Fermilab

Particle Physics Division
Mechanical Department

Date: December 18, 2014, revision March 6, 2015

Project: LArIAT

Project Internal Reference: LArTPC document database, document #1213.
Liquid Argon LARTPC-doc-1213, http://lartpc-docdb.fnal.gov:8080/cgi-bin/ShowDocument?docid=1213

Title: **MC7 Oxygen Deficiency Hazard Assessment for LArIAT**

Author: Russ Rucinski

Reviewer: Print name: Andrew A. Dalesandro

Signature: 3/6/15

Key Words: MC7, ODH, LArIAT

Abstract/Summary: This is the ODH assessment for the MC7 enclosure due to the LArIAT experiment equipment. The assessment concludes that MC7 is ODH class 0. An ODH monitoring system including ODH exhaust fan is necessary to maintain that classification.

Applicable Codes:

Fermilab Oxygen Deficiency Hazards, FESHM Chapter 4240.

Oxygen Deficiency Hazard Assessment for MC7 due to LArIAT cryogenic system

Summary

Filtered liquid argon is supplied to a cryostat that holds 550 liters in MC7. Boil-off is vented outside. An ODH monitoring system is installed and operates an ODH exhaust fan if an oxygen deficiency is detected. Isolation valves on the inert gas source supply lines also close if an ODH is detected. The probability of failures and fatality rates are summed for the components of the system. **The total fatality rate is $3x10^{-8}$/hr and classifies the MC7 area as ODH class 0.** No special precautions are necessary due to the risk of ODH from the cryogenic system.

Introduction

The MC7 beam line enclosure has been recently re-purposed for test beam use. The LArIAT experiment is a cryogenic liquid argon time projection chamber (TPC) that will be installed in MC7. LArIAT stands for **L**iquid **Ar**gon **I**n **A** **T**estbeam. The purpose of LArIAT is to study detector response and calibration using a beam of charged particles of known momentum. The primary element in terms of cryogenics is the Cryostat containing 550 liters of liquid argon and the TPC. The cryogenic system is a simple one pass system where a supply from a vendor dewar (located outside of MC7) keeps the cryostat full. Boil-off from the cryostat or the transfer line is vented outside.

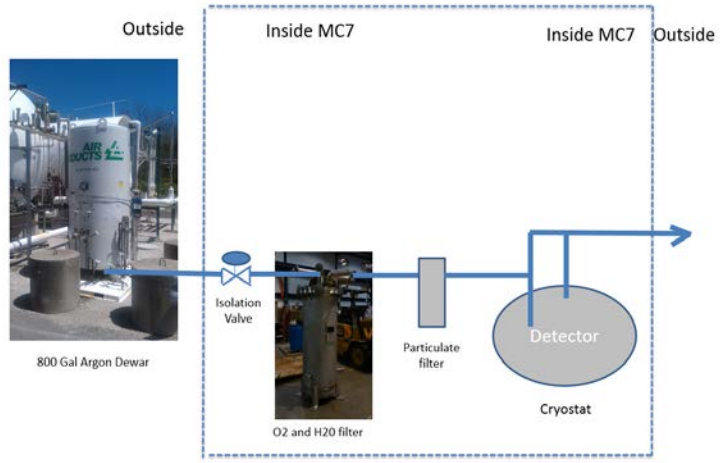


Figure 1. Simplified block diagram of the one-pass cryogenic system.

Building Volume

The MC7 enclosure is a Quonset hut structure along the muon center beam line. The picture below shows the external east side of the MC7 enclosure. The LArIAT experiment is going to be located in the section with the roll up door. The adjacent volumes upstream (towards the building) and downstream are openly connected to the LArIAT equipment area and are considered as the part of the total volume of the building. The building volume was calculated in the appendix as 17,418 cubic feet.

Picture 1 & 2. Exterior and interior of the MC7 Enclosure.

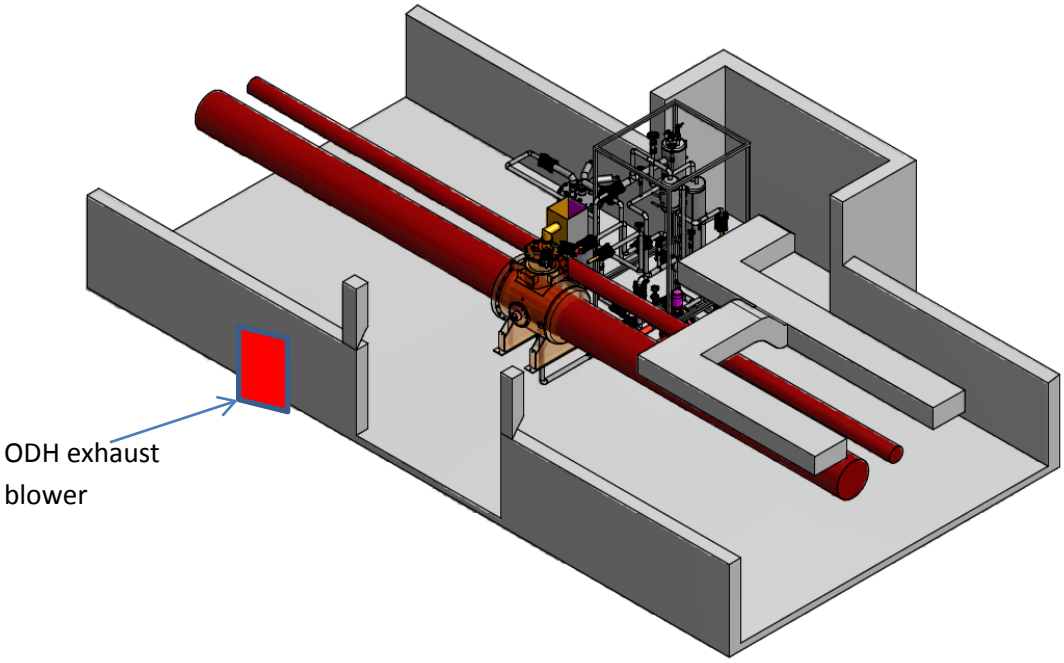


Figure 2. Isometric view of the LArIAT cryostat (orange) and cryogenic equipment skid in the MC7 enclosure. The large red cylindrical shapes are keep clear zones for the primary and tertiary beam.

Ventilation Systems

The MC7 enclosure has comfort heating and cooling system. No credit is taken for this ventilation as it is not continuous or monitored. Instead a dedicated ODH exhaust fan system is in place with 3000 cfm exhaust capability. The blower has its own floor level intake and outlet duct that vents outside. When an ODH condition (set at 19.5%) is signaled by any of the ODH detectors the following automated responses
occur:

A. Activation of ODH alarm horns and lights
B. Activation of the ODH exhaust blower
C. Liquid argon supply valve, LCV-105-A, upstream of filter closes
D. Regeneration gas supply valves close

The blower is positioned in proximity of the LArIAT cryostat. The intake is at floor level to draw in heavier than air gases level and exhaust the gases outside. Fresh air is drawn in through an existing air intake vent located downstream of LArIAT. It is in the roof and is about 16" diameter. When cryogens are present in MC7, the ODH exhaust blower will be energized for a short period of time each day to confirm that the blower is operational. Proper operation is confirmed by a flow switch on the blower's outlet. All blower failure modes (power, fuse, motor, belt, or mechanical linkage) will be detected as a lack of pressure on the blower outlet. The LArIAT PLC will inform the Fermi Facility Information Reporting Utility System (FIRUS) and use its auto dialer to inform LArIAT operational personnel if the blower fails to operate during the test period.

Picture 3. ODH fan mounted on floor of MC7.

ODH Detectors

ODH heads will be located near the cryostat, near the filter, and in the below grade MC7 bottom tunnel that begins about 30 feet downstream of LArIAT. Another will be located at head height under the liquid argon transfer line where it penetrates the wall. See figures 3 and 4 for locations of the ODH heads.

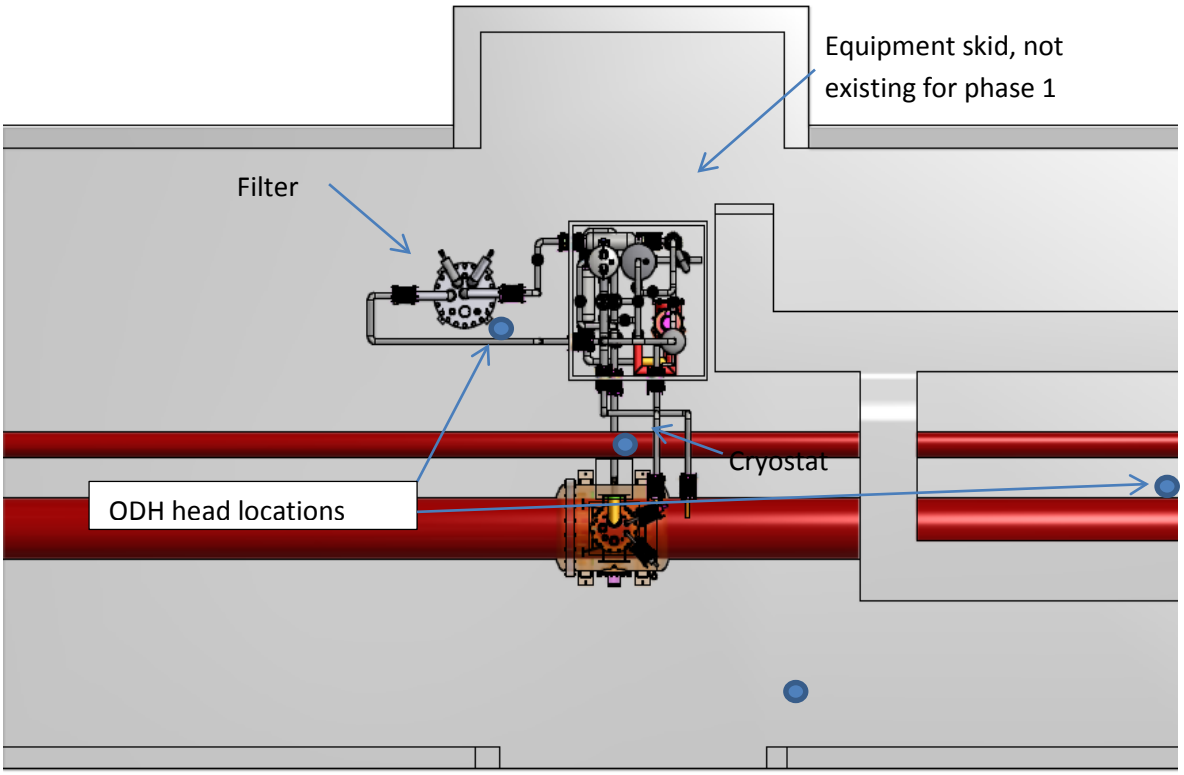


Figure 3. Location of ODH heads in MC7.

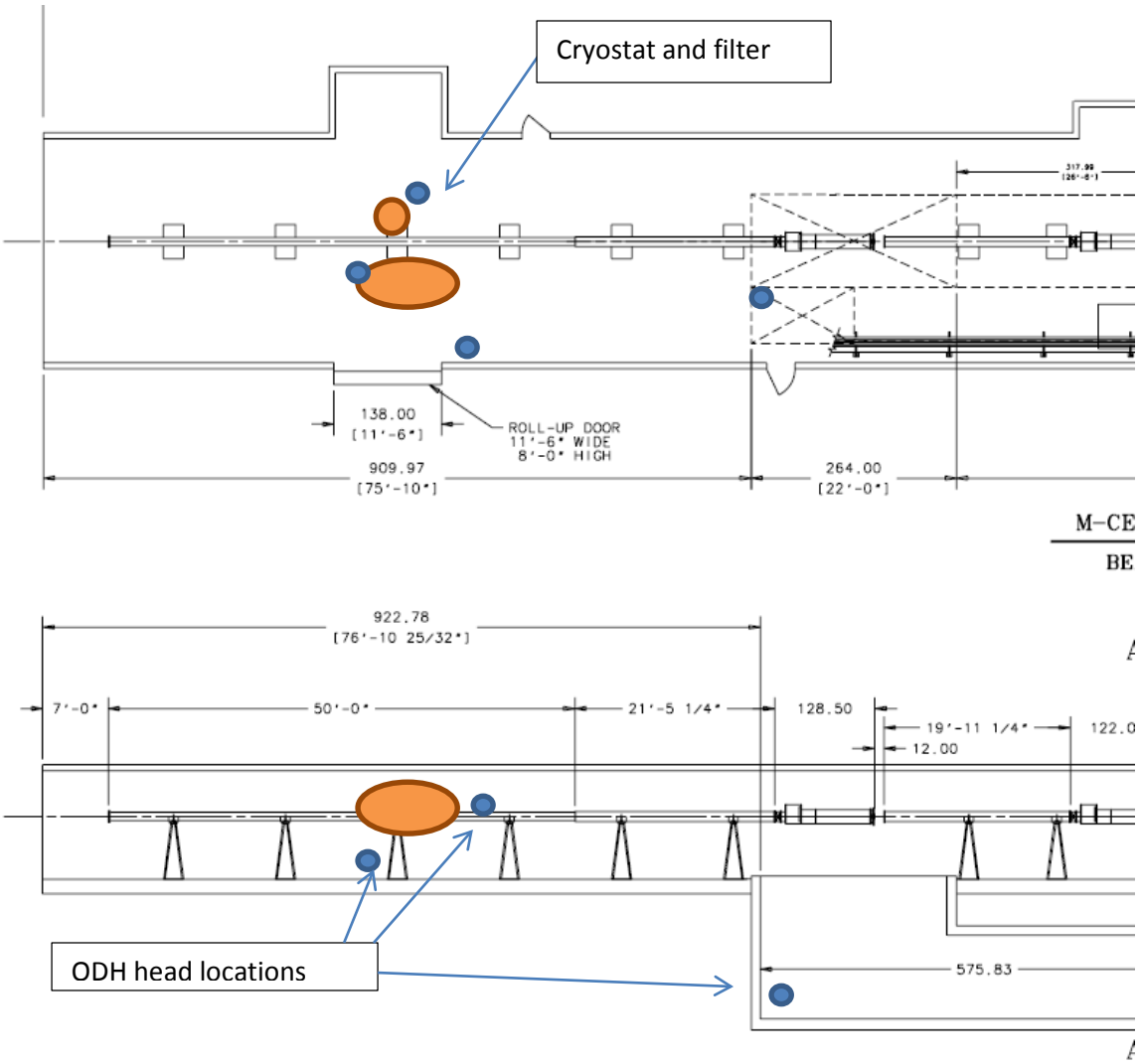


Figure 4. MC7 bottom location and relationship to LArIAT.

