Fermilab

Particle Physics Division

Mechanical Department Engineering Note

Number: CMS-DOC-2996 Date: 09/16/10

Project Internal Reference:

Project: CMS FPIX CO_2 Test Stand

Title: CO_2 Hazard Analysis of CMS CO_2 Test Stand

Author(s): Erik Voirin

Reviewer(s): Richard Schmitt

Key Words: CO2 Hazard, CMS, ODH

Abstract Summary: This analysis calculates the fatality factors of in Lab C and the South Clean Room in Lab C, which will house parts of the CMS FPIX CO_2 cooling test stand. The analyses follow procedures of a conventional ODH assessment, but the fatality factor curve has been shifted to account for the increased hazards of CO_2. Calculations for Lab C and the Clean Room show a fatality factor of $4.75x10^{-11}$ and $6.52x10^{-8}$ respectively, both equivalent to fatality factor rates of a conventional ODH Class Zero.

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CO_2 Hazard Analysis of CMS CO_2 Test Stand

Erik Voirin

September 16, 2010

I. INTRODUCTION

This Assessment is for the CMD FPIX CO_2 Test Stand. The cooling system will use CO_2 as refrigerant, which is classified as a toxic contaminant by The National Institute for Occupational Safety and Health (NIOSH) which is part of the Center for Disease Control (CDC). CO_2 hazard can be assessed in a similar fashion to oxygen deficiency hazard (ODH), detailed in FESHM 5064, however, CO_2 concentrations will yield a fatality factor of 1 before ODH would even be out of the class 0 range. For cases where the displacing gas is CO_2, the CO_2 hazards needs to be assessed. When CO_2 hazards are present the ODH assessment is superseded by the CO_2 hazard and a separate ODH assessment has no meaning within this context.

The test stand has a storage Tank which will hold up to 300 lbs. of Liquid and Vapor CO_2, a phase separator, and two heater vessels, all four being ASME stamped vessels. The system contains roughly 200 ft of piping, and a variable speed pump. All components in the system are rated for high pressure and are capable of holding supercritical CO_2 at room temperature and beyond. The design pressure of the system is 1200 psi.

The analysis is done for two separate rooms, as the system will house some components in the hallway of Lab C and some in the South Clean Room contained in Lab C.

II. SIZES AND VOLUMES

Lab C features an open hallway which leads to Lab A, this extra volume is not considered in the volume, nor are either clean room housed in Lab C. Room dimensions and calculation details are in the appendix.

- Lab C Volume: 73,874 ft^3
- South Clean Room Volume: 21,471 ft^3

The storage tank will hold 300 lbs of CO_2 and be suspended near the ceiling in the Northwest corner of Lab C. When in service the pipes and other vessels will circulate roughly 225 lbs while the storage acts as a reservoir which holds 75 lbs. When not in service, the storage condensers will cool down to -40C, all but the return valves will be closed in order to draw as much CO_2 back into the storage tank as possible. The CO_2 analysis considers the system running at its highest temperature, and saturation pressure, and considers the storage tank always completely full at room temperature (80F) and a saturation pressure 955psi.

III. VENTILATION SYSTEMS

The South Clean room has a McQuay model LYF180CH air roof mounted air handler, which according to drawings [X.2], has a 1000 CFM air exchange with Lab C. 800 CFM exchange was used in calculations to account for underperformance, dirty filters, ect. The fresh air intake will have a flow sensor installed, so in the event the air handler malfunctions, shuts off, or the fresh air vents are closed, horn and lights will sound to evacuate the area until air exchange can be confirmed.

Lab C has a rooftop unit which exchanges outside air at a rate of 500 CFM, however due to the large volume of Lab C no ventilation was considered for a worst case scenario analysis.

IV. CO_2 DETECTORS / MONITORS

Both the Lab C space and the clean room space will be equipped with CO_2 monitors. The detector in Lab C will be in close vicinity to the pump and underneath the storage tank. The monitor in the clean room will be mounted in the frame which holds all the instruments and the phase separator. CO_2 is heavier than air so the gas monitors will be remote head types which will have the heads near the floor. These monitors will detect a CO_2 composition from 0 to 2% and will cause the horns and light to alarm if CO_2 concentration reaches a level above "Class 0" which would be 0.5%.

V. SIGNIFICANT SOURCES OF CO_2

The following are the significant sources of CO_2 hazardous conditions Lab C and the clean room. These are the sources considered in the analysis of component failures or ruptures. The potential leak rates for CO_2 are based on maximum pressures and estimated leak sizes. Both orifice calculations and relief valve calculations were conducted and the larger of the two leak rates used in subsequent calculations. The details can be found in the appendix.

Storage Vessel

The storage vessel holds 300 lbs of CO_2 and is assumed to be full in all calculations. It is the only vessel which remains full even when the system is not operational. In reality it will have roughly 75 lbs of CO_2 while operating. The vessel contains three flanges with gaskets whose failure rate was analyzed in addition to the vessel. (Located in Lab C)

Phase Separator Vessel

This vessel holds a maximum of 25 lbs of CO_2 while operating at the coldest and most dense temperature of -40F. (Located in Clean Room)

Heater Vessels

These vessels hold a maximum of 25 lbs of CO_2 while operating at the coldest and most dense temperature of -40F. (Located in Lab C and Clean Room)

Piping

The piping system consists of 0.5” to 2” schedule 10 Stainless 304 seamless pipe. The piping holds and circulates a maximum of 150 lbs of CO_2 while operating at the coldest and most dense temperature of -40F. (Located in Lab C and Clean Room)

Valves

The piping system consists along the way, obviously they do not hold CO_2, but since it is a circulating high pressure continuous system, a rupture could evacuate the entire system, check valves and automated ball valves are in place to help prevent this but this has not been considered in the analysis, a rupture is analyzed as dumping the entire system. (Located in Lab C and Clean Room)

Welds

The piping system is welded by butt weld connections along the way, obviously they do not hold CO_2, but since it is a circulating high pressure continuous system, a rupture could evacuate the entire system, check valves and automated ball valves are in place to help prevent this but this has not been considered in the analysis, a rupture is analyzed as dumping the entire system. (Located in Lab C and Clean Room)

Relief Valves

The relief valves in the CO_2 system did not contribute much to the Fatality factor at all, the valves are routed to relieve outside, so even if they failed wide open they would not cause a hazard at all. (Located in Lab C and Clean Room)

Pump

The Pump is considered as a failure mode as it may leak or burst, which would cause an evacuation of the system. (Located in Lab C)

Flanges/Gaskets

600# gaskets and flanges are used throughout as connections to vessels, pumps ect. They are considered a failure mode as are the gaskets used to seal them. (Located in Lab C and Clean Room)

Other Components

Even though not listed as failure modes, other components such as sight glasses, to pressure transmitters, strainers, differential pressure transmitters, ect. were included in the analysis and assumed to have the same failure rates and consequences and the manual and check valves. (Located in Lab C and Clean Room)

VI. FAILURES CONTRIBUTING TO CO_2 Hazard

1. Storage Vessel / Phase Separators / Heaters – Leak and Failure

Taylor [X.4] states the more common reasons for failure as corrosion, material and welding faults, excessive vibration, design errors such as under dimensioning, as well as others. None of these common failure causes apply to the the pressure vessels in the CO_2 test stand, as they are all ASME stamped vessel, all dimensions correct to ASME code and specifications. The welds of the vessels were 100% radiographed. They are also constructed entirely of stainless steel, and were pressure tested at 1560 psi. These vessels are estimated to have a far lower failure rate than the data for "all pressure vessels" dictated, however the failure rate of $2.5x10^{-10}$/hr and $2.5x10^{-9}$/hr were used as values for rupture and leak respectively. The details for these failure rates are in the appendix.

2. Piping – Leak and Failure

Piping can fail by leaking or breaking. The leak failure can be further broken down into a small leak and a large leak. A small leak is described by Taylor[X.4]X.4 as an opening of 10 mm^2 or less. A large leak is an opening of $10mm^2$ to 1,000 mm^2. Anything larger is considered a break. These leak sizes are for larger pipe (up to 6") than used in the piping in this system, as the cross sectional area of the 1" pipe is only 610 mm^2. To account for the size difference, the maximum small leak value of 10 mm^2 is scaled by the ratio of circumference of 6" pipe to circumference of 1" pipe, which yields $2mm^2$. The small leak risk rate is $3.05x10^{-10}$ per foot per hour and the pipe break risk is $9.14x10^{-12}$ per foot per hour.

FESHM 5064 has basic piping failure data on a per segment basis. The more recent industry data removes the ambiguity of "failure rate per segment" by assigning failure rates per foot of pipe.

3. *Flanges and Gaskets – Leak and Failure*

Piping flanges can fail by leaking, packing (gasket) blowout or breaking (separating). The flange leak risk rate[1] is 4.0×10^{-8} per hour, flange packing blowout risk rate is 3.0×10^{-8} per hour and the flange break risk rate is 1.0×10^{-9} per hour. The gaskets used on the flanges of the CO_2 test stand are all high quality Flexitallic spiral would ring gaskets. These have a solid metal 316SS inner ring, 316SS spiral would rings, PFTE Filler and a solid metal 316SS Outer ring. They are made for use specifically where corrosive or toxic media are present. Their design of having two solid metal rings ensures they will not rupture as the 600# flange gaskets also meet the requirements of ASME class 2500 flanges, which are rated for over 6000 psi. Therefore blowout risk was considered zero.

