

Final Report

Sub-scale Adsorption and Compression CO₂ Removal System Re-design Team #22014

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Abstract

This system is a re-design of NASA's previously developed Thermally Coupled Temperature Swing Adsorption and Compression (TC-TSAC) systems, providing an air revitalization alternative to assist in the agency's Moon to Mars exploration objectives. The system consists of two half-cycles whereby packed beds of regenerable bulk sorbents and heat cycles simultaneously adsorb and compress carbon dioxide. The team designed the adsorption and compression beds in a cylindrical shape to maximize airflow. A desiccant bed helps lower humidity and the sorbent Zeolite 13X is used to capture carbon dioxide. Both are monitored by sensors. There is a custom heater within the system that lies in the adsorption bed to regenerate the sorbent, and there is a cooler around the compression bed. The system produced for NASA modeling, experimental test results, and operational results to be able to be scaled up to 4kg CO₂ removal per day. The system was found to be 1/16 scale for 1kg of CO₂ removal per day. The adsorption and desorption processes were successful, however issues with making the compression bed airtight resulted in an inability to demonstrate full compression. The team provided design suggestions and alternative solutions given these results. This paper describes the final design, fabrication, assembly, and testing of the TC-TSAC re-design.

1.0 Scope

Introduction

NASA is seeking more efficient ways of removing CO₂ to assist in the advancement of space exploration and life support systems. This system is to be used within the scope of the Moon to Mars eXploration Systems and Habitation mission (M2M X-Hab).

This system is based off of NASA's current TC-TSAC system (Thermally Coupled Temperature Swing Adsorption and Compression). TC-TSAC systems utilize packed beds of regenerable bulk sorbents and heat cycles to simultaneously adsorb and compress CO₂. Although TC-TSAC geometries have already been developed, this project aims to design and test a new system geometry where the compression bed is inside of the adsorption bed. This system will adsorb 1kg of CO₂ per day with a goal to be scalable for adsorbing up to 4kg of CO₂ per day. Sensors will be used to gather measurements and calculate necessary flow rates. Additionally, removal and compression beds of a cylindrical shape will be used. The system shall compress the acquired

CO₂ to 1000 torr. Ultimately, the system will need to use a recyclable sorbent, and be within necessary power, thermal, and performance requirements to improve the efficiency of the current design of the TC-TSAC system.

Stakeholders

The stakeholders for this project are NASA and Biosphere 2. This design has important implications for the Moon to Mars eXploration Systems and Habitation mission as well as the future of space life support systems. Since this project will be involved in the NASA mission critical path, design of the benchtop system is critical in the development of the part of the M2M X-Hab mission.

Product History and Background

TC-TSAC systems have already been developed, but this project aims to design and test a new system. TC-TSAC (Thermally Coupled Temperature Swing Adsorption and Compression) Systems use packed beds of regenerable bulk sorbents and heat cycles to simultaneously adsorb and compress CO₂. This design will continue the exploration of combining both CO₂ removal and compression in one system.

System Boundaries

The system boundary for this design is the CO₂ scrubber being contained in the design. Some of the potential auxiliary equipment for the project includes software and hardware that will be used to compress the carbon dioxide. The system has valves, fans, and beds that are integrated with other equipment such as sensors or other software.

System Environment

The system environment is likely indoors in a space system. The system shall be able to withstand some vibrations, have a controlled temperature, and have minimal particles. It shall also be able to withstand changes in temperature and humidity without degradation. It will need to be able to withstand harsh space conditions as well in terms of traveling from Earth to the Moon/Mars.

System Constraints

The most influential constraint for the system is a budget of \$. The project had to be completed within the timespan of the capstone. The sorbent used in the system is reusable. Additionally, the system should be capable of being scaled up to meet power and temperature requirements as well as withstanding external factors like vibrations and humidity.

System Use

The use for this system is for space life support or anything in space which requires carbon dioxide to be removed for missions. Specifically, this system will be used to separate carbon

dioxide from air for the Moon to Mars eXploration Systems. It will be used for deep space exploration air revitalization. Additionally, using reusable sorbents means this technology can be used as a sustainable way to continue exploring space. The project should hopefully improve mass, volume, and energy requirements, and present an alternative to current air revitalization systems.

Expected Output

The expected output for this project was a system prototype that has been experimentally tested and modeled to be scaled up to a full sized system. This system incorporates TC-TSAC geometry and a reusable sorbent to remove carbon dioxide from the air and compress it, storing it for later use elsewhere. This system should be capable of scaling up to 4kg CO₂/day of removal. It will be compared to a Paragon CO₂ removal system located at Biosphere 2. Additionally, design suggestions and/or alternative solutions should be presented following the completion of the project.

2.0 System Block Diagram

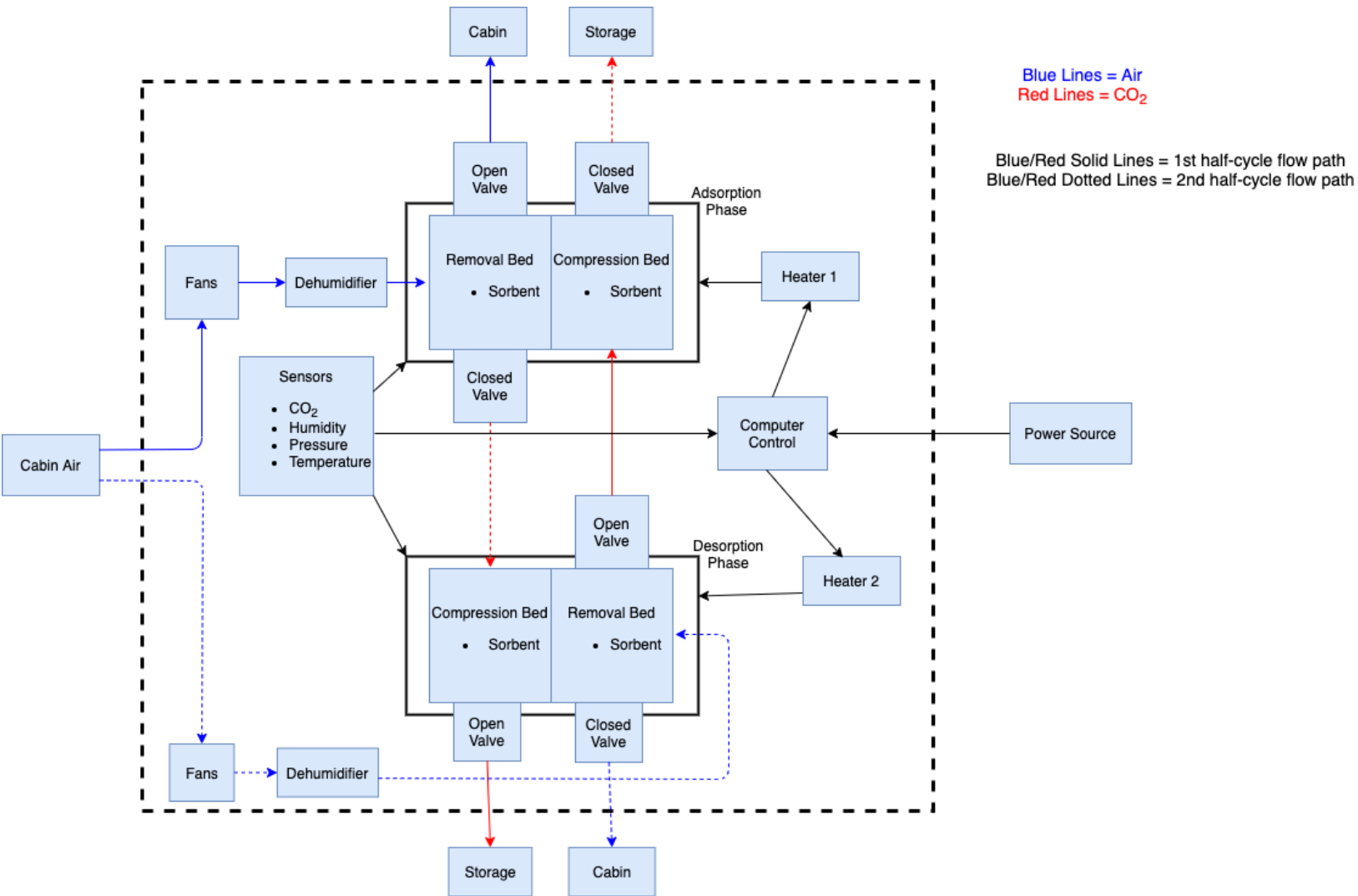


Figure 2.1. System Block Diagram

3.0 Statement of Requirements

1. The TS-TSAC system shall adsorb CO₂ from the circulating air.
2. The TS-TSAC system shall be closed-looped for the purpose of downstream processing.
3. The TS-TSAC system shall implement a recyclable sorbent (Zeolite 13X).
4. The TS-TSAC system shall regenerate sorbent with a heat cycle.
5. The TS-TSAC system shall store and compress CO₂.
6. The TS-TSAC system shall be scalable up to 4kg CO₂ capture per day.

4.0 Technical Data Package Summary

The Technical Data Package full document can be found in Appendix A. The purpose of this document is to provide detailed design documentation and specifications related to the construction of the final system. The project description, functional requirements, system verification plan, design documentation, system requirements document, and software design document can be found in this document.

5.0 Model / Analyses Summary

For our model/analyses of our final system, a benchtop system was constructed in order to see how the system might behave under final conditions. For this benchtop, one half of the system was created with commercially available parts from stores such as ACE Hardware. The initial schematic of the system is shown in Figure 5.1. This system served as a testing vessel for Critical Design Elements 1 and 2, with results detailed below.

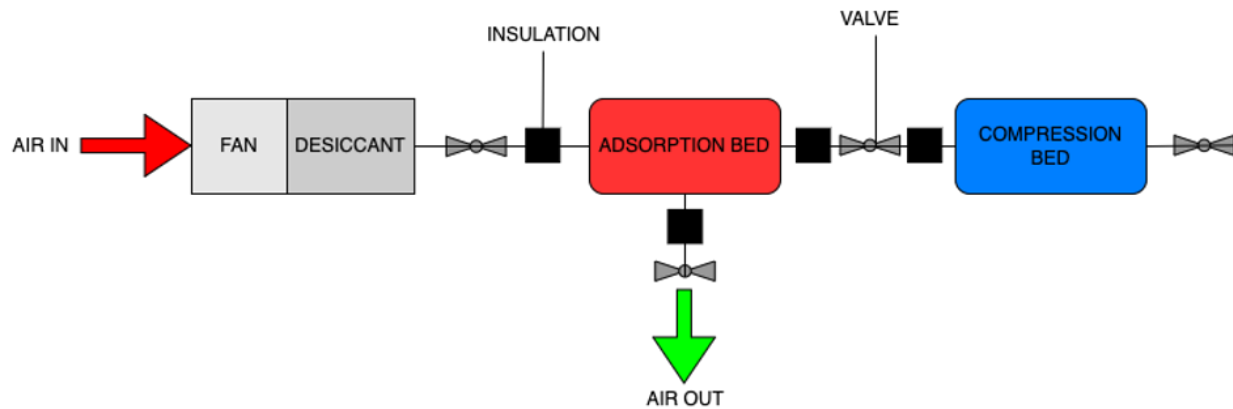


Figure 5.1. Benchtop System Schematic

The SVRM for the benchtop system first set of tests is shown in Table 5.2, and the detailed results and data sheets can be found in the Appendix A. This set of tests focused on testing the desiccant bed, sorbent (adsorption) and the airtight test.

The letters shown in Tables 5.2, 5.3, and 6.1 represent classical requirements verification methods. The letter “I” stands for inspection, which is defined as an observation where at least one of the five senses was used to verify that an item adheres to a specified requirement. The letter “D” stands for demonstration where the operation of an item must successfully complete the required functions under specified conditions. The letter “T” stands for test where the implementation of scientific principles and procedures are utilized to determine the functional capabilities of items within a system. Finally, the letter “A” stands for analysis where established technical models, mathematical models, simulations, analysis, or other scientific principles and procedures are used to create evidence that verifies an item meets requirements.

Table 5.2 Critical Design Element 1 SVRM

System Requirements	Subsystems							
	Bed 1	Bed 2	Airflow	Computer	Connection Assembly	Limit/Reference	Measured/Predicted Value	Pass/Fail
<u>4.4.3 Scalability:</u> The system shall be scalable up to 4kg of carbon dioxide removed per day. (A)	10. (Allocated) The bed shall be modeled to scale up to the larger system.	11. (Allocated) The bed shall be modeled to scale up to the larger system.				< ambient ppm output, measure humidity, temperature and CO ₂	Not fully tested yet	
<u>4.4.4 Airflow rate:</u> The system shall use the sensors and measure the flow rate of the air measuring the system. (A)					7. (Direct) The sensors should measure the flow rate and send the data to the computer.	No reference is needed, just need to analyze results	Not tested yet	
<u>4.4.5 CO₂ capture rate:</u> The system shall measure the carbon dioxide capture rate and display it on the sensor. (A)			4. (Derived) The sensors should measure the CO ₂ capture rate and send the data to the computer.			< ambient ppm output, measure humidity, temperature and CO ₂	CO ₂ was successfully adsorbed with numbers for how much, but more tests are needed to fully quantify rate	Pass

System Requirements	Subsystems							
	Bed 1	Bed 2	Airflow	Computer	Connection Assembly	Limit/Reference	Measured/Predicted Value	Pass/Fail
<u>4.1.1 Power:</u> The system shall be scalable up to approximately 200W for the full scale system. (T)	1. (Direct) Operates within the power consumption limit.	1. (Direct) Operates within the power consumption limit.	1. (Direct) Operates within the power consumption limit.	1. (Direct) Operates within the power consumption limit.	1. (Direct) Operates within the power consumption limit.	Around 200W power	Not tested yet	
<u>4.1.2 Vernier sensors:</u> The system shall use given Vernier sensors. (T)	2. (Direct) The system is connected to the sensors.	2. (Direct) The system is connected to the sensors.	2. (Direct) The system is connected to the sensors.	2. (Direct) The system receives input from the sensors.	2. (Direct) The system is connected to the sensors.	Functional and calibrated	We have been using vernier sensors to sense CO ₂ , humidity, and temperature through this point. In the future we will likely need other sensors as the temperatures will get very high.	Pass

4.2.1 Operational Temperature: The system shall perform without degradation at varying temperatures. (T)	3. (Direct) Operates within the heat cycle temperatures (30-300C)	3. (Direct) Operates within the heat cycle temperatures (30-300C)				Oven test, operates within 30-300 C	Not tested yet	
4.2.2 Operational Pressure: The system shall perform without degradation at different pressures. (T)	4. Operates within ~0-1.5atm	4. Operates within ~0-1.5atm				Operates within 0-1.5 atm	Not tested yet	
4.2.3 Zero Gravity Compatible: The system shall be able to perform its requirements in a zero gravity environment without degradation. (T)	5. (Direct) The system should be able to withstand zero gravity requirements.	5. (Direct) The system should be able to withstand zero gravity requirements.		4. (Direct) The system should be able to withstand zero gravity requirements.	3. (Direct) The system should be able to withstand zero gravity requirements.	System functions in zero gravity environment without falling apart	Not tested yet	

System Requirements	Subsystems							
	Bed 1	Bed 2	Airflow	Computer	Connection Assembly	Limit/Reference	Measured/Predicted Value	Pass/Fail
4.2.4 Operational Humidity: The system shall perform without degradation at different humidity. (T)	6. (Direct) The system should be able to withstand varied humidity levels.	6. (Direct) The system should be able to withstand varied humidity levels.		5. (Direct) The system should be able to withstand varied humidity levels.	4. (Direct) The system should be able to withstand varied humidity levels.	< 5% humidity in system, but can function at higher levels too	The percent humidity that was measured in our desiccant test was 7% which is higher than our target. It isn't so far off that we can't continue but it is definitely something we need to fix in the near future.	Fail
4.3.2 Temperature of the system is within safe range to touch: The system shall have exterior components to operate that are safe to touch and any other components that will not be used to operate the system and are unsafe to touch will be marked. (T/D)					6. (Derived) Parts that are unsafe to touch will be marked.	Parts can be touched without causing harm	Not tested yet	
4.3.3 No leaks: The system shall have no external leaks to the surroundings. (T/D/I)	8. (Derived) The system should have no external leaks.	8. (Derived) The system should have no external leaks.	3. (Derived) The system should have no external leaks.			Soapy water sprayed on system, no bubbles form	Not tested yet	

System Requirements	Subsystems							
	Bed 1	Bed 2	Airflow	Computer	Connection Assembly	Limit/Reference	Measured/Predicted Value	Pass/Fail
<u>4.4.1 Sorbent regeneration reliably:</u> The sorbent used (13X) shall be able to be used multiple times. (T)	9. (Derived) The sorbent should be demonstrated as recyclable.	9. (Derived) The sorbent should be demonstrated as recyclable.				Sorbent can be used multiple times and successfully regenerates through heating	Not tested yet	
<u>4.4.2 Adsorbed CO₂ compression:</u> The system shall compress the carbon dioxide to 1000 torr. (T)		10. (Derived) The system should be demonstrated to compress the CO ₂ to the desired pressure.				System compresses carbon dioxide to 1000 torr	Not tested yet	

The second set of modeling and analysis tests completed focused on passing the same tests as above, but instead using a different brand of silica gel beads as desiccant to pass the humidity requirement. In addition, a heating test was done for the adsorption bed to see if the carbon dioxide could be desorbed, and a compression test was planned. The SVRM shown in Table 5.3, and the detailed results and data sheets can be found in the Appendix.

Table 5.3 Critical Design Element 2 SVRM

System Requirement Verification				
Requirement	Method	Limit/Reference	Measured /Ref Value	Pass/Fail
Interface Requirements	-	-	-	-
a. Power Interface: The system shall be scalable up to approximately 200W for the full scale system.	I	N/A	TBD	TBD
a. Sensor Interface: Sensors work within the system and are calibrated to the correct values.	T	N/A	TBD	TBD
a. User Interface: Display the levels of CO ₂ , humidity, temperature and pressure within the system.	D, I	N/A	TBD	TBD
2. Environmental Requirements	-	-	-	-
a. Operational Temperature: The system shall perform without degradation at varying temperatures.	T	Operates within 30°C-300°C	TBD	TBD
a. Operational Pressure: The system shall perform without degradation at different pressures.	T	Operates within 0-1.5 atm	TBD	TBD
c. Zero Gravity Compatible: The system shall be able to perform its requirements in a zero gravity environment without degradation.	T	System functions in zero gravity environment without falling	TBD	TBD

		apart		
d. Operational Humidity: The system shall perform without degradation at different humidities.	T	<5% relative humidity	~0% relative humidity	Pass

System Requirement Verification				
Requirement	Method	Limit/Reference	Measured/Ref Value	Pass/Fail
3. Safety Requirements	-	-	-	-
a. Emergency Shutoff: The system shall have an emergency shutoff button.	D	N/A	TBD	TBD
a. Outside Temperature: The outside temperature of the system shall be safe enough to touch or marked if unsafe.	T, D	N/A	TBD	TBD
a. Leakage: The system shall be free of any leaks.	T, ,D, I	Negligible measured loss of pressure over time	TBD	TBD
4. Customer Constraints	-	-	-	-
a. Scalability: The system shall be scalable up to adsorbing 4 kg of CO ₂ /day.	A	1kg of CO ₂ /day is adsorbed	TBD	TBD
a. Cost: The system shall cost no more than the given budget to build (\$).	I	<\$, but extra funds may be provided from NASA	\$ left	Pass

System Requirement Verification				
Requirement	Method	Limit/Reference	Measured/Ref Value	Pass/Fail
5. Performance Requirements				
a. Sorbent Regeneration: The sorbent shall be regenerative for multiple uses.	T	Sorbent can be used multiple times and successfully regenerates through heating	TBD	TBD
a. Carbon Dioxide Compression: The adsorbed carbon dioxide shall be compressed to 1000 torr.	T	System compresses carbon dioxide to 1000 torr	TBD	TBD

a. Airflow Rate: The system shall measure the flow rate of air entering the system.	T	N/A since this value will be measured	~4.8 m/s	Pass
e. Carbon Dioxide Capture Rate: The system shall measure the amount of carbon dioxide that is captured.	A	< ambient concentration over time	~0.12-0.18 CO ₂ /day is adsorbed	Pass
6. Design Requirements	-	-	-	-
a. Sorbent: The system shall use zeolite 13X as a sorbent.	I	Zeolite 13X used	13X is used	Pass
a. Sensors: Sensors used within the system shall be able to withstand high temperatures (up to 300°C).	I	Sensors can withstand conditions and successfully record results	TBD	TBD

Overall, this benchtop system analysis helped predict how a final system might behave when fully constructed. We were able to verify everything but compression before even beginning to manufacture and weld the final canisters.

6.0 Acceptance Test Results

In order to fully test the system, baseline tests were conducted in addition to final system tests. These tests occurred at Biosphere 2 in Oracle, Arizona. A sealed system made of 6-mil polyethylene plastic and duct tape, and painters tape was constructed. The volume of the system was 133,980 in³ and the surface area was 28,336 in². In this system, the entire CO₂ scrubber was placed along with all wires and sensors needed, which were then taped up to the floor in order to make the testing location as airtight as possible. A CO₂ canister was used to add carbon dioxide into the system. For every test, humidity, temperature and carbon dioxide concentration sensors were used. Each test was run for over an hour except for the second adsorption test, which was run for 45 minutes. For the desorption and compression tests, thermistors (to measure the heat tape temperature) and a pressure transducer were also used. Tests for the baseline comparison (using a given Paragon scrubber) included:

1. Sealing the system and measuring CO₂ concentration after an hour, so as to determine the leak rate of the area.
2. Repeating the test above, this time running a fan.
3. Adding Zeolite 13X to the Paragon scrubber and running the fan.

Tests for the final system (using re-designed TC-TSAC) included:

1. Sealing the system, running a fan, and measuring CO₂ concentration after an hour, so as to determine the leak rate of the area.

2. Adsorption test, measuring the amount of CO₂ captured.
3. Desorption test, using heat tape to release CO₂, no fan.
4. Second adsorption tests, running the fan again.
5. Desorption and compression test, using heat tape and pressure transducer, no fan.



Figure 6.1. Full TC-TSAC system re-design



Figure 6.2. Paragon CO₂ Scrubber



Figure 6.3. Inside bed with heat tape and zeolite

Figures 6.1, 6.2, and 6.3 show the re-designed TC-TSAC system and Paragon scrubber that were

tested as well as the inside of the re-designed scrubber with zeolite and the heat tape. For more images relating to test setup, see Appendix E.

The verification procedures for each test are as follows:

Verification Procedures

1. Operational Temperature: The system shall perform without degradation at varying temperatures. (T)
 - Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022
 - Procedure: Run heating in the system and make sure temperature within each part will not degrade the system. **Mark Pass/Fail on the datasheet.**
2. Operational Pressure: The system shall perform without degradation at different pressures. (T)
 - Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022
 - Procedure: Run the system and make sure pressure within each part will not degrade the system. **Mark Pass/Fail on the datasheet.**
3. Operational Humidity: The system shall perform without degradation at different humidity. (T)
 - Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022
 - Procedure: Run the system and make sure humidity within each part will not degrade the system. Make sure humidity can be lowered to around ~10% relative humidity. **Mark Pass/Fail on the datasheet.**
4. No leaks: The system shall have no external leaks to the surroundings. (T/D/I)
 - Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022
 - Procedure: Run compression test and ensure pressure can be built up in the system. If not, it means there is a leak. **Mark Pass/Fail on the datasheet.**

5. Sorbent regenerates reliably: The sorbent used (13X) shall be able to be used multiple times. (T)
- Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022
 - Procedure: Run system and use carbon dioxide concentration and desorption results to indicate whether or not the system successfully regenerates the sorbent. **Mark Pass/Fail on the datasheet.**
6. Adsorbed CO₂ compressed to 1000 torr: The system shall compress the carbon dioxide to 1000 torr. (T)
- Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022
 - Procedure: Run system and make sure the carbon dioxide can be compressed to the target pressure. **Mark Pass/Fail on the datasheet.**
7. The system should be scalable up to 4kg CO₂/day: The system shall be scalable up to 4kg of carbon dioxide removed per day. (A)
- Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022
 - Procedure: Use measured values from the sensors to perform this calculation. **Mark Pass/Fail on the datasheet.**
8. Airflow rate: the system shall measure the flow rate of air entering the system: The system shall use the sensors and measure the flow rate of the air measuring the system. (T)
- Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022
 - Procedure: Use an airflow sensor and ensure it works in the system. **Mark Pass/Fail on the datasheet.**
9. CO₂ capture rate: the system shall measure the rate that CO₂ is captured: The system shall measure the carbon dioxide capture rate and display it on the sensor. (A)
- Expected Test Date(s): 04/23/2022
 - Completed Date(s): 04/23/2022

- Procedure: Use measured values from the sensors to perform this calculation. **Mark Pass/Fail on the datasheet.**

The following System Requirements Verification Matrix (SVRM) is a summary of the verifications completed for the full system. The matrix represents four ways of verifying the requirements: Demonstration (D), Inspection (I), Analysis (A), and Test (T).

Table 6.1 System Requirements Verification Matrix

System Requirement Verification				
Requirement	Method	Limit/Reference	Measured/Ref Value	Pass/Fail
1. Interface Requirements	-	-	-	-
a. Power Interface: The system shall be scalable up to approximately 200W for the full scale system.	I	N/A	Gave ourselves this requirement without knowing what the system would look like	ECR
b. Sensor Interface: Sensors work within the system and are calibrated to the correct values.	D	N/A	Sensors connected	Pass
c. User Interface: Display the levels of CO ₂ , humidity, temperature and pressure within the system.	D, I	N/A	Display functional	Pass
2. Environmental Requirements	-	-	-	-
a. Operational Temperature: The system shall perform without degradation at varying temperatures.	T	Operates within 30°C-300°C	Operates within 30°C-300°C without degradation	Pass
b. Operational Pressure: The system shall perform without degradation at different pressures.	T	Operates within 0-1.5 atm	-	Not able to be tested
c. Zero Gravity Compatible: The system shall be able to perform its requirements in a zero gravity environment without degradation.	T	System functions in zero gravity environment without falling apart	-	Not able to be tested
d. Operational Humidity: The system shall perform without degradation at different humidities.	T	<10% relative humidity	<10% relative humidity	Pass
3. Safety Requirements	-	-	-	-
a. Emergency Shutoff: The system shall have an emergency shutoff button.	D	N/A	Unplug system, rather than button	ECR
b. Outside Temperature: The outside temperature of the system shall be safe enough to touch or marked if unsafe.	D, I	N/A	Insulation used	Pass
c. Leakage: The system shall be free of any leaks.	T, D, I	Negligible measured loss of pressure over time	Compression bed leaks	Fail
4. Customer Constraints	-	-	-	-

a. Scalability: The system shall be scalable up to adsorbing 4 kg of CO ₂ /day.	A	1kg of CO ₂ /day is adsorbed	~0.25 kg of CO ₂ /day is adsorbed	Fail
b. Cost: The system shall cost no more than the given budget to build (\$).	I	Under budget	Within budget	Pass
5. Performance Requirements				
a. Sorbent Regeneration: The sorbent shall be regenerative for multiple uses.	T	Sorbent can be used multiple times and successfully regenerates through heating	Desorption process regenerates sorbent	Pass
b. Carbon Dioxide Compression: The adsorbed carbon dioxide shall be compressed to 1000 torr.	T	System compresses carbon dioxide to 1000 torr	Compression bed has leaks - unable to gather data	Fail
c. Airflow Rate: The system shall measure the flow rate of air entering the system.	T	N/A since this value will be measured	Measures flow rate using flow meter	Pass
e. Carbon Dioxide Capture Rate: The system shall measure the amount of carbon dioxide that is captured.	A	< ambient concentration over time	Measures indirectly	Pass
6. Design Requirements				
a. Sorbent: The system shall use zeolite 13x as a sorbent.	I	Zeolite 13X used	13X is used	Pass
b. Sensors: Sensors used within the system shall be able to withstand high temperatures (up to 300°C).	I	Sensors can withstand conditions and successfully record results	Sensors can withstand conditions and successfully record results	Pass

Test Results Summary

This is a summary of the test results and plots achieved. Some additional plots are left out of these results, and can be found in Appendix C.

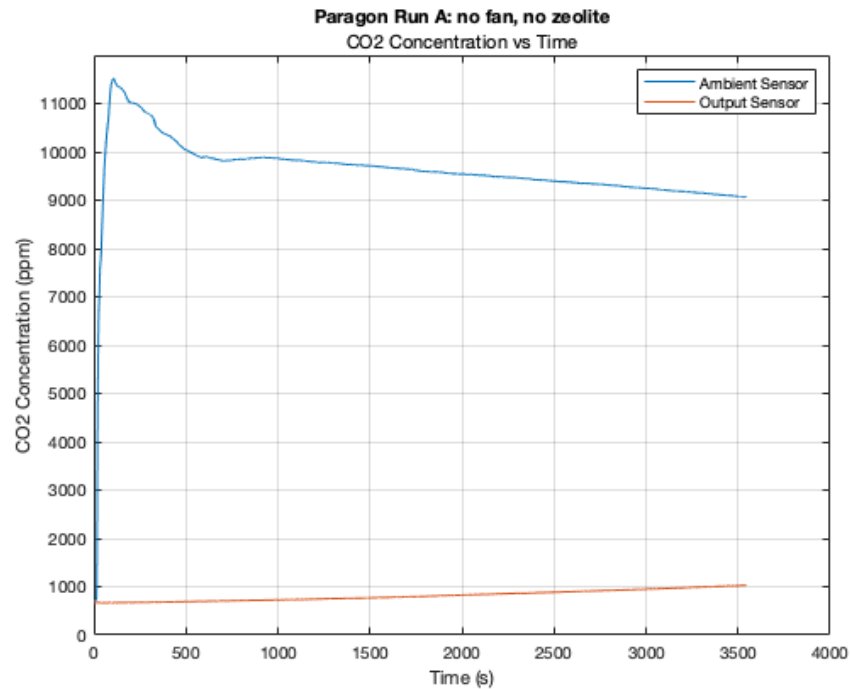


Figure 6.4. Paragon test with no fan and no zeolite.

