3.5a1 - ODH Analysis of the Proton Assembly Building for the FLARE Materials Test Station, TPC Cryostat, Solid Xenon Experiment, the MicroBooNE Photomultiplier Tube Test Stand, and the LAr Distillation Column.

(10.1.10 update – Added the Distillation Column contribution, pages 15-16).

Introduction

The Liquid Argon TPC R&D effort also known as FLARE has fabricated two cryogenic test systems inside the Proton Assembly Building (PAB). In addition, a small cryogenic experiment using solid xenon, a cryogenic photomultiplier test stand, and the Distillation Column share the same space.

Description of the System

The cryogenic system contains both liquid nitrogen and liquid argon. Liquid nitrogen is supplied by an 1875 gallon dewar located outside PAB. The liquid nitrogen flows into PAB thru a half inch stainless steel tube that is vacuum jacketed by 1.5 inch SCH 10 pipe stainless steel pipe. The liquid nitrogen is used in a condenser that liquefies argon boil off so that the argon cryostat can remain a closed system. The nitrogen gas is then vented outdoors after passing thru a heat exchanger. The nitrogen circuit also contains a cool down solenoid valve which directs the nitrogen flow directly thru the heat exchanger and then outside. Nitrogen circuit trapped volume reliefs vent outside PAB.

Liquid argon is supplied by up to four 180 liter high pressure (350 psig relief setpoint) dewars that are supplied by the Fermilab stock room. These dewars are used to fill two 250 liter cryostats. The cryostat known as “Luke” contains the materials test station while the cryostat known as “Bo” contains the TPC wire chamber. Typically four dewars would not be required to fill one cryostat. But there are significant losses due to flashing and system cool down. It has also been our experience that it is difficult to obtain completely full dewars from the stock room. Operational experience with “Luke” indicates that 3 dewars are required to fill one cryostat. The fourth argon spigot has been replaced by a pressure indicator. However, the ODH analysis assumes 4 supply dewars are connected. The argon dewars are plumbed to a manifold to create a common argon source. The argon flows thru a series of valves and filters before it reaches the cryostat. All relief devices on the argon circuit are vented outdoors except for the cryostat rupture disk which is a secondary relief device.

Quantity of Cryogens, Building Volume, and Minimum Oxygen Concentrations

The PAB high bay has a volume of 138,425 cubic feet. The amount of warm gas contained in the 1875 gallon liquid nitrogen dewar is calculated as follows:

$1{,}875 gal \times \frac{ft^3}{7.481 gal} \times \frac{50.4 lb}{ft^3} \times \frac{ft^3}{0.07247 lb} = 174{,}307 ft^3$ where 50.4 lb/ft^3 is the density of liquid nitrogen and 0.07247 lb/ft^3 is the density of nitrogen gas at standard conditions.

Thus there is enough nitrogen contained in the supply dewar to fully inert the PAB high bay enclosure.

The equivalent amount of warm argon gas contained in four stock room dewars is $4 \times 180 liters \times \frac{ft^3}{28.32 liters} \times \frac{87 lb}{ft^3} \times \frac{ft^3}{0.1034 lb} = 21{,}391 ft^3$.

The equivalent amount of warm argon gas in the 250 liter cryostat is

$$250 liters \times \frac{ft^3}{28.32 liters} \times \frac{87 lb}{ft^3} \times \frac{ft^3}{0.1034 lb} = 7{,}428 ft^3.$$

If the four stockroom dewars are instantly vented into PAB, the minimum O2 concentration reached is

$$138{,}425 ft^3_{air} - 21{,}391 ft^3_{argon} = 117{,}034 ft^3_{air}$$

$$117{,}034 ft^3_{air} \times 0.21 = 24{,}577 ft^3_{oxygen}$$

$$\frac{24{,}577 ft^3_{oxygen}}{138{,}425 ft^3_{air}} \times 100 = 17.8\%_{oxygen}.$$

If the four stockroom dewars are instantly vented into PAB along with the two 250 liter cryostats, the minimum O2 concentration reached is

$$138{,}425 ft^3_{air} - \left(21{,}391 ft^3_{argon} + 2 \times 7{,}428 ft^3_{argon}\right) = 102{,}178 ft^3_{air}$$

$$102{,}178 ft^3_{air} \times 0.21 = 21{,}457 ft^3_{oxygen}$$

$$\frac{21{,}457 ft^3_{oxygen}}{138{,}425 ft^3_{air}} \times 100 = 15.5\%_{oxygen}.$$

Argon is heavier than air so it cannot be assumed to perfectly mix with air to create the above minimum oxygen concentrations.

The PAB high bay floor is about 100 feet by 49 feet. If the argon is assumed to spread out across the floor and remain separate from the air, the thickness of the stratified argon layer for four stock room dewars instantly dumped into the room is

$$\frac{21{,}391 ft^3}{100 ft \times 49 ft} = 4.4 ft.$$

If the two 250 liter cryostats are dumped into the room along with the four stock room dewars the argon layer depth is

$$\frac{21{,}391 ft^3 + 2 \times 7{,}428 ft^3}{100 ft \times 49 ft} = 7.4 ft.$$

To keep the analysis simple, it is assumed that the entire liquid argon inventory is vented during an ODH event.

Ventilation System and ODH monitors

PAB is equipped with 3 ceiling exhaust fans. FESS has determined the capacity of each fan to be at least 2000 SCFM Air. All three ceiling fans will turn on in the event of an ODH alarm. They are also wired in a manner that allows each fan to be turned on manually. In addition to the ceiling fans, a dedicated ODH fan has been installed in the cryogenic area. This fan pulls the cold dense gas from the floor and pushes it thru a duct which exhausts outside PAB. Together all four fans yield a volume change in the high bay area every 17 minutes. Only the dedicated ODH fan is included in the ODH analysis. At the end of this section the details of the dedicated ODH fan and ODH hardware layout are documented. Figure 3.5a.1 shows the locations of ODH heads, horns, and fans.

ODH Event Leak rates for Nitrogen Circuit

Severed Line

Several leak rates are postulated for the nitrogen circuit. The most severe of these considers the liquid nitrogen supply line to be severed just inside PAB. The flow rate at this point is then a function of the resistance offered by the piping outside PAB and the pressure of the dewar. The dewar pressure is taken to be the maximum allowable pressure under fire conditions which is 121% of the dewar MAWP of 75 psig or

$$1.21(75 + 15) - 15 = 93.9 psig.$$

The flow rate thru the LN2 piping outside PAB is calculated using the following equation from Crane's Technical Paper 410 for discharge of liquid

$$W = 1891 d^2 \sqrt{\frac{\Delta P \rho}{K}}$$

where

W = rate of liquid nitrogen flow in pounds per hour.

d = internal diameter of pipe, = 0.5 – 2 x 0.035 = 0.43 inches.

ΔP = differential pressure, 93.9 psi.

ρ = density of liquid nitrogen saturated at 93.9 psig, 43.19 lb/ft^3.

K = resistance coefficient, sum of K_{pipe} + K_{elbow} + K_{valve} + K_{exit}

K_{pipe} = resistance of straight pipe outside PAB, $K_{pipe} = f\frac{L}{D}$ where

f = friction factor determined from pipe size and Reynolds number, = 0.029 (page A-25 of Crane 410)

L = length of pipe outside PAB, 227 inches.