Sources of Cryogens or Inert Gas

Argon Storage Dewar

There is an 800 gallon (85,000 scf gas equivalent) liquid argon storage dewar located outside of MC7. A 1" pipe size liquid withdrawal line runs from the dewar and into MC7. Inside MC7, the liquid is filtered and then supplied to the LArIAT cryostat. The LArIAT cryostat vents outside. The Argon storage dewar liquid withdrawal line is a source of inert gas up to an isolation valve located upstream of the filter. The isolation valve closes upon an ODH condition. The argon dewar also supplies gas argon for regeneration sweep purging and cooling the filters during regeneration. A flow control valve on the regeneration line closes upon an ODH condition.

Filter and Cryostat

The LAr filter contains 77 liters of liquid argon (2260 scf gas equivalent). The LArIAT cryostat contains approximately 550 liters of liquid argon (16,150 scf gas equivalent). There will be a liquid inventory of about 10 liters or less in the piping (294 scf gas equivalent).

Regeneration Gas Tube Trailer

A 40,000 scf tube trailer of 97.5% argon, 2.5% hydrogen will be connected to the filter during regeneration. The regeneration gas flow rate is limited by the regulator on the tube trailer and the flow resistance of the transfer line into MC7. A flow control valve on the regeneration line closes upon an ODH condition.

Failures contributing to ODH

Pressure Vessel –Cryostat Leak and Failure

The LArIAT cryostat and LAr filter are considered pressure vessels in this analysis. FESHM 4240 table 2 gives failure rates for a pressure vessel at $8x10^{-8}$/hr for a small, 10 mm^2 leak and $5x10^{-9}$/hr for a disruptive failure. The release rate for a small leak is estimated as flow through a 10 mm^2 orifice with an inlet pressure equal to the vessel MAWP. The release rate for a disruptive failure is estimated as the flow that can occur through the largest piping port on the vessel with an inlet pressure equal to the vessel MAWP.

The LArIAT cryostat has a MAWP of 30 psig. It has its own line in the ODH calculation spreadsheet. A small leak rate was calculated at 188 cfm. The large leak rate thru the 1.5" OD drain stub was calculated to be 15, 116 cfm. That would be the peak flow rate which would occur for about 1 minute while the cryostat and filter drained. The available inventory for a leak in the cryostat is the filter plus cryostat plus that in the transfer lines, 77 liters + 550 liters + 10 liters (2260 scf +16,150 scf +294 scf = 18,704 scf gas equivalent). The inventory in the LAr dewar outside is not available because it will be isolated by the automatic closing of the flow control valve, LCV-105-A, in the event of an ODH. Consideration of the valve, LCV-105-A, not closing is not taken since including the LAr dewar inventory does not change the calculated fatality factors.

Pressure Vessel –Cryostat Relief valve premature open

The failure rate of relief valves premature opening is given at $1x10^{-5}$/hr in FESHM 4240. If the relief valve or rupture disc on the cryostat prematurely opens, then there will be a release of argon until the oxygen concentration drops to 19.5%, triggering the ODH system which closes LCV-105-A and the LAr dewar as a source of cryogen. The remaining inventory of 18,704 scf is available to be released as gas. The release rate would be that driven by the boil-off due to heat load of the system, ~350 watts. The boil-off rate is very small, 3 cfm.

Consider the isolation valve not closing. There is a $3x10^{-4}$/D failure rate for the isolation valve LCV-105-A to not operate. This failure rate is multiplied by the probability of the premature opening failure rate and by two since there are two relief devices. The total failure rate is $1x10^{-5}$/hr*$3x10^{-4}$/D*2 = $6x10^{-9}$/hr. In this case, the complete system inventory, 103,700 scf is available to be released through the open relief device. The leak rate is calculated considering the LAr dewar to be at 100 psig and the physical piping to the cryostat. That flow rate was calculated to be 1345 cfm.

Pressure Vessel – LArIAT Filter Leak and Failure

The LArIAT cryostat and LAr filter are considered pressure vessels in this analysis. FESHM 4240 table 2 gives failure rates for a pressure vessel at $8x10^{-8}$/hr for a small, 10 mm^2 leak and $5x10^{-9}$/hr for a disruptive failure. The release rate for a small leak is estimated as flow through a 10 mm^2 orifice with an inlet pressure equal to the vessel MAWP. The release rate for a disruptive failure is estimated as the flow that can occur through the largest piping port on the vessel with an inlet pressure equal to the vessel MAWP.

The LAr filter has a MAWP of 100 psig. It has its own line in the ODH calculation spreadsheet. A small leak rate was calculated to be 320 cfm. The large leak rate was calculated as a severed 1" schedule 10 pipe, the pipe size inside the filter. That severed pipe leak rate was calculated to be 19,608 cfm. The available inventory for a leak in the filter is limited to that in the filter itself and the transfer lines, 77 liters + 10 liters (2260 scf +294 scf = 2554 scf gas equivalent). The inventory in the cryostat will remain in the cryostat and the LAr dewar outside is not available because it will be isolated by the automatic closing of the flow control valve, LCV-105-A, in the event of an ODH.

Consider that the isolation valve does not close. There is a $3x10^{-4}$/D failure rate for the isolation valve LCV-105-A to not operate. This probability is applied to both the $8x10^{-8}$/hr for a small, 10 mm^2 leak and $5x10^{-9}$/hr for a disruptive failure. The total inventory available now includes the LAr dewar, for a total of 87554 scf.

Pressure Vessel – LArIAT Filter Relief valve premature open

The failure rate of relief valves premature opening is given at $1x10^{-5}$/hr in FESHM 4240. If the relief valve on the filter prematurely opens, then there will be a release of argon until the oxygen concentration drops to 19.5%, triggering the ODH system which closes LCV-105-A and the LAr dewar as a source of cryogen. The remaining inventory of 2554 scf is available to be released as gas. The release rate would be that driven by the boil-off due to heat load of the system, ~350 watts. The boil-off rate is very small, 3 cfm.

Consider the isolation valve not closing. There is a $3x10^{-4}$/D failure rate for the isolation valve LCV-105-A to not operate. This failure rate is multiplied by the probability of the premature opening failure rate. The total failure rate is $1x10^{-5}$/hr*$3x10^{-4}$/D = $3x10^{-9}$/hr. In this case, the complete system inventory, 87554 scf is available to be released through the open relief device. The leak rate is calculated by considering the LAr dewar to be at 100 psig and the physical piping to the filter to be 1997 cfm.

Argon Piping – Leak and Failure

Piping can fail by leaking or breaking. The failure rates for piping are taken from FESHM 4240 table 2. The leak failure in FESHM 4240 is broken down into a small leak and a large leak. A small leak is an opening of 10 mm^2 or less. A small leak failure rate is given as $1x10^{-9}$/m-hr. The small leak rate calculation is the same as a small leak in the filter, 320 cfm. A large leak is an opening of 10 mm^2 to 1000 mm^2. For this analysis, an average of 610 mm^2 is used to represent large leaks. This is because the majority of the piping in the system is 1" sch. 10 pipe with a cross section of 610 mm^2. The large leak failure rate will be less frequent than a small leak. A large leak failure rate is taken at $1x10^{-10}$/m-hr (even though it is listed in FESHM 4240 table 2 as for pipes >2").

The failure of piping is divided into two sections at LCV-105-A. Upstream of LCV-105-A, the available inventory is the LAr dewar, 800 gallons (85,000 scf gas equivalent). There is about 5 meters of piping upstream of LCV-105-A. Downstream of LCV-105-A, say after the cryostat, the flow rate is not limited but the available inventory is limited to the filter and the cryostat and the transfer line, 77 liters + 550 liters + 10 liters (2260 scf +16,150 scf +294 scf = 18,704 scf gas equivalent). There is about 20 meters or less of piping downstream of LCV-105-A.

Argon piping, Flanges and Conflats – Leak and Failure

The piping system upstream of LCV-105-A has no flanges. Downstream of LCV-105-A, the piping system contains a conflat flange on the bottom of the cryostat which is accessible by bellows on the outer vacuum jacket. The conflat flange uses a rigid copper gasket. There are two dielectric gasket type flanges at the cryostat. The dielectric gaskets use a G-10 clad stainless ring and Teflon o-ring sandwiched between smooth face 150# flanges. A flange leak rate of $4x10^{-7}$/hr from FESHM 4240 is used in the analysis. The leak rate is the same as that calculated for a small leak in a pipe. A flange rupture probability of $1x10^{-9}$/hr from FESHM 4240 is used in the analysis along with a large pipe flow rate of 19,600 cfm.

Argon piping, Relief Valves – Premature Opening

The piping system upstream of LCV-105-A has no relief valves. Downstream of LCV-105-A there is one trapped volume relief, PSV-309-A set at 150 psig. The failure rate of relief valves premature opening is given at $1x10^{-5}$/hr in FESHM 4240. The operating pressure in that section of piping is going to less than 10 psig. It is relieved by the upstream filter at 100 psig. Premature opening of the trapped volume relief with inlet pressures less than 80% of the set pressure is not credible therefore the failure rate for the ODH calculation is set to 0. The trapped volume relief would only operate if liquid cryogen is blocked in due to operator error and in that case, the amount of released gas is negligible for ODH.

Regeneration Piping – Leak and Failure

The regeneration piping is non-insulated gas piping that supplies either argon gas or a 97.5% argon, 2.5% hydrogen mix gas into MC7 and into the filters during a filter regeneration operation. The source of inert gas is either the 800 gallon (85,000 scf gas equivalent) argon dewar or a 40,000 scf tube trailer

outside of MC7. Only one source will be on-line at a time. We will use the larger, 85,000 scf source as the available cryogen in the spreadsheet calculation. The regeneration piping enters MC7 and is routed to two flow control valves (FCV-424-H or FCV-653-A) which close in the event of an ODH condition. Upstream of the control valves we have 1"OD x 0.095" wall tubing put together with Swagelok unions. Downstream there are valves, piping, and a relief valve. No credit is taken for the flow control valves closing during the ODH. The small leak failure rate is given as $1x10^{-9}$/m-hr. The small leak rate calculation is done for gas argon at 100 psig leaking out a 10 mm^2 orifice and came out to only 2 cfm. A large leak is an opening of 10 mm^2 to 1000 mm^2. The tubing used is 1.0" OD x 0.095" wall, with a cross sectional area of 332 mm^2. I consider the piping outside of MC7 to be 20 feet and the tube to be severed inside of MC7. The calculated leak rate for this large leak was 509 cfm.

ODH calculations

Oxygen Deficiency Hazard calculations are done using a spreadsheet that has the equations from FESHM 4240 embedded in the cells. This spreadsheet was developed in the PPD/Mechanical department by Mark Adamowski. It has been used for the PC4 ODH analysis. An exhaust ventilation rate of 3000 cfm is used, provided by the ODH fan which comes on at oxygen levels less than 19.5%. The possibility that there is no ventilation is also included for each of the tabulated events.

The possibility that the ventilation fan doesn't run for an ODH event could be the result of A.) The fan failing while running (9E-6/hr), B.) failing to start (1.08E-4/hr), C.) a power failure (1e-4/hr), D.) the ODH panel failing (2.98E-5/hr), or E.) the ODH monitor failing (5.62E-6/hr). The probability of any of these things occurring causing the fan to not run is the summation of them which equals 2.52E-4/hr. This probability is applied with a fatality factor calculated with zero ventilation rate.

The entries in the spreadsheet are in the same order as the "Failures that contribute to ODH" section of this note. The values entered into the spreadsheet are explained in the text. Leak rates were calculated at maximum conditions. For instance where the LAr dewar was the source, the pressure was taken at 100 psig, whereas in operation, we expect to operate around 40 psig. Where the source was the cryostat, the MAWP of the vessel, 30 psig, was taken as the source pressure whereas during operation, we plan to operate around 3 psig.

