Design Review & Critique

Project #	BB1	Date	February 9th, 2017

Project Title	Aircraft System Filters - Means to Extend Useful Life
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Executive Summary

Bombardier Aerospace has asked for a design that can resolve the problem of replacing air filters prematurely, as filters are frequently removed well before their operating lifetime limits. Filters are rated by the supplier for a set number of flight hours, however these do not accommodate for numerous variables in operation. The region's air quality, aircraft frequency of use, and other variables will all have an effect on the operational lifespan of the filters. Currently, air filters are replaced with little indication of remaining life, and once a filter is removed it cannot be reinstalled without significant economic and time costs. Bombardier is searching for an easy way to evaluate the remaining life of the air filters after they get replaced in order to evaluate an average maximum lifespan for filters in their region of origin. The current design will measure the pressure differential across a filter which can then be used to determine the remaining lifespan, as per the Initial Proposal.

The primary stakeholders in the design project are Bombardier, the University of Toronto, and various other technical groups with the expertise to use and maintain the design. Since the design is primarily used by technicians and other trained professionals, the design has limited public exposure, thus the scope and technical constraints can be further refined.

The function of the design is to measure the pressure drop across a filter, and additionally provide information about the flow velocity through the filter. Bombardier has detailed the various testing criteria that must be followed for determining a pass/fail condition. The design has been developed in order to meet the objectives of adaptability to various filter sizes, and can also be deconstructed and transported by a single operator without special tools.

Since the Initial Proposal, several updates have been made to increase satisfaction of the objectives and adhere to stakeholder interests. While each update did not compromise the design's functional requirements, it necessitated an analysis of any possible effects on the design's operation and satisfaction of objectives. Numerous changes were made to the design to improve the testing accuracy with regards to pressure resolution, while achieving excellent cost reductions as well. Several topological design changes were made to better improve the airflow required for the design.

A safety and contingency plan was developed to address the current and future risks to the project, both during the design and implementation/use stages. The safety plan addresses concerns with regards to the operational safety, economics, and downtimes associated with the design. A risk matrix and failure mode effects analysis (FMEA) table identifies the potential risks and solutions to safety concerns, while a contingency plan addresses the concerns related to project management and team dynamics. In addition, opportunities for scheduling and design improvement are addressed in the contingency plan.

1.1 Problem Statement

Bombardier (as the Client) is seeking for a method to easily evaluate the remaining life of cabin and component air filters in the aircraft (Q400) after they are replaced. Currently, replaced filters are not considered to be useable based on the operator's initial glance, as standardized testing methods have not been developed. Purchasing new filters is expensive and further financial costs are incurred by the downtime associated with maintenance. The lifespan of the filters are dependent on the air quality and composition in their regions of origin, as higher particulate levels would reduce the filter's operating lifespan. Therefore, samples from different environments will be used to test remaining life of the air filters.

Bombardier owns a 10 ft long testing bench at headquarter that can simulate the aircraft system airflow to test whether the air filters are meeting the failure criteria indicative of their end-of-life, and thus the ideal replacement rate. However, due to the size of the bench, air filters have to be collected by maintenance operators and shipped to the test center to get tested, and the design has non-standardized parts making replication difficult. This whole process is time-consuming and can be shortened by providing a method to test air filters at the operator's discretion. There are three air filters with different shapes and specifications in air crafts: safety valve filters, display panel filter and cabin filters. Filter samples will be collected from various regions including China/Japan, Africa, North America and Europe. The design should be able to fit for all these three types of filters. The design must be portable to carry and able to be used the at operator's own maintenance schedule.

1.2 Scope

The task for this project is to design a portable prototype that can be used by the operator to easily evaluate the remaining life of the air filters in order to fully use the filters before replacing them. The whole project is divided into three stages:

Stage 1 (Sep.2016 - Dec.2016): Prototype design
Stage 2 (Jan.2017 - Feb.2017): Prototype simulation and testing
Stage 3 (Feb.2017 - March.2017): Design refinement

In Stage 1, Team works on prototype design solutions, and propose an initial design. The prototype is simulated and tested in Stage 2 for design improvement. Stage 3 involves improving the design based on previous test results.

The initial proposal of the design has selected the modular pressure differential measurement system as the baseline for further development, by comparing its functionality against other alternatives through a weighted decision matrix.

The Design Team will start to simulate the prototype for the cabin filter, because it has the highest requirement for the flow rate. Combined with a flow rate control valve, the prototype can be adjusted for other types of filters. The requirement for the project is to design a prototype that can be used for cabin filters, however designing a system that can fit all three types of filters is an extension of the project.

1.3 Identification of Stakeholders

This section identifies parties that will influence the design of the project. The degree of interest expressed by a stakeholder thus affects the extent of their impact on the design. As the design is not intended for use by the general public, the design shall be targeted towards use and distribution by maintenance and management teams.

Table 1: Table of stakeholders & their respective interests in the design

Stakeholder	Interest	Impact on design
Capstone Project Team	Complete 4th year project and build connection with the client	The design must be feasible to produce within the duration of the Capstone course
Capstone Project Supervisor	Meet clients' expectation and ensure students learned through the project	Design team needs to apply the knowledge of engineering design

Bombardier Aerospace	Increased filter lifespans will lead to increased return on equity for Bombardier	The design must be cost efficient and provide accurate data
Commercial Airlines	Reduced maintenance costs from reduced filter replacement frequency	The lifespan calculations must be sufficiently accurate
Design Operators	Ease of operation will lead to increased user satisfaction	The design should meet ergonomic use objectives

1.4 Functions

The function of this design is to accurately evaluate the remaining life the three different types of particulate air filters installed in a Bombardier Q400-series commercial aircraft. The functional basis of the design is to transmit information to the user (maintenance operator), as per the following primary and secondary function.

1.4.1 Primary Functions

The design should:

- Display the input and output air flow criteria through a particulate air filter
    - The design must indicate the air pressure, air temperature, and volumetric **or** mass flow rate before and after the stationary air filter
- Calculate and display the expected life span for a filter type in its region of origin
    - The design must determine the projected flight-hour lifespan for an air filter type in its region of use

1.4.2 Secondary Functions

In order to accomplish the primary functions, the design should:

- Modify testing parameters by user operation
    - The design should be adjustable for the various testing parameters required by each filter
- Develop an extrapolative mathematical model for the expected lifespan of a filter
    - The design should use the OEM rated lifespans for comparison
    - The design will use a clean, unused filter for calibration

In order to complete its intended purpose, the design must be able to determine the input and output air flow rate through a filter, at a preset input temperature and pressure. Once the flow rates are determined, the design must be able to extrapolate the expected lifespan from various filter flow rates and service hours. This will allow for the design to use a mathematical model to determine the expected lifespan of each filter in its region of origin.

1.5 Objectives

In order to improve the user experience, the design should seek to achieve a series of objectives. Each is quantified by an objective goal, and a corresponding metric (where applicable) for the determining the design's success in meeting its goals.
The design should be:

- Easily adjustable for various filters
    - The design's filter adapter assembly should be modular
        - Goal: The operators (normally aircraft maintenance technicians) should spend no more than 5 minutes replacing a filter. (Airplane turn time, time required to unload an airplane and prepare for the next departure, is about 60 minutes[9]. Changing the filter of the device should not take too long so that technicians can finish their work within the turn time..)
        - Metric: Measure the time taken to install a filter
- Portable
    - The design should be easily disassembled to fit in a Q400 cargo hold
        - Goal: The design should be easily disassembled to fit in Q400 cargo holds for transportation from site to site
        - Metric: Measure dimensions of the design to fit cargo loading requirements
    - The design should be easily disassembled into components transportable by a single person
        - Goal: Disassembled components should weigh less than 50lbs to comply with workplace ergonomics standards
        - Metric: Weight components to meet mass goals, component sizes must meet ergonomic design standards [4]
- Easily operated
    - The design should be easy to disassemble and clean for the next test run
        - Goal: The design should allow a single worker to disassemble with standard tools (e.g., wrench, screwdriver) and wash with water or wipe down with cloths. Cleaning process should not take more than 10 minutes.
        - Metric: Measure the time taken to clean the design
- Low cost
    - This design should have lower price-performance ratio
        - Goal: Minimize cost. Avoid any unnecessary cost.
        - Metric: Add up the costs for each component

1.6 Constraints

The constraints are strict design limitations that the design must meet. These limitations determine that the design must:

- Not overestimate the lifespan of the air filters
- Not affect the functions of the filter/filter housing or otherwise modify the filters themselves
- Be safe to operate within the safety protocols specified by component manufacturers
- Comply with Canadian workplace ergonomics standards when transporting or disassembling the design [4]
- Comply with the testing parameters specified by Bombardier Inc. [1,2,3]

1.7 Service Environment

The following section describes the environment in which the design will be operated. Since a prototype will be developed as part of design process to assess the pressure drop across the testing filters, sample filters collection sources, filters specifications and prototype input testing parameters will be included in this section as well.

1.7.1 Physical Environment

The design will be operated inside the workshop to assess the remaining life of filters.

- Temperature Range: Approximately room temperature; Winter: between 19-21 Degree Celsius, Summer: between 23-26 Degree Celsius [7].
- Humidity: Average humidity of a typical workshop; Average of 40%; below average in winter, above in summer [8].
- Pressure: Standard indoor air pressure
- Dirt and Dust: The Design should be cleaned after using and ready for next run
- Corrosive Environment: No corrosive sources near the design

1.7.2 Human Environment

- Any Operating Personnel (i.e. Site Operator or Site Engineer) should be familiar with the testing process and machine before using (i.e. training is required) to ensure safe operating conditions and better performance.

1.7.3 Virtual Environment

- The design should be able to connect with computer (i.e. cable is required) to run simulation and assessment analysis.

1.7.4 Sample filters collection sources

(For Prototype testing and improvement Stage)

Three sets of samples, 12 filters in total will be used to assess the remaining life pattern for each type of filter. Due to the different operating conditions (such as the dusty level, climate conditions in the operating environments), the expected remaining life for each set of sample filters could be different. The Client has specified the input parameters for the filter testing (refer to table 2 Input Testing Parameters) which are estimated based on the average normal operating conditions and it has been decided that the pressure drop is the only Pass/Fail Criteria used for the filter assessment. For each type of filter testing, a new clean filter will be tested as the control filter to set the baseline. Three types of filters will be assessed as required, Pressurization Control Aft Safety Valve Filter, Cabin Air Distribution Recirculation Filter and Front Fuselage LCD Cooling Filter.

4 sample filters from temperate industrial regions (China/Japan) [1]
4 sample filters from tropical climates/dusty operating environments (Africa) [1]
4 sample filters from where the majority of the fleet operated (2 from North America and 2 from Europe), considered as covering temperate rural/cold/arid environments [1]

Notes: The Operators shall tag the filter with the required information and ship the filters to Bombardier as per Q400 Maintenance Program Evolution Sampling Requirements[1]. Otherwise, the design shall be shipped to the location of aircraft maintenance.

1.7.5 Input Testing Parameters

The following figure outlines the testing parameters for each filter, and the respective criteria categorizing failure in the filter. Four used samples of each filter shall be used for testing.

