surrounded on all sides by rigid polyurethane foam insulation that is 1 meter thick, which has a density of 125 kg/m^3 (Figure 1). The volume of insulating foam from which the vacuum pump is to remove the air is:

$$(18\text{m} \times 18\text{m} \times 72\text{ m}) - (16\text{m} \times 16\text{m} \times 70\text{m}) = 5408\text{ m}^3.$$

The pumping speed to be determined is the speed necessary to remove enough air to lower the pressure to either 200mbar (20,000Pa) or 20mbar (2,000 Pa) in the time span of 24 hours.

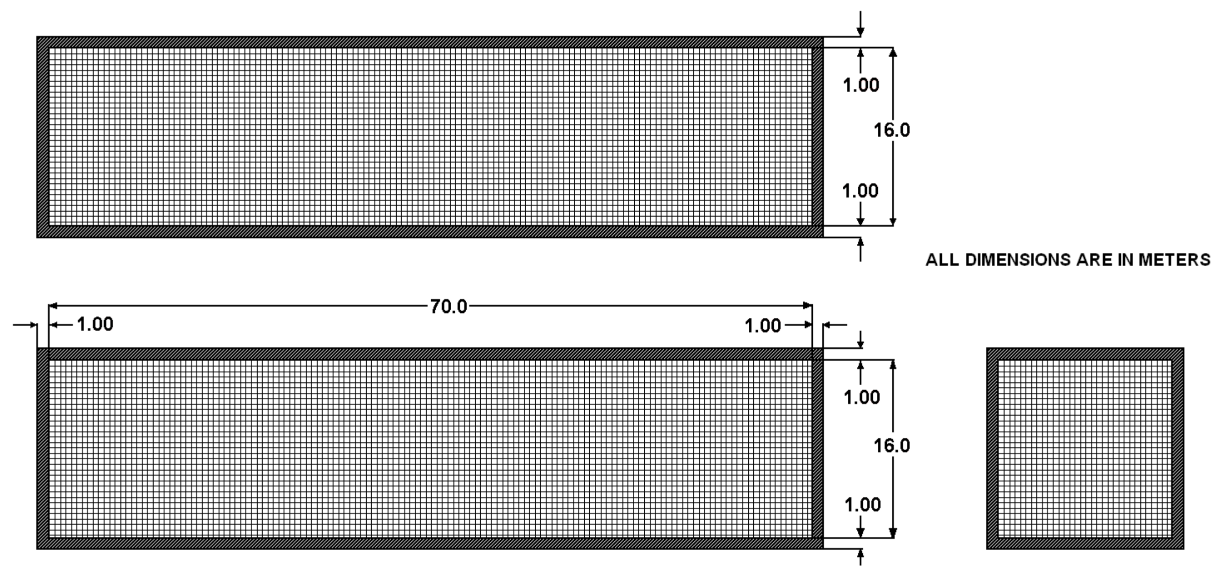

Figure 1. Cryostat and Insulation Dimensions

A portion of the total volume of gas in the cryostat system that is to be pumped is the air that fills the corrugations of the primary membrane (Figure 2). An estimate of the total volume of gas within the system will be necessary to determine this volume. Based on some conceptual designs and models of similar tanks, the stainless steel primary membrane is laid out in such a manner that the corrugations, with a pitch of 340mm, run both vertically and horizontally, which creates a gridded layout of the corrugations. In order to estimate the volume, the cross-sectional area of the corrugation is calculated by simplifying the shape of the corrugations to that of an isosceles triangle. There are two different sizes of corrugation. The smaller corrugation has dimensions of 53 mm in width and a height of 36 mm. The cross-sectional area is then 0.00191m^2. The larger corrugation has a base of 77 mm and a height of 54.5 mm. This yields an area of 0.00420 m^2. With a pitch of 340 mm, there would be a total of 47 corrugations on the sides of the cryostat that have a length of 16 m and 205 corrugations on the sides of the cryostat that are 70 m in length. Based on this information, the total length of the larger corrugation would be 11,400 m while the total length of the smaller corrugation would be 11,300 m. This would yield a total volume of:

