Colorado Space Grant Consortium

High Altitude Ozone Depletion Refrigerant Analysis DemoSat Final Report

TEAM BROZONES

BrO3s

Written by:

Colin Borror, Christopher Harrison, Dennis Porter, Aaron Russ,
Koko Stathopulos, & Marco Villasuso

Advised By:

Jacob Tipsword

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Arapahoe Community College

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1.0 Abstract

The depletion of the Ozone Layer is a colossal threat to continual habitation of the planet Earth. Fortunately, in recent years, the layer has healed. That does not stop the threat of new substances harming it. Our project, with the DemoSat program, tests the chemical 2,3,3,3-tetrafluoropropene, a refrigerant now regulated for use in automobiles and certified by the EPA, to re-verify their testing of the safety of this new chemical. The system utilizes forced induction to transfer air into a sealed test chamber at altitude (measured from our external temperature sensor and pressure sensor) and then introduces the chemical in the test chamber. With mounted ozone sensors, one in the test chamber and one to monitor for control data, the system records the ozone concentration to determine if there is a drop in the test chamber. This project aims to determine our Ozone Layer's continuing safety and re-verify this refrigerant's safety and efficacy.

2.0 Mission Overview

To test the chemical 2,3,3,3-tetrafluoropropene, we will send our experiment up to the stratosphere, once our experiment reached an altitude of approximately 65,000 feet, the intake port will be closed to our test chamber and the chemical, 2,3,3,3-tetrafluoropropene introduced in the test chamber. We predict that a byproduct of the degradation of the chemical will cause the destruction of ozone molecules, therefore decreasing the concentration inside of our test chamber. The ozone sensor mounted inside of the test chamber recorded ozone concentrations throughout the duration of the flight to determine if and when the byproducts have an effect on ozone. Upon touchdown of the balloon, the team will recover the SSD card onboard and upload the flight data for analysis.

3.0 Chemical Background

In the 1920s, scientists at DuPont Chemical created a chemical compound known as R12. At the time, scientists had been researching how to mechanically cool down things with refrigerants, as opposed to using ice, but the refrigerants they used were either too toxic, too flammable, or too much of a health risk. R12 was a miracle chemical that was odorless, nonflammable, and nontoxic. These properties helped it phase out other chemicals used in cooling applications, such as ether and methane. The popularity of R12 was on the rise as automobiles all across the United States began to incorporate it into their air conditioning. Soon, R12 was used for everything, from the air conditionings in homes, to the propellants in spray cans. By the 1970's, you couldn't go a day without using this miracle chemical. From keeping food cold in your fridge, to helping produce uranium for nuclear power plants, R12 was the promise of it all (Jestine, 2022). Everything was looking good for R12 until 1975, when a scientific study was published detailing it as an ozone depleter, and revealed the data of how damaging it truly was to the ozone layer. The scientists found that R12 will break down in the presence of UV light and release a chlorine radical, which goes on to break bonds between ozone molecules.

Three years later, in 1978, the first countries signed the Montreal Protocol, which banned the manufacture of R12. Because of its usefulness and the absence of rival refrigerants, R12 was not fully phased out until 1994. A new refrigerant, R134A was developed after the signing of the Montreal Protocol. Its effect on the ozone layer was negligible, but its cooling properties weren't as efficient as R12. Because of the inefficiencies, it required more work to be done in order to cool something, resulting in higher fuel consumption and therefore more CO2 emissions. This increase in CO2 emissions led to it later being phased out in 2013 when DuPont Chemical and Honeywell collaborated to make a safer refrigerant.

Each company sold their own version of it, but the more widely-used one that you can find in any car developed in the mid-to-late 2010's was R1234YF by DuPont Chemical. DuPont and Honeywell had performed tests on R1234YF before its release to ensure that it was safe for the environment, including testing its ozone depleting and global warming properties. The global warming potential of R1234YF was studied and compared to R134A, and showed that its global warming potential was 357 times less than that of R134A (DuPont, n.d.). The ozone depleting potential was studied alongside its global warming potential, and scientists have reported that it has zero ozone layer depletion potential, but don't go into much detail about the experiments conducted (Cadogan, 2020).

The DemoSat team had suspicions about its ozone depletion potential, and decided to begin researching the chemical. Working with Dr. Jacob Johnson, Clara Sandoval, and colleagues at CU Denver, a bond association energy was calculated for the carbon-fluorine bonds of R1234YF and compared to the carbon-chlorine bonds of R12. Dr. Johnson, Clara Sandoval, and their colleagues at CU Denver found that the bond association energies were very similar, with R1234YF's carbon-fluorine bond being about 541 kJ/mol, and R12's carbon-chlorine bond being 532 kJ/mol. This was sufficient enough evidence for our team to investigate it further and re-verify the EPA's claims that it does not pose any threat to the ozone layer.

4.0 Design and Fabrication

The initial design process focused on what was needed for the experiment to successfully produce meaningful data related to the chemical analysis that was to be performed during extreme conditions. This meant understanding the tolerances for individual systems and components that made up those systems and responding to design challenges as they arose. ***See*** *Fig 4.0.1: Initial System Design Diagram*

One of the early challenges the project faced was maintaining the operating temperature for the ozone sensors within the experiment structure. To function correctly, the sensors required an environmental temperature between -20℃ to 50℃, which was much higher than the temperatures expected at operating altitude for the experiment. To accommodate for this and in an attempt to solve heating issues, the shape of the base structure was changed from hexagonal, which was larger and provided more durability, to a cube. ***See*** *Fig 4.0.2: Hexagonal Structure* The revised design was smaller, more simplified, and lighter. This allowed for better centralized heating of the internal systems. Another challenge the team faced was voltage regulation, as the batteries we were originally using onboard were subject to fluctuations that we feared may affect the integrity of the experiment. Based on a design previously used by members of this team, a voltage regulator was fabricated and installed to help regulate the voltage to the internal systems, and provided an additional benefit of heating from the heat sync.

4.1 DemoSat Design

The finished structure is a six-faced, four-sided cuboid measuring 6.75 inches in width, 7.125 inches in height, and 5.25 inches in depth. The structure was made smaller and more simplistic to concentrate efforts in producing meaningful data while still maintaining durability and stability. These criteria influenced the decision of what material to construct the base structure from.

Because of its properties for being both light-weight and durable enough to survive flight and recovery, foam core board was selected to construct the base of the payload. The base structure's four exterior walls were made from a single piece of the foam core material that was beveled and folded into shape rather than cut out as individual panels and attached with adhesive. ***See*** *Fig 4.1.1: Structure Fabrication* This was done to further increase the structure's edge durability and reduce the use of heavy adhesives, thus reducing the overall weight. Two panels were later cut to finish the base structure's construction and enclose the internal systems.

After the construction of the base structure was finalized, we began to insulate the interior of the walls of the structure using a foam sheet material. ***See*** *Fig 4.1.2: Structure Insulation* This material, aside from providing insulation, also contributed to the overall structure's durability and ability to absorb the final impact from the landing process.

Finally, aluminum tape and hot glue was added to the corners and edges of the structure to help with edge durability and to provide a hinge for easy access to the project's internal systems.

