DOE-FIU SCIENCE & TECHNOLOGY WORKFORCE
DEVELOPMENT PROGRAM

STUDENT SUMMER INTERNSHIP TECHNICAL REPORT
June 9, 2011 to August 12, 2011

Air Flow Calculations for the Centralized Waste Processing Line (CWPL) Glovebox

Principal Investigators:

Mario Vargas (DOE Fellow)
Florida International University

Alan Goldner, Mentor
Lawrence Livermore National Laboratory

Acknowledgements:
John Kerns
Mark Bronson
Lawrence Livermore National Laboratory

Florida International University Collaborator and Program Director:

Leonel Lagos Ph.D., PMP®

Prepared for:

U.S. Department of Energy
Office of Environmental Management
Under Grant No. DE-EM0000598

ABSTRACT

During the 2011 summer, an internship was completed at Lawrence Livermore National Laboratory (LLLN). Engineering support analysis and calculations were performed for the Centralized Waste Processing Line (CWPL) Glovebox. In 2008, DOE Environmental Management (EM-12) issued Contact-handled Transuranic (TRU) Waste Packaging Instructions. All waste compliance includes a complete examination of the waste, including videograph. There are approximately 550 drums on site at LLNL that currently require processing. An additional 250 drums are anticipated by the end FY2012. There is a projections for an additional 100 – 200 drums annually thereafter in Security Cat II operations. A glovebox will be used to process the drums. Each drum will enter the glovebox and its contents will be sorted into solids, debris and sharps.

The work completed throughout the summer was focused on the ventilation system of the glovebox. According to the LLNL's Mechanical Engineering Design Safety Standards, the ventilation system must be designed to maintain a slightly negative pressure [0.47 in H_20 (12mm H_20)] in the enclosure at all times to ensure that any leakage is inward. The inlet air must be pre-filtered and a HEPA filter must be provided at the enclosure exhaust. Flow balancing dampers must be installed to regulate vitalization and to restrict air flow in case of fire. There must be sufficient ventilating capacity so that approximately 125 linear feet per minute of air flow is maintained through any opening, for example, when a glove port ruptures or a pass door is opened.

The air flow analysis was completed for the entire system. That includes the losses in the system as the air runs through the ducting lines and through each of its bends and fittings. Height elevations and material friction was taken into account. Depending on the losses found, different size ducting was recommended to reduce the losses. Orifice openings were calculated to determine the size openings needed to obtain the required pressure in different sections of the glovebox. Finally, equivalent orifice opening were determined to mock pressure drops through the HEPA filters.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1. INTRODUCTION

LLNL is as a research and development institution for science and technology directly applied to national security. Its responsibility is ensuring the safety, security and reliability of the nation's nuclear weapons through the application of advanced science, engineering and technology. The Laboratory also applies its special expertise and multidisciplinary capabilities to preventing the proliferation and use of weapons of mass destruction, bolstering homeland security and solving other nationally important problems, including energy and environmental security, basic science and economic competitiveness. The Weapons and Complex Integration (WCI) Directorate at LLNL has worked to establish a science-based fundamental understanding of nuclear weapons performance, enhanced warhead surveillance tools to detect the onset of problems in the stockpile, and manufacturing capabilities to produce critical components. The most important accomplishment of the Stockpile Stewardship Program is that the nuclear design laboratories have been able to assess and certify the safety, security, and reliability of the stockpile each year without a return to nuclear testing. The Nuclear Materials Technology Program (NMTP) works to assure the safety and reliability of the nation's nuclear stockpile. NMTP provides management of all special nuclear material operations at the Laboratory, including those involving highly enriched uranium, plutonium, and tritium. This work is conducted at LLNL's Superblock facility, one of just two defense plutonium research and development facilities in the U.S.

Completed summer work was on the design of the airflow system of a glovebox capable of processing transuranic waste barrels. The glovebox's vitalization system will be designed to always displace air into the clean section of the glovebox and then into the contaminated section. That ensures that no loose contamination is able to exit when the doors are open. Because workers will be present and in close proximity to the glovebox, all the air flowing around them must also flow past them and into the glovebox. In order to test the amount of air and the direction of air flow around the open doors, smoke testing will be conducted. The qualitative data gathered from the smoke testing will be used to validate the data gathered from the project calculations. There always needs to be a flow of 500 cfm in the glovebox, whether it's in the ducting or through the open doors. The current task being worked on is to determine the pressure drop throughout the system and to incorporate the proper means of maintaining the required flow rate if it were to have a substantial drop. Each section of the duct is being evaluated in each of the eight possible open door configurations.

2. EXECUTIVE SUMMARY

This research work has been supported by the DOE-FIU Science & Technology Workforce Initiative, an innovative program developed by the U.S. Department of Energy's Environmental Management (DOE EM) and Florida International University's Applied Research Center (FIU-ARC). During the summer of 2011, a DOE Fellow intern (Mario Vargas) spent 10 weeks doing a summer internship at Lawrence Livermore National Laboratory under the supervision and guidance of Alan Goldner. The intern's project was initiated in June 9, 2011, and continued through August 12, 2011 with the objective of completing air flow analysis for a glovebox capable of processing transuranic waste barrels.

A glovebox is a sealed container that is designed to allow one to manipulate objects where a separate atmosphere is desired. Built into the sides of the glovebox are gloves arranged in such a way that the user can place their hands into the gloves and perform tasks inside the box without breaking containment. Part or the entire box is usually transparent to allow the user to see what is being manipulated. Two types of gloveboxes exist: one allows a person to work with hazardous substances, such as radioactive materials or infectious disease agents; the other allows manipulation of substances that must be contained within a very high purity inert atmosphere, such as argon or nitrogen. It is also possible to use a glovebox for manipulation of items in a vacuum chamber. Gloveboxes used for hazardous materials generally are maintained at a lower pressure than the surrounding atmosphere, so that microscopic leaks result in air intake rather than hazard outflow. Gloveboxes used for hazardous materials generally incorporate HEPA filters into the exhaust, to keep the hazard contained. HEPA stands for high-efficiency particulate air. A HEPA filter is a type of air filter that satisfies certain standards of efficiency such as those set by the United States Department of Energy (DOE). By government standards, a HEPA air filter must remove 99.97% of all particles greater than 0.3 microns from the air that passes through.

Completed summer work was on the design of the airflow system of a glovebox capable of processing transuranic waste barrels. The glovebox's vitalization system will be designed to always displace air into the clean section of the glovebox and then into the contaminated section. That ensures that no loose contamination is able to exit when the doors are open. Because workers will be present and in close proximity to the glovebox, all the air flowing around them must also flow past them and into the glovebox. In order to test the amount of air and the direction of air flow around the open doors smoke testing will be conducted. The qualitative data gathered from the smoke testing will be used to validate the data gathered from the project calculations. There always needs to be a flow of 500 cfm in the glovebox, whether it's in the ducting or through the open doors. The current task being worked on is to determine the pressure drop throughout the system and to incorporate the proper means of maintaining the required flow rate if it were to have a substantial drop. Each section of the duct is being evaluated in each of the eight possible open door configurations