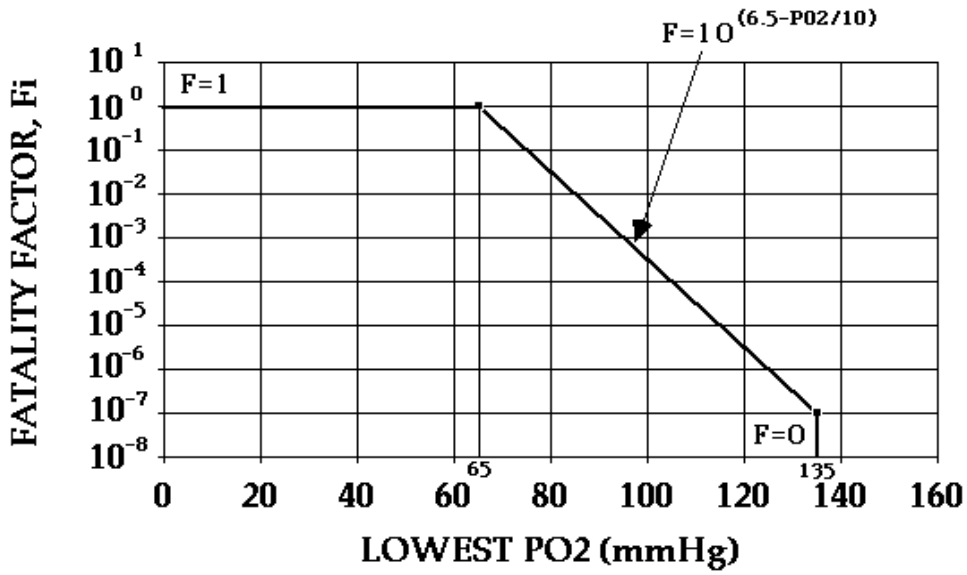
The oxygen deficiency hazard fatality rate is defined as:

$$\phi = \sum_{i=1}^{n} P_i F_i$$

where ϕ = the ODH fatality rate (per hour),

P_i = the expected rate of the ith event (per hour), and

F_i = the probability of a fatality due to event i.



If the leak rate, R was less than the exhaust rate, Q, the oxygen concentration is calculated with equation 4 of FESHM 4240 with time set to infinity: $C(t) = 0.21\left(1 - \frac{R}{Q}\left(1 - e^{-\frac{Q}{V}t}\right)\right)$ = 0.21(1-R/Q)

If the leak rate, R was greater than the exhaust rate, Q, the oxygen concentration is calculated with equation 6 of FESHM 4240 with time set to the time it takes to empty the inventory.

$$C(t) = 0.21\, e^{-\frac{R}{V}t}$$

The fatality factor is arrived at from the oxygen concentration calculation. The fatality factor is multiplied by the total failure rate and the result, the fatality rate is listed in column Q of the table. The fatality rates for all the "failures contributing to ODH" are summed and give a total fatality rate. This total fatality rate sets the ODH classification.

Spreadsheet Calculations

TABLE 1: ODH table using draft 5064 fan failure on demand (start)

People Space:	17,400	cu. ft.			
ODH Exhaust:	3,000	cu. ft./min	HVAC Ventilation	0	cu. ft./min
Total Exhaust Affecting ODH	3000	(vent. + ODH exhaust)	credible duration w/o ventilation	24	hr
P(Fan not avail ODH event):	2.52E-04	/hr	(this value comes from "pfan data" worksheet)		

Data for Fatality Formula				
	F=0	0.182	slope	-75.809
	F=1	0.088	b-intercept	7.78275

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 1=failed (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes
EQUIPMENT																			
LArIAT Cryostat w/ ventilation																			
Vessel	leak	1	8.00E-08	A	8.00E-08	18704	188	0	3000	99	19.68%	-	19.68%	19.68%	0	0	0	-	30 psig, 10 mm^2 hole
Vessel	failure	1	5.00E-09	A	5.00E-09	18704	15116	0	3000	1	-	7.17%	0.00%	7.17%	1.0	5.00E-9	0	0.0	1.5" pipe, 30 psig
relief valve - relief event, isolation valve closes	premature open	2	1.00E-05	A	2.00E-05	18704	3	0	3000	6235	20.98%	-	20.98%	20.98%	0	0	0	-	limited to boil-off rate
relief valve - relief event, isolation valve stays open	premature open	2	1.00E-05	A	6.00E-09	103700	1345	0	3000	77	11.59%	-	11.59%	11.59%	8.45E-3	5.07E-11	0	0.2	valve failure .0003 per demand
LArIAT Cryostat w/o vent.																			
Vessel	leak	1	8.00E-08	A	8.00E-08	18704	188	1	0	99	-	7.17%	0.00%	7.17%	1.0	2.02E-11	0	0.2	30 psig, 10 mm^2 hole
Vessel	failure	1	5.00E-09	A	5.00E-09	18704	15116	1	0	1	-	7.17%	0.00%	7.17%	1.0	1.26E-12	0	0.0	1.5" pipe, 30 psig
relief valve - relief event, isolation valve closes	premature open	2	1.00E-05	A	2.00E-05	18704	3	1	0	6235	-	7.17%	0.00%	7.17%	1.0	5.05E-9	0	13.6	limited to boil-off rate
relief valve - relief event, isolation valve stays open	premature open	2	1.00E-05	A	6.00E-09	103700	1345	1	0	77	-	0.05%	0.00%	0.05%	1.0	1.51E-12	0	0.0	valve failure .0003 per demand
Filter Vessel w/ ventilation																			
VESSEL	leak	1	8.00E-08	A	8.00E-08	2554	320	0	3000	8	19.33%	-	18.76%	19.33%	0	0	0	-	100 psig, 10 mm^2 hole
VESSEL	failure	1	5.00E-09	A	5.00E-09	2554	19608	0	3000	0	-	18.13%	0.00%	18.13%	1.21E-7	6.03E-16	0	0.0	small LAr inventory
VESSEL - isolation valve fails to close, small leak	leak	1	8.00E-08	A	2.40E-11	87554	320	0	3000	274	18.76%	-	18.76%	18.76%	0	0	0	-	valve failure .0003 per demand
VESSEL - isolation valve fails to close, failure	failure	1	5.00E-09	A	1.50E-12	87554	19608	0	3000	4	-	0.14%	0.00%	0.14%	1.0	1.50E-12	0	0.0	valve failure .0003 per demand
relief valve - relief event isolation valve closes	premature open	1	1.00E-05	A	1.00E-05	18704	3	0	3000	6235	20.98%	-	20.98%	20.98%	0	0	0	-	limited by boil-off from heat load
relief valve - relief event isolation valve fails to close	premature open	1	1.00E-05	A	3.00E-09	87554	1997	0	3000	44	7.03%	-	7.02%	7.03%	1.0	3.00E-9	0	0.1	valve failure .0003 per demand
Filter Vessel w/o vent.																			
VESSEL	leak	1	8.00E-08	A	8.00E-08	2554	320	1	0	8	-	18.13%	0.00%	18.13%	1.21E-7	2.44E-18	0	0.1	100 psig, 10 mm^2 hole
VESSEL	failure	1	5.00E-09	A	5.00E-09	2554	19608	1	0	0	-	18.13%	0.00%	18.13%	1.21E-7	1.52E-19	0	0.0	small LAr inventory
VESSEL - isolation valve fails to close	leak	1	8.00E-08	A	2.40E-11	87554	320	1	0	274	-	0.14%	0.00%	0.14%	1.0	6.06E-15	0	0.1	valve failure .0003 per demand
VESSEL - isolation valve fails to close	failure	1	5.00E-09	A	1.50E-12	87554	19608	1	0	4	-	0.14%	0.00%	0.14%	1.0	3.79E-16	0	0.0	valve failure .0003 per demand
relief valve - relief event isolation valve closes	premature open	1	1.00E-05	A	1.00E-05	18704	3	1	0	6235	-	7.17%	0.00%	7.17%	1.0	2.52E-9	0	13.6	limited by boil-off from heat load
relief valve - relief event isolation valve fails to close	premature open	1	1.00E-05	A	3.00E-09	87554	1997	1	0	44	-	0.14%	0.00%	0.14%	1.0	7.57E-13	0	0.0	valve failure .0003 per demand

PIPING																			
Argon Piping upstream of LCV-105-A w/ ventilation																			
PIPE (2" or less)	leak, small	5	1.00E-09	A	5.00E-09	85000	320	0	3000	266	18.76%	-	18.76%	18.76%	0	0	0	-	
PIPE (2" or less)	break	5	1.00E-10	A	5.00E-10	85000	19600	0	3000	4	-	0.16%	0.00%	0.16%	1.0	5.00E-10	0	0.0	
Flanges	leak	1	4.00E-07	A	4.00E-07	85000	320	0	3000	266	18.76%	-	18.76%	18.76%	0	0	0	-	
Flanges	rupture	1	1.00E-09	A	1.00E-09	85000	19600	0	3000	4	-	0.16%	0.00%	0.16%	1.0	1.00E-9	0	0.0	
VALVE	leak	1	1.00E-08	A	1.00E-08	85000	320	0	3000	266	18.76%	-	18.76%	18.76%	0	0	0	-	
Argon Piping upstream of LCV-105-A w/o vent.																			
PIPE (2" or less)	leak, small	5	1.00E-09	A	5.00E-09	85000	320	1	0	266	-	0.16%	0.00%	0.16%	1.0	1.26E-12	0	0.1	
PIPE (2" or less)	break	5	1.00E-10	A	5.00E-10	85000	19600	1	0	4	-	0.16%	0.00%	0.16%	1.0	1.26E-13	0	0.0	0
Flanges	leak	1	4.00E-07	A	4.00E-07	85000	320	1	0	266	-	0.16%	0.00%	0.16%	1.0	1.01E-10	0	0.1	
Flanges	rupture	1	1.00E-09	A	1.00E-09	85000	19600	1	0	4	-	0.16%	0.00%	0.16%	1.0	2.52E-13	0	0.0	
VALVE	leak	1	1.00E-08	A	1.00E-08	85000	320	1	0	266	-	0.16%	0.00%	0.16%	1.0	2.52E-12	0	0.1	
Argon Piping downstream of LCV-105-A w/ ventilation																			
PIPE (2" or less)	leak, small	20	1.00E-09	A	2.00E-08	18704	320	0	3000	58	18.76%	-	18.76%	18.76%	0	0	0	-	
PIPE (2" or less)	break	20	1.00E-10	A	2.00E-09	18704	19600	0	3000	1	-	7.17%	0.00%	7.17%	1.0	2.00E-9	0	0.0	
Flanges	leak	3	4.00E-07	A	1.20E-06	18704	320	0	3000	58	18.76%	-	18.76%	18.76%	0	0	0	-	
Flanges	rupture	3	1.00E-09	A	3.00E-09	18704	19600	0	3000	1	-	7.17%	0.00%	7.17%	1.0	3.00E-9	0	0.0	
VALVE	leak	1	1.00E-08	A	1.00E-08	18704	320	0	3000	58	18.76%	-	18.76%	18.76%	0	0	0	-	
Trapped V reliefs - relief event	premature open	1	0.00E+00	H	0.00E+00	18704	0	0	3000		-	-	21.00%	21.00%	0	0	0	-	not credible, relief set at 150 psig
Argon Piping downstream of LCV-105-A w/o vent.																			
PIPE (2" or less)	leak, small	20	1.00E-09	A	2.00E-08	18704	320	1	0	58	-	7.17%	0.00%	7.17%	1.0	5.05E-12	0	0.1	
PIPE (2" or less)	break	20	1.00E-10	A	2.00E-09	18704	19600	1	0	1	-	7.17%	0.00%	7.17%	1.0	5.05E-13	0	0.0	0
Flanges	leak	3	4.00E-07	A	1.20E-06	18704	320	1	0	58	-	7.17%	0.00%	7.17%	1.0	3.03E-10	0	0.1	
Flanges	rupture	3	1.00E-09	A	3.00E-09	18704	19600	1	0	1	-	7.17%	0.00%	7.17%	1.0	7.57E-13	0	0.0	
VALVE	leak	1	1.00E-08	A	1.00E-08	18704	320	1	0	58	-	7.17%	0.00%	7.17%	1.0	2.52E-12	0	0.1	
Trapped V reliefs - relief event	premature open	1	0.00E+00		0.00E+00	18704	0	1	0		-	-	21.00%	21.00%	0	0	0	-	not credible, relief set at 150 psig
Regeneration Piping w/ ventilation																			
PIPE (2" or less)	leak, small	20	1.00E-09	A	2.00E-08	85000	2	0	3000	42500	20.99%	-	20.99%	20.99%	0	0	0	-	
PIPE (2" or less)	break	20	1.00E-10	A	2.00E-09	85000	509	0	3000	167	17.44%	-	17.44%	17.44%	3.95E-7	7.90E-16	0	0.5	
Flanges	leak	5	4.00E-07	A	2.00E-06	85000	2	0	3000	42500	20.99%	-	20.99%	20.99%	0	0	0	-	
Flanges	rupture	5	1.00E-09	A	5.00E-09	85000	509	0	3000	167	17.44%	-	17.44%	17.44%	3.95E-7	1.97E-15	0	0.5	
VALVE	leak	5	1.00E-08	A	5.00E-08	85000	2	0	3000	42500	20.99%	-	20.99%	20.99%	0	0	0	-	
Relief valve opening	premature open	1	1.00E-05	A	1.00E-05	85000	509	0	3000	167	17.44%	-	17.44%	17.44%	3.95E-7	3.95E-12	0	0.5	Relief set at 100 psig
Regeneration Piping w/o vent.																			
PIPE (2" or less)	leak, small	20	1.00E-09	A	2.00E-08	85000	2	1	0	42500	-	0.16%	0.00%	0.16%	1.0	5.05E-12	0	20.4	
PIPE (2" or less)	break	20	1.00E-10	A	2.00E-09	85000	509	1	0	167	-	0.16%	0.00%	0.16%	1.0	5.05E-13	0	0.1	0
Flanges	leak	5	4.00E-07	A	2.00E-06	85000	2	1	0	42500	-	0.16%	0.00%	0.16%	1.0	5.05E-10	0	20.4	
Flanges	rupture	5	1.00E-09	A	5.00E-09	85000	509	1	0	167	-	0.16%	0.00%	0.16%	1.0	1.26E-12	0	0.1	
VALVE	leak	5	1.00E-08	A	5.00E-08	85000	2	1	0	42500	-	0.16%	0.00%	0.16%	1.0	1.26E-11	0	20.4	
Relief valve opening	premature open	1	1.00E-05	A	1.00E-05	85000	509	1	0	167	-	0.16%	0.00%	0.16%	1.0	2.52E-9	0	0.1	

Detector Building		
	Total Fatality Rate:	**2.561E-08**
	Overall ODH Class:	**0**

Probability of failure data for ODH monitoring equipment and ventilation fan

Data required for probability calculations

		req units	
P(Fan Fails while running)	9.00E-06	1/hr	draft 5064: rate includes failure of motor, starter and fuses
Fan test frequency:	**1**	days	
P(power fails):	1.00E-04	1/hr	FESHM 5064
Is this an ODH fan?	**1**		1 for yes, 0 for no
Is fan continuous running?	**0**		1 for yes, 0 for no

indicates user entered data (can start with default)

indicated user entered data (change to reflect fan type and test frequency)

ODH equipment P's cannot be blank, even if not an ODH fan.
When not an ODH fan or fan is contuous running, the ODH equipment P's are not used.

