Undergraduate Thesis Final Report
Department of Aerospace Engineering
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Air Duct Performance & Air Quality Control

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10 April 2020

Abstract

This report focuses on improving the air performance and air quality of the Bombardier Global 7500. A test rig is designed and built, with the intentions of simulating the inlet ducting of the Global 7500. The performance of the test rig has been measured, and the ducting is prepared for testing. Preparations have been made to test the effect that various air outlets have on the performance of the ducting. The temperature can vary throughout the cabin, causing discomfort for passengers, it is possible that the inlet ducting is responsible for this. Additionally, the effect of numerous air pollutants has been explored and a focus has been made to test particulate matter and carbon monoxide. The Honeywell HPM Series and the Adafruit MiCS5524 have been suggested for detecting particulate matter and carbon monoxide respectively. The ducting designed can be used for various air performance and air quality research in the future.

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Acknowledgements

The author would like to thank Dr. Paul Walsh for his guidance and supervision during the course of the project. Dr. Jeff Xi for providing the opportunity to work on such a vast project where much was learnt. The engineering technical officer, Mr. John Karpynczyk, who was of most help when ideas had to be brought into reality. And Obidah Alawneh for providing support to the author whenever required.

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Nomenclature

CPSC	Consumer Product Safety Commission
EPA	Environmental Protection Agency
EPAAQ	Expert Panel on Aircraft Air Quality
IRC	Industrial Research Chair
OSHA	Occupational Safety and Health Administration
PM_X	Particulate Matter of diameter X in micrometers

I. Introduction

Business aircrafts are made with the purpose of safely and comfortably transporting small groups of people. Only few can afford the luxury of traveling in one of these aircrafts, so comfort is prioritized when designing a business jet. Improving design and pushing the limits of a business jet is a necessity for furthering aircraft capabilities. Military research has improved the performance of commercial aircrafts by implementing technologies that were created and perfected with military funding. Similarly, improving the comfortability of a business aircraft is not only to its own benefit, but for all passenger aircrafts overtime.

The IRC research project at Ryerson University has developed RS^4 with the intent of enhancing travel comfort in Bombardiers Global 7500 cabin (Xi, 2019). RS^4 stands for, reconfigurable cabin, smart seating, smart lighting, smart sound, and smart air, the focus of this paper will be on the smart air section. Smart air entails everything with the ducting and cabin air that can improve comfortability. With regards to smart air, Bombardier has suggested that the focus should be placed on temperature stratification and air quality.

Figure 1: Bombardier Global 7500

In this project a ground test unit was built, this is a duct system that represents the inlet ducts of a Global 7500. It is possible that the air outlets used in the Global 7500 may be effecting the temperature distribution and causing there to be hot spots and cold spots (Epp, 2019). As a result of the air outlets, the air duct may not be working to its maximum potential and causing inconsistencies when heating or cooling the cabin. The ground test unit will be used to test the effect that various outlets have on the duct performance.

When considering air quality there are four major air pollutants to regulate, ozone, particle pollution, carbon monoxide, and sulfur dioxide (EPA, 2014). For the purpose of this research, carbon monoxide and particle pollution will be considered. Although Ozone can be a problem on aircrafts, it is difficult to test for because it normally appears in small concentrations. Carbon monoxide can be dangerous if the cabin were to be exposed to it and on an aircraft there are many ways this can occur. Particle pollution is an even greater problem on business aircrafts than on commercial. There are much fewer regulations on a business aircraft, which allows the passengers to bring on pollutants that can harm each other and the crew of the aircraft. In the ground test unit, a filtering system will be tested to observe how effective it is at preventing harmful particle pollutants from entering the cabin. The filter system will be tested by allowing the smoke from a cigarette to enter the duct from the return of the air stream. Then, the concentration of carbon monoxide and particulate matter will be measured with and without the system. The desire for this project is for the duct performance and air quality research to bring additional comfortability to the Global 7500 cabin.

II. Design of Test Rig

a. Introduction

A test rig is designed with the purpose of carrying out as many experiments as applicable. In this case, the test rig is the ducting for the ground test unit. The ducting for the ground test unit is meant to simulate the supply ducts for the Global 7500. The Global 7500 has four separate supply branches, and air is supplied to the cabin from the bottom and returned at the top. In addition, the air ducts in the Global 7500 vary in shape, while on average having a hydraulic diameter of four inches (Epp, 2019). The discharge from which air is supplied to the cabin are piccolo holes. When designing the ducting for the ground test unit these were the main considerations. The piccolo outlets in the Global 7500 may be affecting the air flow performance. Thus, the performance of various outlets will be tested on the ground test unit. Additionally, the ground test unit will be used to test the effectiveness of an air filtering system.

b. Iterative Design Selection

For the first iteration, a square duct design was chosen. The design came out from the fan, dropped to the ground and, split into two separate branches. The positives and negatives of this design mainly came from the duct shape. A square duct entailed simple drilling, cutting, and rearrangement if need be. With the nature of the project all of these steps will be required eventually. However, building a square duct would be time consuming and expensive. If the duct were to be built to this design, many of the parts would have to be fabricated. Parts in the design are not industry standard parts because of its square cross section. As a result, for the next iteration a similar orientation was considered, however with a round cross section opposed to a square.

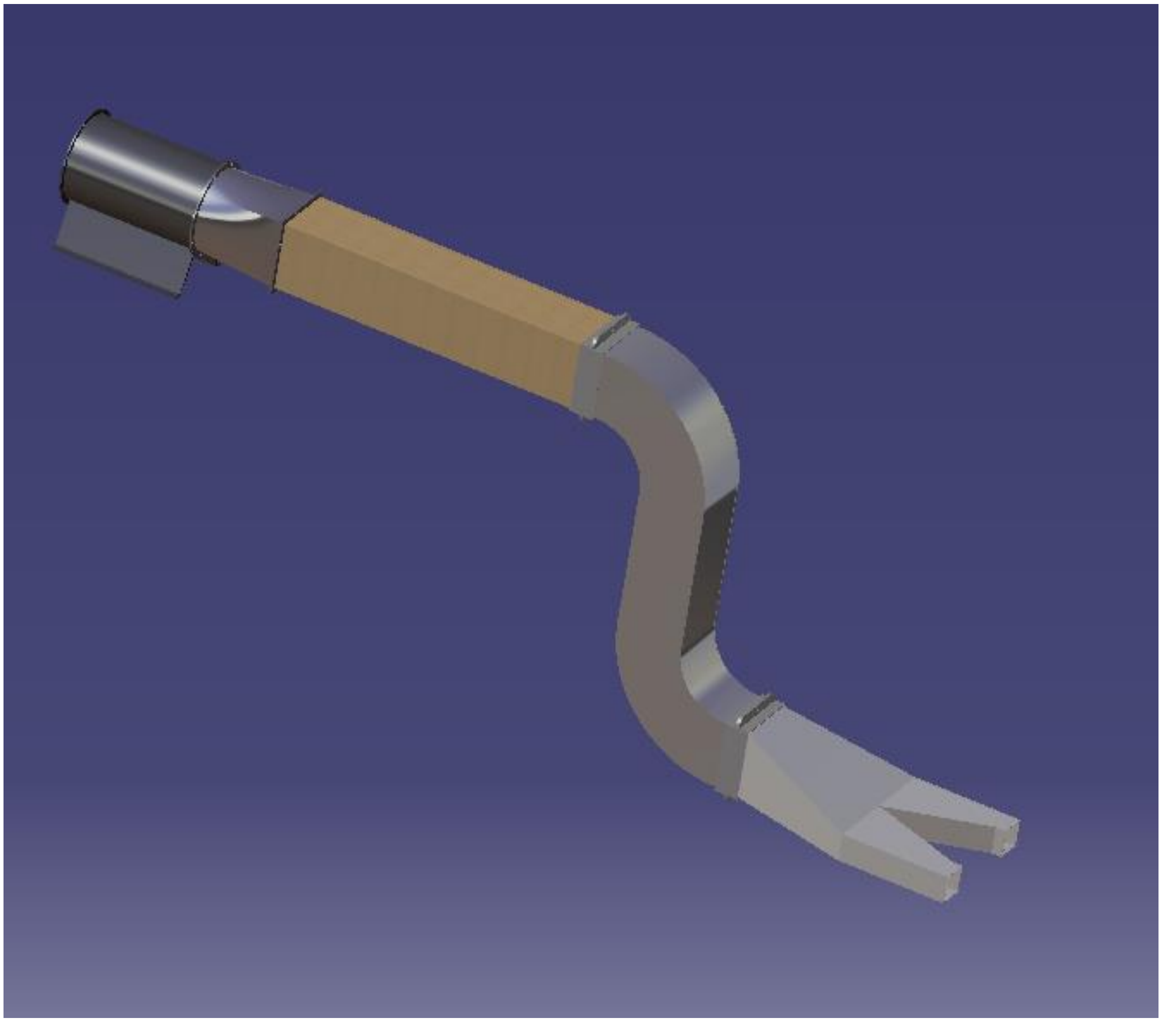

Figure 2: Ground Test Unit First Iteration

The second design iteration was similar to the first, however only industry standard ducts were used. The circular cross section is reduced from a 6 inch diameter to a 4 inch diameter with a reducer, then with the use of a duct tee the design is split into two branches. Each branch has two outlets, one at the end and one at the middle made possible by use of a duct tee. This design is cost efficient and simple to construct. In this design the drop to the ground was removed. The intention was to eventually drop the duct, however when testing the various air outlets this design would suffice and would be quicker to construct.