3. RESEARCH DESCRIPTIONS

In fluid dynamics, Bernoulli's principle states that for an inviscid flow, an increase in the speed of the fluid occurs simultaneously with a decrease in pressure or a decrease in the fluid's potential energy. Bernoulli's principle can be applied to various types of fluid flow, resulting in what is loosely denoted as Bernoulli's equation. In fact, there are different forms of the Bernoulli equation for different types of flow. The simple form of Bernoulli's principle is valid for incompressible flows (most liquid flows) and also for compressible flows (gases) moving at low Mach numbers. More advanced forms may in some cases be applied to compressible flows at higher Mach numbers. Bernoulli's principle can be derived from the principle of conservation of energy. This states that, in a steady flow, the sum of all forms of mechanical energy in a fluid along a streamline is the same at all points on that streamline. This requires that the sum of kinetic energy and potential energy remain constant. Thus an increase in the speed of the fluid occurs proportionately with an increase in both its dynamic pressure and kinetic energy, and a decrease in its static pressure and potential energy. If the fluid is flowing out of a reservoir, the sum of all forms of energy is the same on all streamlines because, in a reservoir, the energy per unit volume (the sum of pressure and gravitational potential $\rho g h$) is the same everywhere. Bernoulli's principle can also be derived directly from Newton's 2nd law. If a small volume of fluid is flowing horizontally from a region of high pressure to a region of low pressure, then there is more pressure behind than in front. This gives a net force on the volume, accelerating it along the streamline. Fluid particles are subject only to pressure and their own weight. If a fluid is flowing horizontally and along a section of a streamline, where the speed increases it can only be because the fluid on that section has moved from a region of higher pressure to a region of lower pressure; and if its speed decreases, it can only be because it has moved from a region of lower pressure to a region of higher pressure. Consequently, within a fluid flowing horizontally, the highest speed occurs where the pressure is lowest, and the lowest speed occurs where the pressure is highest. In most flows of liquids, and of gases at low Mach number, the mass density of a fluid parcel can be considered to be constant, regardless of pressure variations in the flow. For this reason the fluid in such flows can be considered to be incompressible and these flows can be described as incompressible flow. Bernoulli performed his experiments on liquids and his equation in its original form is valid only for incompressible flow. A common form of Bernoulli's equation, valid at any arbitrary point along a streamline where gravity is constant, is:

$$\frac{v^2}{2} + gz + \frac{p}{\rho} = \text{constant}$$

where:

v is the fluid flow speed at a point on a streamline
g is the acceleration due to gravity
z is the elevation of the point above a reference plane
p is the pressure at the chosen point
ρ is the density of the fluid at all points in the fluid

4. RESULTS AND ANALYSIS

4.1 DESCRIPTION

The schematic below will be used as a reference for the air flow analysis provided. The ventilation ducting is broken down into sections in order to better approximate the pressure losses throughout the system. Six-inch circular stainless steel ducts are used throughout the system. Each major length where a potential for greater pressure losses may happen is shown in red; their corresponding lengths are given in Table 3. The exhaust blower is located at the end of the process line; in the schematic below, it is located before section 1 -2. Three 1000 cfm HEPA filters are utilized, each having a pressure drop of 0.38" WG (Water Gauge). All bend radii for the ducting lines are 9"shown as R in the schematic below.

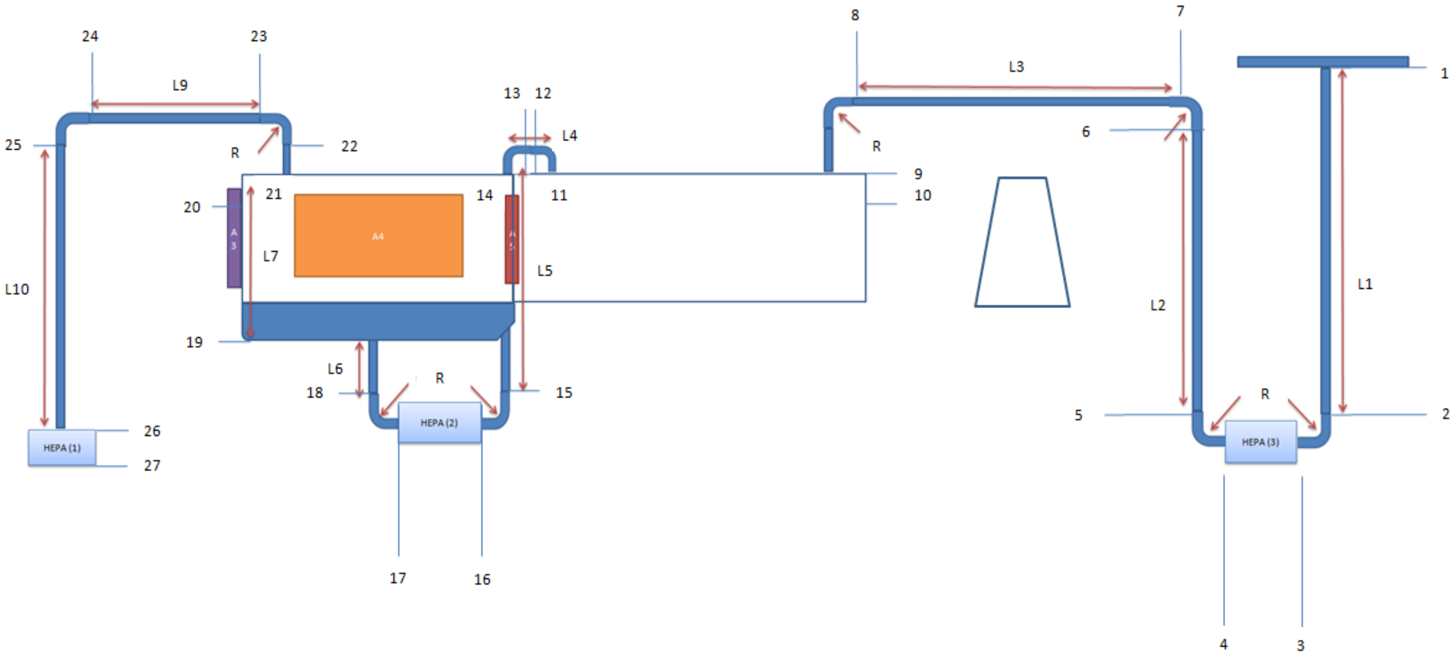
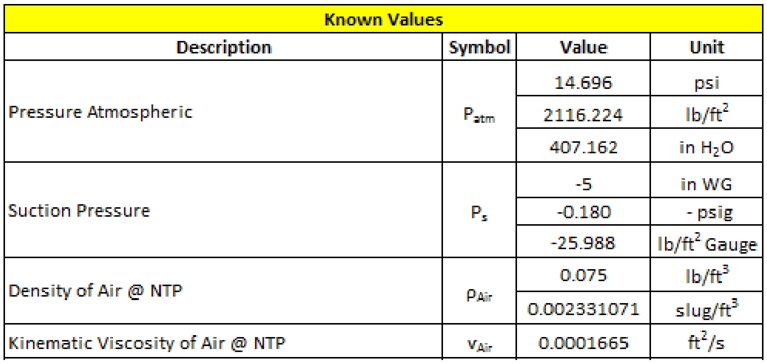


Figure 1. CWPL operations schematic.

4.2 AIR PROPERTY CONSIDERATIONS AND ASSUMPTIONS

The ambient gas is considered to be at 75° F and that there is no substantial change in its density due to the low pressure changes expected to take place in regular glovebox operations. Taking the ambient air at 14.696 psi and its density to be 0.075 lb/ft^2, its kinematic viscosity can be determined. Table 1 shows the air properties used and their corresponding units.

Table 1. Air Properties at 75° F



Known Values			
Description	**Symbol**	**Value**	**Unit**
Pressure Atmospheric	P_{atm}	14.696	psi
		2116.224	lb/ft^2
		407.162	in H_2O
Suction Pressure	P_s	-5	in WG
		-0.180	- psig
		-25.988	lb/ft^2 Gauge
Density of Air @ NTP	ρ_{Air}	0.075	lb/ft^3
		0.002331071	$slug/ft^3$
Kinematic Viscosity of Air @ NTP	v_{Air}	0.0001665	ft^2/s

4.3. CALCULATIONS

4.3.1 MAJOR LOSSES IN VERTICAL AND HORIZONTAL DUCTS

Utilizing an 8-inch circular duct, its area is given by:

$$A = \pi r^2 = \pi \left(\frac{d}{2}\right)^2 \qquad (ft^2)$$

Bernoulli's equation is extensively used in the calculation process. Bernoulli's principle can be derived from the principle of conservation of energy. This states that, in a steady flow, the sum of all forms of mechanical energy in a fluid along a streamline is the same at all points on that streamline. This requires that the sum of kinetic energy and potential energy remain constant. Thus an increase in the speed of the fluid occurs proportionately with an increase in both its dynamic pressure and kinetic energy, and a decrease in its static pressure and potential energy. The equation is given below in terms of pressure loss not head loss.

$$P_1 + \rho g h_1 + \rho \frac{V_1^2}{2} = P_2 + \rho g h_2 + \rho \frac{V_2^2}{2} + P_{loss}$$

where:
P_1 , P_2 – Upstream and downstream pressures (lb/ft^2)
ρ – Density of fluid ($slugs/ft^3$)
V – Flow velocity (ft/s)
g – Acceleration of gravity (ft/s^2)
h – Elevation (ft)

Major losses and minor losses in the system are given by P_{loss}. Major losses only include the losses due to friction that are directly related to the material roughness and minor losses include bends, expansions, contractions and HEPA filter drops.