After the original launch was scrapped due to poor weather we looked into improving our design, originally, a day prior to launch we would have had to bet on proper weather and irradiating the HFO-1234yf in the test chamber with the UV radiation from the sun. A window on the front was added (made of acrylic) to rely more on in flight conditions and UV radiation levels. ***See*** *Fig 4.1.3: Stair test data*

4.2 Test Chamber Design

The test chamber was designed with a good seal in mind. Because of the nature and uncertainty of how HFC1234YF may react with ozone, we made sure to take extra steps to mitigate any potential leaks. All of the threads have been sealed with either a small amount of thread tape, or a thread-locking glue. The connection piece between the gas lines and test chambers has been press-sealed in between the threads with a gasket and thread-locking glue.

The process of choosing a test chamber design was straightforward, as we wanted to limit weight, complexity, and make it structurally rigid under the differences in pressure and temperature that we can expect during flight. Our team opted to use an emptied CO2 cartridge that was originally intended to be used for filling bikes or used in airsoft guns. We chose a CO2 cartridge because its cylindrical shape ensures structural rigidity against the vast differences in pressure, and its standard ⅜" threading ensures that we can find matching parts to connect the gas lines into the cartridge. One of the downsides that came with choosing a CO2 cartridge is weight. Because they were made of alloyed steel, a single cartridge came in at nearly 60 grams, which was equivalent to almost 10% of our weight budget. We decided to continue on with the CO2 cartridge as we decided it would be the most reliable vessel to run the experiment in.

The next problem that our team faced was attaching an ozone sensor inside of the vessel to measure the ozone concentration. With recommendations from Professor Wikowsky and Professor Tipsword, our team decided to drill a hole 1" in diameter at the very bottom of the cartridge, attach the ozone sensor there, and seal it in with an polyurethane adhesive (Betalink K2) meant to attach external parts to cars. This epoxy provided a strong attachment, but we had issues with sealing it properly. To ensure that this attachment was fully sealed and wouldn't pose a risk, we wrapped the test chamber in a latex balloon, sealed it to the cartridge with a silicone bond (Permatex Ultra Black Silicone), and encased the entire contraption with a 3d printed shell. This shell would give the balloon a little bit of room to expand without breaking any seals. Lastly, we attached an adapter piece to the top of the cartridge with a compression fitting and gasket to seal the gas line leading into the test chamber.

4.3 Flight Code

Our payload is responsible for reliably recording sensor data for the duration of the flight while simultaneously triggering the testing protocol when the payload reaches the ozone layer. To achieve this, we use liberal thresholds and multiple checks to ensure the testing protocol is triggered under many different conditions. We also implement an efficient 'problem code' system to detect errors during both setup and flight. A reliable experiment starts on the ground, which is why, during setup, we use a robust error-handling system to check for problems and report them by flashing a recognizable pattern with our LED array. After a successful setup, we immediately begin recording data; from here, if an error is detected, it will trigger a problem code, allowing us to track and potentially recover from errors. Once our payload reaches the proper altitude as determined by applying the barometric formula to our pressure reading, we send a PWM signal to our first servo responsible for closing the atmosphere valve, delay long enough to ensure the valve is fully closed, and introduce the R1234YF by sending a PWM signal to our second servo.

Our ozone sensors use the manufacturer's included library (DFRobot, 2023), which provides all the necessary functionality for setting up and reading from our Ozone sensors over I2C. The implementation for `readOzoneData` automatically reports in parts per billion so there is nothing to do but log this value.

Temperature is read from an analog pin on the Arduino using the built-in analog-digital converter(ADC). This reading must be converted from a 10-bit ADC reading to a voltage value before it can be interpreted as degrees C. We also convert to Fah before logging.

Pressure is also read from an analog pin. Similarly it must first be converted to a voltage value before being interpreted as a pressure in PSI.

5.0 Test Plan and Results

Our team originally planned to begin all required tests and a couple of experiment-specific tests immediately after building the payload. Due to complications that came up during the design stage, we pushed testing back until the week before the original launch date. We tested the payload in a vacuum, in the cold, dropping it down 1 story, whipping it around creating centripetal acceleration, dropping it down a staircase, and against excessive pressure. Our payload did sustain minor damage during some of these tests, such as the stair test when our temperature sensor started malfunctioning. The team was able to quickly repair the damage and continue on with testing.

5.1 Terrestrial Chemical Test

The terrestrial tests were carried out to ensure that the payload will work as intended during flight, and to gather preliminary data so we can better adjust our hypothesis before launch and make adjustments to the experiment as necessary. We began by pulling a slight vacuum on the lighter, just enough to lower the pressure by about 5 psi, and then injecting the HFC-1234YF into the intake port of the lighter for about half a second. An audible “whoosh” was heard giving the signal that the lighter had been charged with a small amount of our target chemical. We then brought the payload into the sun, under clear skies, and let the lighter sit in direct sunlight for one hour. We did this because of our prediction that UV rays will create the free radicals necessary for ozone depletion. After an hour had elapsed, the team went inside and set up an ozone test chamber.

We have an air purifier that makes a trace amount of ozone as a byproduct, and so we emptied out a trash can and used that as our test chamber because it was the only thing in the room large enough to fit the air purifier into. We let the air purifier run for about 30 minutes to build up a good concentration of ozone inside, reaching around 450 parts per billion before we put the payload in. We then let the ozone enter the payload’s test chamber where the concentration inside the test chamber rose to 73 parts per billion. Because of the weak airflow inside of the trash can and the need for forced induction into the test chamber, we decided that 73 ppb was enough to run the experiment with.

The arduino was connected to Marco’s computer and he sent the signal to the board to close the ozone intake valve and then open the HFC-1234YF valve. The team set a timer for 30 minutes and kept an eye on the internal ozone concentration. Some fluctuations in the data were expected as the sensor is very delicate and can’t be moved around much when ozone concentrations are low, so we kept the experiment as steady as we could. Over the course of 30 minutes, the team watched the internal ozone concentration fall from 73 parts per billion down to 63 parts per billion, which equated to a drop of nearly 14%. While doing the calculations for how much ozone was depleted, we took into account the change in volume because the gas may now flow into the lighter and through the tube. The overall change in volume was about 5 cubic centimeters, which we predicted should cause the sensors to drop their concentration by about 4.4%. This still leaves 9.6% of the ozone depleted after testing. We hope to verify these numbers and gather more data during our launch to see the ozone depletion in a contained, real-world scenario.

5.2 Cold Test

We placed the payload into a cooler filled with dry ice during the cold test. We turned on the payload and left it in the dry ice for about one hour. The payload had no damage and all components, besides the external temperature sensor, worked as expected. The external temperature did slowly decrease as expected, but started at a temperature much higher than the actual temperature in the cooler. ***See*** *Fig 5.2.1: Cold Test* The temperature sensor issue was later determined to be a cause of improper wiring, and, as later described in the stair test, the issue has since been fixed and the exterior sensor currently works properly.

5.3 Drop Test

The payload was dropped a little over a story and survived with no damage during the drop test. ***See*** *Fig 5.3.1: Drop Test* However, we discovered a bug in the code that caused the ozone sensor to print in binary, but this was quickly fixed. The issue with the external temperature sensor was also not yet fixed.