Figure 6.4 shows the leak rate of the system, given this test was the concentration of carbon dioxide with no fan or zeolite. Results indicated a loss of around 3000 ppm.

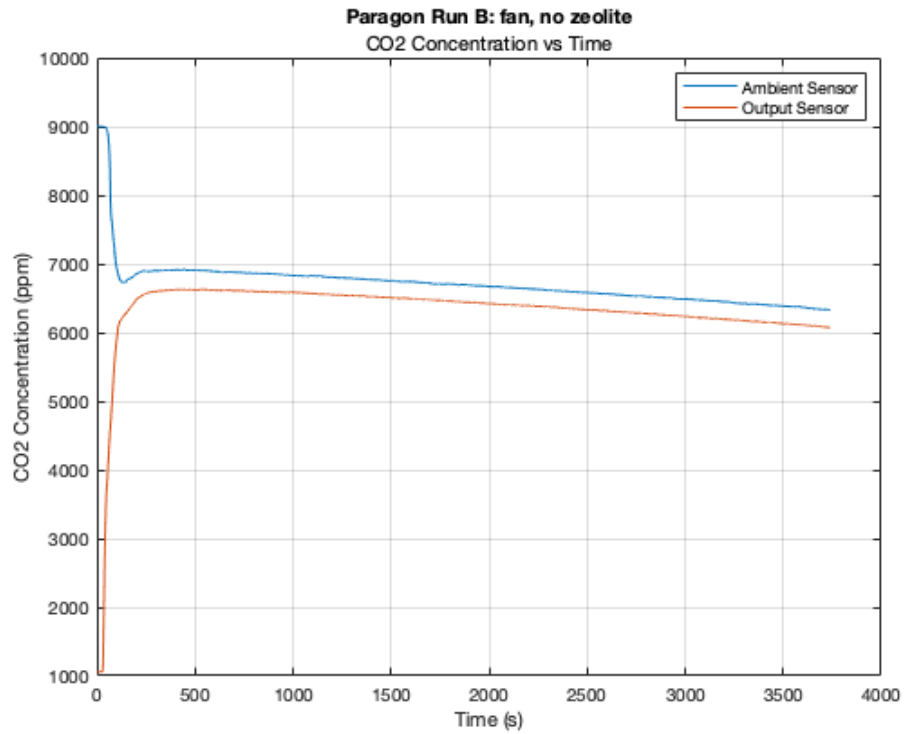


Figure 6.5. Paragon test with fan and no zeolite.

Figure 6.5 shows the leak rate of the system with the fan running. Results indicated a loss of around 2600 ppm.

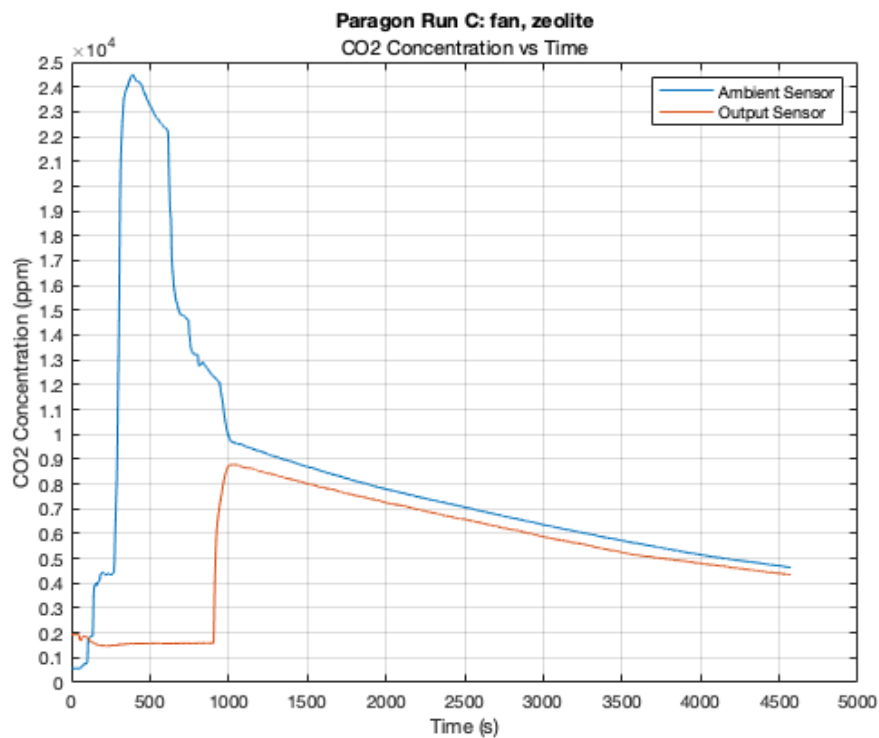


Figure 6.6. Paragon test with fan and zeolite.

Figure 6.6 shows the concentration of carbon dioxide after an hour with the Zeolite 13X and fan running. Results indicated a loss of around 20000 ppm.

Table 6.2 Paragon Test Results

PARAGON		
Test	CO₂ diff (ppm)	Mass of CO₂ adsorbed/lost (kg)
A (no fan)	3099.83	
B (fan)	2677.5	0.008
C (fan, zeolite)	19913	0.013
C w/ leaks	17235.5	0.005

PARAGON	
Velocity Flow Rate (m/s)	0.569
Mass of CO ₂ Adsorbed (kg)	0.005
CO ₂ Adsorption Rate (kg/s)	0.000
CO ₂ produced by 1 human (kg/day)	1.000
CO ₂ adsorption per day (kg/day)	0.092
Volume of zeolite used (in ³)	131.590
CO ₂ adsorption per day per volume zeolite (kg/day/in ³)	0.001

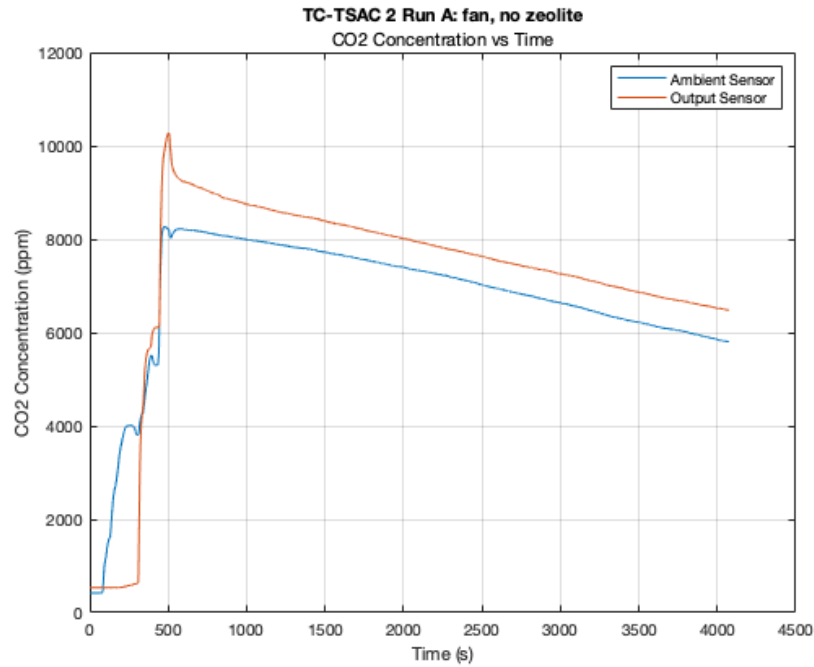


Figure 6.7. TC-TSAC test with fan and no zeolite.

Figure 6.7 shows the concentration of carbon dioxide after an hour with the fan running for the re-designed system. Results indicated a loss of around 2800 ppm.

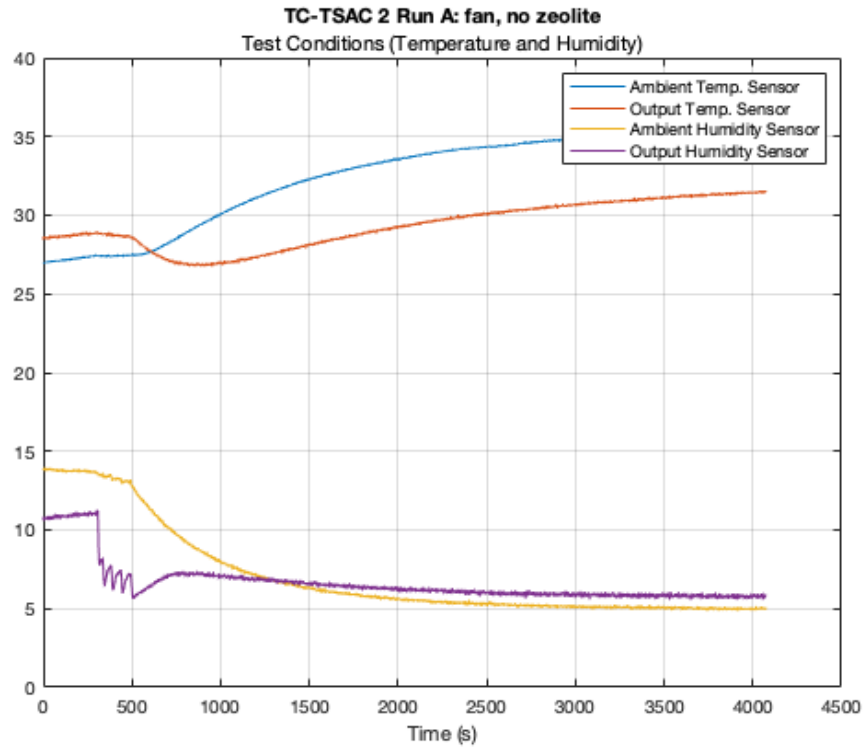


Figure 6.8. TC-TSAC test with fan and no zeolite ambient conditions.

Figure 6.8 shows the temperature and relative humidity conditions for the test A. The desiccant is shown to be relatively effective, reducing the humidity to around 5%. The temperature increase is due to the fan running in the sealed system.

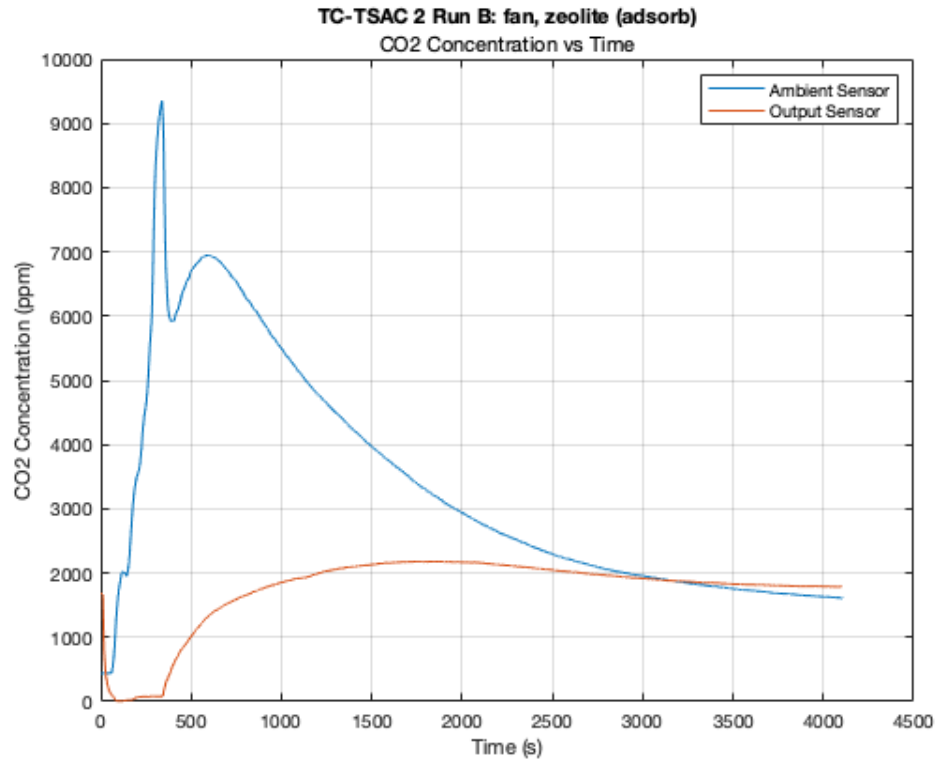


Figure 6.9. TC-TSAC test with fan and zeolite.

Figure 6.9 shows the carbon dioxide concentration over time. The dips towards the start of the curve are due to the fan being kicked on. This allowed the air in the system to mix which explains why it looks like there is a sudden drop in the carbon dioxide concentration. The flattening shows when the zeolite gets saturated. Looking at the humidity graph, it may be due to the fact that excess water is causing the system to saturate faster.

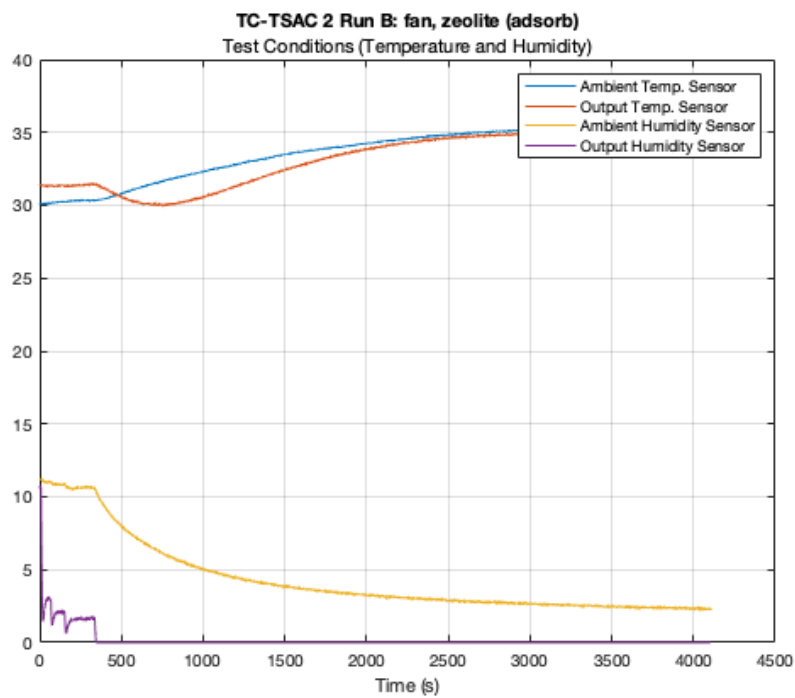


Figure 6.10. TC-TSAC test with fan and zeolite ambient conditions.

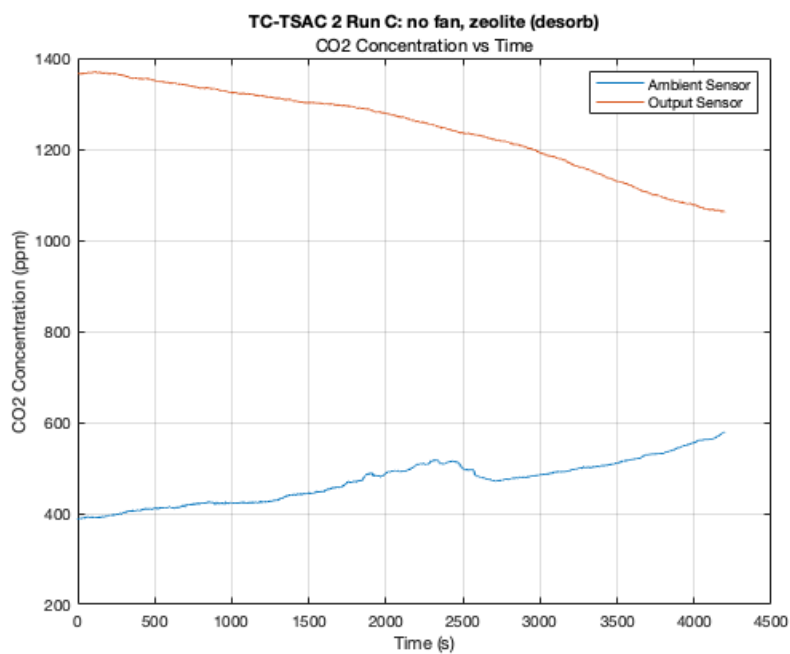


Figure 6.11. TC-TSAC test with heat tape (desorption test).

Shown in Figure 6.11, the desorb test did not release as much carbon dioxide as desired since it took awhile for the heat tape to reach the ideal temperature.

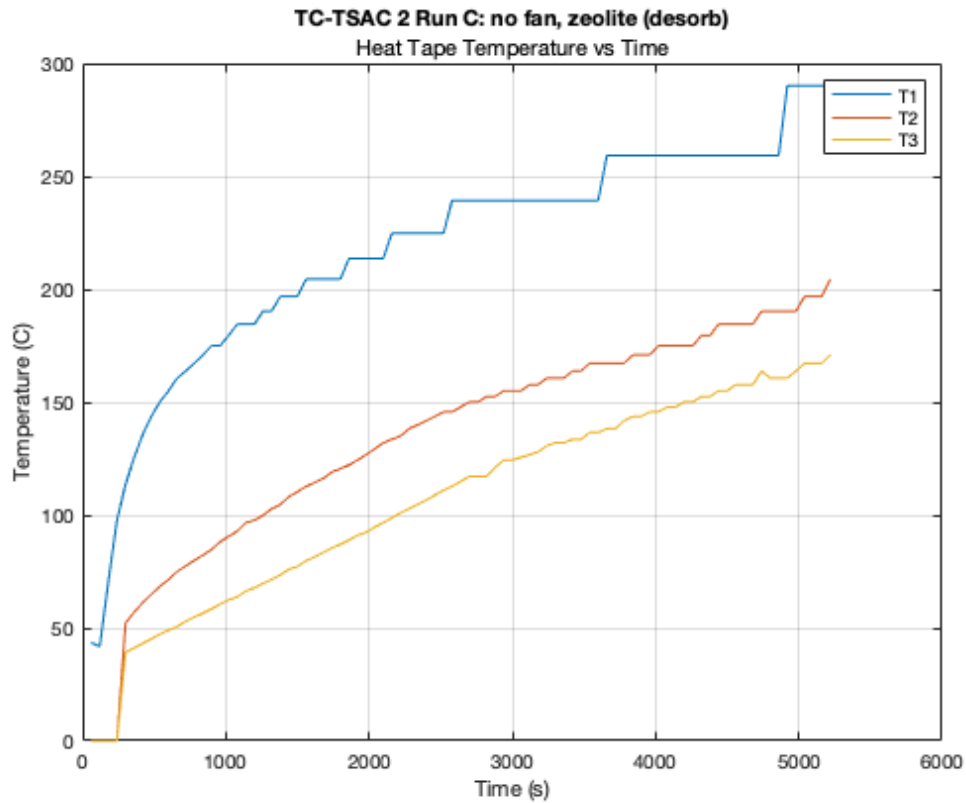


Figure 6.12. TC-TSAC test with heat tape (desorption test) heat tape temperature versus time.

As in Figure 6.12, the step pattern originated from the fact that the microcontroller could perform an analog to digital conversion with 10 bits. With large values it causes the difference between bits to be represented as having large differences. Something to consider in the future is using a separate analog to digital converter that uses more bits to convert and that way the latter pattern will be reduced.

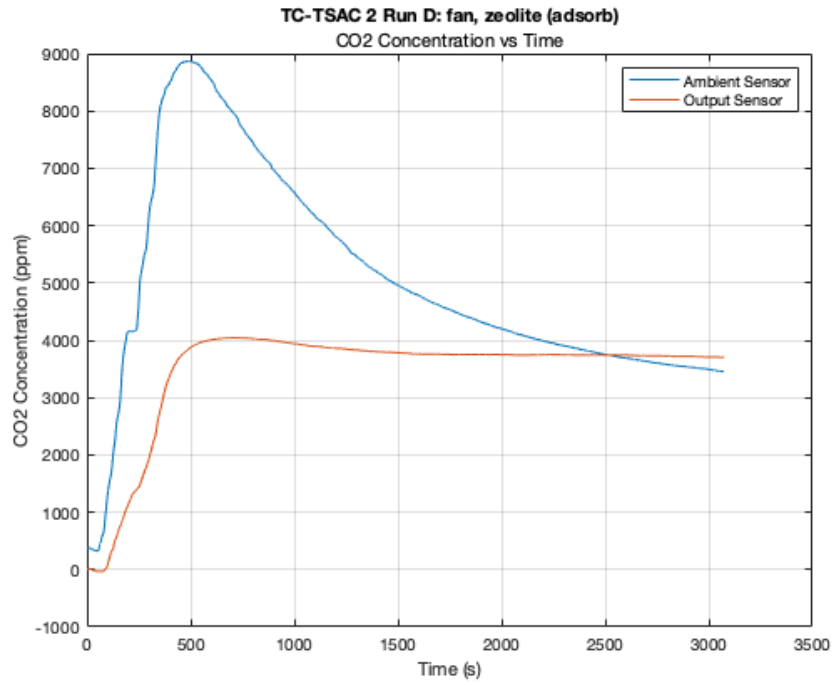


Figure 6.13. TC-TSAC test with fan and zeolite.

Figure 6.13 shows the second adsorption test data.

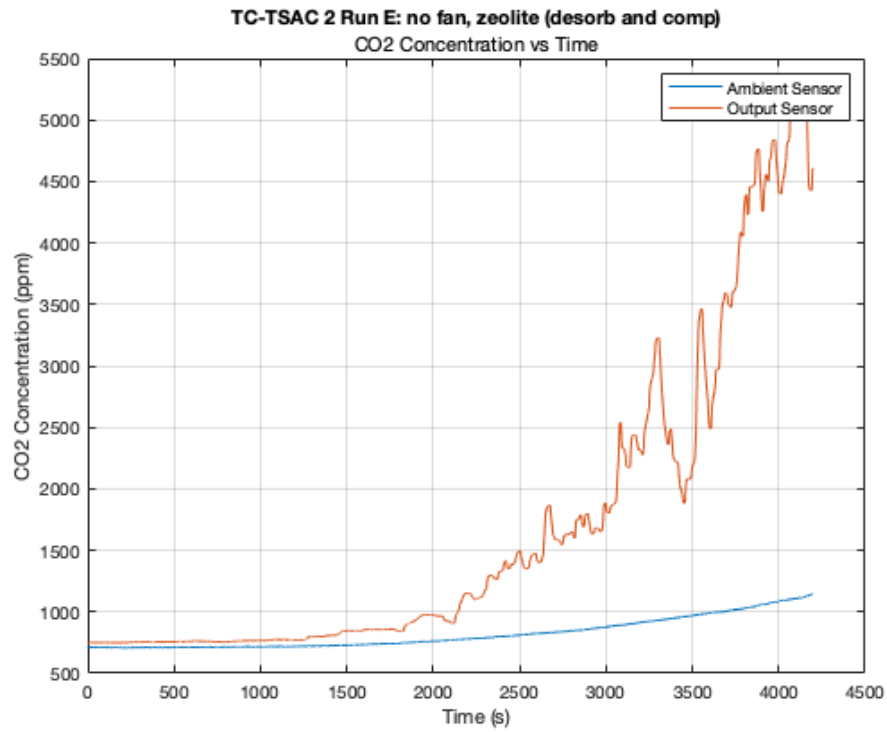


Figure 6.14. TC-TSAC desorption and compression test.

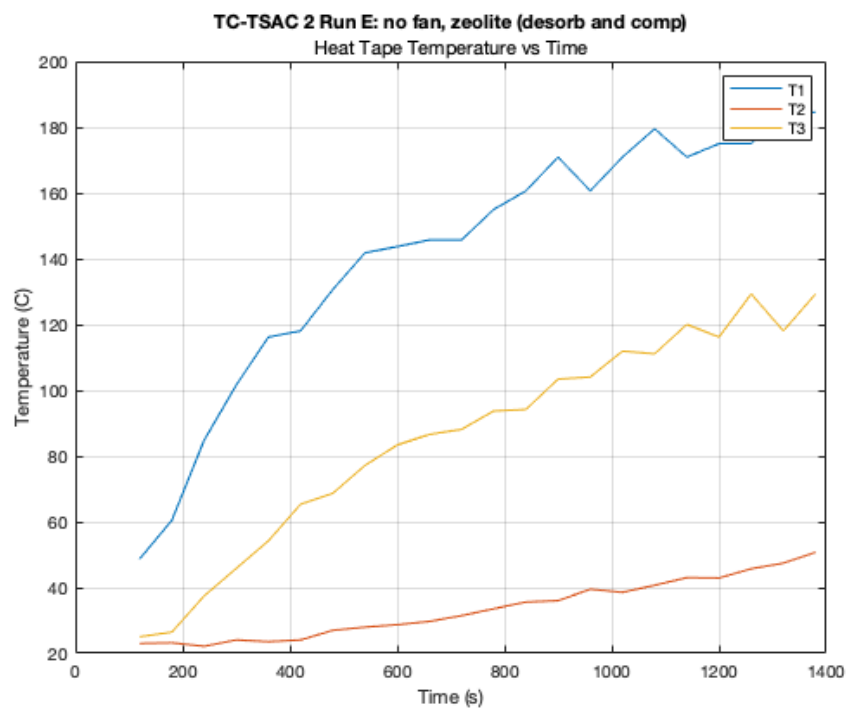


Figure 6.15. TC-TSAC desorption and compression test heat tape temperature versus time.

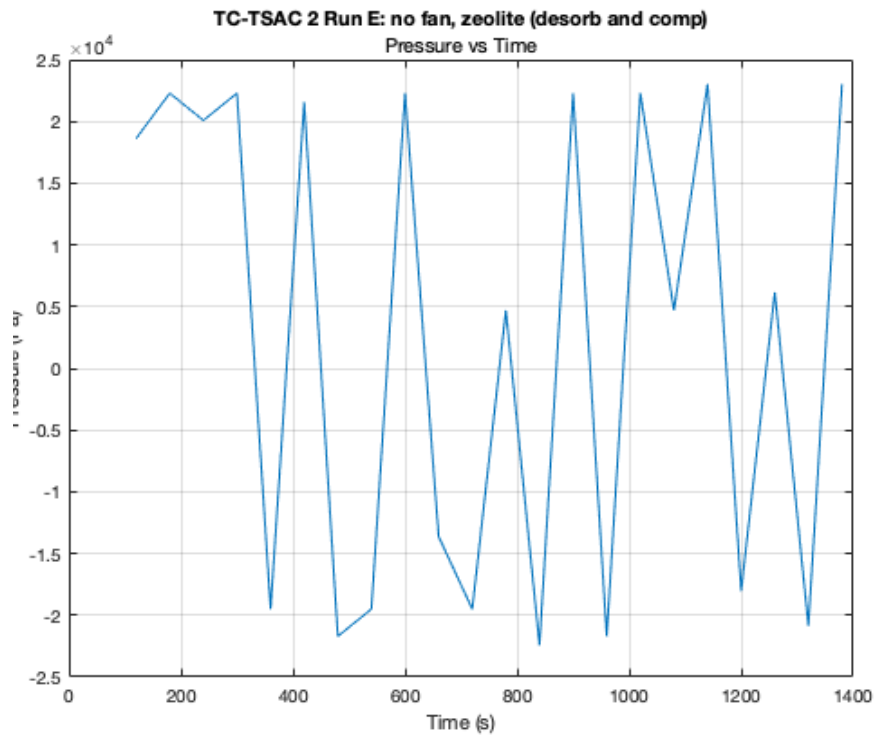


Figure 6.16. TC-TSAC desorption and compression test pressure sensor data.

As in Figures 6.14, 6.15, and 6.16, the compression bed had leaks so the pressure sensor did not accurately capture data. Data was not fully captured for the whole time due to the data acquisition corrupting the data past the 1400 second mark. The temperature data did however follow similar trends as the desorb test.

Table 6.3 TC-TSAC Re-design Test Results

TC-TSAC RE-DESIGN		
Test	CO ₂ diff (ppm)	Mass of CO ₂ adsorbed/lost (kg)
A (fan)	2870.89	0.009
B (adsorb)	7738.67	0.022
B w/ leaks	4867.78	0.012
C (desorb)	191.33	0.001
D (adsorb)	5413	0.019
D w/ leaks	2542.11	0.010
E (desorb comp)	437.83	0.002

TC-TSAC RE-DESIGN	
B (adsorb)	
Velocity Flow Rate (m/s)	4.030
Mass of CO ₂ Adsorbed (kg)	0.012
CO ₂ Adsorption Rate (kg/s)	3.005E-06
CO ₂ produced by 1 human (kg/day)	1.000
CO ₂ adsorption per day (kg/day)	0.260
Volume of zeolite used (in ³)	60.080
CO ₂ adsorption per day per volume zeolite (kg/day/in ³)	0.004

TC-TSAC RE-DESIGN	
D (adsorb)	
Velocity Flow Rate (m/s)	4.820
Mass of CO ₂ Adsorbed (kg)	0.010
CO ₂ Adsorption Rate (kg/s)	2.448E-06
CO ₂ produced by 1 human (kg/day)	1.000
CO ₂ adsorption per day (kg/day)	0.212
Volume of zeolite used (in ³)	60.080
CO ₂ adsorption per day per volume zeolite (kg/day/in ³)	0.004

The results (per Table 6.2 And 6.3) show that overall, per unit volume of zeolite, the re-designed TC-TSAC carbon dioxide scrubber outperformed the Paragon scrubber in terms of adsorption. The adsorption per day for the Paragon was 0.001 kg CO₂ adsorption per day per volume of Zeolite 13X used (kg/day/in³), versus 0.004 for the re-designed scrubber. This indicates that the TS-TSAC is 4 times more efficient than the existing Paragon scrubber. For more details on graphs showing the system performance in various tests, see the Appendix C.

In summary, every requirement except for the compression, airtight, and scalability was verified and passed. A few engineering change requests were done because the requirement was imposed by the team and not by the customer, and was deemed an unnecessary requirement. In addition, due to there being no suitable environment for testing the zero gravity, this requirement was unable to be tested. The main issue came from the compression bed not being airtight, which resulted in the lack of pressure data and compression results. This is also the reason why the airtight requirement failed, even though the rest of the system was free of leaks. Furthermore, it is likely that the calculated scale of the system 1/16 versus 1/4 is a result of the simplicity of the design given budget constraints and alterations that had to be made late on in the project design.

