

# LBNE Tank Purge Pressure Drop Calculation

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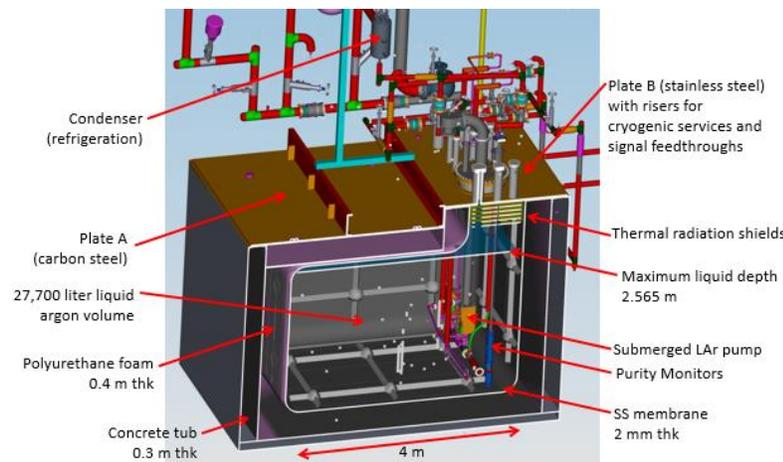


## Abstract

During the purge of the 1st run of the 35T prototype tank for the LBNE, the flow out of the nineteen risers was unevenly distributed and it was observed that risers close to the vent had a greater flow rate than those far from it. Although this run was successful, the 2nd run will have more sources of contamination and therefore it is desired to ensure all risers are effectively purged. In order to achieve this level of efficiency, an orifice will be installed at the outlet of each riser to provide a tuned resistance which when matched with the tubing resistance results in the desired flow out of each orifice. This paper presents the pressure drop calculation across the whole setup with air and argon as tank gases as well as a detailed analysis of how the orifices were sized.

## Introduction

The Long-Baseline Neutrino Experiment (LBNE) seeks to build a very large liquid argon detector using membrane cryostat technology with passive foam insulation to do neutrino physics. This 34kTon detector is planned for installation at 4850 ft. below the surface (to shield it from cosmic ray) at the Sanford Underground Research Facility (SURF) in Lead, SD. This massive construction would be carried out in a phased approach with the first phase of a volume of  $2 \times 7,134 \text{ m}^3$  membrane cryostat followed by a second with  $2 \times \sim 15,000 \text{ m}^3$  volume and it is expected to start in 2020 while operations and experiment would commence around 2024. The target material in this time projection chamber is liquified argon and it is required that it contains less than **200 parts per trillion** (ppt) oxygen equivalent contamination to ensure the success of the technology. To ensure that membrane technology is suitable for this experiment a 35T prototype has been built and operated, which is the first and only membrane cryostat for scientific purpose available to scientists. It should be noted that the first run of this prototype achieved an electron lifetime of 2.5-3 ms which is well above the desired 1.4 ms threshold. However, for the second run a TPC will be installed as well as other cryogenic upgrades which will increase the sources of contamination in the system. Therefore, there is a need for a more rigorous analysis to ensure the desired purge in the system is effective.



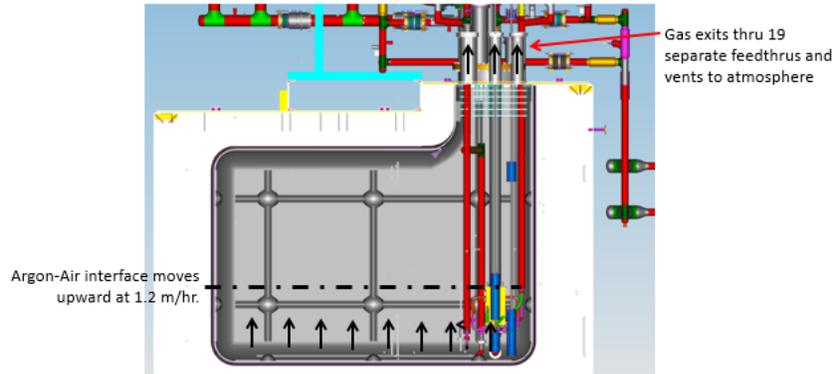
**Figure 1: Detailed Overview of the 35T Prototype**

As shown above, the 35T prototype has a size of 4 m x 2.7 m<sup>2</sup> and a volume of 27,700 liters. All 19 risers used in the purge process sit on a stainless steel plate as they extend from the liquid compartment to an outside vent. Insulation with polyurethane foam and thermal radiation shield both help to minimize all forms of heat transfer within the vessel.