$$(11400m) * (0.00420\ m^2) + (11300m) * (0.00191m^2) = 69.5\ m^3$$

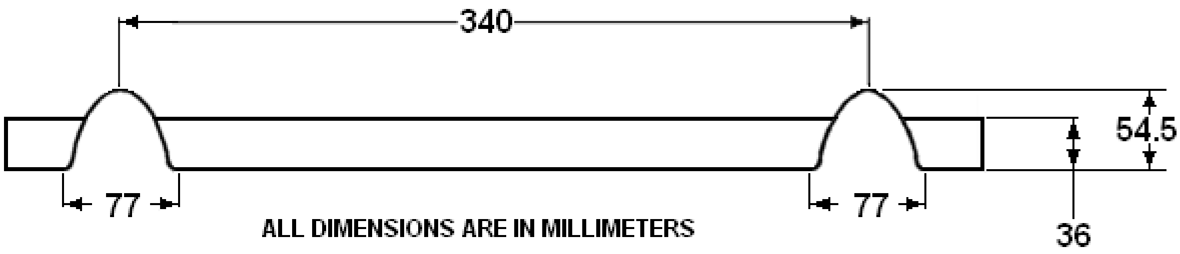

Figure 2. Primary Membrane Corrugation Dimensions

Another addition to the amount of gas to be pumped from the system is the amount of gas present in the insulating foam. It is assumed that, due to the nature of the foam (rigid, closed-cell), the amount of gas present in the insulation that is capable of being pumped will be minimal in comparison to the total volume of the foam.

<u>Pumping Speed Required</u>

Based on information in *Cryogenic Systems* (Barron, p. 548), one method of determining the necessary pumping speed is by using the equation:

$$t_p = \frac{2.303 * F_{S*} V_{TOTAL}}{S_S} * \log_{10}\left(\frac{p_1}{p_2}\right)$$

where t_p is the required pumping time, F_S is the system allowance factor for pump-down, V_{TOTAL} is the volume of the vacuum system, and p_1 and p_2 are the initial and final pressures, respectively. The system allowance factor is based on the pressure range of the system. For this vacuum system, the system allowance factor for a final pressure of 20,000Pa is 1.0; for a final pressure of 2000 Pa, the system allowance factor is 1.25.

The equation was rearranged to yield:

$$S_S = \frac{2.303 * F_S * V_{TOTAL}}{t_p} * \log_{10}\left(\frac{p_1}{p_2}\right)$$

The solutions are

$$S_{S,20,000Pa} = \frac{2.303 * 1.0 * (5408m^3 + 69.5m^3)}{24\ hrs} * \log_{10}\left(\frac{101325\ Pa}{20{,}000Pa}\right)$$

$$S_{S,20,000Pa} = 463\ \frac{m^3}{hr}$$

$$S_{S,2000\ Pa} = \frac{2.303 * 1.25 * (5408m^3 + 69.5m^3)}{24\ hrs} * \log_{10}\left(\frac{101325Pa}{2{,}000Pa}\right)$$

$$S_{S,2000Pa} = 1120\frac{m^3}{hr}$$

After searching through the catalogs of several vacuum roughing pump manufacturers, it was determined that only one pump would be necessary for either of the two desired final pressures, since several companies sell vacuum pumps capable of handling the gas loads that would be present based on the calculations above.

In order to determine the line size necessary for the vacuum system, an online table of values was used to determine the conductance and diameter of the pipes needed (http://www.lesker.com/newweb/technical_info/conductance_calc.cfm). The values in the table were recorded in a spreadsheet and then plotted and fitted with trend-lines for each of the series. The trend-lines were then used to interpolate values for the line pipe size based on the pumping speeds that were just determined. For a pressure of 20,000 Pa, the maximum line size based on the table is about 11.8cm. For a pressure of 2,000 Pa, the maximum line size is about 20.6cm.