7.0 Lessons Learned & Recommended Next Steps

Due in part to COVID-19, there were some challenges when it came to budgeting and timeline. Delays took longer than anticipated and purchasing parts were more costly in comparison to the years before the pandemic. Additionally, due to high temperature requirements, it was difficult to find parts at an affordable price because high temperature equipment is very expensive. For these reasons, our ideal design would have significantly exceeded our budget.

We could have ordered parts and scheduled fabrication further in advance to allow for the final system to be completed earlier so small issues could be resolved. One of these issues was the need for the compression bed to be airtight. Although two different types of gasket material were used (silicone and CeraTex 3170 Ceramic Fiber Paper) in an attempt to make the compression bed airtight, both types of material were unable to do so. Our conclusion for this issue is that the cap for the compression bed needed more tabs so more pressure could be applied for a tighter seal. Our sponsor suggested an alternative solution, which is to use an O-ring with a groove design. Additionally, we needed a pressure sensor with a lower range and higher resolution than the one that was purchased. Communicating more with NASA would have helped resolve these issues. Communication with others who are more experienced and knowledgeable is crucial for a successful system.

If this project were to be continued, it would be nice to see the original design come to life. Due to budget constraints, we had to substitute our custom heater design for heat tape. Having a good heater can greatly improve how the system functions. Furthermore, repeating a similar design setup, but with a more robust desiccant system, different solenoid valves, and a different fan would help improve the overall performance of the system. An airtight seal for the compression bed needs to be created and additional test runs would be ideal for having a better collection of data.

8.0 Summary

In summary, the team successfully built a re-design of the Sub-scale Adsorption and Compression CO₂ Removal System. All requirements have been tested and verified, although not all of them were met. Specifically, it was found that the system was able to adsorb and desorb carbon dioxide effectively, but, due to issues with sealing of the system and the compression bed not being airtight, the compression requirement did not pass. Additionally, likely due to the changes made to the system which resulted in it being more simplistic, such as the use of heat tape, a 1/16 scaled system was created rather than a 1/4 as verified by testing. A recommended next step for the design would be to integrate a more custom heater, full desiccant system, fan, and make the system automated.

Appendix A

Technical Data Package

Sub-scale Adsorption and Compression CO₂ Removal System Re-design Team #22014

Joaquin Pesqueira
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1.0 Project Description

Introduction

NASA is seeking more efficient ways of removing CO₂ to assist in the advancement of space exploration and life support systems. This system is to be used within the scope of the Moon to Mars eXploration Systems and Habitation mission (M2M X-Hab).

This system is based off of NASA's current TC-TSAC system (Thermally Coupled Temperature Swing Adsorption and Compression). TC-TSAC systems utilize packed beds of regenerable bulk sorbents and heat cycles to simultaneously adsorb and compress CO₂. Although TC-TSAC geometries have already been developed, this project aims to design and test a new system geometry where the compression bed is inside of the adsorption bed. This system will adsorb 1kg of CO₂ per day with a goal to be scalable for adsorbing up to 4kg of CO₂ per day. Sensors will be used to gather measurements and calculate necessary flow rates. Additionally, removal and compression beds of a cylindrical shape will be used. The system shall compress the acquired CO₂ to 1000 torr. Ultimately, the system will need to use a recyclable sorbent, and be within

necessary power, thermal, and performance requirements to improve the efficiency of the current design of the TC-TSAC system.

Stakeholders

The stakeholders for this project are NASA and Biosphere 2. This design has important implications for the Moon to Mars eXploration Systems and Habitation mission as well as the future of space life support systems. Since this project will be involved in the NASA mission critical path, design of the benchtop system is critical in the development of the part of the M2M X-Hab mission.

Product History and Background

TC-TSAC systems have already been developed, but this project aims to design and test a new system. TC-TSAC (Thermally Coupled Temperature Swing Adsorption and Compression) Systems use packed beds of regenerable bulk sorbents and heat cycles to simultaneously adsorb and compress CO₂. This design will continue the exploration of combining both CO₂ removal and compression in one system.

System Boundaries

The system boundary for this design is the CO₂ scrubber being contained in the design. Some of the potential auxiliary equipment for the project includes software and hardware that will be used to compress the carbon dioxide. The system has valves, fans, and beds that are integrated with other equipment such as sensors or other software.

System Environment

The system environment is likely indoors in a space system. The system shall be able to withstand some vibrations, have a controlled temperature, and have minimal particles. It shall also be able to withstand changes in temperature and humidity without degradation. It will need to be able to withstand harsh space conditions as well in terms of traveling from Earth to the Moon/Mars.

System Constraints

The most influential constraint for the system is a budget of \$. The project had to be completed within the timespan of the capstone. The sorbent used in the system is reusable. Additionally, the system should be capable of being scaled up to meet power and temperature requirements as well as withstanding external factors like vibrations and humidity.

System Use

The use for this system is for space life support or anything in space which requires carbon dioxide to be removed for missions. Specifically, this system will be used to separate carbon dioxide from air for the Moon to Mars eXploration Systems. It will be used for deep space

exploration air revitalization. Additionally, using reusable sorbents means this technology can be used as a sustainable way to continue exploring space. The project should hopefully improve mass, volume, and energy requirements, and present an alternative to current air revitalization systems.

Expected Output

The expected output for this project was a system prototype that has been experimentally tested and modeled to be scaled up to a full sized system. This system incorporates TC-TSAC geometry and a reusable sorbent to remove carbon dioxide from the air and compress it, storing it for later use elsewhere. This system should be capable of scaling up to 4kg CO₂/day of removal. It will be compared to a Paragon CO₂ removal system located at Biosphere 2. Additionally, design suggestions and/or alternative solutions should be presented following the completion of the project.

2.0 Functional Requirements

1. The TS-TSAC system shall adsorb CO₂ from the circulating air.
2. The TS-TSAC system shall be closed-looped for the purpose of downstream processing.
3. The TS-TSAC system shall implement a recyclable sorbent (Zeolite 13X).
4. The TS-TSAC system shall regenerate sorbent with a heat cycle.
5. The TS-TSAC system shall store and compress CO₂.
6. The TS-TSAC system shall be scalable up to 4kg CO₂ capture per day.

3.0 System Verification Plan

Overview

The following presents details of the verification plan that will be used to test the functionality of the full system. The basics of the verification involve multiple tests of each sub-component of the system. This includes individually testing the adsorption bed and compression bed, as well as testing them together. The Critical Design Element 1 is the sorbent bed with the dehumidifier, the Critical Design Element 2 adds in the compression bed. The main parameters that will be tested are carbon dioxide concentration, temperature, pressure, and humidity levels. The specific verification plan follows.

Figure 3.1. Verification Flow Diagram

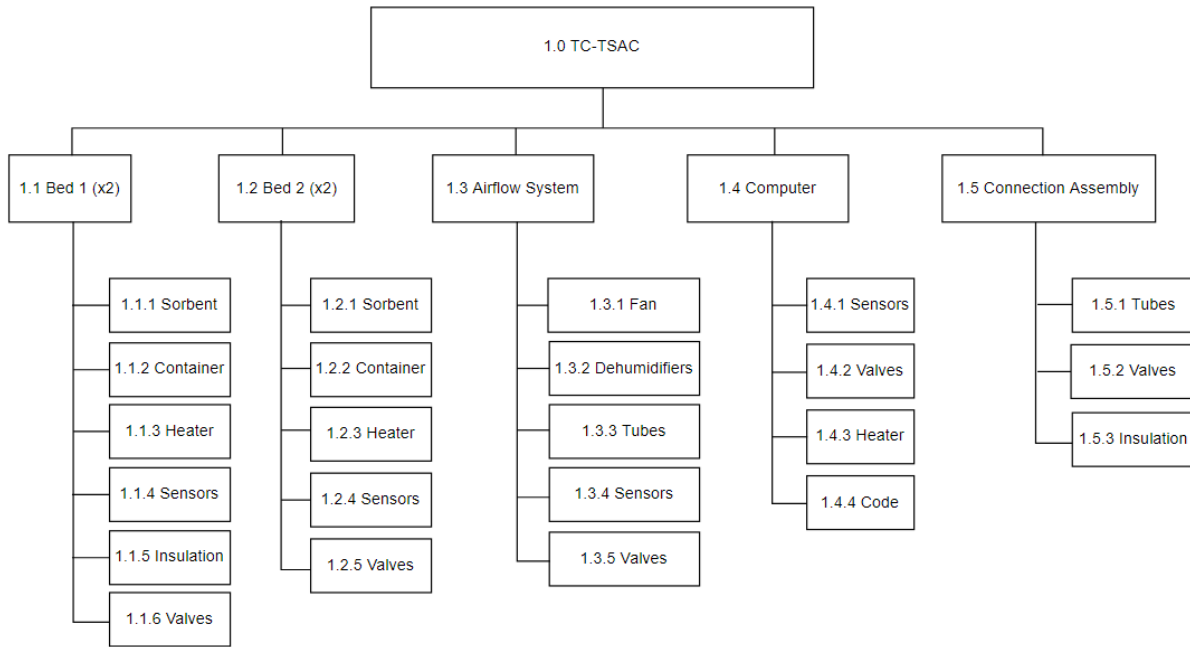


Table 3.1 Verification Requirements

System Requirements	Subsystems				
	Bed 1	Bed 2	Airflow	Computer	Connection Assembly
<u>4.1.1 Power:</u> The system shall be scalable up to approximately 200W for the full scale system. (I)	1. (Direct) Operates within the power consumption limit.	1. (Direct) Operates within the power consumption limit.	1. (Direct) Operates within the power consumption limit.	1. (Direct) Operates within the power consumption limit.	1. (Direct) Operates within the power consumption limit.
<u>4.1.2 Sensors:</u> Sensors work within the system and are calibrated to the correct values. (D)	2. (Direct) The system is connected to the sensors.	2. (Direct) The system is connected to the sensors.	2. (Direct) The system is connected to the sensors.	2. (Direct) The system receives input from the sensors.	2. (Direct) The system is connected to the sensors.

<u>4.1.3 User Interface:</u> Display the levels of CO ₂ , humidity, temperature and pressure within the system. (D/I)				3. (Direct) The system displays the information from the sensors.	
<u>4.2.1 Operational Temperature:</u> The system shall perform without degradation at varying temperatures. (T)	3. (Direct) Operates within the heat cycle temperatures (30-300C)	3. (Direct) Operates within the heat cycle temperatures (30-300C)			
<u>4.2.2 Operational Pressure:</u> The system shall perform without degradation at different pressures. (T)	4. Operates within ~0-1.5atm	4. Operates within ~0-1.5atm			
<u>4.2.3 Zero Gravity Compatible:</u> The system shall be able to perform its requirements in a zero gravity environment without degradation. (T)	5. (Direct) The system shall be able to withstand zero gravity requirements.	5. (Direct) The system shall be able to withstand zero gravity requirements.		4. (Direct) The system shall be able to withstand zero gravity requirements.	3. (Direct) The system shall be able to withstand zero gravity requirements.
<u>4.2.4 Operational Humidity:</u> The system shall perform without degradation at different humidity. (T)	6. (Direct) The system shall be able to withstand varied humidity levels.	6. (Direct) The system shall be able to withstand varied humidity levels.		5. (Direct) The system shall be able to withstand varied humidity levels.	4. (Direct) The system shall be able to withstand varied humidity levels.

<u>4.3.1 Emergency Shutoff Button:</u> The system shall have a shutoff button in order to shut down all components at once in the case of an emergency. (D)	7. (Direct) The system shall be able to be shut off with the emergency button.	7. (Direct) The system shall be able to be shut off with the emergency button.		6. (Direct) The system should be able to be shut off with the emergency button.	5. (Direct) The system shall be able to be shut off with the emergency button.
<u>4.3.2 Temperature of the system is within safe range to touch:</u> The system shall have exterior components to operate that are safe to touch and any other components that will not be used to operate the system and are unsafe to touch will be marked. (I/D)					6. (Derived) Parts that are unsafe to touch will be marked.
<u>4.3.3 No leaks:</u> The system shall have no external leaks to the surroundings. (T/D/I)	8. (Derived) The system shall have no external leaks.	8. (Derived) The system shall have no external leaks.	3. (Derived) The system shall have no external leaks.		
<u>4.4.1 Sorbent regeneration reliably:</u> The sorbent used (Zeolite 13X) shall be able to be used multiple times. (T)	9. (Derived) The sorbent shall be regenerable to be used within multiple cycles before replacement.	9. (Derived) The sorbent shall be regenerable to be used within multiple cycles before replacement.			

<u>4.4.2 Adsorbed CO₂ compression:</u> The system shall compress the carbon dioxide to 1000 torr. (T)		10. (Derived) The system shall be demonstrated to compress the CO ₂ to the desired pressure.			
<u>4.4.3 Scalability:</u> The system shall be scalable up to 4kg of carbon dioxide removed per day. (A)	10. (Allocated) The bed shall be modeled to scale up to the larger system.	11. (Allocated) The bed shall be modeled to scale up to the larger system.			
<u>4.4.4 Airflow rate:</u> The system shall use the sensors and measure the flow rate of the air measuring the system. (T)					7. (Direct) The sensors shall measure the flow rate and send the data to the computer.
<u>4.4.5 CO₂ capture rate:</u> The system shall measure the carbon dioxide capture rate and display it on the sensor. (A)			4. (Derived) The sensors shall measure the CO ₂ capture rate and send the data to the computer.		
<u>4.5.1 Size and weight:</u> The system shall be a sub-scale system that can be easily transported. (I)	11. (Allocated) The beds shall be a reasonable size and weight to integrate into the system.	12. (Allocated) The beds shall be a reasonable size and weight to integrate into the system.			

<u>4.5.2 Cost</u> : The final system design shall be under the \$ given to us for the budget. (I)	12. (Allocated) The part shall not cost more than the budget.	13. (Allocated) The part shall not cost more than the budget.		7. (Allocated) The part shall not cost more than the budget.	9. (Allocated) The part shall not cost more than the budget.
<u>4.5.3 Use zeolites as a sorbent</u> : Zeolite 13X shall be used as the sorbent for the system. (I)	13. (Direct) Use recyclable sorbent.	14. (Direct) Use recyclable sorbent.			
<u>4.5.4 Adsorption beds</u> : The system shall have adsorption beds for the carbon dioxide. (I)	17. (Direct) The bed shall be an adsorption bed.				
<u>4.5.5 Compression beds</u> : The system shall have compression beds for the carbon dioxide. (I)		18. (Direct) The bed shall be a compression bed.			

*Table 3.2. System Requirements Verification Matrix (SRVM) *before completion of verification*

System Requirement Verification				
Requirement	Method	Limit/Reference	Measured/Ref Value	Pass/Fail
1. Interface Requirements	-	-	-	-
a. Power Interface: The system shall be scalable up to approximately 200W for the full scale system.	I	N/A		
b. Sensor Interface: Sensors work within the system and are calibrated to the correct values.	D	N/A		
c. User Interface: Display the levels of CO ₂ , humidity, temperature and pressure within the system.	D, I	N/A		
2. Environmental Requirements	-	-		
a. Operational Temperature: The system shall perform without degradation at varying temperatures.	T	Operates within 30°C-300°C		

b. Operational Pressure: The system shall perform without degradation at different pressures.	T	Operates within 0-1.5 atm		
c. Zero Gravity Compatible: The system shall be able to perform its requirements in a zero gravity environment without degradation.	T	System functions in zero gravity environment without falling apart		
d. Operational Humidity: The system shall perform without degradation at different humidities.	T	<10% relative humidity		
3. Safety Requirements	-	-		
a. Emergency Shutoff: The system shall have an emergency shutoff button.	D	N/A		
b. Outside Temperature: The outside temperature of the system shall be safe enough to touch or marked if unsafe.	D, I	N/A		
c. Leakage: The system shall be free of any leaks.	T, D, I	Negligible measured loss of pressure over time		
4. Customer Constraints	-	-		
a. Scalability: The system shall be scalable up to adsorbing 4 kg of CO ₂ /day.	A	1kg of CO ₂ /day is adsorbed		
b. Cost: The system shall cost no more than the given budget to build (\$).	I	Under budget		
5. Performance Requirements				
a. Sorbent Regeneration: The sorbent shall be regenerative for multiple uses.	T	Sorbent can be used multiple times and successfully regenerates through heating		
b. Carbon Dioxide Compression: The adsorbed carbon dioxide shall be compressed to 1000 torr.	T	System compresses carbon dioxide to 1000 torr		
c. Airflow Rate: The system shall measure the flow rate of air entering the system.	T	N/A since this value will be measured		
e. Carbon Dioxide Capture Rate: The system shall measure the amount of carbon dioxide that is captured.	A	< ambient concentration over time		
6. Design Requirements	-	-		
a. Sorbent: The system shall use zeolite 13X as a sorbent.	I	Zeolite 13X used		

b. Sensors: Sensors used within the system shall be able to withstand high temperatures (up to 300°C).	I	Sensors can withstand conditions and successfully record results		
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Critical Design Element 1 Verification

System Requirements

4.1. Interface Requirements

4.1.2 Vernier sensors: The system shall use given Vernier sensors and any additional necessary sensors.

4.1.3 User Interface: The system shall display carbon dioxide levels, humidity, and temperature.

4.3. Safety Requirements

4.3.2 Temperature of the system is within safe range to touch: The system shall have exterior components to operate that are safe to touch and any other components that will not be used to operate the system and are unsafe to touch will be marked.

4.3.3 No leaks: The system shall have no external leaks to the surroundings.

4.4. Performance Requirements

4.4.1 Sorbent regenerates reliably: The sorbent used shall be able to be used multiple times.

4.4.4 Airflow rate: the system shall measure the flow rate of air entering the system: The system shall use the sensors and measure the flow rate of the air in the system.

4.4.5 CO₂ capture rate: the system shall measure the rate that CO₂ is captured: The system shall measure the carbon dioxide capture rate and display it on the sensor.

4.5 Design Features

4.5.1 Size and weight: The system shall be a sub-scale system that can eventually be integrated into Biosphere 2.

4.5.2 Cost - no more than given budget: The final system design shall be under the \$ given to us for the budget.

4.5.3 Use zeolites as a sorbent: Zeolite 13X shall be used as the sorbent for the system.

4.5.4 Vernier hardware: The system shall use Vernier hardware and sensors.

4.5.6 The system shall have a cylinder shape: The compression system shall have a cylinder shape.

4.5.7 Adsorption beds: The system shall have adsorption beds for the carbon dioxide.

Step-by-step procedure:

1. Desiccant Test

- Equipment: Air pump, desiccant bed, sensors
- Connect equipment in series
 - Pump, desiccant beds, sensors
- Before the test, measure ambient temperature and humidity.
- Run the air pump. Let the test run for a set duration (for example, an hour).
- Measure the output humidity and temperature for the duration. The temperature shall not exceed 40°C, the output humidity shall be less than 5%. **Mark Pass/Fail on the datasheet.**
- After the test, measure ambient temperature and humidity.
- If possible, vary temperature (20-40°C) to see how output temperature changes.
- If possible, vary flow rate (power to pump) to see how output temperature changes.

2. Sorbent Test

- Equipment: Air pump, desiccant bed, sorbent bed, sensors, valves
- Assemble sorbent bed with in/out valves and prepare the sorbent.
- Assemble air pump, desiccant bed, sorbent bed assembly, output sensors.
- Before the test, measure ambient temperature, CO₂ concentration, and humidity.
- Run the air pump. Let the test run for a set duration (for example, an hour).
- Measure the output humidity, temperature, CO₂ concentration, and adsorption rate for the duration. The temperature shall not exceed 40C, the output humidity shall be less than 5%. CO₂ concentration shall be less than output, ~less than 400 ppm. **Mark Pass/Fail on the datasheet.**
- After the test, measure ambient temperature, CO₂ concentration, and humidity.
- If possible, vary input temperature (20-40C) to see how adsorption rate changes.
- If possible, vary flow rate (power to pump) to see how adsorption rate changes.

Acceptance Test Data Sheet

Referenced ATP Paragraph Number: Paragraph 1

Analysis Referenced (for verification by T/A): N/A

Name of Test: Desiccant Test

Unit Under Test (UUT):

Name: Desiccant Test

Part Number: Silica Gel 2-4mm beads, rechargeable
(ASIN - B087T2GBPX)

Serial Number: ASIN - B087T2GBPX

Results (Pass / Fail): Fail

Date of Test: 11/21/21

Recording of Test Measurement:

$\sim 7\%$ humidity

Requirement (SRD,
with Tolerances):

 $\sim < 5\%$ humidity

Test Equipment
Error:

- $\pm 5\%$
- $\pm 0.5^{\circ}\text{C}$

Adjusted Test Limit:

Computations, (Include Analyses Results, if any):

Signatures:

Tester _____

Customer _____

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 2			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Sorbent Test			
Unit Under Test (UUT): Name: Sorbent Test Part Number: Zeolite 13X Serial Number: 5A48B			
Results (Pass / Fail): Pass		Date of Test: 11/21/21	
Recording of Test Measurement:	Requirement (SRD, with Tolerances): Less than ambient air/starting air ppm	Test Equipment Error: - 0 to 1,000 ppm: ± 100 ppm - 1,000 to 10,000 ppm: $\pm 5\%$ of reading + 100 ppm - 10,000 ppm to 50,000 ppm: $\pm 10\%$ of reading - 50,000 to 100,000 ppm: $\pm 15\%$ of reading	Adjusted Test Limit:
Computations, (Include Analyses Results, if any):			
Signatures: Tester _____ Customer _____			

Critical Design Element 2 Verification

System Requirements

4.1. Interface Requirements

4.1.2 Vernier sensors: The system shall use given Vernier sensors.

4.1.3 User Interface: The system shall display carbon dioxide levels, humidity, and temperature.

4.2. Environmental Requirements

4.2.1 Operational Temperature: The system shall perform without degradation at varying temperatures.

4.2.2 Operational Pressure: The system shall perform without degradation at different pressures.

4.2.4 Operational Humidity: The system shall perform without degradation at different humidity.

4.3. Safety Requirements

4.3.2 Temperature of the system is within safe range to touch: The system shall have exterior components to operate that are safe to touch and any other components that will not be used to operate the system and are unsafe to touch will be marked.

4.3.3 No leaks: The system shall have no external leaks to the surroundings.

4.4. Performance Requirements

4.4.1 Sorbent regenerates reliably: The sorbent used shall be able to be used multiple times.

4.4.2 Adsorbed CO₂ compressed to 1000 torr: The system shall compress the carbon dioxide to 1000 torr.

4.4.3 The system should be scalable up to 4kg CO₂/day: The system shall be scalable up to 4kg of carbon dioxide removed per day.

4.4.4 Airflow rate: the system shall measure the flow rate of air entering the system: The system shall use the sensors and measure the flow rate of the air measuring the system.

4.4.5 CO₂ capture rate: the system shall measure the rate that CO₂ is captured: The system shall measure the carbon dioxide capture rate and display it on the sensor.

4.5 Design Features

4.5.1 Size and weight: The system shall be a sub-scale system that can eventually be integrated into Biosphere 2.

4.5.2 Cost - no more than given budget: The final system design shall be under the \$ given to us for the budget.

4.5.3 Use zeolites as a sorbent: Zeolite 13X shall be used as the sorbent for the system.

4.5.4 Vernier hardware: The system shall use Vernier hardware and sensors.

4.5.6 The system shall have a cylinder shape: The compression system shall have a

cylinder shape.

4.5.7 Adsorption beds: The system shall have adsorption beds for the carbon dioxide.

4.5.8 Compression beds: The system shall have compression beds for the carbon dioxide.

Verification Overview

- Heating test for adsorption bed (make sure we can desorb CO₂)
- Tests for temp and pressure sensors (final system working conditions)
- Adsorption and compression test for compression bed (compress CO₂ from Bed 1)

Step-by-step procedure:

1. Desiccant Test

- Equipment: Air pump, desiccant bed, sensors
- Connect equipment in series
 - Pump, desiccant beds, sensors
- Before the test, measure ambient temperature and humidity.
- Run the air pump. Let the test run for a set duration (for example, an hour).
- Measure the output humidity and temperature for the duration. The temperature shall not exceed 40°C, the output humidity shall be less than 5%. **Mark Pass/Fail on the datasheet.**
- After the test, measure ambient temperature and humidity.
- If possible, vary temperature (20-40°C) to see how output temperature changes.
- If possible, vary flow rate (power to pump) to see how output temperature changes.

2. Sorbent Test

- Equipment: Air pump, desiccant bed, sorbent bed, sensors, valves
- Assemble sorbent bed with in/out valves and prepare the sorbent.
- Assemble air pump, desiccant bed, sorbent bed assembly, output sensors.
- Before the test, measure ambient temperature, CO₂ concentration, and humidity.
- Run the air pump. Let the test run for a set duration (for example, an hour).
- Measure the output humidity, temperature, CO₂ concentration, and adsorption rate for the duration. The temperature shall not exceed 40°C, the output humidity shall be less than 5%. CO₂ concentration shall be less than output, ~less than 400 ppm. **Mark Pass/Fail on the datasheet.**
- After the test, measure ambient temperature, CO₂ concentration, and humidity.
- If possible, vary input temperature (20-40°C) to see how adsorption rate changes.
- If possible, vary flow rate (power to pump) to see how adsorption rate changes.

3. Heating Test

- Equipment: Air pump, desiccant bed, sorbent bed, sensors, valves, heat tape
- Assemble sorbent bed with in/out valves and prepare the sorbent.

- Assemble air pump, desiccant bed, sorbent bed assembly, output sensors.
- Before the test, measure ambient temperature, CO₂ concentration, temperature, and humidity.
- Run the air pump. Let the test run for a set duration (for example, an hour).
- Using heat tape, ensure that the system can reach the desired temperature for the heat cycle. **Mark Pass/Fail on the datasheet.**
- After the test, measure ambient temperature, CO₂ concentration, and humidity.
- If possible, vary input temperature (20-40°C) to see how adsorption rate changes.
- If possible, vary flow rate (power to pump) to see how adsorption rate changes.

4. Compression Test

- Equipment: Air pump, desiccant bed, sorbent bed, sensors, valves, compression bed, heat tape
- Assemble sorbent bed with in/out valves and prepare the sorbent.
- Assemble air pump, desiccant bed, sorbent bed assembly, output sensors.
- Before the test, measure ambient temperature, CO₂ concentration, and humidity.
- Run the air pump. Let the test run for a set duration (for example, an hour).
- Measure the output humidity, temperature, CO₂ concentration, and adsorption rate for the duration. The temperature shall not exceed 40°C, the output humidity shall be less than 5%. CO₂ concentration shall be less than output, ~less than 400 ppm.
- Determine that when the air moves to the second bed it can be compressed to the desired pressure. **Mark Pass/Fail on the datasheet.**
- After the test, measure ambient temperature, CO₂ concentration, and humidity.
- If possible, vary input temperature (20-40°C) to see how adsorption rate changes.
- If possible, vary flow rate (power to pump) to see how adsorption rate changes.

Acceptance Test Data Sheet

Referenced ATP Paragraph Number: Paragraph 1

Analysis Referenced (for verification by T/A): N/A

Name of Test: Desiccant Test

Unit Under Test (UUT):

Name: Desiccant Test

Part Number: Silica Gel 2-4mm beads, rechargeable
(ASIN - B087T2GBPX)

Serial Number: ASIN - B087T2GBPX

Results (Pass / Fail): Pass

Date of Test: 02/01/22

Recording of Test Measurement:

0-5% humidity

Requirement (SRD,
with Tolerances):

 $\sim < 5\%$ humidity

Test Equipment
Error:

- $\pm 5\%$
- $\pm 0.5^{\circ}\text{C}$

Adjusted Test Limit:

10% humidity

Computations, (Include Analyses Results, if any):

Signatures:

Tester

Customer _____

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 2			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Sorbent Test			
Unit Under Test (UUT): Name: Sorbent Test Part Number: Zeolite 13X Serial Number: 5A48B			
Results (Pass / Fail): Pass		Date of Test: 02/01/22	
Recording of Test Measurement: Less than ambient air for a certain amount of time then reaches toward ambient	Requirement (SRD, with Tolerances): Less than ambient air/starting air ppm	Test Equipment Error: - 0 to 1,000 ppm: ± 100 ppm - 1,000 to 10,000 ppm: $\pm 5\%$ of reading + 100 ppm - 10,000 ppm to 50,000 ppm: $\pm 10\%$ of reading - 50,000 to 100,000 ppm: $\pm 15\%$ of reading	Adjusted Test Limit:
Computations, (Include Analyses Results, if any):			
Signatures: Tester _____ Customer _____			

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 3			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Heating Test			
Unit Under Test (UUT): Name: Heating Test Part Number: Serial Number:			
Results (Pass / Fail): Pass		Date of Test: 02/20/22	
Recording of Test Measurement:	Requirement (SRD, with Tolerances):	Test Equipment Error:	Adjusted Test Limit:
Heat tape works	Testing whether the heat tape can be controlled		
Computations, (Include Analyses Results, if any):			
Signatures: Tester _____ Customer _____			

Acceptance Test Data Sheet

Referenced ATP Paragraph Number: Paragraph 4

Analysis Referenced (for verification by T/A): N/A

Name of Test: Compression Test

Unit Under Test (UUT):

Name: Compression Test

Part Number:

Serial Number:

Results (Pass / Fail): Did not test

Date of Test: 02/20/22

Recording of Test Measurement:

Requirement (SRD,
with Tolerances):

Test Equipment
Error:

Adjusted Test Limit:

Computations, (Include Analyses Results, if any):

Signatures:

Tester _____

Customer _____

Full Assembly Verification

Given that Demonstration and Inspection verifications can be done through visuals or simple display of function without a fully-fledged verification plan, the following verification procedures showcase those requirements that need to be analyzed and tested.

