Fermilab

Particle Physics Division

Mechanical Department Engineering Note

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Project: Lab 6 ODH Analysis (Clean Room)

Title: Lab 6 Clean Room Nitrogen Delivery System ODH Analysis

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Abstract Summary:

Lab 6 has a nitrogen delivery system which feeds nitrogen into the Lab 6 Clean room. A flow restricting orifice has been placed on the inlet line which feeds all of Lab 6's nitrogen nozzles. Calculations show the flow of nitrogen could reach nearly 5.1 SCFM and risk analysis of the clean room was conducted following procedures of FESHM 5064, which resulted in ODH Class Zero Classification.

Layout of Lab 6 Clean Room:

The following table 1 shows only the room where at least one nitrogen port is present, the room volumes and the number of nitrogen ports. Table 2 gives the air flow from the ventilation system.

Table 1: Lab 6 Room volumes with nitrogen ports

Room Name	Nitrogen Ports	Room Volume (ft^3)
Clean Room	1	6380

Table 2: Lab 6 Room ventilation rates

Room Name	Minimum air flow (SCFM)	Minimum fresh flow (SCFM)
Clean Room	250	25

Nitrogen System Description:

The Supply is a 600 Gallon Liquid Nitrogen Tank located outside the building. The nitrogen goes through two vaporizers and a regulator panel where the pressure is set at 30 psig. From there, a ¾" stainless steel tube enters the building and branches out with ¾" tube to the ports in table 1. The flow restricting orifice is placed in this main line before branching out, so the flow is restricted to all lines together. The restrictor has been sized to limit the flow to 5.07 SCFM. Flow and calculations are shown in appendix A, pages A1 and A2. Numerous conservative assumptions were made throughout calculations. The most conservative was the nitrogen system is continuously open, venting into the room, where in reality it is a supply line which will be used much less frequently.

Ventilation Rates:

The Clean Room has a dedicated air handler unit with the control box. Since flow capacity of the unit was not readily available, as the unit was installed in the 1980's, flow estimations were made, by observing the flow through the exhaust ports. These flow estimates were set at an extremely conservative 250 SCFM, and a 10% fresh air exchange rate.

Natural ventilation was determined from previous walkthroughs of Lab 6 rooms, and other building similar to Lab 6, which state an air exchange every 6 hours is more than reasonable. Reference ODH analysis by Stefano Moccia dated 10/07/2005.

ODH analysis:

In this analysis all oxygen concentrations were calculated at the limit as time approaches infinity.

The following 4 scenarios were analyzed and their contributing fatality rates displayed as well:

1. Indefinite Nitrogen leak of 5.07 SCFM in room with ventilation.
    a. Fatality Rate 1 = 4.245×10^{-8} / hour
2. Indefinite Nitrogen leak of 5.07 SCFM with ventilation failure.
    a. Fatality Rate 2 = 8.459×10^{-9} / hour
3. Indefinite Nitrogen leak of 5.07 SCFM from piping failure (with and without ventilation).
    a. Fatality Rate 3 = 4.03×10^{-15} / hour
4. Indefinite Nitrogen leak of 5.07 SCFM in room with ventilation and human error failure.
    a. Fatality Rate 4 = 2.719×10^{-8} / hour

Total fatality rates of these four scenarios combined additively yields a room fatality rate of 7.8×10^{-8} / hour, which is classified as an ODH class zero, even with the multiple conservative assumptions. See appendix A for detailed calculations.

Recommendations / Procedures:

It is recommended and necessary that whenever the nitrogen supply line is used in the Lab 6 clean room, operators check to make sure the air handling system is operational and flowing before opening the nitrogen supply valve. A sign should be posted near the nitrogen supply to remind users to make sure the air handler is activated before dispensing nitrogen. The clean room has air handling monitor gauges visible from the nitrogen supply valve, and the air handling system can easily be heard running in the room by anyone without major hearing damage. If the air handling system fails while the nitrogen supply valve is open, the valve should be immediately shut, and not opened until the air handling system is again operational.