5.4 Whip Test

During the whip test, our team leader attached the payload to a string and spun it around and in random directions to create a centripetal acceleration on the payload. ***See*** *Fig 5.4.1: Whip Test* No issues were found during the test.

5.5 Stair Test

We rolled our experiment down a flight of stairs whilst it was reading data to subject it to harsh, real world conditions, and ensure that it can withstand that while recording reliable data. During this test, we discovered two issues with our external temperature sensor, one being that it outputs strange data ***See*** *Fig 5.5.1: Stair test data*, and also extends too far out from the experiment box and thus could be damaged. Afterwards, we made sure to place it in a more secure, less easy to damage location. We found the issue with the sensor outputting strange data was due to improper voltage being fed into it. We promptly made sure to connect it to the proper voltage and thus had eliminated the issues.

5.6 Pressure Test

Originally, our plan for the pressure test was to put the entire payload into the vacuum chamber, however, our payload turned out too big to fit into the chamber. Instead, we rigorously tested each component of the payload in the vacuum chamber. ***See** Fig 5.6.1: Pressure Test* Each component held up very well and recorded data as expected.

6.0 Launch Operations

To ensure the success of our project, we began to prepare for launch 3 days before our payload flew. We started by doing a final testing runthrough of all the onboard systems, including power supply, data read/write, sensors, and valves. When we were confident that our critical onboard components work, we switched our focus to priming the gas system. To eliminate some variables from our experiment, we began to pull a vacuum on the lighter that contained our HFC1234YF in preparation for charging it. This is both to reduce the pressure difference when we're up at altitude, and to make sure we only inject the chemical we want to measure without it being diluted.

For our initial operations we would have charged the lighter 24 hours before launch. During the final 24 hours, we let the lighter portion of the payload sit in direct sunlight. This is done to both increase the temperature and expose it to UV radiation, which both helped to facilitate the formation of fluorine radicals and trifluoroacetic acid, which are predicted to interact with ozone and disassociate the bonds, therefore depleting it. After the sun went down and the payload had been exposed to enough UV. Due to the delay in launch we updated our system with a window to allow the UV radiation in during flight. The batteries were charged 24 hours before for one final charge before launch.

On the morning of launch day, we did one final power test to ensure that power is flowing to all systems, taped down the power button to ensure it doesn't switch off during flight, and began recording data. As the payload ascended, it collected a continuous stream of data, monitoring pressure, external temperature, internal ozone concentration, and external ozone concentration. After the lighter had sat in a steady vacuum state, we charged the lighter with HFC1234YF about 20 minutes before launch. As the balloon reached about 65,000 feet, we closed the valve that lets ozone into the test chamber and opened the valve that lets fluorine radicals flow into the test chamber. The valves remained in this state indefinitely to ensure that none of the gasses inside of the vessel leaked outside of our experiment. When the payload touched down, we recovered the SD card and uploaded the data to a server for public access and final conclusions.

7.0 Expected Flight Results

Based on terrestrial testing and conversations with the ACC Chemistry department, we expect ozone levels in the test chamber to begin to drop as soon as R1234YF is released into the chamber. When the valve containing the R1234YF is opened, our total system volume is increased by about 5 cubic centimeters, which will affect the overall ozone concentration. Because we are expecting a reaction to take place between free radicals in the test chamber and ozone, we expect ozone concentrations to drop noticeably below this. During terrestrial testing, we saw a 14% decrease in ozone concentrations after the introduction of R1234YF, which seems to verify this prediction.

We originally utilized the ideal gas equation, to estimate how much the ozone concentration will fall due to the change in volume and were accounting for it in our final equations, but due to both ozone and the chemical reaction (and for an indeterminable amount of time with our current data) the ideal gas law would not apply.

8.0 Flight Results

We finally flew our payload on May 4th, 2024. The payload was working as expected at launch, and the sensors were all reading correctly. On the ascent up to the ozone layer, the sensors began to read that there was a larger change in the concentration of ozone. ***See*** *Fig 8.0.4:* Control Ozone Concentration vs Time Graph. The climb in ozone concentration was followed by an abrupt dip in concentration that continued on a downward spiral until it reached its baseline concentration again. This was unexpected as it was supposed to be the control for the experiment, but no valves had yet been opened. The ozone concentration inside of our experiment chamber followed the same path, rapidly climbing during ascent and then randomly falling before any valves had been opened ***See*** *Fig 8.0.5:* Experiment Ozone Concentration vs Time Graph.

The other sensors, pressure and temperature, were working as expected and did not see any anomalies throughout the course of the flight. The altitude calculator also worked very well, reading that our maximum altitude was 85,402 ft. The official EOSS data says that the maximum altitude reached by the balloon was 89,485 ft, representing an error of only 4.5%. Because the data from the actual flight is inconclusive, our conclusions are drawn from the terrestrial testing. During the testing, we noticed a 10% drop in ozone concentration, showing an indication that HFC1234YF is a threat to the safety of our planet and its ozone layer.

9.0 Potential Improvements

The structure of the project, while currently adequate for current planned testing and analysis, could benefit from the incorporation of an access window to help in the UV light penetration of the chemical chamber, thus aiding in the process of creating fluorine radicals.

Another improvement that we would have liked to incorporate into the final design is a less mechanically-reliant valve design. While the current one does do the job well, we have had issues in the past with the superglue used to secure the servo arms to the arms of the valves to control them. To solve this problem, we simply put more superglue onto the control arms. If we were to redesign this, our team would have chosen pneumatic valves which can be operated digitally, require less maintenance, and have less uncertainty of structural rigidity.

We also had very little time to get our PCB ordered before our expected launch date, and after some testing, improvements could be made. The 5v side of the board should have been connected directly to the 5v rail of the Arduino instead of through Vin since we are already regulating a stable 5v from our batteries. A silk screen layer with logos and labels for all of our connections could have helped us avoid some confusion, and a shorter board design would have had better clearance against the Arduino's built-in USB port.

10.0 Management

To start off the semester Colin, Marco, Aaron, Dennis, and Koko set off to prioritize being organized (utilizing Discord), with Christopher joining the team after the Preliminary Design Review. With previous experience from last semester, Colin was made the Team Lead and as well as Marco being appointed Tech Lead. Aaron then was prioritized with assembly of the DemoSat itself as our Assembly Lead, Dennis volunteered as our Chief of Testing, Koko as our Software Lead, and Christopher as our Media Manager.

Though we all had set roles, we all contributed to various parts throughout the project. Throughout the semester we utilized our meeting times as planning time for other meetings and to work on different aspects of the project easier done as a group and to update each other on our progress, with various of us meeting about 2-4 times outside of our meeting times to keep pace with our goals. We all endeavored to achieve groundbreaking accomplishments in this DemoSat experiment.