Mass Flow Rate

The next part of the analysis of the cryostat vacuum pumping system was to determine the mass flow rate, $\dot{m}$, that is necessary to reduce the pressure within the cryostat by 0.2 mbar/hr (20Pa/hr). In order to determine the mass flow rate, the Ideal Gas law was used to determine the change in the number of moles in the system that results from a given pressure change.

Ideal Gas Law:

$$PV = nRT$$

which is modified to reflect a pressure/molar amount change, in which the equation becomes:

$$\Delta PV = \Delta nRT$$

In this equation, ΔP is the pressure change within the system, V is the system volume, Δn is the change in the number of moles of air present in the system, R is the universal gas constant, and T is the temperature of the system. After isolating the change in the number of moles on one side of the equation, we are left with:

$$\Delta n = \frac{\Delta PV}{RT}$$

In order to determine the solution, several assumptions are made. These assumptions are:
-Air is the only gas that is to be evacuated (this yields a constant, known molecular mass over the entire pumping period).
-The amount of air that can be evacuated is based on the amount of air that fills the stainless steel primary membrane corrugations and the amount of air that can be evacuated from the polyurethane foam. Therefore, the total volume of air to be evacuated is the sum of the volume of the corrugation and less than 1% of the total volume of the insulation.

$$\Delta n = \frac{\left(\frac{-20Pa}{hr}\right) * [(0.01) * (5408m^3) + (69.5m^3)]}{\left(8.3145\frac{kJ}{kmol * K}\right) * (293K)}$$

$$\Delta n = \frac{\left[\left(-20\frac{\cancel{Pa}}{hr}\right) * \left(\frac{1N/_{m^2}}{\cancel{Pa}}\right)\right] * (124m^3)}{\left[\left(8.3145\frac{\cancel{kJ}}{kmol * \cancel{K}}\right) * \left(\frac{1000N * m}{\cancel{kJ}}\right)\right] * (293\cancel{K})}$$

$$\Delta n = \frac{-2.47 * 10^3 \left(\frac{\cancel{N} * \cancel{m^3}}{hr * \cancel{m^2}}\right)}{2.44 * 10^6 \left(\frac{\cancel{N} * \cancel{m}}{kmol}\right)}$$

$$\Delta n = -1.01 * 10^{-3}\frac{1/_{hr}}{1/_{kmol}} = 1.01 * 10^{-3}\frac{kmol}{hr}\ evacuated\ from\ cryostat$$

The molar mass for air, M, is 28.97 kg/kmol.

$$\dot{m} = \Delta n * M$$

$$\dot{m} = \left(1.01 * 10^{-3}\frac{kmol}{hr}\right) * \left(28.97\frac{kg}{kmol}\right)$$

$$\dot{m} = 0.0294\frac{kg}{hr}$$

<u>Permeability of the insulation</u>

Another factor that needs to be accounted for is the permeability of the polyurethane foam insulation. There are essentially two different ways of looking at the calculation of vapor/air transmission through a material: based on the material's permeability or its permeance. Permeability is the ability for air or vapor to be transmitted through a material, which is strictly a property of the material. Permeance is basically the permeability of the material divided by its thickness. There are two different formulas that relate permeability or permeance to the pressure difference across a material and the rate of vapor/air transmission through the material. The first formula, taken from the *2005 ASHRAE Handbook-Fundamentals* (p.14-30) is:

$$W_v" = -\mu * \frac{dP}{dx}$$

where W_V" is the mass of vapor diffusing through a unit area per unit time, µ is the vapor permeability and dP/dx is the pressure gradient.

The other formula, taken from the *Handbook of tables for Applied Engineering Science, 2nd Ed.* (p. 547) is

$$W = nA\Delta P$$

where W is the rate of vapor transmission, n is the permeability, A is the area through which the vapor/air is transmitted, and ΔP is the pressure difference. For each of these two equations, the rate of transmission is linearly related to the change in pressure across the material.