## Argon Piston Purge

The piston method is used for the purge of air out of the tank through the risers using argon gas. This method involves argon gas at room temperature being injected into the tank via 25 nozzles aimed downward just above the tank floor to prevent turbulent mixing of the argon and air. With a flow rate of 2.43 hours per volume change, argon gas is pushing the less dense air out and both

gases exiting through all 19 risers, through the vent and then to the atmosphere. Note that the conventional vacuum pump method for evacuation was not feasible for this process because the tank is not designed to withstand the external pressure forces that occur during evacuation. The cost and complexity of a very large evacuable tank and associated evacuation system is prohibitive such that the purge method was developed. The purge is then followed by a room temperature gas filtration phase which removes outgassing in a manner similar to an extended evacuation.



**Figure 2: Argon Piston Purge Method**

### **LBNE 35T 1st and 2nd Run**

The first run of the LBNE 35T tank was carried out with an empty tank and it validated the piston purge method of air removal. It was observed from this run that the risers close to the vent had a greater flow rate than those farther away as expected because the increase in length increases the friction of the flow thereby reducing flow rate.

For the second run, the tank will contain TPCs, wiring and other cryogenic upgrades which will lead to an increase in the sources of contamination in the system, especially on risers where this wiring will pass through. To account for this, an orifice will be installed on all risers to dictate the flow from these risers by affecting the flow resistances due to the different tubing lengths.

### **Pressure drop during Air flow**

Since both air and argon pass through all risers a pressure drop calculation across the system using both air and argon as tank gases is necessary. Initially air exits the risers and by the end of the first volume exchange the riser flow has transitioned to argon. For all calculations in this paper equations, tables and charts were obtained from crane 410, which is the “bible” of basic engineering pressure drop calculations.

During the purge of air out of the LBNE 35 T tank, tank gas is withdrawn through nineteen (19) vertical risers of varying internal diameters. The purge flow rate of argon gas is given as 7.4 SCFM (Standard Cubic Feet per Minute). This overall flow rate is the summation of the individual flow rates of all risers. Therefore in order to estimate the flow rate due to each riser, the fraction of the total flow rate due to each riser is determined based on the ratio of its cross-sectional area to that of the total cross-sectional area. Note that these risers are manifolded together with stainless steel

tubing with outer diameter of 0.5” and an inner diameter of 0.43”. An orifice will be installed where the stainless steel tubing connects to each riser to obtain the desired flow rate through each riser.

## Methods

With a slight modification of the Darcy’s formula, the equation for the pressure drop across a piping network is given as;

$$\Delta P = 3.62 \frac{K\rho q^2}{d^4} \quad (1)$$

Where,  $\Delta P$  is the change in pressure in Psi

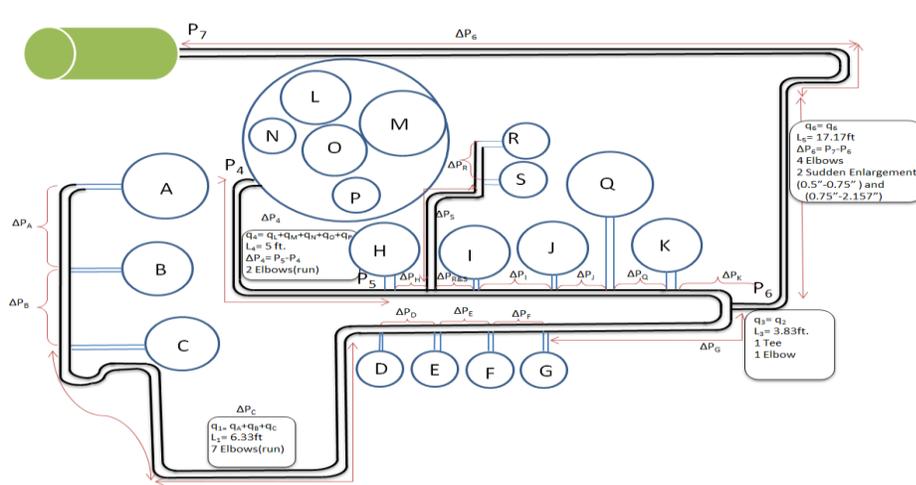
$K$  is the equivalent resistance coefficient

$P$  is the density of the fluid

$q$  is the flow rate

$d$  is the internal diameter of the pipe.