Table 2: Input Parameters For Testing Filter Failure

	Pressurization Control Aft Safety Valve Filter	Cabin Air Distribution Recirculation Filter	Front Fuselage LCD Cooling Filter
Air flow rate	0.102 lb/min	57 lb/min	2.4 lb/min
Temperature	21 °C	27 °C	5-25 °C
Pressure	14.7 psi	14.7 psi	14.7 psi
Failure Criteria (Max Pressure Drop)	1.61’’ WC	4” WC	0.40” WC
Relative Decrease* Inlet flow / Max Pressure Drop	4% / 10%	0.5% / 1%	0.18% / 40.25%

*Cabin Air Recirculation Filter is used as basis for comparison

1.7.6 Filter Dimensions

The following diagrams illustrate the installation of the various filters into their respective areas of service in the Q400, and the general shape of each respective filter. The y-axis on each of the following three sets of diagrams has been selected to display the flow axis of air.

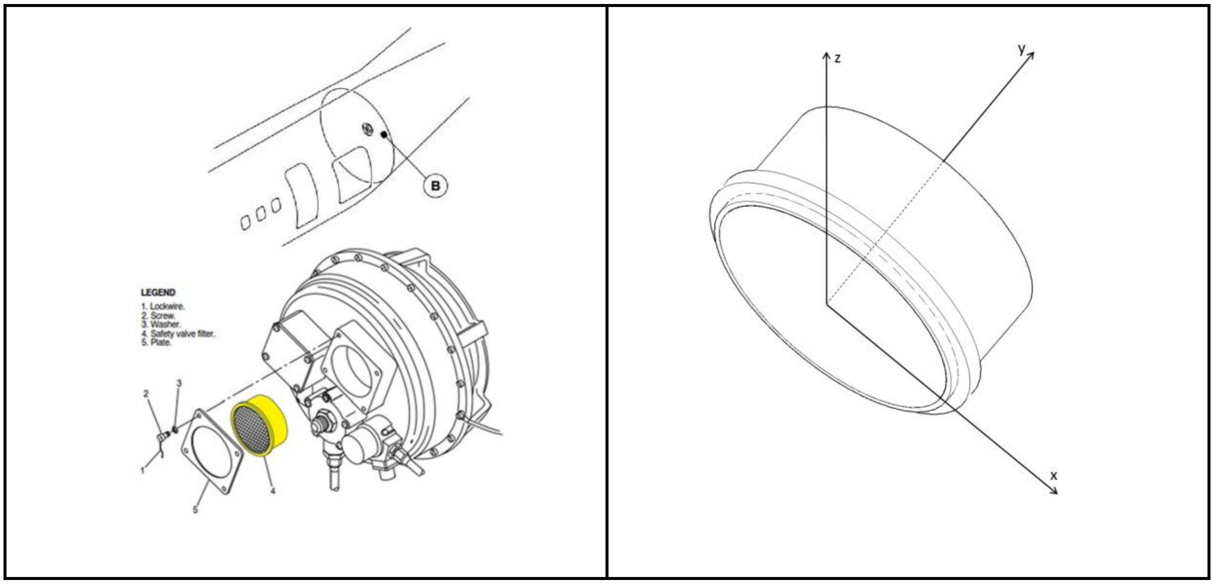

Figure 1: Pressurization Control Aft Safety Valve Filter [1]

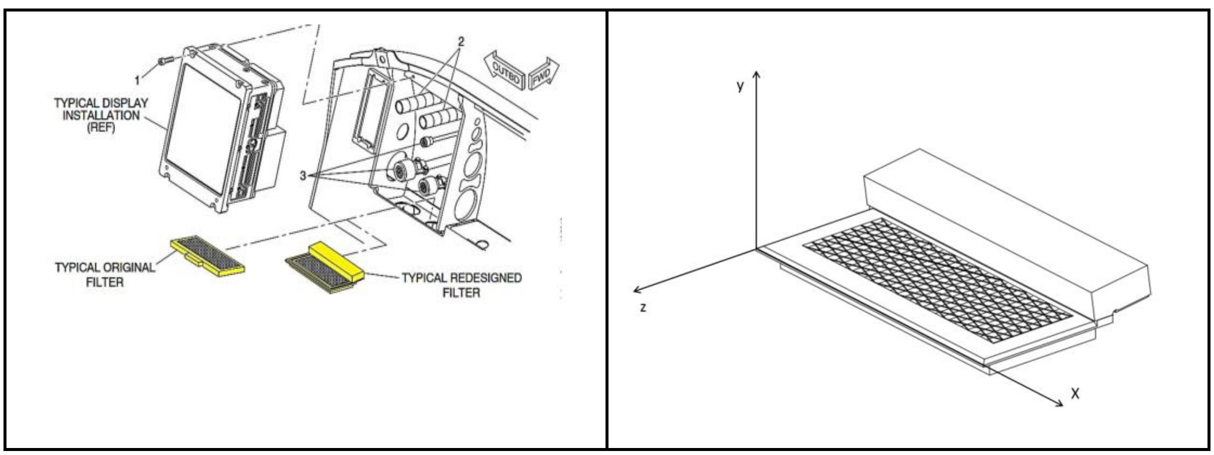

Figure 2: Front Fuselage LCD Cooling Filter [2]

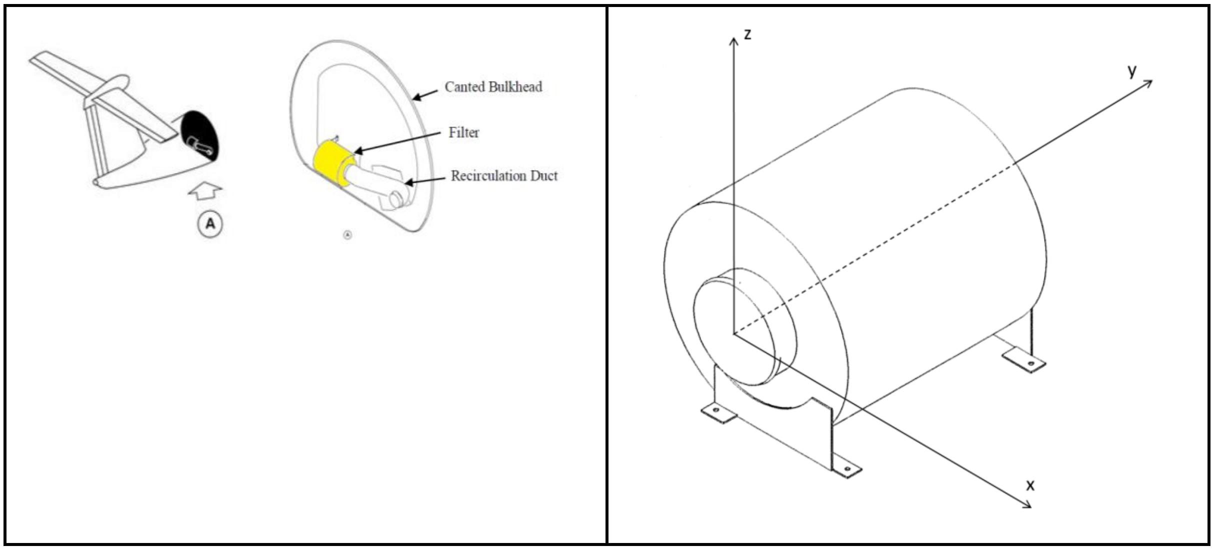

Figure 3: Cabin Air Recirculation Filter [3]

Table 3: Filter Dimensions [5][6]

Filter Type	X (including the frame) -inc	X (filter media) - inc	Y (including the frame) -inc	Y (filter media) - inc	Z (including the frame) -inc	Z (filter media) - inc
Pressurization Control Aft Safety Valve Filter	27.5 (radius)	25 (radius)	23	23	27.5 (radius)	25 (radius)
Front Fuselage LCD Cooling Filter (Type one- P621895)	7.48 ± 0.03	6.96	0.11± 0.03	0.01	4.62 ± 0.06	2.85
Front Fuselage LCD Cooling Filter (Type two- P621888)	7.57± 0.03	6.96	0.11± 0.03	0.01	4.62 ± 0.06	2.85
Cabin Air Recirculation Filter	6.25 (radius)	-	13.50	-	6.25 (radius)	-

Notes: Flow direction is along y axis for all three types of filters

2.0 Proposed Design

The proposed pressure drop monitor was selected by using a pairwise comparison and weighted decision matrix system, originally developed in the Initial Proposal (decision system in [Appendix A]). The pairwise comparisons and weighted decision matrices were used to determine each design's ability to meet the design project objectives outlined in Section 1.5. The design's modular components prove the high portability of the design, while the adapter system allows for multiple filter types to be quickly tested, leading to a much-improved ease of use.

Implementing the pressure drop monitor design requires recreating a testing environment identical to the parameters specified in Section 1.7.5. The air pump system is intended to recreate the filtration systems as found on the aircraft of installation. Adapters specific for each filter shall be used to mount the respective filters to the design (see drafts for adapters for Aft Safety Valve filters and LCD filters in Figure 4.a-4.c below. The filters are easily placed inside the adapters and are secured with bolts.

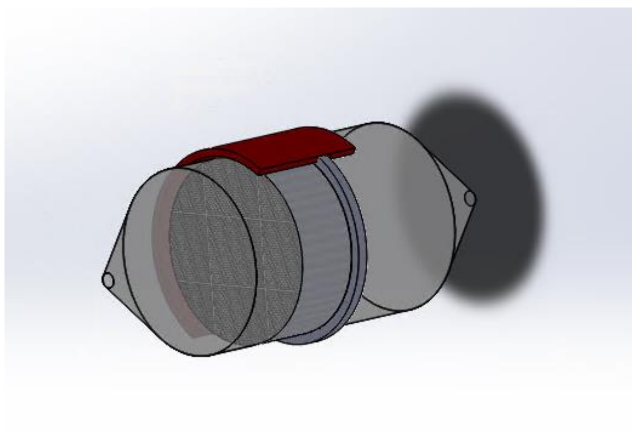

Figure 4.a: adapters for Aft Safety Valve filter

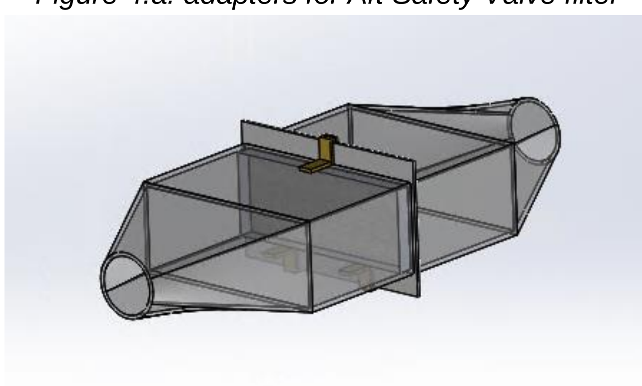

Figure 4.b: adapters for LCD filters

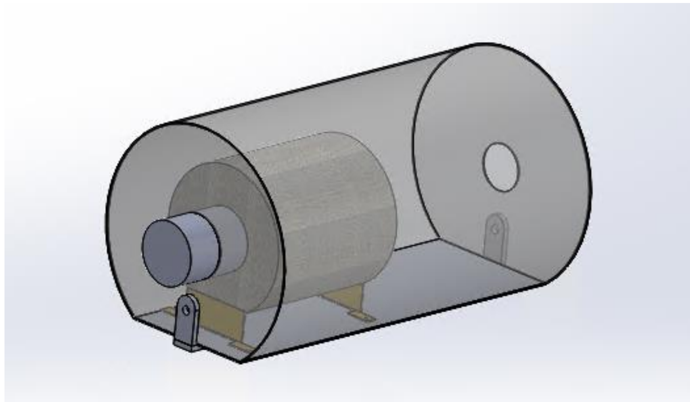

Figure 4.c: adapters for Cabin Air Recirculation Filter

For the Cabin Air Recirculation Filter, since the outlet air flows in the axial direction, a chamber is designed to contain the filter and the pressure drop is then the difference between the pressure inside the chamber and the pressure upstream from the filter.