D = internal diameter of pipe, 0.43 inches.

K_{elbow} = resistance of a standard elbow which = 30 x f_T where f_T is the friction factor in the zone of complete turbulence for 0.43 inch internal diameter pipe which is 0.029. Piping outside PAB has 2 elbows.

K_{exit} = resistance of a sharp edged pipe exit for the severed pipe, = 1.0

K_{valve} = resistance of the Cryolab isolation valve at the dewar exit,

$$K_{valve} = \frac{894 d^4}{C_v^2}$$ where

C_v = flow coefficient for valve, C_v = 12 for Cryolab valve

R_e = Reynolds number, ratio of inertial and viscous forces

$$R_e = 6.31\frac{W}{d\mu} \text{ where}$$

μ = absolute viscosity of LN2 saturated at 93.9 psig, = 0.088 centipoise

The above equations yield

$$K = 0.029\frac{227}{0.43} + 2\times 30\times 0.029 + \frac{894(0.43)^4}{12^2} + 1.0 = 18.26$$

$$R_e = 6.31\frac{4889}{(0.43)0.088} = 815264$$

$W = 1891(0.43)^2\sqrt{\frac{93.9(43.19)}{18.26}} = 5211\frac{lb}{hr}$ which converts to SCFM in the following manner

$$5211\frac{lb}{hr}\times\frac{ft^3}{0.07247lb}\times\frac{hr}{60\min} = 1198\frac{ft^3}{\min}.$$

Thus the maximum flow the liquid nitrogen dewar can supply into PAB is equivalent to 1198 SCFM of nitrogen gas.

LN2 Dewar Vacuum Pump

A vacuum pump inside the PAB high bay is connected to the vacuum jacket of the LN2 dewar which is outside PAB thru piping constructed of 2 inch welded stainless steel tubing. Thus in the event of a LN2 tank failure that leaks into the vacuum jacket this is an additional nitrogen gas path into the PAB high bay. In this vacuum line a MKS Series 225 AUTO-SOFT Flow Actuated Check Valve has been installed outside PAB to limit the potential flow of gas from the vacuum jacket. This valve closes at a flow rate of 6 CFM according to the manufacturer and then reopens at 2 Torr. In testing performed by the PAB calibration shop, with an inlet pressure of 5 psig the valve closed and allowed a gas flow rate of less than 50 SCFH while closed. The ODH analysis assumes that the maximum flow into the PAB high bay from a nitrogen leak into the vacuum jacket is restricted to 6 CFM by this valve.

GN2 Instrument Purge

A ¼ tube brings purge gas from the LN2 dewar into the PAB high bay. The purge gas is assumed to always vent into the room. A Swagelok 0.5 micron sintered metal orifice (part # SS-4-VCR-2-.5M) installed outside limits the flow into the high bay. The orifice was tested in the PAB Calibration Shop and the maximum flow was found to be 15 SCFH at 75 psig which is the LN2 dewar

MAWP. At 15 SCFH it would take over 7 weeks to bring the PAB high bay down to 18 % oxygen with this purge.

Valve and Instrument Leakage

For leakage from valves and instruments on the LN2 supply line, the leak was modeled as an orifice whose diameter is 25% of the pipe diameter. It is unlikely that valve bodies or instruments will fail in a manner that completely opens up the supply piping. Before use, all piping will be pressure tested and helium leak checked.

The leak rate is calculated using the following equation from Crane Technical Paper 410 for liquid flow thru nozzles and orifices

$W = 1891 d_1^2 C \sqrt{\Delta P \rho}$ where

all variables except C and d_1 are previously defined.

d_1 = orifice diameter, 25% of 0.5 inch nominal tube diameter = 0.125 inch.

C = flow coefficient for nozzles and orifices (Crane 410 Page A-20), = 0.60 for this case.

The maximum flow of nitrogen thru such a leak is

$W = 1891\left(0.125^2\right)0.60\sqrt{(93.9)43.19} = 1129\frac{lb}{hr}$ which converts to

$1129\frac{lb}{hr} \times \frac{ft^3}{0.07247 lb} \times \frac{hr}{60 \min} = 260\frac{ft^3}{\min}$ of warm atmospheric N2 gas.

The factor C was found from the plot on page A-20 using

$R_e = 6.31\frac{1129}{(0.125)0.088} = 647635$ and $\beta = \frac{d_1}{d_2} = \frac{0.125}{0.43} = 0.29$ where d_2 is the actual ID of the LN2 supply pipe.

Thus on the liquid nitrogen supply line, the leak rate for components is estimated as 260 SCFM which is 23% of the total mass flow available inside PAB.

ODH Event Leak rates for Argon Circuit

Severed Line

The four argon supply dewars are each equipped with a liquid isolation valve with a C_v of 1.08. Thus the worst case leak is a severed line just after all four dewars are tied together. From Crane 410, the flow rate out of one dewar can be calculated as

$$Q = C_v \sqrt{\Delta P \frac{62.4}{\rho}}$$ where

Q = rate of liquid argon flow in gallons per minute.

C_v = flow coefficient for valve, C_v = 1.08 for dewar liquid isolation valve according to Airgas.

ΔP = differential pressure, 350 psi based on stockroom supplied high pressure liquid argon dewars with reliefs set at 350 psig.

ρ = density of liquid argon saturated at 350 psig, 63.37 lb/ft^3.

The maximum liquid flowrate out of one stock room dewar is found to be

$$Q = 1.08\sqrt{350\frac{62.4}{63.37}} = 20.05\frac{gal}{\min}$$ which converts to

$$20.05\frac{gal}{\min} \times \frac{1 ft^3}{7.48 gal} \times \frac{63.37 lb}{ft^3} \times \frac{ft^3}{0.1034 lb} = 1643\frac{ft^3}{\min}$$ where 0.1034 lb/ft^3 is the

density of argon gas at standard conditions. Thus four dewars could

supply 6572 SFCM of warm argon gas. This is conservative because the hoses and tubing connecting the four dewars would provide additional restriction that would lower this flow rate.

<u>LAr Supply Dewar Relief Valves</u>

The relief valves on the LAr supply dewars could prematurely open. The typical relief valve on the Airgas supplied dewars is a Generant LCV-250B-K-350 which according to the manufacturer has a maximum flow of 81.4 SCFM Nitrogen at 120% of its 350 psig set point. This converts to lb/hr as

$$\frac{81.4 ft^3}{\min} \times \frac{60 \min}{hr} \times \frac{0.07247 lb}{ft^3} = 354\frac{lb}{hr}.$$

This can be converted to SCFM argon using the method outlined in ASME Section VIII Appendix 11 Division 1 entitled “Capacity Conversions for Safety Relief Valves.”

For any gas or vapor,

$W = CKAP\sqrt{\frac{M}{T}}$ where

W = rated capacity in lb/hr, 354 lb/hr for nitrogen, argon value to be solved for.

C = constant for gas or vapor which is a function of the ratio of specific heats, C = 356 for nitrogen and 378 for argon.

KAP = constant for the relief valve.

M = molecular weight, 28.02 for nitrogen and 39.9 for argon.

T = absolute temperature in Rankin, choose 530 ^{o}R.