4. *Relief Valve - Leak and Release*

All the pressure vessel relief valves are vented to the outside. There are eight Anderson Greenwood relief valves in the system. Their failure rate to open is given by FESHM 5064 as 1.0×10^{-5}/demand.

5. *Human Error – Opening / Closing Valves*

The CO_2 Test Stand has numerous manual operated valves. All the valves will be lockable, which will prevent most human error. They will also be tagged with warnings. The drain valves will also be plugged by means of a plug or blind flange, so the system would to release even if a drain valve which should be locked were left unlocked and mistakably opened. The only scenario human error which could affect the system is if an operator opened one of the flanged valves causing a leak, then panicked and walked away leaving the leak, or could not close the valve. This is seen as a human error with a rate of 10^{-3}/demand, followed by the operator attempting to compensate for that mistake, with an error rate given in FESHM 5064 as $2^{(n-1)}x$, which yields an overall scenario rate of 8.33×10^{-11}/hr. Details are contained in the appendix.

VII. CO_2 CALCULATIONS

Carbon dioxide concentrations are calculated using leak rate vs. fresh air intake ratios. This is a conservative approach as it gives maximum concentration at time approaches infinity. The attainable CO_2 levels would be somewhat lower than the value calculated from eq.1. The intake of the exchanged airs maximum CO_2 level was included in the calculations as well.

$$CO_2\% = \frac{L}{Q} + P \qquad \text{(eq. 1)}$$

- L - is the rate of the carbon dioxide leak through the crack, hole, ect.
- Q - is the exchanged air rate through the air handler, (800 CFM).
- P - is the maximum concentration of CO_2 the exchanged air could have (2.88%).

It is assumed that all ruptures would cause an immediate evacuation of all contents in the system, where the CO_2 concentration would be calculated by the volume of the expanded CO_2 divided by the room volume.

VIII. Fatality Factor

As CO_2 concentration rises, the hazard level begins and increases to a fatality factor of 1 before oxygen levels drop below 18.9%. This yields any subsequent ODH calculations useless as they have already been covered in the much more stringent CO_2 assessment. One can see in the Fig.1 below the fatality factor curves for CO_2 as opposed to ODH, the curve fit for CO_2 is defined by the equation:

$$F_i = 4.28133 * 10^{-8} e^{169.6641647*(C)} \quad \text{(eq. 2)}$$

- F_i - is the fatality factor in fatalities per hour
- C – carbon dioxide percentage of the airspace as computed by eq.1 or other means

A direct leak rate to Fatality factor can be attained by combining eq.1 and eq.2 to form eq.3:

$$F_i = 4.28133 * 10^{-8} e^{169.6641647*(\frac{L}{Q}+P)} \quad \text{(eq. 3)}$$

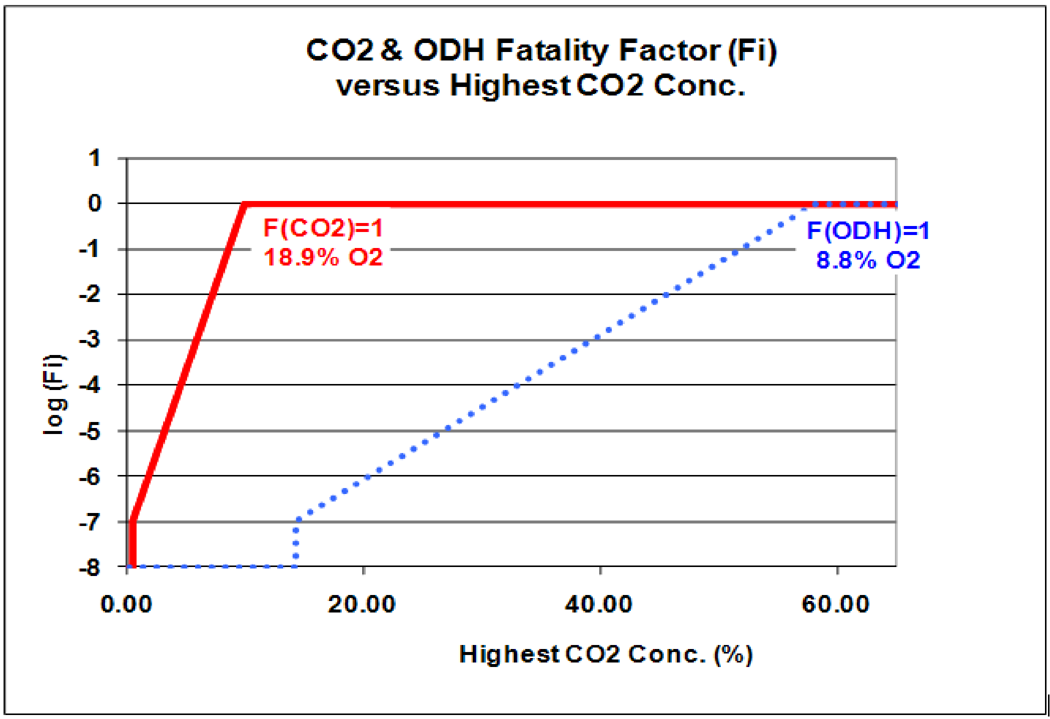


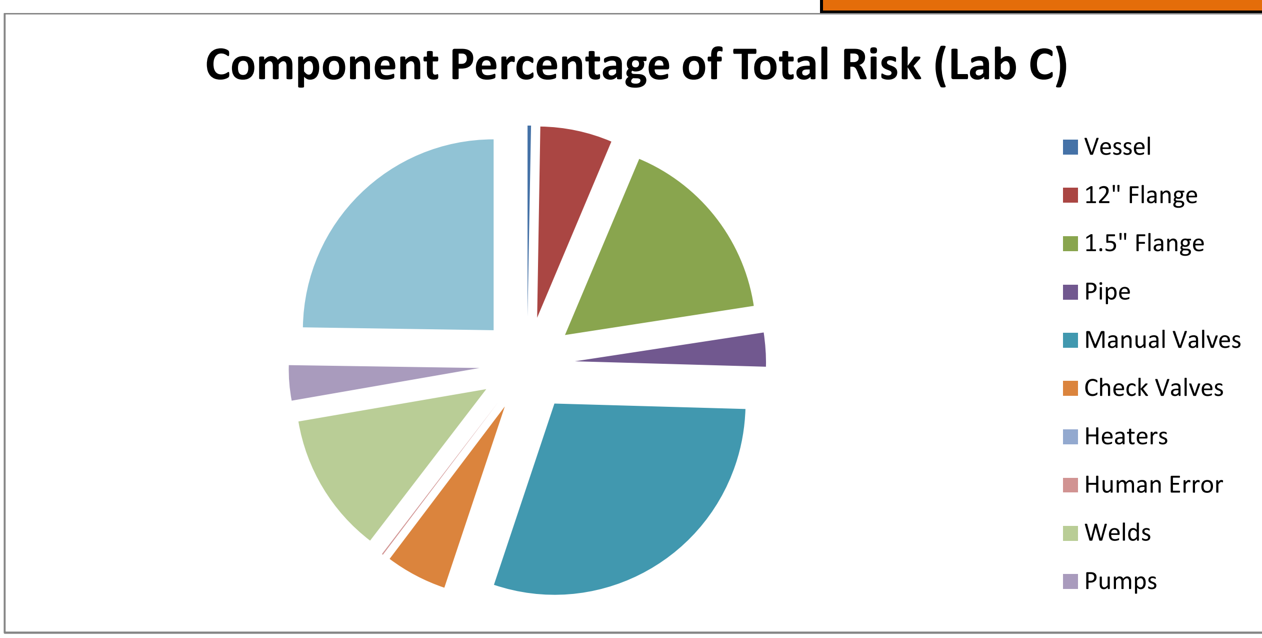
Fig.1: Fatality Factor comparison of CO_2 hazard vs. associated ODH hazard [X.1]

The following tables summarize the failure mode components in the test stand and their respective fatality factor contributions of Rupture FnR, of Leak, FnL, and of the component FnC. A graphical representation of each components contribution of the total fatality factor if shown in the segmented pie charts for below, their percentage following the equation:

$$SegmentSize = \frac{F_{nC}}{\sum_{n=1}^{11} F_{nC}}$$

CO2 Hazard Summary for Lab C								
Component / Scenario	number analyzed (number, feet)	Rupture Failure Rate (1/hr)	Rupture Fatality Factor (1/hr)	F_{nR} (1/hr)	Leak Failure Rate (1/hr)	Leak Fatality Factor (1/hr)	F_{1L} (1/hr)	F_{1C} (1/hr)
Vessel	2	2.50E-10	2.35E-05	1.18E-14	2.50E-09	2.35E-05	1.175E-13	1.29E-13
12" Flange	3	1.00E-09	2.35E-05	7.05E-14	4.00E-08	2.35E-05	2.82E-12	2.89E-12
1.5" Flange	8	1.00E-09	2.35E-05	1.88E-13	4.00E-08	2.35E-05	7.52E-12	7.71E-12
Pipe	185	9.14E-12	2.35E-05	3.97E-14	3.05E-10	2.35E-05	1.326E-12	1.37E-12
Manual Valves	6	1.00E-10	2.35E-05	1.41E-14	1.00E-07	2.35E-05	1.41E-11	1.41E-11
Check Valves	1	5.00E-09	2.35E-05	1.18E-13	1.00E-07	2.35E-05	2.35E-12	2.47E-12
Heaters	1	4.17E-16	2.35E-05	9.80E-21	0.00E+00	0.00E+00	0	9.80E-21
Human Error	1	8.33E-11	2.35E-05	1.96E-15	0.00E+00	0.00E+00	0	1.96E-15
Welds	80	0.00E+00	2.35E-05	0.00E+00	3.00E-09	2.35E-05	5.64E-12	5.64E-12
Pumps	1	3.00E-08	2.35E-05	7.05E-13	3.00E-08	2.35E-05	7.05E-13	1.41E-12
Other misc.	5	1.00E-10	2.35E-05	1.18E-14	1.00E-07	2.35E-05	1.175E-11	1.18E-11