It is evident from the above equation that the internal diameter of the pipe has the greatest effect on the pressure drop as it is raised to the fourth power, followed by the flow rate which is raised to the power of 2, while the resistance coefficient and density of the tank gas vary linearly with respect to the pressure drop.



**Figure 3: Schematic showing flow path and pressure drop across all risers to large vent.**

Based on the schematic above, the resistance coefficient and the flow rates were obtained for each section in the flow network.

### The Flow rate, q

The flow per riser is calculated by multiplying the obtained ratio of the riser’s cross-sectional area to the total cross-sectional area by 7.4 SCFM (total flow rate). The flow rate obtained in SCFM is

then converted to standard units of cubic feet per second. Since the flow rate follows a converging pattern, the actual flow rate at each section of the network is obtained by summing all the flow rates that contribute to the flow at that point based on the flow schematic. For instance, the flow at A is the flow rate due riser A, while the flow at B is the flow rate due to risers A and B and the flow rate at F is a summation of all the flows from A to F. Note that the flow rate at P<sub>4</sub> is the summation of all the flow rates of all 5 risers involved in that flow path and the flow rate at P<sub>6</sub> is due to all 19 risers, as the two flow paths meet in that region. Note that the flow rates are heavily dependent on the internal diameter of the risers which are in three sizes (3.87", 5.87" and 7.87") across network.

### Resistance Coefficient, K

For this analysis, a simple calculation was first carried out using only the flow resistance due to a straight pipe. However, the results obtained showed that the pressure drops was not in sync with what happens in reality as there was a significant difference between the two paths before they combine. Also regions of multiple modification such as the flow from H to K showed flaws in the assumption that other resistance were negligible. Therefore, a more detailed analysis was needed to obtain the desired pressure drops across the network. This is necessary and a big part of engineering as engineers do not want to put more effort than necessary in any task if a simpler analysis is sufficient.

Four different flow resistances were included in this analysis and they are;

#### I. Pressure loss due to a straight pipe

The nature of the flow in the pipe at different sessions is determined by obtaining the Reynolds number of the flow at the desired location. The Reynolds number is the ratio of inertia and viscous forces. It should be noted that a Reynolds number less than 2000 indicates that the flow is laminar while a Reynolds number higher than 4000 shows that the flow in the pipe is turbulent.

The general equation for the Reynolds number is obtained from equation 3-3 in crane 410 and it is given as;

$$Re = \frac{22700 \times q \times \rho}{d \times \mu} \quad (2)$$

Where,  $q$  is the flow rate in cubic feet per second

$\rho$  is the density of the fluid in pounds per cubic feet,

$d$  is the internal diameter of the tubing in inches and

$\mu$  is the dynamic viscosity of the fluid in centipoise.

From the Reynolds number obtained, two types of flows occur within the network. Two regions of laminar flow at R and S, while the other regions are fully developed turbulent flow. The friction factor  $f$ , which depends greatly on the Reynolds number is estimated for each region to determine

the flow characteristics (mainly pressure drops) in such region. For laminar flow regions, the friction factor is given as;

$$f = \frac{64}{Re} \quad (3)$$

Note that for laminar flow  $f$  is only dependent on Reynolds number.

For the turbulent flow regions, the friction factor  $f$  depends on Reynolds number as well as the pipe relative roughness ( $\epsilon/D$ ). Since this calculation involves commercial steel pipes, the Moody chart on page A-25 in crane 410 is used to directly estimate the friction factor at each location using the Reynolds number obtained earlier and the pipe's internal diameter.

Pressure losses in piping systems result from a number of system characteristics, one of which is the resistance coefficient  $K_B$  of the piping system due to a straight pipe, and is given as;

$$K_B = \frac{fL}{D} \quad (3)$$

Where,  $f$  is the friction factor

$L$  is the length of the straight pipe in feet

$D$  is the internal diameter of the pipe in feet.