In order to fully test the system, baseline tests were conducted in addition to final system tests. These tests occurred at Biosphere 2 in Oracle, Arizona. A sealed system made of 6-mil polyethylene plastic and duct tape, and painters tape was constructed. In this system, the entire CO₂ scrubber was placed along with all wires and sensors needed, which were then taped up to the floor in order to make the testing location as airtight as possible. A CO₂ canister was used to add carbon dioxide into the system. For every test, humidity, temperature and carbon dioxide concentration sensors were used. Each test was run for over an hour except for the second adsorption test, which was run for 45 minutes. For the desorption and compression tests, thermistors (to measure the heat tape temperature) and a pressure transducer were also used.

For these requirements, the following tests were performed. Tests for the baseline comparison (using a given Paragon scrubber) included:

1. Sealing the system and measuring CO₂ concentration after an hour, so as to determine the leak rate of the area.
2. Repeating the test above, this time running a fan.
3. Adding Zeolite 13X to the Paragon scrubber and running the fan.

Tests for the final system (using re-designed TC-TSAC) included:

1. Sealing the system, running a fan, and measuring CO₂ concentration after an hour, so as to determine the leak rate of the area.
2. Adsorption test, measuring the amount of CO₂ captured.
3. Desorption test, using heat tape to release CO₂, no fan.
4. Second adsorption tests, running the fan again.
5. Desorption and compression test, using heat tape and pressure transducer, no fan.

Verification Procedures

4.2.1 Operational Temperature: The system shall perform without degradation at varying temperatures. (T)

- Expected Test Date(s): 04/23/2022
- Completed Date(s): 04/23/2022
- 1. Procedure: Run heating in the system and make sure temperature within each part will not degrade the system. **Mark Pass/Fail on the datasheet.**

4.2.2 Operational Pressure: The system shall perform without degradation at different pressures. (T)

- Expected Test Date(s): 04/23/2022
- Completed Date(s): 04/23/2022
- 2. Procedure: Run the system and make sure pressure within each part will not degrade the system. **Mark Pass/Fail on the datasheet.**

4.2.4 Operational Humidity: The system shall perform without degradation at different humidity. (T)

- Expected Test Date(s): 04/23/2022
- Completed Date(s): 04/23/2022
- 3. Procedure: Run the system and make sure humidity within each part will not degrade the system. Make sure humidity can be lowered to around ~10% relative humidity. **Mark Pass/Fail on the datasheet.**

4.3.3 No leaks: The system shall have no external leaks to the surroundings. (T/D/I)

- Expected Test Date(s): 04/23/2022
- Completed Date(s): 04/23/2022
- 4. Procedure: Run compression test and ensure pressure can be built up in the system. If not, it means there is a leak. **Mark Pass/Fail on the datasheet.**

4.4.1 Sorbent regenerates reliably: The sorbent used (13X) shall be able to be used multiple times. (T)

- Expected Test Date(s): 04/23/2022
- Completed Date(s): 04/23/2022
- 5. Procedure: Run system and use carbon dioxide concentration and desorption results to indicate whether or not the system successfully regenerates the sorbent. **Mark Pass/Fail on the datasheet.**

4.4.2 Adsorbed CO₂ compressed to 1000 torr: The system shall compress the carbon dioxide to 1000 torr. (T)

- Expected Test Date(s): 04/23/2022

- Completed Date(s): 04/23/2022
- 6. Procedure: Run system and make sure the carbon dioxide can be compressed to the target pressure. **Mark Pass/Fail on the datasheet.**

4.4.3 The system should be scalable up to 4kg CO₂/day: The system shall be scalable up to 4kg of carbon dioxide removed per day. (A)

- Expected Test Date(s): 04/23/2022
- Completed Date(s): 04/23/2022
- 7. Procedure: Use measured values from the sensors to perform this calculation. **Mark Pass/Fail on the datasheet.**

4.4.4 Airflow rate: the system shall measure the flow rate of air entering the system: The system shall use the sensors and measure the flow rate of the air measuring the system. (T)

- Expected Test Date(s): 04/23/2022
- Completed Date(s): 04/23/2022
- 8. Procedure: Use an airflow sensor and ensure it works in the system. **Mark Pass/Fail on the datasheet.**

4.4.5 CO₂ capture rate: the system shall measure the rate that CO₂ is captured: The system shall measure the carbon dioxide capture rate and display it on the sensor. (A)

- Expected Test Date(s): 04/23/2022
- Completed Date(s): 04/23/2022
- 9. Procedure: Use measured values from the sensors to perform this calculation. **Mark Pass/Fail on the datasheet.**

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 1			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Operational Temperature			
Unit Under Test (UUT): Whole system			
Results (Pass / Fail): Pass		Date of Test: 04/23/22	
Recording of Test Measurement: System parts do not degrade.	Requirement (SRD, with Tolerances): Operational Temperature: The system shall perform without degradation at varying temperatures. Operates within 30°C-300°C	Test Equipment Error:	Adjusted Test Limit:
Computations, (Include Analyses Results, if any):			
Signatures: Tester _____ Customer _____			

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 2			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Operational Pressure			
Unit Under Test (UUT): Whole system			
Results (Pass / Fail): Not tested fully		Date of Test: 04/23/22	
Recording of Test Measurement: Unable to keep system pressurized, therefore this requirement was unable to be fully tested.	Requirement (SRD, with Tolerances): System parts do not degrade. Operates within 0-1.5 atm	Test Equipment Error:	Adjusted Test Limit:
Computations, (Include Analyses Results, if any): 			
Signatures: Tester _____ Customer _____			

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 3			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Operational Humidity			
Unit Under Test (UUT): Whole system			
Results (Pass / Fail): Pass		Date of Test: 04/23/22	
Recording of Test Measurement: System parts do not degrade. Relative humidity levels were consistently less than 10%.	Requirement (SRD, with Tolerances): The system shall lower the humidity levels for the air in the system. <10% relative humidity	Test Equipment Error:	Adjusted Test Limit:
Computations, (Include Analyses Results, if any): 			
Signatures: Tester _____ Customer _____			

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 4			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: No leaks			
Unit Under Test (UUT): Whole system			
Results (Pass / Fail): Fail		Date of Test: 04/23/22	
Recording of Test Measurement: Compression bed had leaks.	Requirement (SRD, with Tolerances): System is airtight and should be free of any leaks.	Test Equipment Error:	Adjusted Test Limit:
Computations, (Include Analyses Results, if any):			
Signatures: Tester _____ Customer _____			

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 5			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Sorbent Regeneration			
Unit Under Test (UUT): Whole system			
Results (Pass / Fail): Pass		Date of Test: 04/23/22	
Recording of Test Measurement: Desorbed around 191.33 ppm of CO2.	Requirement (SRD, with Tolerances): Run system and ensure desorption process is successful.	Test Equipment Error:	Adjusted Test Limit:
Computations, (Include Analyses Results, if any):			
Signatures: Tester _____ Customer _____			

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 6			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Adsorbed Carbon Dioxide compresses to 1000 torr			
Unit Under Test (UUT): Whole system			
Results (Pass / Fail): Fail		Date of Test: 04/23/22	
Recording of Test Measurement: Compression bed was not airtight.	Requirement (SRD, with Tolerances): Run system and make sure the carbon dioxide can be compressed to the target pressure.	Test Equipment Error:	Adjusted Test Limit:
Computations, (Include Analyses Results, if any):			
Signatures: Tester _____ Customer _____			

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 7			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Scalability			
Unit Under Test (UUT): Whole system			
Results (Pass / Fail): Fail		Date of Test: 04/23/22	
Recording of Test Measurement: 1/16 scale rather than 1/4	Requirement (SRD, with Tolerances): The system shall be scalable up to adsorbing 4 kg of CO ₂ /day.	Test Equipment Error:	Adjusted Test Limit:

Computations, (Include Analyses Results, if any):

~0.25 kg/day of CO₂ adsorption

B (adsorb)	
Velocity Flow Rate (m/s)	4.03
Mass of CO2 Adsorbed (kg)	0.012342464
CO2 Adsorption Rate (kg/s)	3.00449E-06
CO2 produced by 1 human (kg/day)	1
CO2 adsorption per day (kg/day)	0.259588345
CO2 adsorption per day (kg/day)	0.004320711

D (adsorb)	
Velocity Flow Rate (m/s)	4.82
Mass of CO2 Adsorbed (kg)	0.01005684
CO2 Adsorption Rate (kg/s)	2.4481E-06
CO2 produced by 1 human (kg/day)	1
CO2 adsorption per day (kg/day)	0.21151672
CO2 adsorption per day (kg/day)	0.00352058

Signatures:

Tester _____

Customer _____

Acceptance Test Data Sheet			
Referenced ATP Paragraph Number: Paragraph 8			
Analysis Referenced (for verification by T/A): N/A			
Name of Test: Airflow rate			
Unit Under Test (UUT): Whole system			
Results (Pass / Fail): Pass		Date of Test: 04/23/22	
Recording of Test Measurement: ~4-4.8 m/s	Requirement (SRD, with Tolerances): The system shall measure the flow rate of air entering the system.	Test Equipment Error:	Adjusted Test Limit:

Computations, (Include Analyses Results, if any):

B (adsorb)	
Velocity Flow Rate (m/s)	4.03
Mass of CO2 Adsorbed (kg)	0.012342464
CO2 Adsorption Rate (kg/s)	3.00449E-06
CO2 produced by 1 human (kg/day)	1
CO2 adsorption per day (kg/day)	0.259588345
CO2 adsorption per day (kg/day)	0.004320711

Acceptance Test Data Sheet

Referenced ATP Paragraph Number: Paragraph 9

Analysis Referenced (for verification by T/A): N/A

Name of Test: Carbon Dioxide Capture Rate

Unit Under Test (UUT): Whole system

Results (Pass / Fail): Pass

Date of Test: 04/23/22

Recording of Test
Measurement:

~0.25 kg/day of CO₂
adsorption

Requirement (SRD, with
Tolerances):

The system shall measure the
amount of carbon dioxide that is
captured.

Test
Equipment
Error:

Adjusted
Test Limit:

Computations, (Include Analyses Results, if any):

B (adsorb)	
Velocity Flow Rate (m/s)	4.03
Mass of CO2 Adsorbed (kg)	0.012342464
CO2 Adsorption Rate (kg/s)	3.00449E-06
CO2 produced by 1 human (kg/day)	1
CO2 adsorption per day (kg/day)	0.259588345
CO2 adsorption per day (kg/day)	0.004320711

D (adsorb)	
Velocity Flow Rate (m/s)	4.82
Mass of CO2 Adsorbed (kg)	0.01005684
CO2 Adsorption Rate (kg/s)	2.4481E-06
CO2 produced by 1 human (kg/day)	1
CO2 adsorption per day (kg/day)	0.21151672
CO2 adsorption per day (kg/day)	0.00352058

Signatures:

Tester _____

Customer _____

Table 3.3 Final System Requirements Verification Matrix

System Requirement Verification				
Requirement	Method	Limit/Reference	Measured/Ref Value	Pass/Fail
1. Interface Requirements	-	-	-	-
a. Power Interface: The system shall be scalable up to approximately 200W for the full scale system.	I	N/A	Gave ourselves this requirement without knowing what the system would look like	ECR
b. Sensor Interface: Sensors work within the system and are calibrated to the correct values.	D	N/A	Sensors connected	Pass
c. User Interface: Display the levels of CO ₂ , humidity, temperature and pressure within the system.	D, I	N/A	Display functional	Pass
2. Environmental Requirements	-	-	-	-
a. Operational Temperature: The system shall perform without degradation at varying temperatures.	T	Operates within 30°C-300°C	Operates within 30°C-300°C without degradation	Pass
b. Operational Pressure: The system shall perform without degradation at different pressures.	T	Operates within 0-1.5 atm	-	Not able to be tested
c. Zero Gravity Compatible: The system shall be able to perform its requirements in a zero gravity environment without degradation.	T	System functions in zero gravity environment without falling apart	-	Not able to be tested
d. Operational Humidity: The system shall perform without degradation at different humidities.	T	<10% relative humidity	<10% relative humidity	Pass
3. Safety Requirements	-	-	-	-
a. Emergency Shutoff: The system shall have an emergency shutoff button.	D	N/A	Unplug system, rather than button	ECR
b. Outside Temperature: The outside temperature of the system shall be safe enough to touch or marked if unsafe.	D, I	N/A	Insulation used	Pass
c. Leakage: The system shall be free of any leaks.	T, D, I	Negligible measured loss of pressure over time	Compression bed leaks	Fail
4. Customer Constraints	-	-	-	-
a. Scalability: The system shall be scalable up to adsorbing 4 kg of CO ₂ /day.	A	1kg of CO ₂ /day is adsorbed	~0.25 kg of CO ₂ /day is adsorbed	Fail
b. Cost: The system shall cost no more than the given budget to build (\$).	I	Under budget	Within budget	Pass
5. Performance Requirements				
a. Sorbent Regeneration: The sorbent shall be regenerative for multiple uses.	T	Sorbent can be used multiple times and	Desorption process regenerates	Pass

		times and successfully regenerates through heating	regenerates sorbent	
b. Carbon Dioxide Compression: The adsorbed carbon dioxide shall be compressed to 1000 torr.	T	System compresses carbon dioxide to 1000 torr	Compression bed has leaks - unable to gather data	Fail
c. Airflow Rate: The system shall measure the flow rate of air entering the system.	T	N/A since this value will be measured	Measures flow rate using flow meter	Pass
e. Carbon Dioxide Capture Rate: The system shall measure the amount of carbon dioxide that is captured.	A	< ambient concentration over time	Measures indirectly	Pass
6. Design Requirements	-	-	-	-
a. Sorbent: The system shall use zeolite 13X as a sorbent.	I	Zeolite 13X used	13X is used	Pass
b. Sensors: Sensors used within the system shall be able to withstand high temperatures (up to 300°C).	I	Sensors can withstand conditions and successfully record results	Sensors can withstand conditions and successfully record results	Pass

4.0 Design Documentation

IDL

<u>Part Number</u>	<u>Document</u>
100000	System
100100	Adsorb & Comp Assem - x2
100110	Comp bed
100120	Comp bed lid
100130	Adsorb bed
100140	Adsorb bed lid - x2
100150	Mesh - x2
100020	Connection Assembly - x2
100210	Tubing
100220	Small valve - x2
100230	Emergency valve - x2
100240	Pressure Sensor - x2
100030	Bulk Air Moving Assembly
100310	Tubing
100320	Large valve - x4
100330	Tee
100040	Air Preprocessing
100410	Tubing
100420	Pump
100430	Dryer
100050	Heating Assembly
100060	Electrical Assembly

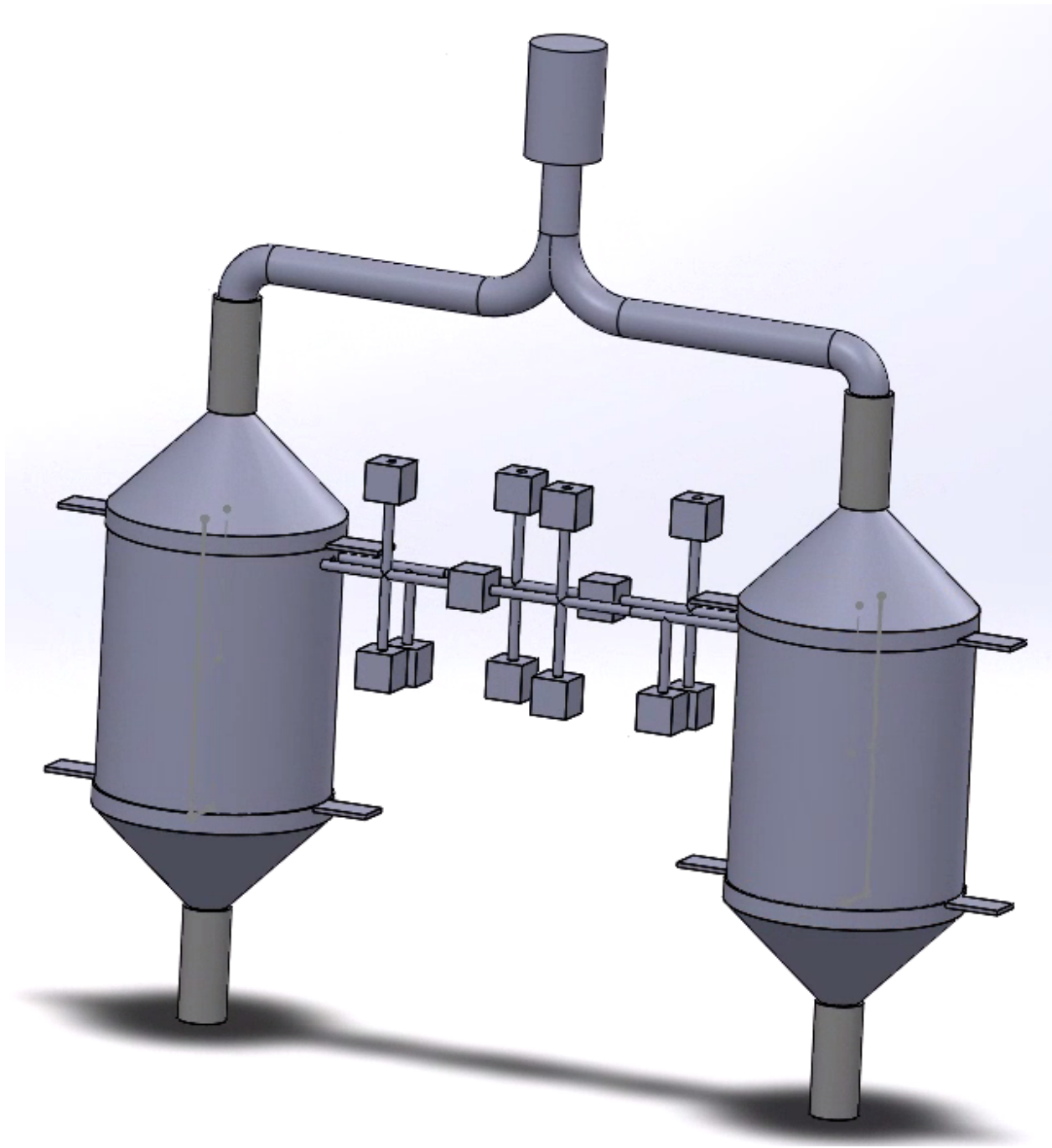


Figure 4.2. Preliminary Overall Canister Layout (SolidWorks)

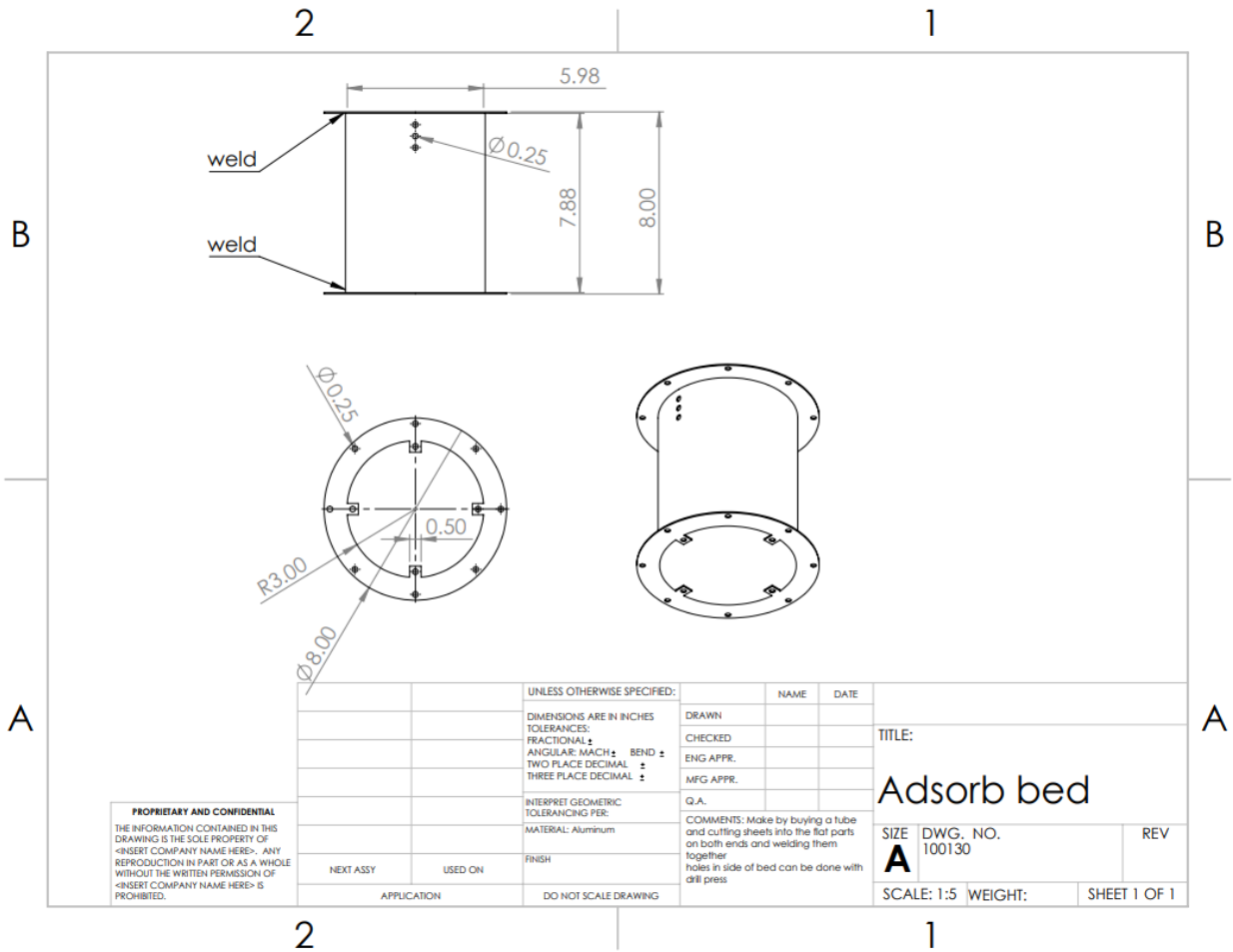


Figure 4.3. Adsorption Bed.

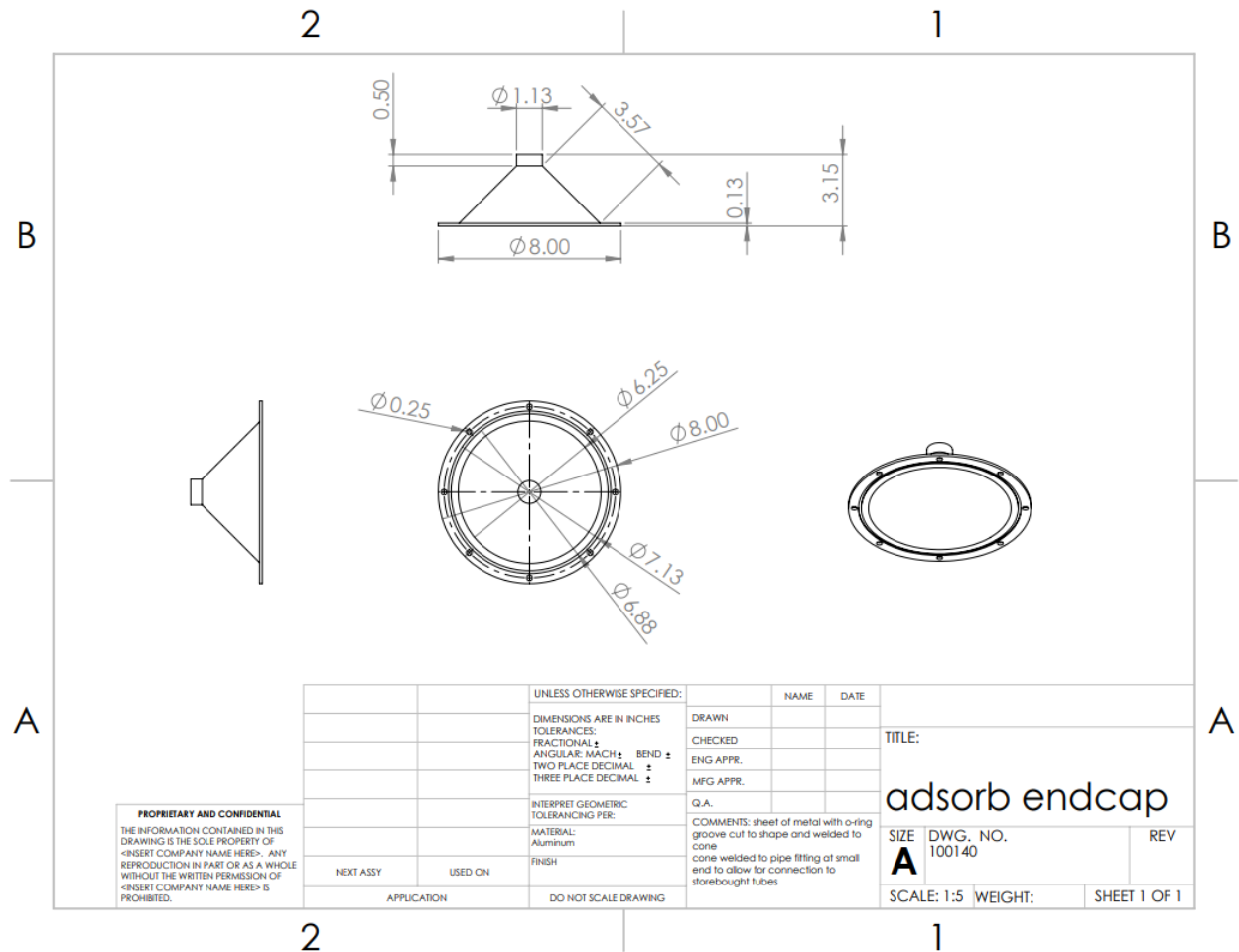


Figure 4.4. Adsorption Bed End Cap.

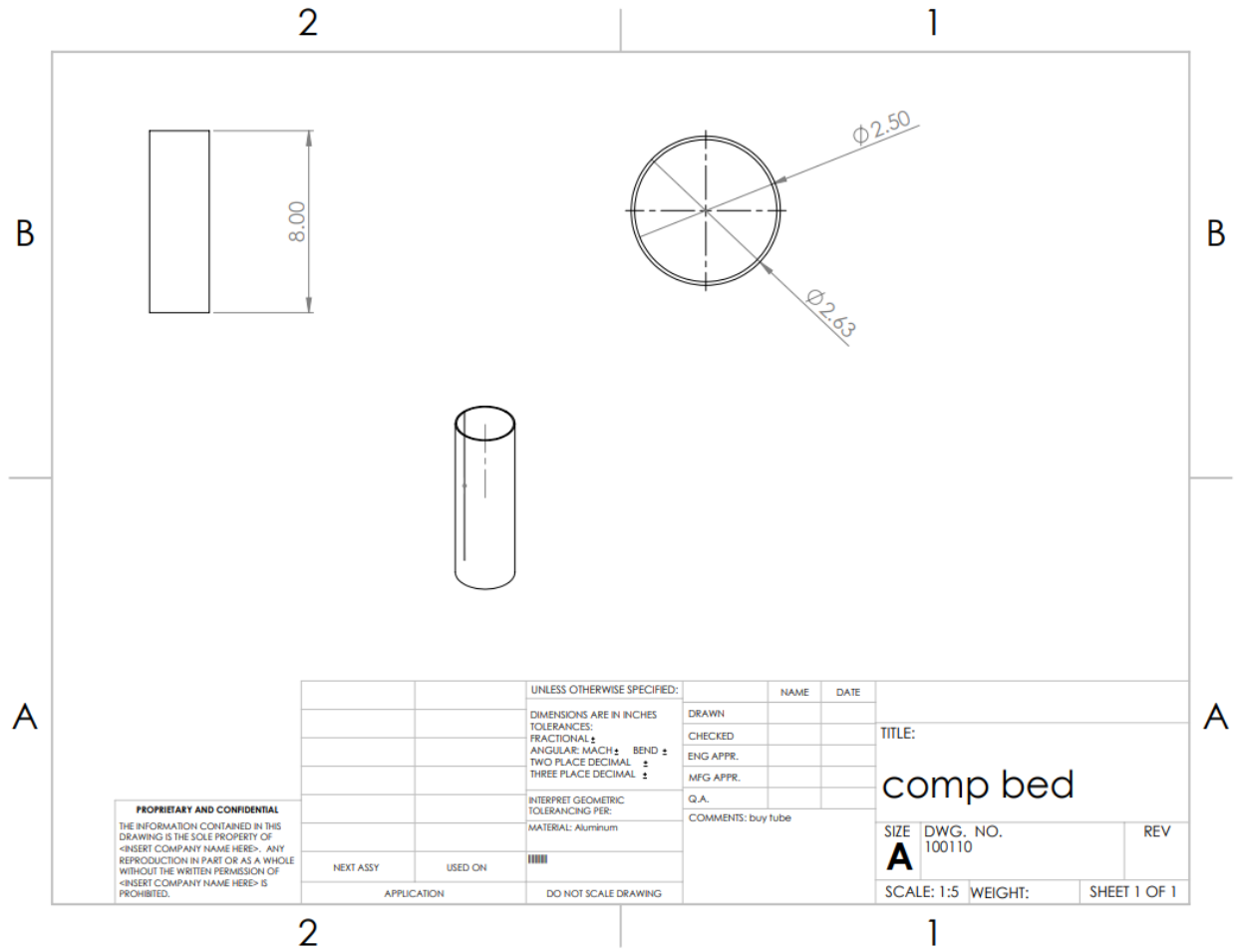


Figure 4.5. Compression Bed.