Testing equipment to monitor the pressure and volumetric flow rates will be installed in the design, before and after the filter. A piping and instrumentation diagram for the design is shown in Figure 5 below.

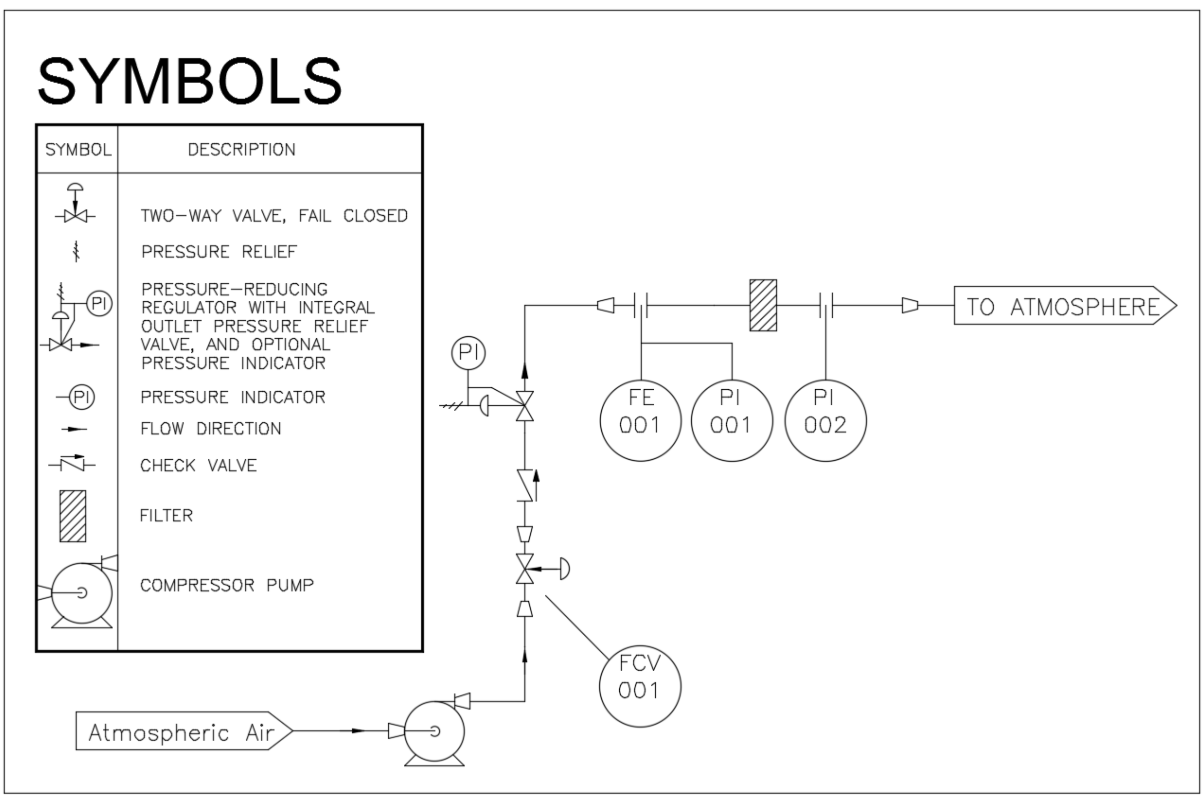

Figure 5. Piping and instrumentation diagram, proposed design.

As shown in the P&ID, the filters to be tested will be installed in the design. All three types of filters will be tested using different adapters custom-made for this design. A compressor pump is used to push the whole system. A flow control valve and a pressure-reducing valve are used to control the volumetric flowrate and the pressure upstream of the filter, according to the testing environment specified in Section 1.7.5. The pressure reducing valve is used to deal with the risk that air flow downstream pressurized by the compressor. After the air flow rate is stabilized and the pressure become steady, which can be read from the flow element and pressure indicator, the readings in the two pressure indicator upstream and downstream the filter show the pressure drop interested.

To ensure a safe operation environment, a pump trip is installed in the system. Intensive pluggage inside of testing filter or uncleaned adapters could cause the high high pressure drop across the testing filter (HH). If the pressure drop across the filter is too high, the pressure control loop will automatically shut down the pump, which could protect the compressor pump from damage due to overheating. Loose connections or flow meter failures could cause the low values shown on flow indicators. The flow control valve will be closed and tripped the pump to ensure an accurate testing results. After troubleshooting is completed, pump can be re-started manually by operator. An emergency shut down bottom is installed on the air pump.

2.1 Operational Principles

The operation of the pressure drop system is based on the principles of volumetric flow rate and relative pressure changes in a fluid system. A filter system's internal geometry will cause internal pressure and volumetric flow changes, due to kinetic energy changes inversely proportional to potential energy changes. This is the functional theory behind Bernoulli's principle, which is the primary factor governing the operation of this design for measuring the pressure drop.

The design assumes that the air is a compressible fluid moving at subsonic speeds, given the testing parameters outlined in Section 1.7.5 and the dimensions outlined in Section 1.7.6.

2.2 Preliminary Implementation Requirements

The Air Compressor (or the Blower) should provide a constant airflow across the filter. According to the Table 2 Input Parameters for Testing under Section 1.7.5, the minimum required airflow crossing the filter for testing process is 0.102 lb/min and the maximum required airflow is 57lb/min. When air is traveling through the pipelines and connecting joints, there will be a significant amount of pressure drop. Therefore, the capacity for this Air Compressor should be fit the following range: 0.1 lb to 114 lb of air provided per min.

Since the whole testing process is conducted at the ATM environment, the regular PVC tubes with standard size will be used to transfer the air from Blower to the adapter in where a tested filter will be placed. A tube Adapter is used to fit the tested filter. Since there are three types of filters with different dimensions (refer to table 3 under section 1.7.6) will be assessed, three adapters will be designed by the team.

Two pressure gauges will be installed before and after the filter to minor the pressure changes. Two flow meters in the system (one is installed right after the Blower, the other one is placed before the tested filter) to adjust and maintain the required flow rate (refer to section 1.7.5).

The air pump, connecting tubes and all other instruments can be purchased from local store by the Client. The user must assemble the Modular Filter Pressure Drop Tester as per the design manual.

2.3 Preliminary Economics

The design is composed primarily of a series of off-the-shelf and custom parts. Custom parts are to be constructed out of stainless steel [7]. The off-the-shelf components for the design were chosen for their generic specifications and ease of replacement and maintenance. These components are shown in the table below:

Table 4: Table of Required Off-The-Shelf Parts and Estimated Costs

Section	Item Description	Quantity	Picture	Operating Condition	Estimated Cost (each)
Air source	Standard rectangular blower	1		Maximum airflow rate: 1000 CFM	$397.27
	Pump-adapter duct	1		2” outer diameter; 5’ long	$22.42
	Flow adjustment valve	1		2” outer diameter; HVAC butterfly valve	$185.25
Testing chambers	Anemometer	1		Range: 100-5500 CFM	$116.94
	Pressure gauge - basic [11]	1		Connection size ¼ Range: 0-15 psi	$11.55
	Pressure gauge - accurate [12]	2		Range: 0-30 ps; 0.01 psi resolution	$92.60
Safety	Safety Relief valve [13]	1		Connection size: ¼ Range: 25-200 psi	$5.88
Other	Seal materials/ Connection units	various	---	---	$75
				Total (13% Tax Rate)	**$1,129.45**

The filters to be tested are specific to Bombardier Inc. planes, thus there are no commercially-available filter adapters. Any fittings or adapters need to be custom made and compatible with the off-the-shelf parts listed above. The following custom components and their respective material costs are listed in the table below:

Table 5: Table of Custom Components and Estimated Material Costs [7]

Section	Item Description	Quantity	Dimensions	Manufacturing	Estimated Cost (each)
Cabin filter adapter	Filter adapter fitting	2	50” diameter, 36” long	Rolled 304 stainless steel; welded into cylinder	$259.20
	Flat adapter end	2	50” diameter, 24” long	Stamped 304 stainless steel; clamped onto filter adapter fitting	$86.40
Aft safety filter adapter	Filter adapter fitting	2	50” diameter, 36” long	Rolled 304 stainless steel; welded into cylinder	$259.20
	Tapered adapter end	2	50” diameter, 24” long	Stamped 304 stainless steel; welded into cone	~$400
LCD filter adapter	Filter adapter fitting	2	7.50” wide, 6.48” tall, 30” long	Stamped & pressed 304 stainless steel; welded along seam into box shape	$49.74
	Tapered adapter end	2	4.2” wide*tall (narrow end); 7.50” wide * 6.48” tall (broad end)	Stamped and pressed 304 stainless steel; welded along seam; clamped to filter adapter fitting	$49.74
	Flat adapter end (for duct)	2	4.2” wide*tall	Stamped 304 stainless steel with removed hole	$13.17
				Total (13% Tax Rate)	**$2,525.44**

The custom component costs are taken as the semi-finished material costs, as the components must then be welded or folded to their final shape. Individual component costs are taken as the semi-finished material costs before labor.

2.4 Preliminary Life Cycle & Environmental Impact

Considering a large amount of air filters are installed every year, recycling or disposing them would be a problem [15].

There are three main components for a typical air filter: filter media, cardboard and metal. Each of those elements have its own recycling methods. However, it is not easy to separate those elements in a cost-effective manner [16]. Disposing the used air filters in the landfill will have a negative impact as it leads to greenhouse gas emission [16].

According to the Q400 Maintenance Packages, a typical Front Fuselage LCD Cooling Filter has a 1000 FH lifetime with a view to evolve to 1600 FH or higher and the current lifetime for a Pressurization Control Aft Safety Valve Filters is less than 4000 FH (but with a view to be evolved to 4800 FH or higher)[1][2]. As for the Cabin Air Distribution Recirculation Filter, a typical filter is discarded at the 5000 FH and the Client wanted to assess if it can last 5600 FH or higher[3].

By assessing the filters remaining lifetime and extending the current filter's operating hours, the frequency of air filters replacement can be reduced, which helps lower the negative environmental impact.

With the proper maintenance program implemented (refer to section 2.5), this Modular Filter Pressure Drop Tester could last about 15 years.

2.5 Preliminary Human Factors & Operational Method

The buddy system must be used during the testing process to ensure the safe operation. The adapter should be light enough to be lifted, moved or held by maximum two operators. The total weight of a single adapter should be less than 50 kg based on the ISO Standard 11228 Part 1 [17] to meet the objective - portability. Handles are available on the adapter as part of inherent design. The operator can easily compare the pressure drop in inches of water (WC) and filter failure criteria (refer to section 1.7.5), using both pressure gauges installed in the system.

The air compressor and connecting tubes should be inspected at regular time intervals to prevent any gas leakage [18]. Instruments such as pressure gauges and flow meter should have visual inspection prior to each testing, and then after each run, the adapter should be cleaned by flashing the dry air and examined thoroughly to ensure the accuracy of testing results. The detailed maintenance plan has been shown in the Table 6. The operator/user shall assemble and connect the parts as per the design manual.