Appendix A

Regulator is set at 30 psig, so maximum pressure drop across the orifice could be 30 psid

Crane 4.10 equation 6.32 $$Max_{flow} = \frac{40700}{60} Y_{critical} \cdot d_1^{\,2} \cdot C \cdot \sqrt{\frac{\Delta P \cdot P_1}{T_1 \cdot S_g}}$$

Diameter of orifice

$$d := 0.097in$$

Unitless diameter

$$d_1 := \frac{d}{in} = 0.097$$

Discharge Coefficient

$C := .6$ typical

Diameter of tube

$$D := .75in$$

Expansion Ratio

$$\beta := \frac{d}{D} = 0.129$$

Claim pressure Drop across orifice

$$\Delta P := 30psi$$

Area of orifice

$$A_i := \frac{\pi}{4} \cdot d^2 = 0.0074 \cdot in^2$$

Unitless Area

$$A := \frac{A_i}{ft^2} = 5.132 \times 10^{-5}$$

$$P_2 := 14.3$$

$$P_1 := 30 + 14.3$$

$$\frac{P_2}{P_1} = 0.323$$

we are below the critical pressure ratio which is: $r_c := .535$

$$\Delta P := P_1 \cdot (1 - r_c) = 20.599$$

This value will be used in calculation

$k := 1.54$ Refprop gives 1.54

Net expansion Factor of claimed Pressure Drop and actual (critical) pressure drop

$$Y := 1 - \left(0.351 + .256 \cdot \beta^4 + 0.93 \cdot \beta^8\right) \cdot \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{1}{k}}\right] = 0.817$$

$$Y_{critical} := 1 - \left(0.351 + .256 \cdot \beta^4 + 0.93 \cdot \beta^8\right) \cdot \left[1 - \left(r_c\right)^{\frac{1}{k}}\right] = 0.883$$

This value will be used in calculation

Temperature of Nitrogen (coldest ambient possible)

$T_1 := (-40 + 460)$ (Rankine)

Specific gravity WRT air

$$S_g := \frac{28}{29}$$

Crane 4.10 equation 6.32

$$MaxFlow_{N2} := \frac{40700}{60} Y_{critical} \cdot d_1^{\,2} \cdot C \cdot \sqrt{\frac{\Delta P \cdot P_1}{T_1 \cdot S_g}} \cdot SCFM = 5.07 \cdot SCFM$$

The original calculation (Lab 6 ODH Analysis by Stefano Moccia 10/07/2005) used the wrong Y-value, wrong ΔP, and wrong temperature. This resulted in the equation being off by a factor of 1.25. If the flow needs to be limited to a value of 4 SCFM, the size of the orifice should be at maximum a diameter of 0.0861 inches:

Diameter of orifice

$d := 0.0861\text{in}$

Unitless diameter

$d_1 := \frac{d}{in} = 0.086$

Discharge Coefficient

$C := .6$ typical

Diameter of tube

$D := .75\text{in}$

Expansion Ratio

$\beta := \frac{d}{D} = 0.115$

Claim pressure drop across orifice

$\Delta P := 30\text{psi}$

Area of orifice

$A_i := \frac{\pi}{4} \cdot d^2 = 0.0058 \cdot in^2$

Unitless Area

$A := \frac{A_i}{ft^2} = 4.043 \times 10^{-5}$

$P_2 := 14.3$

$P_1 := 30 + 14.3$

$\frac{P_2}{P_1} = 0.323$

we are below the critical pressure ratio which is: $r_c := .535$

$\Delta P := P_1 \cdot (1 - r_c) = 20.599$

This value will be used in calculation

$k := 1.54$ RefProp gives 1.54

Net expansion Factor of claimed Pressure Drop and actual (critical) pressure drop

$$Y := 1 - \left(0.351 + .256 \cdot \beta^4 + 0.93 \cdot \beta^8\right) \cdot \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{1}{k}}\right] = 0.817$$

$$Y_{critical} := 1 - \left(0.351 + .256 \cdot \beta^4 + 0.93 \cdot \beta^8\right) \cdot \left[1 - \left(r_c\right)^{\frac{1}{k}}\right] = 0.883$$