For the nitrogen rating,

$$KAP = \frac{W}{C\sqrt{\frac{M}{T}}} = \frac{354}{356\sqrt{\frac{28.02}{530}}} = 4.325.$$

The argon mass flow rate is then

$W = (356)(4.325)\sqrt{\frac{39.9}{530}} = 422.5\frac{lb}{hr}$ which converts to

$422.5\frac{lb}{hr} \times \frac{ft^3}{0.1034\,lb} \times \frac{hr}{60\min} = 68.1\frac{ft^3}{\min}$. Thus the maximum rate at which the supply dewar can relieve itself is 68.1 SCFM.

<u>MV-204-Ar, MV-218-Ar, MV-365-V, and MV-366-V</u>

MV-204-Ar is an isolation valve where a vacuum pump can be connected to pump out the argon source manifold. If this valve with a C_v of 1.2 is left wide open while the circuit is pressurized, the leak rate is found to be

$Q = C_v \sqrt{\Delta P \frac{62.4}{\rho}} = 1.20\sqrt{350\frac{62.4}{63.37}} = 22.28\frac{gal}{\min}$. This converts to a warm argon gas flow rate of $22.28\frac{gal}{\min} \times \frac{1 ft^3}{7.48 gal} \times \frac{63.37 lb}{ft^3} \times \frac{ft^3}{0.1034 lb} = 1825\frac{ft^3}{\min}$. This leak rate is also used for MV-218-Ar, MV-365-V, and MV-366-V which are identical to MV-204-Ar and is conservative because these three valves are separated from the argon source by significant piping restrictions.

<u>Valve and Instrument Leakage for Components Upstream of the Cryostat</u>

For leakage from valves and instruments on the LAr transfer line, the leak is modeled as an orifice whose diameter is 0.125 inches which is 33% of the nominal 3/8 inch tube diameter used to construct most of the LAr piping. It is unlikely that valve bodies or instruments will fail in a manner that completely opens up the supply piping. Most valves on the argon circuit are high quality stainless steel construction with metal bellows seal to atmosphere.

The leak rate is calculated using the following equation from Crane Technical Paper 410 for liquid flow thru nozzles and orifices

$W = 1891 d_1^2 C \sqrt{\Delta P \rho}$ where

d_1 = orifice diameter, 33% of 0.375 inch nominal tube diameter = 0.125 inch.

C = flow coefficient for nozzles and orifices (Page A-20 from Crane 410), = 0.60 for this case.

μ = absolute viscosity of liquid argon saturated at 350 psig, 0.0751 centipoise.

The maximum flow of argon thru such a leak is

$W = 1891\left(0.125^2\right)0.61\sqrt{(350)63.37} = 2684\frac{lb}{hr}$ which converts to

$2684\frac{lb}{hr} \times \frac{ft^3}{0.1034 lb} \times \frac{hr}{60\min} = 433\frac{ft^3}{\min}$ of warm atmospheric argon gas.

The factor C was found from the plot on Crane 410 page A-20 using

$R_e = 6.31\frac{2684}{(0.125)0.0751} = 1804105$ and $\beta = \frac{d_1}{d_2} = \frac{0.125}{0.305} = 0.41$ where d_2 is the actual

ID of the LAr supply pipe (3/8 inch OD – 2 x 0.035 inch wall = 0.305 inch).

Thus on the liquid argon transfer line, the leak rate for components upstream of the cryostat is estimated as 433 SCFM.

Valve and Instrument Leakage for Components Attached to the Cryostat

From the relief valve calculations, the maximum mass flow rate into the cryostat was found to be 1437 pounds per hour. This equates to warm argon gas flowrate of 232 SCFM using the following conversion

$1437\frac{lb}{hr}\times\frac{ft^3}{0.1034\,lb}\times\frac{hr}{60\min}=232\frac{ft^3}{\min}$. This value was used as the leak rate for all components attached to the cryostat.

ODH Risk Assessment

As explained in Section 5064 of Fermilab's ES&H Manual, the ODH classification of an enclosure is determined by calculating the ODH fatality rate, ϕ. It is defined as:

$\phi=\sum_{i=1}^{n}P_iF_i$ where

P_i = the expected rate of the i^{th} failure per hour

F_i = the fatality factor for the i^{th} event.

The summation is taken over all events, which may cause oxygen deficiency and result in fatality. Fatality factors are calculated based on the maximum spill rate, the rate of ventilation, and the size of the PAB enclosure. Events that could potentially lead to an ODH condition were identified and tabulated for the PAB high bay area in the tables at the end of this section. A single event probability was estimated in most cases using Table 2 "NRC Equipment Failure Rate" on page 5064TA-4 of Fermilab's ES&H Manual. In some cases, a failure probability was based on Fermilab experience since an applicable number was not readily available in the NRC table. Based on the number of components present in the PAB enclosure, a total event probability was calculated. The lowest oxygen concentration (as time approaches infinity) was computed by applying equation 4 on page 5064TA-8 of Fermilab's ES&H Manual:

$C_r(t)=0.21\left\{1-\frac{R}{Q}\left[1-e^{\left(\frac{-Qt}{V}\right)}\right]\right\}=0.21\left\{1-\frac{R}{Q}\right\}\ as\ t\Rightarrow\infty$ where

R = spill rate into enclosure, SCFM.

Q = enclosure ventilation rate, CFM.

This equation assumes complete mixing of the gases with the ventilation fans drawing contaminated atmosphere from the confined volume. A fatality factor was then determined from Figure 1 on page 5064TA-2 of Fermilab's ES&H Manual. By multiplying this fatality factor by the total event probability, an ODH rate in fatalities/hour was calculated. The sum of all the ODH rates gives the total ODH rate for the enclosure.

This ODH analysis relies on the use of mechanical ventilation to remove the inert gas from PAB. Although this ventilation reduces the overall ODH risk, it is also subject to failure. Therefore, the probability that these failures will occur and compromise the ventilation system needs to be factored into the overall risk assessment. There are two main areas of concern. One is the failure of a ventilation fan motor to turn on or the fan louvers to open. The second is an unplanned electrical power outage during cryogenic operation. The total probability of any one of these events occurring is simply the sum of their probabilities. The ODH rate calculation table includes two cases. The first case is for the ventilation system running. The second case considers the loss of the ventilation system. In that case the failure rate of the forced ventilation is factored into the calculation. The probability of a component event failure and a ventilation failure occurring is the product of their failure probabilities since they are independent events.

The probability of ventilation failure was determined as follows. The probability of a power outage is 1×10^{-4} / hr based on Fermilab equipment failure rates. The probability of an electric motor not starting is $3 \times 10^{-4} / D$ based on NRC data. To be conservative, the demand (D) is taken to be once an hour such that $D = 1$. This probability is used for both the fan motor starting and the actuated louvers opening. Thus the probability of a ventilation failure is $1 \times 10^{-4} + 2 \times 3 \times 10^{-4} = 7 \times 10^{-4}$ / hr. This value is used in the table that considers a ventilation failure. The fan availability rate is then $1 – 7 \times 10^{-4}$ or 0.9993. This value is used in the table that considers the ventilation to be running.

The probability of a valve such as MV-204-Ar being left wide open was taken to be (0.1 / D) which is much greater than the value of (3×10^{-3} / D) described as a general human error of commission in Table 3 of FESHM 5064TA. If the valve is assumed to be cycled once per day, then the probability of an error is (0.1 / D) x (D / hr) = (0.1 / 1) x (1/24 hr) = 4.17×10^{-3} per hour.