Major Loss:

$$P_{loss} = f\left(\frac{L}{D_H}\right)\left(\rho\frac{V^2}{2}\right)$$

Minor Loss:

$$P_{loss} = k\left(\rho\frac{V^2}{2}\right)$$

where:
P_{loss} – Pressure loss (lb/ft^2)
f – Friction coefficient
L – Length of duct (ft)
D_H – Hydraulic Diameter (ft)
ρ – Density of fluid (slugs/ft^3)
V – Flow velocity (ft/s)
k – Minor loss coefficient

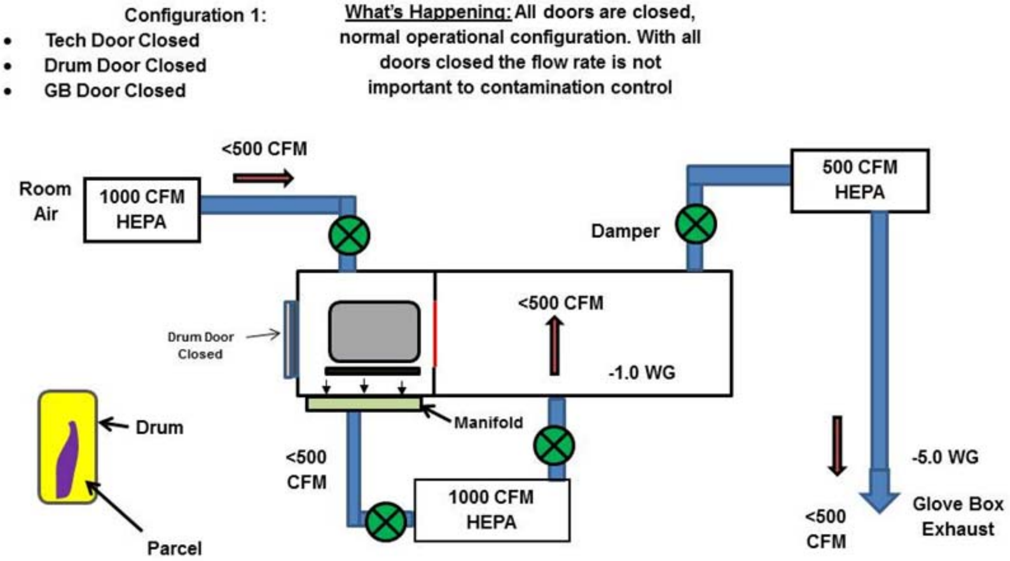


Figure 2. Flow configuration 1.

Figure 2 illustrates the flow configuration before the drum is loaded and all the access doors are closed. The system is running 500 cfm through the blower and assuming that there are no leaks in the system, all the lines and both gloveboxes will also displace 500 cfm of air. Given the flow rate and the cross-sectional duct area, the flow velocity can be determined:

$$Q = VA \quad \xrightarrow{yields} \quad V = \frac{Q}{A}$$

$$V = \frac{500}{\pi\left(\frac{8/12}{2}\right)^2} = 1432.39\ \frac{ft}{min} = 23.87\ \frac{ft}{sec}$$

In order to determine whether the flow is turbulent or laminar, the Reynolds number is needed:

Re < 2000 → Laminar Flow Re > 4000 → Turbulent Flow

$$Re = \frac{\rho V D_H}{\mu} = \frac{V D_H}{\nu}$$

$$Re = \frac{(42.441323.8732)(8/12)}{0.0001665} = 95588.55 > 4000 \quad \boldsymbol{Turbulent\ Flow}$$

The absolute roughness coefficient for stainless steel is $5X10^{-5}$ ft. Using the Moody diagram in Appendix A, the friction coefficient is found to be 0.017. To determine the pressure loss in section 1 – 2, Bernoulli's equation is utilized with the previously obtained data:

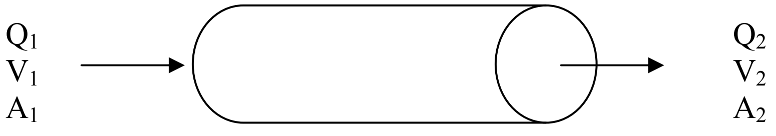
$$P_1 + \rho g h_1 + \rho \frac{V_1^2}{2} = P_2 + \rho g h_2 + \rho \frac{V_2^2}{2} + P_{loss}$$

Solving for P_2:

$$P_2 = P_1 + \rho g (h_1 - h_2) + \rho \left(\frac{V_1^2}{2} - \frac{V_2^2}{2} \right) + P_{loss}$$

$h_1 > h_2$ $\qquad (h_1 - h_2) = +13.583$

When a fluid is in motion, it must move in such a way that mass is conserved. To see how mass conservation places restrictions on the velocity field, consider the steady flow of fluid through a duct (that is, the inlet and outlet flows do not vary with time). The inflow and outflow are one-dimensional, so that the velocity V and density are constant over the area A. The velocity at point 2 is the same velocity at point 1 because the gas is traveling through the same cross-sectional area of duct.



$$Q_1 = Q_2$$

$$\rho_1 V_1 A_1 = \rho_2 V_2 A_2 \qquad \rho_1 = \rho_2$$
$$V_1 A_1 = V_2 A_2 \qquad A_1 = A_2$$

$$V_1 = V_2$$

Since the velocity at both ends are the same, the velocity terms in the Bernoulli equation cancel out.

Due to the initial negative gauge pressure, the pressure loss, P_{loss}, will actually increase the pressure at point two rather than reducing it. In the above equation, P_{loss} is added rather than subtracted. The pressure loss is treated as if a turbine were being evaluated rather than a pump:

$$P_{loss} = f\left(\frac{L_1}{D_H}\right)\left(\rho\frac{V^2}{2}\right) = 0.017 * \left(\frac{13.583}{0.667}\right) * \left[0.002331071\left(\frac{23.873^2}{2}\right)\right] = 0.228068\, psf$$

P_1 = -5" WG = -25.988 psfg = 2090.23 psf

$$P_2 = 2090.23 + (0.002331071 * 32.2)(13.583) + \ 0.228068 = 2091.486\, psf$$
$$= \ -4.760 \text{ " WG}$$

Table 2 below shows the data used in order to obtain the pressure at point 2. In the table, as in the equation for P_{loss}, it shows the major loss to friction in the section. Table 3 shows the major lengths taken into consideration for the analysis that correspond to the schematic shown in Figure 1. It also shows the constant for gravity and its corresponding value and the bend radii for the duct lines (9 inch = 0.75 ft).