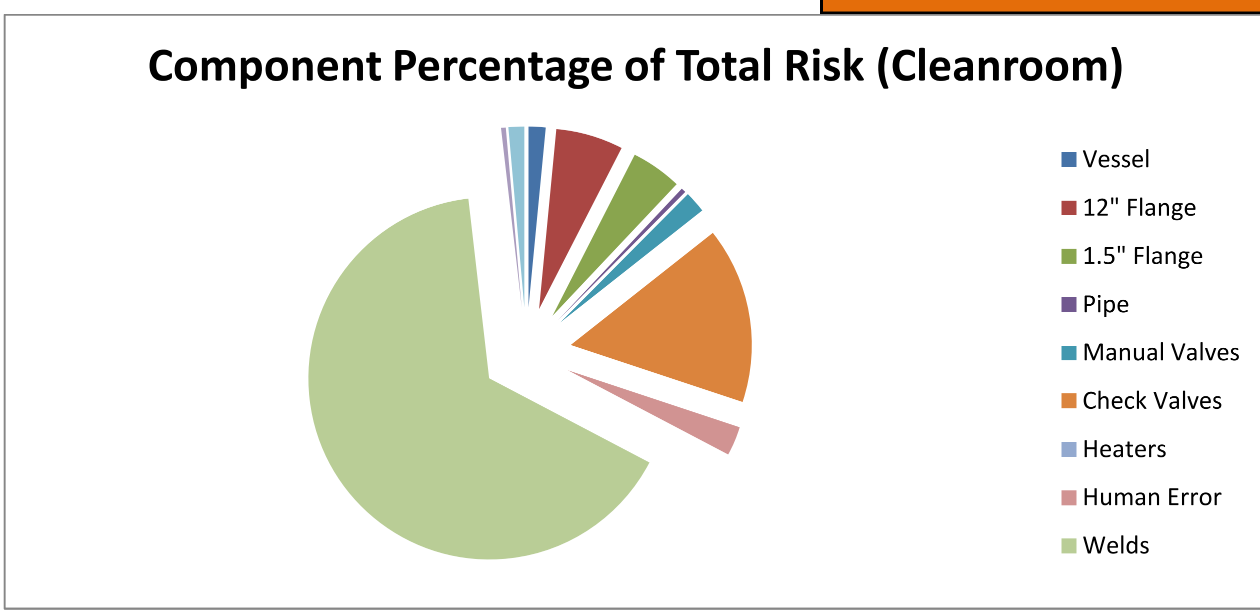
Fatality Rate from Ruptures	1.16E-12
Fatality Rate from Leaks	4.63E-11
Total Fatality Rate of Lab C	4.75E-11
CO2 Assessment comparable to ODH Class Zero	



CO_2 Hazard Summary for South Clean Room

Component / Scenario	number analyzed (number, feet)	Rupture Failure Rate (1/hr)	Rupture Fatality Factor (1/hr)	F_{nR} (1/hr)	Leak Failure Rate (1/hr)	Leak Fatality Factor (1/hr)	F_{1L} (1/hr)	F_{1C} (1/hr)
Vessel	2	2.50E-10	1.00	5.00E-10	2.50E-09	1.03E-01	5.15E-10	1.02E-09
12" Flange	4	1.00E-09	1.00	4.00E-09	4.00E-08	6.15E-05	9.84E-12	4.01E-09
1.5" Flange	3	1.00E-09	1.00	3.00E-09	4.00E-08	1.53E-04	1.84E-11	3.02E-09
Pipe	30	9.14E-12	1.00	2.74E-10	3.05E-10	7.63E-04	6.98E-12	2.81E-10
Manual Valves	12	1.00E-10	1.00	1.20E-09	1.00E-07	6.58E-05	7.90E-11	1.28E-09
Check Valves	2	5.00E-09	1.00	1.00E-08	1.00E-07	2.60E-03	5.20E-10	1.05E-08
Heaters	1	4.17E-16	1.00	4.17E-16	0.00E+00	0.00E+00	0.00E+00	4.17E-16
Human Error	1	8.33E-11	1.00	8.33E-11	0.00E+00	0.00E+00	0.00E+00	8.33E-11
Welds	95	0.00E+00	0.00	0.00E+00	3.00E-09	1.54E-01	4.38E-08	4.38E-08
Leak w/o Vent	1	0.00E+00	0.00	0.00E+00	2.97E-10	1.00E+00	2.97E-10	2.97E-10
Other misc.	9	1.00E-10	1.00	9.00E-10	1.00E-07	6.58E-05	5.92E-11	9.59E-10

Fatality Rate from Ruptures	2.00E-08
Fatality Rate from Leaks	4.53E-08
Total Fatality Rate of Clean Room	6.52E-08
CO_2 Assessment comparable to ODH Class Zero	



IX. Safety Precaution Summary

It is important to note these additional safety measures were implemented as redundancies and are not necessary for risk factor classification camparable to ODH class 0. The Analysis involved does not include the benefits of these additional measures, which would lower the risk factors involved in a CO_2 contamination scenario. These additional safety measures include:

1. Valves will be tagged with warnings according to FESHM 5051.
   CO_2 monitors will be installed in lab C as well as the clean room
2. Ventilation fan will be installed in Lab C with a ventilation rate greater than 800 SCFM. This centrifugal fan will be placed in close vicinity to the pump, trim heater and storage vessel.
3. Flow switches will be installed on clean room fresh air intake as well as Lab C ventilation fan. The Lab C ventilation fan will be activated by the PLC and its flow tested via the flow monitor on a weekly basis.
4. Isolation valve and check valve installed at entrance to clean room which can isolate the piping in the clean room if a leak should occur.

Proactive Steps and Alarms aimed at personnel safety:

Regarding the Clean Room

- Trouble alarm at 0.3% CO_2
- Trouble alarm if the fresh air makeup is off
- Close isolation valve and stop pump at 0.5% CO_2
- Evacuate at 2% CO_2 concentration

Regarding the Lab C hallway

- Trouble alarm at 0.3% CO_2
- Trouble alarm if local exhaust fan fails regular test
- Start exhaust fan at 0.5% CO_2
- Evacuate at 2% CO_2 concentration

X. References

1. *Adamowski, Mark. CO_2 Hazard and ODH - PPD #MD-ENG-250. PPD Fermilab, 27 May 2010. Pdf.*

2. *Hammond, Lee. Lab C Workspace, Mechanical Plan. Dwg.#8-2-125: M1, M2, M3. Fermilab, 16 June 1997. Pdf.*

3. *Klebaner, Arkadiy. FESHM 5064 - OXYGEN DEFICIENCY HAZARDS (ODH). Fermilab, May 2009. Doc.*

4. *Taylor, J. R. Risk Analysis for Process Plant, Pipelines and Transport. London [etc.: E and FN Spon, 1994. Print.*