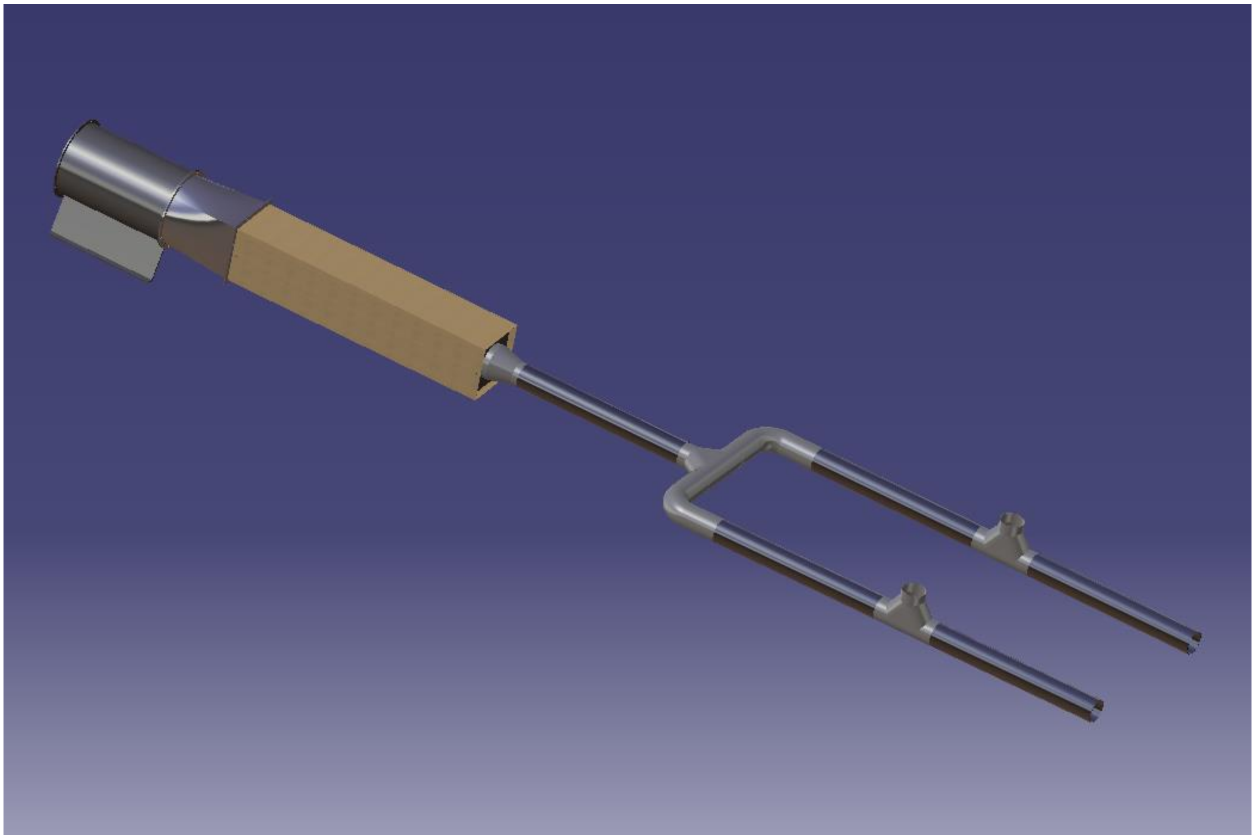

Figure 3: Ground Test Unit Second Iteration

The third design iteration is identical to the second, except the design is dropped to the ground. Initially, the second design was meant to be built and have testing performed on it. However, due to the time constraints of the project the second design was not built. The third design could be used for testing both the performance of each outlet, and for the air quality research. This was the design that best simulated the supply ducting in the Global 7500, and will give the most accurate results.

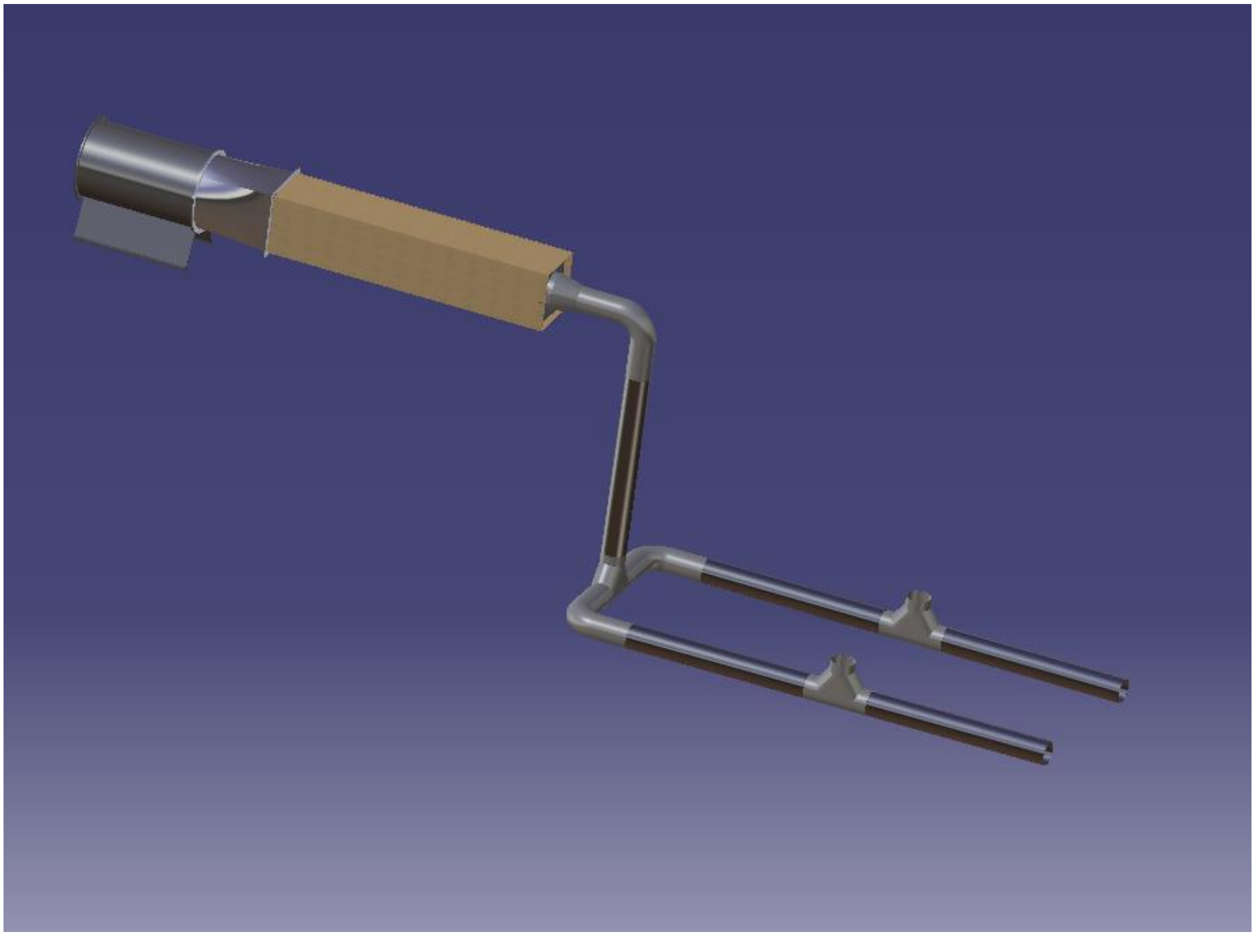

Figure 4: Ground Test Unit Third Iteration

c. Detailed Design and Build

The ground test unit was designed so that its build was simply and cost effectively. The fan implemented in the ducting of the ground test unit is CANARM's model DDA12T10033B, which has a rated RPM of 1750 and a maximum CFM of 1450. The fan was bolted to a sheet metal transition duct, which transferred the ducting from circular to square. The square ducting is bolted to the transition duct, and serves the purpose of a settling chamber. The air velocity is diffused and stabilized in this section. The square duct was built with four pieces of ¾" plywood good one side. The plywood is drilled together to make a square duct with the smooth side on the inner walls. At the end of the settling chamber a flat plat with a six inch circular opening is mounted, this is when the test ducting begins. The test ducting consists of a reducer, three duct tees, three elbows, and five 30" straight pipes. All parts were purchased from Home Depot and all were implemented in the ducting exactly how they were purchased, except the straight pipes.