Table 2. Results for Section 1 - 2 Analysis (Major Loss)

Section 1 - 2			
Pressure at outlet	P_1	2090.236	lb/ft^2
Velociy	V	1432.394	ft/min
		23.873	ft/sec
Reynolds Number	Re_{1-2}	95588.55	N/A
Relative Roughness	k/d	0.000075	N/A
Friction Factor (from Moody Chart)	f	0.017	N/A
Pressure loss due to friction (not head loss)	$P_{L\ Major}$	0.230	lb/ft^2
Pressure at 2	P_2	2091.486	lb/ft^2
		-4.760	in WG

Table 3. Duct Line Lengths, Gravity Constants and Bend Radii

Known Values			
Absolute Roughness Coefficient (Stainless Steel)	k	0.00005	N/A
Duct Length	L1	13.583	ft
	L2	10.865	ft
	L3	17.083	ft
	L4	2.471	ft
	L5	9.813	ft
	L6	3.698	ft
	L7	5.385	ft
	L8	2.365	ft
	L9	6.750	ft
	L10	10.979	ft
Gravity	g	32.2	ft/s^2
Bend Radius	R	0.75	ft

4.3.2 MINOR LOSSES THROUGH BENDS

Section 2 – 3 involves a 90^o rounded radius bend. There are many publications that can be found to determine the loss coefficient associated with fittings and valves. A standard of 0.25 was used as the minor loss coefficient determined by the ratio of the bend radius to the duct diameter. The elevation change between both ends of the bend is about 9.585 in = (9.585/12) ft.

$$\frac{radius}{diameter} > 1 \qquad \boldsymbol{\xi = 0.25 = K_L} \qquad\qquad \frac{9\text{ inch}}{8\text{ inch}} = 1.125$$

Bernoulli equation:

$$P_2 + \rho g h_2 + \rho\frac{V_2^2}{2} = P_3 + \rho g h_3 + \rho\frac{V_3^2}{2} + P_{loss}$$

Solving for the pressure at 3:

$$P_3 = P_2 + \rho g(h_2 - h_3) + \rho\left(\cancelto{}{\frac{V_2^2}{2} - \frac{V_3^2}{2}}\right) + P_{loss}$$

$$P_{loss} = k\left(\rho\frac{V^2}{2}\right) = 0.25\left[0.002331071\left(\frac{23.873^2}{2}\right)\right] = 0.166066\,psf$$

$$\begin{aligned} P_3 &= 2092.225 + (0.002331071 * 32.2)(9.585/12) + 0.52486 = 2092.810\,psf \\ &= -4.505\,WG \end{aligned}$$

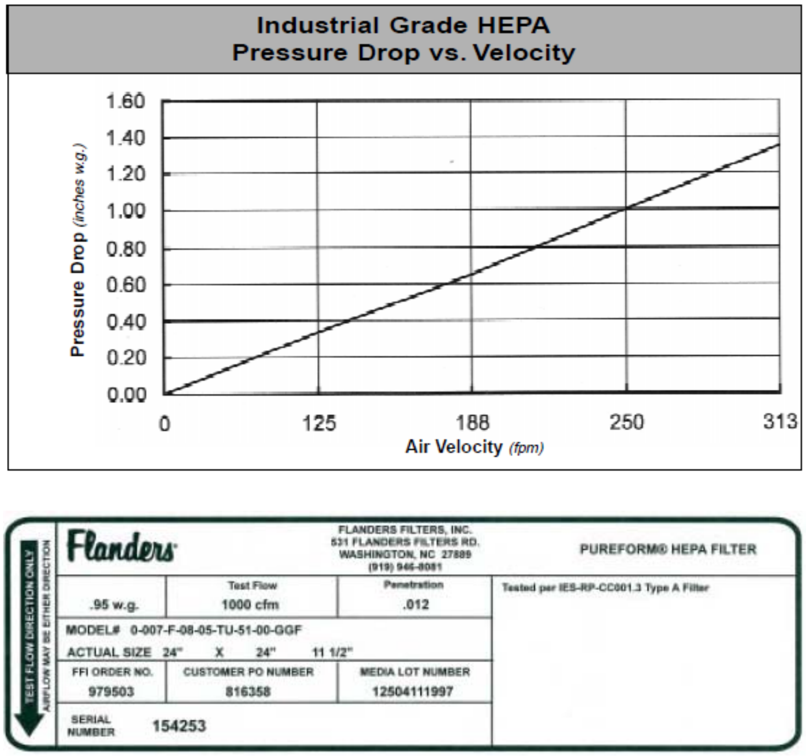
Table 4. Results for Section 2 - 3 Analysis (Minor Loss)

Section 2 - 3			
Pressure 2	P_2	2091.486	lb/ft^2
Veloctiy	V	1432.394	ft/min
		23.873	ft/sec
Reynolds Number	Re_{2-3}	95588.55	N/A
Relative Roughness	k/d	0.000075	N/A
Loss Coefficient (R1/D > 1)	K_L	0.25	N/A
Pressure loss due to bend	$P_{L\ Minor}$	0.166	lb/ft^2
Pressure at 3	P_3	2091.712	lb/ft^2
		-4.716	in WG

Table 4 shows the data used in order to obtain the pressure at point 3. In the table, as in the equation for P_{loss}, it shows the minor loss due to the fitting in the section. The remaining bends in the system can be evaluated in the exact same way as previously shown; P_{loss} for all of them will be the same.

4.3.3 PRESSURE DROPS THROUGH HEPA FILTERS

Three 1000 cfm filters are used in the ventilation design. Their pressure drops at different flow rates are shown in the accompanying plot of Figure 3 below.



FLANDERS FILTERS, INC.
531 FLANDERS FILTERS RD.
WASHINGTON, NC 27889
(919) 946-8081

PUREFORM® HEPA FILTER

	Test Flow	Penetration
.95 w.g.	1000 cfm	.012

Tested per IES-RP-CC001.3 Type A Filter

MODEL# 0-007-F-08-05-TU-51-00-GGF
ACTUAL SIZE 24" X 24" 11 1/2"

FFI ORDER NO.	CUSTOMER PO NUMBER	MEDIA LOT NUMBER
979503	816358	12504111997

SERIAL NUMBER 154253

Figure 3. Sample HEPA filter pressure drops at 1000 cfm.

The analysis for the pressure drop, section 3 – 4, and the resulting pressures on either side of the filter are shown below.

ΔP_{HEPA} at 1000 cfm = 0.38“ WG

$$\Delta P_{HEPA} = P_4 - P_3$$

$$P_4 = \Delta P_{HEPA} + P_3 = 0.38 + (-4.505) = -4.125\text{ "}WG$$

The pressures in the following sections:

4-5
5-6
6-7
7-8
8-9

can be obtained using the same analysis as either sections 1 - 2 (major loss) or section 2 - 3 (minor loss).

4.3.4 ORIFICE SIZING FOR PRESSURE REDUCTION

In order to maintain the contaminated section of the glovebox at -1” WG, an orifice needs to be placed before the contraction to limit the amount of negative pressure reaching the “gloved” section. Figure 4 below illustrates the position of the orifice and the position of the taps for the pressure gauges.

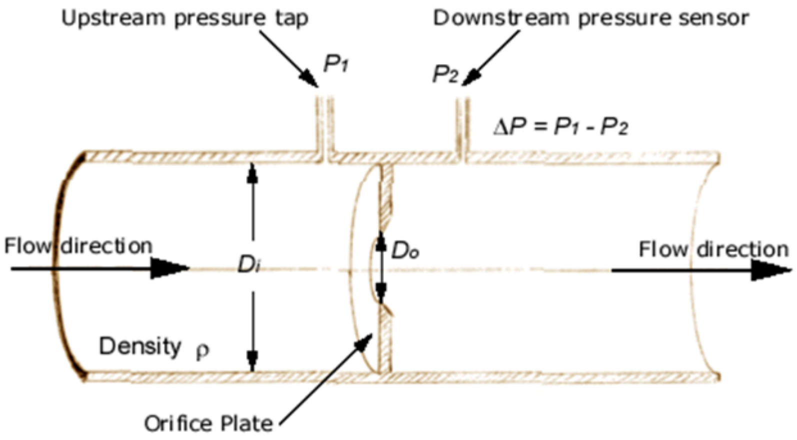


Figure 4. Flow through an orifice.