The probability of the operator ignoring high pressure liquid or gas audibly venting into the room is also taken to be (0.1 / D). If the valve is again assumed to be cycled once per day, the probability of the operator ignoring the error is 4.17×10^{-3} per hour.

These two tasks are independent events such that the total probability of a valve staying in the wide open position and its venting into the room being ignored is the product of the two task probabilities or 4.17 x 10^{-3} x 4.17 x 10^{-3} = 1.74 x 10^{-5} per hour.

Solid Xenon ODH Contribution

A solid xenon test setup has been constructed at PAB. This test setup uses liquid argon to condense and freeze xenon gas. The test setup allows for the connection of only one stockroom liquid argon dewar at a time. The xenon gas inventory of 15 SCF is insignificant. A cool down valve allows venting of the argon dewar into the PAB high bay. Previously in this document the maximum mass flow out of a supply dewar was found to be 1,643 SCFM of argon.

The following shows that one stockroom liquid argon dewar can reduce the PAB high bay oxygen concentration to 20.2%.

$$1 \times 180 liters \times \frac{ft^3}{28.32 liters} \times \frac{87 lb}{ft^3} \times \frac{ft^3}{0.1034 lb} = 5{,}348 ft^3$$

$$138{,}425 ft^3_{air} - 5{,}348 ft^3_{argon} = 133{,}077 ft^3_{air}$$

$$133{,}077 ft^3_{air} \times 0.21 = 27{,}946 ft^3_{oxygen}$$

$$\frac{27{,}946 ft^3_{oxygen}}{138{,}425 ft^3_{air}} \times 100 = 20.2\%_{oxygen}.$$

Compared to other sources of cryogens in the PAB high bay the xenon test setup is insignificant. It is included because the system may grow significantly in the future. In this simple system, the likely failure is opening the liquid argon cool down valve and simply allowing the entire supply dewar to vent in a negligent manner. The probability of the cool down valve being left wide open and unattended was taken to be (0.1 / D) which is much greater than the value of (3 x 10^{-3} / D) described as a general human error of commission in Table 3 of FESHM 5064TA. If the valve is assumed to be cycled once per day, then the probability of an error is (0.1 / D) x (D / hr) = (0.1 / 1) x (1/24 hr) = 4.17 x 10^{-3} per hour. This contribution is listed in tables 3.5a.1 and 3.5a.2.

PAB Stockroom Dewar Inventory

With multiple experiments using stock room dewars in the PAB high bay this note suggests that 5 LAr dewars and 5 LN2 dewars is a reasonable supply inventory. There are two scenarios that may lead to venting from these off line dewars.

One is discharge from a relief device which fails to re-close. The second is someone deliberately venting a set of five dewars into the room. This behavior is not expected such that the rate is set at once per year or 1.1 x 10^{-4} per hour.

Multiplying the maximum flow out of single dewar by 5 leads to a maximum flow of 8,215 SCFM argon and 8,395 SCFM nitrogen.

The following shows that five stockroom liquid argon dewars negligently vented into the PAB high bay can reduce the PAB high bay oxygen concentration to 16.9%. And 5 liquid nitrogen dewars reduce the PAB high bay oxygen concentration to 17.6%.

Argon:

$$5 \times 180 liters \times \frac{ft^3}{28.32 liters} \times \frac{87 lb}{ft^3} \times \frac{ft^3}{0.1034 lb} = 26{,}739 ft^3$$

$$138{,}425 ft^3_{air} - 26{,}739 ft^3_{argon} = 111{,}686 ft^3_{air}$$

$$111{,}686 ft^3_{air} \times 0.21 = 23{,}454 ft^3_{oxygen}$$

$$\frac{23{,}454 ft^3_{oxygen}}{138{,}425 ft^3_{air}} \times 100 = 16.9\%_{oxygen}.$$

Nitrogen:

$$5 \times 180 liters \times \frac{ft^3}{28.32 liters} \times \frac{50.4 lb_{(\rho LN_2)}}{ft^3} \times \frac{ft^3}{0.0725 lb_{(\rho GN_2)}} = 22{,}092 ft^3.$$

$$138{,}425 ft^3_{air} - 22{,}092 ft^3_{\mathrm{nitrogen}} = 116{,}333 ft^3_{air}$$

$$116{,}333 ft^3_{air} \times 0.21 = 24{,}430 ft^3_{oxygen}$$

$$\frac{24{,}430 ft^3_{oxygen}}{138{,}425 ft^3_{air}} \times 100 = 17.6\%_{oxygen}.$$

These contributions are listed in tables 3.5a.1 and 3.5a.2.

MicroBooNE Photomultiplier Tube Test Stand

A photomultiplier tube test stand has been constructed at PAB. This test setup uses liquid nitrogen to submerge a photomultiplier tube in 352 liter dewar. The test setup allows for the connection of only one 180 liter stockroom liquid nitrogen dewar at a time for filling.

A FNAL stockroom (provided by Airgas) high pressure liquid nitrogen supply dewar is equipped with a liquid isolation valve with a C_v of 1.08. Thus the worst case leak rate is the maximum flow that can pass thru this isolation valve. From Crane 410, the flow rate out of one dewar can be calculated as

$$Q = C_v \sqrt{\Delta P \frac{62.4}{\rho}}$$ where

Q = rate of liquid argon flow in gallons per minute.

C_v = flow coefficient for valve, C_v = 1.08 for dewar liquid isolation valve according to Airgas.

ΔP = differential pressure, 350 psi based on stockroom supplied high pressure liquid nitrogen dewars with reliefs set at 350 psig.

ρ = density of liquid nitrogen saturated at 350 psig, 32.6 lb/ft^3.

The maximum liquid flow rate out of one stock room dewar is found to be

$$Q = 1.08\sqrt{350\frac{62.4}{32.6}} = 28.0\frac{gal}{\min}$$ which converts to

$$28.0\frac{gal}{\min} \times \frac{1 ft^3}{7.48 gal} \times \frac{32.6 lb}{ft^3} \times \frac{ft^3}{0.0727 lb} = 1679\frac{ft^3}{\min}$$ where 0.0727 lb/ft^3 is the

density of nitrogen gas at standard conditions.

The following shows that one stockroom liquid nitrogen dewar can reduce the PAB high bay oxygen concentration to 20.3%.

$$1 \times 180 liters \times \frac{ft^3}{28.32 liters} \times \frac{50.4 lb}{ft^3} \times \frac{ft^3}{0.0727 lb} = 4{,}406 ft^3$$

$$138{,}425 ft^3_{air} - 4{,}406 ft^3_{\text{nitrogen}} = 134{,}019 ft^3_{air}$$

$$134{,}019 ft^3_{air} \times 0.21 = 28{,}144 ft^3_{oxygen}$$

$$\frac{28{,}144 ft^3_{oxygen}}{138{,}425 ft^3_{air}} \times 100 = 20.3\%_{oxygen}.$$

If the 352 liter photomultiplier dewar was to fail and release its entire volume into the PAB high bay the oxygen concentration would be reduced to 19.7%.

$$352 liters \times \frac{ft^3}{28.32 liters} \times \frac{50.4 lb}{ft^3} \times \frac{ft^3}{0.0727 lb} = 8{,}617 ft^3$$

$$138{,}425 ft^3_{air} - 8{,}617 ft^3_{\text{nitrogen}} = 129{,}908 ft^3_{air}$$

$$129{,}908 ft^3_{air} \times 0.21 = 27{,}281 ft^3_{oxygen}$$

$$\frac{27{,}281 ft^3_{oxygen}}{138{,}425 ft^3_{air}} \times 100 = 19.7\%_{oxygen}.$$

Compared to other sources of cryogens in the PAB high bay the Photomultiplier Tube Test Stand is insignificant. In this simple system, the likely cryogen release is opening the liquid nitrogen supply valve and simply allowing the entire supply dewar to empty in a negligent manner (either overfilling the pmt test dewar or missing it entirely). The probability of the supply dewar valve being left wide open and unattended was taken to be (0.1 / D) which is much greater than the value of (3×10^{-3} / D) described as a general human error of commission in Table 3 of FESHM 5064TA. If the valve is assumed to be cycled once per day, then the probability of an error is (0.1 / D) x (D / hr) = (0.1 / 1) x (1/24 hr) = 4.17×10^{-3} per hour.