## II. Pressure loss due to elbows.

Elbows are regions of bends that causes a change in the direction of the flow. Due to the presence of standard elbows in the different parts of the system, another resistance coefficient  $K_{Elbow}$  due to 90° bends at several points of the network is accounted for in our analysis, and is given as;

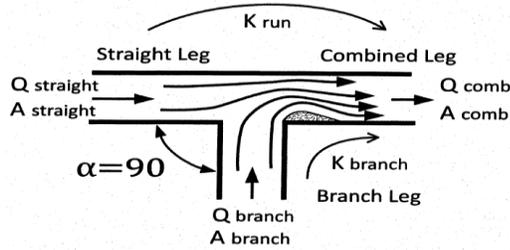
$$K_{Elbow} = 30f_T \quad (4)$$

Where  $f_T$  is the friction factor based on the nominal size of the pipe (i.e. pipe ID), and it is obtained from page A-26 in crane 410 which shows the pipe friction data for clean commercial steel pipe with flow in zones of complete turbulence.

## III. Pressure loss due to flow through tees

Tees are employed in flow system to either combine the flow of two streams or the divide a single stream flow. A converging flow analysis is employed as the tees in this network help to combine flows of two streams. This flow resistance is in two categories, the flow resistance due to the flow through run,  $K_{Run}$  and the flow resistance due to the branch,  $K_{Branch}$ . Figure 2-14 and 2-15 on the 2009 edition of crane 410 shows the resistance coefficients for the branch and run paths for tees with all leg diameters equal respectively. Both  $K_{Run}$  and  $K_{Branch}$  can be obtained directly once the flow ratio is known.

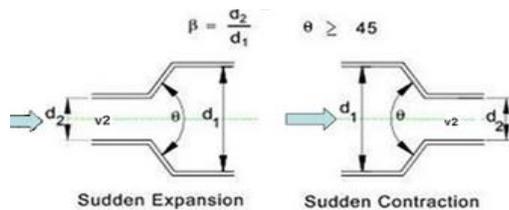
$$Flow\ Ratio = \frac{Q_{Branch}}{Q_{Combined}} \quad (5)$$



**Figure 4: Converging Flow in a tee.**

IV. Pressure loss due to sudden changes in pipe size

Regions of sudden and gradual contraction and enlargement also exist across the network and they contribute to the pressure changes in those regions where they are present. The first occurrence is the regions between K and where the two flows combine and between G and where the two flows combine. Sudden contractions occur in these regions due to a ceramic isolator on each path just before they combine as the 0.43" steel tubing shrinks down to 0.32" and afterwards a sudden enlargement from 0.32" back to 0.43". The second region of sudden enlargement occurs between the region where these two flow paths combine and P<sub>6</sub> where the 0.43" tubing is attached to a 0.652" tubing. The last region connects this 0.652" tubing to the vent pipe whose internal diameter is 2.157".



**Figure 5: Shows regions of sudden changes in pipe size**

The angle of divergence or convergence in all these regions is approximately 180° and the coefficient of resistance to account for the pressure drop due to this modifications is given below;

For sudden and gradual contraction

$$K_{contract} = 0.5 \times (1 - \beta^2)^2 \times \sqrt{\sin \frac{\theta}{2}} \quad (6)$$

For sudden and gradual enlargement

$$K_{enlarge} = (1 - \beta^2)^2 \quad (7)$$

Where  $\beta$  is the ratio of the smaller internal diameter to the larger internal diameter of the two pipes, and  $\theta$  is the angle of divergence or convergence.

Finally, an equivalent resistance coefficient is then obtained which is the summation of all the resistance coefficients of the different components at each point within the network.

## Result

Comparing both flow paths at P<sub>6</sub>, there was a slight difference in pressure drop. This is contrary to what happens in reality because flows arriving at a single point tend to adjust to achieve equilibrium in pressure changes. In order to correct for this difference, the size of risers A, B and E were increased in order to increase the flow rate from these risers as these risers contain more contaminants, while risers M and O were reduced to decrease the flow rate from these risers. Note that although the riser size is adjusted for the flow rate calculations, in reality the riser tube diameters do not change. As shown in the tables below, these modifications in riser size help ensure that the pressure at P<sub>6</sub> is the same when approaching from both paths of the network and that the whole flow network correctly represents what happens in reality. A similar calculation is done using argon gas as the tank gas since both gases pass through all the risers during the purge, air first and then followed by argon gas. The only major change is the density of the gas and all other steps and analysis remain the same as in the case with air. Tables below show calculations for both air and argon gas respectively.