Flow through an orifice: $Q = CA\sqrt{2gh_l}$

$$h_l = \frac{144\Delta P}{\rho} \qquad C = \frac{C_d}{\sqrt{1 - \left(\frac{d_o}{d_1}\right)^4}} \qquad A = \pi\left(\frac{{d_o}/{2}}{12}\right)^2$$

$$Q = \frac{C_d}{\sqrt{1 - \left(\frac{d_o}{d_1}\right)^4}}\ \pi\left(\frac{{d_o}/{2}}{12}\right)^2\ \sqrt{\frac{2g * 144\Delta P}{\rho}}$$

where:
Q – Volumetric flow rate (ft^3/sec)
C_d – Discharge coefficient (0.60 – 0.65)
A – Area of orifice (ft^2)
g – Gravity (ft/sec^2)
h_L – head loss (ft)
ΔP – Pressure drop across orifice (psi)
ρ – Gas Density (lb/ft^3)
d_o – Orifice Diameter (ft)
d_1 – Duct Diameter (ft)

$$|\Delta P| = P_9 - (-1) = -4.318 - (-1) = |-3.318|''\ WG$$

3.318” WG = 0.11976 psi
500 cfm = 8.333 cfs

$$Q = \frac{C_d}{\sqrt{1 - \left(\frac{d_o}{d_1}\right)^4}}\ \pi\left(\frac{{d_o}/{2}}{12}\right)^2\ \sqrt{\frac{2g * 144\Delta P}{\rho}}$$

$$8.333 = \frac{0.60}{\sqrt{1-\left(\frac{d_o}{8}\right)^4}} \quad \pi\left(\frac{d_o/2}{12}\right)^2 \sqrt{\frac{2*32.2*144*0.11976}{0.075}}$$

Solving for $\mathbf{d_o}$ **= 4.459 inches.**

4.3.5 MINOR LOSSES: EXPANSIONS AND CONTRACTIONS

Sections 9-10, 10 – 11, 18 – 19 and 19 – 20 are either expansions or contractions. The pressure loss in both cases can be expressed using P_{loss}. The larger flow velocity is always used in the equation:

$$P_{loss} = k\left(\rho\frac{V^2}{2}\right)$$

Pressure loss is used instead of head loss. In the case of a sudden contraction, *k* is a function of the two areas (A_2/A_1). A graph of area ratios to loss coefficient is used to determine the *k* value used. Figure 5 illustrates the sudden contraction plot.

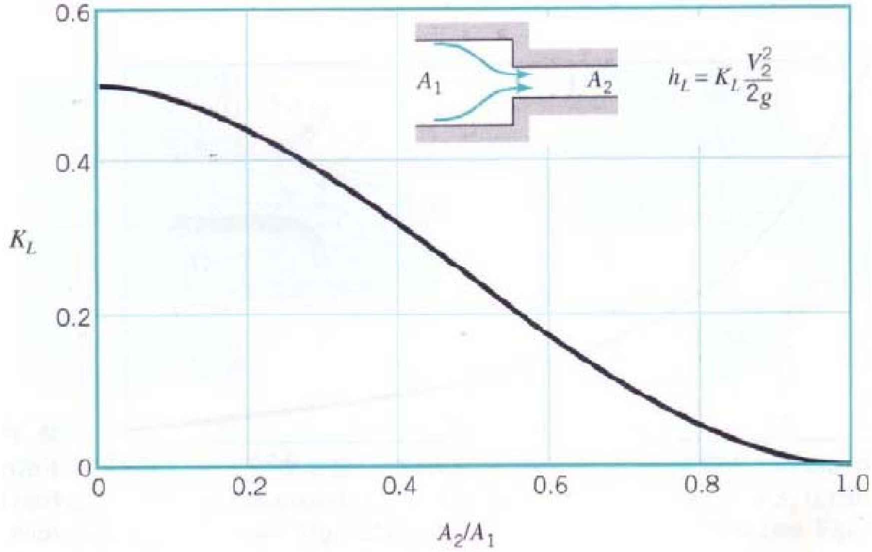


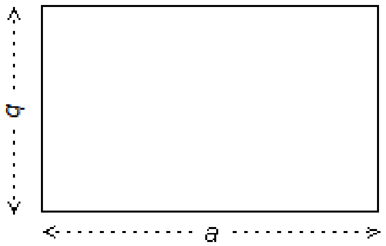
Figure 5. Loss coefficients for sudden contractions.

Evaluating section 9 – 10, the two areas involved are the cross-sectional areas of the duct and the contaminated section of the glovebox that has dimensions of 244.875” by 31.956”. Figure 5 shows that A_1 is the larger area and A_2 is the smaller one. In this case, A_2 corresponds to the ducting cross-sectional area.

$$A_2 = \pi r^2 = \pi \left(\frac{\mathrm{d}}{2}\right)^2 = \pi \left(\frac{8/12}{2}\right)^2 = 0.34907\, ft^2$$

A_1 needs to be converted into an equivalent circular cross section due to the fact the data provided in the plot is only for circular ducting.

Calculating the hydraulic diameter for rectangular tubes or ducting:



$$D_H = \frac{2(ab)}{a+b} = \frac{2\left[\left(\frac{244.875}{12}\right)\left(\frac{31.956}{12}\right)\right]}{\left(\frac{244.875}{12}\right)+\left(\frac{31.956}{12}\right)} = 4.711\, ft$$

$$A_1 = \pi r^2 = \pi \left(\frac{\mathrm{d}}{2}\right)^2 = \pi \left(\frac{4.711}{2}\right)^2 = 17.4308\, ft^2$$

$$\frac{A_2}{A_1} = \frac{0.34907}{17.4308} = 0.020026$$

From Figure 5, *k* is estimated to be around 0.50.

$$P_{loss} = k\left(\rho \frac{V^2}{2}\right) = 0.50\left[0.002331071\left(\frac{23.873^2}{2}\right)\right] = 0.332131 \text{ psf}$$

For a sudden expansion:

$$P_{loss} = k\left(\rho \frac{V^2}{2}\right)$$

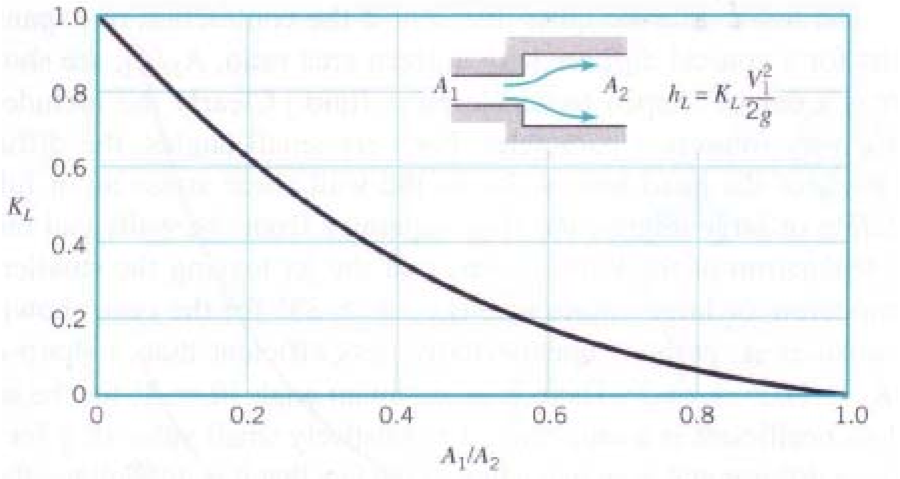


Figure 6. Loss coefficients for sudden expansions.

$$A_1 = \pi r^2 = \pi \left(\frac{\mathrm{d}}{2}\right)^2 = \pi \left(\frac{8/12}{2}\right)^2 = 0.34907\ ft^2$$

$$A_2 = \pi r^2 = \pi \left(\frac{\mathrm{d}}{2}\right)^2 = \pi \left(\frac{4.711}{2}\right)^2 = 17.4308\ ft^2$$

$$k = \left(1 - \frac{A_1}{A_2}\right)^2 = 0.960$$

$$P_{loss} = k\left(\rho \frac{V^2}{2}\right) = 0.960\left[0.002331071\left(\frac{23.873^2}{2}\right)\right] = 0.637923 \text{ psf}$$