The straight pipes were purchased as flat sheets and required riveting to form a pipe. Every consecutive sections were bolted together, giving a firm structure while also allowing for simple configuration when needed. Detailed drawings of each component have been provided in the appendix of the report.

III. Outlet Duct Performance

a. Introduction

A major problem expressed by Bombardier is that the cabin of the Global 7500 contains hot spots and cold spots. An aircraft cabin that varies in temperature can cause discomfort to the passengers aboard, and the crew. There can be many reasons for this, such as, uniformity of airflow, location of supply and return air ducts, location of temperature sensors, ineffective temperature control system, and more such problems. Most of the issues regarding temperature inconsistencies would require a mock cabin with supply and return air to test effectively, while the ground test unit only contains supply ducting. However, Bombardier representatives stated their concern with the supply air outlet ducting, and specifically the piccolo exit used to distribute air into the cabin (Epp, 2019). The piccolo outlet duct in the Global 7500 is a linear duct with many small evenly distributed circular openings, and from each opening air is supplied to the cabin. The ground test unit will be used to test the effect of four different supply outlets, circular opening, circular diffuser, linear opening, and a linear grille. The effect on the flow rate downstream the outlet and the noise produced by each opening will be tested to determine the performance.

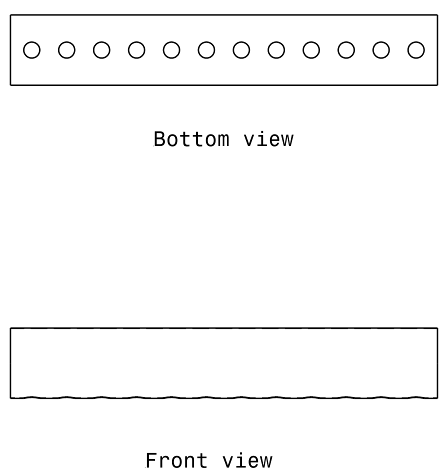

Figure 5: Piccolo Duct Demonstration

b. Outlet Selection

There are many different types of outlets that can be used on a supply air duct. The most common being diffusers and grilles. Diffusers are used to decrease the velocity of the supply air, while also evenly distributing the flow (Air Distribution Engineering Guide, 2011). The geometry of a diffuser achieves this by increasing the static pressure, this may also impact the noise produced by the outlet. Grilles only work to distribute the flow uniformly, and have no effect on the velocity of the air (Understanding the Differences in Air Vents, 2016). Two common shapes used for outlet ducts are rectangular and round, both of which can be adapted in an aircraft.

Figure 6: Round Diffuser Outlet

Figure 7: Rectangular Linear Grille

The process of selecting which air outlets to test came with a certain methodology, to test as many outlet combinations while minimizing the cost. Ideally, every possible combination would be used for the ground test unit, however this would not be cost or time efficient. The plan is for the tests of the initial outlet ducts to determine which type of outlets should be selected for further testing. The outlets chosen for initial testing are, a round opening (no diffuser or grille), a round diffuser, a linear opening, and a linear grille. The block diagram in *Figure 8* displays the next steps for testing depending on which shape and outlet type combination produces the best results.

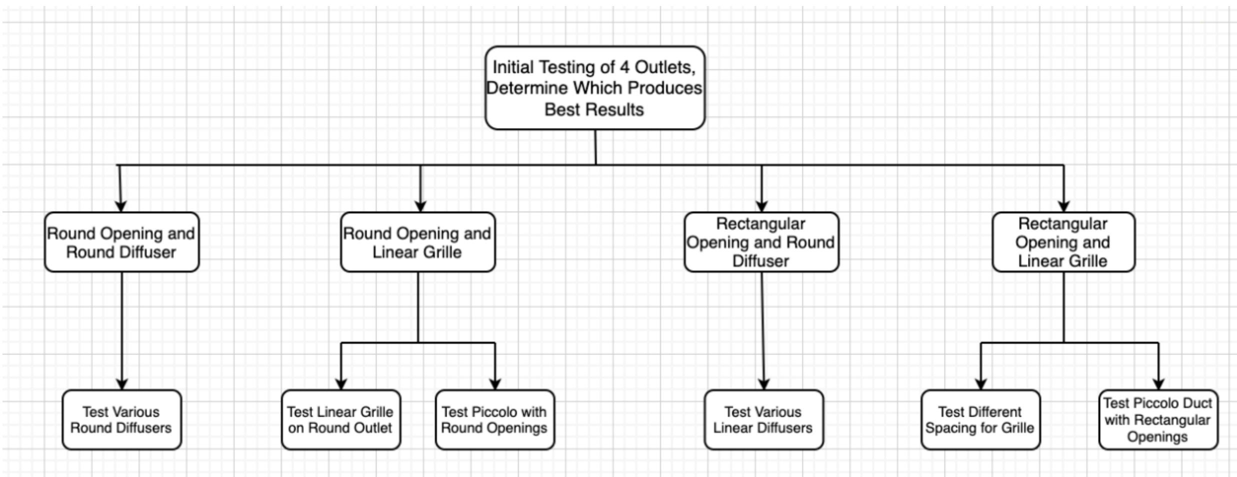

Figure 8: Flowchart of Outlet Testing Methodology

c. Testing

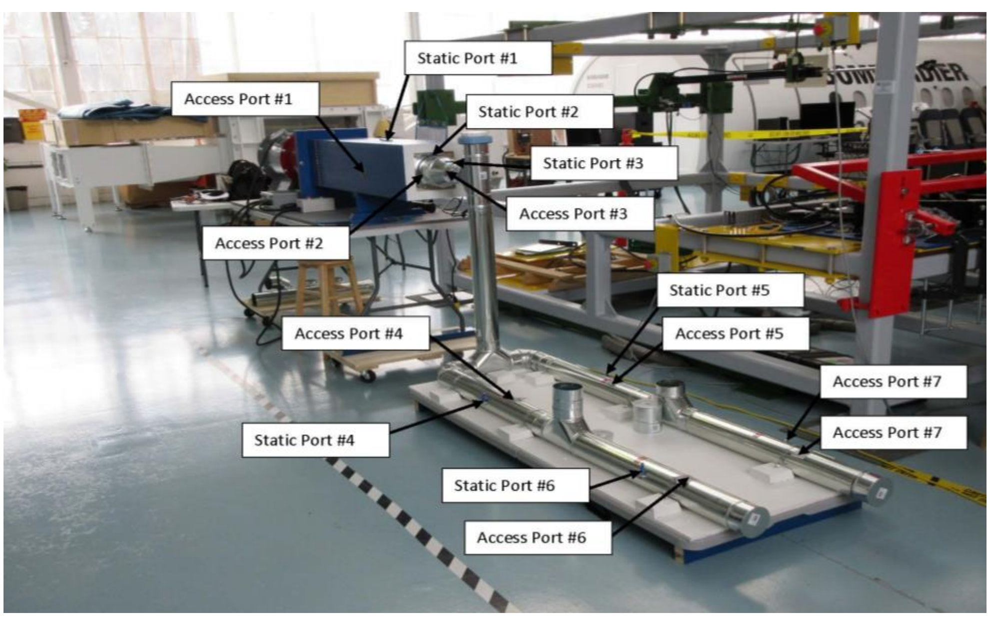

Figure 9: Ground Test Unit Test Port Locations (Karpynczyk, 2020)

Before any outlets can be tested for their performance, the initial performance of the ground test unit must be evaluated. Five separate preliminary performance tests of the ducting will provide results for the static pressure and velocity. The details of all five preliminary tests are provided below. The airflow MEDM model 5k micromanometer was used for measuring the average static pressure and velocity along a cross section in the ducting. The manometer works by taking several static pressure and velocity readings along a cross section, the device analyzes the data and gives an average measurement for both values. Measuring the average provides less detail about what is happening to the airflow in the duct, such as what the pressure gradient and velocity profile look like. However, for determining air flow rate and pressure losses, average readings will suffice.