This value will be used in calculation

Temperature of Nitrogen (coldest ambient possible)

$T_1 := (-40 + 460)$ (Rankine)

Specific gravity WRT air

$S_g := \frac{28}{29}$

Crane 4.10 equation 6.32

$$MaxFlow_4 := \frac{40700}{60} Y_{critical} \cdot d_1{}^2 \cdot C \cdot \sqrt{\frac{\Delta P \cdot P_1}{T_1 \cdot S_g}} \cdot SCFM = 4 \cdot SCFM$$

Calculations of oxygen concentrations, fatality factors, failure rates, and fatality rates for the previous (correct) flow rate of nitrogen of 5.07 SCFM follow.

Scenario 1: Nitrogen leak of 5.07 SCFM into room with ventilation on

Room Dimensions

$$\text{Height} := 10\text{ft} + 8\text{in}$$

$$\text{Length} := 26\text{ft}$$

$$\text{Width} := 23\text{ft}$$

$$\text{BldgVolume} := \text{Height}\cdot\text{Length}\cdot\text{Width} = 6379\cdot\text{ft}^3$$

$$\text{Natural}_{\text{intoRoom}} := \frac{\text{BldgVolume}}{6\text{hr}} = 17.719\cdot\text{cfm}$$

$$\text{Ventilation}_{\text{intoRoom}} := 250\text{cfm}\cdot 10\% = 25\cdot\text{cfm}$$

$$\text{oxygen}_{\text{intoRoom}} := \left(\text{Ventilation}_{\text{intoRoom}} + \text{Natural}_{\text{intoRoom}}\right)\cdot 21\% = 8.971\cdot\text{cfm}$$

$$\text{Total}_{\text{intoRoom}} := \text{Natural}_{\text{intoRoom}} + \text{Ventilation}_{\text{intoRoom}} + \text{MaxFlow}_{\text{N2}} = 47.79\cdot\text{cfm}$$

$$\text{O}_{\text{2Percent}} := \frac{\text{oxygen}_{\text{intoRoom}}}{\text{Total}_{\text{intoRoom}}} = 18.771\cdot\%$$

$$\text{PO2} := \text{O}_{\text{2Percent}}\cdot 739\cdot\text{torr} = 138.721\cdot\text{torr}$$

$$\text{F}_{\text{f}} := 10^{\left(6.5 - \frac{\text{PO2}}{10\cdot\text{torr}}\right)} = 4.245\times 10^{-8}$$

Probability (Failure Rate) of a leak will be considered as 1 since the nitrogen is a supply line and any leak will be intentional.

$$\text{Probability} := 1$$

$$\text{FatalityRate}_1 := \text{F}_{\text{f}}\cdot\text{Probability} = 4.245\times 10^{-8}$$ per hour

ODH Classification Per FESHM 5064:

$$\text{Class(FatalityRate1)} := \begin{cases} 0 & \text{if } \text{FatalityRate}_1 < 10^{-7} \\ 1 & \text{if } \text{FatalityRate}_1 < 10^{-5} \wedge \text{FatalityRate}_1 > 10^{-7} \\ 2 & \text{if } \text{FatalityRate}_1 < 10^{-3} \wedge \text{FatalityRate}_1 > 10^{-5} \\ 3 & \text{if } \text{FatalityRate}_1 > 10^{-3} \end{cases}$$