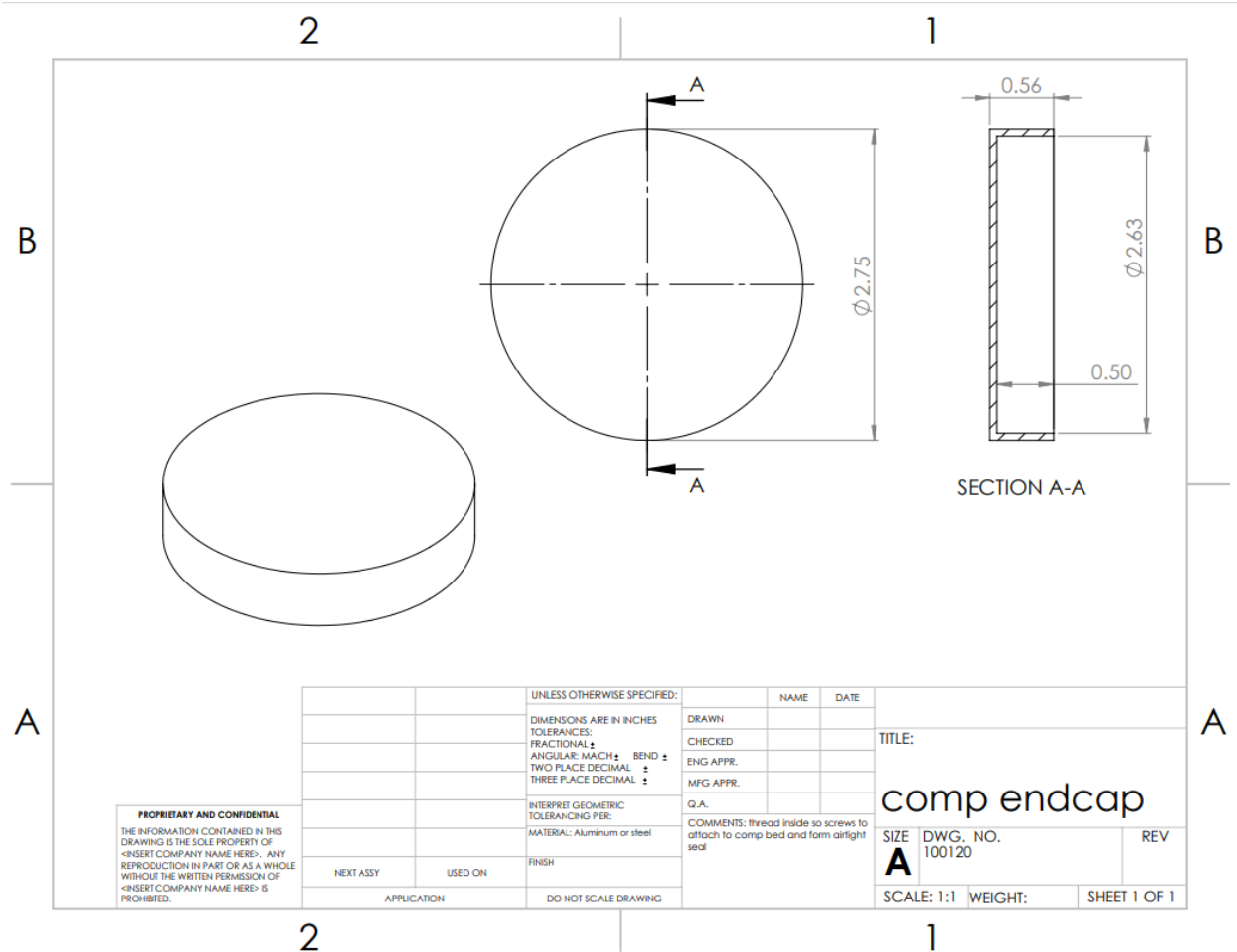


Figure 4.6. Compression Bed End Cap.

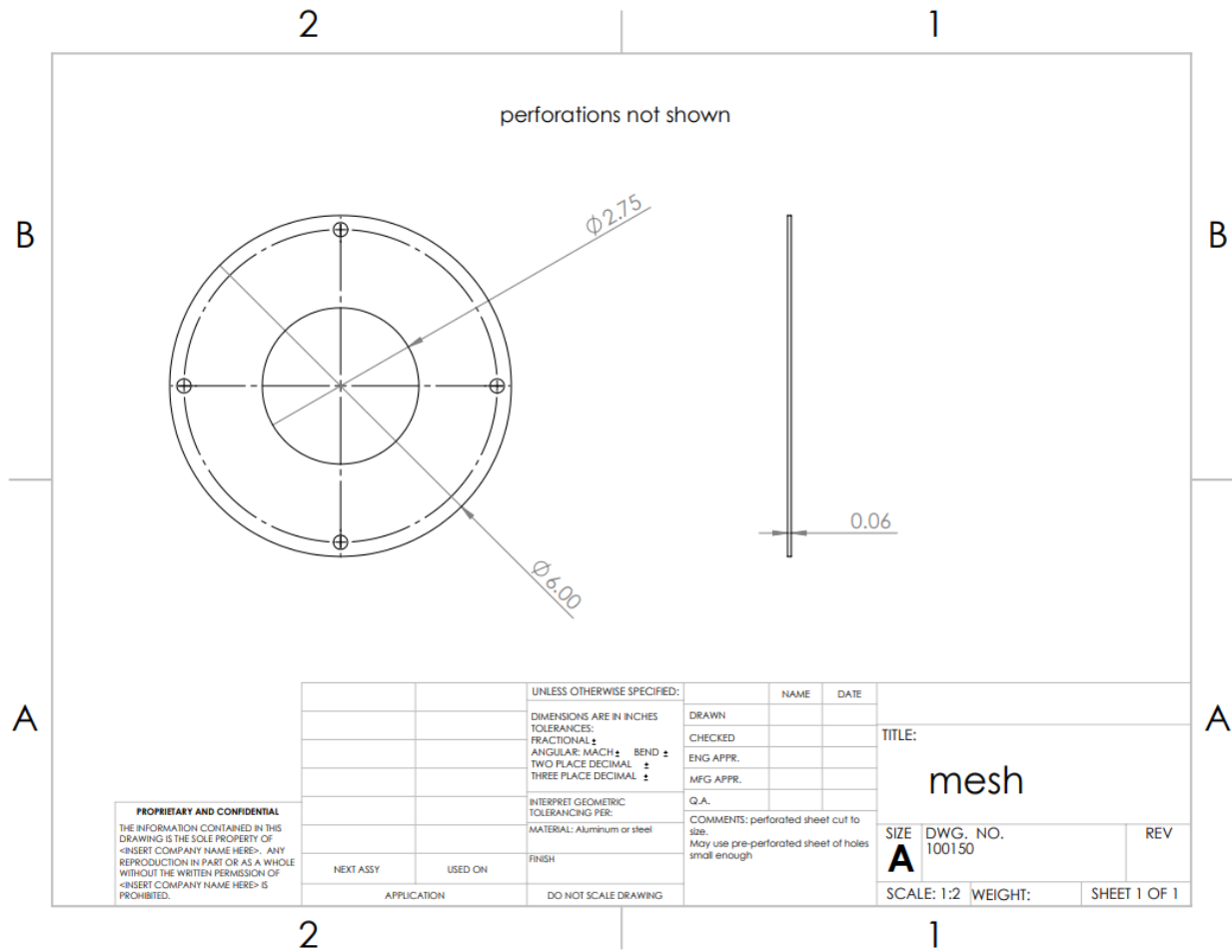


Figure 4.7. Mesh.

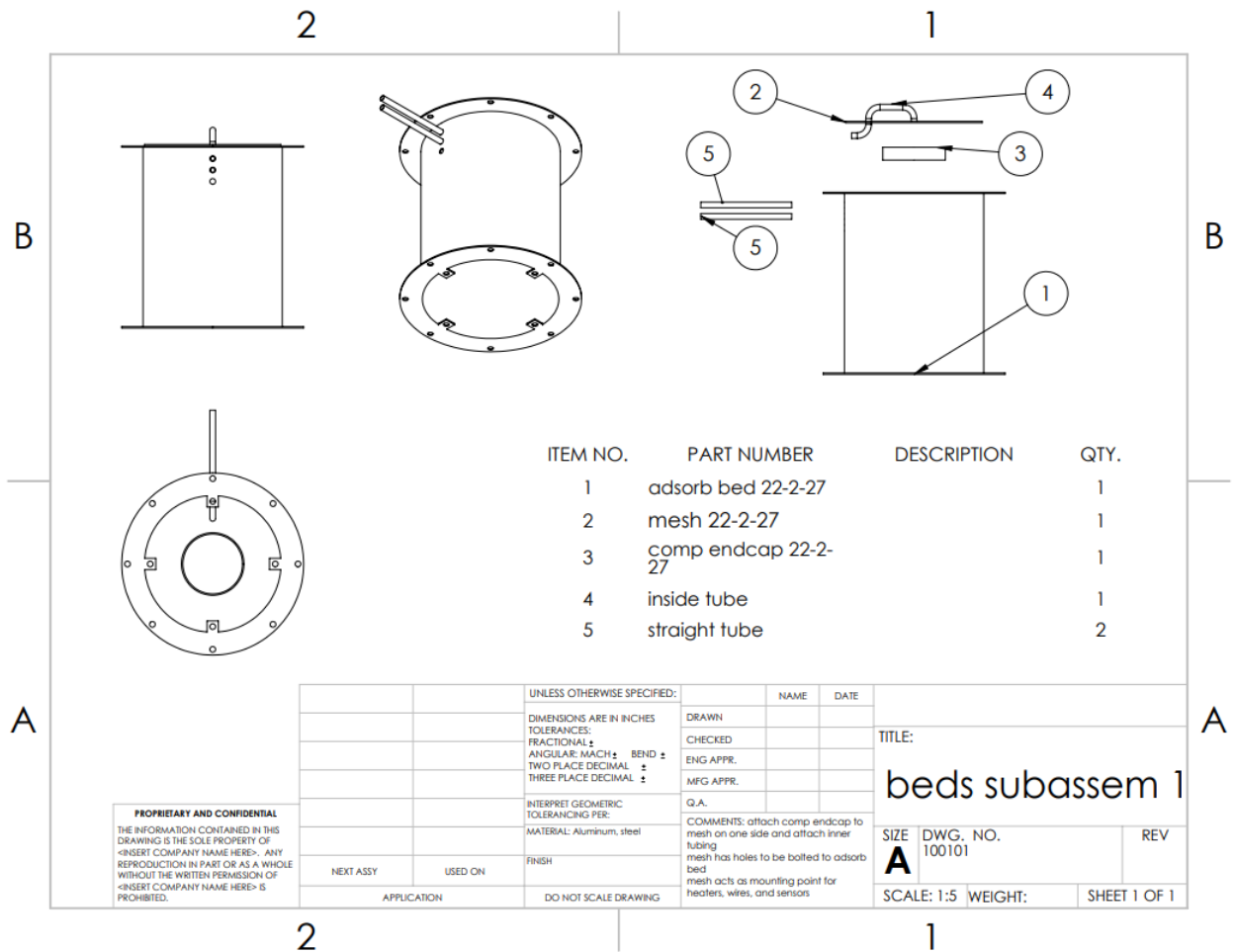


Figure 4.8. Subassembly 1 For Beds.

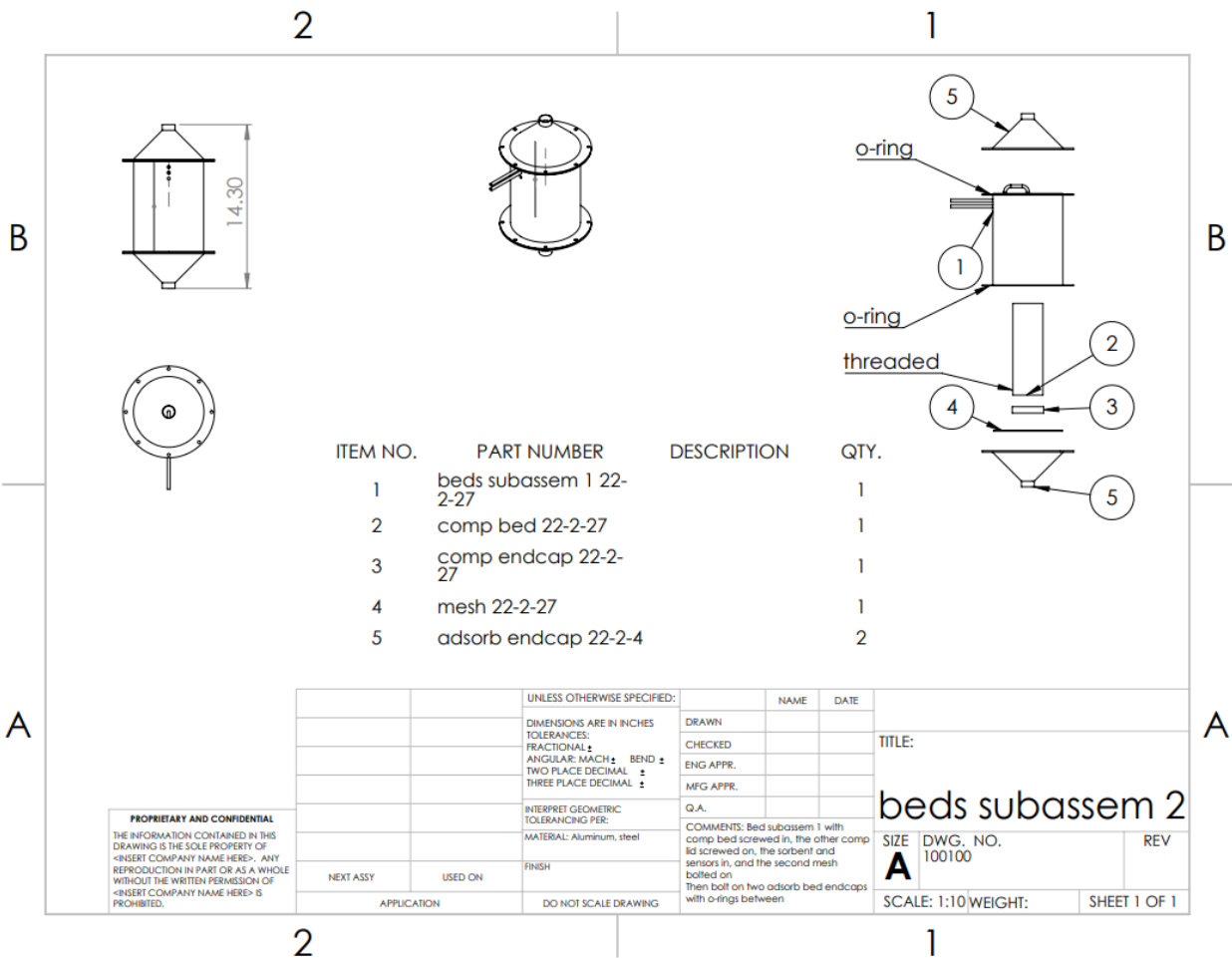


Figure 4.9. Subassembly 2 for Beds.

5.0 System Requirements Document

Sub-scale Adsorption and Compression CO₂ Removal System Re-design Team #22014

Joaquin Pesqueira
Brianna Otero
William Fowler
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1.0 Introduction and Scope

This document contains the system requirements for a sub-scale adsorption and compression CO₂ removal system for Biosphere 2 and NASA. Biosphere 2 is located in Oracle, Arizona, and the main facility is SAM (Space Analog for the Moon and Mars) which will use this redesigned system. Additionally, NASA is looking for more efficient ways of removing CO₂ for the future of space exploration and life support systems. This system is to be used within the scope of the Moon to Mars eXploration Systems and Habitation mission (M2M X-Hab).

This system is based off of the current TC-TSAC system (Thermally Coupled Temperature Swing Adsorption and Compression). TC-TSAC systems use packed beds of regenerable bulk sorbents and heat cycles to simultaneously adsorb and compress CO₂. TC-TSAC geometries have already been developed, but this project aims to design and test a new system geometry. This system will need to be scalable to up to 4kg of CO₂ per day. The main requirements are sensors to gather measurements and calculate necessary flow rates. Additionally, removal and compression beds of a cylindrical shape will be used. The system shall compress the carbon dioxide to 1000 torr. Ultimately the system will need to use a recyclable sorbent, and be within necessary power, thermal, and performance requirements to improve the efficiency of the current design of the TC-TSAC system.

2.0 Applicable Documents

2.1 Proposal

2.2 The Integrated Carbon Dioxide Removal, Compression, and Storage (CRCS) System, ICES, 2017

2.3 Current Development Status of the Temperature Swing Adsorption Systems and Updated Trade Study Results, ICES, 2019

2.4 A Trade-off Study of the Spacecraft Carbon Dioxide Management System using the Analytical Hierarchy Process, ICES, 2018

3.0 Definitions, Acronyms, and Abbreviations

TC-TSAC = Thermally Coupled Temperature Swing Adsorption and Compression

SAM = Space Analog for the Moon and Mars

M2M X-Hab = Moon to Mars eXploration Systems and Habitation

CO₂ = carbon dioxide

NASA = National Aeronautics and Space Administration

4.0 Requirements

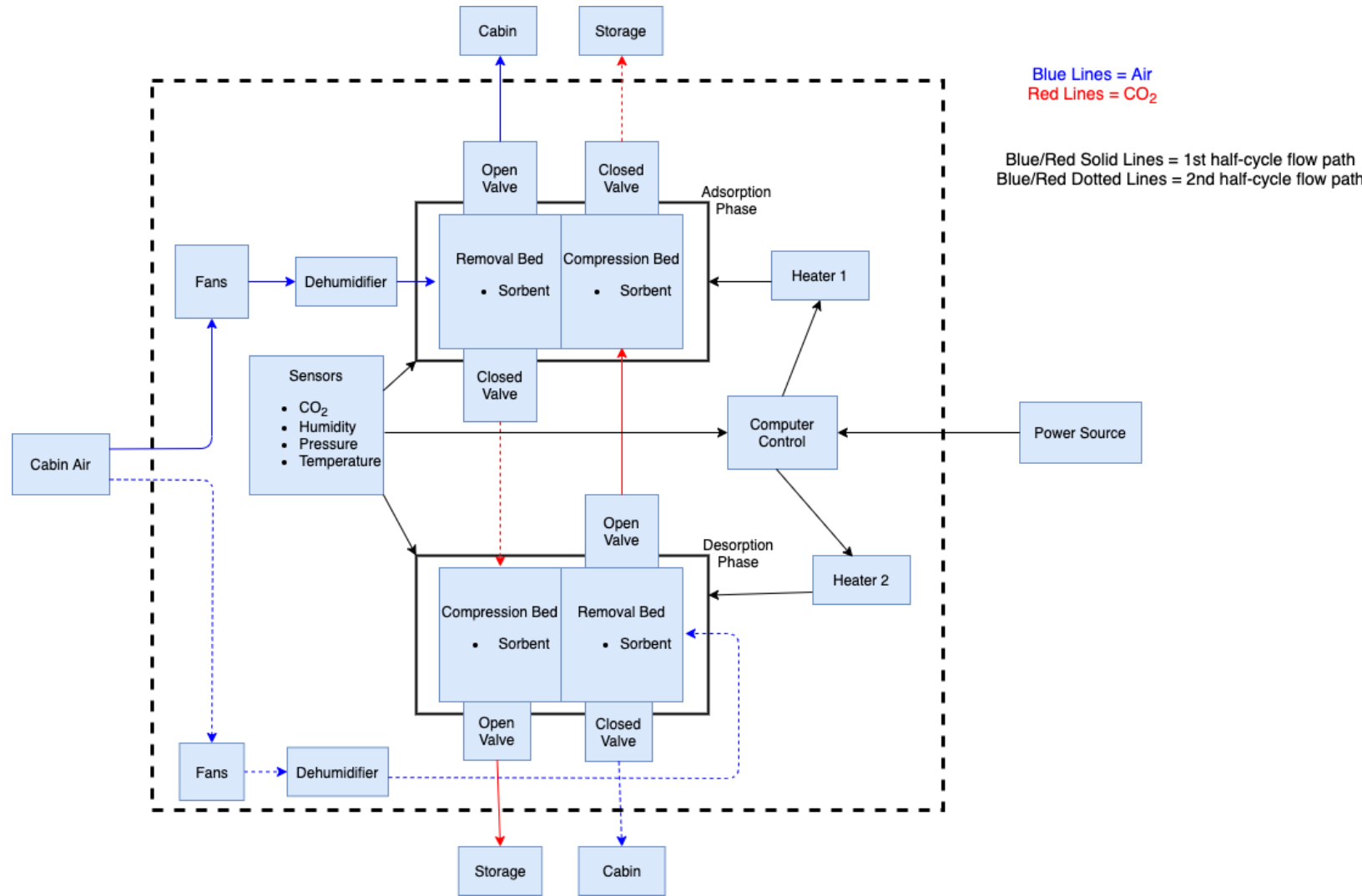


Figure 4.1 System Block Diagram

Requirements

4.1. Interface Requirements

4.1.1 Power: The system shall be scalable up to approximately 200W for the full scale system.

4.1.2 Sensor Interface: Sensors work within the system and are calibrated to the correct values.

4.1.3 User Interface: The system shall display carbon dioxide levels, humidity, and temperature.

4.2. Environmental Requirements

4.2.1 Operational Temperature: The system shall perform without degradation at varying temperatures.

4.2.2 Operational Pressure: The system shall perform without degradation at different pressures.

4.2.3 Zero Gravity Compatible: The system shall be able to perform its requirements in a zero gravity environment without degradation.

4.2.4 Operational Humidity: The system shall perform without degradation at different humidity.

4.3. Safety Requirements

4.3.1 Emergency Shutoff Button: The system shall have a shutoff button in order to shut down all components at once in the case of an emergency.

4.3.2 Temperature of the system is within safe range to touch: The system shall have exterior components to operate that are safe to touch and any other components that will not be used to operate the system and are unsafe to touch will be marked.

4.3.3 No leaks: The system shall have no external leaks to the surroundings.

4.4. Customer Constraints

4.4.1 The system should be scalable up to 4kg CO₂/day: The system shall be scalable up to 4kg of carbon dioxide removed per day.

4.4.2 Cost - no more than given budget: The final system design shall be under the \$ given to us for the budget.

4.5 Performance Requirements

4.5.1 Sorbent regenerates reliably: The sorbent used (13X) shall be able to be used multiple times.

4.5.2 Adsorbed CO₂ compressed to 1000 torr: The system shall compress the carbon dioxide to 1000 torr.

4.5.3 Airflow rate: the system shall measure the flow rate of air entering the system: The system shall use the sensors and measure the flow rate of the air measuring the system.

4.5.4 CO₂ capture rate: the system shall measure the rate that CO₂ is captured: The system shall measure the carbon dioxide capture rate and display it on the sensor.

4.6 Design Requirements

4.6.1 Use zeolites as a sorbent: Zeolite 13X shall be used as the sorbent for the system.

4.6.2 Sensors: Sensors used within the system shall be able to withstand high temperatures (up to 300°C).

5.0 Verification Requirements

Table 5.1 Verification Requirements Test/Analysis

Requirement	Method
2. Environmental Requirements	-
a. Operational Temperature: The system shall perform without degradation at varying temperatures.	T
b. Operational Pressure: The system shall perform without degradation at different pressures.	T
c. Zero Gravity Compatible: The system shall be able to perform its requirements in a zero gravity environment without degradation.	T
d. Operational Humidity: The system shall perform without degradation at different humidities.	T
3. Safety Requirements	-
a. Leakage: The system shall be free of any leaks.	T, D, I
4. Customer Constraints	-
a. Scalability: The system shall be scalable up to adsorbing 4 kg of CO ₂ /day.	A
5. Performance Requirements	
a. Sorbent Regeneration: The sorbent shall be regenerative for multiple uses.	T
b. Carbon Dioxide Compression: The adsorbed carbon dioxide shall be compressed to 1000 torr.	T
c. Airflow Rate: The system shall measure the flow rate of air entering the system.	T
e. Carbon Dioxide Capture Rate: The system shall measure the amount of carbon dioxide that is captured.	A

6.0 System Requirements Verification Matrix

Table 6.1 System Requirement Verification Matrix

System Requirement Verification				
Requirement	Method	Limit/Reference	Measured/Ref Value	Pass/Fail
1. Interface Requirements	-	-	-	-
a. Power Interface: The system shall be scalable up to approximately 200W for the full scale system.	I	N/A	Gave ourselves this requirement without knowing what the system would look like	ECR
b. Sensor Interface: Sensors work within the system and are calibrated to the correct values.	D	N/A	Sensors connected	Pass
c. User Interface: Display the levels of CO ₂ , humidity, temperature and pressure within the system.	D, I	N/A	Display functional	Pass
2. Environmental Requirements	-	-	-	-
c. Operational Temperature: The system shall perform without degradation at varying temperatures.	T	Operates within 30°C-300°C	Operates within 30°C-300°C without degradation	Pass
d. Operational Pressure: The system shall perform without degradation at different pressures.	T	Operates within 0-1.5 atm	-	Not able to be tested
c. Zero Gravity Compatible: The system shall be able to perform its requirements in a zero gravity environment without degradation.	T	System functions in zero gravity environment without falling apart	-	Not able to be tested
d. Operational Humidity: The system shall perform without degradation at different humidities.	T	<10% relative humidity	<10% relative humidity	Pass
3. Safety Requirements	-	-	-	-
b. Emergency Shutoff: The system shall have an emergency shutoff button.	D	N/A	Unplug system, rather than button	ECR
c. Outside Temperature: The outside temperature of the system shall be safe enough to touch or marked if unsafe.	D, I	N/A	Insulation used	Pass
d. Leakage: The system shall be free of any leaks.	T, D, I	Negligible measured loss of pressure over time	Compression bed leaks	Fail
4. Customer Constraints	-	-	-	-
b. Scalability: The system shall be scalable up to adsorbing 4 kg of CO ₂ /day.	A	1kg of CO ₂ /day is adsorbed	~0.25 kg of CO ₂ /day is adsorbed	Fail
c. Cost: The system shall cost no more than the given budget to build (\$).	I	Under budget	Within budget	Pass
5. Performance Requirements				

d. Sorbent Regeneration: The sorbent shall be regenerative for multiple uses.	T	Sorbent can be used multiple times and successfully regenerates through heating	Desorption process regenerates sorbent	Pass
e. Carbon Dioxide Compression: The adsorbed carbon dioxide shall be compressed to 1000 torr.	T	System compresses carbon dioxide to 1000 torr	Compression bed has leaks - unable to gather data	Fail
f. Airflow Rate: The system shall measure the flow rate of air entering the system.	T	N/A since this value will be measured	Measures flow rate using flow meter	Pass
e. Carbon Dioxide Capture Rate: The system shall measure the amount of carbon dioxide that is captured.	A	< ambient concentration over time	Measures indirectly	Pass
6. Design Requirements	-	-	-	-
a. Sorbent: The system shall use zeolite 13x as a sorbent.	I	Zeolite 13X used	13X is used	Pass
b. Sensors: Sensors used within the system shall be able to withstand high temperatures (up to 300°C).	I	Sensors can withstand conditions and successfully record results	Sensors can withstand conditions and successfully record results	Pass

7.0 Notes

7.1 - The system shall also make use of code to integrate components and sensors.