Preliminary Test 1:

- Main supply exit duct (6-4 reducer) capped
- Static pressure and velocity is measured at access port #1

Preliminary Test 2:

- Main supply exit duct is opened to atmosphere
- Static Pressure and velocity is measured at access ports #1, #2, #3

Preliminary Test 3:

- All air exit ducts are capped
- Static Pressure and velocity is measured at all 7 access ports

Preliminary Test 4:

- Branch tee outlets are capped, branch end outlets are opened to atmosphere
- Static pressure and velocity is measured at all 7 access ports

Preliminary Test 5:

- Branch tee outlets are opened to atmosphere, branch end outlets are capped

- Static pressure and velocity is measured at all 7 access ports

Once the preliminary testing is complete, the performance of each outlet can then be accurately measured and analyzed. To determine the effect an outlet has on the system, the static pressure and air velocity before and after the outlet will be tested. Measuring before and after will make the drop within the system clear, while these values can also be compared to the rated performance established in the initial testing.

d. Results

Preliminary Test 1:

Table 1 – Preliminary Test 1 Results

Access Port	Velocity (ft/min)	Static Pressure (inH20)	Air Flow Rate (CFM)	Total Pressure (inH20)
1	0	2.06	0	2.06

Preliminary Test 2:

Table 2 – Preliminary Test 2 Results

Access Port	Velocity (ft/min)	Static Pressure (inH20)	Air Flow Rate (CFM)	Total Pressure (inH20)
1	1637	1.45-1.46	1137	1.61-1.62
2	3325	1.17-1.18	652.9	1.84-1.85
3	5120	0.36	447.0	1.95

Preliminary Test 3:

Table 3 – Preliminary Test 3 Results

Access Port	Velocity (ft/min)	Static Pressure (inH20)	Air Flow Rate (CFM)	Total Pressure (inH20)
1	0	1.85-1.86	0	1.85-1.86
2	0	1.77-1.78	0	1.77-1.78
3	0	1.55-1.57	0	1.55-1.57
4	0	1.26-1.27	0	1.26-1.27
5	0	1.26-1.27	0	1.26-1.27

6	0	1.26-1.27	0	1.26-1.27
7	0	1.26-1.27	0	1.26-1.27

Preliminary Test 4:

Table 4 – Preliminary Test 4 Results

Access Port	Velocity (ft/min)	Static Pressure (inH20)	Air Flow Rate (CFM)	Total Pressure (inH20)
1	1035	1.54-1.55	683.3	1.61-1.62
2	2199	1.31-1.32	431.8	1.60-1.61
3	4433	0.69-.070	387.0	1.88-1.89
4	1280	0.03-0.04	111.7	0.13-0.14
5	1295	0.04	113.1	0.14
6	1276	0.01	111.4	0.11
7	1284	0.01	112.1	0.11

Preliminary Test 5:

Table 5 – Preliminary Test 5 Results

Access Port	Velocity (ft/min)	Static Pressure (inH20)	Air Flow Rate (CFM)	Total Pressure (inH20)
1	N/A	1.53	N/A	N/A
2	N/A	1.30	N/A	N/A
3	N/A	.69	N/A	N/A
4	1252	.03	109.3	0.13
5	1240	.03	108.3	0.12
6	0	.11	0	.11
7	0	.11	0	.11

IV. Air Quality Control

a. Introduction

Particle pollution has become a major concern for air quality experts recently, so much so that the EPA has labelled it as one of four major air pollutants. Particulate matter typically forms during a combustion process, and comes in the form of liquid or solid droplets (EPA, 2014). The particles that are of highest concern to human health are those smaller than 10 micrometers in diameter. At that size, they are small enough to enter the lungs and cause serious health problems. Particle pollutants are classified into either fine particles, less than 2.5 micrometer diameter ($PM_{2.5}$, PM_1), and coarse particles, 2.5 to 10 micrometer diameter (PM_{10}, PM_4).

The EPA has begun developing standards for inhalable particles in 1987, and have come to a conclusion in 2012. When developing exposure limits for air pollutants there are primary standards and secondary standards. Primary focus on protecting the health of 'sensitive' groups, while secondary standards ensure the safety of public welfare (EPA, 2019). The primary and secondary standards are the same for particulate matter. The $PM_{2.5}$ annual standard is 12 micrograms per meter cubed ($\mu g/m^3$), and the 24-hour standard is 35 $\mu g/m^3$. The PM_{10} 24-hour standard is 150 $\mu g/m^3$, while there is a lack of evidence that links long term exposure of PM_{10} to health problems (EPA, 2019).

Carbon monoxide is an odorless gas that forms during the incomplete combustion of a carbon fuel. It is also one of the four major air pollutants specified by the EPA. Carbon monoxide is of even more concern in confined spaces, such as an aircraft cabin or cockpit. Even low quantities of carbon monoxide can cause dizziness and nausea, while high concentrations can lead to loss of consciousness or death.

CPSC has developed standards for carbon monoxide exposure, in order to prevent any health problems. CPSC prohibits exposure of more than 50ppm over an eight hour period. However, symptoms start becoming noticeable once the concentration exceeds 70ppm. Between 150ppm and 200ppm carbon monoxide exposure can result in unconsciousness and even death (CPSC, n.d.).

Table 6 – Air Pollutant Health Effects

Air Pollutant	Short Term Effects	Long Term Effects
Particulate Matter	• Chest Pain • Palpitations • Shortness of Breath • Fatigue	• Cardiac Arrythmia • Heart Attacks • Aggravated Asthma • Decreased Lung Function
Carbon Monoxide	• Dizziness • Nausea • Headache • Vomiting	• Permanent brain or heart damage • Heart disease

b. Proposed Future Work

Both particulate matter and carbon monoxide are released in cigarette smoke. The ground test unit can be used to measure the concentration released from both of these air pollutants, and how well a filtering system can prevent contamination. Additionally, measuring the effect that tobacco smoke has on the air quality of a cabin can be particularly useful for business jets. Given that the passengers of a business jet have the liberty to bring on what they please, studying and preventing the harm caused by these pollutants will be beneficial to the crew and passengers safety.

A study performed by Goethe-University in 2016 aimed to discover the particulate matter released from second hand cigarette smoke. They measured the concentration of PM_{10}, $PM_{2.5}$, and PM_1 for various cigarette brands. In their study an aerosol spectrometer was used to measure the individual concentrations. The study concluded that cigarettes produce a considerable amount of particulate matter, and PM_1 the most of the three sizes measured (Kant, Muller, Braun , Gerber, & Groneberg, 2016). This was alarming since smaller particles have the most detrimental health effects when inhaled. Monitoring, and preventing these particles from entering and recirculation in the cabin is the only way to ensure the health of the people on board.

The Honeywell HPM Series particulate matter sensor detects the size and concentration of particles using light scattering (Honeywell, 2019). It has the ability to detect at four particle diameters, and up to a concentration of 1000 micrograms per meter cubed. It can be used in the ground test unit to monitor particle pollution. The Adafruit MiCS5524 can measure the concentration of many gases, and is a cost effective way of monitoring carbon monoxide. It is sensitive to carbon monoxide for concentrations up to 1000ppm (Adafruit, n.d.). However, it also detects various alcohols and is unable to distinguish between gases. It will be able to provide meaningful readings if carbon monoxide is the only gas concentration changing within the duct, that the sensor can detect.