APPENDIX CONTENTS

rev. 04-12-11

Calculation Methods and Conservative Approach

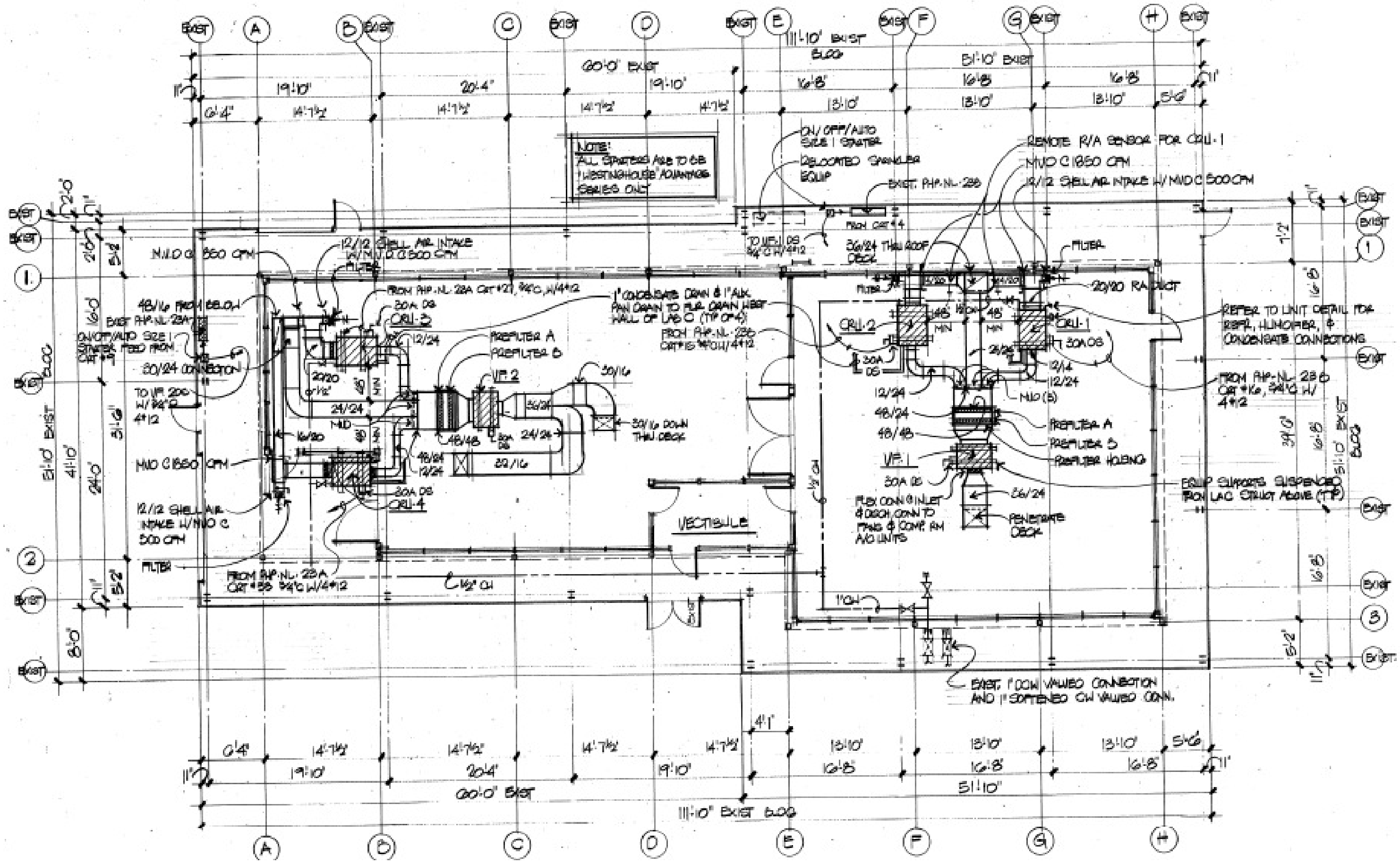
The following calculations show how the fatality factors for both Lab C and the Clean Room were calculated. Conservative methods were used throughout calculation as CO_2 leak concentrations were analyzed at the limit as time approaches infinity, for an absolute maximum CO_2 level analysis.

Both Lab C and the Clean Room will be equipped with CO_2 monitoring equipment, which will be connected to lights and horns, warning to evacuate the area if CO_2 reaches anything above a 0.5%. These warning systems were not taken into account in the analysis, as if there were no safety monitoring systems at all.

Ventilation was not considered in Lab C to produce a higher safety factor, in reality the building has a rooftop unit which exchanges 500 CFM with outside air.
Ventilation was considered in the Clean Room, as well as the maximum amount of CO_2 which could re-enter through the ventilation.

Lab C Volume

This is an estimate of the air space that will contain the CO_2 Storage Vessel (in Lab C outside of cleanroom) as well as the air space in the clean room where the detector test stand will be located.



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UNITED STATES DEPARTMENT OF ENERGY

LAB C WORKSPACE

MECHANICAL PLAN, MEZZANINE LEVEL & MECHANICAL SCHEDULES

DRAWING NO. 8-2-125 M-2 REV.

Clean Room 1 dimensions

$$x_{CL1} := 57ft + 9in$$

$$y_{CL1} := 31ft + 6in$$

$$CleanRoom1_{area} := x_{CL1} \cdot y_{CL1} - x_V \cdot y_V - 145ft^2$$

Vestibule dimensions

$$x_V := 18ft + 9in$$

$$y_V := 7ft$$

Clean Room 2 dimensions

$$x_{CL2} := 41ft + 6in$$

$$y_{CL2} := 39ft + 6in$$

$$CleanRoom2_{area} := x_{CL2} \cdot y_{CL2}$$

Building Dimensions

$$x_{labC1} := 60ft \qquad x_{labC2} := 51ft + 10in$$

$$y_{labC1} := 41ft + 10in \qquad y_{labC2} := 51ft + 10in$$

$$Bldg_{area} := x_{labC1} \cdot y_{labC1} + x_{labC2} \cdot y_{labC2} = 5197 \cdot ft^2$$

$$LabC_{area} := Bldg_{area} - CleanRoom1_{area} - CleanRoom2_{area} - x_V \cdot y_V = 1883\,ft^2$$

Total Volumes

$$LabC_{vol} := LabC_{area} \cdot 206.5in + Bldg_{area} \cdot (302.25in - 206.5in) = 73874 \cdot ft^3$$

$$CR1_{vol} := CleanRoom1_{area} \cdot 167in = 21472 \cdot ft^3$$

List and Number of Failure Mode Components

Lab C

$num_{ASMEvessel} := 2$

$num_{12inFlangeGasket} := 3$

$num_{1.5inFlangeGasket} := 8$

$L_{Pipe} := 185ft = 185\,ft$

$num_{MOV} := 6$

$num_{CheckV} := 1$

$num_{ReliefV} := 4$

$num_{welds} := 80$

$num_{OtherCmpnts} := 5$

$num_{Heaters} := 1$

$num_{Pumps} := 1$

Clean room

$num_{ASMEvesselCL} := 2$

$num_{1inFlangeGasketCL} := 4$

$num_{1.5inFlangeGasketCL} := 3$

$L_{PipeCL} := 30ft = 30\,ft$

$num_{MOVCL} := 14$

$num_{CheckCL} := 2$

$num_{ReliefVCL} := 4$

$num_{weldsCL} := 95$

$num_{OtherCmpntsCL} := 9$

$num_{Heaters} := 1$

These Components were either listed as failure modes in FESHM 5064, listed as failure modes in "Risk Analysis for Process Plant, Pipelines and Transport", 1st edition, or added by engineering judgment as possible sources of failure.

Other sources of failure have been addressed, for example, if a severed line in the heat exchanger occurs it may allow high pressure CO_2 to enter the R404a lines the pressure may be above the rated pressure for the copper pipe. Therefore in-line burst disks which then vent outside will be installed on the copper tubing to prevent leakage into the building.

Component Failure Rates

Pressure Vessel Failure Rate

From: Risk Analysis for Process Plant, Pipelines and Transport, 1st ed

This source has catastrophic failure rates, reported as failures per annum and failures per 10^6 hours. The source also states the more common reasons for failure as corrosion, material and welding faults, excessive vibration, design errors, such as under dimensioning as well as others, The Vessels used in the CO2 Test stand are ASME stamped vessels with all welds radiographed, built entirely of stainless steel and have been pressure tested at 1560psi.

Pressurized Vessel, Catastrophic Failure

$$\frac{\left(3\cdot 10^{-6}\right)}{365\cdot 24\cdot hr} = 3.42\times 10^{-10}\cdot\frac{1}{hr} \qquad \frac{2.5\times 10^{-4}}{10^{6}\cdot hr} = 2.5\times 10^{-10}\cdot\frac{1}{hr}$$

Pressurized Vessel, Small Leak

The source listed failure rate data per annum and per 10^6 hours the value is shown converted to per hour.

$$\frac{2.5\times 10^{-3}}{10^{6}\cdot hr} = 2.5\times 10^{-9}\frac{1}{hr}$$

Note that the difference between the vessel failure rate and the vessel leak rate is an order of magnitude.

$$F_{ASMEvessel\_Rupture} := \frac{2.5\times 10^{-10}}{hr} \qquad F_{ASMEvessel\_Leak} := \frac{2.5\times 10^{-9}}{hr}$$

Pump Failure Rate

The pump housing used in the CO_2 system has been pressure tested at over 1800 psi, which is 600psi over what the relief valve would relieve. The pump is also a sealed unit with a mag drive, decreasing the possibility of a leak, however, conservative given values are still used for calculation.

From: "Risk Analysis for Process Plant, Pipelines and Transport" Taylor J.R.

$$F_{Pump\_Leak} := \frac{3\cdot 10^{-8}}{hr} \qquad F_{Pump\_Rupture} := \frac{3\cdot 10^{-8}}{hr}$$

Piping Failure Rate

Piping can fail by developing a leak or totally breaking.

From: Risk Analysis for Process Plant, Pipelines and Transport, 1st ed

This source has failure rates for small piping (<2 inches), reported as failures per 10^6 hours, per meter of pipe. These failure rates, per million hours, per meter of pipe are converted to failure rates per hour per foot of pipe.

The failure rates are for small leak, large leaks and pipe breaks.

A small Leak is defined as a small crack or pinhole leaks, 10 mm^2 or less.

Small Leak, in Pipe 1/2 to 2"

$$F_{Pipe\_Leak} := \frac{\frac{0.001}{10^6 \cdot hr}}{m} = 3.05 \times 10^{-10} \frac{1}{ft \cdot hr}$$

Break, in Pipe 1/2" to 2"

$$F_{Pipe\_Rupture} := \frac{\frac{0.00003}{10^6 \cdot hr}}{m} = 9.14 \times 10^{-12} \frac{1}{ft \cdot hr}$$

Notes on Piping Failure Rate Data

Chemical plants and petroleum refineries failure data reflects the failures of the piping in those environments.