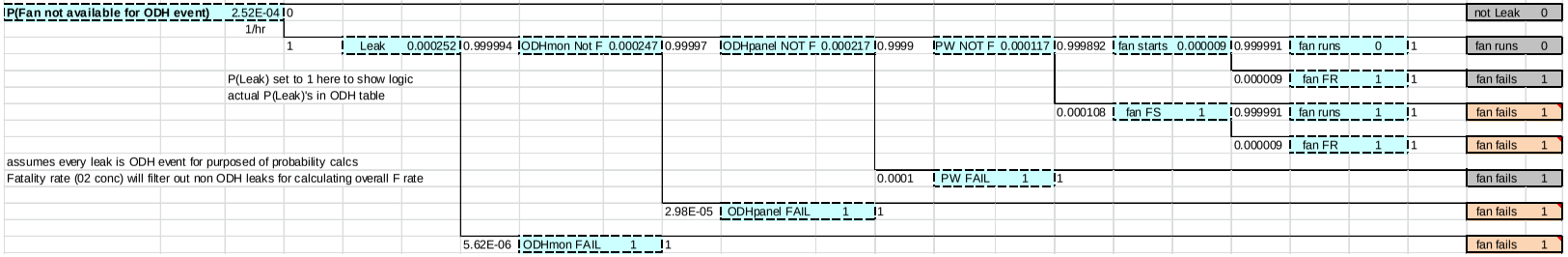
P(ODH monitor fails):	5.62E-06	1/hr	MSA Ultima XE/XL or equivalent
P(ODH panel fails):	2.98E-05	1/hr	MSA Gasguard XL or equivalent

Calculated values below (use caution in making modifications)

Fan test frequency:	24	hrs	calculated from days above
P(Fan fails to start)	1.08E-04	1/hr	

indicates calculated value (do not change)

outcomes for P calc are flagged below	
not part of this P calc	0
is part of this P calc	1
outcomes w/ this cell color are controlled by answers to fan questions above:	



P(Leak) set to 1 here to show logic
actual P(Leak)'s in ODH table

assumes every leak is ODH event for purposed of probability calcs
Fatality rate (02 conc) will filter out non ODH leaks for calculating overall F rate

APPENDIX - ODH TABLE NOTES

Columns (A) through (H) and (T) are user entered.

Column (I) is user entered ventilation flag that indicates whether a row is to be treated as having or not having ventilation.

(A) Equipment - Cryogen containing equipment and general item of failure.

(B) Failure Type – Failure type for specific general item identified under equipment (A). For example, equipment can be "Tank" and failure type can be leak and failure. Each having a different failure rate and consequence.

(C) Number of items – This refers to the number of that Equipment type with the scenario identified on this line.

(D) Individual Failure Rate – This is the failure rate for an individual equipment item having the failure type noted. This is in units of 1/hr.

(E) Source – Here one of the footnote letters is listed to identify the source of the failure rate data.

(F) Total Failure Rate for Item – This is the calculated total failure rate which is the number of items times the individual failure rate. The resulting value is in units of 1/hr.

$$F27 = C27 \cdot D27$$

(G) Available Cryogen Volume – If a value is entered here then the cryogen volume will be used to check the O2 concentration at the point of empty and the time to ODH condition is calculated. The units are cubic feet.

(H) Leak Rate into people space – This is the leak rate for the cryogen release scenario represented in that row. The units are standard cubic feet per minute. Leak rate is also referred to as R.

(I) Vent Failure – This is a flag used to indicate if ventilation failure is assumed. For each release scenario there should be a vent failed and vent not failed case so that "with" and "without" ventilation are represented in the overall fatality rate.

(J) Q – This is the ventilation flow that will be used in determining the impact on O2 concentration. This field is automatically filled depending whether vent failed in (I). If vent failed=0 then Q is set to the total ventilation flowrate located just above the table. If vent failed is anything other than 0 then Q will be zero.

$$J27 = \text{IF}(\$I27 = \text{""}, \text{"V?"}, \text{IF}(\$I27 = 0, Q, 0))$$

(K) Time to Empty – Time to empty the cryogen reservoir will be calculated if an available cryogen volume was entered and the ventilation rate is greater than 0. If the conditions are not met then the Time to Empty is not meaningful and it is set to zero.

$$K27 = \text{IF}\left[\text{AND}(\$G27 > 0, \$H27 > 0), \frac{\$G27}{\$H27}, 0\right]$$

(L) C(O2) at Empty when Q>R – Concentration of O2 in the space when the cryogen source leaks down to empty. This is only calculated when the ventilation Q (J) is greater than the leak rate (H) and a Time to Empty (K) is greater than zero.
The C(O2) formula is specific for when the ventilation is greater than the leak rate.

$$L27 = IF\left[AND(\$J27 > \$H27\ ,\ \$K27 > 0)\ ,\ 0.21 \cdot \left[1 - \frac{H27}{\$J27}\right] + \left[0.21 - 0.21 \cdot \left[1 - \frac{\$H27}{\$J27}\right]\right] \cdot e^{\left[-\left[\frac{\$J27}{V}\right] \cdot \$K27\right]}\ ,\ "-"\right]$$

(M) C(O2) at Empty when Q<R – Concentration of O2 in the space when the cryogen source leaks down to empty. This is only calculated when the ventilation Q (J) is less than the leak rate, R (H) or Q is zero along with the time to empty being greater than zero. The C(O2) formula is specific for the situation when the ventilation is less than the leak rate.

$$M27 = IF\left[AND(OR(\$J27 < \$H27\ ,\ \$J27 = 0)\ ,\ \$K27 > 0)\ ,\ 0.21 \cdot e^{\left[-\left[\frac{\$H27}{V}\right] \cdot \$K27\right]}\ ,\ "-"\right]$$

(N) C(O2) at infinity (infinity supply) – Concentration of O2 in the space assuming an infinite supply of cryogen, calculated at time = infinity. C(O2) is calculated by formula when the leak rate is less than the ventilation, R<Q, otherwise C(02) is assumed to reach 0%.

$$N27 = IF\left[\$H27 < \$J27\ ,\ \left[0.21 \cdot \left[1 - \frac{\$H27}{\$J27}\right]\right]\ ,\ IF(\$H27 = 0\ ,\ 0.21\ ,\ 0)\right]$$

(O) C(O2) for fatality rate – The maximum C(O2) of the three possible cases is used, C(O2) at empty for Q>R (L), C(O2) at empty for Q<R (M) or C(02) at infinity time. This way a realistic C(O2) is used for subsequent fatality rate calculations.

$$O27 = MAX(\$L27 : \$N27)$$

(P) Fatality factor – This is the fatality factor for that line item (scenario). The factor is calculated only of the Time to Reach ODH Condition (S) is less than the maximum credible time without ventilation, listed above the table. F_0 is = 0.182 = 135/740, the value that which above the fatality factor is zero. F_1 is = 65/740, the value at which below this fraction, the fatality factor is 1.0. Between F_0 and F_1, the formula follows the power law from FESHM 2040.

```
P27 = IF($S27<(credible_duration),(IF($O27>F_0,0,(IF($O27<=F_1,1,POWER(10,6.5-(O27*740/10))))))),0)
```

(Q) Fatality Rate – This is the location specific fatality rate for the line item (scenario). It is calculated at 1-fatality factor for that line item (scenario). The factor is calculated only of the Time to Reach ODH Condition (S) is less than the maximum credible time wthout ventilation, listed above the table. The Fatality Rate is calculated with ventilation or without (failed) based on the ventilation failed flag (I).

```
Q27 = $F27 · ($P27) · ((1 - $I27) · (1 - p_Ventilation_Failure) + ($I27 · p_Ventilation_Failure))
```

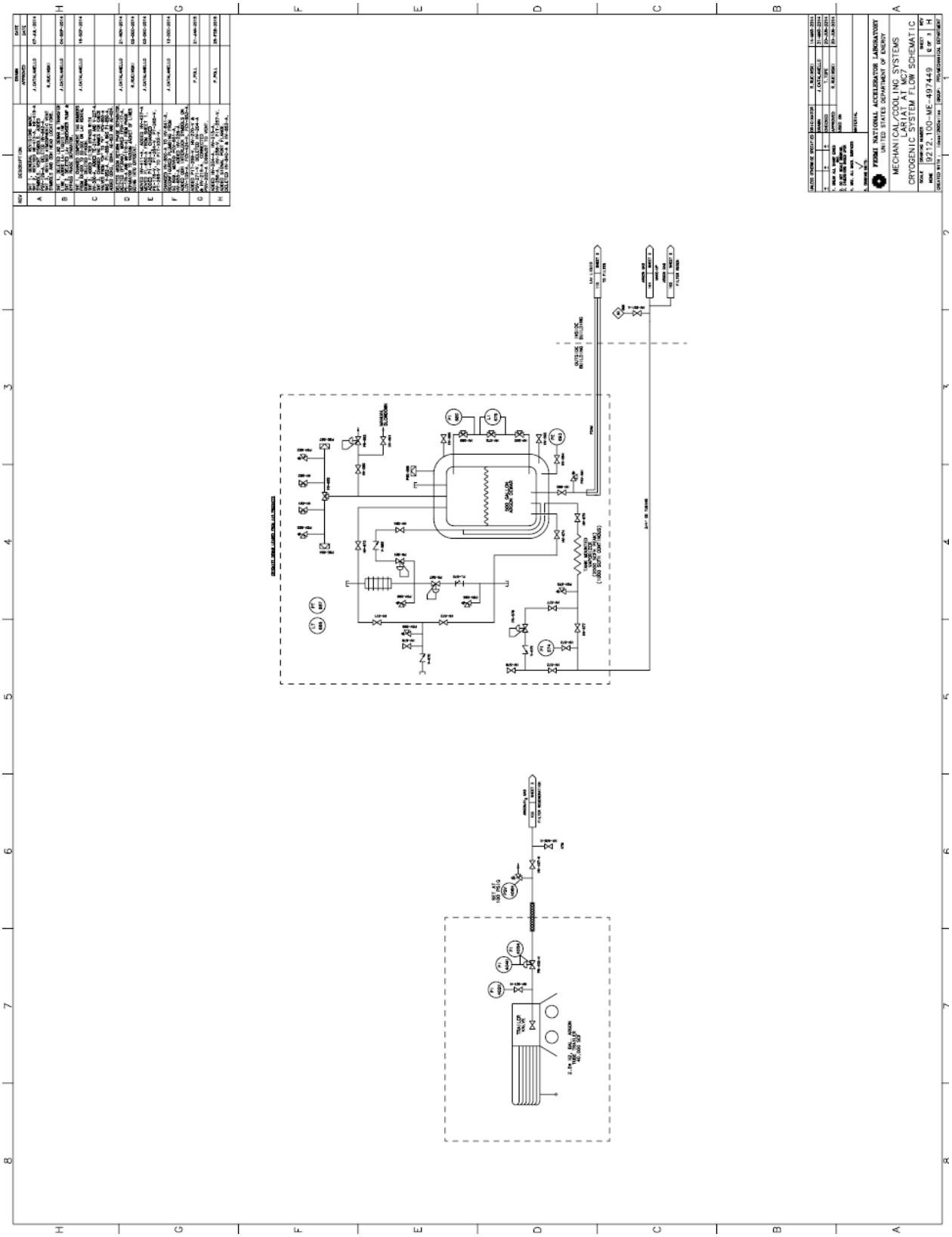
(R) ODH Class* – This is the ODH Class for the line item (scenario). ODH 0, 1, or 2 will be indicated. If ODH 2 is exceeded then it will say "RE-DESIGN". The overall ODH Class is listed at the bottom of the table.