Table 6: Scheduled Maintenance Plan [20]

Procedure	Daily	Weekly	Monthly	Annually (200 hours)
Check pump oil level	X			
Oil leak inspection	X			
Check for weird noise and vibration	X			
Inspect all air leaks	X			
Inspection belts	X			
Check air filters, clean or replace		X		
Check safety relief valve			X	
Check belts if necessary			X	
Check and tighten all bolts			X	
Check connections for leaks			X	
Service pump or engine				X
Testing the Control System			X	

2.6 Revision Plan

This section focuses on the testing of the objectives in Section 1.5 to demonstrate that the recommended design is successful and best meet these essential objectives. The objectives are to reduce the operating time and devices weight.

The phase of the project following the design proposal involves the initial development of a physical design prototype. The client, Bombardier, will provide a series of filters, as outlined in Section 1.7.4. The operating procedure is as discussed in Section 2.1. The time for stabilizing the flow as well as the time takes to change the filters (which need to partly disassemble and device and reassemble it) will be measured and compared with that of the apparatus the client is currently using. The weight of the disassembled components will also be measured.

3.0 Design Review And Critique

The original proposed design was developed as the minimum viable product that would satisfy the project's functional requirements. All iterations of the design were developed to consider stakeholder interests, while complying with the design constraints. Thus, each iteration has been developed in order to better satisfy the design objectives and respective stakeholder interests. Sections 3.1-3.3 will detail the previous design revisions, and will present the timeline for planned future updates.

3.1 Design Updates

Several updates were made to the original design to better comply with stakeholder interests and satisfy the design objectives. The updates and their respective definitions have been outlined in the table below:

Table 7: Table of Design Updates with Cause for Update and Effects

Design Update	Cause for Update	Effect
Removal of plate metal used for filter adapters	Mass of adapter too high, extra strength not required	Reduced adapter mass; Cost savings of $1,525.50
Changing the design of LCD filter adapter	Previous design did not have fully developed airflow through the filter	Reduced design complexity
Replacement of single-stage blower for standard blower	Previous blower did not meet volumetric flow rate requirements; Redundant low-pressure/vacuum option	Increased max volumetric flow rate (31% higher than required max flow); Cost savings of $439.17
Removal of one anemometer	Redundant	Reduced design complexity; Cost savings of $1,058.65
Substituting analog anemometer to digital variant	Analog variant did not provide sufficient resolution	Increased ease of operation; Cost savings of $588.77
Substituting analog pressure gauges for digital variants	Analog variant did not provide sufficient resolution	Increased resolution to 0.01 psi in 0-15 psi range; Cost increase of $183.17

3.2 Safety Analysis and Fall Back Plan

For each major component of the design, we address the safety concerns with the following four steps: Identify the functions of the component in the design, identify the potential functional failures, identify the types, frequency and severity of the failure mode, then determine actions to take for improvement.

We use a risk matrix to identify the risk level of each failure mode. There are two dimensions to a risk matrix, as it analyzes the severity and likelihood of each failure. These two dimensions create a standard matrix. The combination of likelihood and severity will give any event a place on the risk matrix. The risk matrix can determine the size of a risk of each failure mode and be used as a tool for operator to decide the kind of risk control plan to choose.

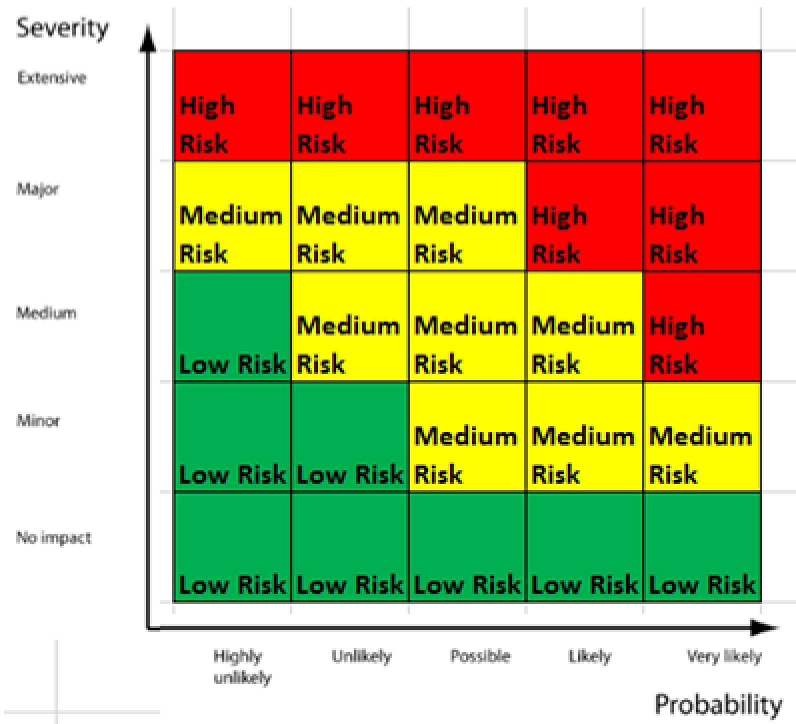

Figure 6: Risk Matrix

Table 8: Failure Mode and Effect Analysis of Pressure Gauges

Function of Pressure Gauge			Functional Failure	Failure Mode	Likelihood	Severity	Risk Level	Plan of Action
Location: Safety Valve Filter: To be able to read the air pressure before and after the filter, at a flowrate at 57 ± 0.5% lb/min at a pressure at 14.7 ± 1% psi and at the temperature of 27°C	Location: Cabin Air Filter: To be able to read the air pressure before and after the filter, at a flowrate at 57 ± 0.5% lb/min at a pressure at 14.7 ± 1% psi and at the temperature of 27°C	Location: LCD Cooling Filter: To be able to read the air pressure before and after the filter, at a flowrate at 57 ± 0.5% lb/min at a pressure at 14.7 ± 1% psi and at the temperature of 27°C	No readings on the pressure gauges.	Vibration effect during the operation	Very likely	Medium	High risk	Use of Liquid -filled gauge to reduce the vibration effect
				Extreme high operating temperature	Unlikely	Extensive	High risk	Installation of Temperature sensor and High temperature alarm
				Overpressure	Unlikely	Extensive	High risk	Installation of pressure relief valve
				Corrosion	Highly unlikely	Medium	Low risk	Installation a separator pre-filter to ensure corrosive media doesn’t enter the system
				Not properly installed	Likely	Minor	Medium risk	Training program and procedure booklet

			Readings on the pressure gauges are not able to read.	Pulsation effect	Very likely	Minor	Medium risk	Use of Liquid -filled gauge to reduce the pulsation effect
				Clogging in the gauge	Likely	Medium	Medium risk	Implementing a maintenance schedule for the gauge

Vibration effect:
Many pieces of equipment vibrate. Excess vibration can result in pressure gauge failure. It's very likely that vibration effect will happen during the operation process. For both digital or dial gauges, it's critically important to ensure the pressure gauge is not affected by vibration.

Action Plan: The fallback plan for this is to use liquid-filled gauge that can resist more vibration and pulsation during operation.

Extreme High Temperature:
Extreme high operating temperature can cause sweating and loosening in the metal joints and eventually cause the pressure gauge breakdown. The operation temperature is at 27°C. It's unlikely to have extreme high temperature during operation. However, the consequence is extremely severe if this happens. This is a high risk failure mode.

Action Plan: Temperature sensor and high temperature alarm are recommended to be included in the design.

Overpressure:
Overpressure will cause the pressure exceeding the pressure limit of the gauge, which will cause it to break down eventually. Similar to the risk of high temperature, it's unlikely to have overpressure issue in the system. The operating pressure is atmosphere pressure. However, the consequence of overpressure damages the instrument and other equipment.

Action Plan: This is a high risk. A safety relief valve is recommended to be included in the design.

Corrosion:
Highly corrosion media in the operation process will damage the sensing material in the gauges. The media flows through the system is air. Therefore, it is highly unlikely to have corrosion problem for the design. If corrosion happens, the severity will be medium.

Action Plan: A separator pre-filter can be installed to eliminate this risk.

Not properly installed
If the pressure gauges are not proper installed in the design system, it may not provide any readings due to pressure leakage. It's likely that the system is not properly assembled. This is a minor risk.

Action Plan: A proper training for the maintenance trade and a detailed installation procedure booklet can be used to prevent this.

Pulsation:
A rapidly cycling medium within a pressure system can make a gauge pointer move erratically

and eventually can lead to breakdown of internal part. It is also highly likely to have turbulent flow within the chamber. These effects would results in unstable readings on the gauges.

Action Plan: This is a medium risk and can be prevented by using fluid-filled gauge.

Clogging:
If the medium that contains materials that are viscous, it can clog the pressure gauge and make the readings unreliable. This is a medium risk due to the likelihood and severity.

Action Plan: The fallback plan for this can be implementing a regular maintenance schedule to check the working condition of the pressure gauges. If there is any sign of clogging, the pressure gauges need to be take apart for cleaning.

Table 9: Failure Mode and Effect Analysis of Chambers

Function of Chamber			Functional Failure	Failure Mode	Likelihood	Severity	Risk Level	Plan of Action
Location: Safety Valve Filter: To be able to isolate the Safety Valve air filter from the environment, at the air flowrate at ± 0.5%lb/min at a pressure at 14.7 ± 1%psi and at the temperature of 27°C	Location: Cabin Ari Filter: To be able to isolate the cabin air filter from the environment, at the air flowrate at57 ± 0.5% lb/min at a pressure at 14.7 ± 1% psi and at the temperature of 27°C	Location: LCD Cooling Filter: To be able to isolate the LCD cooling air filter from the environment, at the air flowrate at 57 ± 0.5% lb/min at a pressure at 14.7 ± 1%psi and at the temperature of 27°C	Chamber leakage	Seal problem caused by over temperature, pressure or flowrate	Very likely	Minor	Medium Risk	A regular maintenance check on chamber and a training program for the operators.
				Sheet metal broke	Possible	Major	Medium Risk	
				Not proper installation	Unlikely	Major	Medium Risk	
			Chamber broke	Damage caused during transportation	Likely	Major	High Risk	Safety Storage Box for the design

Seal Problem:
Seal problem is the most common cause for chamber leakage. It can be caused by over pressure, high temperature and high flow rate. It can also be caused by not properly use of the seal during installation process. This is a medium risk failure mode.

Action plan: a regular maintenance check for leakage on the chamber is recommended.

Sheet metal broke:
The chamber is made of sheet metals. A broken sheet can cause the leak of the chamber. The broken piece can potentially cause the injury of the operator and have other potential risks to the public, therefore the severity level is high. The overall risk level is medium.

Action plan: broken sheet metals can be caused by variety of reasons. A regular maintenance check is recommended to prevent this failure mode.

Not properly installed:
If the chamber is not properly installed, it will cause air leaking in the chamber. This is unlikely to occur, because the design team will have an installation menu for the operator. However, if the chamber is not properly installed, the leakage could lead to the break of the chamber..

Action plan: besides the regular maintenance check on the chamber, all the operators are recommended to be trained on the installation of the chamber.

Transportation:
The chamber can be damaged during the transportation. This is likely to occur, since the chamber will be carried on the plane. There is a major consequence of this failure mode, because it can cause permanent damages to the design product.

Action plan: a safety storage box is recommended to reduce the risk of this failure mode. The inner side of the safety box will be attached with foams in order to reduce the effect of external force.