Riser Label	Actual flow rate (q)/ft <sup>3</sup> /s	Re#	friction factor-f	K <sub>g</sub>	K <sub>branch</sub>	K <sub>run</sub>	K <sub>elbow</sub>	K <sub>eq</sub>	ΔP <sub>r</sub> (Psi)	Initial Pressure (Psi)
	nominal based on area, summing risers	for half inch pipe	for half inch pipe						nominal	with 0.55 initial pressure
A	0.01596281	3182.368566	0.048	1.33966				0.81	2.14966	0.004343397
B	0.025864023	5156.288308	0.044	1.228021	0.15	0.4			1.778021	0.009431272
C	0.03288664	6556.327319	0.041	7.243371	-0.15	0.35	5.67		13.11337	0.112459088
D	0.035939063	7164.862744	0.04	1.149874	-0.5	0.15			0.799874	0.008192124
E	0.040713406	8116.682375	0.0395	1.135501	-0.55	0.13			0.715501	0.009404296
F	0.043765829	8725.217799	0.039	1.121128	-0.6	0.1			0.621128	0.009433922
G	0.046818252	9333.753223	0.0385	4.115406	-0.6	0.09	0.81	4.825427	0.083870133	0.396735901
L										P6 from G = 0.312865768
M										
N										
O										
P										
From tank to H	0.029696483	5920.333059	0.0395	5.512141			1.62	7.132141	0.049873646	0.55
H	0.036719101	7320.37207	0.038	0.54513	-0.2	0.25		0.59513	0.006362634	0.500126354
R	0.003052423	608.5354243	0.105170541	2.935265			0.81	3.745265	0.000276703	0.55
S	0.006104846	1217.070849	0.052585271	2.935265	0.4	0.52	1.62	5.475265	0.001618064	0.549723297
tee of R&S	0.042823947	8537.442918	0.0375	0.537957	-0.45	0.17		0.257957	0.003751128	0.49376372
I	0.049846565	9937.481929	0.0375	1.078007	-0.45	0.17		0.798007	0.015722387	0.490012592
J	0.056869182	11337.52094	0.037	0.530784	-0.5	0.15		0.180784	0.004636132	0.474290205
Q	0.069492464	13854.11635	0.036	0.516439	-0.2	0.25		0.566439	0.021690499	0.469654073
K	0.076515081	15254.15536	0.0355	1.813145	-0.55	0.13	0.81	2.613166	0.121311604	0.447963574
from p6 to Vent	0.123333333	16215.95198	0.035	11.06722	-0.9		3	14.31211	0.326579724	0.32665197
										P6 from G = 0.312865768
										P6 from K = 0.32665197
										P7 at Vent = 7.22462E-05
	K <sub>contract</sub> @ K & G =	0.210938081	K <sub>enlarge</sub> @ K & G =	0.199083						
	K <sub>enlarge-1</sub> @ P6 =	0.319278804								
	K <sub>enlarge-1</sub> @ P7 =	0.825611812								

Initial pressure is reduced from 0.75 to 0.55 to ensure system consistency With reality

P6 from both branches of the flow maintain same pressure and the Outlet pressure is approx. zero showing Consistency with reality

Table 1: Pressure Drop calculation for Air

Riser Label	ARGON	Re#	friction factor-f	K <sub>B</sub>	K <sub>branch</sub>	K <sub>run</sub>	K <sub>elbow</sub>	K <sub>eq</sub>	ΔP <sub>air</sub> (Psi)	Initial Pressure (Psi)
		for half inch pipe	for half inch pipe						nominal	with 0.8 initial pressure
A		4098.296679	0.044	1.228021			0.81	2.038021	0.006123987	0.8
B		6640.336848	0.04	1.116383	0.15	0.4		1.666383	0.0131454	0.793876013
C		8443.325757	0.038	6.713369	-0.15	0.35	5.67	12.58337	0.160488088	0.780730612
D		9227.005792	0.0375	1.078007	-0.5	0.15		0.728007	0.011088584	0.620242525
E		10452.77181	0.037	1.063634	-0.55	0.13		0.643634	0.012581157	0.609153941
F		11236.45184	0.0365	1.04926	-0.6	0.1		0.54926	0.012406677	0.596572783
G		12020.13188	0.036	3.848172	-0.6	0.09	0.81	4.558193	0.117822969	0.584166107
L									P6 from G =	0.466343138
M										
N										
O										
P										
From tank to H		7624.283867	0.039	5.442367			1.62	7.062367	0.073445835	0.8
H		9427.272776	0.0375	0.537957	-0.2	0.25		0.587957	0.009348383	0.726554165
R		783.6800348	0.081665982	2.279263			0.81	3.089263	0.000339431	0.8
S		1567.36007	0.040832991	2.279263	0.4	0.52	1.62	4.819263	0.002118054	0.799660569
tee of R&S		10994.63285	0.037	0.530784	-0.45	0.17		0.250784	0.005423511	0.717205782
I		12797.62175	0.036	1.034887	-0.45	0.17		0.754887	0.022118683	0.711782271
J		14600.61066	0.0355	0.509266	-0.5	0.15		0.159266	0.006074127	0.689663588
Q		17841.51579	0.035	0.502093	-0.2	0.25		0.552093	0.03144088	0.683589461
K		19644.5047	0.034	1.736534	-0.55	0.13	0.81	2.536555	0.175123804	0.652148581
from p6 to Vent		20883.11921	0.034	10.75101	-0.9		3	13.9959	0.474954695	0.477024777
									P6 equal from	0.466343138
									Both ends and zero	0.477024777
									outlet pressure at P7	0.002070082