Table 7 – Sensor Specifications

Sensor	Purpose	Details
Honeywell HPM Series	• Detect concentration of particle pollution	• Detection range: 0 $\mu g/m^3$-1000 $\mu g/m^3$ • Particle size range: PM_1, $PM_{2.5}$, PM_4, PM_{10} • 10 year reliability • 6s response time • $\pm$15% accuracy • 44mm x 36mm x 12mm
Adafruit MiCS5524	• Detect concertation of carbon monoxide	• Sensitive to CO, Ammonia, Ethanol, H2, Methane, etc. • CO detection range: 0ppm – 1000ppm • Cannot distinguish between gases • 20mm x 12.7mm x 3.1mm

Figure 10: Honeywell HPM Series Sensors

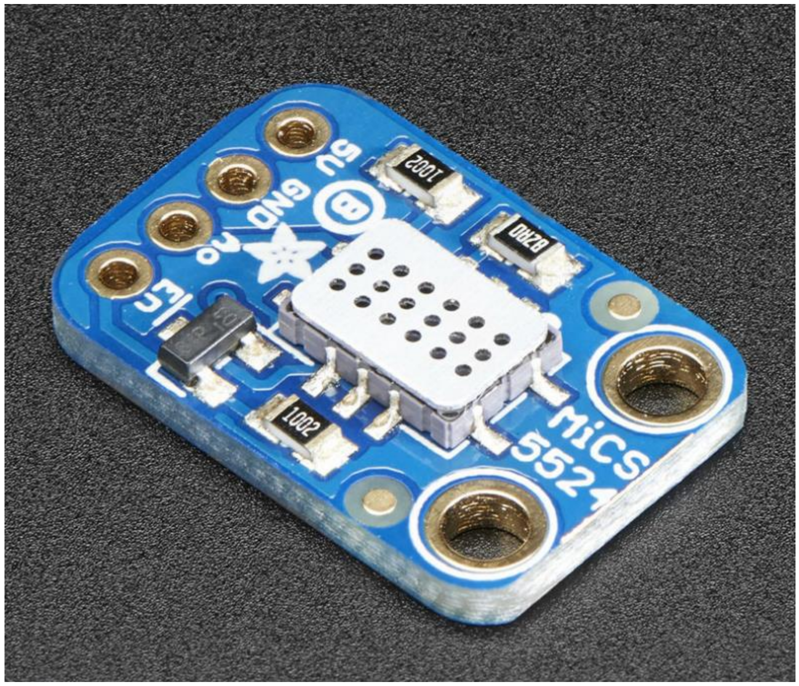

Figure 11: Adafruit MiCS5524

A true HEPA air filter claims to capture 99.97% of particles that are greater than 0.3 micrometer in diameter (Sarah, 2014). The HEPA filter is expected to be effective in trapping particle pollutants, however will likely have minimal effect on the concentration of a gas like carbon monoxide. In addition to the HEPA filter, a UV purifier will be placed in the ground test unit in an attempt to prevent carbon monoxide from entering the cabin. The combination of the true HEPA filter, and UV purifier will be the air filtering system in the ground test unit. Initially, its effectiveness on filtering particle pollution and carbon monoxide will be tested, however many air pollutants and biological agents can be passed through the system in the future.

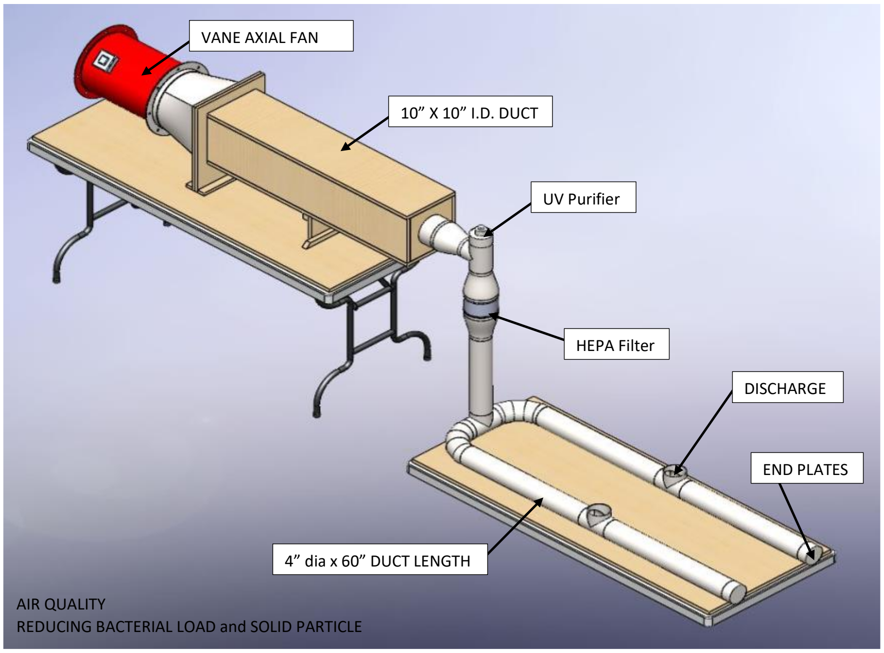

Figure 12: Proposed Ground Test Unit With Filtering System (Karpynczyk, 2020)

V. Concluding Remarks

The project achieved most of what was expected from it. Due to the COVID-19 pandemic, the performance of various air outlets was not able to be tested within the time frame. Additionally, the effect that the air filtering system has on particulate matter, carbon monoxide, and other air pollutants did not get the chance to be monitored. However, the project was successful in designing a ducting system that simulates the inlet ducts of the Bombardier Global 7500. The performance of the test rig has been determined, and is prepared to preform numerous tests. Specific outlets and air pollutants have been suggested for future work, however the next tests do not need to be the ones that were suggested. Future testing can be decided by which air quality research is of most interest at the time of testing. The current pandemic is expected to cause air quality research to focus more on viruses and bacteria that can be spread through the air. The ducting designed can be used for this purpose, and the air filtering system can always be adjusted to meet specific needs. To conclude, the project has been successful in designing, building, and calibrating a test rig for future air performance and air quality research in the cabin of a business jet.

VI. References

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VII. Appendix A – Detailed Test Rig Design