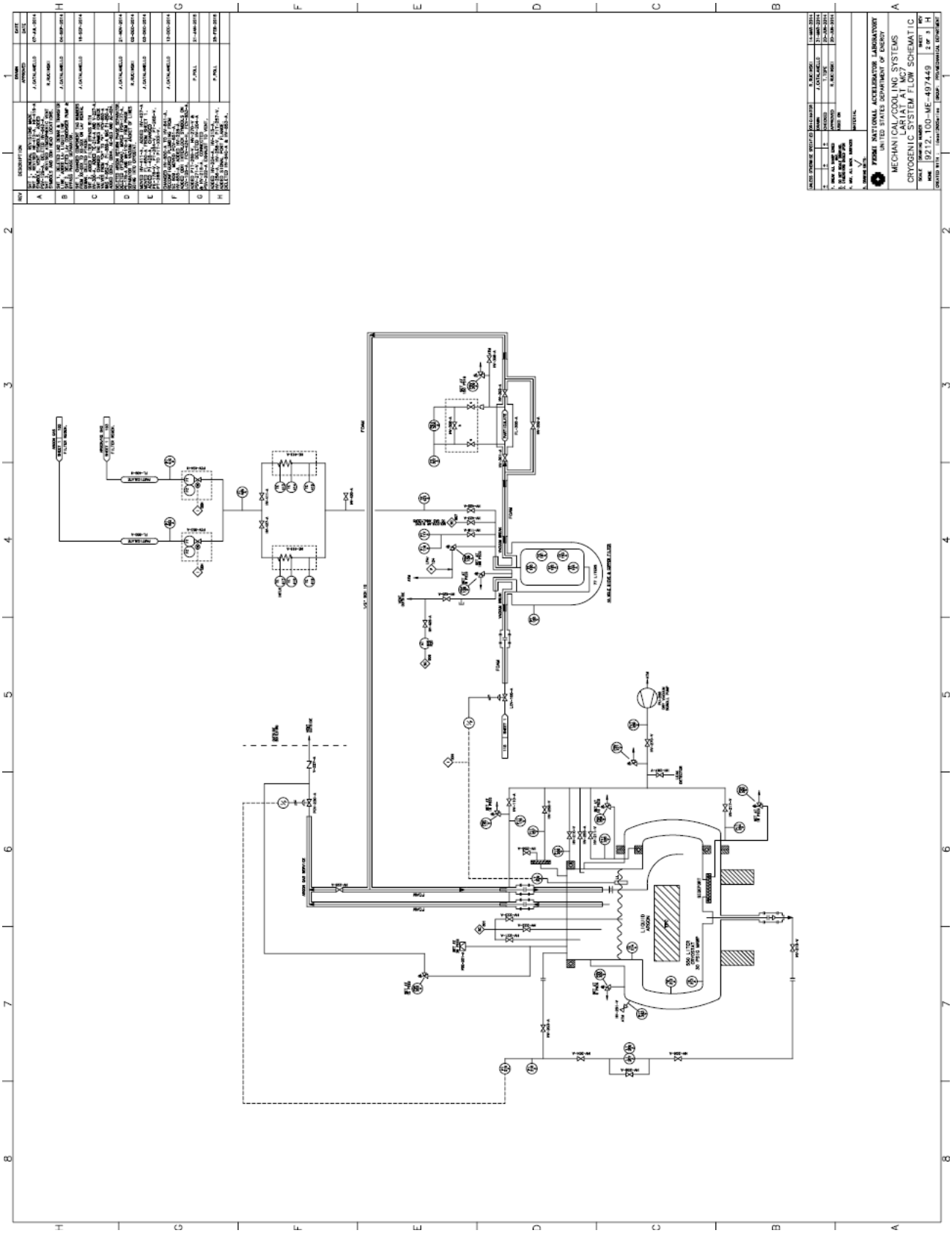
```
R27 = IF ($Q27 <= 0.0000001 , 0 , IF ($Q27 <= 0.00001 , 1 , IF ($Q27 <= 0.001 , 2 , "RE-DESIGN")))
```

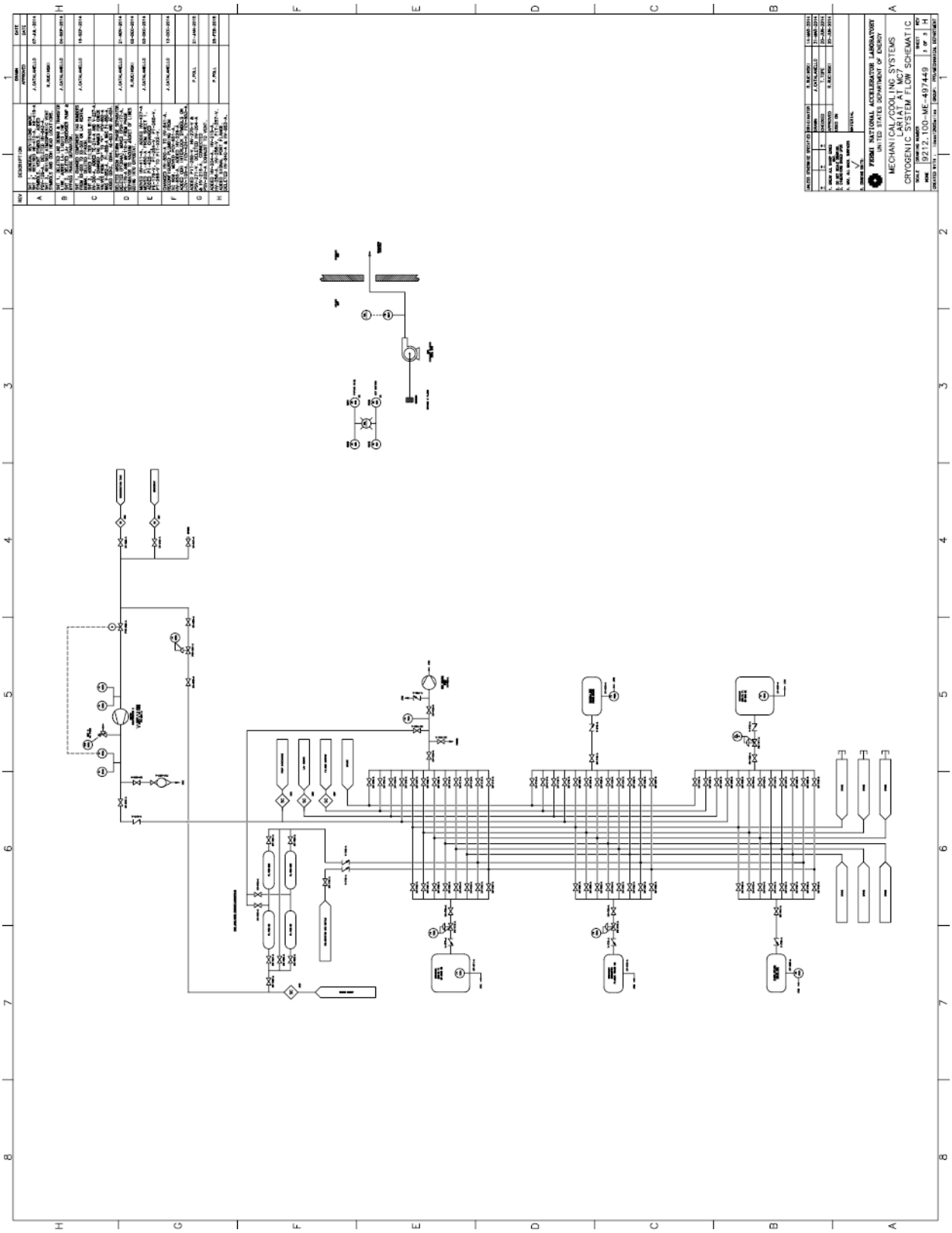
(S) Time to reach ODH condition – This is the time it will take ODH Class for the line item (scenario). he units are hours.

$$S27 = \text{IF}\left[\$O27 <= F_0\ ,\ \text{IF}\left[\$J27 > \$H27\ ,\ \frac{\left[\frac{-V}{\$J27}\right] \cdot \text{LN}\left[\frac{\frac{F_0 - 0.21 \cdot \left[1 - \frac{\$H27}{\$J27}\right]}{0.21} \cdot \$H27}{\$J27}\right]}{60}\ ,\ \frac{\frac{-V}{\$H27} \cdot \text{LN}\left[\frac{F_0}{0.21}\right]}{60}\right]\ ,\ \text{"-"}\right]$$

Flow Schematics as of ODH assessment




FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
MECHANICAL/COOLING SYSTEMS
LARIAT AT MC7
CRYOGENIC SYSTEM FLOW SCHEMATIC
922.1.100-ME-497449


FERMI NATIONAL ACCELERATOR LABORATORY
UNITED STATES DEPARTMENT OF ENERGY
MECHANICAL/COOLING SYSTEMS
LARIAT MC7
CRYOGENIC SYSTEM FLOW SCHEMATIC
92212.100-ME-497449

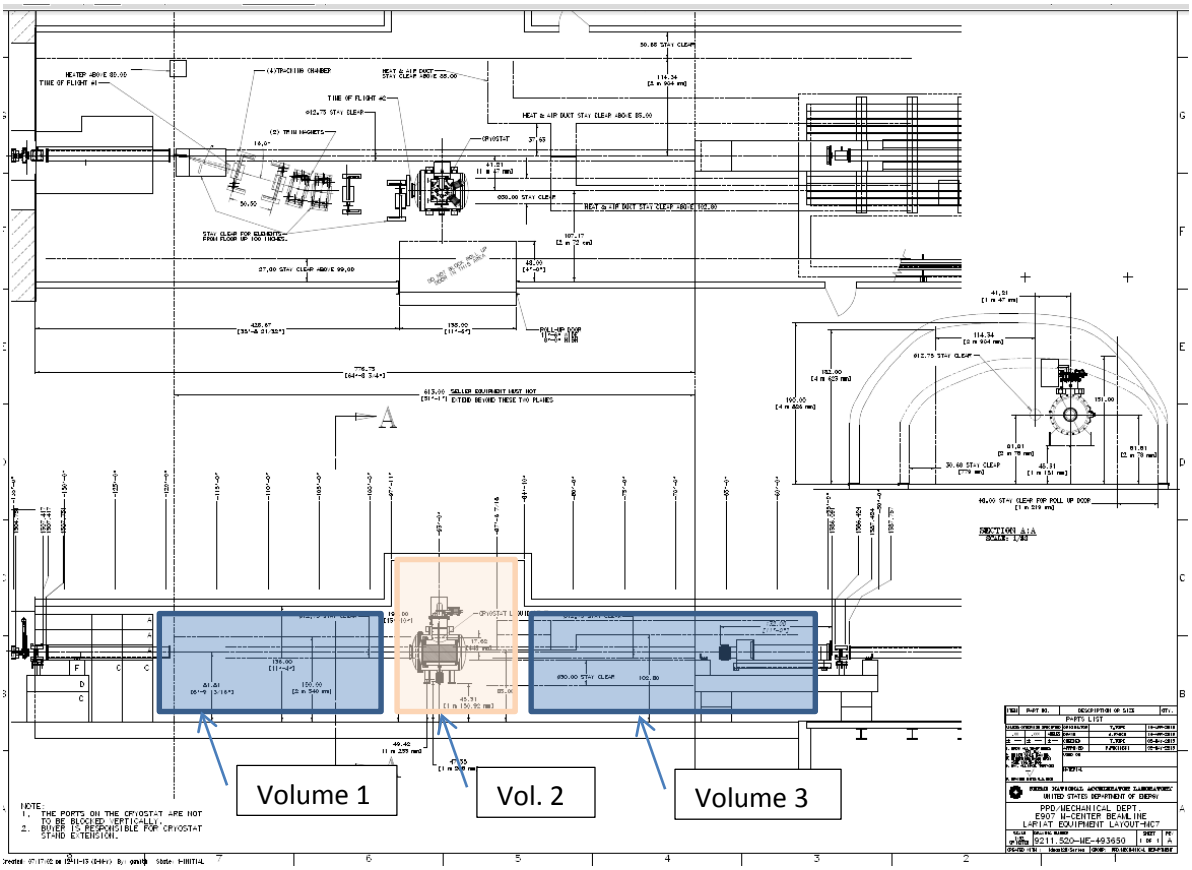
Results and Recommendations

The total fatality rate is $3x10^{-8}$/hr and classifies the MC7 area as ODH class 0. No special precautions are necessary due to the risk of ODH from the cryogenic system. The ODH system is required to be present in MC7 to turn on the dedicated ODH exhaust fan if oxygen levels are sensed to fall below 19.5%. The operation of the blower will be tested daily.

Appendix

<u>MC-7 Enclosure Volume Calculation</u>

The MC7 building has the shape of a Quonset hut. See Section A:A on drawing 9211.520-ME-493650. There are three volumes. See figure xx below. There is an upstream area from the shield blocks to the larger cross sectional area around the cryostat that I'll call volume 1. There is the larger cross section at the LArIAT cryostat that I'll call volume 2. There is a downstream area I'll call volume 3. The enclosure continues beyond volume 3, but is not included in this analysis since it is not what I would consider to be a continuous volume.



MC-7 ODH Assessment for LArIAT

Reviewer questions and Note Preparer responses.

Question: Can fresh air intake be blocked by snow, ice, debris? Answer: The fresh air intake is elevated over the roof and has a rain cap. It is my opinion that it would not be blocked by snow, ice, etc.

Question: Is the floor level blower intake protected by "stay-clear" zone? Answer: The intake is up off the floor and is protected by a screen. It wouldn't be readily blocked by boxes or other stuff.

Question: Can the flow switch be influenced by weather (heavy wind or rain)? Answer: No, the flow switch is in the plenum just beyond the fan which is about a foot in from the outside louvers.

Question: What are the subsequent steps after blower failure is detected? Answer: The blower test will occur daily in the morning. The PLC compares the Fan control output to the ODH fan flow switch input. If the two do not match, an autodialer alarm will be generated. The autodialer will notify Russ Rucinski of an ODH fan failure alarm. The alarm will need to be acknowledged. If not acknowledged within 15 minutes, the autodialer will call the next person on the list. The list has yet to be set up. The person who acknowledges the fan failure alarm will be responsible to investigate and resolve the matter. If it was me, I would open I-FIX and look at the ODH head readings to be sure that there is no real ODH issue. I would look at the system overall for indications of a control system problem. I would look at the AC power status.

I would try to turn the fan on manually and see if the fan switch changed state. If it did change state, then I would be confident that the ODH system is okay and it was maybe just a momentary failure of the flow switch. If it did not, then I would suspect a failure of power to the fan or a failure of the fan flow switch. The MC-7 enclosure will be interlocked during beam on conditions so no access will be allowed without doing a controlled access. I would call the LArIAT shifter and schedule an access at the next available opportunity. During that access, I would turn the fan on manually at the power control box and see if the fan came on. If it did, I would suspect a problem with the flow switch or blocked louvers or wind pushing air backward in the plenum. I would investigate and solve the problem. If the fan did not come on, then I would suspect a power or motor problem. I would call the controls group or an electrician to assist. I note that the ODH horns and strobes would still be alive and active during the investigation period. If anybody was in the enclosure and a head dropped below 19.5%, the horns and strobes would sound and those persons would evacuate.