3.3 Construction Plan

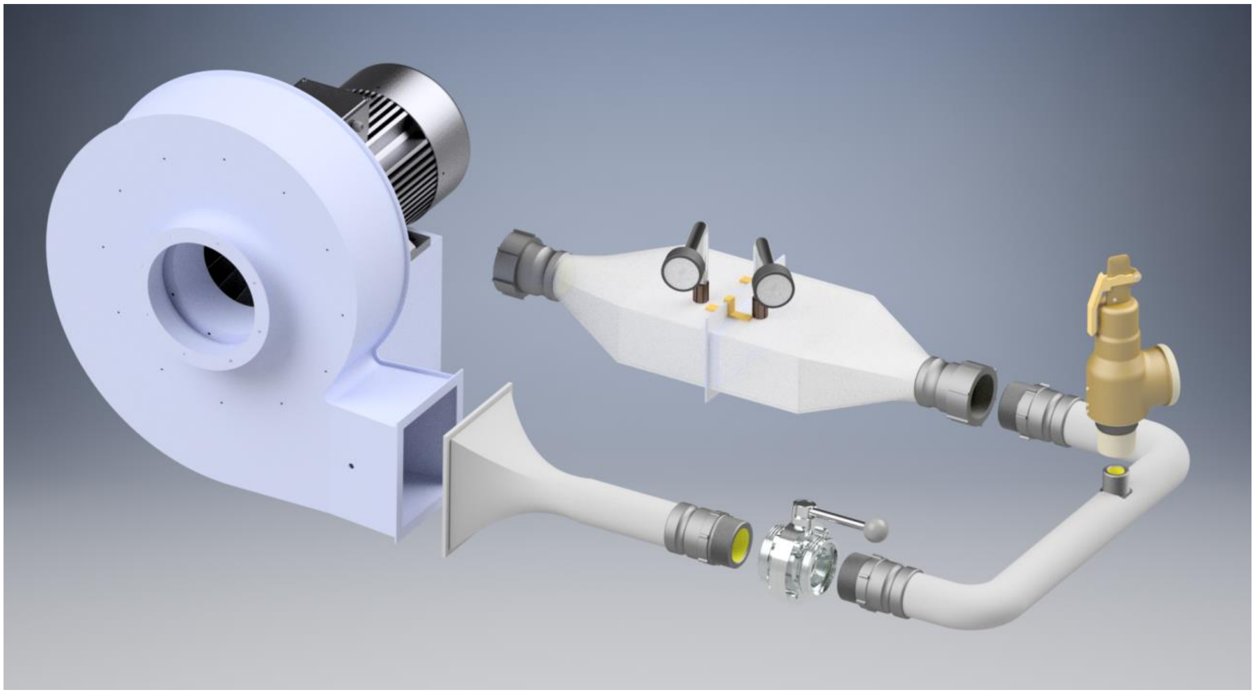

Figure 7: Scaled CAD model

The design has been developed to allow for ease of replacement by the use of standardized components for ease of replacement and repair. Custom components are primarily stainless steel, which requires welding to complete their preparation into finished products. Any welding is assumed to be using 308L stainless steel filler for preventing excessive thermal expansion and maintaining a low carbon content, ideal for welding.

Shaping the metal for folding and bending can be done via standard press brake forming tools, or the use of air bending. Curved adapter ends such as those included with the aft safety valve filters can be prepared using tapering rolls to achieve a conical shape for welding.

Completed custom components can then be joined together by the use of bolts and clamps, while filters can be placed into the custom adapters and sealed via the same bolting and clamping mechanisms. Filters are additionally sealed by the use of rubber gaskets between the stainless steel adapter and filter, in order to prevent air leaks.

Off-the-shelf parts have been selected to use a standard duct diameter of 4” and can be connected by the use of generic pipe fittings.

The dimensions of the filters and the exploded views of all adapters are shown below:
Dimensions of Adapters