11.0 Budget

Budget, like with any other of the Space Grant projects, was a huge concern for us, as we prioritized spending money on high quality resources and saving where we could to have reserves if any big set back occurred, such as brokens sensors. We attempted to salvage what we could from the previous year's DemoSat, such as the Arduino Uno, the temperature sensor, the pressure sensors, and any LEDs we required. To make up for what we couldn't salvage from last year but still had on-hand, we used back supply from the ACC Space Grant and ACC's Automotive Department. In the end we ordered 11 different items totaling $169.35, including the ozone sensors and the test chambers. **See** Fig 11.0.1: Price Chart, for more information.

12.0 Conclusions

To wrap up this experiment, our team has spent countless hours in the workshop putting this experiment together, and we hope to change people's perception of what threatens our existence and safety here on planet Earth. We want this planet to be safe for future generations, and ignorance is no excuse to neglect important things that affect our planet's ozone layer. Because R1234YF is significantly heavier than air, it has an atmospheric life of about 11 days. Our team predicts that this short life is what lessens its ozone depleting potential, but regardless can still pose a threat to the ozone layer if the product's applications expand higher into the atmosphere.

13.0 Message to Next Year

Our main message to future projects is to develop your ideas early, especially experiment, test again and again, be flexible, but do not prioritize aesthetics over a functioning payload. Getting caught up in the little details in the experiment is okay, but be sure that you keep the rest of the team on the same page and designate tasks so other priorities can be completed while someone focuses on the smaller details. Also be sure that you test the system rigorously. Our ozone sensors didn't work as expected, randomly dropping back down to their baseline reading mid-flight. This has been a common occurrence with past DemoSat missions involving ozone, too.

14.0 Acknowledgements

We would like to thank Jacob Tipsword for mentoring us through this DemoSat project. To also thank Jennifer Jones and Jacob Wikowsky for additional questions and support. As well as ACC's Chemistry Department, Dr. Jacob Johnson, Clara Sandoval, and CU Denver for Chemistry support. As well to thank Bernadette Garcia Galvez and all of the Colorado Space Grant Consortium, Edge of Space Sciences, and NASA.

15.0 Appendix

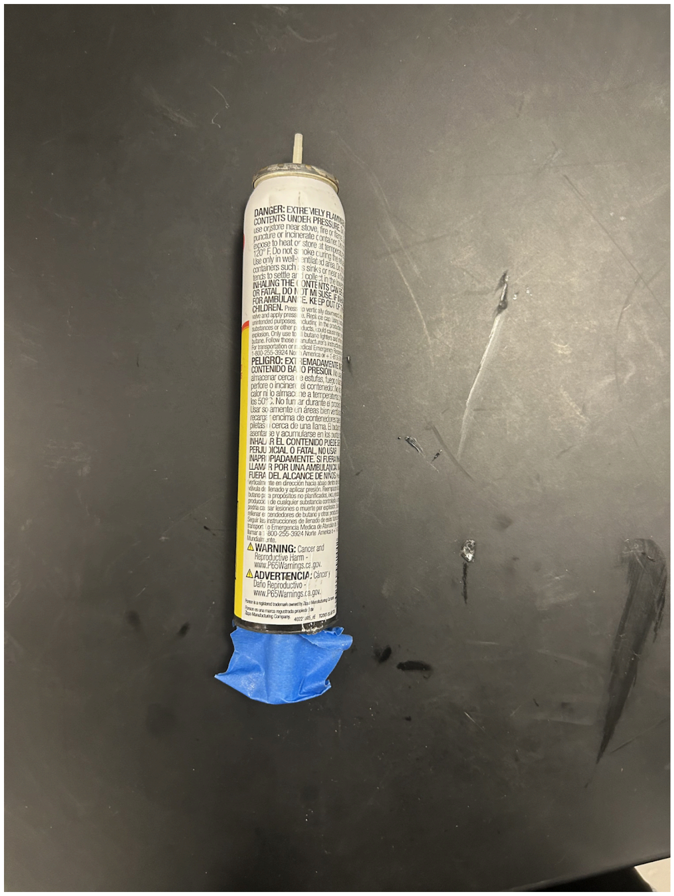

Fig 3.0.1: The container filled with HFC1234YF. Photo by Colin Borror

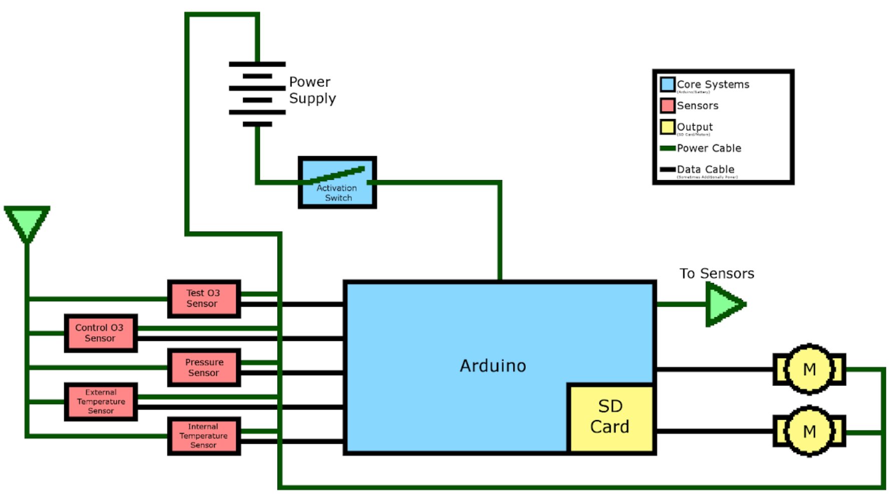

Fig 4.0.1: Initial System Design Diagram illustrated by Christopher Harrison

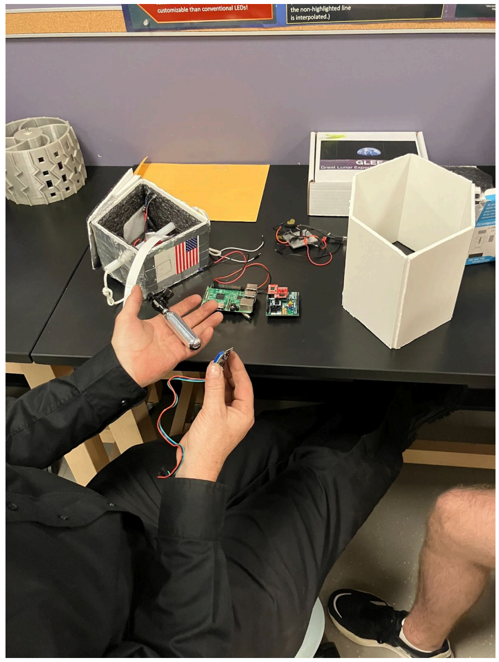

Fig 4.0.2: *Hexagonal Structure* photo by Christopher Harrison

Fig 4.0.3: The final payload design without flight tube. Photo by Colin Borror

Fig 4.1.1: *Structure Fabrication* - Team Lead Colin Borror folding the base structure's exterior walls. Photo by Aaron Russ