4.3.6 OVERALL SYSTEM PRESSURES

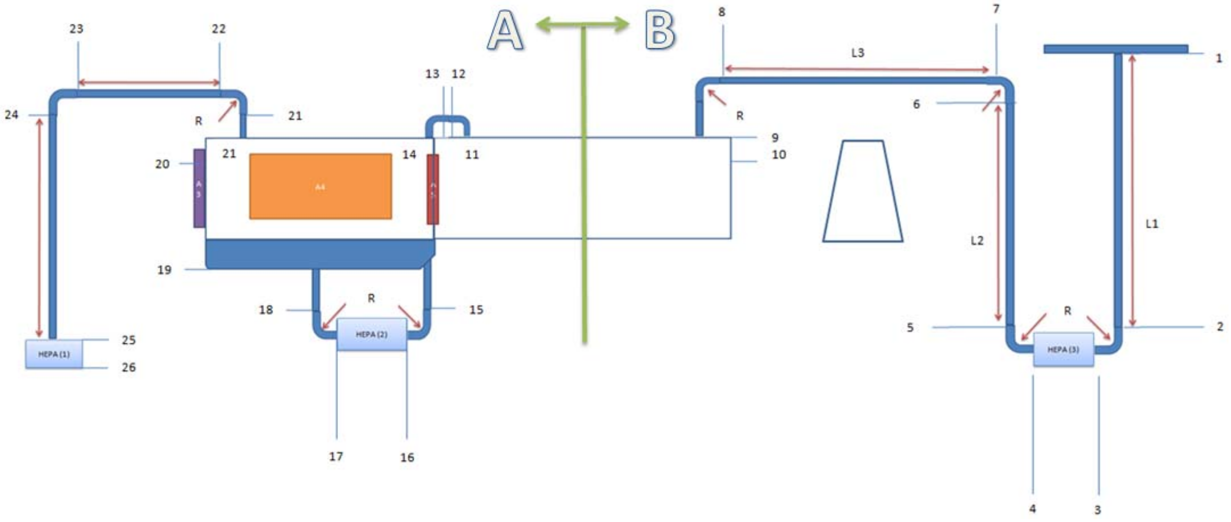


Figure 7. Overall system pressure schematic.

Combining all the analysis per section, the loss throughout the system can be analyzed depending on the flow through the lines. At 500 cfm and using a 6-inch duct and with a -1” WG pressure in the contaminated section of the glovebox, there will too much loss in the system due to friction. If a flow of 410 cfm is used with a -1.5” WG pressure difference and a high efficiency HEPA filter that has a drop of around .28” WG, all of the initial pressure will be used without having to exceed what’s being applied. Table 6 provides the changes in pressure per section with given initial inputs.

Results obtained through an alternative process utilizing a ducting calculator are shown below. The table shows the pressure increases through section A and B of the schematic. It does not take into account the pressure in the contaminated section of the glovebox. If the pressure was kept at -1” WG at 500 cfm, according to the table below, the pressure at point 26 would 0.081” + 1” = 1.081”.

Table 5. Overall Pressure Drops using Ducting Calculator

Pressure Increases Obtained Using Ducting Calculator			
Intial Pressure (" WG)	-5		
Flow rate (cfm)	400	450	500
Overall Pressure Increase (" WG)	3.62	4.412	5.081
Pressure before HEPA (1) (" WG)	-1.38	-0.588	0.081
Pressure Increase in section B	1.317	1.605	1.87
Pressure Increase in section A	2.303	2.807	3.211

Table 6. Overall System Pressures using an 8-inch Duct

Inputs	
Flow Rate (cfm)	500
Pressure @ outlet (" WG) (Section 1)	-5
Pressure in Isolation Box (" WG)	-1
HEPA Filter Drop (" WG)	0.38
Duct Diameter (inch)	8

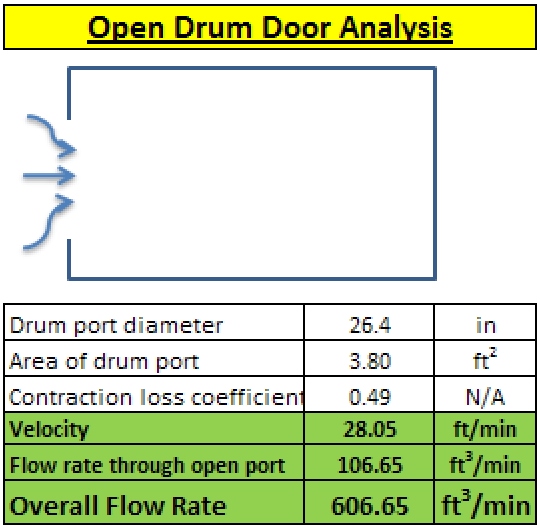
Section	Pressure (" WG)	Pressure (psfg)
1	-5	-25.99
1 - 2	-4.76	-24.74
2 - 3	-4.72	-24.51
3 - 4	-4.34	-22.54
4 - 5	-4.32	-22.43
5 - 6	-4.44	-23.06
6 - 7	-4.42	-22.96
7 - 8	-4.36	-22.67
8 -9	-4.32	-22.44
9 - 10	-4.12	-21.41
10 - 11	-1.01	-5.24
11 - 12	-0.99	-5.14
12 - 13	-0.98	-5.10
13 - 14	-0.94	-4.87
14 -15	-0.76	-3.97
15 - 16	-0.72	-3.74
16 - 17	-0.34	-1.77
17 - 18	-0.32	-1.66
18 - 19	-0.36	-1.87
19 - 20	-0.25	-1.29
20 - 21	-0.26	-1.37
21 - 22	-0.24	-1.26
22 - 23	-0.22	-1.15
23 - 24	-0.18	-0.92
24 - 25	-0.14	-0.73
25 - 26	0.24	1.24

Inputs	
Flow Rate (cfm)	500
Pressure @ outlet (" WG) (Section 1)	-5
Pressure in Isolation Box (" WG)	-1.3
HEPA Filter Drop (" WG)	0.38
Duct Diameter (inch)	8

Section	Pressure (" WG)	Pressure (psfg)
1	-5	-25.99
1 - 2	-4.76	-24.74
2 - 3	-4.72	-24.51
3 - 4	-4.34	-22.54
4 - 5	-4.32	-22.43
5 - 6	-4.44	-23.06
6 - 7	-4.42	-22.96
7 - 8	-4.36	-22.67
8 -9	-4.32	-22.44
9 - 10	-4.12	-21.41
10 - 11	-1.31	-6.80
11 - 12	-1.29	-6.70
12 - 13	-1.28	-6.65
13 - 14	-1.24	-6.43
14 -15	-1.06	-5.53
15 - 16	-1.02	-5.30
16 - 17	-0.64	-3.33
17 - 18	-0.62	-3.22
18 - 19	-0.66	-3.43
19 - 20	-0.55	-2.85
20 - 21	-0.56	-2.93
21 - 22	-0.54	-2.82
22 - 23	-0.52	-2.71
23 - 24	-0.48	-2.48
24 - 25	-0.44	-2.29
25 - 26	-0.06	-0.32

4.3.7 FLOW THOUGH OPEN ACCESS DOORS

4.3.7.1 Tech Door



Open Drum Door Analysis

Drum port diameter	26.4	in
Area of drum port	3.80	ft^2
Contraction loss coefficient	0.49	N/A
Velocity	**28.05**	**ft/min**
Flow rate through open port	**106.65**	**ft^3/min**
Overall Flow Rate	**606.65**	**ft^3/min**

With the tech door open, an additional 123 cfm will flow into the system, creating a flow of 623 cfm; soon after, the flow should reduce due to the transient state.

$$P_1 + \rho g h_1 + \rho\frac{V_1^2}{2} = P_2 + \rho g h_2 + \rho\frac{V_2^2}{2} + P_{loss}$$

$$P_1 + \rho g h_1 + \rho\frac{V_1^2}{2} = P_2 + \rho g h_2 + \rho\frac{V_2^2}{2} + k\left(\rho\frac{V^2}{2}\right)$$

Assuming that h_1 and h_2 are at the same height and that point 1 is sufficiently far from the opening, $V_1 = 0$.

$$P_1 + \rho g \cancel{h_1 +} \rho\cancel{\frac{V_1^2}{2}} = P_2 + \rho g h_2 \cancel{+ \rho}\frac{V_2^2}{2} + P_{loss}$$

$$V_2 = 2\sqrt{\frac{\frac{\Delta P}{[k+1]}}{\rho}}$$

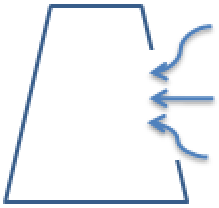
After solving for V, the flow rate can be determined knowing the area of the tech door opening:

$$Q = VA$$

4.3.7.2 Drum Door

The same analysis applies to the drum door; the only difference being the area of the opening. The drum door has a smaller cross-sectional area than the tech access door.