Question: Is the PLC "safety" rated or are there redundant PLC's? Answer: No the PLC is not "safety" rated. The ODH system is hardwired independent of the PLC.

Question: Are all the ODH heads at the floor/ground level? Are some at the head or ceiling level? Answer: Three ODH heads are at about 1 or 2 feet off the floor. One ODH head under the LAr delivery piping is now about 4 feet off the floor, head height at your suggestion.

Question: Do both types of valves (LCV-105-A) and FCV-424-H and FCV-653-A normally fail closed? Answer: Yes. The control valve, LCV-105-A, is a Badger Meter type 884 control valve with type 766 positioner/actuator. It does fail closed with loss of electrical signal or gas pressure. The flow control valves FCV-424-H and FCV-653-A are Alicat Scientific type MCR mass flow controllers which are normally closed without power.

Question: Are both valves located inside MC-7 or outside? Answer: The valves are located inside MC-7.

Question: How long do the valves remain closed after the O2% returns to normal levels? Answer: The valves latch closed and will not re-open until an operator resets the ODH interlock on IFIX.

Question: Is the tube trailer only connected during regeneration or is it always connected with the valve closed? Answer: The tube trailer is only connected during regeneration operations. The tube trailer would interfere with liquid argon deliveries so it is likely only going to be there for a few days.

Question: Are the reliefs piped inside MC7 or outside? Answer: The relief valve for the filter, PSV-109-A, and the cryostat operational relief, PSV-202-A, are vented out of the MC-7 enclosure. The main cryostat rupture disc, PSE-201-A, vents into the building.

ODH table modifications

I added line items, row 28 and row 36, LArIAT filter vessel has a small leak and the isolation valve fails to operate. This was added per comments in the review. Text in the note was revised as well.

Liquid argon piping, large leak, it was suggested to change the area of the large leak from 500 mm^2 to 610 mm^2 which is the area of a severed pipe. The flow rate for the 500 m^2 area was 1598 cfm. An error was found in that flow rate calculation. The value should have been 15,999 cfm. The revised flow rate for 610 mm^2 area is 19,600 cfm. The spreadsheet was updated in four cells, H44, H51, H58, H66.

Argon Piping flanges, a flange rupture case was added. The probability was 1E-9 hr-1. The leak rate was the same as for the piping, large leak, 19,600 cfm. The added rows are rows 46, 53, 60, and 68. Text was added noting the flange rupture case.

Regeneration piping flanges. The flange rupture case was added. The added rows are 76 and 84. The leak rate was that of a large leak.

The formula for Fatality Factor was replaced with the one that the reviewer came up with.
=IF($S14<(credible_duration),(IF($O14>F_0,0,(IF($O14<=F_1,1,POWER(10,6.5-(O14*740/10))))))),0)

The slope and intercept are no longer used.

Question: Please explain the origin of the probability of the fan not being on at 2.5E-4/hr. Answer: This probability was arrived at using the probability tree on the Pfan data sheet. The fan failing to run for an ODH event could be the result of A.) The fan failing while running (9E-6/hr), failing to start (1.08E-4/hr), a power failure (1e-4/hr), the ODH panel failing (2.98E-5/hr), or the ODH monitor failing (5.62E-6/hr). the probability of any of these things occurring is the summation of them which equals 2.52E-4/hr. The failure rate of the fan failing to start, 1.08E-4/hr is a function of how frequently the fan is tested. For daily testing it is 1.08E-4/hr.

Conclusion/recommendation. The total fatality rate summed from the table increased from $2x10^{-8}$/hr to $3x10^{-8}$/hr.

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 1=failed (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes
EQUIPMENT																			
LArIAT Cryostat w/ ventilation																			
Vessel	leak	1	8.00E-08	A	8.00E-08	18704	188	0	3000	99	19.68%	-	19.68%	19.68%	0	0	0	-	30 psig, 10 mm^2 hole
Vessel	failure	1	5.00E-09	A	5.00E-09	18704	15116	0	3000	1	-	7.17%	0.00%	7.17%	1.0	5.00E-9	0	0.0	1.5" pipe, 30 psig
relief valve - relief event, isolation valve closes	premature open	2	1.00E-05	A	2.00E-05	18704	3	0	3000	6235	20.98%	-	20.98%	20.98%	0	0	0	-	limited to boil-off rate
relief valve - relief event, isolation valve stays open	premature open	2	1.00E-05	A	6.00E-09	103700	1345	0	3000	77	11.59%	-	11.59%	11.59%	8.45E-3	5.07E-11	0	0.2	valve failure .0003 per demand
LArIAT Cryostat w/o vent.																			
Vessel	leak	1	8.00E-08	A	8.00E-08	18704	188	1	0	99	-	7.17%	0.00%	7.17%	1.0	2.02E-11	0	0.2	30 psig, 10 mm^2 hole
Vessel	failure	1	5.00E-09	A	5.00E-09	18704	15116	1	0	1	-	7.17%	0.00%	7.17%	1.0	1.26E-12	0	0.0	1.5" pipe, 30 psig
relief valve - relief event, isolation valve closes	premature open	2	1.00E-05	A	2.00E-05	18704	3	1	0	6235	-	7.17%	0.00%	7.17%	1.0	5.05E-9	0	13.6	limited to boil-off rate
relief valve - relief event, isolation valve stays open	premature open	2	1.00E-05	A	6.00E-09	103700	1345	1	0	77	-	0.05%	0.00%	0.05%	1.0	1.51E-12	0	0.0	valve failure .0003 per demand
Filter Vessel w/ ventilation																			
VESSEL	leak	1	8.00E-08	A	8.00E-08	2554	320	0	3000	8	19.33%	-	18.76%	19.33%	0	0	0	-	100 psig, 10 mm^2 hole
VESSEL	failure	1	5.00E-09	A	5.00E-09	2554	19608	0	3000	0	-	18.13%	0.00%	18.13%	1.21E-7	6.03E-16	0	0.0	small LAr inventory
VESSEL - isolation valve fails to close, small leak	leak	1	8.00E-08	A	2.40E-11	87554	320	0	3000	274	18.76%	-	18.76%	18.76%	0	0	0	-	valve failure .0003 per demand
VESSEL - isolation valve fails to close, failure	failure	1	5.00E-09	A	1.50E-12	87554	19608	0	3000	4	-	0.14%	0.00%	0.14%	1.0	1.50E-12	0	0.0	valve failure .0003 per demand
relief valve - relief event isolation valve closes	premature open	1	1.00E-05	A	1.00E-05	18704	3	0	3000	6235	20.98%	-	20.98%	20.98%	0	0	0	-	limited by boil-off from heat load
relief valve - relief event isolation valve fails to close	premature open	1	1.00E-05	A	3.00E-09	87554	1997	0	3000	44	7.03%	-	7.02%	7.03%	1.0	3.00E-9	0	0.1	valve failure .0003 per demand
Filter Vessel w/o vent.																			
VESSEL	leak	1	8.00E-08	A	8.00E-08	2554	320	1	0	8	-	18.13%	0.00%	18.13%	1.21E-7	2.44E-18	0	0.1	100 psig, 10 mm^2 hole
VESSEL	failure	1	5.00E-09	A	5.00E-09	2554	19608	1	0	0	-	18.13%	0.00%	18.13%	1.21E-7	1.52E-19	0	0.0	small LAr inventory
VESSEL - isolation valve fails to close	leak	1	8.00E-08	A	2.40E-11	87554	320	1	0	274	-	0.14%	0.00%	0.14%	1.0	6.06E-15	0	0.1	valve failure .0003 per demand
VESSEL - isolation valve fails to close	failure	1	5.00E-09	A	1.50E-12	87554	19608	1	0	4	-	0.14%	0.00%	0.14%	1.0	3.79E-16	0	0.0	valve failure .0003 per demand
relief valve - relief event isolation valve closes	premature open	1	1.00E-05	A	1.00E-05	18704	3	1	0	6235	-	7.17%	0.00%	7.17%	1.0	2.52E-9	0	13.6	limited by boil-off from heat load
relief valve - relief event isolation valve fails to close	premature open	1	1.00E-05	A	3.00E-09	87554	1997	1	0	44	-	0.14%	0.00%	0.14%	1.0	7.57E-13	0	0.0	valve failure .0003 per demand
PIPING																			
Argon Piping upstream of LCV-105-A w/ ventilation																			
PIPE (2" or less)	leak, small	5	1.00E-09	A	5.00E-09	85000	320	0	3000	266	18.76%	-	18.76%	18.76%	0	0	0	-	
PIPE (2" or less)	break	5	1.00E-10	A	5.00E-10	85000	19600	0	3000	4	-	0.16%	0.00%	0.16%	1.0	5.00E-10	0	0.0	

TABLE 1

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 1=failed (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes
Flanges	leak	1	4.00E-07	A	4.00E-07	85000	320	0	3000	266	18.76%	-	18.76%	18.76%	0	0	0	-	
Flanges	rupture	1	1.00E-09	A	1.00E-09	85000	19600	0	3000	4	-	0.16%	0.00%	0.16%	1.0	1.00E-9	0	0.0	
VALVE	leak	1	1.00E-08	A	1.00E-08	85000	320	0	3000	266	18.76%	-	18.76%	18.76%	0	0	0	-	
Argon Piping upstream of LCV-105-A w/o vent.																			
PIPE (2" or less)	leak, small	5	1.00E-09	A	5.00E-09	85000	320	1	0	266	-	0.16%	0.00%	0.16%	1.0	1.26E-12	0	0.1	
PIPE (2" or less)	break	5	1.00E-10	A	5.00E-10	85000	19600	1	0	4	-	0.16%	0.00%	0.16%	1.0	1.26E-13	0	0.0	0
Flanges	leak	1	4.00E-07	A	4.00E-07	85000	320	1	0	266	-	0.16%	0.00%	0.16%	1.0	1.01E-10	0	0.1	
Flanges	rupture	1	1.00E-09	A	1.00E-09	85000	19600	1	0	4	-	0.16%	0.00%	0.16%	1.0	2.52E-13	0	0.0	
VALVE	leak	1	1.00E-08	A	1.00E-08	85000	320	1	0	266	-	0.16%	0.00%	0.16%	1.0	2.52E-12	0	0.1	
Argon Piping downstream of LCV-105-A w/ ventilation																			
PIPE (2" or less)	leak, small	20	1.00E-09	A	2.00E-08	18704	320	0	3000	58	18.76%	-	18.76%	18.76%	0	0	0	-	
PIPE (2" or less)	break	20	1.00E-10	A	2.00E-09	18704	19600	0	3000	1	-	7.17%	0.00%	7.17%	1.0	2.00E-9	0	0.0	
Flanges	leak	3	4.00E-07	A	1.20E-06	18704	320	0	3000	58	18.76%	-	18.76%	18.76%	0	0	0	-	
Flanges	rupture	3	1.00E-09	A	3.00E-09	18704	19600	0	3000	1	-	7.17%	0.00%	7.17%	1.0	3.00E-9	0	0.0	
VALVE	leak	1	1.00E-08	A	1.00E-08	18704	320	0	3000	58	18.76%	-	18.76%	18.76%	0	0	0	-	
Trapped V reliefs - relief event	premature open	1	0.00E+00	H	0.00E+00	18704	0	0	3000		-	-	21.00%	21.00%	0	0	0	-	not credible, relief set at 150 psig
Argon Piping downstream of LCV-105-A w/o vent.																			
PIPE (2" or less)	leak, small	20	1.00E-09	A	2.00E-08	18704	320	1	0	58	-	7.17%	0.00%	7.17%	1.0	5.05E-12	0	0.1	
PIPE (2" or less)	break	20	1.00E-10	A	2.00E-09	18704	19600	1	0	1	-	7.17%	0.00%	7.17%	1.0	5.05E-13	0	0.0	0
Flanges	leak	3	4.00E-07	A	1.20E-06	18704	320	1	0	58	-	7.17%	0.00%	7.17%	1.0	3.03E-10	0	0.1	
Flanges	rupture	3	1.00E-09	A	3.00E-09	18704	19600	1	0	1	-	7.17%	0.00%	7.17%	1.0	7.57E-13	0	0.0	
VALVE	leak	1	1.00E-08	A	1.00E-08	18704	320	1	0	58	-	7.17%	0.00%	7.17%	1.0	2.52E-12	0	0.1	
Trapped V reliefs - relief event	premature open	1	0.00E+00		0.00E+00	18704	0	1	0		-	-	21.00%	21.00%	0	0	0	-	not credible, relief set at 150 psig
Regeneration Piping w/ ventilation																			
PIPE (2" or less)	leak, small	20	1.00E-09	A	2.00E-08	85000	2	0	3000	42500	20.99%	-	20.99%	20.99%	0	0	0	-	
PIPE (2" or less)	break	20	1.00E-10	A	2.00E-09	85000	509	0	3000	167	17.44%	-	17.44%	17.44%	3.95E-7	7.90E-16	0	0.5	
Flanges	leak	5	4.00E-07	A	2.00E-06	85000	2	0	3000	42500	20.99%	-	20.99%	20.99%	0	0	0	-	
Flanges	rupture	5	1.00E-09	A	5.00E-09	85000	509	0	3000	167	17.44%	-	17.44%	17.44%	3.95E-7	1.97E-15	0	0.5	
VALVE	leak	5	1.00E-08	A	5.00E-08	85000	2	0	3000	42500	20.99%	-	20.99%	20.99%	0	0	0	-	
Relief valve opening	premature open	1	1.00E-05	A	1.00E-05	85000	509	0	3000	167	17.44%	-	17.44%	17.44%	3.95E-7	3.95E-12	0	0.5	Relief set at 100 psig
Regeneration Piping w/o vent.																			
PIPE (2" or less)	leak, small	20	1.00E-09	A	2.00E-08	85000	2	1	0	42500	-	0.16%	0.00%	0.16%	1.0	5.05E-12	0	20.4	
PIPE (2" or less)	break	20	1.00E-10	A	2.00E-09	85000	509	1	0	167	-	0.16%	0.00%	0.16%	1.0	5.05E-13	0	0.1	0
Flanges	leak	5	4.00E-07	A	2.00E-06	85000	2	1	0	42500	-	0.16%	0.00%	0.16%	1.0	5.05E-10	0	20.4	