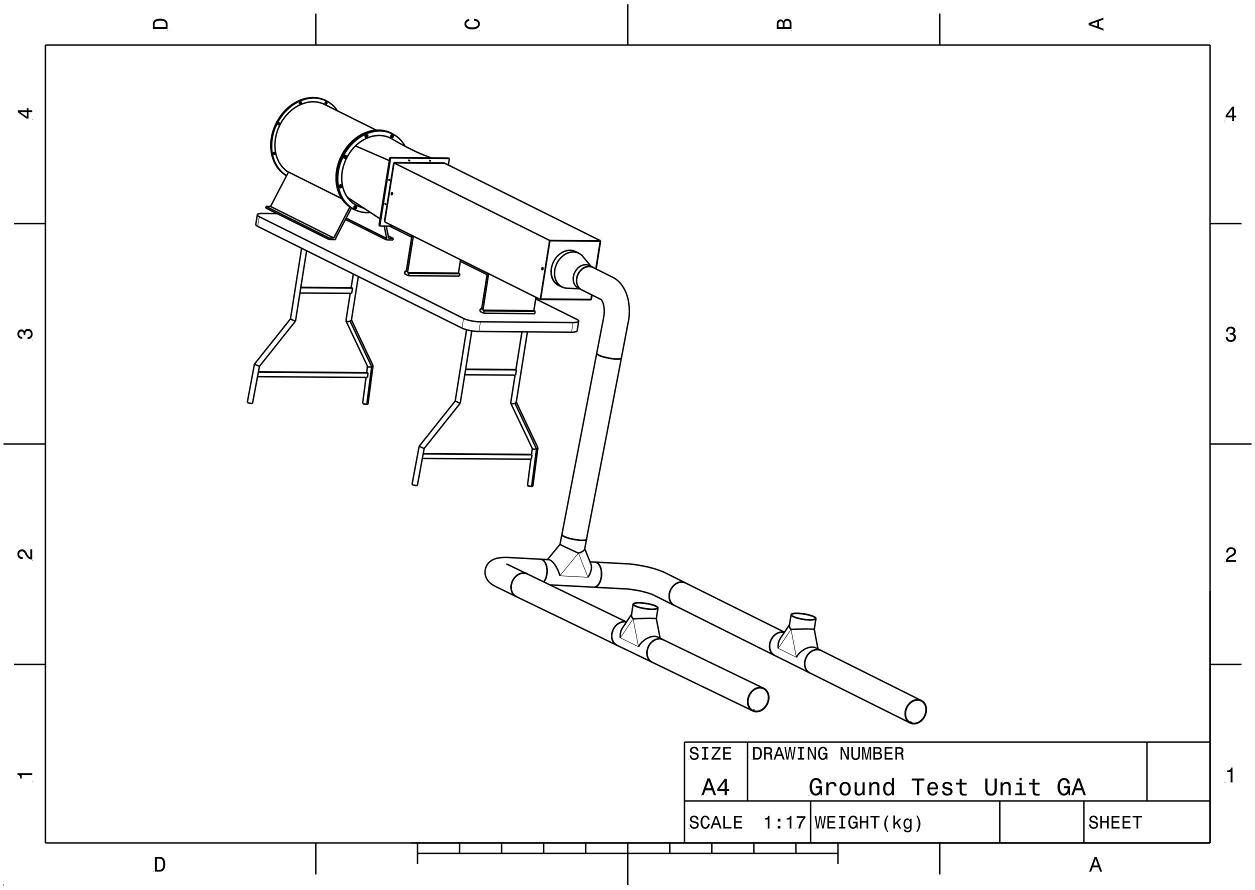

Figure 13: Ground Test Unit General Arrangement

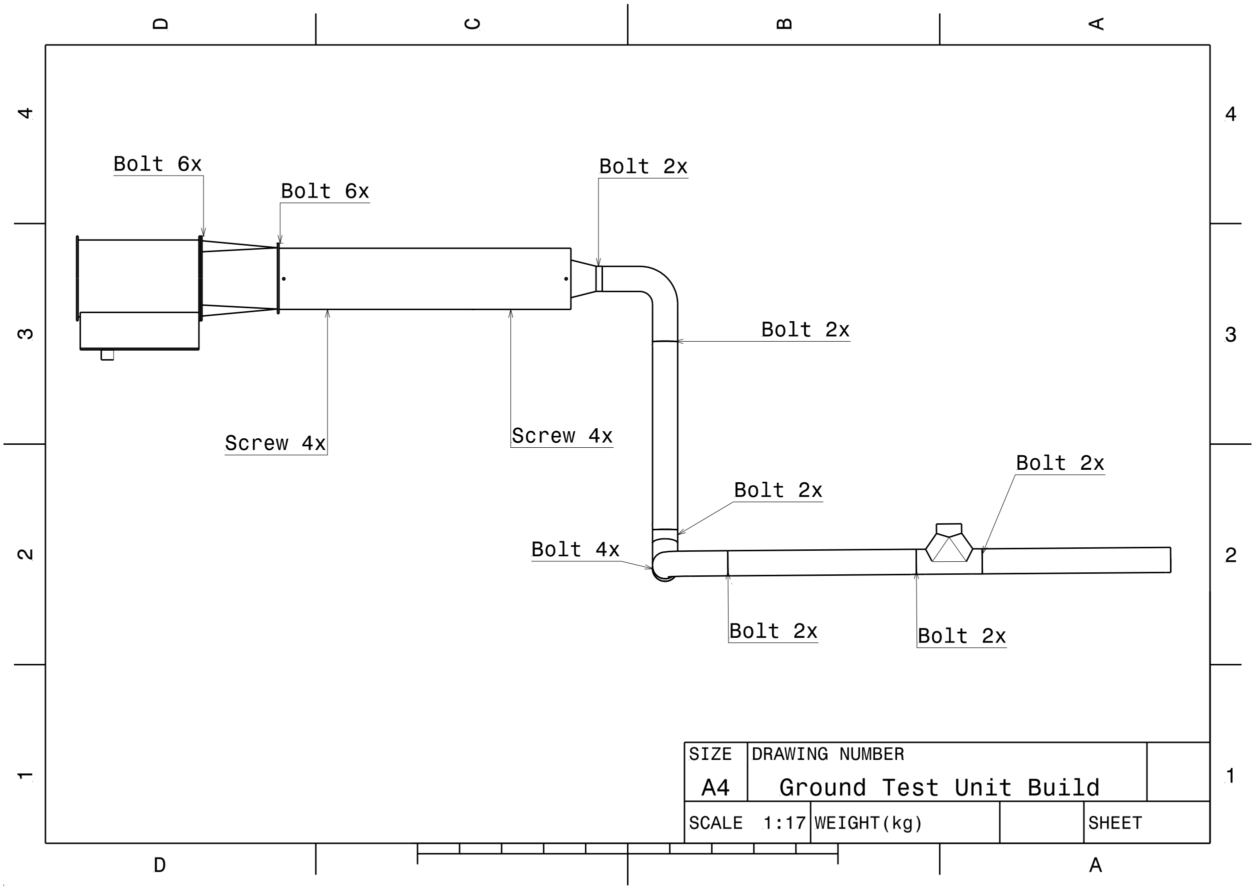

Figure 14: Ground Test Unit Build View

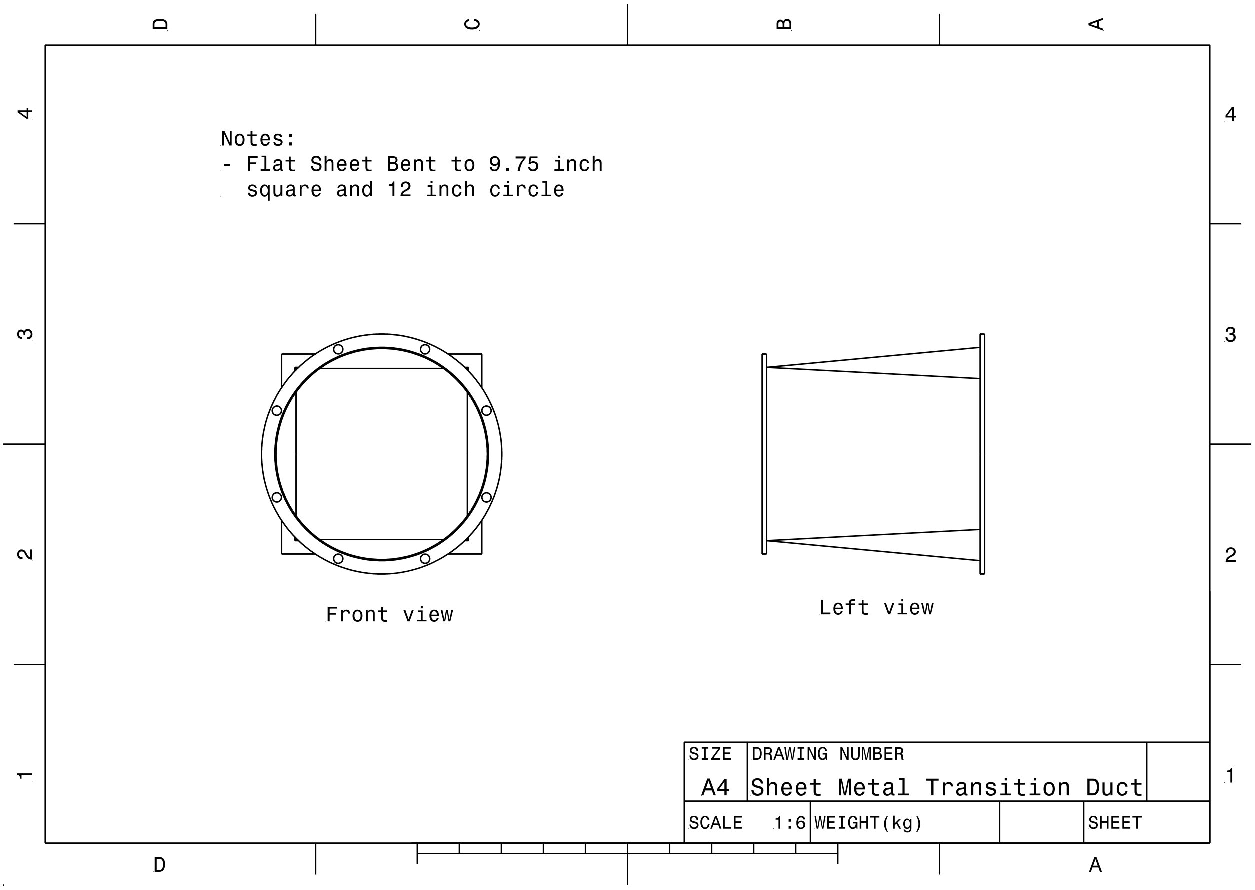