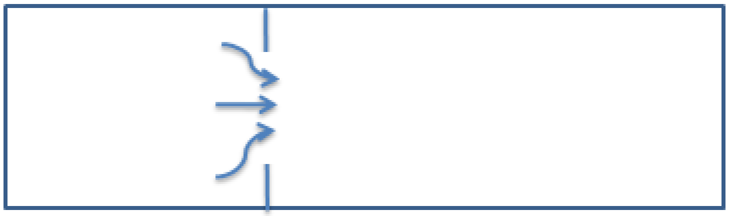
Open Tech Access Door Analysis



Tech Access Door Area	4.383681	ft^2
Equivalent Circular Access Door Diamet	2.051	ft
Area of Equivalent Tech Access Door	3.303	ft^2
Contraction loss coefficient	0.49	N/A
Velocity	**28.05**	**ft/min**
Flow rate through open port	**92.67**	**ft^3/min**
Overall Flow Rate	**592.67**	**ft^3/min**

4.3.7.3 Open Isolation Door

Open Isolation Door



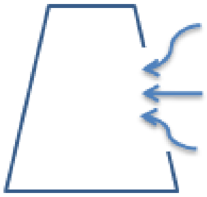
Isolation Door	4.208333333	ft^2
Equivalent Circular Access Door Diameter	2.051	ft
Area of Equivalent Tech Access Door	3.303	ft^2
Contraction loss coefficient	0.49	N/A
Velocity	**54.95**	**ft/min**
Flow rate through open port	**181.50**	**ft^3/min**
Overall Flow Rate	**681.50**	**ft^3/min**

For 10-inch duct:

Open Drum Door Analysis

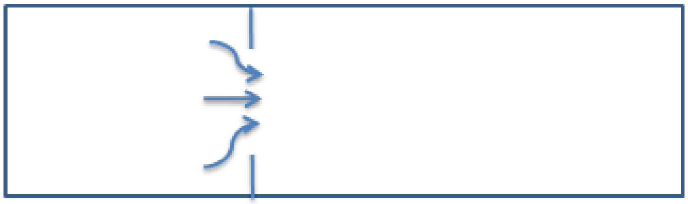
Drum port diameter	26.4	in
Area of drum port	3.80	ft^2
Contraction loss coefficient	0.49	N/A
Velocity	**38.00**	**ft/min**
Flow rate through open port	**144.45**	**ft^3/min**
Overall Flow Rate	**644.45**	**ft^3/min**

Open Tech Access Door Analysis



Tech Access Door Area	4.383681	ft^2
Equivalent Circular Access Door Diamet	2.051	ft
Area of Equivalent Tech Access Door	3.303	ft^2
Contraction loss coefficient	0.49	N/A
Velocity	**38.00**	**ft/min**
Flow rate through open port	**125.51**	**ft^3/min**
Overall Flow Rate	**625.51**	**ft^3/min**

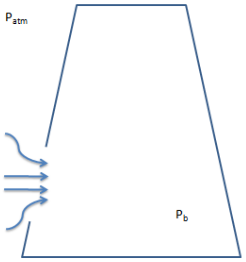
Open Isolation Door



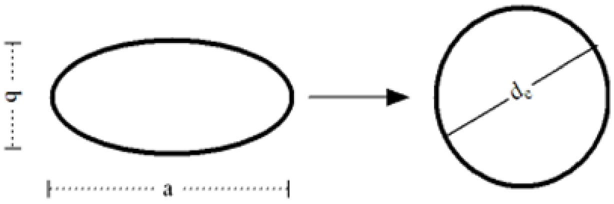
Isolation Door	4.208333333	ft^2
Equivalent Circular Access Door Diameter	2.051	ft
Area of Equivalent Tech Access Door	3.303	ft^2
Contraction loss coefficient	0.49	N/A
Velocity	**54.93**	**ft/min**
Flow rate through open port	**181.45**	**ft^3/min**
Overall Flow Rate	**681.45**	**ft^3/min**

4.3.8 PRESSURE DROPS THROUGH PORT OPENINGS

Assuming that one of the gloves rips and that the system is running at 500 cfm, the pressure drop through the port is shown below:



Converting the elliptical opening into a circular opening:



$$d_e = \frac{1.55\,A^{0.625}}{P^{0.2}} \qquad A = \pi\,\frac{ab}{4} \qquad P = 2\pi\sqrt{\left[\frac{1}{2}\left(\left(\frac{a}{2}\right)^2 + \left(\frac{b}{2}\right)^2\right)\right]}$$

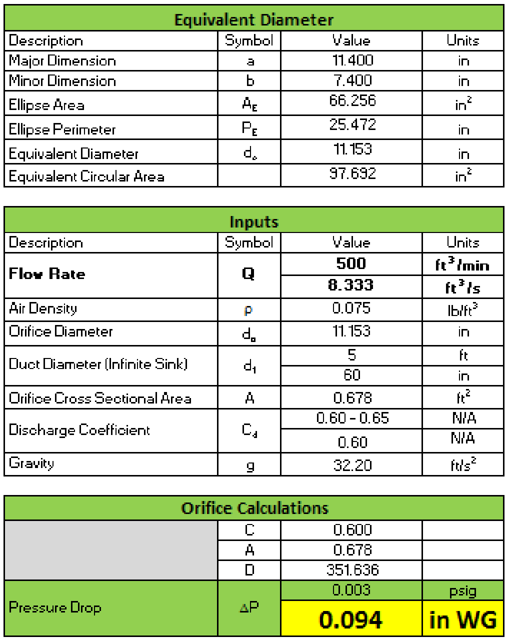
And using flow through an orifice equations, the results are shown in Table 7:

$$Q = CA\sqrt{2gh_l} \qquad h_l = \frac{144\Delta P}{\rho} \qquad C = \frac{C_d}{\sqrt{1-\left(\frac{d_o}{d_1}\right)^4}} \qquad A = \pi\left(\frac{{d_o}/{2}}{12}\right)^2$$

$$Q = \frac{C_d}{\sqrt{1-\left(\frac{d_o}{d_1}\right)^4}}\,\pi\left(\frac{{d_o}/{2}}{12}\right)^2\sqrt{\frac{2g * 144\Delta P}{\rho}}$$

$$Let\ D = \sqrt{\frac{2g * 144}{\rho}}$$

Table 7. Pressure Drop through Glove Port Opening



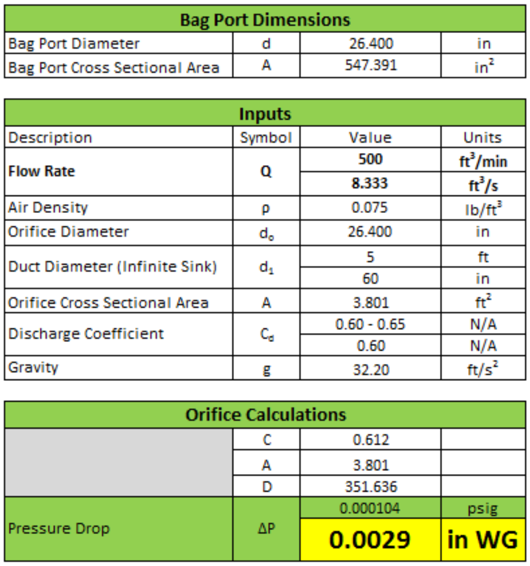
Equivalent Diameter			
Description	Symbol	Value	Units
Major Dimension	a	11.400	in
Minor Dimension	b	7.400	in
Ellipse Area	A_E	66.256	in^2
Ellipse Perimeter	P_E	25.472	in
Equivalent Diameter	d_e	11.153	in
Equivalent Circular Area		97.692	in^2

Inputs			
Description	Symbol	Value	Units
Flow Rate	**Q**	**500**	**ft^3/min**
		8.333	**ft^3/s**
Air Density	ρ	0.075	lb/ft^3
Orifice Diameter	d_o	11.153	in
Duct Diameter (Infinite Sink)	d_1	5	ft
		60	in
Orifice Cross Sectional Area	A	0.678	ft^2
Discharge Coefficient	C_d	0.60 - 0.65	N/A
		0.60	N/A
Gravity	g	32.20	ft/s^2

Orifice Calculations			
	C	0.600	
	A	0.678	
	D	351.636	
Pressure Drop	ΔP	0.003	psig
		0.094	**in WG**

The same analysis can be used to find the pressure drop through the drum opening. An equivalent circular diameter is not needed.