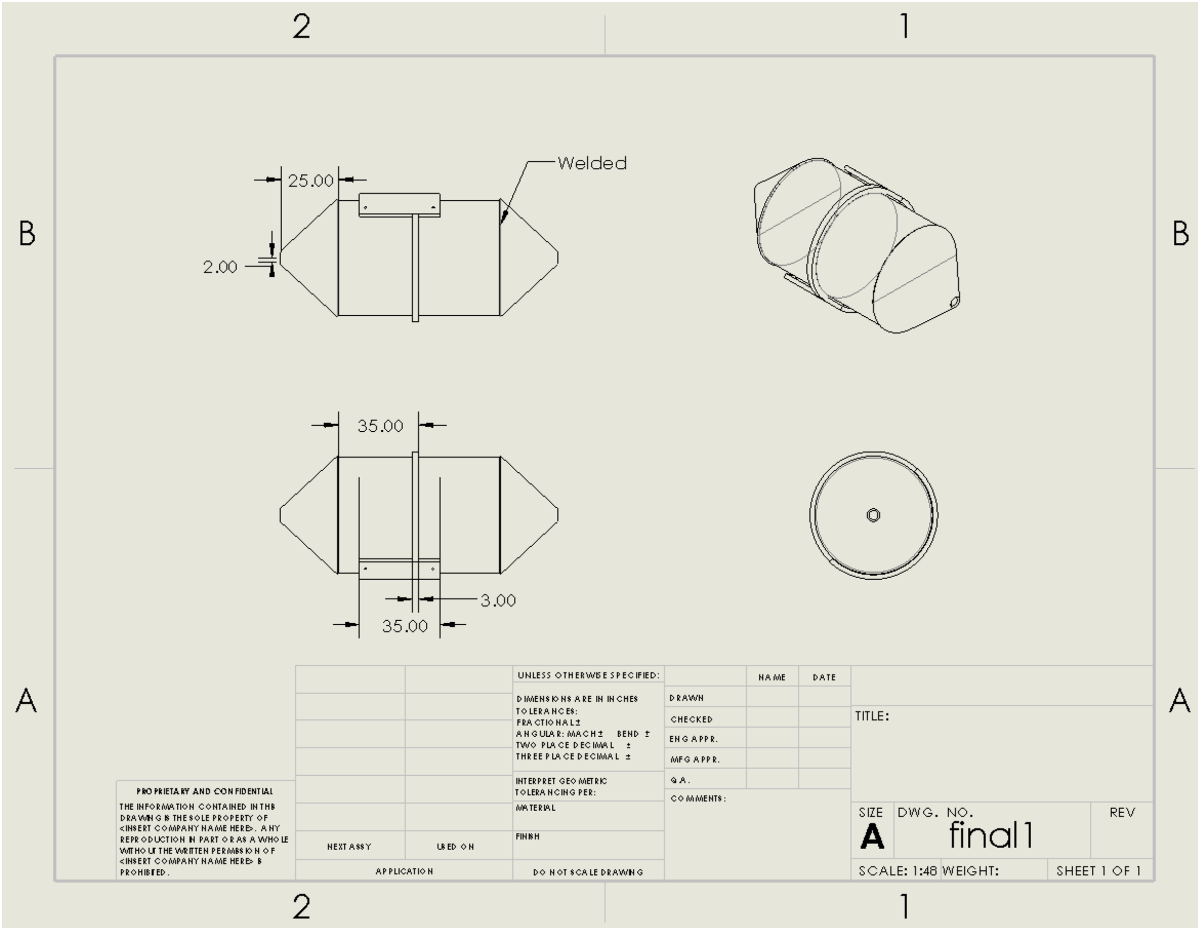

Figure 8.a: Dimensions of Safety Valve Filter Adapter

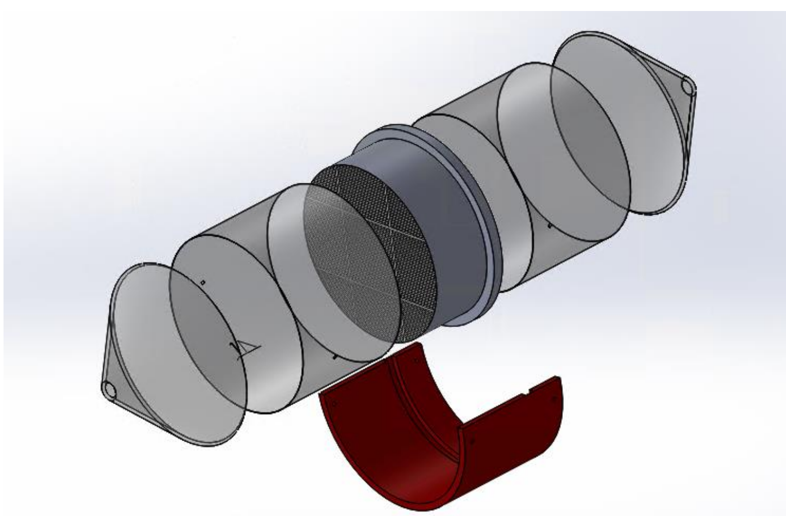

Figure 8.b: adapters for Aft Safety Valve filter

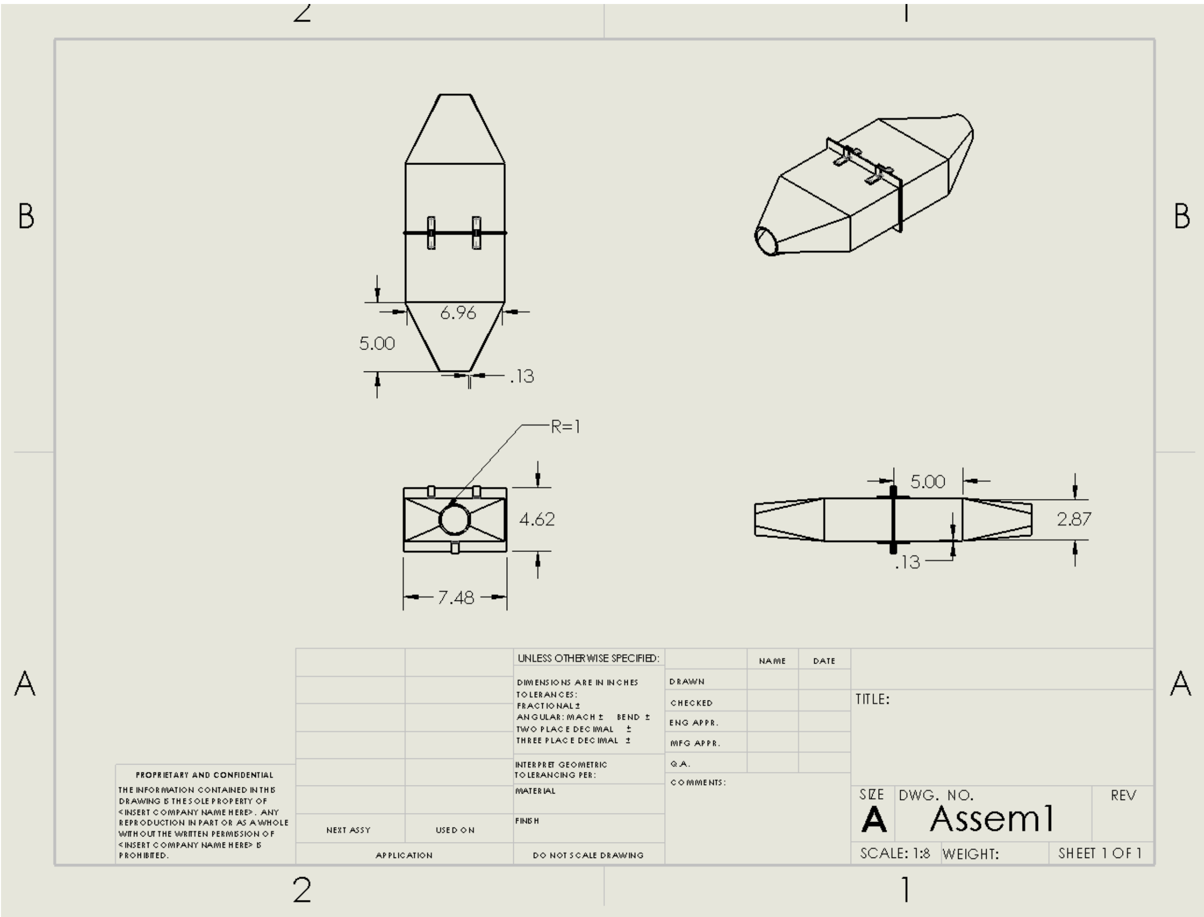

Figure 9.a: Dimensions of LCD Filter Adapter

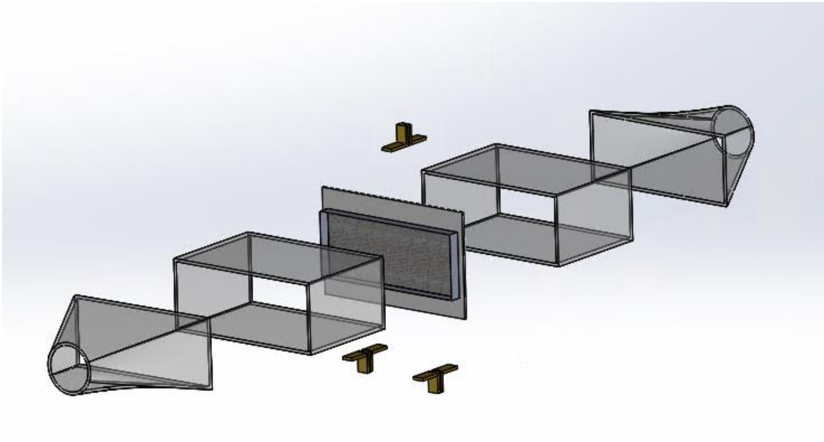

Figure 9.b: adapters for LCD filters

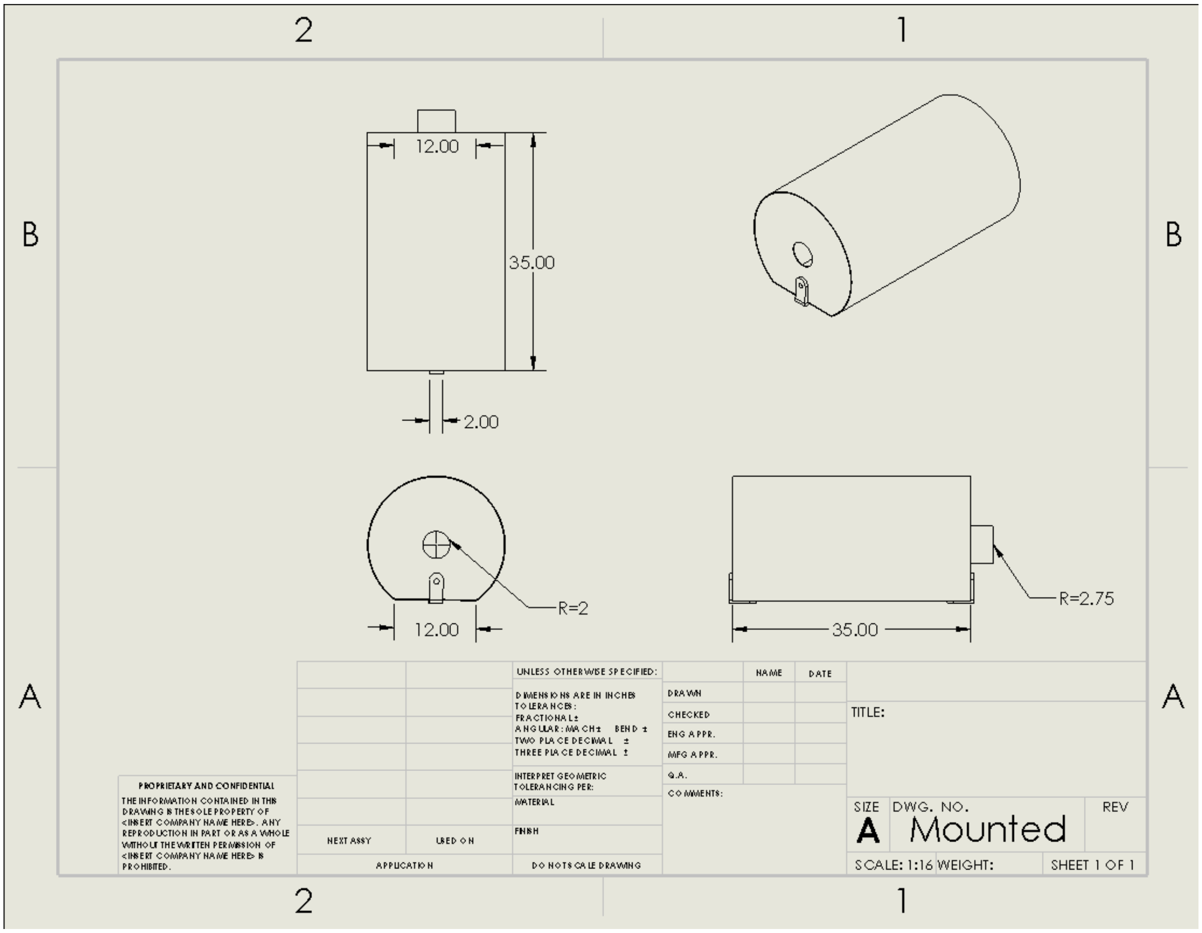

Figure 10.a: Dimensions for Cabin Air Recirculation Filter

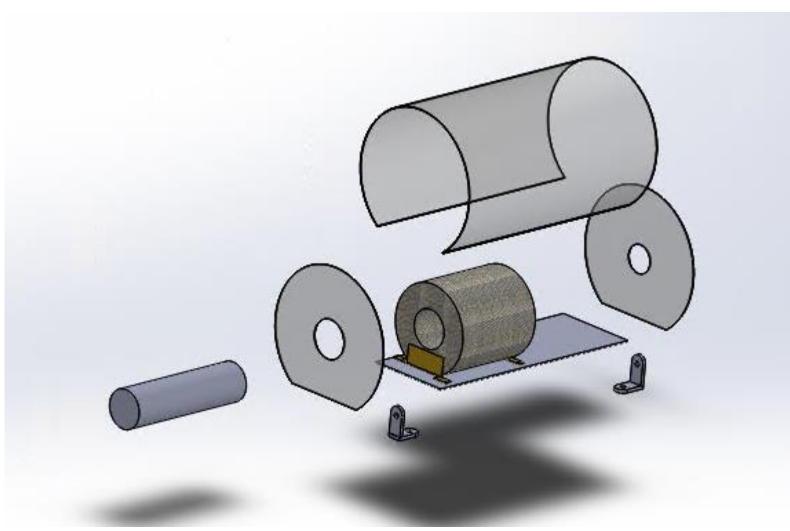

Figure 10.b: adapters for Cabin Air Recirculation Filter

3.4 Computational Fluid Dynamics Analysis

Since the adapter systems in our design requires are custom made for the filters, CFD analysis is carried out to verify the feasibility of the adapters. The simulation of the whole system can help to make sure the airflow inside the adapters before the filter is fully developed, stabilized, with negligible pressure gradient in the radial direction and also meet the mass flow rate requirement specified by the testing environment. The following shows the details and results of the CFD analysis.

The figure below shows the volume of upstream part of the system from the outlet of the compressor to the adapter before the filter (using LCD cooling filter as an example). The rectangular surface on the right is the inlet surface of the simulation model which represent the outlet of the compressor. The boundary condition is set by the performance curve of the compressor (provided by the manufacturer). The surface on the left represent the outlet of the simulation model and is a cross section of the adapter. The boundary condition is set by the mass flow rate specified by the client (2.4lbm/min for LCD cooling filter). The initial condition of the inlet is the maximum pressure of the compressor and outlet, zero fluid velocity at atmospheric pressure.

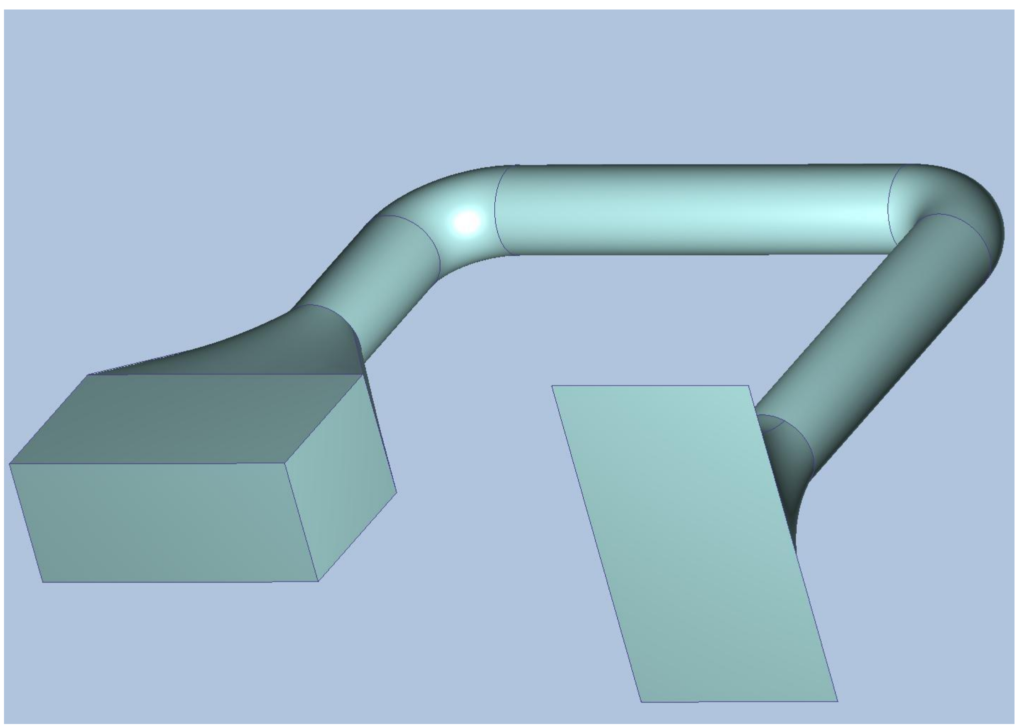

Figure 11: The volume of upstream part of the system from the outlet of the compressor to the adapter before the filter (for measuring LCD cooling filter).

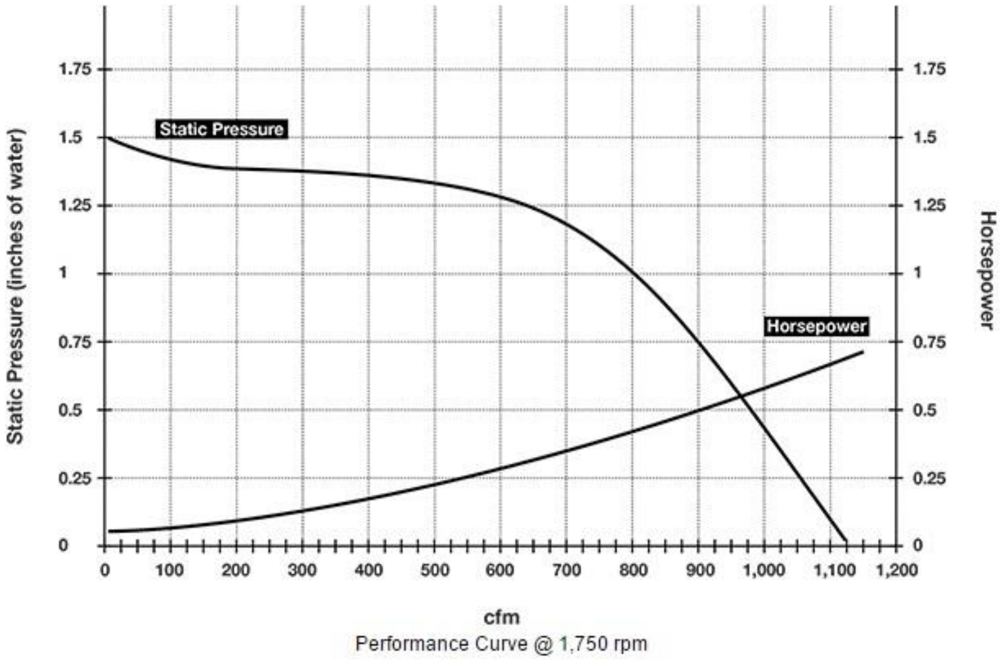

Figure 12: Performance curve for the compressor used as boundary condition for the inlet of the simulation model.