Those environments include;
- outdoor, year round operation
- high temperature (decreasing strength) and pressure
- large temperature range operation - crude cracking to liquefying gases
- stress cracks and embrittlement due to high temperature chemical attack
- surface corrosion, inside and outside surfaces
- chemical attack of gasketing materials
- frequent operation at eroding line velocities

Cryogenic operations of concern for ODH are indoors. The cryogens contained are not corrosive to the metals and gasketing materials used. Cryogenic operation is in the direction of higher metal strength (decreasing temperature).

Cryogenic operation is different from chemical/refinery operation but at the same time suffers from fewer sources of failure over time.

The chemical/refinery failure data will be used even though it reflects failures from additional sources not seen in cryogenic service.

Flange Failure Rate

The flanges will be ASME B16.5 600# flanges, constructed of stainless steel and designed for high pressure. The source listed below states 0.01 failures per million hours, and that for high pressure systems designed to high standards the values may be divided by 10, which is reflected in the calculation.

From: "Risk Analysis for Process Plant, Pipelines and Transport" Taylor J.R.

Flanges can fail by developing a leak, blowing packing, or breaking open.

This source has failure rates reported as failures per m per 10^6 hours.

The reported failure rates include failure modes such as flange corrosion, packing corrosion, overstressing due to heating and aging of packing. The corrosion and overstressing from heating do not apply to cryogenic service. The metal gaskets that will be used do not degrade with age. To account for these differences, the reported data for packing blowout and flange break will be reduced by an order of magnitude.

Flange Leak

$$F_{Gasket\_Leak} := \frac{\frac{0.4}{10^6 \cdot hr}}{10} = 4 \times 10^{-8} \frac{1}{hr}$$

Flange Packing Blowout

$$F_{Gasket\_Blowout} := \frac{0.03}{10^6 \cdot hr} = 3.0 \times 10^{-8} \frac{1}{hr}$$

Flange Breaks Open

$$F_{Flange\_Rupture} := \frac{\frac{0.01}{10^6 \cdot hr}}{10} = 1.0 \times 10^{-9} \frac{1}{hr}$$

Valve Failure Rate

The Valves used in the CO_2 Test stand are High quality all stainless steel valves with Teflon seals. They are rated to 2000 psi, and will not even see half that pressure even at the highest saturation pressure caused by room temperature while the system is not in service.

From: "Risk Analysis for Process Plant, Pipelines and Transport" Taylor J.R.

Valves can fail by leaking into over its seat which is usually caused by corrosion, erosion, or trapping of foriegn objects on closure. They may also crack or rupture

This source has failure rates reported as failures per 10^6 hours.

The reported failure rates include failure modes such as corrosion, packing corrosion, overstressing due to heating and aging of packing. The corrosion and overstressing from heating do not apply to refrigerated service of stainless steel. As the source allows and where applicable, to account for these differences, the reported data for leak, crack, and rupture were be reduced by an order of magnitude.

$$F_{MOV\_Rupture} := \frac{1\cdot 10^{-10}}{hr} \qquad F_{CheckV\_Leak} := \frac{2\cdot 10^{-7}}{hr} \qquad F_{CheckV\_LeakLarge} := \frac{2\cdot 10^{-7}}{3hr}$$

$$F_{MOV\_Leak} := \frac{1\cdot 10^{-7}}{hr} \qquad F_{CheckV\_LeakOut} := \frac{1\cdot 10^{-7}}{hr}$$

$$F_{MOV\_Crack} := \frac{1\cdot 10^{-8}}{hr} \qquad F_{CheckV\_Rupture} := \frac{5\cdot 10^{-9}}{hr}$$

It is also assumed all other components (Differential pressure transmitters, pressure transmitters, sight glasses ect.) have the same failure rates as the manual and check valves. Other components are not listed as failure modes in either FESHM or the risk Analysis text, they are being considered for a conservative analysis.

Other Failure Rates

These were taken directly from FESHM 5064 (Revised 05/2009), a weld rupture failure rate is not addressed in FESHM 5064, and it is assumed the weld will have the same strength as the piping itself. A piping note on the system per 5031 will demonstrate the pipe strength. The ventilation rate is the sum of the circuit breaker, fan motor, and electrical power failures, which are rated at 10^{-6}, 10^{-5}, and 10^{-4} respectively.

$$F_{Welds\_Leak} := \frac{3 \cdot 10^{-9}}{hr} \qquad F_{ReliefV\_PrematureOpen} := \frac{1 \cdot 10^{-5}}{hr} \qquad F_{Ventilation} := \frac{1.11 \cdot 10^{-4}}{hr}$$

$$F_{Wires\_ShortToPower} := \frac{1 \cdot 10^{-8}}{hr} \qquad F_{ReliefV\_FailOpen} := \frac{1 \cdot 10^{-5}}{demand} = 1 \times 10^{-5}$$

Relief Valve Premature opens and fails to open

The relief valves for the CO_2 test stand are routed to release outside, so a premature open would only cause a small loss of the fluid, and pose no danger. A fail to open would only be a danger is some other mistake were already made or another system failed. If the relief valve needed to relieve and failed to open the pressure would continue increasing. The pipe and valves are rated to 2000 psi, 800 psi above where the relief valve should go off, The vessels were pressure tested at 1560psi, and all flanges and other components are 600# rated (1480psi). The relief valve , even if miscalibrated would still protect the system before rupture. In the event it failed to open at all, which would be unlikely, it would cause a rupture and would dump the contents of the system all, 300 lb of CO_2 will enter the airspace, CO_2 monitors will alarm to evacuate the building.

This could happen if: While operating an operator closed a valve that should remain open, then closed another adjacent valve that should remain open, then the relief valve failed.

$$F_{ReliefV\_FailOpenSeq1} := F_{ReliefV\_FailOpen} \cdot F_{Human\_WrongValve} \cdot F_{Human\_WrongValve} \cdot hr = 1.736 \times 10^{-14} \frac{1}{hr}$$

This could happen if: While not operating either heater turns on and begins heating due to wires shorting to power. Then the relief valve would have to fail to open as well.

$$F_{ReliefV\_FailOpenSeq2} := F_{ReliefV\_FailOpen} \cdot F_{Wires\_ShortToPower} = 1 \times 10^{-13} \frac{1}{hr}$$

Human Error Analysis

The CO_2 Test Stand has numerous drain valves which could be opened by mistake which would cause a release of CO_2 into the containing rooms. Several precautions have been implemented to reduce this risk:

1.) These valves are be tagged with a caution tag.
2.) These valves will also be equipped with either blind flanges or plugs to prevent a large release of CO_2.

Changes to the additional flanged connections and drain valves will follow written procedures that will reference tagged valves.
It is assumed even is a valve is left unlocked, which is then missed by the monitoring person, and then mistakenly open, the person who opened the valve would hear the hiss of leaking CO_2 through the hole and close the valve, yielding no overall hazard due to the safety precautions taken. However a person could open, and then panic and walk away, causing a leak in the system, this would be two consecutive human errors.

Rate that a user would mistakenly open a flanged, or drain valve, releasing CO2 into the room.
(value from FESHM 5064): "10-3(per demand) Selection of a switch (or pair of switches) dissimilar in shape or location to the desired switch (or pair of switches), assuming no decision error. For example, operator actuates large handled switch rather than small switch."

$$F_{Human\_WrongValve} := \frac{10^{-3}}{demand} \cdot \frac{1demand}{day} = 4.17 \times 10^{-5} \frac{1}{hr}$$

Rate that a user would observe this leak they had just caused by opening the valve, but instead of immediately closing the valve, which would be the natural reaction, leaving it open and watching it release the contents of the entire system.
(value from FESHM 5064): $2^{(n-1)}x$ Given severe time stress, as in trying to compensate for an error made in an emergency situation, the initial error rate, x, for an activity doubles for each attempt, n, after a previous incorrect attempt, until the limiting condition of an error rate of 1.0 is reached or until time runs out. This limiting condition corresponds to an individual's becoming completely disorganized or ineffective.

$$\text{AttemptFailureRate} := \left| \begin{array}{l} \text{for } n \in 1..11 \\ \quad \text{AttemptFailureRate}_n \leftarrow 2^{n-1} \cdot \frac{10^{-3}}{\text{demand}} \\ \text{return AttemptFailureRate} \end{array} \right. =$$

	1
1	$1 \cdot 10^{-3}$
2	$2 \cdot 10^{-3}$
3	$4 \cdot 10^{-3}$
4	$8 \cdot 10^{-3}$
5	$1.6 \cdot 10^{-2}$
6	$3.2 \cdot 10^{-2}$
7	$6.4 \cdot 10^{-2}$
8	$1.28 \cdot 10^{-1}$
9	$2.56 \cdot 10^{-1}$
10	$5.12 \cdot 10^{-1}$
11	$1.02 \cdot 10^{0}$

Rate at which a number, n, of these errors would be made consecutively.

$$\text{EquivelentFailureRate} := \left| \begin{array}{l} \text{for } n \in 1 \\ \quad \text{EquivelentFailureRate}_1 \leftarrow \text{AttemptFailureRate}_1 \\ \text{for } n \in 2..11 \\ \quad \text{EquivelentFailureRate}_n \leftarrow \text{EquivelentFailureRate}_{n-1} \cdot \text{AttemptFailureRate}_n \\ \text{return EquivelentFailureRate} \end{array} \right.$$

EquivelentFailureRate =

	1
1	$1 \cdot 10^{-3}$
2	$2 \cdot 10^{-6}$
3	$8 \cdot 10^{-9}$
4	$6.4 \cdot 10^{-11}$
5	$1.024 \cdot 10^{-12}$
6	$3.277 \cdot 10^{-14}$
7	$2.097 \cdot 10^{-15}$
8	$2.684 \cdot 10^{-16}$
9	$6.872 \cdot 10^{-17}$
10	$3.518 \cdot 10^{-17}$
11	$3.603 \cdot 10^{-17}$

$\cdot \frac{1}{\text{demand}}$

We will assume the user could make only two attempts to correct their mistake before the room would be filled with CO2, meaning "time had run out"
Then we have a total equivilent failure rate for this scenario of:

$$F_{HumanError2consec} := \text{EquivelentFailureRate}_2 \cdot F_{Human\_WrongValve} = 8.33 \times 10^{-11} \frac{1}{hr}$$

Leak Rates

12 in gasket rupture

Gaskets are High Quality Flexitallic spiral wound ring gaskets 12.75" ID and 18" OD. They have a solid metal 316SS inner ring, 316SS spiral would rings, PFTE Filler and a solid metal 316SS Outer ring. This design ensures they will not rupture as they also meet the requirements of ASME class 2500 flange gasket requirements.