Figure 15: Sheet Metal Transition Drawing

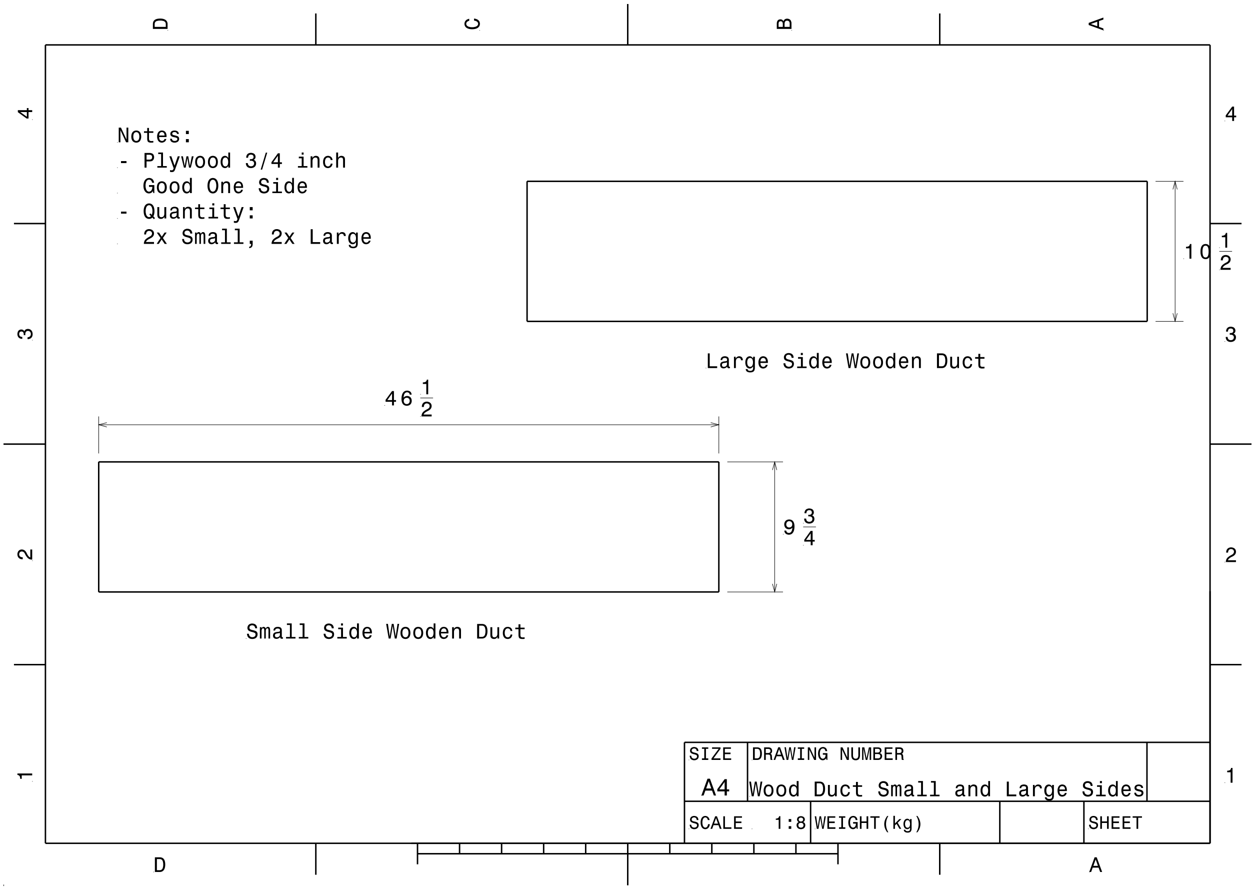

Figure 16: Wooden Duct Sides Drawing

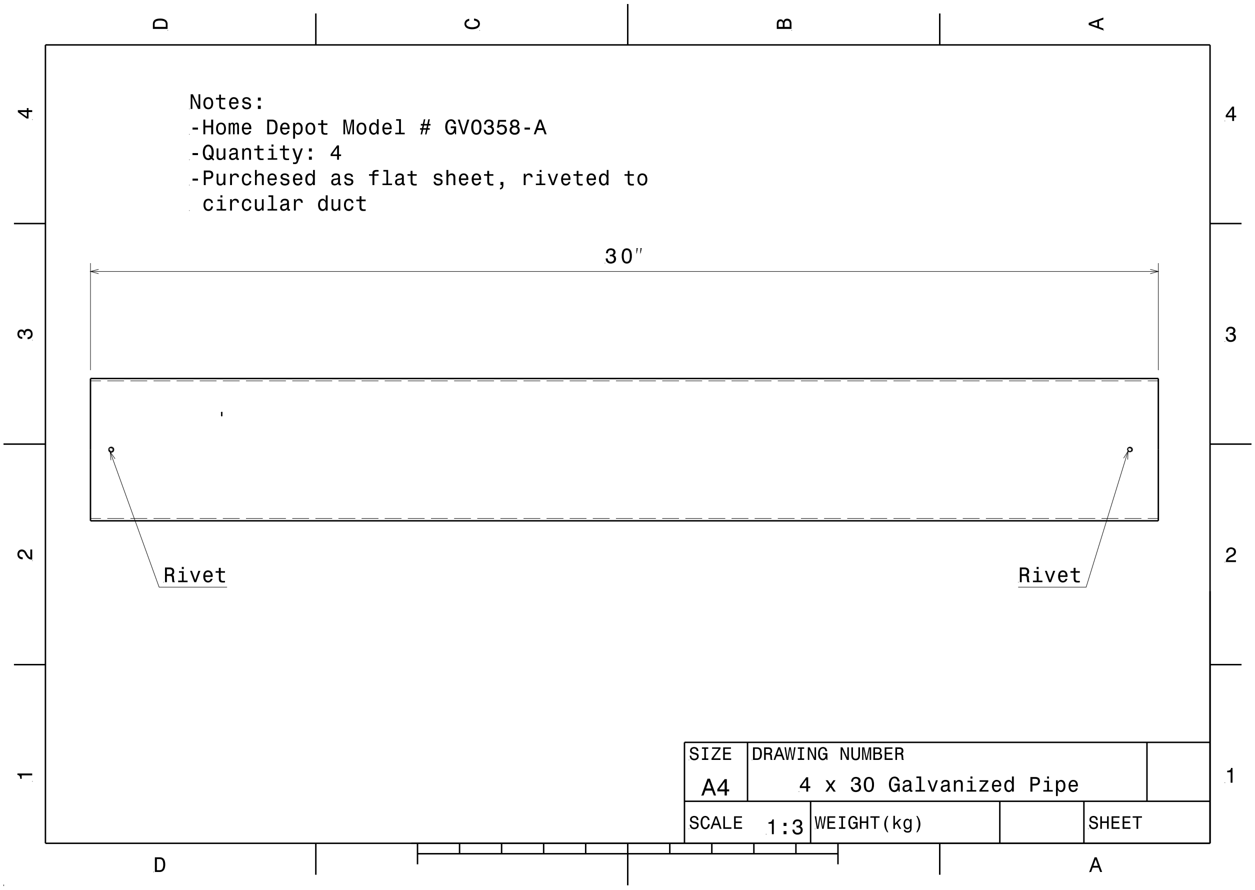

Figure 17: Straight Pipe Drawing