Results for LCD cooling filter

The simulation results for the LCD cooling filter is shown in the particle traces diagram below. All diagrams are plotted based on the steady state of the system. The plot visualizes the traces of fluid elements in the blue plane. According to this diagram, there is little backflow and turbulence in the adapter which shows that the flow in the adapter is fully developed and stabilized.

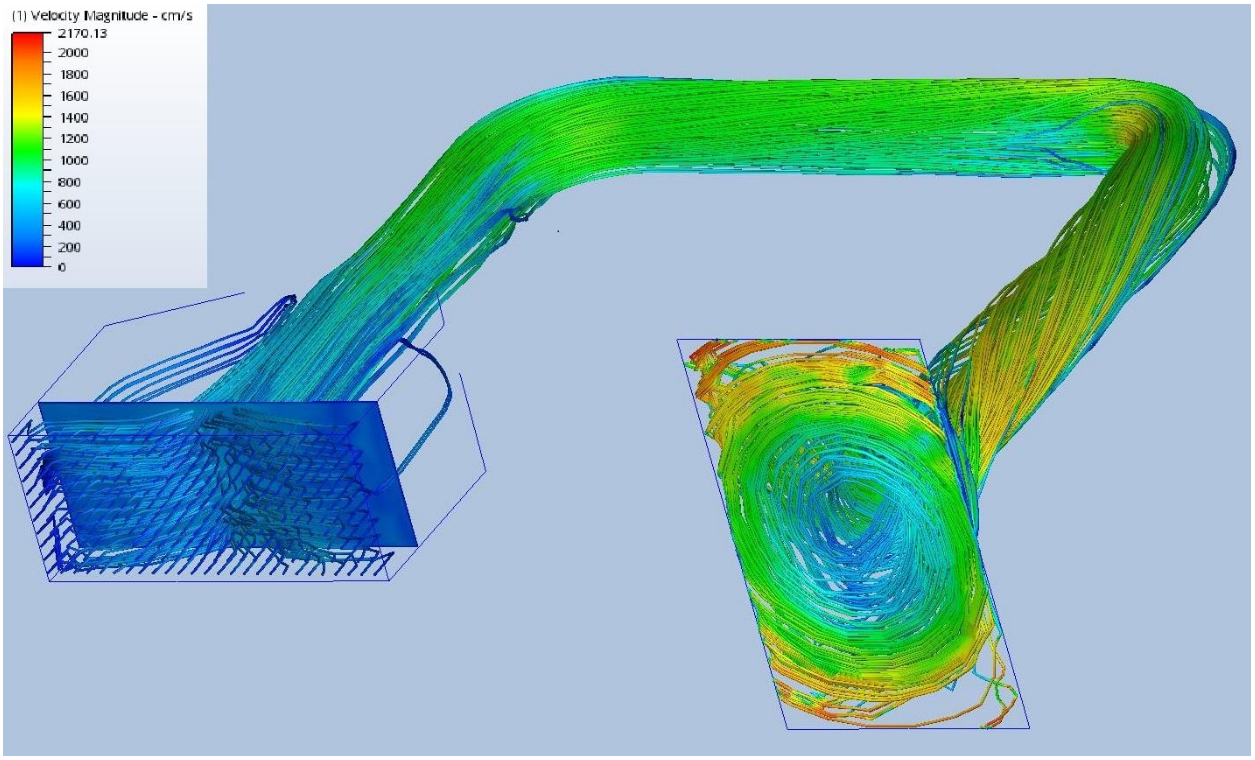

Figure 13: particle traces diagram showing the traces all fluid elements in the blue plane. (Little backflow and turbulence shown.)

The velocity vectors at the outlet of the system also shows that the velocity gradient is negligible and the flow before the filter is stabilized.

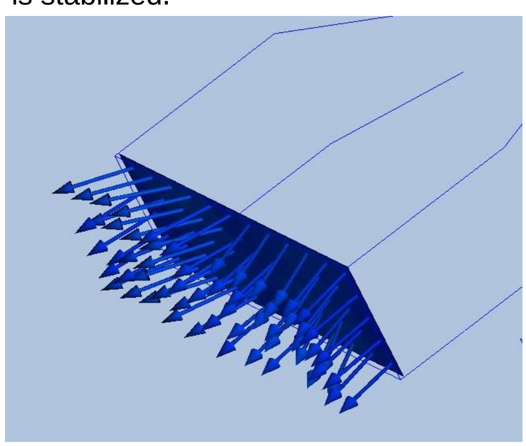

Figure 14: Velocity Vectors of the fluid element at the outlet of the adapter.

The average pressure at the outlet and inlet of the system under steady state is also calculated through the simulation. The pressure at the compressor's outlet is 15.0 psi and the pressure before the filter is 15.2 psi. The system is assumed to operate under the maximum output of the compressor. Therefore, adjusting the flow control valve and pressure reducing valve will allow users to regulate the pressure to 14.7 psi and mass flow rate to 2.4lbm/min as specified by the testing environment.

Therefore, it can be concluded that our system will perform well in measuring the pressure drop across the LCD cooling filter.

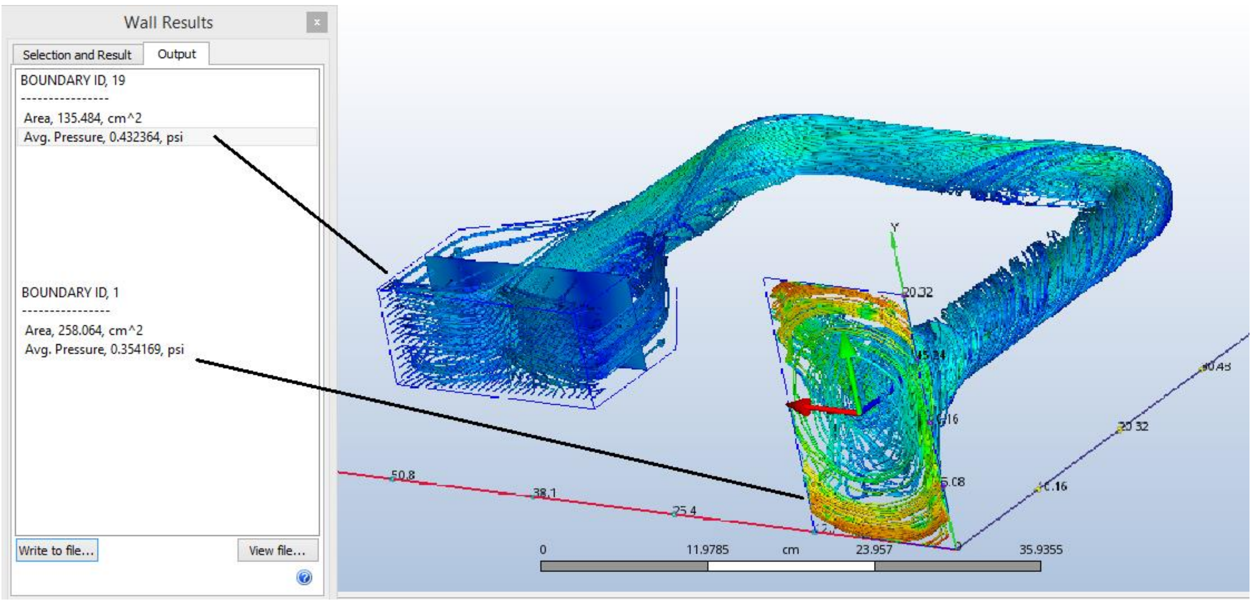

Figure 15: Wall calculation of the inlet and outlet surfaces of the simulation model in the Autodesk CFD software.

4.0 Updated Project Management Plan

This section will display detailed tasks in our project that correspond to different time period and explain our strategies to make the project both cost and time efficient. Detailed tasks and timeline of the project are displayed in the Gantt Chart (Appendix C; Figure C.1) In order to summarize the entire project, milestones are displayed in the aforementioned Gantt Chart which includes all important activities for all three periods.

4.1 Future Plan

This section focuses on the changes that may be made as we move on to the details of the design. The modification will probably be made for safety and convenience reasons.

- Pressure Profile, Velocity Profile and Momentum Profile should be completed and finalized in order to start to build the physical design prototype
- Optimizing the pressure profile will improve the efficiency of the system. Simulating the flow profile would allow the team to verify if there is the significant turbulent flow occurred in the system that need to be avoided. By increasing the length of adapter or modifying the shape of adapter, the turbulent flow effect could be minimized.
- The dimensions of adapters may be modified based on those quantified calculations
- The control valve used to adjust the volumetric flow rate in the system is not the typical arrangement generally used as shown in the figure below. The drain valves, block valves and the bypass designed for safety is removed for this design because the testing environment is under standard air pressure and room temperature, and the fluid in the system is atmospheric air. As we start to test our design, more fluid components may be added for better control.

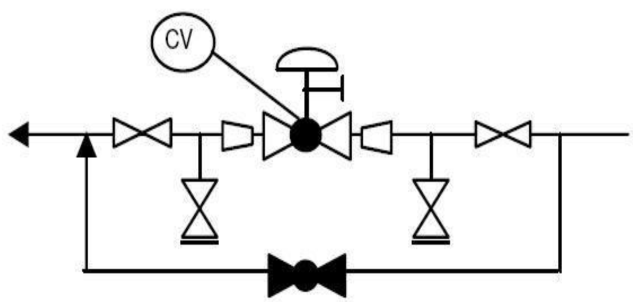

Figure 16: Generally used control valve arrangement [19]

- The arrangement of the pressure reducing valve may also be changed if the stabilization of the flow takes too long.
- The shape of the adapters designed for each filters may be changed, if necessary, in order to achieve a smaller pressure gradient near the filter. Therefore, the testing results will be more accurate and reliable. For example, a hole-structured plate may be installed inside the adapter to minimize the turbulent flow effects.
- Since the CFD analysis results for the safety valve filter are not as good as those of the other two types of filters. This is because the safety valve filter is much larger in diameter and requires a higher fluid velocity. Therefore, we are working on adjusting the configuration of the adapters. We are also thinking about other possible solutions for example as shown in the following figure, a thin circular mesh plate can be placed at the inlet of the adapter to mediate the turbulence and pressure gradient. All possible solutions will be verified by the CFD analysis.

4.2 Contingency Plan

The nature of the project is sensitive to the requirements of several stakeholders, due to the joint ownership by Bombardier Inc. and the University of Toronto. Several possible operational and design risks have been identified, with the corresponding strategy for action outlined. However, the possibility of potential opportunities have been addressed as well. The respective contingencies are addressed in the table below.