Table 8. Pressure Drop through Drum Port



Bag Port Dimensions			
Bag Port Diameter	d	26.400	in
Bag Port Cross Sectional Area	A	547.391	in^2

Inputs			
Description	Symbol	Value	Units
Flow Rate	**Q**	**500**	**ft^3/min**
		8.333	**ft^3/s**
Air Density	ρ	0.075	lb/ft^3
Orifice Diameter	d_o	26.400	in
Duct Diameter (Infinite Sink)	d_1	5	ft
		60	in
Orifice Cross Sectional Area	A	3.801	ft^2
Discharge Coefficient	C_d	0.60 - 0.65	N/A
		0.60	N/A
Gravity	g	32.20	ft/s^2

Orifice Calculations			
	C	0.612	
	A	3.801	
	D	351.636	
Pressure Drop	ΔP	0.000104	psig
		0.0029	**in WG**

5. CONCLUSION

At 500 cfm and using a 8-inch duct, there will be enough suction provided to ensure that there is always a negative pressure in the glovebox. A 1000 cfm HEPA filter running 500 cfm has a pressure drop of 0.38" WG. Utilizing that drop in the analysis, a -1" WG pressure can be kept in the contaminated section of the glovebox but -1.3" WG would be advised in order to ensure there is enough suction in the front half of the glovebox. A higher capacity HEPA filter can be used rather than lowering the pressure in that section. As shown below, any HEPA filter that has a drop of 0.25" WG or lower can be used to replace the 1000 cfm capacity filter.

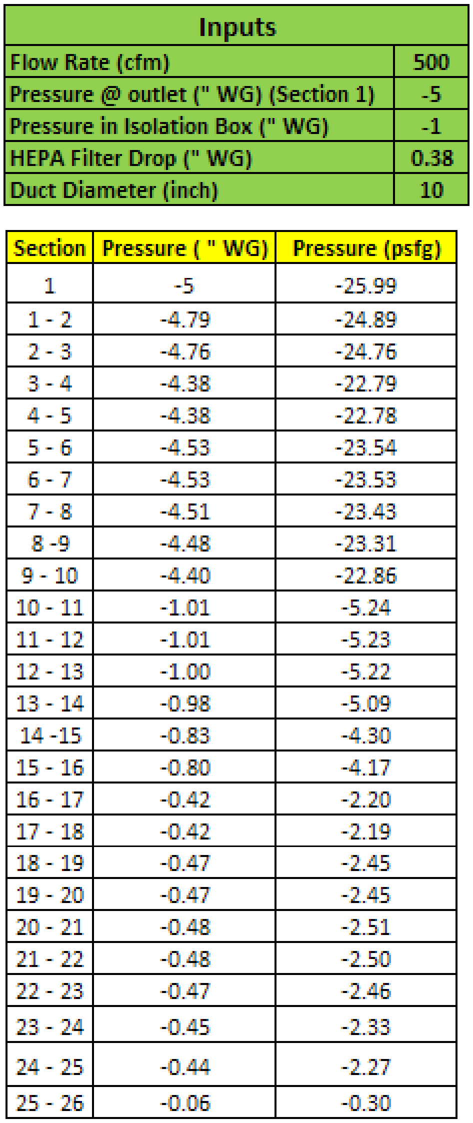
Table 9. Pressure Changes using 8-inch Duct

Inputs	
Flow Rate (cfm)	500
Pressure @ outlet (" WG) (Section 1)	-5
Pressure in Isolation Box (" WG)	-1
HEPA Filter Drop (" WG)	0.25
Duct Diameter (inch)	8

Section	Pressure (" WG)	Pressure (psfg)
1	-5	-25.99
1 - 2	-4.76	-24.74
2 - 3	-4.72	-24.51
3 - 4	-4.47	-23.21
4 - 5	-4.45	-23.11
5 - 6	-4.57	-23.74
6 - 7	-4.55	-23.63
7 - 8	-4.49	-23.34
8 -9	-4.45	-23.12
9 - 10	-4.25	-22.08
10 - 11	-1.01	-5.24
11 - 12	-0.99	-5.14
12 - 13	-0.98	-5.10
13 - 14	-0.94	-4.87
14 -15	-0.76	-3.97
15 - 16	-0.72	-3.74
16 - 17	-0.47	-2.44
17 - 18	-0.45	-2.34
18 - 19	-0.49	-2.55
19 - 20	-0.38	-1.97
20 - 21	-0.39	-2.04
21 - 22	-0.37	-1.94
22 - 23	-0.35	-1.82
23 - 24	-0.31	-1.60
24 - 25	-0.27	-1.41
25 - 26	-0.02	-0.11

Running the system at 500 cfm and having 10-in ducts, the resulting pressure will occur in the system.

Table 10. Pressure Changes using 10-inch Duct



Inputs	
Flow Rate (cfm)	500
Pressure @ outlet (" WG) (Section 1)	-5
Pressure in Isolation Box (" WG)	-1
HEPA Filter Drop (" WG)	0.38
Duct Diameter (inch)	10

Section	Pressure (" WG)	Pressure (psfg)
1	-5	-25.99
1 - 2	-4.79	-24.89
2 - 3	-4.76	-24.76
3 - 4	-4.38	-22.79
4 - 5	-4.38	-22.78
5 - 6	-4.53	-23.54
6 - 7	-4.53	-23.53
7 - 8	-4.51	-23.43
8 -9	-4.48	-23.31
9 - 10	-4.40	-22.86
10 - 11	-1.01	-5.24
11 - 12	-1.01	-5.23
12 - 13	-1.00	-5.22
13 - 14	-0.98	-5.09
14 -15	-0.83	-4.30
15 - 16	-0.80	-4.17
16 - 17	-0.42	-2.20
17 - 18	-0.42	-2.19
18 - 19	-0.47	-2.45
19 - 20	-0.47	-2.45
20 - 21	-0.48	-2.51
21 - 22	-0.48	-2.50
22 - 23	-0.47	-2.46
23 - 24	-0.45	-2.33
24 - 25	-0.44	-2.27
25 - 26	-0.06	-0.30

6. REFERENCES

[1] Kay, J.M. *An Introduction to Fluid Mechanics and Heat Transfer*. 2nd. New York: The Syndics of the Cambridge University Press, 1963. 323. Print.

[2] Massey, B.S. *Mechanics of Fluids*. 5th. Berkshire, England: Van Nostrand Reinhold (UK) Co. Ltd., 1983. 614. Print.

[3] Ower, E., and R.C. Pankhurst. *The Measurement of Air Flow* . 4th. Oxford: Pergamon Press, 1966. 359. Print.

[4] Berry, C. Harold. *Flow and Fan - Principles of Moving Air Through Ducts*. 2nd. New York: The Industrial Press, 1963. 209. Print

[5] Li, Wen-Hsiung, and Sau-Hai LAm Lam. *Principles of Fluid Mechanics*. Reading, Massachusetts: Addison-Wesley Publishing Company, INC., 1964. 373. Print.

[6] Baumeister, Theodore, Eugene A. Avallone, and Theodore Baumeister III. "Thermal Dynamics of Flow and Compressible Fluids." *Marks' Standard Handbook for Mechanical Engineers*. 8th. New York: McGraw-Hil Book Company, 1978`. Print.

APPENDIX A: Moody Friction Diagram