Appendix B: Drawings

IDL

<u>Part Number</u>	<u>Document</u>
100000	System
100100	Adsorb & Comp Assem - x2
100110	Comp bed
100120	Comp bed lid
100130	Adsorb bed
100140	Adsorb bed lid - x2
100150	Mesh - x2
100020	Connection Assembly - x2
100210	Tubing
100220	Small valve - x2
100230	Emergency valve - x2
100240	Pressure Sensor - x2
100030	Bulk Air Moving Assembly
100310	Tubing
100320	Large valve - x4
100330	Tee
100040	Air Preprocessing
100410	Tubing
100420	Pump
100430	Dryer
100050	Heating Assembly
100060	Electrical Assembly

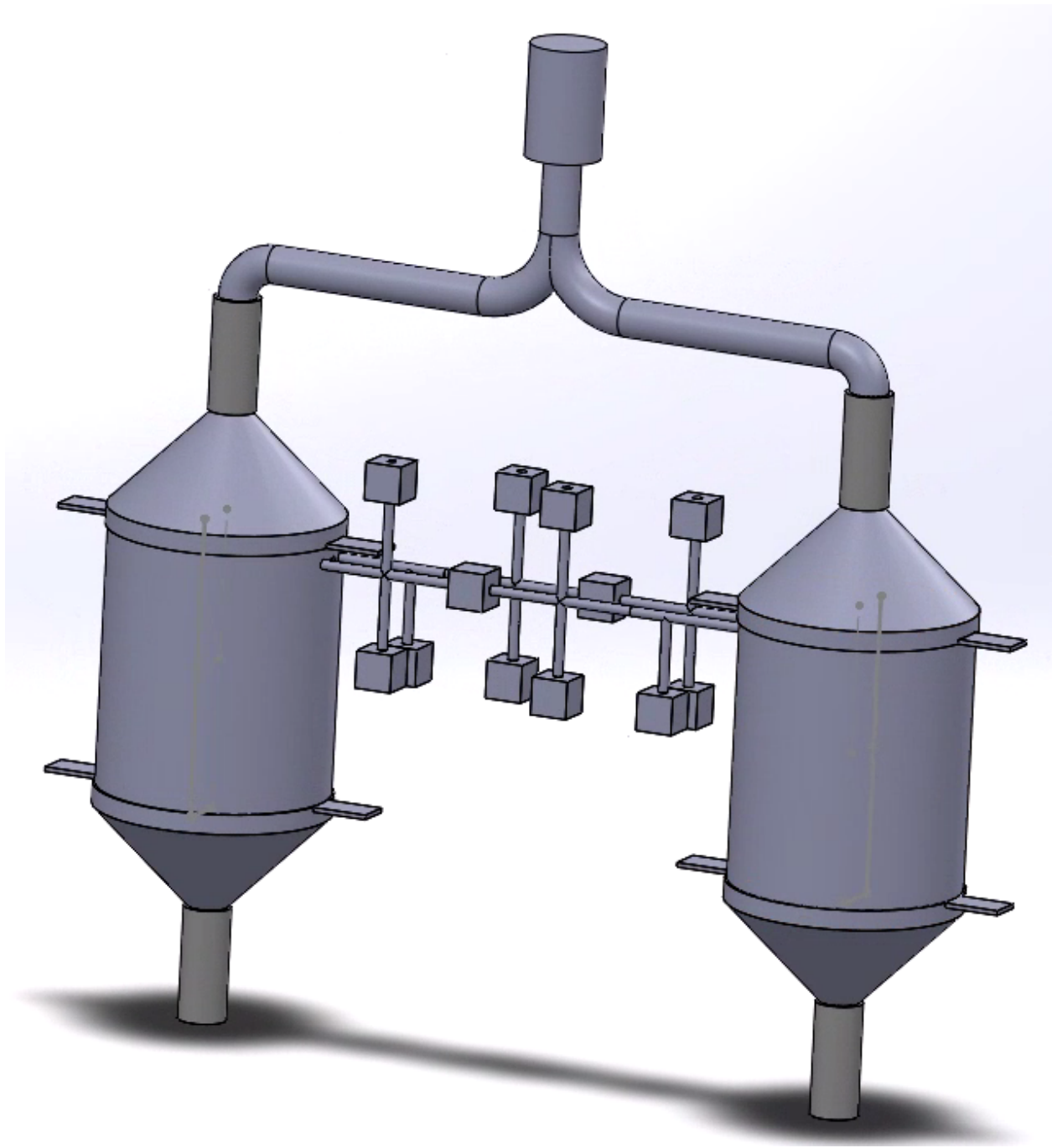


Figure 4.2. Preliminary Overall Canister Layout (SolidWorks)

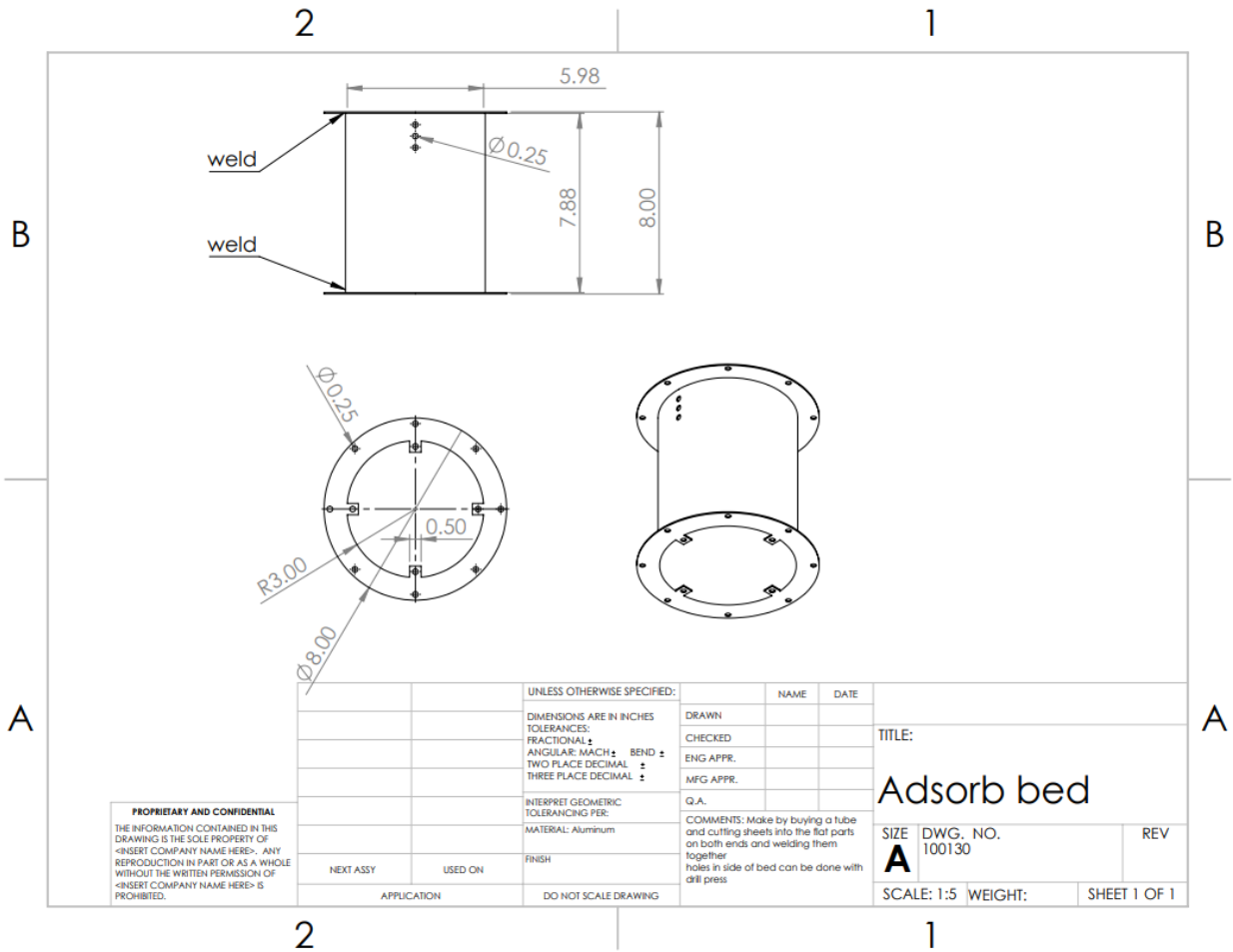


Figure 4.3. Adsorption Bed.

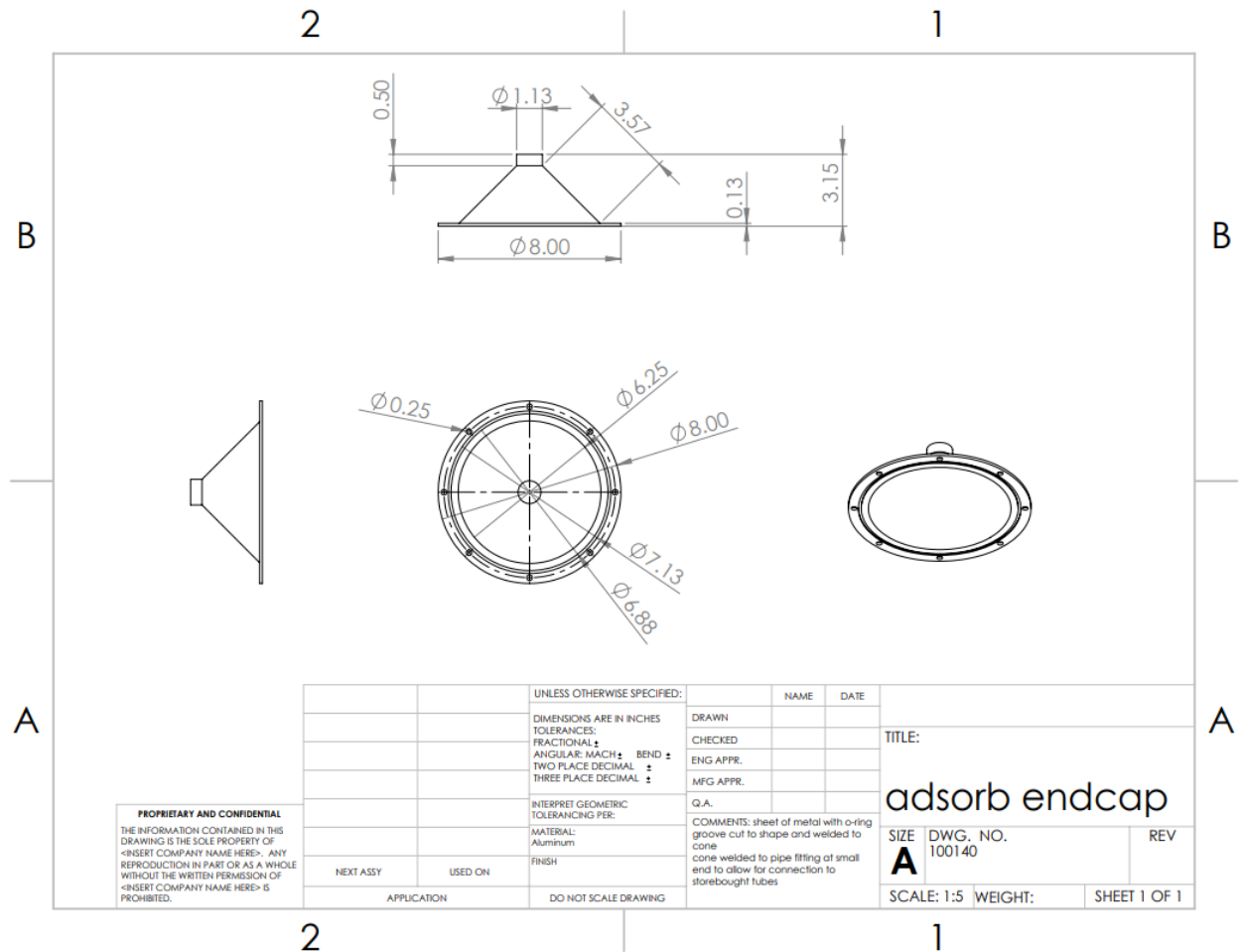


Figure 4.4. Adsorption Bed End Cap.

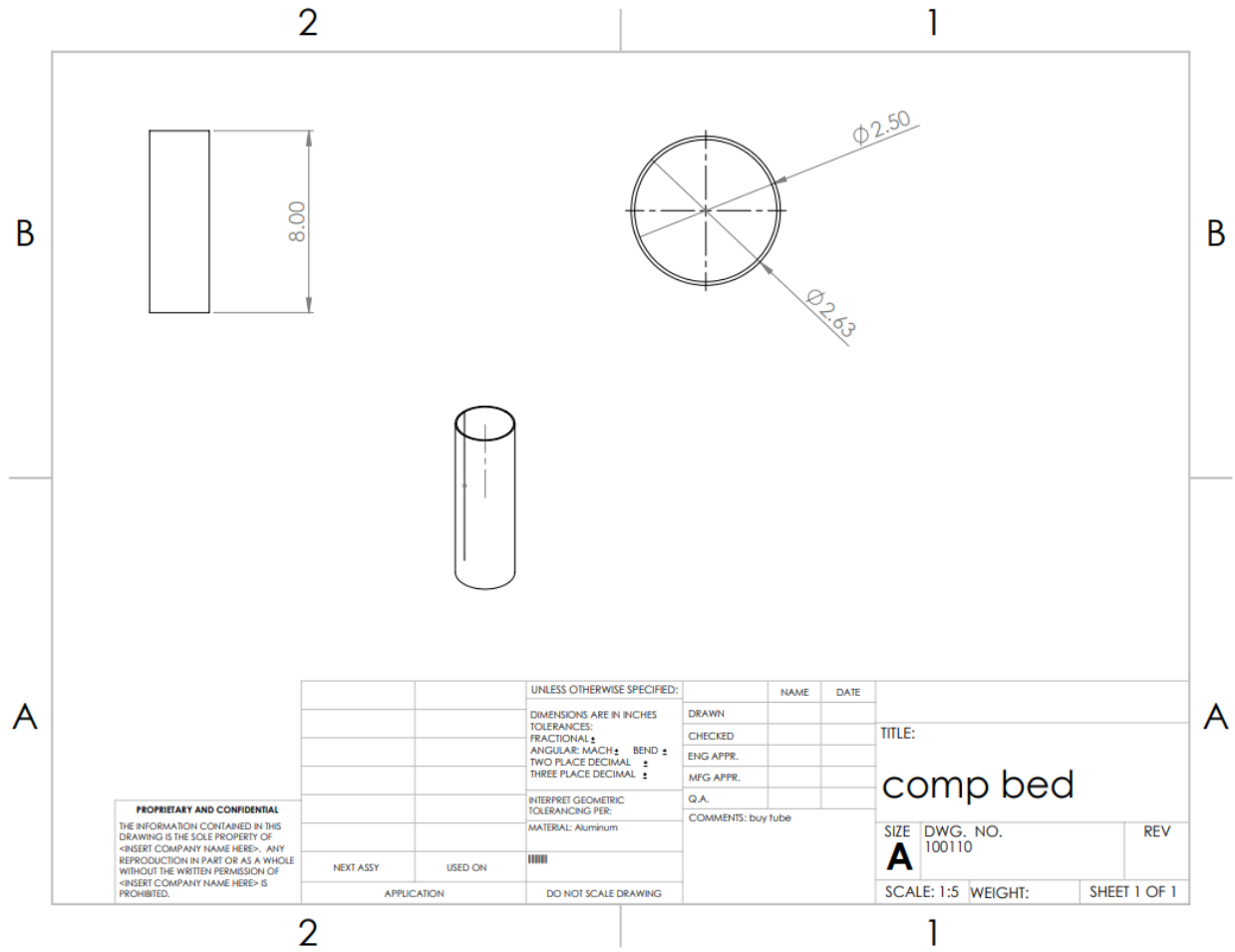


Figure 4.5. Compression Bed.

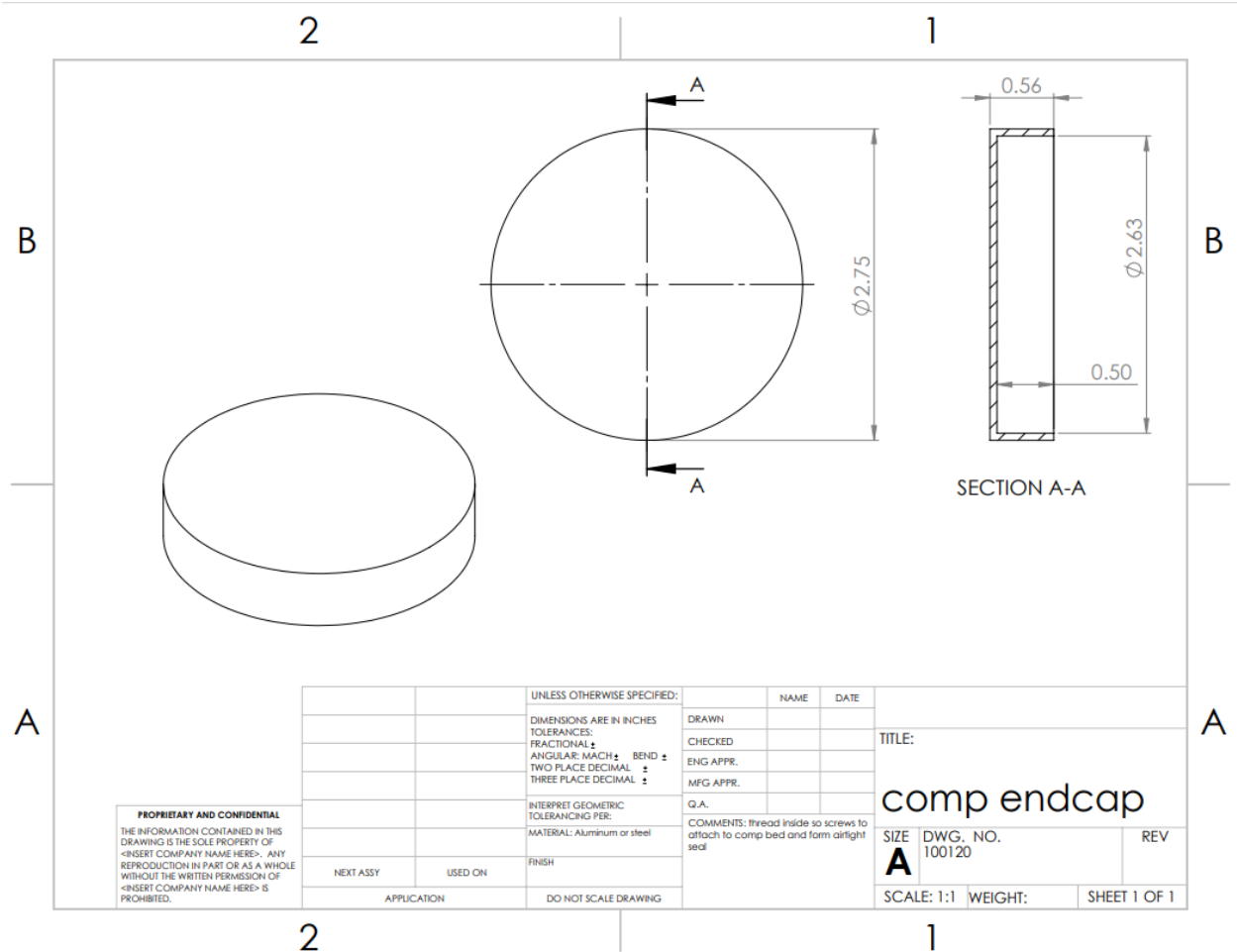
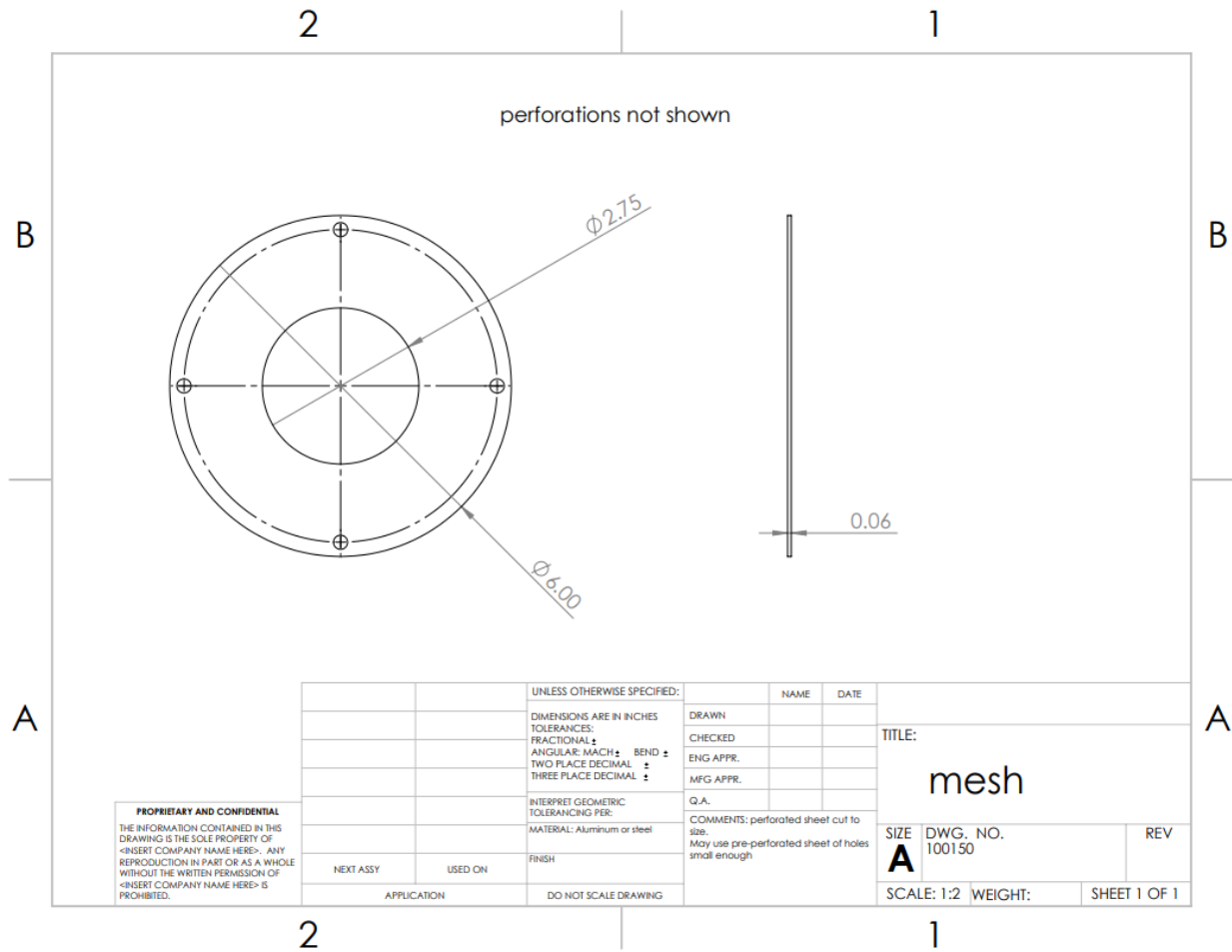


Figure 4.6. Compression Bed End Cap.



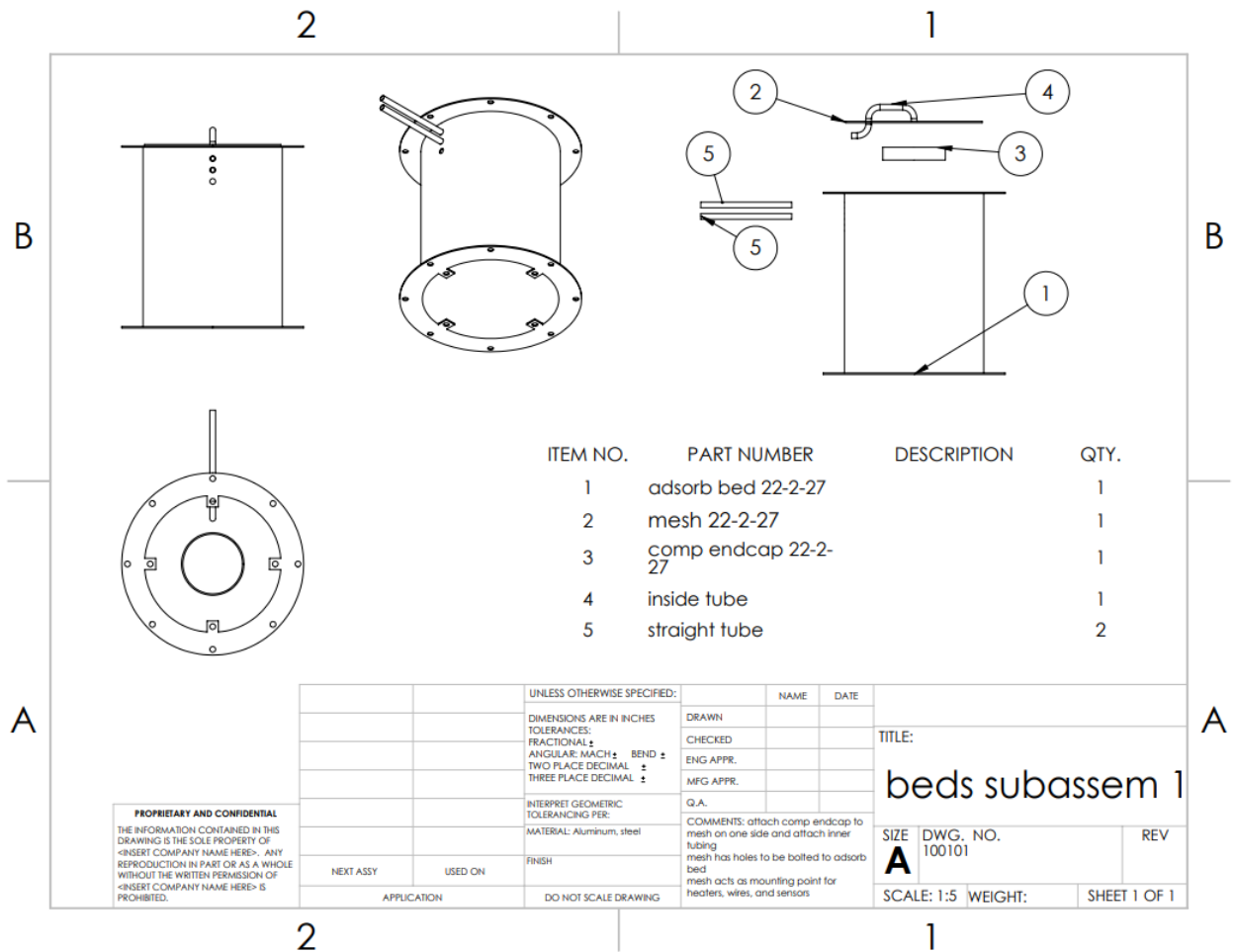


Figure 4.8. Subassembly 1 For Beds.

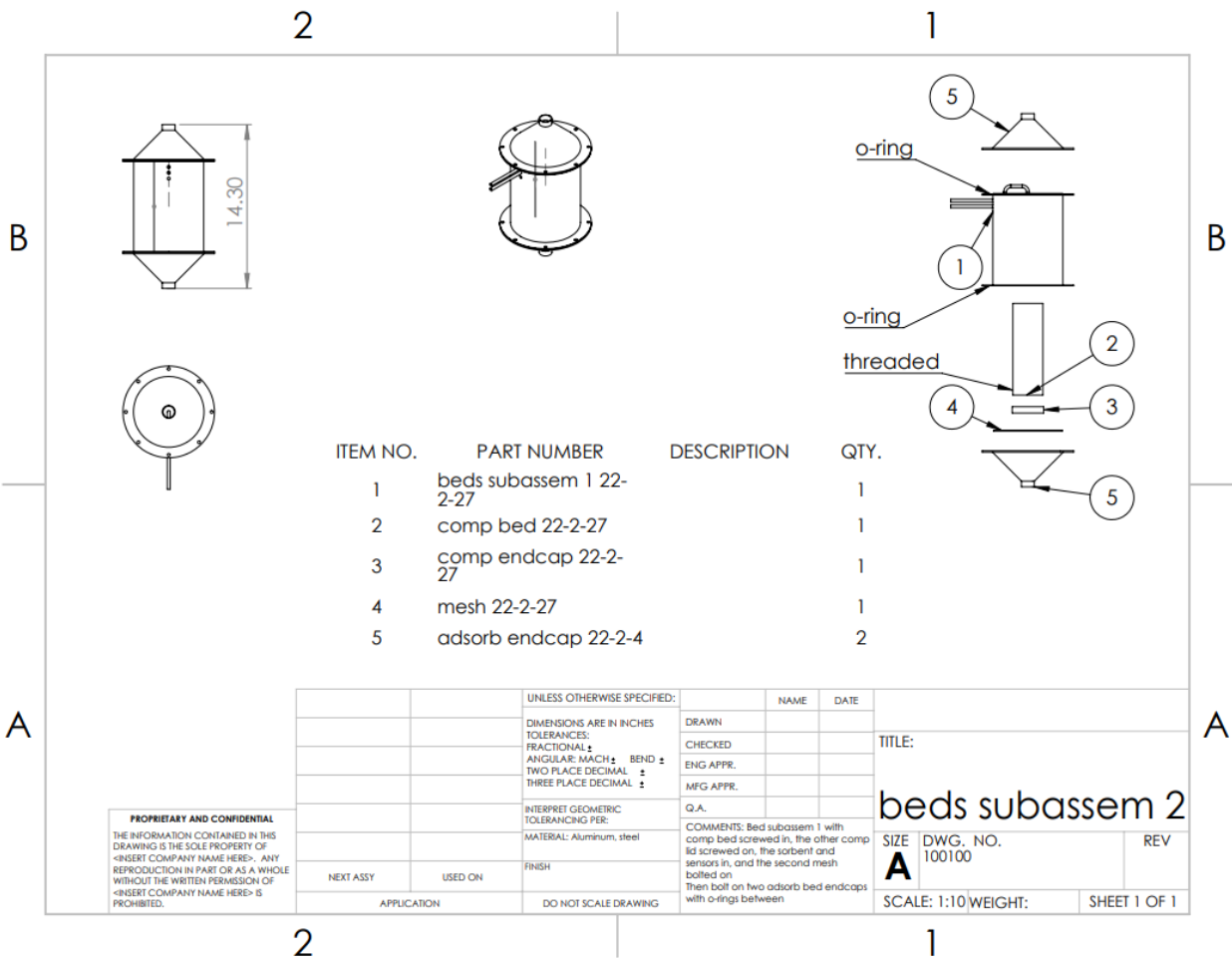


Figure 4.9. Subassembly 2 for Beds.