$LR_{Gasket\_Rupture} := 0$

12 in gasket Leak

Gaskets are to be compressed to 0.09 to 0.1" and the leak thickness is assumed to be an order of magnitude less than the of the gasket space, a leak would take place between two of the twenty 1.25" diameter bolts on the flange order of magnitude less than the distance from bolt to bolt in width.

$Gasket_{LeakHeight} := \frac{0.095in}{10} = 0.0095 \cdot in$

$Gasket_{LeakWidth} := \frac{18\pi - 20 \cdot 1.25}{20 \cdot (10)} in = 0.16 \cdot in$

$Gasket_{LeakArea} := Gasket_{LeakHeight} \cdot Gasket_{LeakWidth} = 0.0015 \cdot in^2$

Density of CO2 gas at STP

$\rho_{gas} := 1.75 \frac{kg}{m^3}$

$A := Gasket_{LeakArea}$ $\quad C := 0.6$ $\quad \Delta P := 955psi$

Density of CO2 gas at -110F (relieving)

$\rho_{cold} := 3.62 \frac{kg}{m^3}$

Orifice calculation Crane 6-31

$q := C \cdot A \cdot \sqrt{2 \cdot g \cdot \frac{\Delta P}{\rho_{cold} \cdot g} \cdot \left(\frac{\rho_{cold}}{\rho_{gas}}\right)} = 290.97 \cdot \frac{ft^3}{hr}$

flow calculation and CO_2 properties

A leak in the system will result in the CO_2 released flashing down to a solid / vapor mixture temperature near -110F, therefore relief valve type calculations should be performed to calculate the expected release rate instead of orifice calculations.

Assuming saturated liquid/vapor mixture in the storage Tank at 80 degrees F

Coeff. of Discharge

$K_1 := 0.6$

C Value for CO2

$C := 345$

Compressibility factor

$Z := .5$

Molecular weight

$M := 44$

Pressure

$P_1 := 955$

Backpressure Coefficient

$K_b := 1$

Absolute temperature

$T := (80 + 460)$

$$Area = \frac{W_u \cdot \sqrt{T} \cdot \sqrt{Z}}{C \cdot K_1 \cdot P_1 \cdot K_b \cdot \sqrt{M}}$$

$$W_u := \frac{\frac{Gasket_{LeakArea}}{in^2} \cdot C \cdot K_1 \cdot P_1 \cdot K_b \cdot \sqrt{M}}{\sqrt{T} \cdot \sqrt{Z}} \cdot \frac{lb}{hr} = 119.6 \frac{lb}{hr}$$

$$LR_{Gasket\_Leak\_12} := \frac{W_u}{\rho_{gas}} = 1095 \cdot \frac{ft^3}{hr}$$

Actual cubic feet after expanding to room temperature

1.5 in gasket Leak

Gaskets are to be compressed to 0.09 to 0.1" and the leak space is assumed to be an order of magnitude less than the of the gasket space, a leak would take place between two of the four 3/4" diameter bolts on the flange one order of magnitude less than the distance from bolt to bolt in width.

$$Gasket_{LeakHeight} := \frac{0.095in}{10} = 0.0095 \cdot in$$

$$Gasket_{LeakWidth} := \frac{3.75\pi - 4 \cdot 0.75}{4 \cdot (10)} in = 0.22 \cdot in$$

$$Gasket_{LeakArea} := Gasket_{LeakHeight} \cdot Gasket_{LeakWidth} = 0.00209 \cdot in^2$$

flow calculation and $C0_2$ properties

Assuming saturated liquid/vapor mixture in the pipes at a maximum running temperature of 50 degrees F.

Coeff. of Discharge

$K_1 := 0.6$

C Value for CO2

$C := 345$

Compressibility factor

$Z := .63$

$\rho_{gas} := 1.75 \frac{kg}{m^3}$

Molecular weight

$M := 44$

Pressure

$P_1 := 638$

Backpressure Coefficient

$K_b := 1$

Absolute temperature

$T := (50 + 460)$

$$Area = \frac{W_u \cdot \sqrt{T} \cdot \sqrt{Z}}{C \cdot K_1 \cdot P_1 \cdot K_b \cdot \sqrt{M}}$$

$$W_u := \frac{\frac{Gasket_{LeakArea}}{in^2} \cdot C \cdot K_1 \cdot P_1 \cdot K_b \cdot \sqrt{M}}{\sqrt{T} \cdot \sqrt{Z}} \cdot \frac{lb}{hr} = 101.9 \frac{lb}{hr}$$

$$LR_{Gasket\_Leak\_1.5} := \frac{W_u}{\rho_{gas}} = 933 \cdot \frac{ft^3}{hr}$$

Actual cubic feet after expanding to room temperature

For a maximum operating temperature of 50F (638psi). The leaked flow will vary linearly with the size of the leak, that correlation will be calculated to assist in further calculations.

$$\frac{C \cdot K_1 \cdot P_1 \cdot K_b \cdot \sqrt{M}}{\sqrt{T} \cdot \sqrt{Z}} = 48872.21 \qquad LeakRate := \frac{\frac{48872.21}{in^2} \cdot \frac{lb}{hr}}{\rho_{gas}}$$

1" gasket Leak

Gaskets are to be compressed to 0.09 to 0.1" and the leak space is assumed to be an order of magnitude less than the of the gasket space, a leak would take place between two of the four 5/8" diameter bolts on the flange one order of magnitude less than the distance from bolt to bolt in width.

$$Gasket_{LeakHeight} := \frac{0.095in}{10} = 0.0095 \cdot in$$

$$Gasket_{LeakWidth} := \frac{2.88\pi - 4 \cdot 0.675}{4 \cdot (10)} in = 0.16 \cdot in$$

$$Gasket_{LeakArea} := Gasket_{LeakHeight} \cdot Gasket_{LeakWidth} = 0.00151 \cdot in^2$$

$$LR_{Gasket\_Leak\_1} := LeakRate \cdot Gasket_{LeakArea} = 674.42 \cdot \frac{ft^3}{hr}$$

Manual Valve Leaks and Ruptures

The small leak will be assumed to be a pinhole leak of 1 mm^2 since it would most likely be through the stem or seal and be very small. Other components, although not listed as failure modes will also be considered with the same leak rate as Manual Valves.

$$MOV_{area} := 1mm^2$$

$$LR_{MOV\_Leak} := LeakRate \cdot MOV_{area} = 693.39 \cdot \frac{ft^3}{hr} \qquad LR_{OtherCmpnts} := LR_{MOV\_Leak} = 693.39 \cdot \frac{ft^3}{hr}$$

A Rupture is going to dump the contents of the system all 300 lb of CO2 will enter the airspace, CO_2 monitors will alarm to evacuate the building.

Check Valve Leaks and Ruptures

The small leak will be assumed to be a small
(along a seal or a small crack) 2.5 mm^2

$CV_{area} := 2.5mm^2$

$LR_{CheckV} := LeakRate \cdot CV_{area} = 1733.47 \cdot \frac{ft^3}{hr}$

A Rupture is going to dump the contents of the system all 300 lb of CO_2 will enter the airspace, CO2 monitors will alarm to evacuate the building.