The calculation of the pressure change is based on pumping the air through the foam insulation from the corrugations of the stainless steel primary membrane, which means that the thickness of foam is constant at 1 meter throughout the entire system. As a means of simplifying the calculation, the area through which the air is being pumped is taken to be 1 m^2. Due to the fact that the corrugations from which the air would be pumped are arranged in a gridded fashion, they essentially act as a crude piping system, allowing the air to be removed evenly throughout the entire system. Based on information in the two previously mentioned sources, the permeability of rigid polyurethane foam is 1.0 perms, which is equivalent to 57.2×10^{-12} kg/s*N.

The pressure at the interface between the primary membrane and the insulation is held at zero, due to the fact that the pump will be continuously removing the air from this area, once the corrugations of the primary membrane have been completely evacuated. The insulation was broken into sections with a thickness of 1 cm each. Using the latter of the two formulas listed above, the pressure values at each centimeter of thickness were calculated using a spreadsheet. The overall pressure profile can be seen in Fig. 3 and the pressure at thickness, T = 1m, is pictured in Fig. 4.

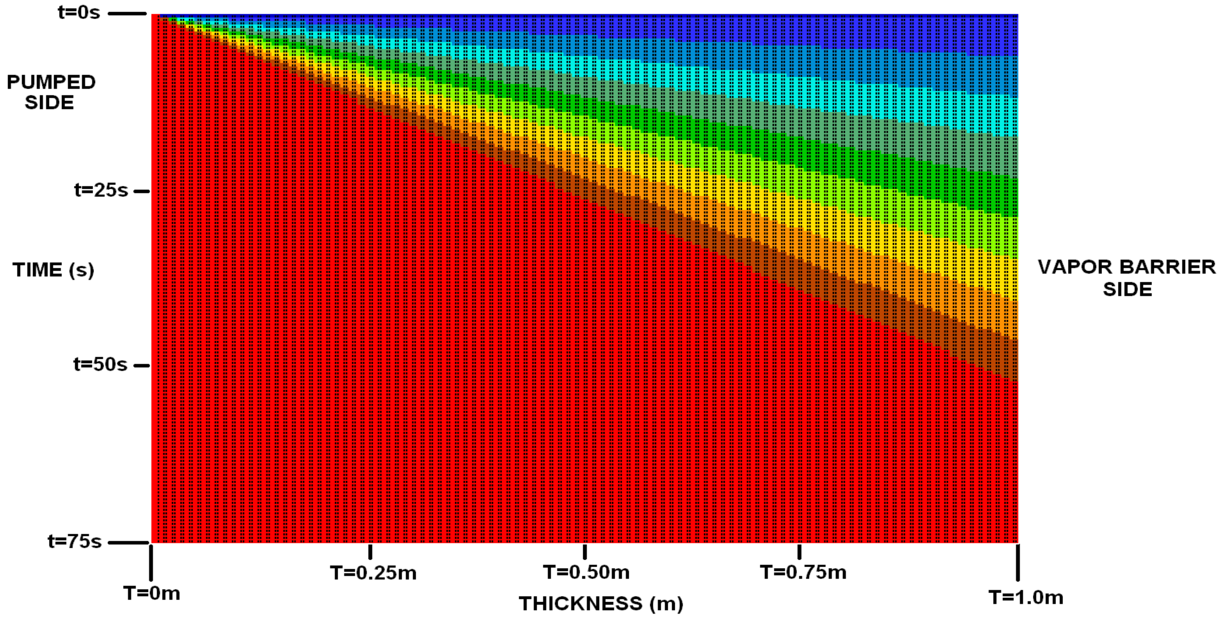

Figure 3: Pressure Profile for Entire Thickness

In Fig. 3, each of the color bands represents 10% of the total pressure, or about 10100 Pa. In this figure, the thickness of the insulation runs horizontally across the figure from a thickness of T=0m on the left side to T = 1m on the right side. The vertical axis of the figure represents time, starting at t = 0s at the top and running down to t = 75s at the bottom. The color bands are defined below in Table 1.