Appendix C: Models/Analyses

Thermal Desktop

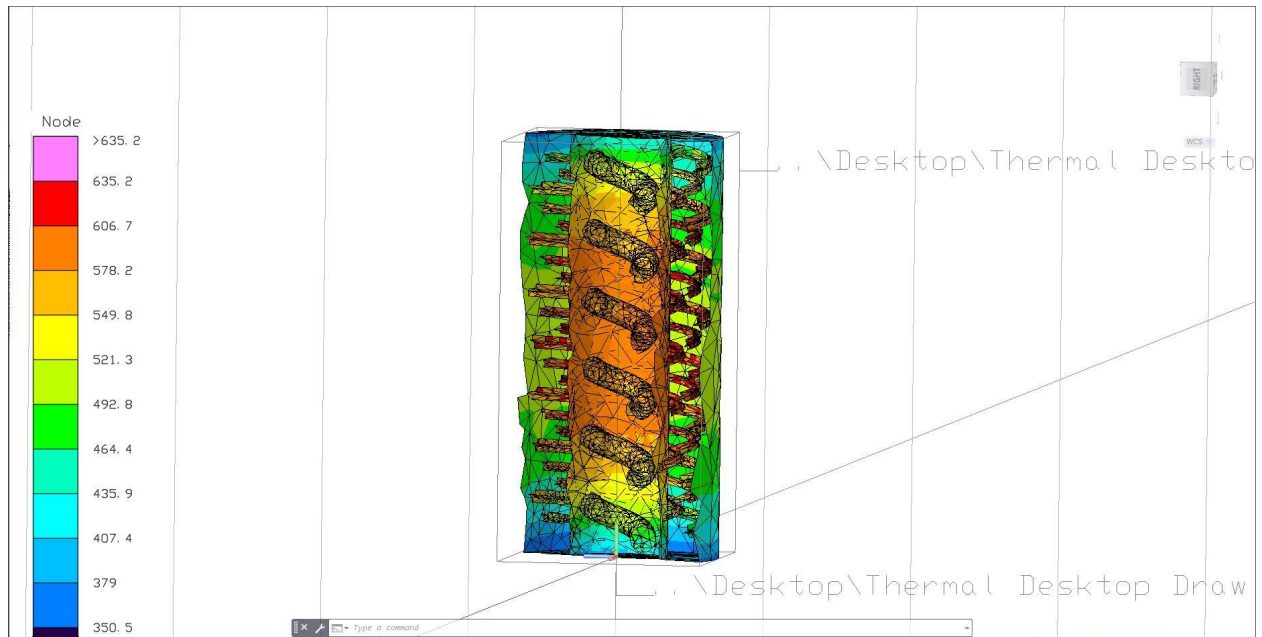
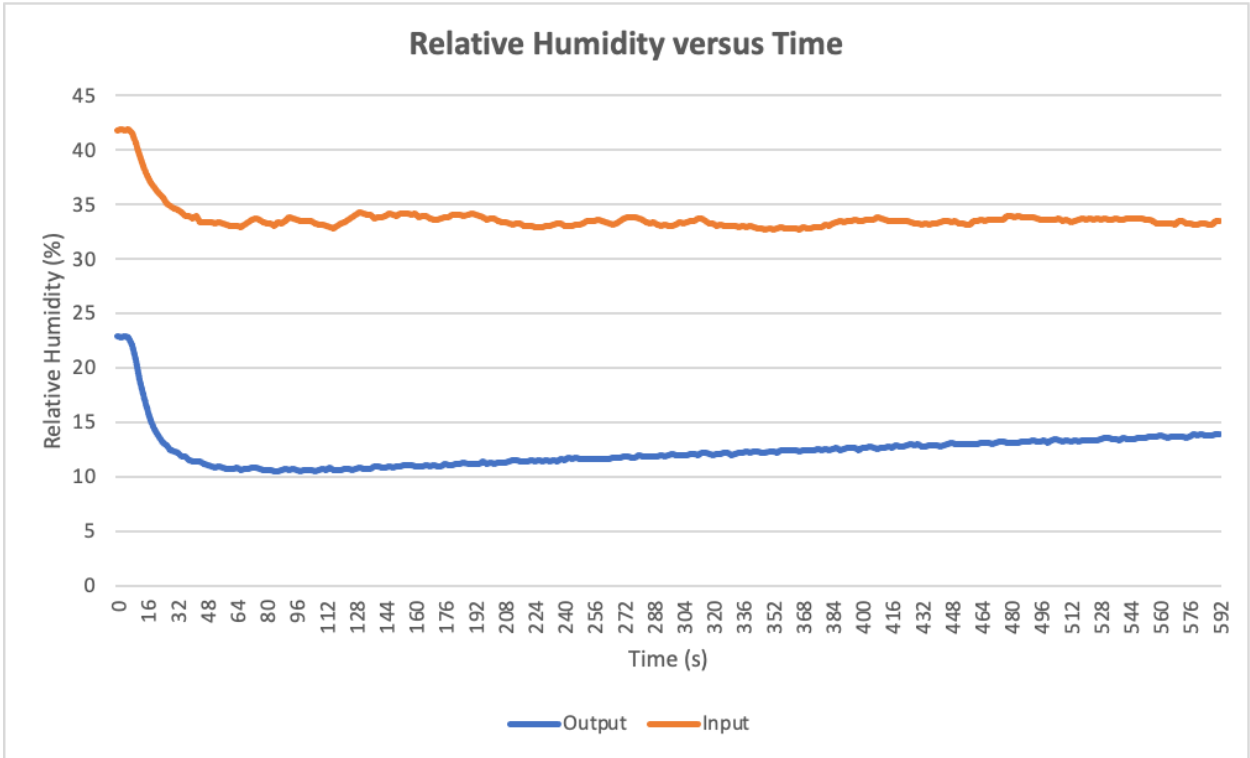
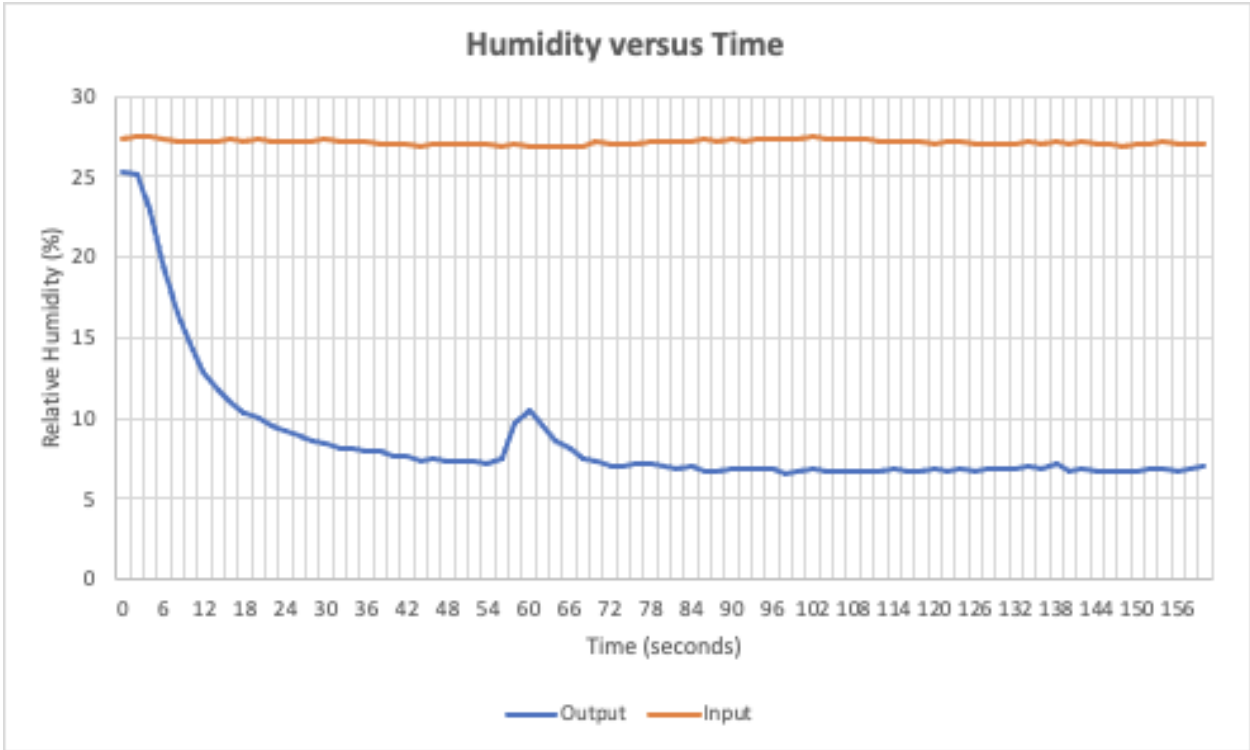


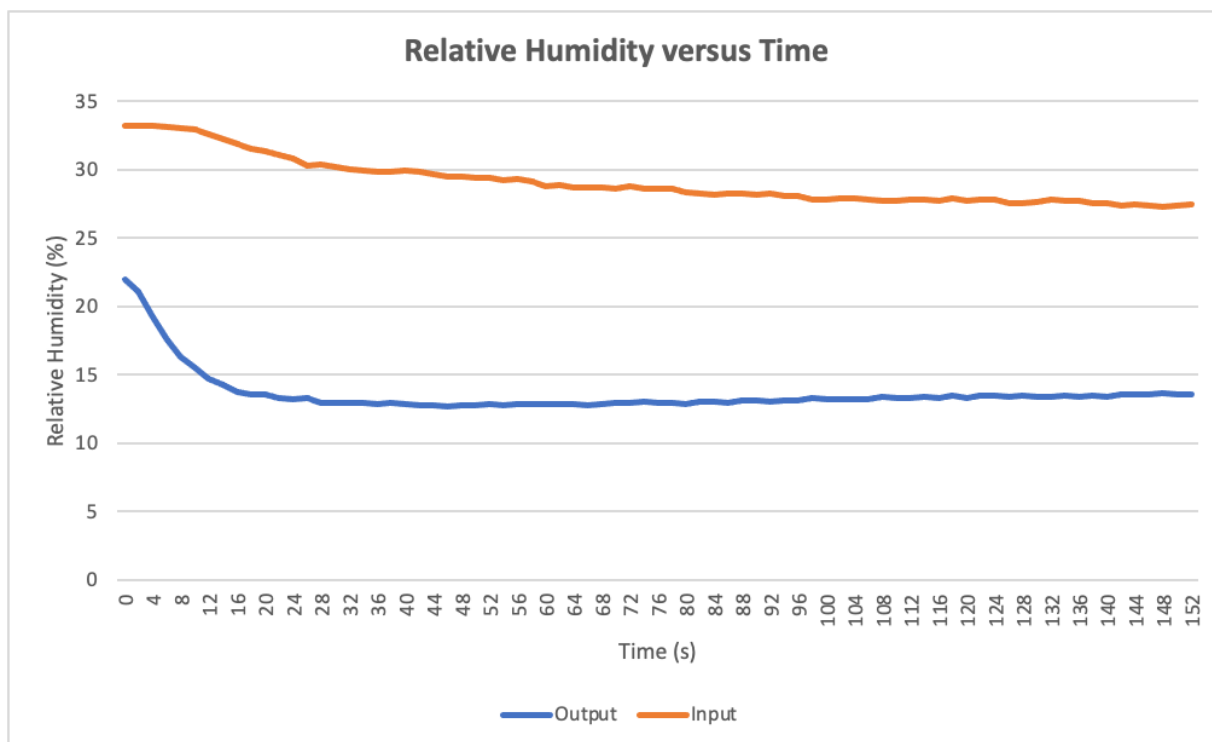
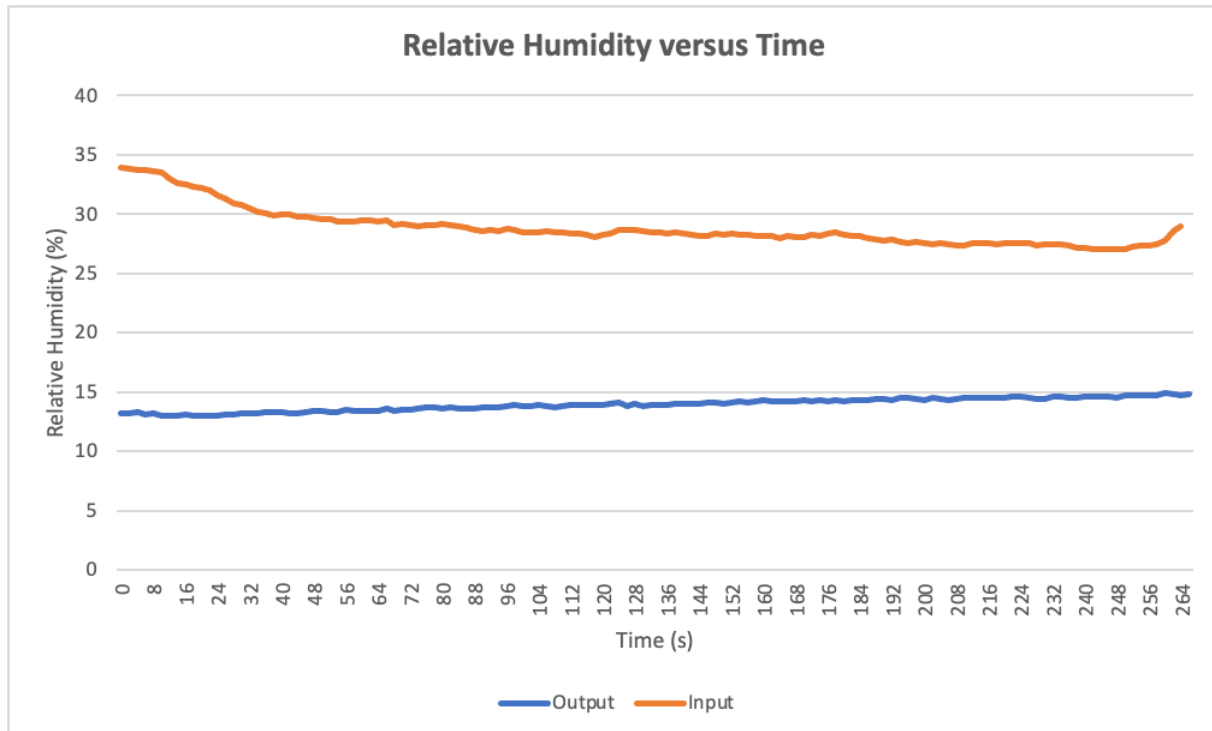
Figure 4.10. Inner heater with no power.



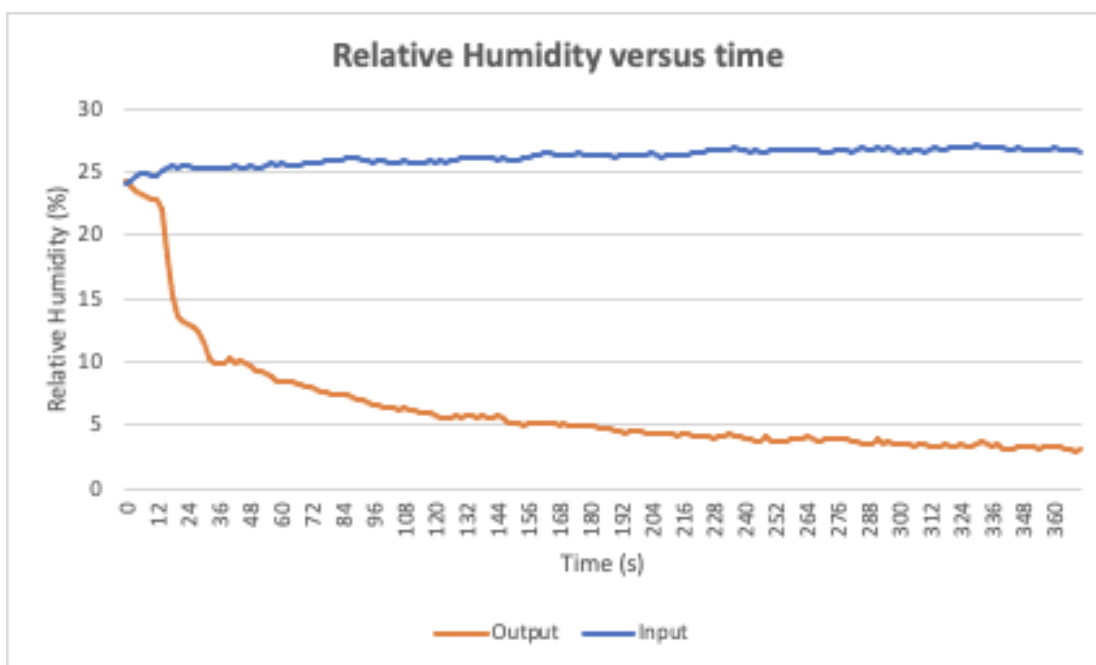
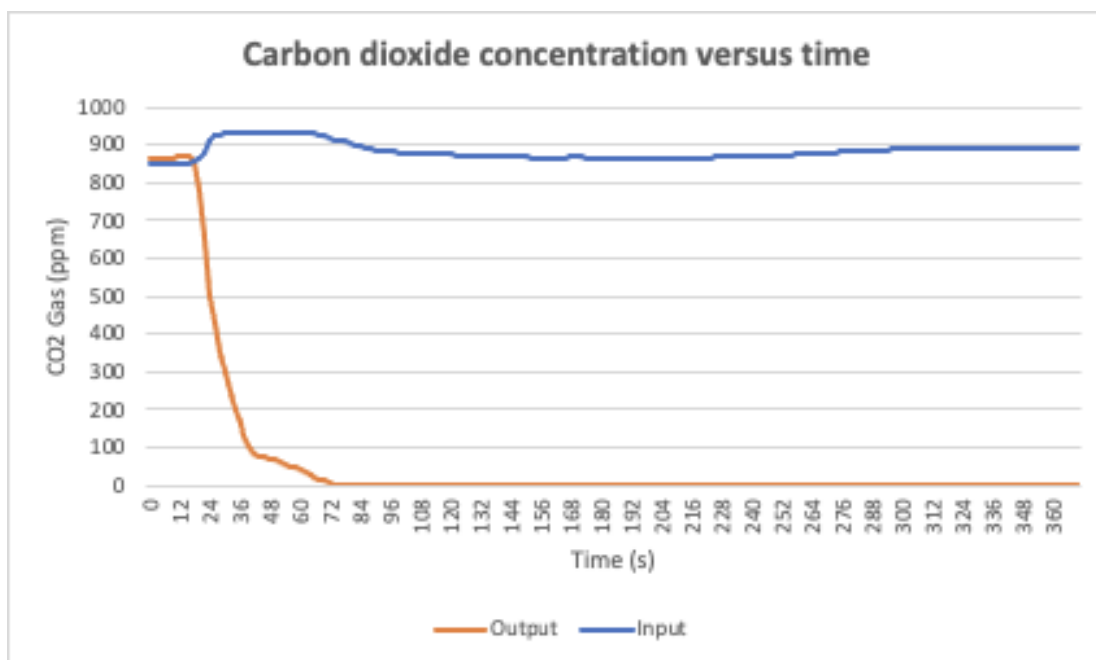
Figure 4.11. Cooling using negative wattage on heater.

Critical Design Element 1

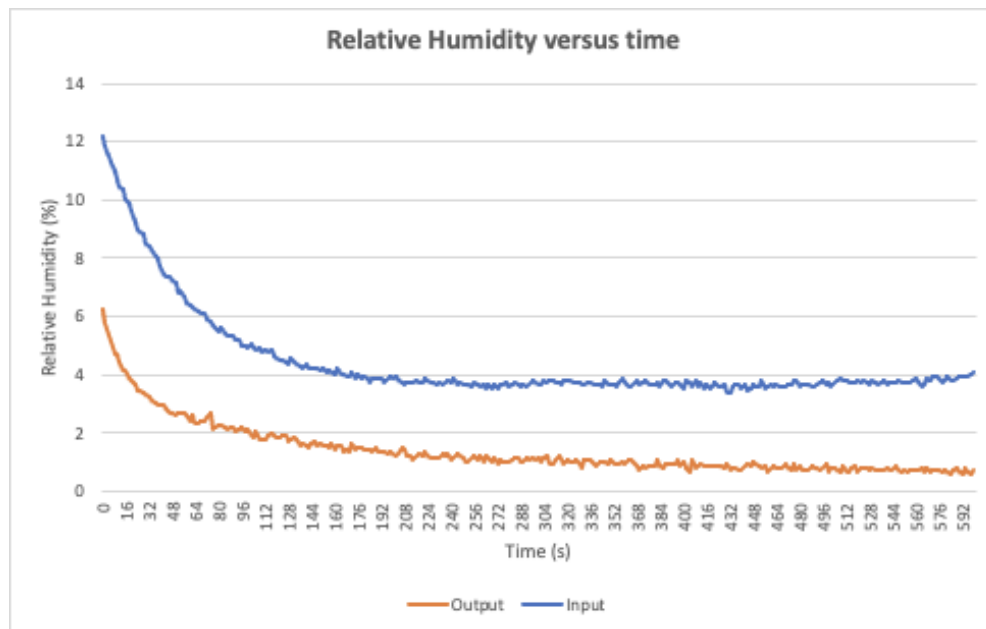
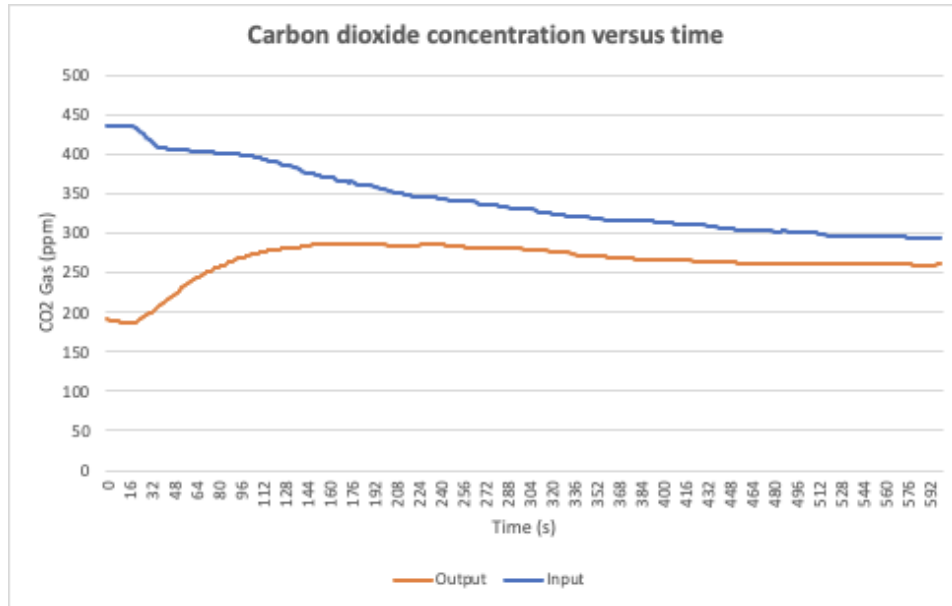


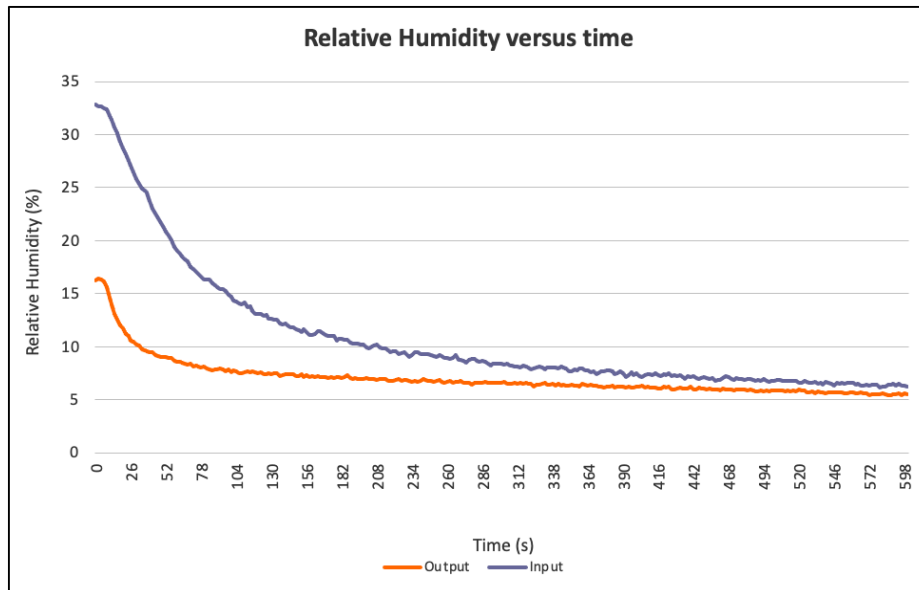
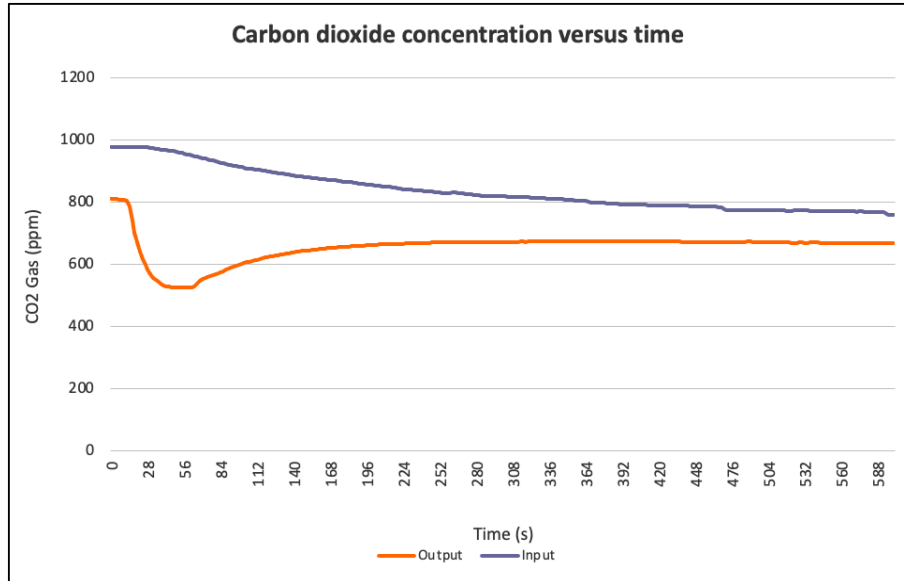


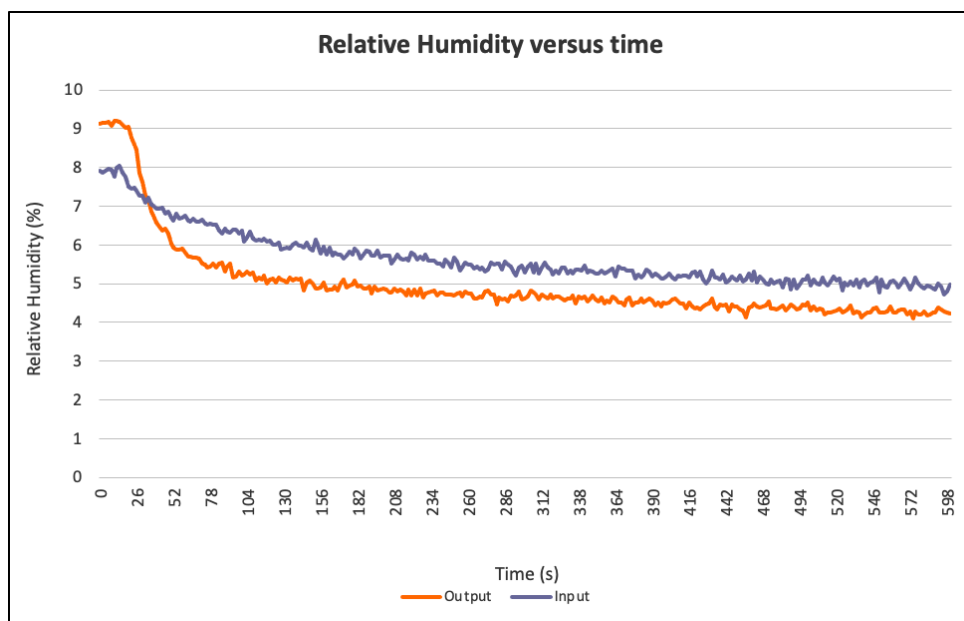
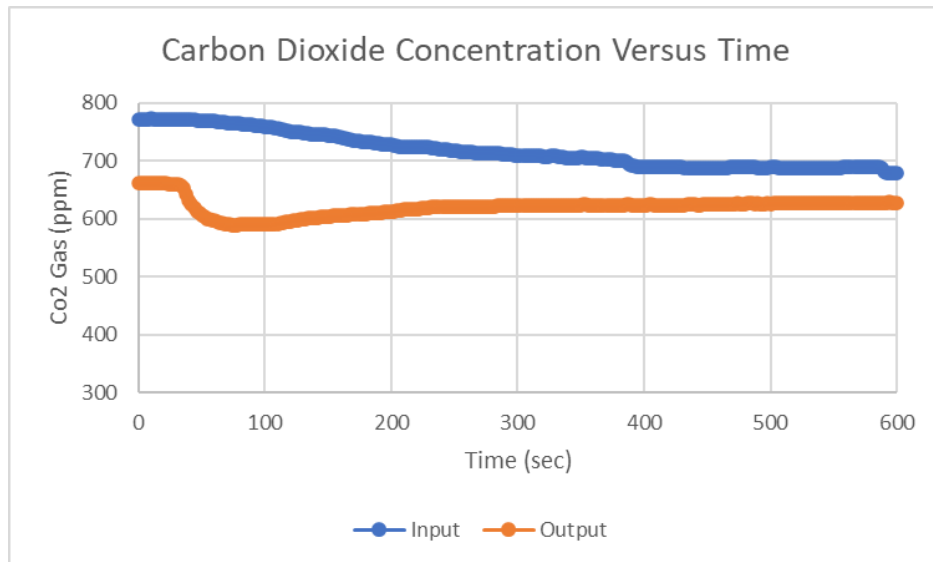
Preliminary Desiccant Tests.



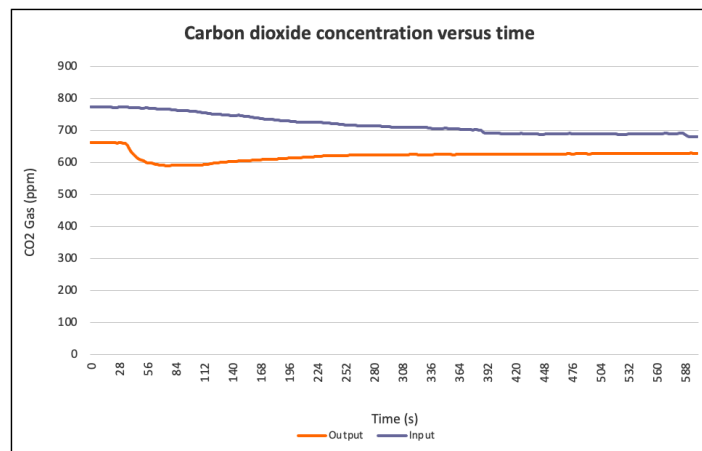
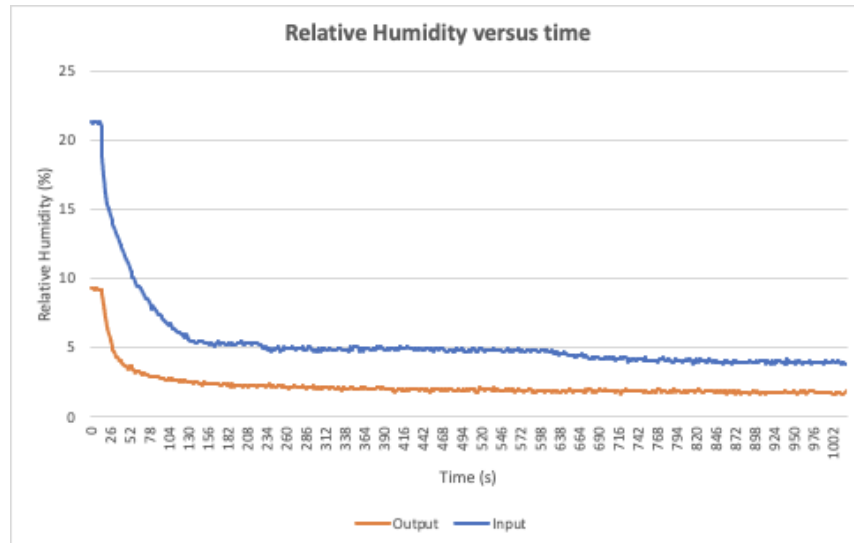
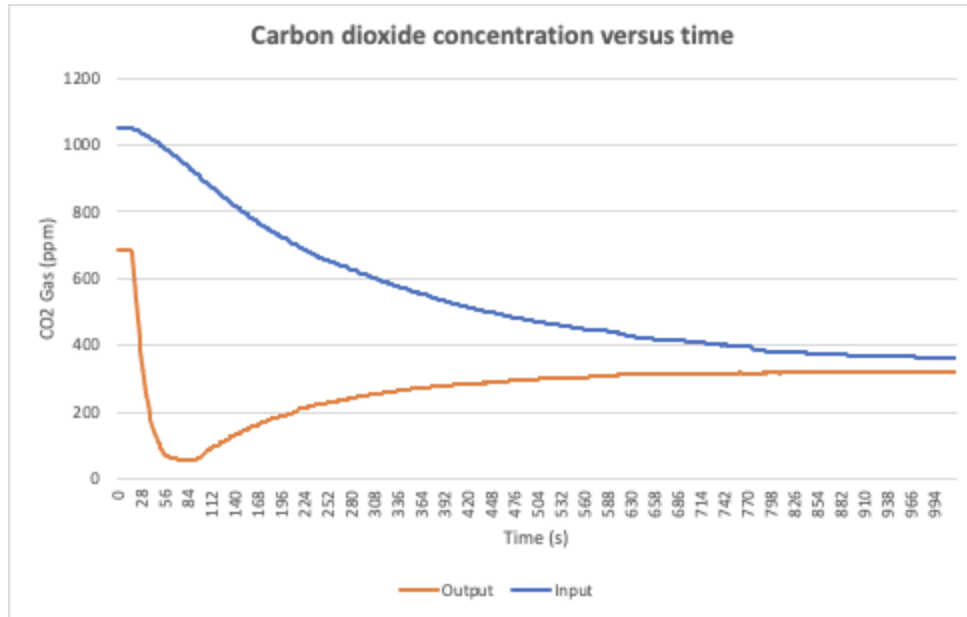
Initial Sorbent Tests.