Weld Leaks

The small leak will be assumed to be a leak of 10% the length (circumfirential crack) the crack will be assumed to be 1/64" in thickness

$OD_1 := 1.315in$

$thickness_{crack} := \frac{1}{64}in$

$Weld_{area} := OD_1 \cdot \pi \cdot 10\% \cdot thickness_{crack} = 4.16 \cdot mm^2$

$LR_{Welds} := LeakRate \cdot Weld_{area} = 2887.62 \cdot \frac{ft^3}{hr}$

Pipe Leaks

The small leak will be assumed to be a leak of 2 mm^2 (assumption justified in report)

$Pipe_{area} := 2mm^2$

$LR_{Pipe} := LeakRate \cdot Pipe_{area} = 1386.78 \cdot \frac{ft^3}{hr}$

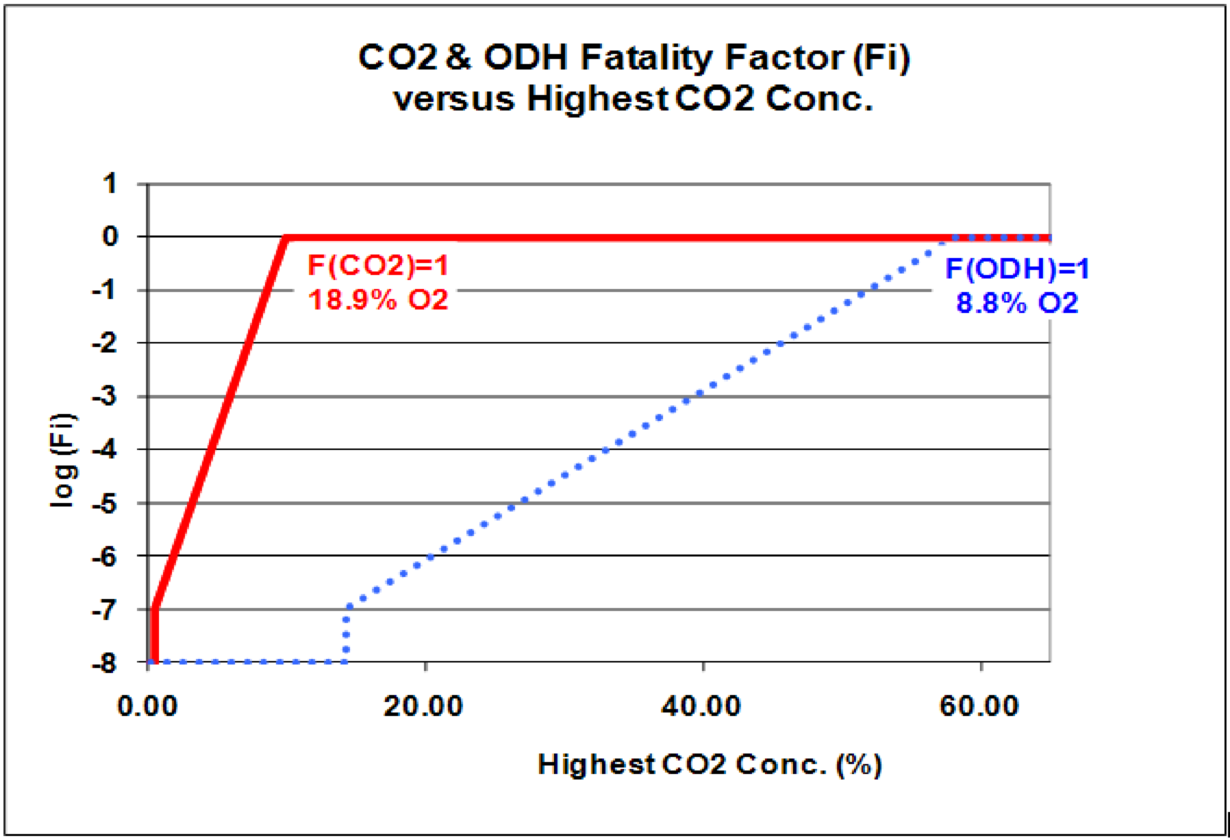
Vessel Leaks

The small leak will be assumed to be twice that of the pipe or
4r

$Vessel_{area} := 4mm^2$

$LR_{Vessel} := LeakRate \cdot Vessel_{area} = 2773.56 \cdot \frac{ft^3}{hr}$

Fatality Factors and CO_2 Compositions WRT leak rate



The above graph is a visual representation of the shifted fatality factor curve for CO_2 concentration vs. Oxygen concentration. Taken from MD-ENG-250 by M. Adamowski.

The correlation line between the CO_2% and F_i is:

$CO2_{percent} := .5\%$ $\quad F_i := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{percent})}$

$F_i = 10 \times 10^{-8}$

$CO2_{percent} := 5\%$ $\quad F_i := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{percent})}$

$F_i = 2.1 \times 10^{-4}$

$CO2_{percent} := 10\%$ $\quad F_i := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{percent})}$

$F_i = 1$

Summation of fatality factors in Lab C:

Total release of CO2 in Lab C

$$Volume_{CO2} := \frac{300lb}{\rho_{gas}} = 2746.02 \cdot ft^3$$

$$Percent\_CO2\_in\_LabC := \frac{Volume_{CO2}}{LabC_{vol}} = 3.72 \cdot \%$$

Fatality factor of a Sudden Total release in lab C

$$F_{TR\_LC} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (Percent\_CO2\_in\_LabC)} = 2.347162929 \times 10^{-5}$$

Ruptures, will lead to a total release and fatality factor of F_{TR_LC}

$$F_{flange} := \left(num_{12inFlangeGasket} + num_{1.5inFlangeGasket}\right) \cdot F_{TR\_LC} \cdot F_{Flange\_Rupture} = 2.58 \times 10^{-13} \frac{1}{hr}$$

$$F_{fCV} := num_{CheckV} \cdot F_{TR\_LC} F_{CheckV\_Rupture} = 1.17 \times 10^{-13} \frac{1}{hr}$$

$$F_{fVessel} := num_{ASMEvessel} \cdot F_{TR\_LC} F_{ASMEvessel\_Rupture} = 1.17 \times 10^{-14} \frac{1}{hr}$$

$$F_{fPipe} := L_{Pipe} \cdot F_{TR\_LC} F_{Pipe\_Rupture} = 3.97 \times 10^{-14} \frac{1}{hr}$$

$$F_{fValves} := num_{MOV} \cdot F_{TR\_LC} F_{MOV\_Rupture} = 1.408 \times 10^{-14} \cdot \frac{1}{hr}$$

$$F_{fElectrical} := num_{Heaters} \cdot F_{TR\_LC} \cdot F_{ReliefV\_FailOpenSeq2} = 2.35 \times 10^{-18} \frac{1}{hr}$$

$$F_{fHumanError} := num_{Heaters} \cdot F_{TR\_LC} \cdot F_{ReliefV\_FailOpenSeq1} = 4.07 \times 10^{-19} \frac{1}{hr}$$

$$F_{fOC} := num_{OtherCmpnts} \cdot F_{TR\_LC} \cdot F_{MOV\_Rupture} = 1.174 \times 10^{-14} \frac{1}{hr}$$

$$F_{fpump} := num_{Pumps} \cdot F_{TR\_LC} \cdot F_{Pump\_Rupture} = 7.04 \times 10^{-13} \frac{1}{hr}$$

$$F_{fHuman} := F_{HumanError2consec} \cdot F_{TR\_LC} = 1.956 \times 10^{-15} \frac{1}{hr}$$

$$F_{Rupt\_LabC} := \begin{pmatrix} F_{flange} \\ F_{fCV} \\ F_{fVessel} \\ F_{fPipe} \\ F_{fValves} \\ F_{fElectrical} \\ F_{fHumanError} \\ F_{fOC} \\ F_{fpump} \\ F_{fHuman} \end{pmatrix}$$

$$\boxed{F_{Rupture\_LabC} := \sum_{i=1}^{10} F_{Rupt\_LabC_i} = 1.159 \times 10^{-12} \frac{1}{hr}}$$

Leaks will lead to varying a CO_2 compositions as well as varying fatality factors with respect to time after leak occurs, For a conservative approach, the leaks, even though small, will be considered as a sudden total release of the entire amount of CO_2 capacity.

$$F_{flange} := \left(num_{12inFlangeGasket} + num_{1.5inFlangeGasket}\right) \cdot F_{TR\_LC} \cdot F_{Gasket\_Leak} = 1.03 \times 10^{-11} \frac{1}{hr}$$

$$F_{fCV} := num_{CheckV} \cdot F_{TR\_LC} F_{CheckV\_LeakOut} = 2.35 \times 10^{-12} \frac{1}{hr}$$

$$F_{fVessel} := num_{ASMEvessel} \cdot F_{TR\_LC} F_{ASMEvessel\_Leak} = 1.17 \times 10^{-13} \frac{1}{hr}$$

$$F_{fPipe} := L_{Pipe} \cdot F_{TR\_LC} F_{Pipe\_Leak} = 1.32 \times 10^{-12} \frac{1}{hr}$$

$$F_{fValves} := num_{MOV} \cdot F_{TR\_LC} F_{MOV\_Leak} = 1.408 \times 10^{-11} \frac{1}{hr}$$

$$F_{fOC} := num_{OtherCmpnts} \cdot F_{TR\_LC} \cdot F_{MOV\_Leak} = 1.174 \times 10^{-11} \frac{1}{hr}$$

$$F_{fpump} := num_{Pumps} \cdot F_{TR\_LC} \cdot F_{Pump\_Leak} = 7.04 \times 10^{-13} \frac{1}{hr}$$

$$F_{fWelds} := num_{welds} \cdot F_{TR\_LC} \cdot F_{Welds\_Leak} = 5.63 \times 10^{-12} \frac{1}{hr}$$

$$F_{Leak\_LabC} := \begin{pmatrix} F_{flange} \\ F_{fCV} \\ F_{fVessel} \\ F_{fPipe} \\ F_{fValves} \\ F_{fOC} \\ F_{fpump} \\ F_{fWelds} \\ 0 \end{pmatrix}$$

$$F_{Leak\_LabC} := \sum_{i=1}^{9} F_{Leak\_LabC_i} = 4.627 \times 10^{-11} \frac{1}{hr}$$

$$F_{Total\_LabC} := F_{Leak\_LabC} + F_{Rupture\_LabC} = 4.74 \times 10^{-11} \frac{1}{hr}$$