$$\text{Class(FatalityRate1)} = 0$$ Class Zero

Fatality Rate for Scenario 1

$$\text{FatalityRate}_1 = 4.245\times 10^{-8}$$ per hour

Scenario 2: Nitrogen leak of 5.07 SCFM into room with ventilation failure

Ventilation Failure

$$oxygen_{intoRoom} := (Natural_{intoRoom}) \cdot 21\% = 3.721 \cdot cfm$$

$$Total_{intoRoom} := Natural_{intoRoom} + MaxFlow_{N2} = 22.79 \cdot cfm$$

$$O_{2Percent} := \frac{oxygen_{intoRoom}}{Total_{intoRoom}} = 16.327 \cdot \%$$

$$PO2 := O_{2Percent} \cdot 739 \cdot torr = 120.656 \cdot torr$$

Probability (Failure Rate) of Ventilation system

$$F_{fVentFail} := 10^{\left(6.5 - \frac{PO2}{10 \cdot torr}\right)} = 2.719 \times 10^{-6}$$

Ventilation system can fail if:

1. Power Outage
2. Circuit Breaker/fuse Fails
3. Motor failure
4. Ventilation turned off (human error)

$$FR_{power} := \frac{10^{-4}}{hr}$$

$$FR_{circuit} := \frac{10^{-6}}{hr}$$

$$FR_{motor} := \frac{10^{-5}}{hr}$$

$$FR_{off} := \frac{3 \cdot 10^{-3}}{demand}$$

assume demand is once per hour

$$FR_{ventilation} := FR_{power} + FR_{circuit} + FR_{motor} + FR_{off} = 3.111 \times 10^{-3} \cdot \frac{1}{hr}$$

$$FatalityRate_2 := F_{fVentFail} \cdot FR_{ventilation} \cdot hr = 8.459 \times 10^{-9}$$ per hour

$$Class(FatalityRate2) := \begin{cases} 0 & \text{if } FatalityRate2 < 10^{-7} \\ 1 & \text{if } \begin{cases} FatalityRate2 < 10^{-5} \\ FatalityRate2 > 10^{-7} \end{cases} \\ 2 & \text{if } \begin{cases} FatalityRate2 < 10^{-3} \\ FatalityRate2 > 10^{-5} \end{cases} \\ 3 & \text{if } FatalityRate2 > 10^{-3} \end{cases}$$

$$Class(FatalityRate2) = 0$$ Class Zero

Fatality Rate for Scenario 2

$$FatalityRate_2 = 8.459 \times 10^{-9}$$ per hour

Scenario 3: Nitrogen leak of 5.07 SCFM into room from piping failure

Assuming all the nitrogen leaks into the Clean Room,
the oxygen percentage and associated risk would be:

$$Ventilation_{intoRoom} := 500cfm \cdot 10\% = 50 \cdot cfm$$

$$Natural_{intoRoom} := \frac{BldgVolume}{6hr} = 17.719 \cdot cfm$$

$$oxygen_{intoRoom} := \left(Ventilation_{intoRoom} + Natural_{intoRoom}\right) \cdot 21\% = 14.221 \cdot cfm$$

$$Total_{intoRoom} := Natural_{intoRoom} + Ventilation_{intoRoom} + MaxFlow_{N2} = 72.79 \cdot cfm$$

$$O_{2Percent} := \frac{oxygen_{intoRoom}}{Total_{intoRoom}} = 19.537 \cdot \%$$

$$PO2 := O_{2Percent} \cdot 739torr = 144.378 \cdot torr$$

Piping Failure Rate

$$F_{f\_PipeSystemO2} := 10^{\left(6.5 - \frac{PO2}{10 \cdot torr}\right)} = 1.154 \times 10^{-8}$$

Piping is 165 feet long and has 20 ball valves

$num_{valves} := 20$ Failure rate of ball valves (rupture) $$FR_{ballValves} := \frac{10^{-8}}{hr} \cdot num_{valves} = 2 \times 10^{-7} \cdot \frac{1}{hr}$$