A second failure mode is the rupture of the 352 liter pmt dewar. The FESHM dewar loss of vacuum failure rate is used for this event. The leak rate for this scenario was arbitrarily chosen to be the supply dewar leak rate.

These contributions are listed in tables 3.5a.1 and 3.5a.2.

Distillation Column ODH Contribution

A Distillation Column has been constructed at PAB. This test setup uses distillation to separate argon from other gases.

The column is supplied by fifteen 4,500 psig gas bottles which have 45 liter internal volumes. The supply gas is a mixture that is assumed to be entirely inert. The column destination (pure argon) is also a 45 liter bottle but with a lower maximum pressure of 3,000 psig. For the available gas volume calculation the destination bottle is assumed to be at the higher supply bottle pressure. Thus the total volume of the room temperature supply bottles and destination bottle is

$$16\ bottles \times \frac{45\ liters}{1\ bottle} \times \frac{4{,}500\ psig}{14.4\ psig} \times \frac{1\ ft^3}{28.31\ liters} = 7{,}948\ ft^3.$$

The cryogenic portion of the Distillation Column can contain at most 18 liters of liquid argon which corresponds to the following warm gas volume:

$$18\ liters \times \frac{ft^3}{28.32\ liters} \times \frac{87\ lb}{ft^3} \times \frac{ft^3}{0.1034\ lb} = 535\ ft^3.$$

Thus the total possible inert release from the column is

$$7{,}948\ ft^3 + 535\ ft^3 = 8{,}483\ ft^3.$$

The following shows that releasing all the inert gas associated with the Distillation Column would reduce the PAB high bay oxygen concentration to 19.7%.

$$138{,}425\ ft^3_{air} - 8{,}483\ ft^3_{\text{argon}} = 129{,}942\ ft^3_{air}$$

$$129{,}942\ ft^3_{air} \times 0.21 = 27{,}287\ ft^3_{oxygen}$$

$$\frac{27{,}287\ ft^3_{oxygen}}{138{,}425\ ft^3_{air}} \times 100 = 19.7\%_{oxygen}.$$

For the ODH tabulation, this event is assumed to occur once per year.

ODH Results

Table 1 finds the ODH fatality rate to be 1.44×10^{-9} which is less than 10^{-7} such that with ventilation running the PAB high bay enclosure is ODH class zero.

Table 2 finds the ODH fatality rate to be 5.51×10^{-9} which is less than 10^{-7} such that when ventilation failure is considered the PAB high bay enclosure is ODH class zero.

<u>ODH Hardware Layout and Dedicated ODH Fan Details</u>

Figure 3.5a.1 shows the ODH hardware layout for PAB. Four ODH heads mounted 6 inches from the floor surround the cryogenic area. One alarm horn is mounted inside the high bay area. The second alarm horn is mounted in the room adjacent to the high bay.

The dedicated ODH fan is a GreenHeck SWB backward inclined centrifugal utility fan rated at 2000 SCFM air at 4 inches of water static pressure. The fan pushes the cold vapor from a spill thru a duct that includes two elbows, a 15 foot vertical rise, a damper, and two enlargements.

To verify the fan installation is adequate, the pressure drop thru the duct is estimated.

Equation 3-20 shown below from Crane Technical Paper 410 was used to calculate the pressure drop due to the flow of gas thru the duct

$$W = 1891Yd^2\sqrt{\frac{\Delta P}{K\overline{V}_1}} \Rightarrow \Delta P = \left(\frac{W}{1891Yd^2}\right)^2 K\overline{V}_1$$

where

W = rate of flow in lbs per hour. ODH analysis is based on a 2000 SCFM flow of either nitrogen or argon. The nitrogen mass flow rate is then

$$2{,}000\frac{ft^3}{\min}N_2 \times \frac{60\min}{hr} \times 0.07247\frac{lb}{ft^3} = 8{,}696\frac{lb}{hr}N_2$$ and the argon mass flow rate is

$$2{,}000\frac{ft^3}{\min}Ar \times \frac{60\min}{hr} \times 0.1034\frac{lb}{ft^3} = 12{,}408\frac{lb}{hr}Ar.$$

Y = net expansion factor for compressible flow, 1.0 for the small pressure drops in this duct flow analysis.

d = internal diameter of duct, inches. Duct is square, so an equivalent diameter is calculated as

$$d = 4\frac{cross\ sectional\ flow\ area}{wetted\ perimeter} = 4\frac{13 \times 20}{13 \times 2 + 20 \times 2} = 15.76\ in.$$

$\overline{V}_1$ = specific volume of fluid, 2.774 ft^3/lb for saturated argon vapor, 9.673 ft^3/lb for argon gas at STP, 3.465 ft^3/lb for saturated nitrogen vapor, and 13.8 ft^3/lb for nitrogen gas at STP.

ΔP = pressure drop in psi, converted to inches of water for comparison.

K = total resistance coefficient, sum of K_{elbow}, $K_{enlarge1}$, $K_{enlarge2}$, $K_{straight}$, $K_{entrance}$, and K_{exit}.

K_{elbow} = 30 x f_T where f_T is the friction factor in the zone of complete turbulence, 0.0132 for the ~16 inch equivalent duct diameter.

$K_{enlarge1}$ = resistance of enlargement from 9.625 x 13 inch fan outlet to 13 x 20 inch duct, 1.0 to be conservative.

$K_{enlarge2}$ = resistance of enlargement from 13 x 20 duct to 20 x 20 inch duct, 1.0 to be conservative.

$K_{straight}$ = resistance to flow thru straight pipe, $K_{straight} = f \times L / d$ where f is the friction factor based on Reynolds # and L is the length of the straight section which is 15 feet x 12 inches per ft. = 180 inches.

$K_{entrance}$ = resistance due to entrance into duct, 0.78.

K_{exit} = resistance due to exit from duct, 1.0.

Re = Reynolds number, $Re = 6.31\frac{W}{d\mu}$ (ratio of inertial to viscous forces).

μ = dynamic viscosity, 0.007029 centipoise for saturated argon vapor, 0.02246 centipoise for argon gas at STP, 0.005373 centipoise for saturated nitrogen vapor, and 0.01769 centipoise for nitrogen gas at STP.