TABLE 1

	Failure Type (B)	# of (C)	Individual Failure Rate (/hr) (D)	SOURCE	Total Failure Rate for Item (F)	Avail. Cryogen volume (CF) (G)	Leak into people space (CFM) (H)	Vent Failure 1=failed (I)	Q (J)	time to empty (min) (K)	C(O2) at empty R>0, Q>R (L)	C(O2) at empty Q<R or Q=0 (M)	infinite supply C(O2) at infinity (N)	C(O2) at infinity or C(O2) at empty (O)	Fatality Factor (P)	Fatality Rate (Q)	ODH CLASS (R)	Time to reach ODH (hrs) (S)	Notes
Flanges	rupture	5	1.00E-09	A	5.00E-09	85000	509	1	0	167	-	0.16%	0.00%	0.16%	1.0	1.26E-12	0	0.1	
VALVE	leak	5	1.00E-08	A	5.00E-08	85000	2	1	0	42500	-	0.16%	0.00%	0.16%	1.0	1.26E-11	0	20.4	
Relief valve opening	premature open	1	1.00E-05	A	1.00E-05	85000	509	1	0	167	-	0.16%	0.00%	0.16%	1.0	2.52E-9	0	0.1	

Detector Building	**Total Fatality Rate:**	**2.561E-08**
	Overall ODH Class:	**0**

FERMILAB
ENGINEERING NOTE

SECTION	PROJECT	SERIAL-CATEGORY	PAGE
			1

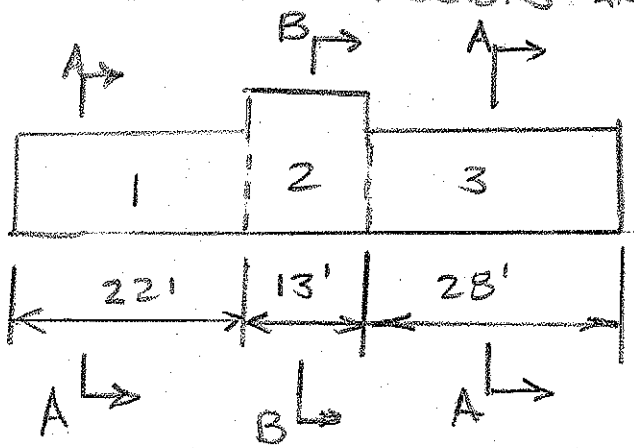
SUBJECT: CALCULATE VOLUME OF MC7

NAME: RUSS RUCINSKI

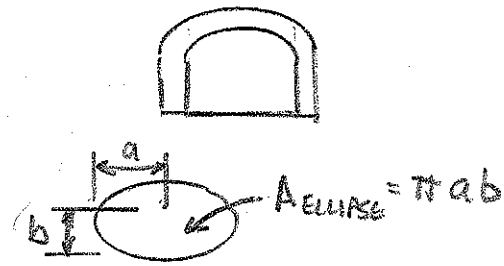
DATE: 6-11-14

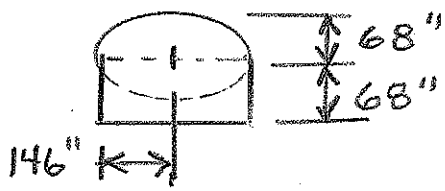
REVISION DATE:

THERE ARE THREE REGIONS AND TWO CROSS SECTIONS



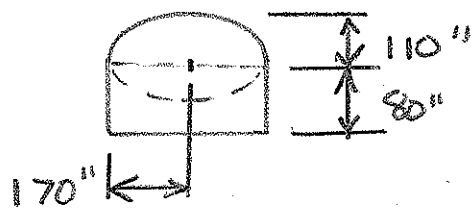
SIDE ELEVATION





SECTION A-A

2 PLACES



SECTION B-B

$$A_{A-A} = \frac{\pi}{2}(68)(146) + 2(146\,in)(68\,in) = 35{,}451\,in^2 = 246.2\,ft^2$$

$$A_{B-B} = \frac{\pi}{2}(110)(170) + 2(170\,in)(80\,in) = 56{,}574\,in^2 = 392.9\,ft^2$$

$$VOLUME = 246.2\,ft^2(22 + 28\,ft) + 392.9\,ft^2(13\,ft)$$

$$VOLUME = 17{,}418\,ft^3$$

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE 2
SUBJECT: LArIAT INVENTORY		NAME		
		DATE	REVISION DATE MAR 5, 2015	

- LAr DEWAR = 800 GALLONS

  PRESSURE = 40 PSIG. OPERATING = 0.38 MPa

  $\rho_{LAr\,SAT} = 1300\ kg/m^3$

  $M = (800\ GAL.)\left(1300\ \frac{kg}{m^3}\right)\left(\frac{1\ m^3}{264.2\ gal}\right)\left(2.2\ \frac{lb}{kg}\right)$

  $M = 8660\ lbs$

  $V_{SCF} = 8660\ lbs \cdot 9.8\ \frac{ft^3}{lb} = \underline{85{,}000\ SCF}$

  SPECIFIC VOLUME OF GAr @ 290 K 1 ATM

- FILTER = 77 LITERS

  PRESSURE = 10 PSIG. = 0.17 MPa

  $\rho_{LAr\,SAT} = 1362\ kg/m^3$

  $M = \left(1362\ kg/m^3\right)(77\ LITERS)\left(\frac{1\ m^3}{1000\ L}\right)\left(2.2\ \frac{lb}{kg}\right)$

  $M = 231\ lbs$

  $V_{SCF} = 231\ lbs \cdot 9.8\ ft^3/lb = 2260\ SCF$

- CRYOSTAT = 550 LITERS

  $V_{SCF} \approx 2260\ SCF \times \frac{550\ L}{77\ L} = 16{,}150\ SCF$

SUBJECT: LArIAT CRYOSTAT LEAK RATES

NAME: RUSS RUCINSKI

DATE: 12-3-14 | REVISION DATE:

SMALL LEAK, 10 mm². CRYOSTAT PRESSURE = 30 PSIG.

$q = AC\sqrt{2gh_L}$ EQUATION 3-21 IN CRANE TECHNICAL PAPER 410 FLOW THRU AN ORIFICE

$$A = (10\ mm^2)\left(\frac{1\ in}{25.4\ mm}\right)^2\left(\frac{1\ ft^2}{144\ in^2}\right) = 1.076\times10^{-4}\ ft^2$$

$C = 0.62$ SQUARE EDGED ORIFICE.

$g = 32.2\ ft/s^2$

$$h_L = \frac{\Delta P}{\rho} = \frac{30\ psi\left(\frac{144\ in^2}{ft^2}\right)}{\left(82.4\ \frac{lb}{ft^3}\right)}$$

$h_L = 52.4\ ft$

$P_{ATM} = 14.3\ PSIA$ AT FERMILAB

$P(30\ psig) = 44.3\ PSIA = 0.305\ MPa$

$\rho_{LIQ\ SAT.}(.305\ MPa) = 1318.7\ kg/m^3$

$= 82.4\ lb/ft^3$ REF-PROP ARGON

- SUBSTITUTING VALUES INTO EQ'N 3-21:

$$q = AC\sqrt{2gh_L} = (1.076\times10^{-4}\ ft^2)(.62)\sqrt{2(32.2\ ft/s^2)(52.4\ ft)}$$

$q = 3.88\times10^{-3}\ ft^3/s = 1.74\ gpm$ ✓ REASONABLE RATE

$$w = (3.88\times10^{-3}\ ft^3/s)(82.4\ lb/ft^3)\left(\frac{3600\ s}{1\ hr}\right) = \underline{1150\ lb/hr}$$

- CONVERT TO CFM OF GAS ARGON FOR ODH TABLE

$\rho_{GAr}(1\ ATM,\ T=290K) = \rho(.0986\ MPa, 290K) = 1.6347\ \frac{kg}{m^3} = .102\ lb/ft^3$

$$Q_{LEAK\ RATE} = \frac{1150\ lb/hr}{.102\ lb/ft^3} \times \frac{1\ hr}{60\ min} = \boxed{188\ CFM}$$

CHECK $C = 0.62$ ASSUMPTION

$Re = 6.31 \frac{W}{d\mu}$ EQ. 3-3 IF $A = 10\,mm^2$, THEN $d = .140\,in$

$$\mu_{LIQ} = 185\,\mu Pa\text{-}s \times \frac{1000\,cp}{Pa\cdot s} \times \frac{1\,Pa\cdot s}{10^6\,\mu Pa\text{-}s} = .185\,cp$$

$$Re = 6.31 \frac{(1150\,lb/hr)}{(.14\,in)(.185\,cp)} = 2.8 \times 10^5$$

PAGE A-20

$$\beta = d_1/d_2 = \frac{.14}{d_2} \approx 0.1 \quad Re > 10^4 \Rightarrow C = 0.6 \checkmark$$

OK.

SUBJECT: LARIAT CRYOSTAT LEAK RATES

NAME | DATE | REVISION DATE

LARGE LEAK / CATASTROPHIC FAILURE.

CRYOSTAT PRESSURE = 30 PSIG.

LARGEST PORT IS DRAIN PIPE STUB ON BOTTOM OF THE VESSEL.

STUB IS 1½" OD x .12" WALL TUBE x ≈ 12" LONG.

CALCULATE AS FLOW THRU AN ORIFICE

$$q = AC\sqrt{2gh_L}$$ EQN 3-21 IN CRANE.

$$A = \frac{\pi}{4}d^2 = \frac{\pi}{4}(1.26\,in)^2 \times \left(\frac{1\,ft^2}{144\,in^2}\right) = 8.66\times10^{-3}\,ft^2$$

$C = 0.62$ SQUARE EDGE ORIFICE

$h_L = 52.4$ ft FROM SMALL LEAK CALCULATION

$$q = AC\sqrt{2gh_L} = (8.66\times10^{-3}\,ft^2)(0.62)\sqrt{2\left(32.2\,\tfrac{ft}{s^2}\right)(52.4\,ft)}$$

$$= 0.312\ ft^3/s$$

$$w = (.312\ ft^3/s)(82.4\ lb/ft^3)\left(\frac{3600\,s}{hr}\right) = 92{,}512\ lb/hr$$

$$Q_{\substack{LEAK\\RATE}} = \frac{w}{\rho_{\substack{GAS\\STP}}} = \frac{92{,}512\ lb/hr}{.102\ lb/ft^3} \times \frac{1\,hr}{60\,min} = \boxed{15{,}116\ CFM}$$

SUBJECT: LArIAT FILTER VESSEL LEAK RATES

NAME | DATE | REVISION DATE

SMALL LEAK, 10 mm². FILTER PRESSURE = 100 PSIG = .79 MPa

$q = AC\sqrt{2gh_L}$ EQN. 3-21 CRANE TECH PAPER 410

$A = 10\ mm^2 = 1.076\times10^{-4}\ ft^2$

$C = 0.60$

$\rho_{LIQ\ SAT} = 76.4\ lb/ft^3$

$$h_L = \frac{\Delta P}{\rho} = \frac{100\ psi}{76.4\ lb/ft^3}\times 144\ \frac{in}{ft^2} = 188.5\ ft.$$

$$q = AC\sqrt{2gh_L} = (1.076\times10^{-4})(0.6)\sqrt{2(32.2\ ft/s^2)(188.5\ ft)}$$

$$q = 7.1\times10^{-3}\ ft^3/s$$

$$w = (7.1\times10^{-3}\ ft^3/s)(76.4\ lb/ft^3)(3600\ s/hr) = 1956\ lb/hr.$$

$$Q_{LEAK\ RATE} = \frac{w}{\rho_{GAS\ STP}} = \frac{1956\ lb/hr}{.102\ lb/ft^3}\cdot\frac{1\ HR}{60\ MIN} = \boxed{320\ CFM}$$

SUBJECT: LARIAT FILTER LEAK RATE

NAME | DATE | REVISION DATE

LARGE LEAK/ CATASTROPHIC FAILURE

FILTER PRESSURE = 100 PSIG.

LARGES PORT IS 1" SCH. 10 PIPING INSIDE THE VACUUM JACKET. I.D. = 1.097" {DRG 3942.330-ME-466500}

CALCULATE AS FLOW THRU AN ORIFICE.