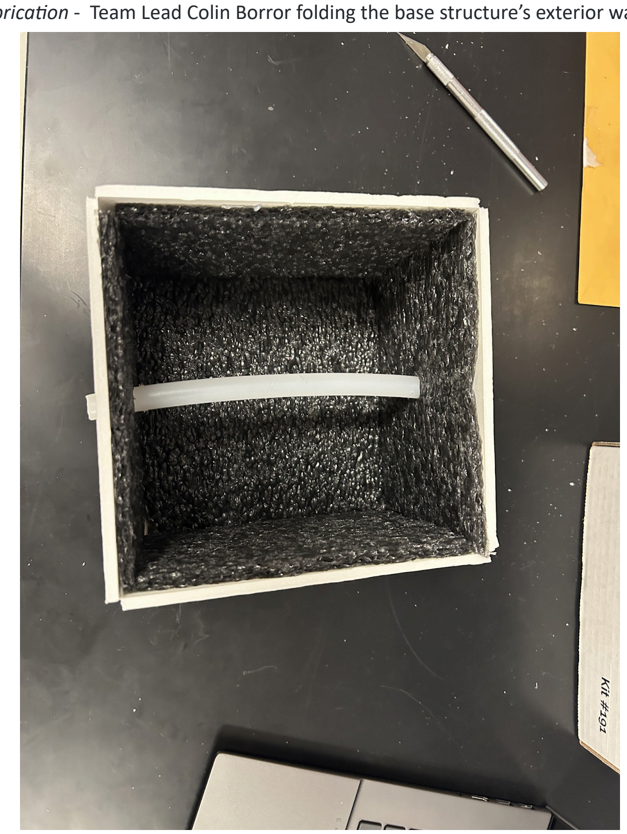

Fig 4.1.2: *Insulated Structure* photo by Colin Borror

Fig 4.1.3: The final payload test the night before flight. Photo by Marco Villasuso

Fig 4.2.1: The CO2 cartridge we planned to use for the test chamber. Photo by Colin Borror

Fig 4.2.2: The top of the test chamber, lighter, and servo/valve manifold after assembly. Photo by Marco Villasuso

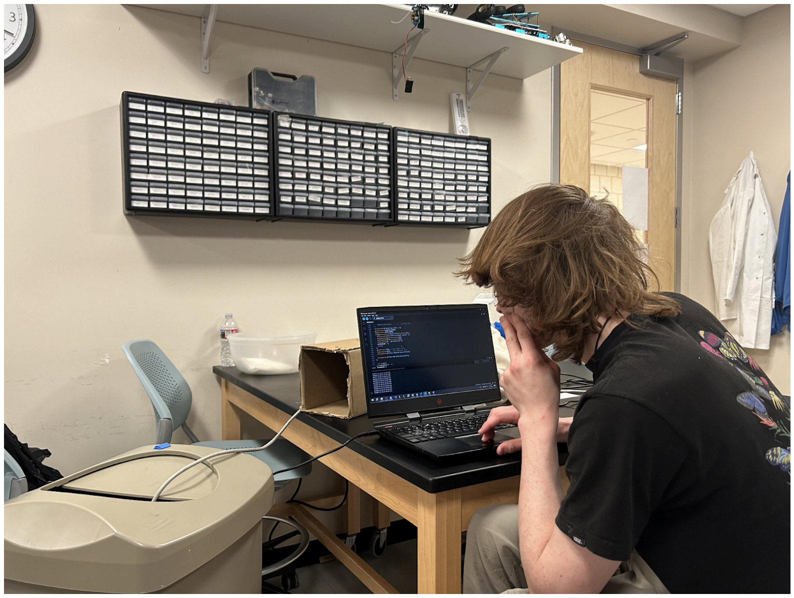

Fig 5.1.1: Marco watching ozone concentration during terrestrial test. Photo by Colin Borror

Fig 5.1.2: The terrestrial test setup. Photo by Marco Villasuso

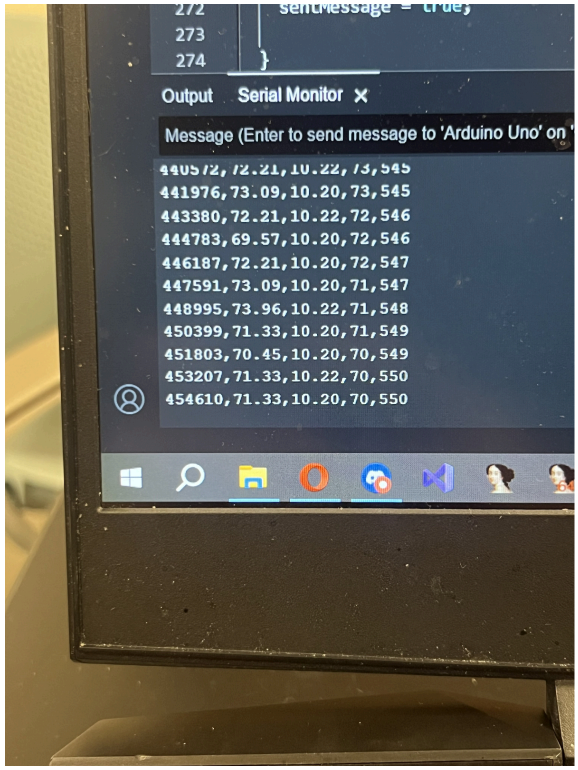

Fig 5.1.3: The ozone concentration falling in real time during tests (2nd to last number per row). Photo by Marco Villasuso