Summation of fatality factors in Clean Room:

Total release of CO2

$$Volume_{CO2} := \frac{300lb}{\rho_{gas}} = 2746.02 \cdot ft^3$$

$$Percent\_CO2\_in\_CR1 := \frac{Volume_{CO2}}{CR1_{vol}} = 12.79 \cdot \%$$ **Fatality Factor = 1**

Fatality factor of a Sudden Total release in lab C

$$F_{TR\_CR} := 1 \qquad F_1 := 1$$

Ruptures, will lead to a fatality factor of 1

$$F_{flange} := \left(num_{1inFlangeGasketCL} + num_{1.5inFlangeGasketCL}\right) \cdot F_1 \cdot F_{Flange\_Rupture} = 7 \times 10^{-9} \frac{1}{hr}$$

$$F_{fCV} := num_{CheckCL} \cdot F_1 F_{CheckV\_Rupture} = 1 \times 10^{-8} \frac{1}{hr}$$

$$F_{fVessel} := num_{ASMEvesselCL} \cdot F_1 F_{ASMEvessel\_Rupture} = 5 \times 10^{-10} \frac{1}{hr}$$

$$F_{fPipe} := L_{PipeCL} \cdot F_1 F_{Pipe\_Rupture} = 2.74 \times 10^{-10} \frac{1}{hr}$$

$$F_{fValves} := num_{MOVCL} \cdot F_1 F_{MOV\_Rupture} = 1.4 \times 10^{-9} \frac{1}{hr}$$

$$F_{fElectrical} := num_{Heaters} \cdot F_1 \cdot F_{ReliefV\_FailOpenSeq2} = 1 \times 10^{-13} \frac{1}{hr}$$

$$F_{fHumanError} := num_{Heaters} \cdot F_1 \cdot F_{ReliefV\_FailOpenSeq1} = 1.74 \times 10^{-14} \frac{1}{hr}$$

$$F_{fOC} := num_{OtherCmpnts} \cdot F_1 \cdot F_{MOV\_Rupture} = 5 \times 10^{-10} \frac{1}{hr}$$

$$F_{fHuman} := F_{HumanError2consec} \cdot F_1 = 8.33 \times 10^{-11} \frac{1}{hr}$$

$$F_{Rupt\_CR} := \begin{pmatrix} F_{flange} \\ F_{fCV} \\ F_{fVessel} \\ F_{fPipe} \\ F_{fValves} \\ F_{fElectrical} \\ F_{fHumanError} \\ F_{fOC} \\ F_{fHuman} \end{pmatrix}$$

$$F_{Rupture\_CleanRoom} := \sum_{i=1}^{9} F_{Rupt\_CR_i} = 1.976 \times 10^{-8} \frac{1}{hr}$$

Leaks, will lead to varying a CO_2 compositions as well as varying fatality factors with respect to time after leak occurs.

The roof mounted air handling unit is a McQuay model LYF180CH with a air circulation rate of 8000 CFM, and a 10% outside air draw (from lab C) rate.

$$Flow_{McQuay} := 8000 \frac{ft^3}{min}$$

$$Air_{exchange} := Flow_{McQuay} \cdot 10\% = 800 \cdot \frac{ft^3}{min}$$

CO_2 compositions with respect to leak rates for all leak prone components. For a conservative approach, the CO_2 compositions will be analyzed at the maximum which would be the Limit as time approaches infinity. In reality, the leak rate would lower, and the CO_2 composition would rise until the system exhausted all the fluid. The air is not exchanged with outside air however. It is exchanged with air from Lab C, which could then become more saturated with CO_2. No air exchange is considered for Lab C for a conservative approach.

$$CO2_{MaxIntake} := \frac{Volume_{CO2}}{LabC_{vol} + CR1_{vol}} = 2.88 \cdot \%$$

$$CO2_{Percent\_1.5GasketLeak} := \frac{LR_{Gasket\_Leak\_1.5}}{Air_{exchange}} + CO2_{MaxIntake} = 4.82 \cdot \%$$

$$F_{1.5GL} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{Percent\_1.5GasketLeak})} = 1.53 \times 10^{-4}$$

$$CO2_{Percent\_1GasketLeak} := \frac{LR_{Gasket\_Leak\_1}}{Air_{exchange}} + CO2_{MaxIntake} = 4.29 \cdot \%$$

$$F_{1GL} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{Percent\_1GasketLeak})} = 6.15 \times 10^{-5}$$

$$CO2_{Percent\_PipeLeak} := \frac{LR_{Pipe}}{Air_{exchange}} + CO2_{MaxIntake} = 5.77 \cdot \%$$

$$F_{Pipe} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{Percent\_PipeLeak})} = 7.63 \times 10^{-4}$$

$$CO2_{Percent\_OtherCmpnts} := \frac{LR_{OtherCmpnts}}{Air_{exchange}} + CO2_{MaxIntake} = 4.32 \cdot \%$$

$$F_{OtherCmnts} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{Percent\_OtherCmpnts})} = 6.58 \times 10^{-5}$$

$$CO2_{Percent\_MOV} := \frac{LR_{MOV\_Leak}}{Air_{exchange}} + CO2_{MaxIntake} = 4.32 \cdot \%$$

$$F_{MOV} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{Percent\_MOV})} = 6.58 \times 10^{-5}$$

$$CO2_{Percent\_CV} := \frac{LR_{CheckV}}{Air_{exchange}} + CO2_{MaxIntake} = 6.49 \cdot \%$$

$$F_{CV} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{Percent\_CV})} = 2.6 \times 10^{-3}$$

$$CO2_{Percent\_Welds} := \frac{LR_{Welds}}{Air_{exchange}} + CO2_{MaxIntake} = 8.9 \cdot \%$$

$$F_{Welds1} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{Percent\_Welds})} = 0.15$$

$$CO2_{Percent\_Vessel} := \frac{LR_{Vessel}}{Air_{exchange}} + CO2_{MaxIntake} = 8.66 \cdot \%$$

$$F_{Vessel} := 4.28133 \cdot 10^{-8} \cdot e^{169.6641647 \cdot (CO2_{Percent\_Vessel})} = 0.103$$

Fatality Factors for Component Leaks

$$F_{flange1} := (num_{1inFlangeGasketCL}) \cdot F_{1GL} \cdot F_{Gasket\_Leak} = 9.84 \times 10^{-12} \frac{1}{hr}$$

$$F_{flange1.5} := (num_{1.5inFlangeGasketCL}) \cdot F_{1.5GL} \cdot F_{Gasket\_Leak} = 1.84 \times 10^{-11} \frac{1}{hr}$$

$$F_{fCV} := num_{CheckCL} \cdot F_{CV} F_{CheckV\_LeakOut} = 5.2 \times 10^{-10} \frac{1}{hr}$$

$$F_{fPipe} := L_{PipeCL} \cdot F_{Pipe} F_{Pipe\_Leak} = 6.98 \times 10^{-12} \frac{1}{hr}$$

$$F_{fValves} := num_{MOVCL} \cdot F_{MOV} F_{MOV\_Leak} = 9.21 \times 10^{-11} \frac{1}{hr}$$

$$F_{fOC} := num_{OtherCmpnts} \cdot F_{OtherCmnts} \cdot F_{MOV\_Leak} = 3.289 \times 10^{-11} \frac{1}{hr}$$

$$F_{fWelds} := num_{weldsCL} \cdot F_{Welds1} \cdot F_{Welds\_Leak} = 4.38 \times 10^{-8} \frac{1}{hr}$$

$$F_{fVessel} := num_{ASMEvesselCL} \cdot F_{Vessel} \cdot F_{ASMEvessel\_Leak} = 5.13 \times 10^{-10} \frac{1}{hr}$$

If the ventilation system fails to operate, it will trigger a flow switch. Not taking this flow switch into account, if the ventilation = 0 the fatality factors of all leaks would = 1. Calculation of a leak taking place as the vetilation system fails is calculated below:

$$F_{fLwoVent} := Sum_{AllLeakFactors} \cdot F_{Ventilation} \cdot hr = 2.97 \times 10^{-10} \frac{1}{hr}$$

$$F_{Leak\_CR} := \begin{pmatrix} F_{flange1} \\ F_{flange1.5} \\ F_{fCV} \\ F_{fPipe} \\ F_{fValves} \\ F_{fOC} \\ F_{fWelds} \\ F_{fVessel} \\ F_{fLwoVent} \end{pmatrix}$$

$$F_{Leak\_CleanRoom} := \sum_{i=1}^{9} F_{Leak\_CR_i} = 4.528 \times 10^{-8} \frac{1}{hr}$$

$$F_{Total\_CleanRoom} := F_{Leak\_CleanRoom} + F_{Rupture\_CleanRoom} = 6.5 \times 10^{-8} \frac{1}{hr}$$

CO_2 pooling in Lab C and Clean Room:

$$HeightCO2_{CleanRoom} := \frac{Volume_{CO2}}{CleanRoom1_{area}} = 1.78\,ft$$

$$HeightCO2_{LabC} := \frac{Volume_{CO2}}{LabC_{area}} = 1.46\,ft$$

These pooling heights are below breathing space and show the maximum height the CO_2 monitors should be placed. Each of the monitor will be placed close to 12" from ground level or below.