Table 1: Pressure Color Bands in Fig. 3

P =101325 Pa	101325
90%*101325Pa < P < 100%*101325Pa	91200 Pa – 101325 Pa
80%*101325Pa < P < 90%*101325Pa	81100 Pa – 91200 Pa
70%*101325Pa < P < 80%*101325Pa	70900 Pa – 81100 Pa
60%*101325Pa < P < 70%*101325Pa	60800 Pa – 70900 Pa
50%*101325Pa < P < 60%*101325Pa	50700 Pa – 60800 Pa
40%*101325Pa < P < 50%*101325Pa	40500 Pa – 50700 Pa
30%*101325Pa < P < 40%*101325Pa	30400 Pa – 40500 Pa
20%*101325Pa < P < 30%*101325Pa	20300 Pa – 30400 Pa
10%*101325Pa < P < 20%*101325Pa	10100 Pa – 20300 Pa
0%*101325Pa </= P < 10%*101325Pa	0 Pa – 10100 Pa

*Note: the color band for $P=P_{atm}$ (101325 Pa) is a very thin band that may be difficult to see in the figure. It appears only across the top of the figure when time, t=0, due to the fact that once pumping of the insulation commences, air will be continuously removed from the insulation.

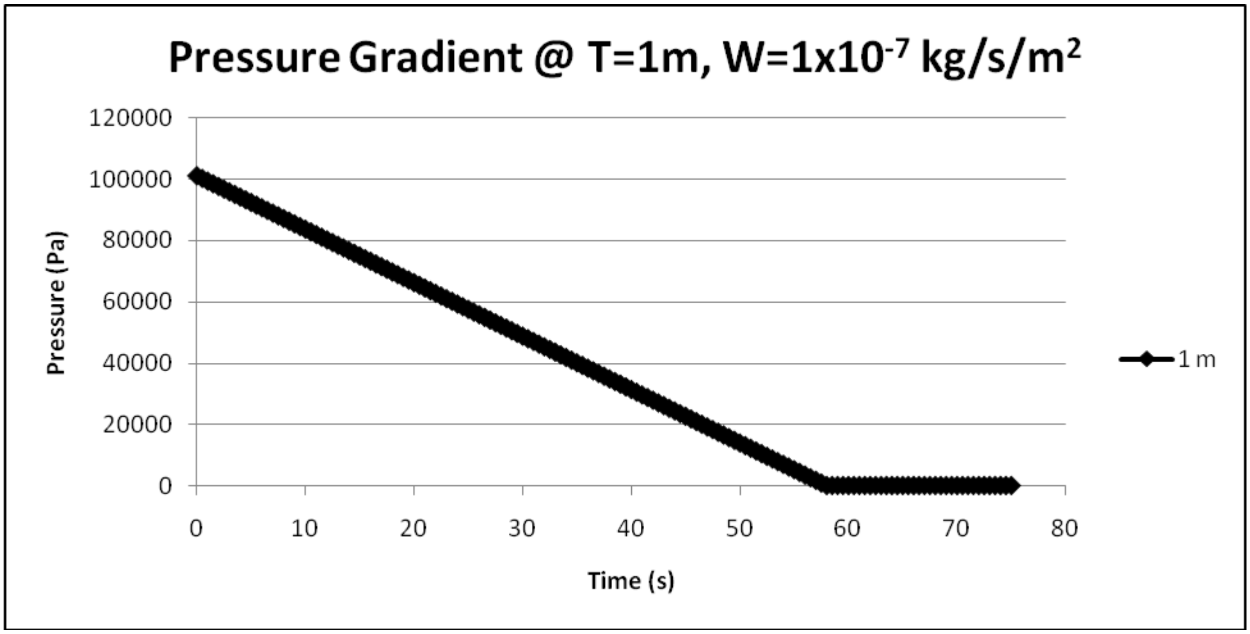

Figure 4: Pressure Profile at T = 1 m

For different mass flow rates and different points throughout the thickness of the insulation, the time to reach a pressure of 0 Pa will vary, but the same general linear profile will remain. The pumping speed used in this calculation is much smaller than the mass flow rates in earlier sections of this note. It was used in order to show an expanded version of how the pump-down of the insulation would occur without having to use a time period that used fractions of a second to show the entire pump-down process.