The static head loss is calculated from the specific volume of the gas and the height of the duct as shown below

$$\frac{1}{\overline{V}_1}\frac{lb}{ft^3} \times \frac{L\ in}{1} \times \frac{ft}{12\ in} \times \frac{1\,ft^2}{144\ in^2} \times \frac{27.6799\ in.\,H2O}{1\,psi}.$$

For saturated argon vapor, the static head is found to be

$$\frac{1}{2.774}\frac{lb}{ft^3} \times \frac{180\ in}{1} \times \frac{ft}{12\ in} \times \frac{1\,ft^2}{144\ in^2} \times \frac{27.6799\ in.\,H2O}{1\,psi} = 1.039\ in.\,H2O.$$

The louver pressure drop was provided by the vendor for a 2000 SCFM air flow. It would be slightly more for the warm argon flow and less for the cold gas flows. For the warm argon gas flow, the louver pressure drop is adjusted upward by the ratio of the warm argon to nitrogen flowing pressure drops, 0.887 / 0.622 = 1.43.

Table 3.5a.3 provides estimates of pressure drop for the various cases. The fan rating of 2000 SCFM at 4 inches of H_2O is more than adequate to handle the flow rates considered in the ODH analysis.

Table 3.5a.3: Pressure drop for both warm and cold gas flow thru the ODH duct.

	Re	*f*	*K*	Flowing ΔP in. H_2O	Static Head ΔP in. H_2O	Louver ΔP in. H_2O	Total ΔP in. H_2O
Warm N_2	196,815	0.016	4.742	0.622	0.209	0.12	0.950
Cold N_2	648,150	0.014	4.72	0.155	0.832	<0.12	1.107
Warm Ar	221,181	0.016	4.743	0.887	0.298	~0.17	1.355
Cold Ar	706,870	0.014	4.72	0.253	1.039	<0.12	1.412

Table 3.5a.1: PAB ODH Risk Analysis with ventilation running.

ITEM	Comment	Type of Failure	# of Items	Pi Fail Rate events/hr	Source of Fail Rate	Group Fail Rate (Pi x #) events/hr	Exhaust fan Availability events/hr	R leak rate SCFM	Q vent rate SCFM	O2 Concentration %	Fi Fatality Factor fatality/event	ϕ=∑PiFi ODH Rate fatality/hr	
Nitrogen circuit													
LN2 supply piping	< 3" diameter, max flow into PAB	Rupture - severed line	1	1.00E-09	NRC	1.00E-09	0.9993	1198	2000	8.42	1.00E+00	9.99E-10	
Condensor	Treat as dewar, 25% pipe diameter	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	0.9993	260	2000	18.27	3.95E-08	3.95E-14	
EV-104-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
EV-105-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
EV-106-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
LT-10-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	260	2000	18.27	3.95E-08	1.18E-14	
MV-119-N	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
MV-120-N	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
PI-44-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	260	2000	18.27	3.95E-08	1.18E-14	
PI-133-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	260	2000	18.27	3.95E-08	1.18E-14	
PT-1-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	260	2000	18.27	3.95E-08	1.18E-14	
PT-27-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	260	2000	18.27	3.95E-08	1.18E-14	
PSV-101-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
PSV-101-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
PSV-101-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
TE-6-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	260	2000	18.27	3.95E-08	1.18E-14	
SV-117-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
Welds	Max flow thru 25% pipe diameter	Leak/rupture	50	3.00E-09	NRC	1.50E-07	0.9993	260	2000	18.27	3.95E-08	5.92E-15	
Flanges	Max flow thru 25% pipe diameter	Leak/rupture	10	3.00E-07	NRC	3.00E-06	0.9993	260	2000	18.27	3.95E-08	1.18E-13	
LN2 vent piping	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-09	NRC	1.00E-09	0.9993	260	2000	18.27	3.95E-08	3.95E-17	
PCV-388-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
PSV-389-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
MV-375-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	260	2000	18.27	3.95E-08	3.95E-16	
LN2 tank vacuum	Rupture into vacuum space, vacuum pumped into PAB	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	0.9993	6.00	2000	20.94	3.69E-10	3.69E-16	
GN2 purge supply**	Restricted by orifice outside PAB	Normally vents	1	1.00E+00	FNAL	0.00E+00	0.9993	0.25	2000	21.00	0.00E+00	0.00E+00	

** The GN2 purge that vents into the PAB high bay would take over 7 weeks to reduce the oxygen concentration to 18 % thus it is not considered to have a probability of producing a fatality.