Table 10: Table of Risks and Opportunities with Associated Strategies for Planning

Risk	**Probability**	**Time of Occurrence**	**Effects**	**Strategy**
Inadequate testing accuracy	Negligible	March - April	Postponed delivery and changes to projected cost	Ensure selected components meet minimum testing resolution
Insufficient client feedback	Low	Present - March	Expected project scope may change; Majority of design already complete	Maintain weekly correspondence and iteratively update design
Other schoolwork delays project	Low	Present - April	Insufficient time to analyze potential room for improvement	Utilize weekly meetings to schedule around incompatibilities
Opportunity	**Probability**	**Time of Occurrence**	**Effects**	**Strategy**
Successful operational simulation	Moderate	Present - March	Reduced time required for design revisions; Delivery date moves ahead	Use existing CAD models for CFD simulations; Test design setup to optimize placement of chosen parts

Any possible functional failures may have effects on the safety of operation of the design. These issues and fallback plans are detailed in Section 3.5.

5.0 References

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Appendices

Appendix A - Decision-Making Methodology

This appendix details the decision-making method for selecting the final design from the options proposed in sections 2.1-2.4. The final design was selected by first ranking the project's objectives by importance, using a pairwise comparison table (Appendix A, Figure 1). Next, using a weighted decision matrix, the objectives were given an importance weighting based on their rank from the pairwise comparison (Appendix A Figure 2). Each design was then evaluated for how well it could meet the objectives, with a 100% score indicating complete satisfaction (Appendix A, Figure 3). Finally, each design's evaluation score was multiplied by the objective weight to determine the overall success of the design, quantifying the modular filter pressure drop monitor as the final design.

The pairwise comparison chart compares two objectives based on their relative importance to the project, versus each other. The more important objective is awarded a point (1), while the less important objective is awarded none (0). Once all objectives have been compared, the total score is tallied up, and then the ranking of importance for the objective can be determined.

Figure A.1 - Pairwise Comparison Chart for Design Objectives

	Objectives	Easily adjustable for various filters	Portable	Easy to use	Low cost	Objective Score
1	Easily adjustable for various filters		0	0	1	1
2	Portable	1		1	1	3
3	Easy to use	1	0		1	2
4	Low cost	0	0	0		0

For this table, we compare the four objectives with each other. Each objective is assigned with a number. For example, objective 1 is easily adjustable for various filters and objective 2 is being portable. The more important objective between each two objectives will be recorded on the table. The objective score indicate the numbers of each objective appears on the table. From the figure we can see that being portable is the most important objective among all the four objective.

The objective weight for each respective objective was determined by the rank determined in the pairwise comparison from Figure A.1. Then, based on the willingness to compromise between objectives, the weighting of each objective could be determined. Higher ranks will maintain higher weights, while lower weights indicate how willingly a client may sacrifice features of the design. See Figure A.2 below:

Figure A.2: Objective Weight For Each Objective

Objective	Rank	Weight
Portable	1	45%
Easy to use	2	30%
Easily adjustable for various filters	3	20%
Low cost	4	5%
	Total	100%

Each design is rated based on how well it meets a particular objective. Complete, uncompromising satisfaction is rated 100, with zero satisfaction garnering a rating of 0. These ratings are theoretical and based purely on the information provided for this project. See Figure A.3 below:

Figure A.3: Design Objective Scoring Table

	Design 2.1	Design 2.2	Design 2.3
Portable	80	100	80
Easy to use	95	70	50
Easily adjustable	70	30	70
Low cost	60	80	30

The final score, and thus proposed design, is determined by taking the design's objective scoring from Figure A.3, and multiplying it by the respective objective weight from Figure A.2. This yields the weighted score, which can be used to determine a design's theoretical feasibility with regards to the design objectives. The following figure demonstrates that Design 2.1, the modular filter pressure drop monitor, is the ideal candidate for the project:

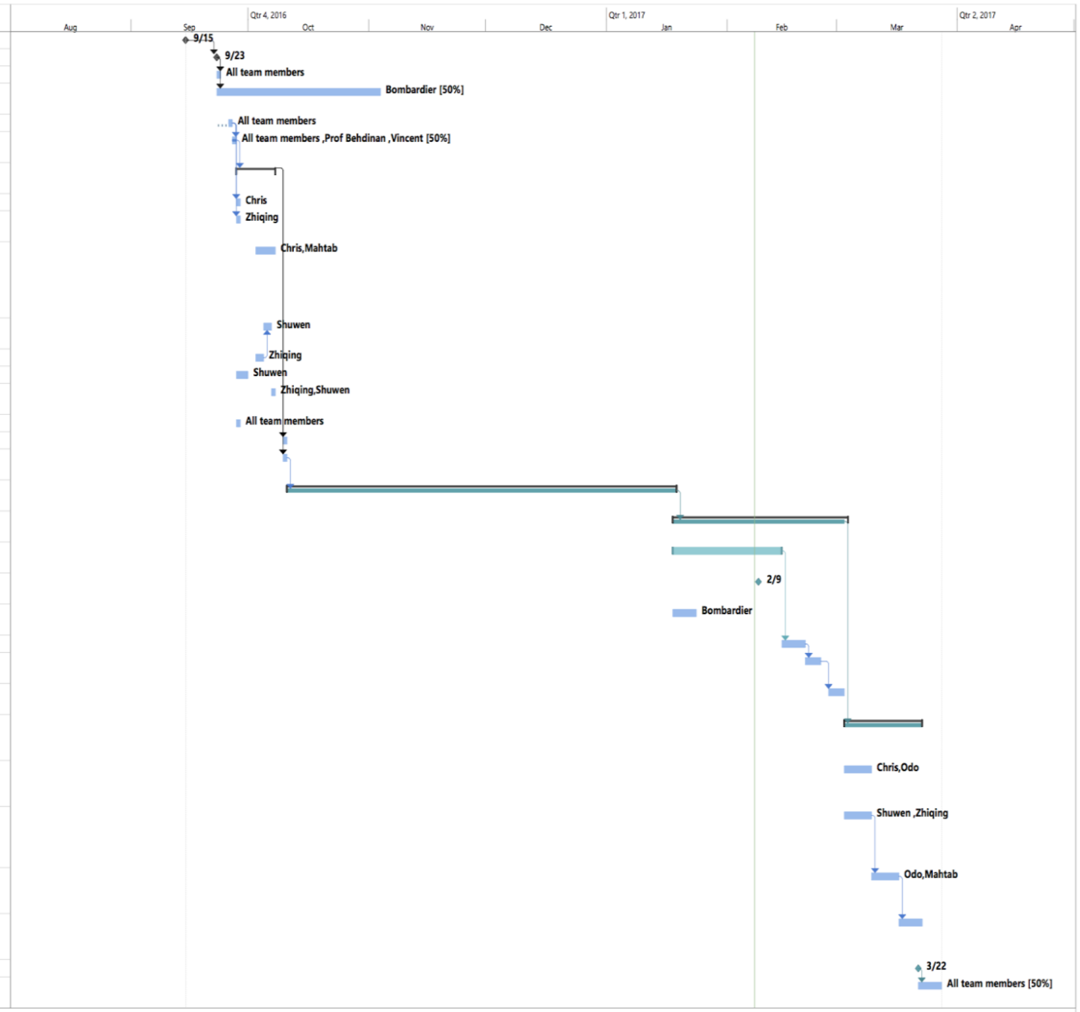
Figure A.4: Weighted Decision Matrix For Objective-Based Design Selection

	Design 2.1	Design 2.2	Design 2.3
Portable	80*0.45 = 36	100*0.45 = 45	80*0.45 = 36
Easy to use	95*0.3 = 28.5	70*0.3 = 21	50*0.3 = 15
Easily adjustable	70*0.2 = 14	30*0.2 = 6	70*0.2 = 14

Low cost	60*0.05 = 3	80*0.05 = 4	30*0.05 = 1.5
Total	**81.5**	**76**	**66.5**

Appendix C - Gantt Chart

ID	Task Mode	Task Name	Duration	Start	Finish	Predecessors
1		Project Kick-off Meeti	0 days	Thu 9/15/16	Thu 9/15/16	
2		Client Meeting	0 days	Fri 9/23/16	Fri 9/23/16	1
3		Define Project Scope	1 day	Fri 9/23/16	Fri 9/23/16	2
4		Filter Specs from Client	30 days	Fri 9/23/16	Thu 11/3/16	2
5		Draft Project Stateme	1 day	Fri 9/23/16	Mon 9/26/16	
6		Discuss the Project Statement	1 day	Tue 9/27/16	Tue 9/27/16	5
7		**Project Requirement**	**8 days**	**Wed 9/28/16**	**Fri 10/7/16**	**6**
8		Function	1 day	Wed 9/28/16	Wed 9/28/16	5
9		Objectives and Constrains	1 day	Wed 9/28/16	Wed 9/28/16	5
10		Project Plan and Deliverables (includes price quoting from manufactures/supp	5 days	Mon 10/3/16	Fri 10/7/16	
11		Tables and editing	2 days	Wed 10/5/16	Thu 10/6/16	12
12		Dimensions	2 days	Mon 10/3/16	Tue 10/4/16	
13		Project Manageme	3 days	Wed 9/28/16	Fri 9/30/16	
14		Service Environment	1 day	Fri 10/7/16	Fri 10/7/16	
15		Finalize the PR	1 day	Wed 9/28/16	Wed 9/28/16	
16		Final Version of PR	1 day	Mon 10/10/16	Mon 10/10/17	
17		Start to design the Prototype	1 day	Mon 10/10/16	Mon 10/10/16	7
18		**Prototype Design**	**72 days**	**Tue 10/11/16**	**Wed 1/18/17**	**17**
25		**Prototype Testing and improvement**	**33 days**	**Wed 1/18/17**	**Fri 3/3/17**	**18**
26		Prototype Construction	20 days	Wed 1/18/17	Tue 2/14/17	
27		Design Review and Critique	0 days	Thu 2/9/17	Thu 2/9/17	
28		Order filters from Client	4 days	Wed 1/18/17	Mon 1/23/17	
29		Prototype Testing	4 days	Wed 2/15/17	Mon 2/20/17	26
30		Prototype improvement	4 days	Tue 2/21/17	Fri 2/24/17	29
31		Prototype re-testing	4 days	Mon 2/27/17	Thu 3/2/17	30
32		**Simulation to get the pressure drop measurement**	**14 days**	**Fri 3/3/17**	**Wed 3/22/17**	**25**
33		Pressure drop measurement for safty valve filter	5 days	Fri 3/3/17	Thu 3/9/17	
34		Pressure drop measurement for front cooling filter	5 days	Fri 3/3/17	Thu 3/9/17	
35		pressure drop measurement for cabin filter	5 days	Fri 3/10/17	Thu 3/16/17	34
36		Performance Report / Final Report	4 days	Fri 3/17/17	Wed 3/22/17	35
37		Final Report Due	0 days	Wed 3/22/17	Wed 3/22/17	
38		Design Poster / Showcase	4 days	Wed 3/22/17	Mon 3/27/17	37



Project: Project1
Date: Wed 2/8/17

Task		Summary		Inactive Milestone		Duration-only		Start-only		External Milestone	Manual Progress
Split		Project Summary		Inactive Summary		Manual Summary Rollup		Finish-only		Deadline	
Milestone		Inactive Task		Manual Task		Manual Summary		External Tasks		Progress	

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