Table 2: Pressure drop calculations for argon

From the tables above, the pressure at P6 from both flow paths are approximately equal and the pressure at the vent is also approximately zero for both air and argon gas.

Note that the pressure drop using argon gas is greater than that of air because argon is denser than air. Since the same flow rate is assumed for both gases the major changes would be due to the density of the gas involved according to equation (1).

### Sizing the orifice

The most significant task in the 2nd run of the LBNE 35T tank is the sizing of the orifice to obtain the desired flow out of each riser. Since there are 19 risers, there would also be 19 orifices installed with varying diameters based on the resistance they are designed to provide. An orifice is a flow meter and the flow rate through an orifice is given as;

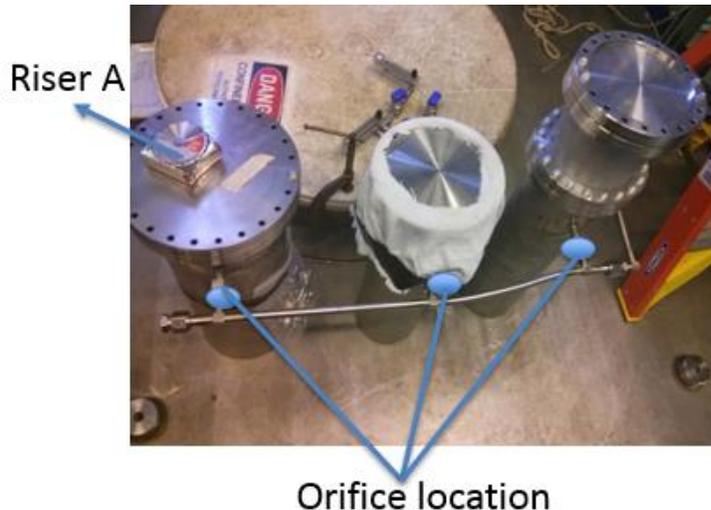
$$q = YCA \sqrt{\frac{2g(144)\Delta P}{\rho}} \quad (8)$$

Where  $Y$  is the expansion factor,

$C$  is the flow coefficient and

$A$  is the orifice cross sectional area.

The orifice diameter is then obtained from the cross-sectional area using equation for cylindrical cross-sections ( $\pi D^2/4$ ). A pressure drop of 0.75 psi is assumed across the first orifice location at A, and since the pressure obtained from the previous calculation indicate a pressure of 0.55 after the orifice sizing, this results in an initial pressure of 1.3 psi on all risers using air as tank gas, and with initial pressure of 0.8 an initial pressure of 1.55 was set for all risers with argon.



**Figure 6: Shows Risers at Proton Center Enclosure (PC4) and where the orifices will be installed.**

### **Conclusion**

The pressure drop model obtained from analysis and calculation during the purge of air and argon out of the LBNE 35T tank is consistent with reality, as the pressure at location P6 was the same from both ends of the network and the pressure at the vent was also zero. Also the tank purge operating pressure for air and argon were 1.3 psig and 1.55 psig respectively, which is comfortably less than the maximum allowable tank pressure of 3 psig. Finally, this model allows for changes and easy modification of the system in order to obtain the desired flow rate from any of the risers.

### **Acknowledgement**

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Personal communications with Terry Tope.

LBNE Science Collaboration.