ITEM	Comment	Type of Failure	# of Items	Pi Fail Rate events/hr	Source of Fail Rate	Group Fail Rate (Pi x #) events/hr	Exhaust fan Availability events/hr	R leak rate SCFM	Q vent rate SCFM	O2 Concentration %	Fi Fatality Factor fatality/event	ϕ=∑PiFi ODH Rate fatality/hr	
Argon Circuit													
LAr supply piping	< 3" diameter, max flow into PAB	Rupture - severed line	1	1.00E-09	NRC	1.00E-09	0.9993	6572	2000	15.5	5.06E-06	5.06E-15	*
LAr supply dewar reliefs	Max flow thru relief valve	Premature open	4	1.00E-05	NRC	4.00E-05	0.9993	68.1	2000	20.28	1.16E-09	4.63E-14	
PSV-203-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-204-Ar	Max flow thru valve (Cv = 1.2)	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	0.9993	1825	2000	15.50	5.06E-06	8.81E-11	*
MV-204-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-213-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-218-Ar	Max flow thru valve (Cv = 1.2)	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	0.9993	1825	2000	15.50	5.06E-06	8.81E-11	*
MV-218-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
PSV-219-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-217-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-365-V	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-366-V	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-365-V	Max flow thru valve (Cv = 1.2)	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	0.9993	1825	2000	15.50	5.06E-06	8.81E-11	*
MV-366-V	Max flow thru valve (Cv = 1.2)	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	0.9993	1825	2000	15.50	5.06E-06	8.81E-11	*
MV-480-HAr	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-461-HAr	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
PSV-250-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
PSV-249-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-202-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-208-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-239-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-244-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
MV-370-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	433	2000	16.45	9.53E-07	9.52E-15	
LT-13-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
MV-360-V	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-360-V	Max flow into cryostat	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	0.9993	232	2000	18.56	2.36E-08	4.10E-13	
MV-241-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-247-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-248-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
DPT-67-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
DPT-153-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
MV-248-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
EP-307-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
EP-78-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
PSV-156-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-242-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
PI-243-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
MV-246-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-128-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
PSV-136-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-132-N2	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-132-N2	Max flow into cryostat	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	0.9993	232	2000	18.56	2.36E-08	4.10E-13	
MV-131-N2	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-127-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-251-V	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-252-V	Max flow into cryostat	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	0.9993	232	2000	18.56	2.36E-08	4.10E-13	
MV-252-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-253-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-290-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-254-V	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
PT-185-V	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
PT-186-V	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
MV-256-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
CV-256-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-291-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-294-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-295-V	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-296-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
PI-12-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
PT-19-V	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
PSV-210-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
PT-11-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
PT-33-V	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
MV-255-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
EP-205-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
RD-302-V	Max flow into cryostat	Premature Open	1	1.00E-05	NRC	1.00E-05	0.9993	232	2000	18.56	2.36E-08	2.36E-13	
PSV-313-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-354-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
PI-345-Ar	Treat as flange, Max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	433	2000	16.45	9.53E-07	2.86E-13	
MV-327-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-327-Ar	Max flow into cryostat	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	0.9993	232	2000	18.56	2.36E-08	4.10E-13	
Luke Cryostat	Treat as dewar, max flow into cryostat	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	0.9993	232	2000	18.56	2.36E-08	2.36E-14	
Welds up to and including Luke	Max flow thru 25% pipe diameter	Leak/rupture	100	3.00E-09	NRC	3.00E-07	0.9993	433	2000	16.45	9.53E-07	2.86E-13	
Flanges up to and including Luke	Max flow thru 25% pipe diameter	Leak/rupture	40	3.00E-07	NRC	1.20E-05	0.9993	433	2000	16.45	9.53E-07	1.14E-11	
Luke LAr vent piping	Max flow into cryostat	Leak/rupture	1	1.00E-09	NRC	1.00E-09	0.9993	232	2000	18.56	2.36E-08	2.36E-17	
LT-372-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
PT-373-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
PT-374-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
PI-363-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	0.9993	232	2000	18.56	2.36E-08	7.07E-15	
RD-376-Ar	Max flow into cryostat	Premature Open	1	1.00E-05	NRC	1.00E-05	0.9993	232	2000	18.56	2.36E-08	2.36E-13	
PSV-377-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
PSV-378-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-379-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-380-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
MV-381-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	0.9993	232	2000	18.56	2.36E-08	2.36E-16	
Bo Cryostat	Treat as dewar, max flow into cryostat	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	0.9993	232	2000	18.56	2.36E-08	2.36E-14	
Welds associated with Bo	Max flow into cryostat	Leak/rupture	50	3.00E-09	NRC	1.50E-07	0.9993	232	2000	18.56	2.36E-08	3.54E-15	
Flanges associated with Luke	Max flow into cryostat	Leak/rupture	20	3.00E-07	NRC	6.00E-06	0.9993	232	2000	18.56	2.36E-08	1.41E-13	
Bo LAr vent piping	Max flow into cryostat	Leak/rupture	1	1.00E-09	NRC	1.00E-09	0.9993	232	2000	18.56	2.36E-08	2.36E-17	
Solid Xenon Experiment													
Argon cooling circuit	Max flow out of stockroom LAr dewar	Valve left wide open	1	4.17E-03	33 x 5064 TBL 3	4.17E-03	0.9993	1643	2000	20.20	1.34E-09	5.59E-12	*
Photomultiplier Tube Test Stand													
LN2 fill of PMT test stand	Max flow out of stockroom LN2 dewar	Valve left wide open	1	4.17E-03	33 x 5064 TBL 3	4.17E-03	0.9993	1679	2000	20.30	1.13E-09	4.69E-12	*
Failure of PMT test dewar	Treat as pressure vessel failure	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	0.9993	1679	2000	19.70	3.22E-09	3.22E-15	*
PAB Inventory	***Assume five unconnected stockroom LAr dewars and five unconnected stockroom LN2 dewars***												
LAr supply dewar reliefs	Max flow thru one stockroom dewar relief valve	Premature open	5	1.00E-05	NRC	5.00E-05	0.9993	68.1	2000	20.20	1.34E-09	6.71E-14	*
LAr supply dewar isolation valves	Max flow out of five stockroom LAr dewars	5 Valves left wide open	1	1.14E-04	Estimate	1.14E-04	0.9993	8215	2000	16.90	4.36E-07	4.97E-11	*
LN2 supply dewar reliefs	Max flow thru one stockroom dewar relief valve	Premature open	5	1.00E-05	NRC	5.00E-05	0.9993	81.4	2000	20.30	1.13E-09	5.63E-14	*
LN2 supply dewar isolation valves	Max flow out of five stockroom LN2 dewars	5 Valves left wide open	1	1.14E-04	Estimate	1.14E-04	0.9993	8395	2000	17.60	1.28E-07	1.46E-11	*
Distillation Column													
Full discharge	All inert gas leaves column and gas bottles	total failure	1	1.14E-04	Estimate	1.14E-04	0.9993	N/A	2000	19.70	3.22E-09	3.67E-13	*
					SUM	**8.90E-03**					**SUM**	**1.44E-09**	

* Denotes that the minimum O2 concentration is equal to the amount of cryogens present because the leak rate creates a minimum O2 concentration that exceeds the amount of cryogens present.
N/A denotes that the gas is assumed to be instantaeously released, a leak rate is not calculated.

Table 3.5a.2: PAB ODH Risk Analysis with NO ventilation running.

ITEM	Comment	Type of Failure	# of Items	Pi Fail Rate events/hr	Source of Fail Rate	Group Fail Rate (Pi x #) events/hr	Fan Availability Rate events/hr	R leak rate SCFM	Q vent rate SCFM	O2 Concentration %	Fi Fatality Factor fatality/event	ϕ=∑PiFi ODH Rate fatality/hr
Nitrogen circuit												
LN2 supply piping	< 3" diameter, max flow into PAB	Rupture - severed line	1	1.00E-09	NRC	1.00E-09	7.00E-04	1198	0	0	1.00E+00	7.00E-13
Condensor	Treat as dewar, 25% pipe diameter	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	7.00E-04	260	0	0	1.00E+00	7.00E-10
EV-104-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
EV-105-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
EV-106-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
LT-10-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	260	0	0	1.00E+00	2.10E-10
MV-119-N	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
MV-120-N	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
PI-44-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	260	0	0	1.00E+00	2.10E-10
PI-133-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	260	0	0	1.00E+00	2.10E-10
PT-1-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	260	0	0	1.00E+00	2.10E-10
PT-27-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	260	0	0	1.00E+00	2.10E-10
PSV-101-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
PSV-101-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
PSV-101-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
TE-6-N2	Treat as flange, max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	260	0	0	1.00E+00	2.10E-10
SV-117-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
Welds	Max flow thru 25% pipe diameter	Leak/rupture	50	3.00E-09	NRC	1.50E-07	7.00E-04	260	0	0	1.00E+00	1.05E-10
Flanges	Max flow thru 25% pipe diameter	Leak/rupture	10	3.00E-07	NRC	3.00E-06	7.00E-04	260	0	0	1.00E+00	2.10E-09
LN2 vent piping	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-09	NRC	1.00E-09	7.00E-04	260	0	0	1.00E+00	7.00E-13
PCV-388-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
PSV-389-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
MV-375-N2	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	260	0	0	1.00E+00	7.00E-12
LN2 tank vacuum	Rupture into vacuum space, vacuum pumped into PAB	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	7.00E-04	6.00	0	0	1.00E+00	7.00E-10
GN2 purge supply**	Restricted by orifice outside PAB	Normally vents	1	1.00E+00	FNAL	1.00E+00	7.00E-04	0.25	0	21.00	0.00E+00	0.00E+00

** The GN2 purge that vents into the PAB high bay would take over 7 weeks to reduce the oxygen concentration to 18 % thus it is not considered to reduce the high bay oxygen content in the event of an ODH fan failure.