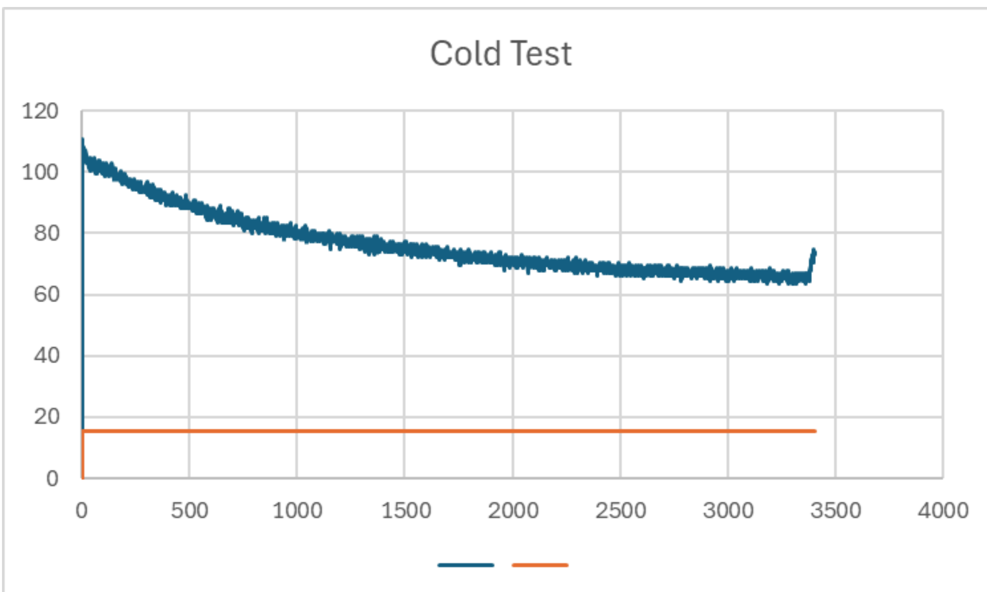

Fig 5.2.1: Cold Test Data

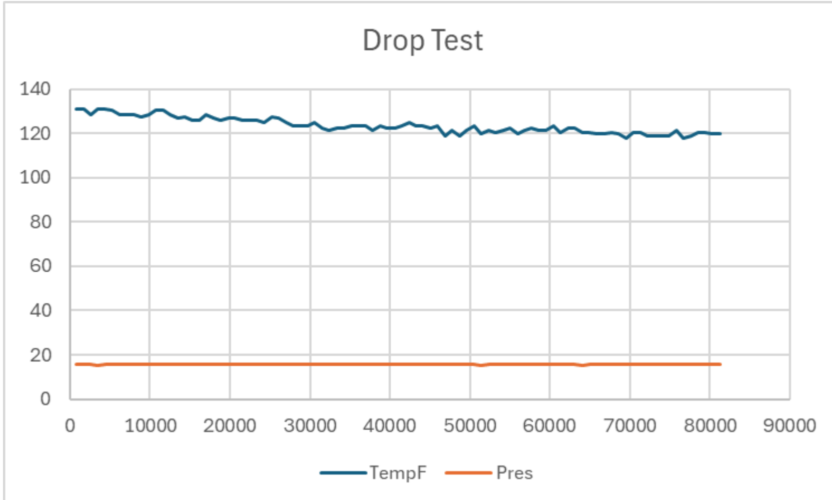

Fig 5.3.1: Drop Test Data

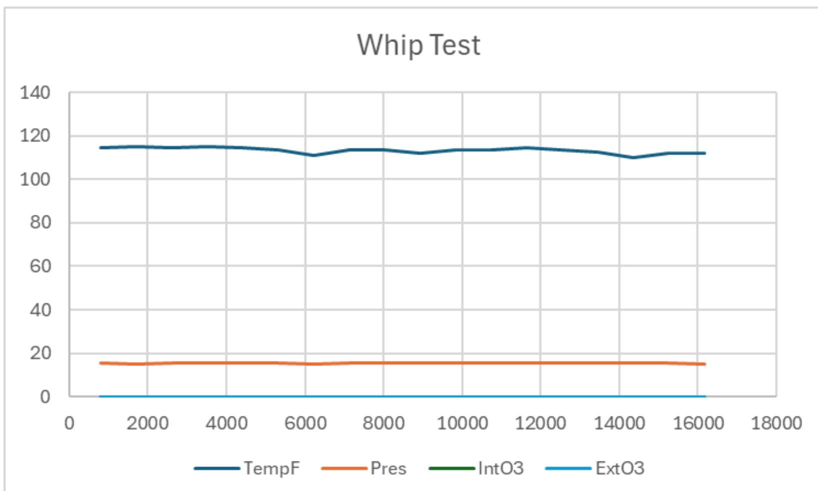

Fig 5.4.1: Whip Test Data

Fig 5.5.1: *Stair Test Data* - Data from sensors during stair test.