$q = AC\sqrt{2gh_L}$ EQN. 3-21 IN CRANE TECH. PAPER 410

$A = \frac{\pi}{4}d^2 = 6.6\times10^{-3}\ ft^2$

$C = 0.6$

$h_L = 188.5\ ft$ SEE SMALL LEAK CALCULATION

$q = AC\sqrt{2gh_L} = 6.6\times10^{-3}\ ft^2(.6)\sqrt{2(32.2\ ft/s^2)(188.5\ ft)}$

$q = 0.43\ ft^3/s$

$w = (0.43\ ft^3/s)(76.4\ lb/ft^3)(3600\ s/hr) = 1.2\times10^5\ lb/hr.$

$Q_{LEAK\ RATE} = \frac{w}{\rho_{GAS\ STP}} = \frac{1.2\times10^5\ lb/hr}{.102\ lb/ft^3}\times\frac{1\ hr}{60\ MIN} = \boxed{19{,}608\ CFM}$

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE 8
SUBJECT: LARIAT FILTER - RELIEF OPEN		NAME		
		DATE	REVISION DATE	

IF THE RELIEF VALVE PREMATURELY OPENS ON THE FILTER, THE INITIAL FLOW RATE COULD BE QUITE HIGH, THE SAME AS THE LARGE LEAK RATE CALCULATION FOR THE FILTER ≤ 45,842 CFM.

THE ODH SYSTEM WOULD BE TRIGGERED, CLOSING LCV-105-A.

THE REMAINING RELEASE RATE WOULD BE FROM BOIL-OFF FROM HEATLOAD. HEAT LOAD ON THE FILTER & CRYOSTAT AND X-FER LINES ALL CONTRIBUTE.

$Q_{TOTAL} \approx 350$ WATTS OR LESS

$$\dot{m} = \frac{Q}{h_{fg}} = \frac{350\ J/s}{160\ J/g} \times \frac{2.2\ lb}{1000\ g} \times \frac{3600\ s}{hr} = 17.3\ lb/hr$$

$$Q_{LEAK\ RATE} = \frac{17.3\ lb/hr}{.102\ lb/ft^3} \times \frac{1\ hr}{60\ min} = \boxed{2.8\ CFM}$$

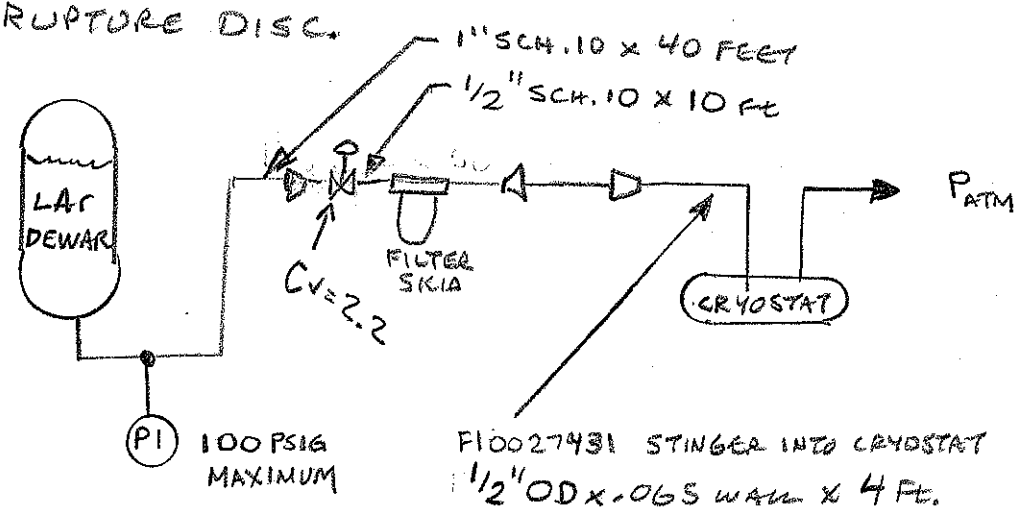
SUBJECT: LARIAT CRYOSTAT RELIEF OPEN LEAK RATE

NAME: RUSS RUCINSKI

DATE: 12-5-14 | REVISION DATE:

RELIEF VALVE - RELIEF EVENT.

WORST CASE HAVE THE LAr DEWAR OUTSIDE @ 100 PSIG AND SUPPLYING LIQUID TO FULL OPEN RELIEF VALVE OR RUPTURE DISC.



FIND EQUIVALENT LENGTH OF PIPE. IN TERMS OF 1" SCH. 10.

$d_{1''SCH.10} = 1.097$ INCHES $\qquad f_{1''} .023''$

$d_{1/2''SCH.10} = .674$ INCHES $\qquad f_{1/2''} = .027''$

$d_{1/2''OD \times .065} = .37$ INCHES $\qquad f_{1/2''} = .030''$

$$K = \frac{fL}{D} \quad \text{AND} \quad K_a = K_b \left(\frac{d_a}{d_b}\right)^4$$

EQN. 2-4 EQN 2-5 CRANE TECH-PAPER 410

$$K_{1''SCH.10} = \frac{fL}{D} = \frac{.023\,(40\,ft)}{1.097\,IN/12\,IN/ft} = \underline{10.1}$$

$$K_{1/2''SCH.10} = \frac{fL}{D} = \frac{.027(10\,ft)}{\frac{.674}{12}\,ft} = 4.8$$

CONVERT TO 1" SCH. 10

$$K_{1''SCH.10} = K_{1/2''SCH.10}\left(\frac{d_{1''}}{d_{1/2}}\right)^4 = 4.8\left(\frac{1.097}{.674}\right)^4 = \underline{33.7}$$

SUBJECT: LARIAT CRYOSTAT RELIEF OPEN LEAK RATE

NAME | DATE | REVISION DATE

$$K_{VALVE\ CV=2.2} = \left[\frac{29.9\ d^2}{C_V}\right]^2$$ EQUATION 2-6 FROM CRANE

$$K_{VALVE} = \left[\frac{29.9\ (1.097)^2}{2.2}\right]^2 = 268$$ EQUIVALENT K 1" SCH. 10

$$K_{1\frac{1}{2}''OD\times.065} = \frac{fL}{D} = \frac{.03\,(4\,Ft)}{\frac{.37}{12}\,Ft} = 3.9$$

CONVERT TO 1" SCH. 10

$$K_{1''SCH.10} = 3.9\left(\frac{1.097}{.37}\right)^4 = 301$$

$$K_{TOTAL\ 1''} = 10.1 + 33.7 + 268 + 301 = 613$$

EQUIVALENT LENGTH $L_{EQ.} = \frac{KD}{f} = \frac{613\left(\frac{1.097}{12}\,Ft\right)}{.023} = 2436\ Ft.$

CALCULATE THE FLOW

$$\Delta P = 3.36\times10^{-6}\,\frac{fLW^2}{\rho d^5}$$ EQN. 3-5 IN CRANE TECH PAPER 410.

$$W = \left[\frac{\Delta P\cdot\rho\cdot d^5}{3.36\times10^{-6}\,fL}\right]^{1/2} = \left[\frac{100\,PSI\,(80.3\,lb/ft^3)(1.097\,IN)^5}{3.36\times10^{-6}(.023)(2436\,Ft)}\right]^{1/2}$$

$$W = 8232\ lb/hr$$

$$Q_{LEAK} = \frac{W}{\rho_{GAS\ Ar\ STP}} = \frac{8232\ lb/hr}{.102\ lb/ft^3}\times\frac{1\ hr}{60\,MIN} = \boxed{1345\ CFM}$$

SUBJECT: LAPIAT FILTER RELIEF VALVE OPEN

NAME | DATE | REVISION DATE

IF THE ISOLATION VALVE CLOSES, THE STEADY STATE LEAK RATE WILL BE 3 CFM, THE SAME AS THAT FOR THE CRYOSTAT.

IF THE ISOLATION VALVE REMAINS OPEN THE FLOW RATE IS BASED ON THE PIPING UPSTREAM OF THE FILTER. (SEE CRYOSTAT CALCS.)

$$K_{TOTAL_{1''}} = K_{1'' \, 40\,ft} + K_{VALVE_{CV=2.2}}$$

$$= 10.1 + 268 = 278$$

$$L_{EQ.} = \frac{KD}{f} = \frac{278\left(\frac{1.097}{12}\,ft\right)}{.023} = 1105\ ft.$$

CALCULATE FLOW BY SCALING CRYOSTAT CALCULATION

$$Q_{LEAK} = 1345\,CFM \times \left[\frac{2436\,ft}{1105\,ft}\right]^{1/2} = \boxed{1997\,CFM}$$

FERMILAB ENGINEERING NOTE	SECTION	PROJECT	SERIAL-CATEGORY	PAGE 13
SUBJECT: LARIAT ARGON PIPING LEAK RATE		NAME		
		DATE	REVISION DATE FEB. 23, 2015	

ARGON PIPING;

LIQUID LINE, SMALL LEAK = 10 mm^2 AREA.

AVAILABLE PRESSURE = 100 PSIG.

THIS IS THE SAME AS A SMALL LEAK CALCULATION FOR THE FILTER

$$Q_{\substack{LEAK\\RATE}} = \boxed{320 \text{ CFM}}$$

LARGE LEAK = 500 mm^2 AREA

CALCULATE AS AN ORIFICE

$$q = AC\sqrt{2gh_L}$$

$$A = \overset{610}{\cancel{500}}\,mm^2 \times \left[\frac{1\,in}{25.4\,mm}\right]^2 \times \frac{1\,ft^2}{144\,in^2} = \overset{6.6\times10^{-3}\,ft^2}{\cancel{5.38}\times10^{-3}\,ft^2}$$

$C = 0.6$

$h_L = 188.5$ ft. (100 PSIG) SEE SMALL FILTER LEAK CALCULATION

$$q = AC\sqrt{2gh_L} = (\overset{6.6}{\cancel{5.38}}\times10^{-3}\,ft^2)(0.6)\sqrt{2(32.2\,ft/s^2)(188.5\,ft)}$$

$$q = \overset{.436}{\cancel{0.356}}\,ft^3/s$$

$$w = \overset{.436}{\cancel{0.356}}\,ft^3/s\,(76.4\,lb/ft^3)(3600\,s/hr) = \overset{12,0000}{\cancel{9782}}\,lb/hr$$ ← WAS IN ERROR

$$Q_{\substack{LEAK\\RATE}} = \frac{w}{\rho_{\substack{GAS\\STP}}} = \frac{\overset{1.2\times10^5}{\cancel{9782}}\,lb/hr}{.102\,lb/ft^3} \times \frac{1\,hr}{60\,min} = \boxed{\cancel{1598}\text{ CFM}}$$

$$\boxed{19,600 \text{ CFM}}$$

SUBJECT: REGENERATION PIPING LEAKRATE

NAME | DATE | REVISION DATE

A SMALL LEAK, 10 mm^2 AREA
MAXIMUM PRESSURE = 100 PSIG 0.79 MPa.
FLUID IS ROOM TEMPERATURE GAS ARGON

USE ORIFICE COMPRESSIBLE FLUID EQUATION, 3-22 IN CRANE TECH. PAPER 410.

$$q'_m = 412 \frac{Y d_1^2 C}{S_g} \sqrt{\Delta P \rho_1} \qquad \text{EQN. 3-22}$$

$d_1 = .81$ INCHES (1" OD × .095" WALL)

$\Delta P = 100$ PSI $\quad P_1'' = 114.3$ PSIA $\quad \frac{\Delta P}{P_1''} = .875$

$\beta = d_1/d_2 = \frac{.81}{\infty} = \underline{\underline{0}}$

$K_{ARGON} = C_p/C_v = 1.67$

$Y = 0.710$

PAGE A-22 OF CRANE USED K=1.4 SINCE NO K=1.67

$C = 0.6$

$S_g = 1.379$ TABLE ON PAGE A-8

$$\rho_1 = \left(13.162 \, kg/m^3\right)\left(.06248 \frac{lb/ft^3}{kg/m^3}\right) = 0.822 \, lb/ft^3$$

REFPROP, GAS @ T=290K & P=0.79 MPa

SUBSTITUTE INTO EQN. 3-22

$$q'_m = 412 \frac{(0.710)(0.81 \text{ in})^2 (0.6)}{1.379} \sqrt{(100 \text{ psi})(.822 \, lb/ft^3)}$$

$$\boxed{q'_m = 1.8 \text{ SCFM}}$$

SUBJECT: REGENERATION PIPING LEAK RATE

NAME | DATE | REVISION DATE

A LARGE LEAK RATE. CONSIDER THE TUBING TO BE SEVERED.

$$A = \frac{\pi}{4}(.81\,\text{in})^2\left(\frac{25.4\,\text{mm}}{\text{in.}}\right)^2 = \underline{332\,\text{mm}^2}$$

LET $\Delta P = 100$ PSI. THE LENGTH OF TUBING FROM THE SOURCE TO MC7 IS AT LEAST 20 FEET.

$$\Delta P = 3.36\times10^{-6}\,\frac{fLW^2}{\rho d^5} \quad \text{EQN. 3-5 CRANE}$$

RE-ARRANGE

$$W = \left[\frac{\Delta P\,\rho\,d^5}{3.36\times10^{-6}\,fL}\right]^{1/2}$$

$$\rho = \left(7.479\,\frac{\text{Kg}}{\text{m}^3}\right)\left(.06248\,\frac{\text{lb/ft}^3}{\text{Kg/m}^3}\right) = 0.467\,\text{lb/ft}^3$$

REFPROP, GAr @ T = 290 K, P = 0.45 MPa (50 PSIG)

$d = 0.81''$ (1.0" OD x .095" WALL TUBE)

$f = .025$

$$W = \left[\frac{(100\,\text{psi})(.467\,\text{lb/ft}^3)(.81\,\text{in})^5}{3.36\times10^{-6}(.025)(20\,\text{FEET})}\right]^{1/2}$$

$$W = 3114\,\text{lb/hr}$$

$$Q_{\substack{\text{LEAK}\\\text{RATE}}} = \frac{W}{\rho_{\substack{\text{GAr}\\\text{STP}}}} = \frac{3114\,\text{lb/hr}}{.102\,\text{lb/ft}^3}\times\frac{1\,\text{hr}}{60\,\text{MIN}} = \boxed{509\ \text{CFM}}$$