$L_{pipe} := 165ft$ Failure rate of pipe (rupture) $$F_{Pipe\_Rupture} := \frac{\frac{0.00003}{10^{6} \cdot hr}}{m} \cdot 165ft = 1.51 \times 10^{-9} \cdot \frac{1}{hr}$$

Failure Rate of piping system

$$FR_{pipingSystem} := FR_{ballValves} + F_{Pipe\_Rupture} = 2.015 \times 10^{-7} \cdot \frac{1}{hr}$$

Fatality Rate of piping system failure and leaking into the Room with ventilation on

$$F_{f\_PipingFailure} := FR_{pipingSystem} \cdot F_{f\_PipeSystemO2} \cdot hr = 2.326 \times 10^{-15}$$ Class Zero

Fatality Rate of piping system and ventilation system failure

$$FR_{PS\_a\_VS} := FR_{pipingSystem} \cdot FR_{ventilation} \cdot \left(F_{fVentFail}\right) \cdot hr = 1.705 \times 10^{-15} \cdot \frac{1}{hr}$$ Class Zero

Combined Fatality Rate of Piping System Failure (Ventilation On and Off)

$$FatalityRate_{3} := F_{f\_PipingFailure} + FR_{PS\_a\_VS} \cdot hr = 4.03 \times 10^{-15}$$ Class Zero

Scenario 3:
Nitrogen leak of 5.07 SCFM with ventilation failure and human error

Human Error Analysis:
Operator enters room after ventilation fan has already failed, and does not notice there is no ventilation into the room, and uses nitrogen valve anyway.

General human error of omission where there is no display in the control room of the status of the item omitted, e.g., failure to return manually operated test valve to proper configuration after maintenance

$$F_{human} := 10^{-2} \frac{1}{demand}$$

$$oxygen_{intoRoom} := \left(Natural_{intoRoom}\right) \cdot 21\% = 3.721 \cdot cfm$$

$$Total_{intoRoom} := Natural_{intoRoom} + MaxFlow_{N2} = 22.79 \cdot cfm$$

$$O_{2Percent} := \frac{oxygen_{intoRoom}}{Total_{intoRoom}} = 16.327 \cdot \%$$

$$PO2 := O_{2Percent} \cdot 739 \cdot torr = 120.656 \cdot torr$$

$$F_{f4} := 10^{\left(6.5 - \frac{PO2}{10 \cdot torr}\right)} = 2.719 \times 10^{-6}$$

In this case, the rate of ventilation failure and frequency of this scenario are inversely proportional, so the demand rate has no effect on this scenario. For a conservative approach we can assume the air handler is always in the off position and the demand rate is once per hour, meaning users would have to turn it on each time they come in the room.

$F_{human} = 0.01$ per hour

$FatalityRate_4 := F_{f4} \cdot F_{human} = 2.719 \times 10^{-8}$ per hour

Total Supply Line Fatality Rate for the Clean Room

$$FatalityRate_{supplyLine} := \sum_{i=1}^{4} FatalityRate_i = 7.81 \times 10^{-8}$$ per hour

$$Class(FatalityRate_{supplyLine}) := \begin{cases} 0 & \text{if } FatalityRate_{supplyLine} < 10^{-7} \\ 1 & \text{if } \left| \begin{array}{l} FatalityRate_{supplyLine} < 10^{-5} \\ FatalityRate_{supplyLine} > 10^{-7} \end{array} \right. \\ 2 & \text{if } \left| \begin{array}{l} FatalityRate_{supplyLine} < 10^{-3} \\ FatalityRate_{supplyLine} > 10^{-5} \end{array} \right. \\ 3 & \text{if } FatalityRate_{supplyLine} > 10^{-3} \end{cases}$$

$$Class(FatalityRate_{supplyLine}) = 0$$

The Supply Line shows a risk which falls under the ODH Class Zero classification.