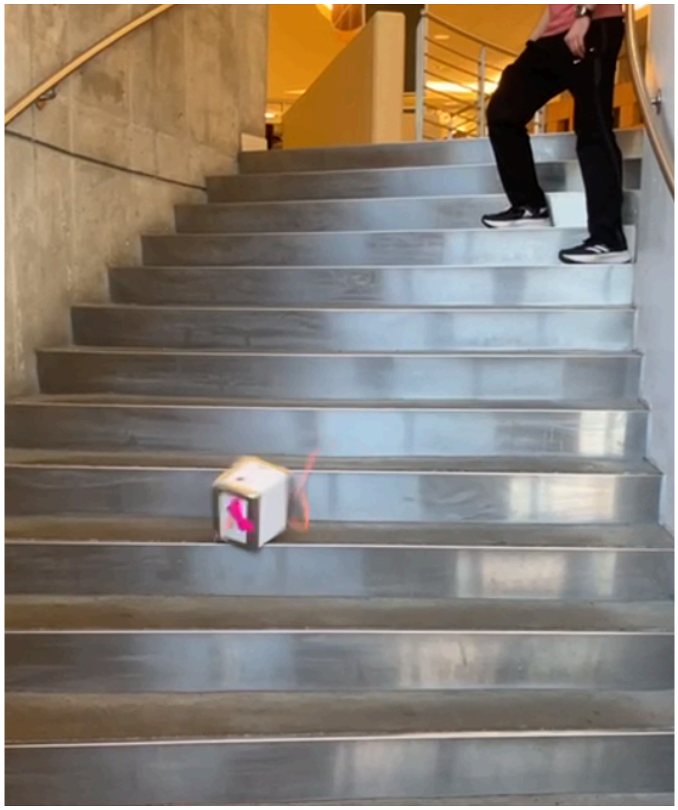

Fig 5.5.2: *Stair test* photo by Christopher Harrison and Colin Borror

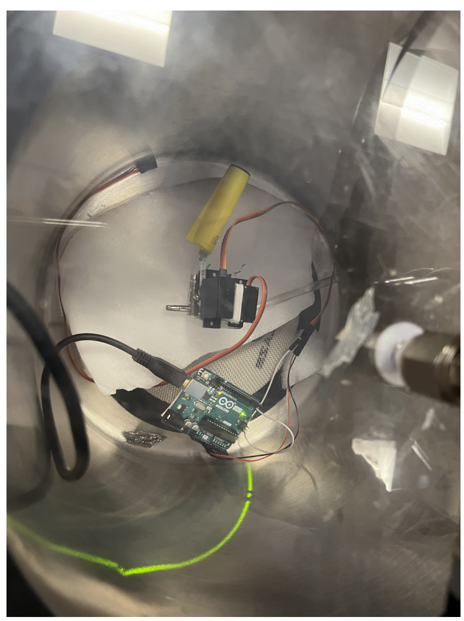

Fig 5.6.1: Pressure Test

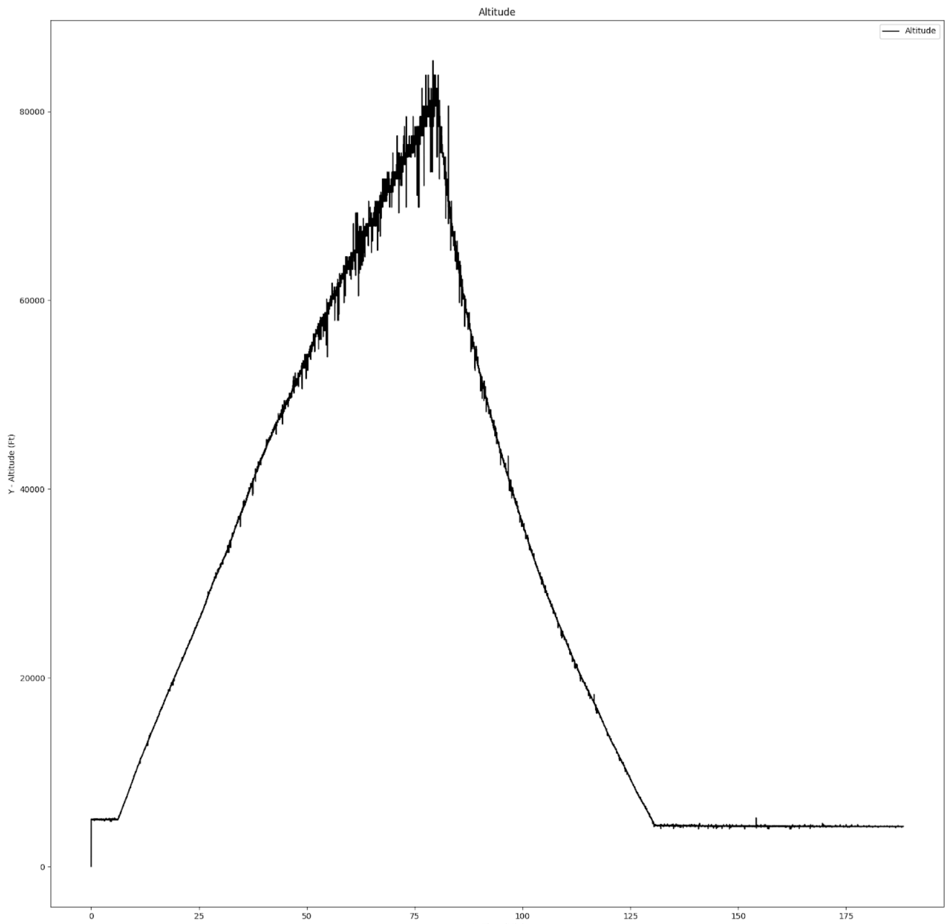

Fig 8.0.1: Altitude vs Time Graph

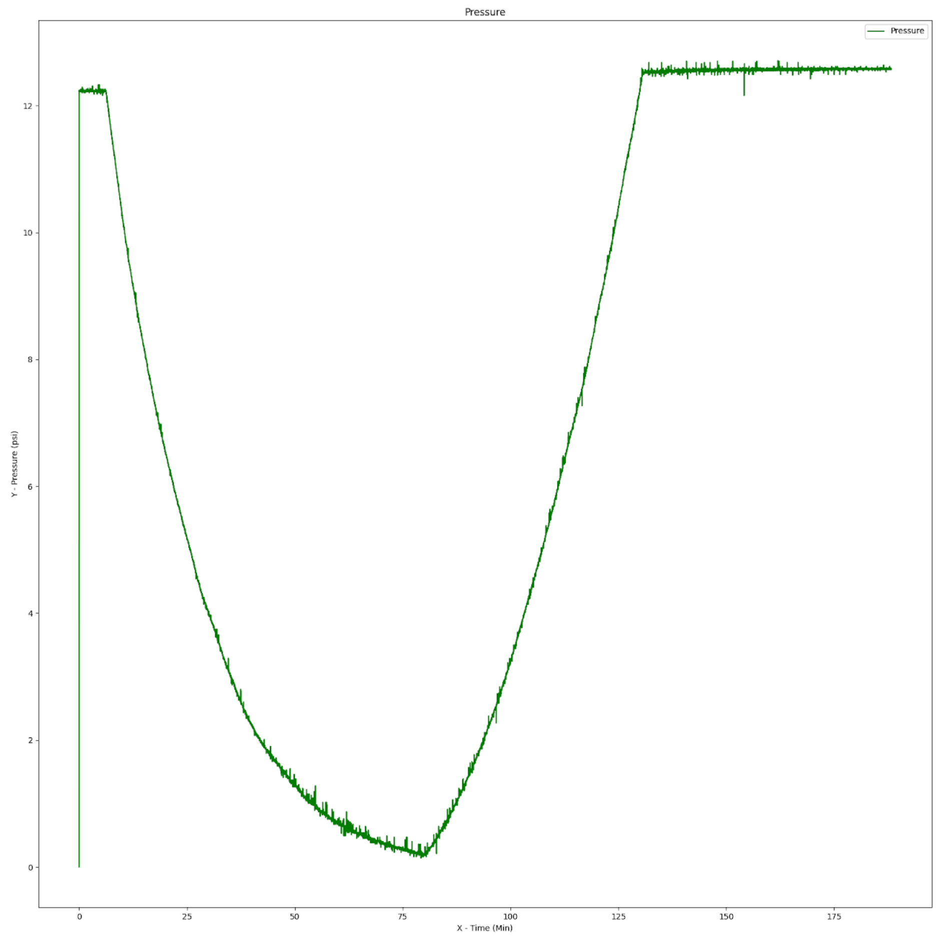

Fig 8.0.2: Pressure vs Time Graph

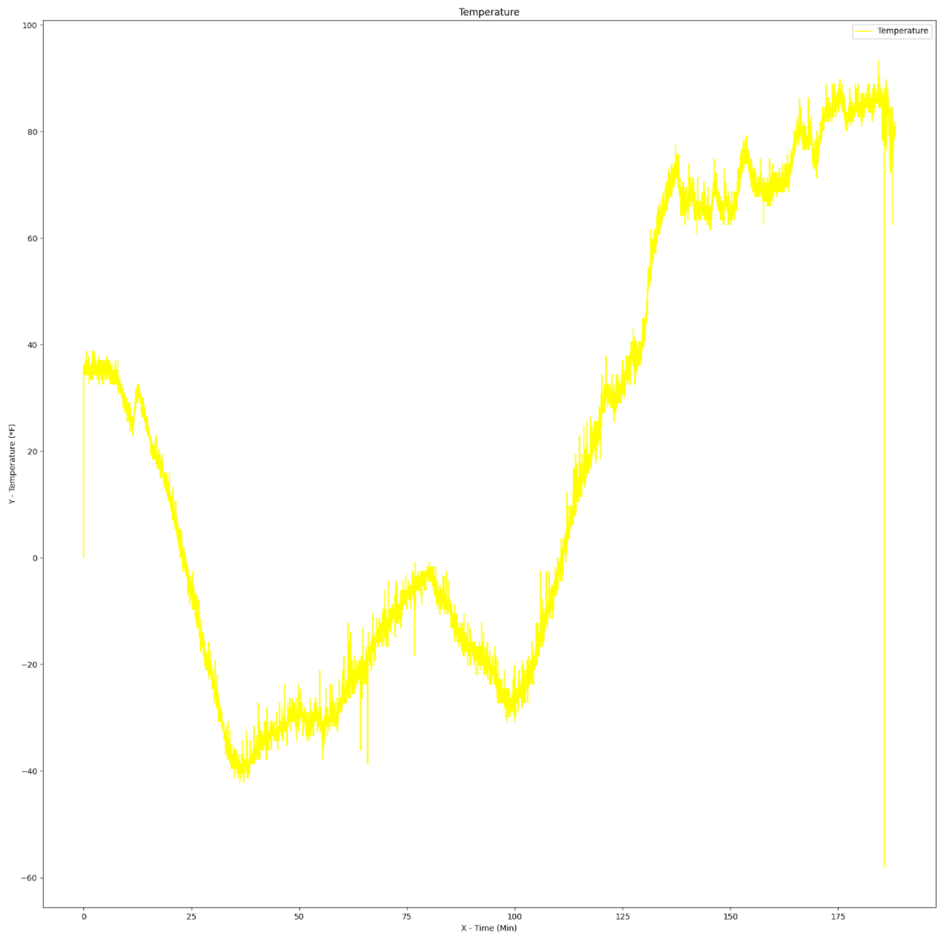

Fig 8.0.3: External Temperature vs Time Graph

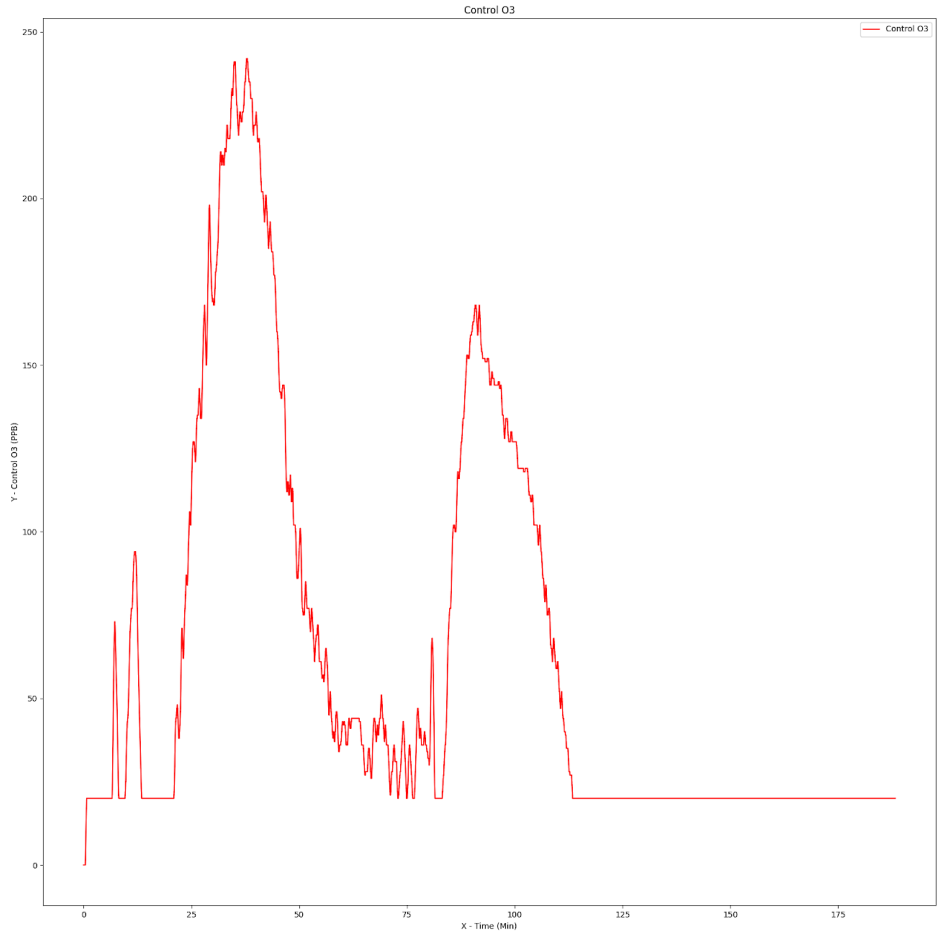

Fig 8.0.4: Control Ozone Concentration vs Time Graph

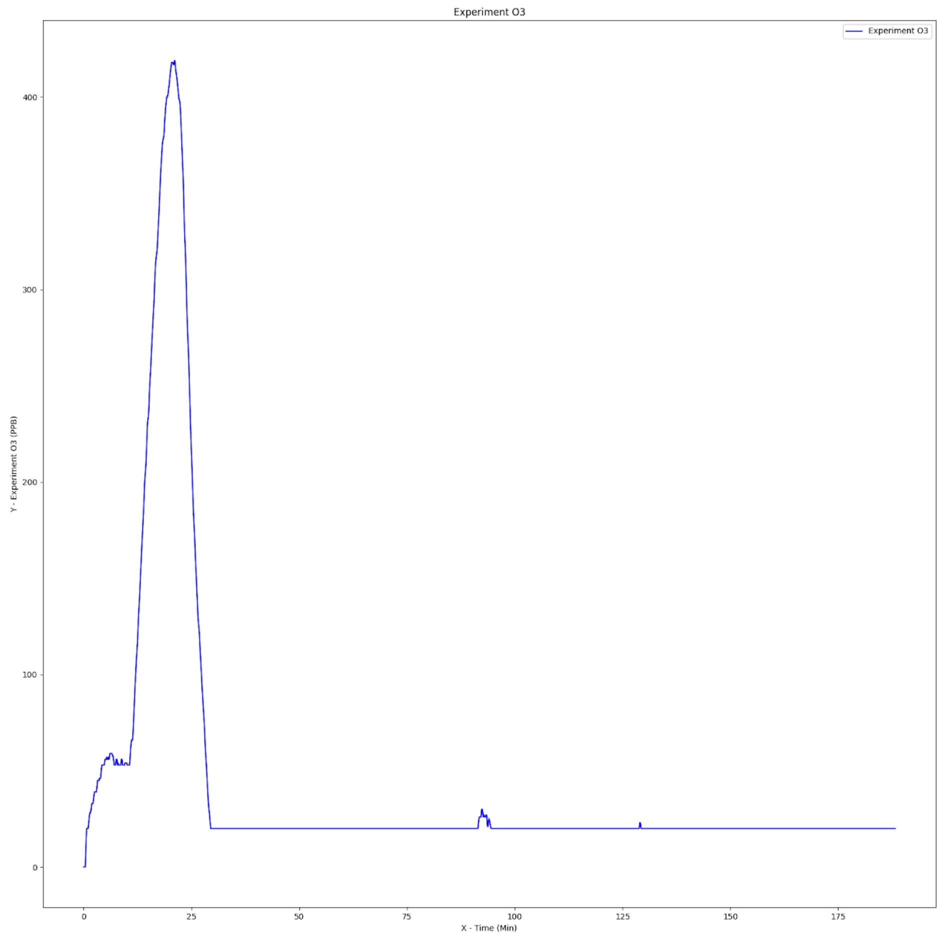

Fig 8.0.5: Experiment Ozone Concentration vs Time Graph

Component Name	Description	Price Spent
Arduino Stackable Header Kit - R3	Board Construction	$3.50
Break Away Headers - Straight	Board Construction	$3.50
Briskmore CO2 Cartridges	Test Chamber	$23.90
Clipper Lighters	Chemical Chamber	$14.15
DIP Sockets Solder Tail - 8-Pin	Board Construction	$1.10
Header - 6-pin Female (PTH, 0.1\")	Board Construction	$1.50
JST Jumper 2 Wire Assembly	Board Construction	$ 8.45
JST Jumper 3 Wire Assembly	Board Construction	$3.20
JST Jumper 4 Wire Assembly (x4)	Board Construction	$8.00
Ozone Sensors (x2)	Experiment and Control Sensors	$100.45
TMP36 Temperature Sensor	Replacement Part	$1.60
	Total Cost =	$169.35

Fig 11.0.1 - Price Chart

16.0 References

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