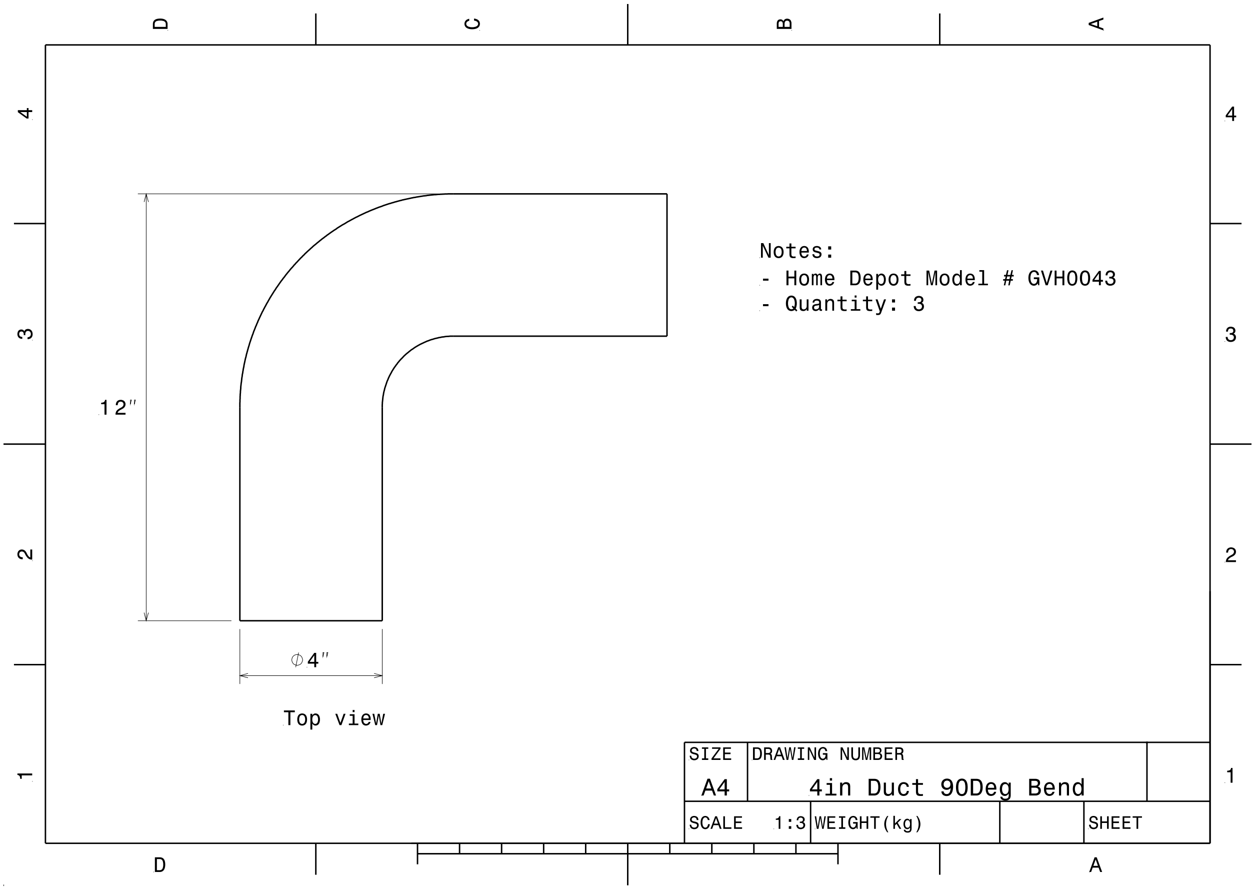

Figure 18: 90 Degree Elbow Drawing

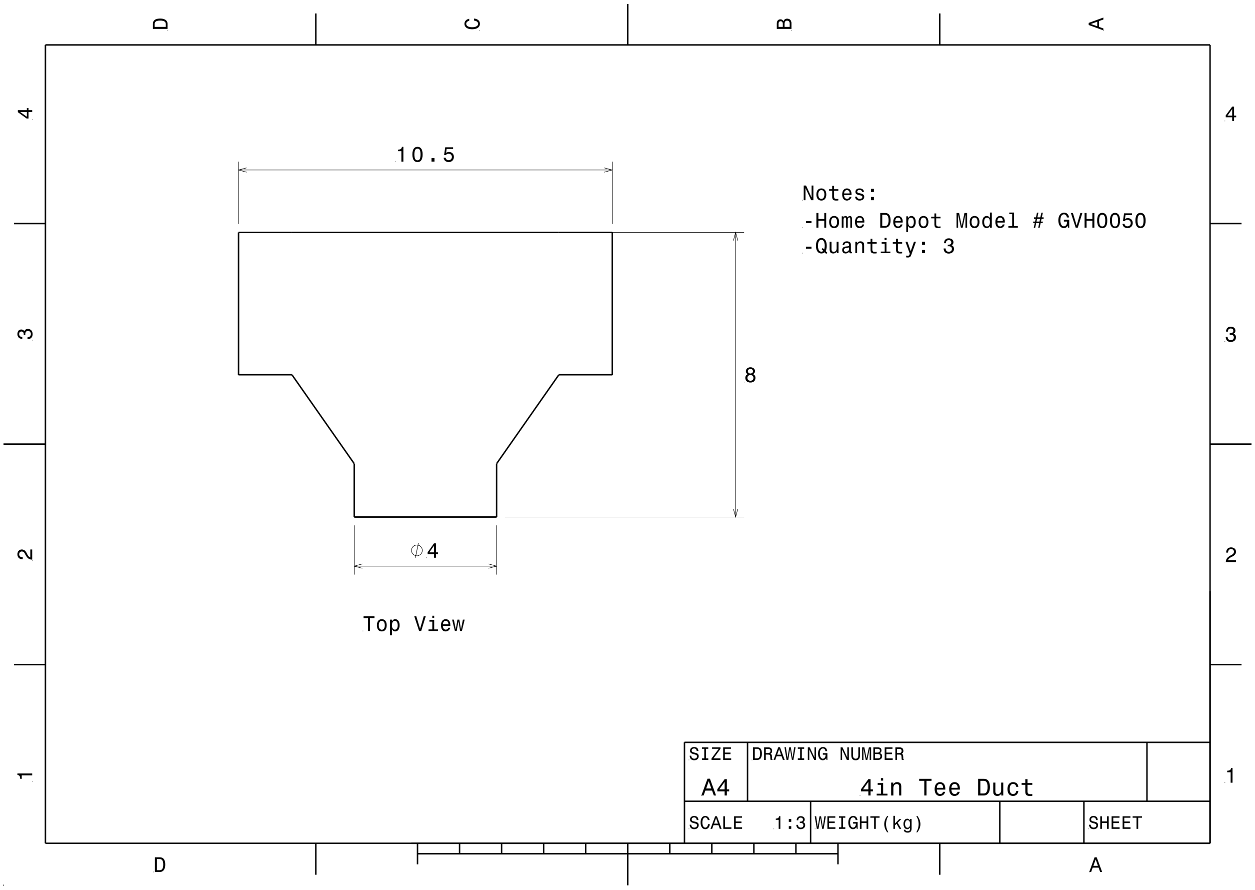

Figure 19: Duct Tee Drawing

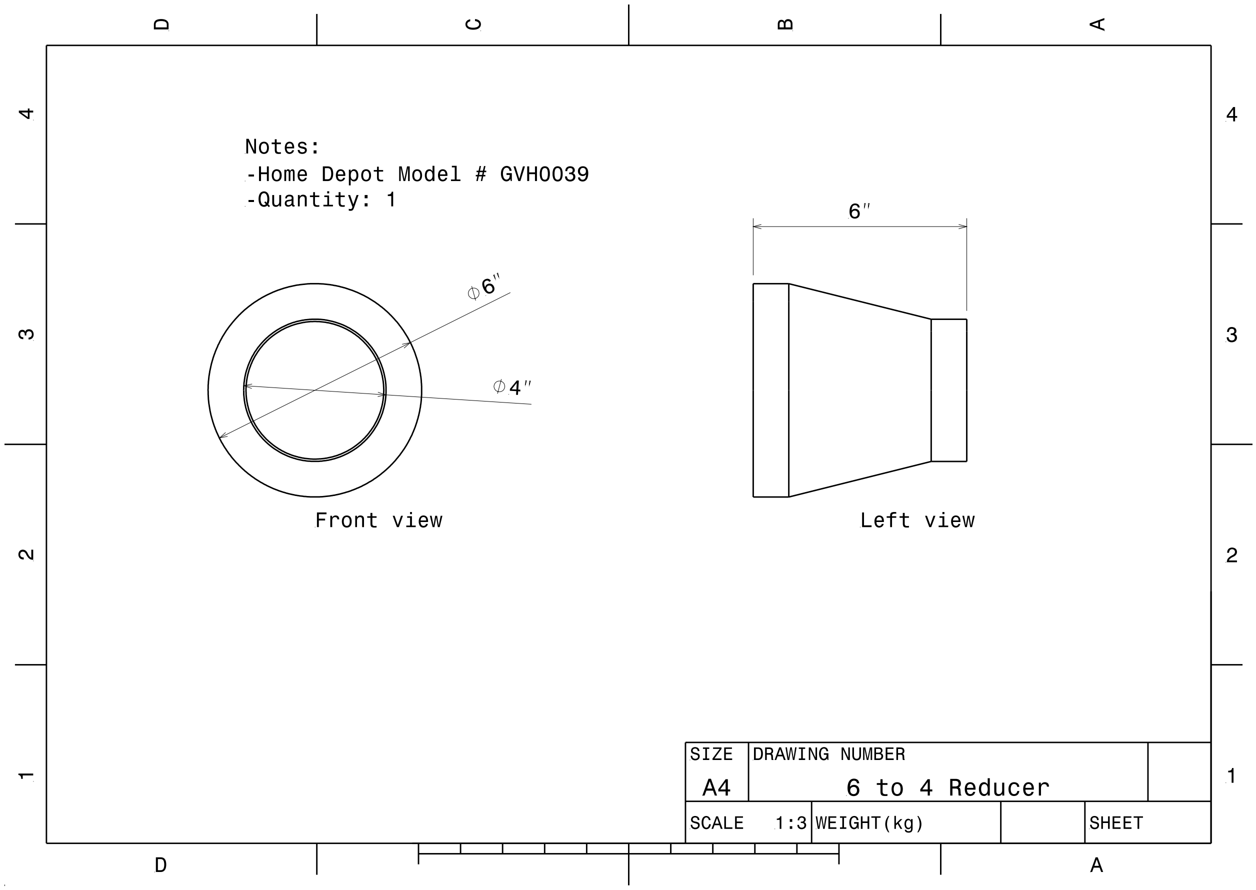

Figure 20: 6-4 Reducer Drawing