ITEM	Comment	Type of Failure	# of Items	Pi Fail Rate events/hr	Source of Fail Rate	Group Fail Rate (Pi x #) events/hr	Fan Availability Rate events/hr	R leak rate SCFM	Q vent rate SCFM	O2 Concentration %	Fi Fatality Factor fatality/event	ϕ=∑PiFi ODH Rate fatality/hr
Argon Circuit												
LAr supply piping	< 3" diameter, max flow into PAB	Rupture - severed line	1	1.00E-09	NRC	1.00E-09	7.00E-04	6572	0	15.5	5.06E-06	5.06E-15
LAr supply dewar reliefs	Max flow thru relief valve	Premature open	4	1.00E-05	NRC	4.00E-05	7.00E-04	68.1	0	15.5	5.06E-06	2.03E-10

PSV-203-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-204-Ar	Max flow thru valve (Cv = 1.2)	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	7.00E-04	1825	0	15.5	5.06E-06	8.81E-11
MV-204-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-213-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-218-Ar	Max flow thru valve (Cv = 1.2)	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	7.00E-04	1825	0	15.5	5.06E-06	8.81E-11
MV-218-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
PSV-219-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-217-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-365-V	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-366-V	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-365-V	Max flow thru valve (Cv = 1.2)	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	7.00E-04	1825	0	15.5	5.06E-06	8.81E-11
MV-366-V	Max flow thru valve (Cv = 1.2)	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	7.00E-04	1825	0	15.5	5.06E-06	8.81E-11
MV-480-HAr	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-461-HAr	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
PSV-250-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
PSV-249-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-202-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-208-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-239-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-244-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
MV-370-Ar	Max flow thru 25% pipe diameter	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	433	0	15.5	5.06E-06	3.54E-17
LT-13-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
MV-360-V	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-360-V	Max flow into cryostat	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	7.00E-04	232	0	15.5	5.06E-06	6.17E-14
MV-241-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-247-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-248-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
DPT-67-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
DPT-153-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
MV-248-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
EP-307-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
EP-78-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
PSV-156-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-242-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
PI-243-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
MV-246-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-128-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
PSV-136-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-132-N2	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-132-N2	Max flow into cryostat	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	7.00E-04	232	0	15.5	5.06E-06	6.17E-14
MV-131-N2	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-127-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-251-V	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-252-V	Max flow into cryostat	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	7.00E-04	232	0	15.5	5.06E-06	6.17E-14
MV-252-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-253-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-290-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-254-V	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
PT-185-V	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
PT-186-V	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
MV-256-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
CV-256-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-291-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-294-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	2.36E-08	2.36E-16
MV-295-V	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	2.36E-08	2.36E-16
MV-296-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	2.36E-08	2.36E-16
PI-12-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
PT-19-V	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
PSV-210-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
PT-11-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
PT-33-V	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
MV-255-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
EP-205-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
RD-302-V	Max flow into cryostat	Premature Open	1	1.00E-05	NRC	1.00E-05	7.00E-04	232	0	15.5	5.06E-06	3.54E-14
PSV-313-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-354-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
PI-345-Ar	Treat as flange, Max flow thru 25% pipe diameter	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	433	0	15.5	5.06E-06	1.06E-15
MV-327-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	2.36E-08	2.36E-16
MV-327-Ar	Max flow into cryostat	Valve left wide open	1	1.74E-05	33 x 5064 TBL 3	1.74E-05	7.00E-04	232	0	15.5	2.36E-08	4.10E-13
Luke Cryostat	Treat as dewar, max flow into cryostat	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	7.00E-04	232	0	15.5	5.06E-06	3.54E-15
Welds up to and including Luke	Max flow thru 25% pipe diameter	Leak/rupture	100	3.00E-09	NRC	3.00E-07	7.00E-04	433	0	15.5	5.06E-06	1.06E-15
Flanges up to and including Luke	Max flow thru 25% pipe diameter	Leak/rupture	40	3.00E-07	NRC	1.20E-05	7.00E-04	433	0	15.5	5.06E-06	4.25E-14
LAr vent piping	Max flow into cryostat	Leak/rupture	1	1.00E-09	NRC	1.00E-09	7.00E-04	232	0	15.5	5.06E-06	3.54E-18
LT-372-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
PT-373-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
PT-374-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
PI-363-Ar	Treat as flange, max flow into cryostat	Leak/rupture	1	3.00E-07	NRC	3.00E-07	7.00E-04	232	0	15.5	5.06E-06	1.06E-15
RD-376-Ar	Max flow into cryostat	Premature Open	1	1.00E-05	NRC	1.00E-05	7.00E-04	232	0	15.5	5.06E-06	3.54E-14
PSV-377-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
PSV-378-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-379-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-380-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
MV-381-Ar	Max flow into cryostat	Leak/rupture	1	1.00E-08	NRC	1.00E-08	7.00E-04	232	0	15.5	5.06E-06	3.54E-17
Bo Cryostat	Treat as dewar, max flow into cryostat	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	7.00E-04	232	0	15.5	5.06E-06	3.54E-15
Welds associated with Bo	Max flow into cryostat	Leak/rupture	50	3.00E-09	NRC	1.50E-07	7.00E-04	232	0	15.5	5.06E-06	5.32E-16
Flanges associated with Luke	Max flow into cryostat	Leak/rupture	20	3.00E-07	NRC	6.00E-06	7.00E-04	232	0	15.5	5.06E-06	2.13E-14
Bo LAr vent piping	Max flow into cryostat	Leak/rupture	1	1.00E-09	NRC	1.00E-09	7.00E-04	232	0	15.5	5.06E-06	3.54E-18
Solid Xenon Experiment												
Argon cooling circuit	Max flow out of stockroom LAr dewar	Valve left wide open	1	4.17E-03	33 x 5064 TBL 3	4.17E-03	7.00E-04	1643	0	20.20	1.34E-09	3.92E-15
Photomultiplier Tube Test Stand												
LN2 fill of PMT test stand	Max flow out of stockroom LN2 dewar	Valve left wide open	1	4.17E-03	33 x 5064 TBL 3	4.17E-03	7.00E-04	1679	0	20.30	1.13E-09	3.29E-15
Failure of PMT test dewar	Treat as pressure vessel failure	Leak/rupture	1	1.00E-06	FNAL	1.00E-06	7.00E-04	1679	0	19.70	3.22E-09	2.26E-18
PAB Inventory	***Assume five unconnected stockroom LAr dewars and five unconnected stockroom LN2 dewars***											
LAr supply dewar reliefs	Max flow thru relief valve	Premature open	5	1.00E-05	NRC	5.00E-05	7.00E-04	68.1	0	20.20	1.34E-09	4.70E-17
LAr supply dewar isolation valves	Max flow out of 5 stockroom LAr dewars	5 Valves left wide open	1	1.14E-04	Estimate	1.14E-04	7.00E-04	8215	0	16.90	4.36E-07	3.48E-14
LN2 supply dewar reliefs	Max flow thru relief valve	Premature open	5	1.00E-05	NRC	5.00E-05	7.00E-04	81.4	0	20.30	1.13E-09	3.94E-17
LN2 supply dewar isolation valves	Max flow out of five stockroom LN2 dewars	5 Valves left wide open	1	1.14E-04	Estimate	1.14E-04	7.00E-04	8395	0	17.60	1.28E-07	1.02E-14
Distillation Column												
Full discharge	All inert gas leaves column and gas bottles	total failure	1	1.14E-04	Estimate	1.14E-04	7.00E-04	N/A	o	19.70	3.22E-09	2.57E-16 *
					SUM	**1.01E+00**					**SUM**	**5.51E-09**