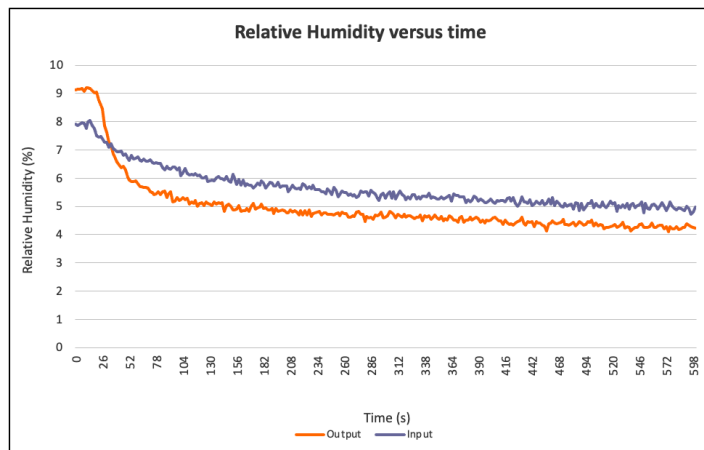
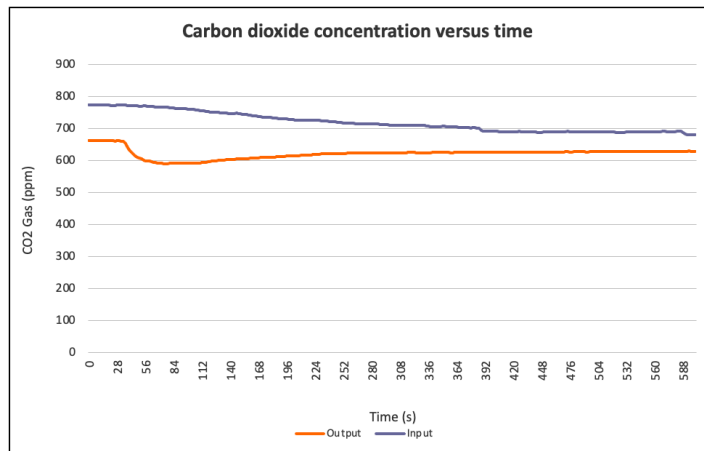
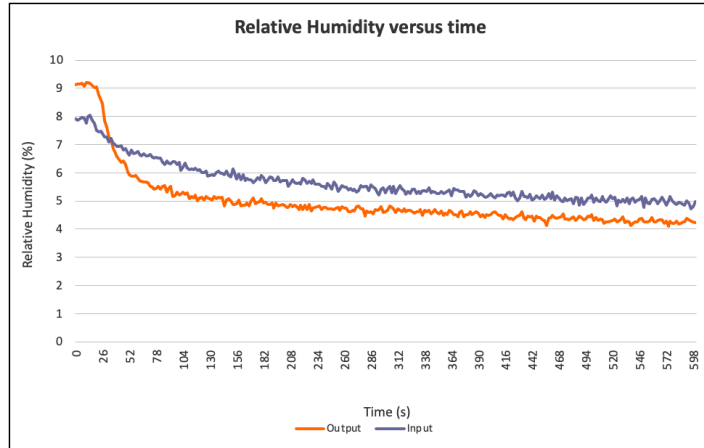




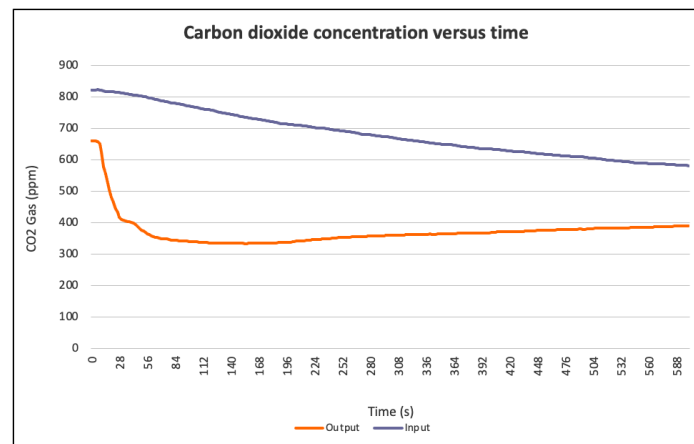
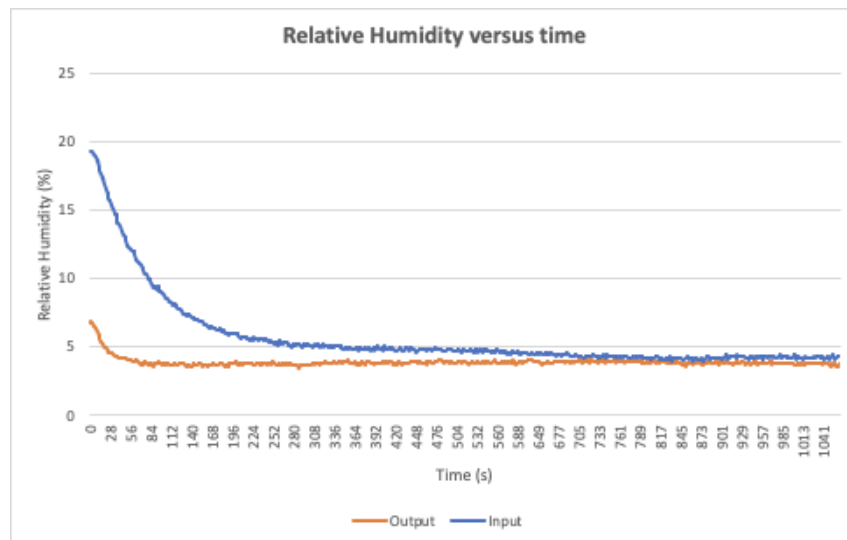
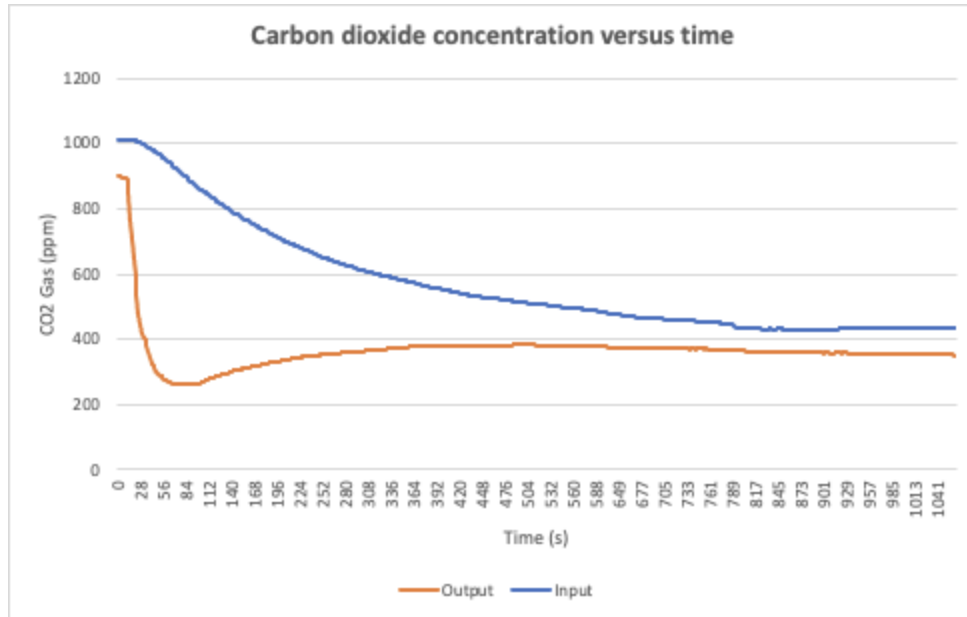


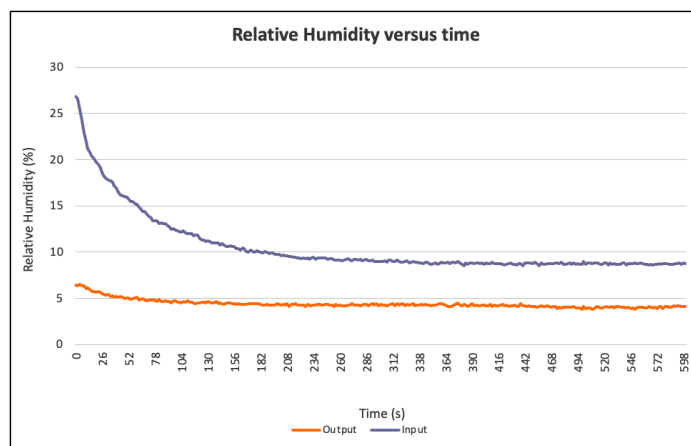
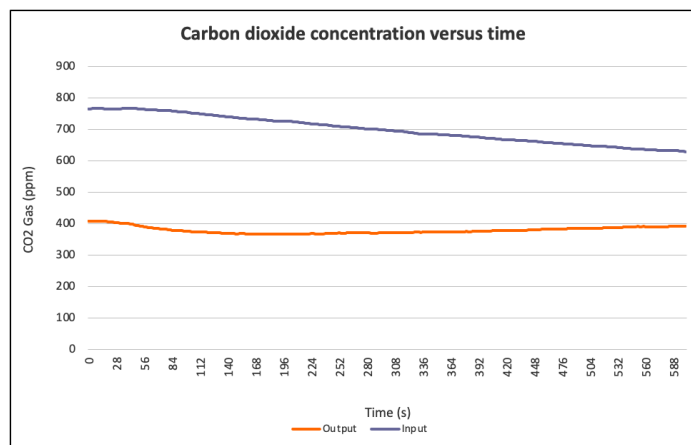
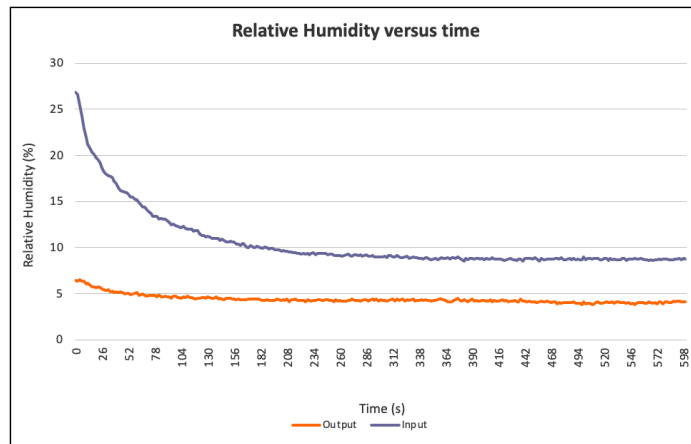
Closed System Sorbent Test 1 (short tube).



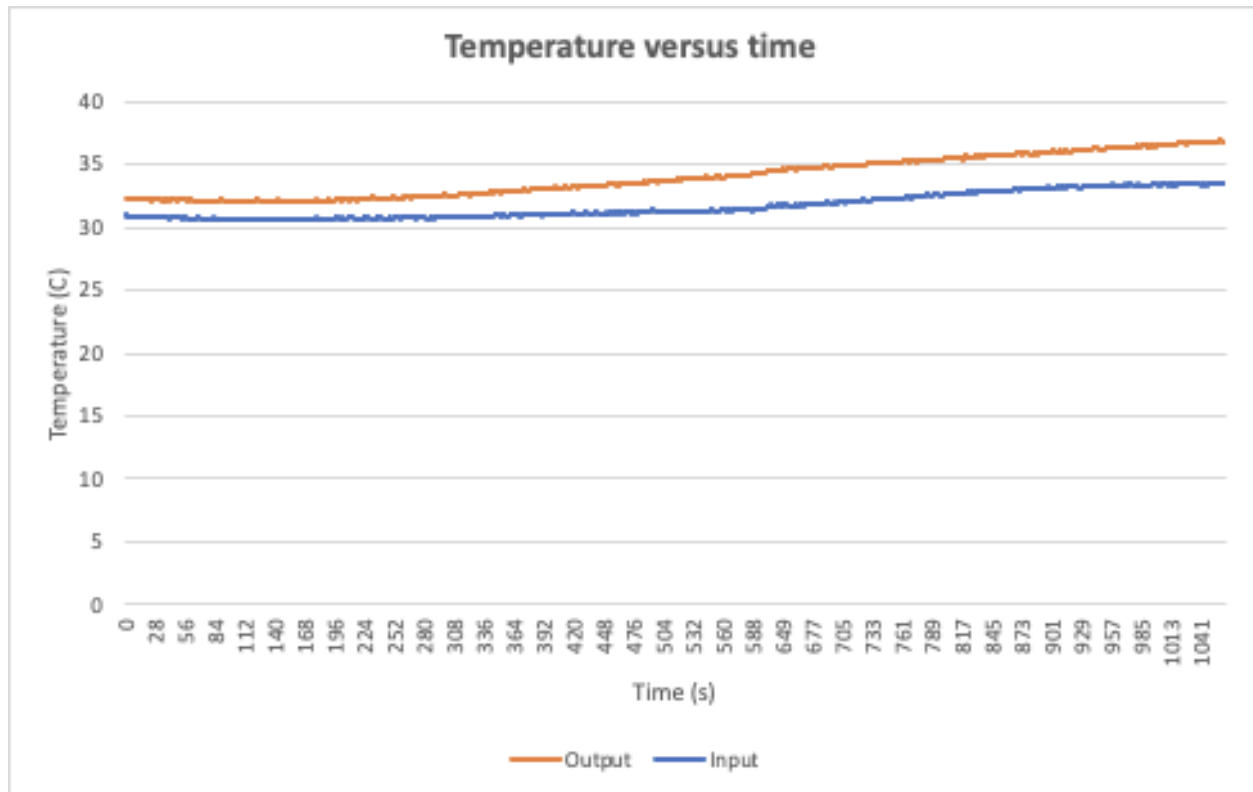


Closed System Sorbent Test 2 (medium tube).





Closed System Sorbent Test 3 (long tube).

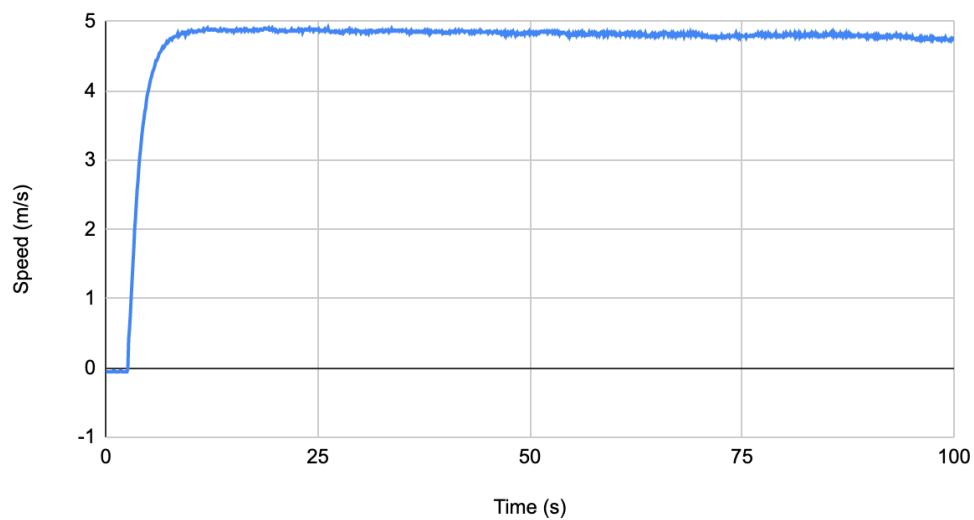


Closed System Temperature Effects.

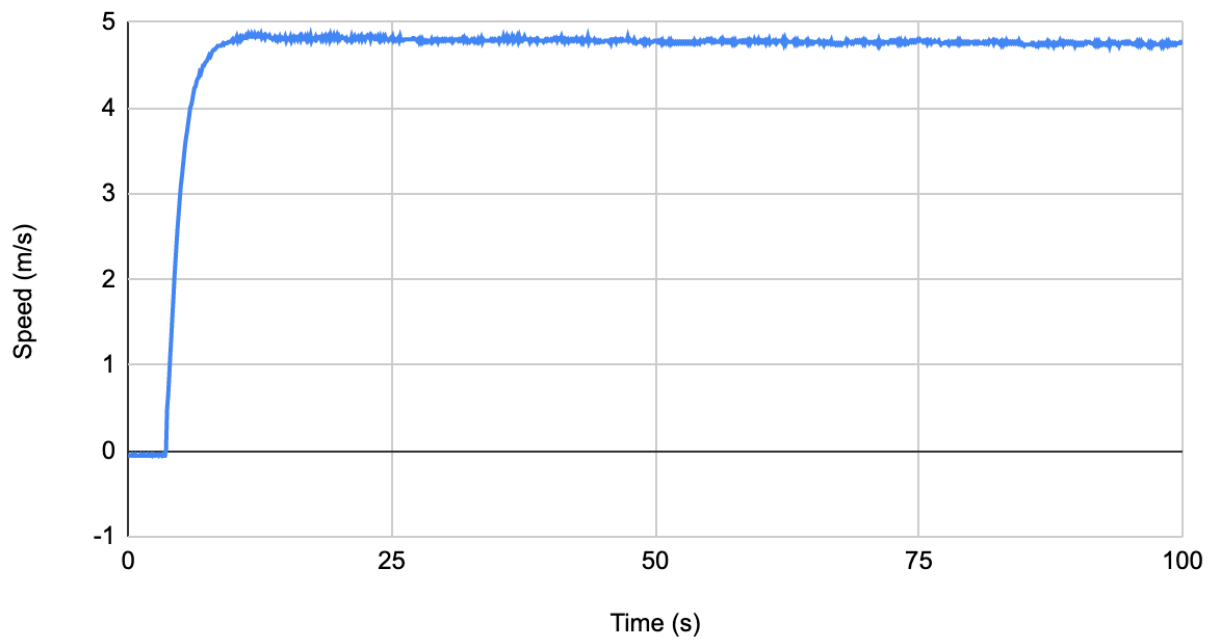
Critical Design Element 2

Testing conditions: no steel wool, sorbent, desiccant, ran for 100s

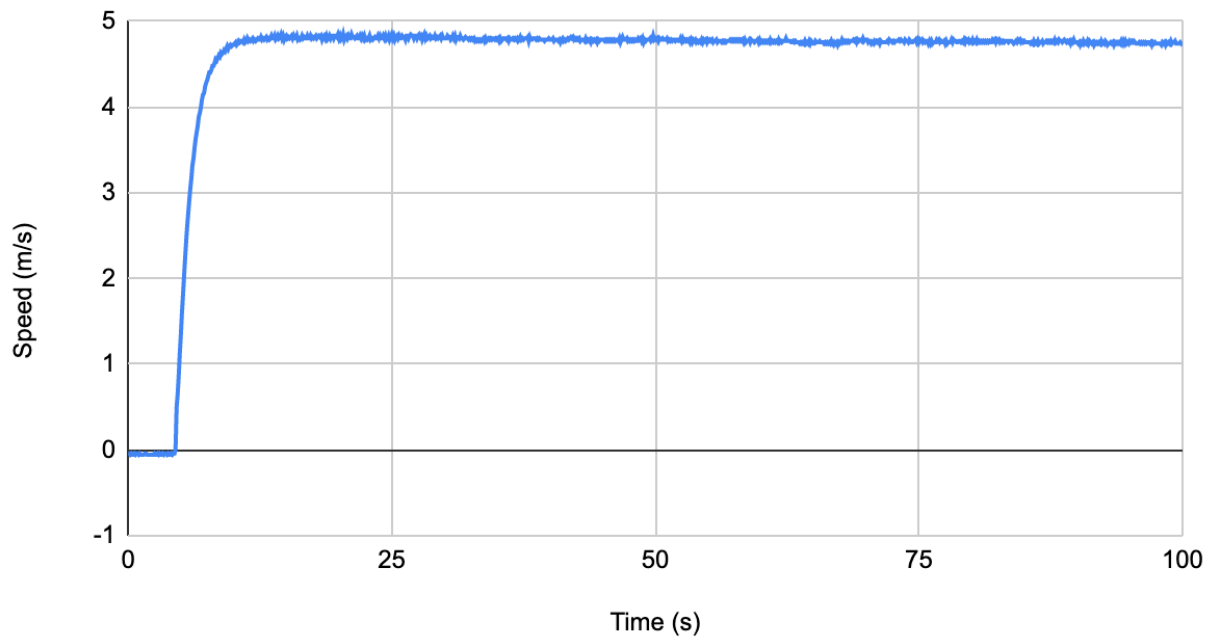
Speed (m/s) vs. Time (s)



Speed (m/s) vs. Time (s)



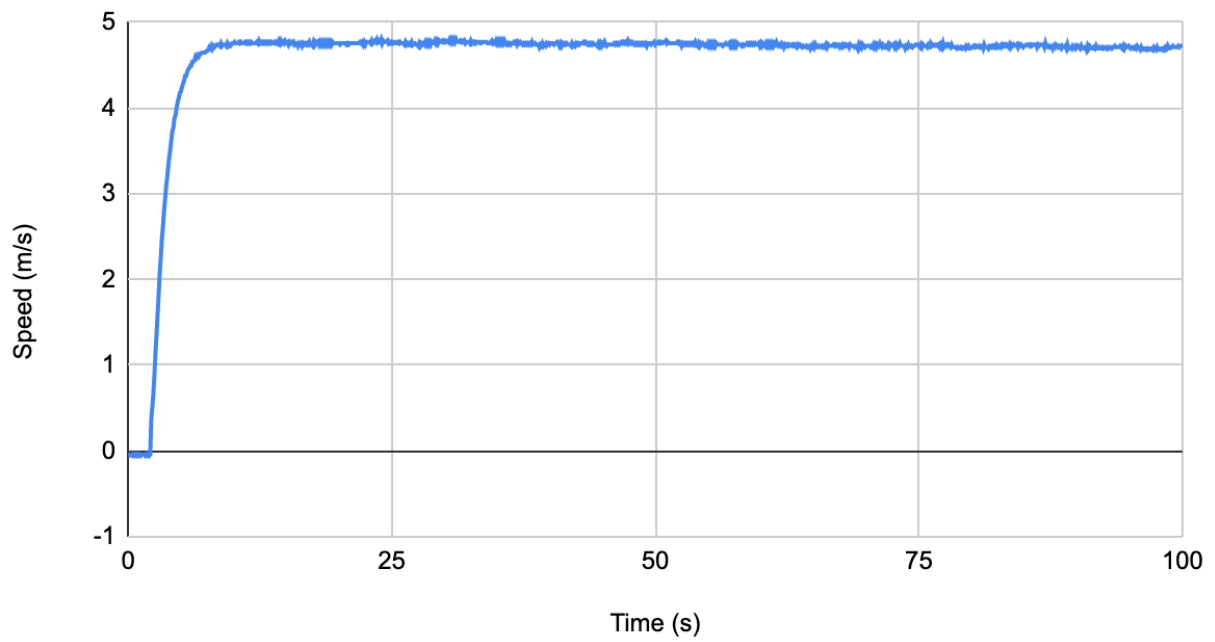
Speed (m/s) vs. Time (s)



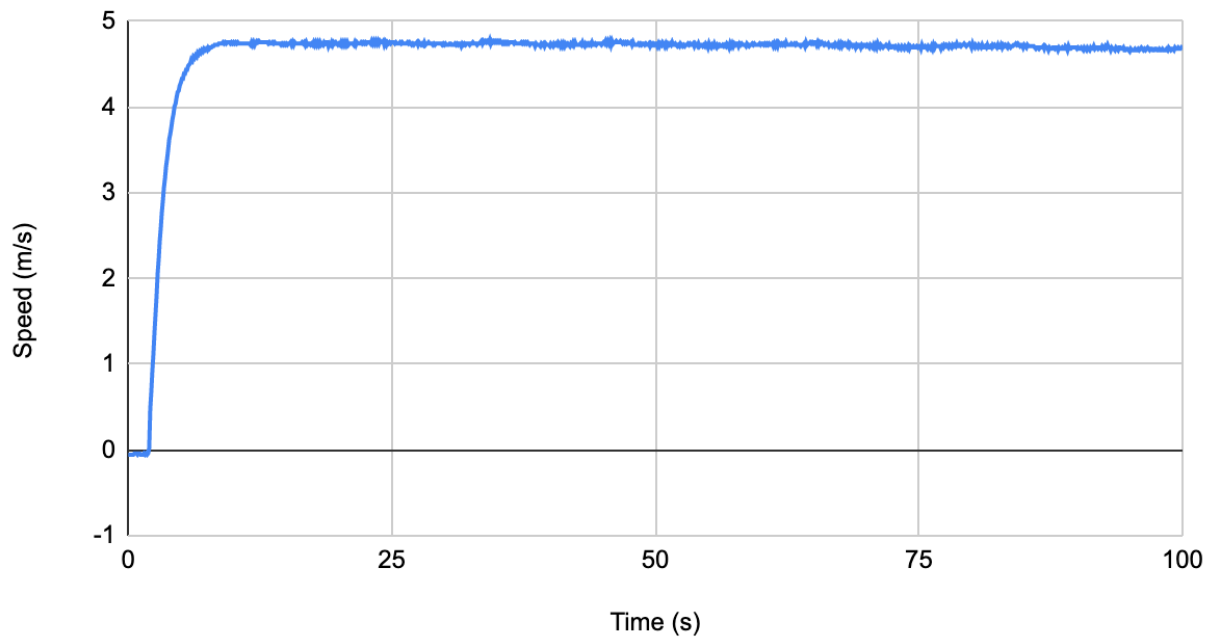
Flow rate tests.

Testing conditions: steel wool, no sorbent, no desiccant, ran for 100s

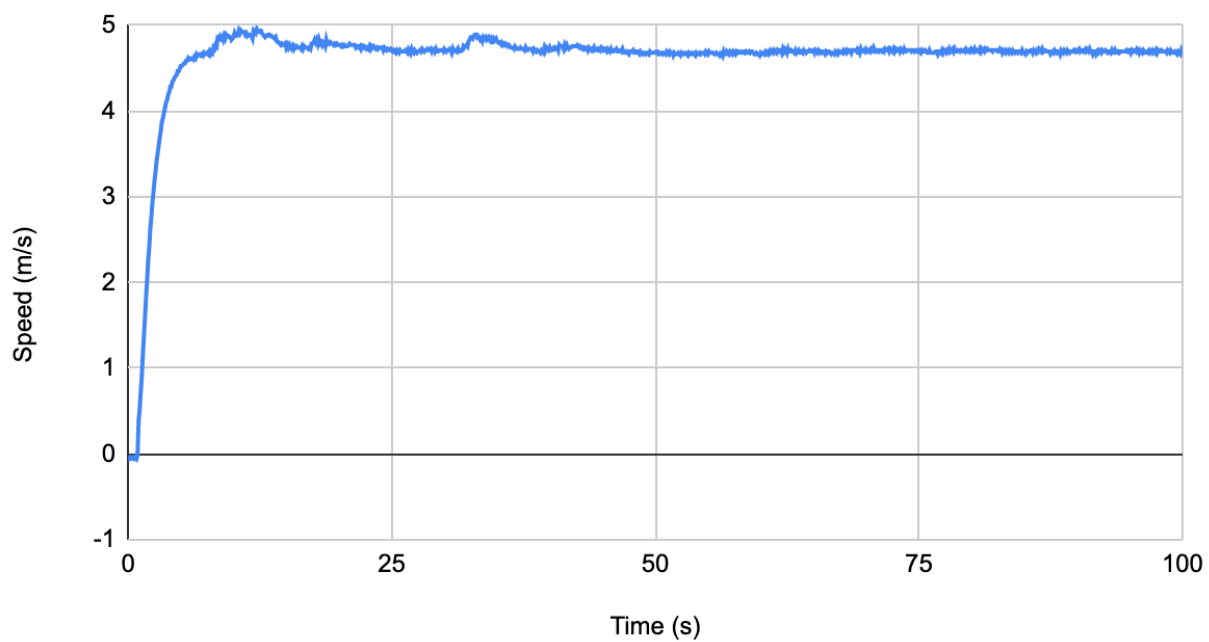
Speed (m/s) vs. Time (s)



Speed (m/s) vs. Time (s)



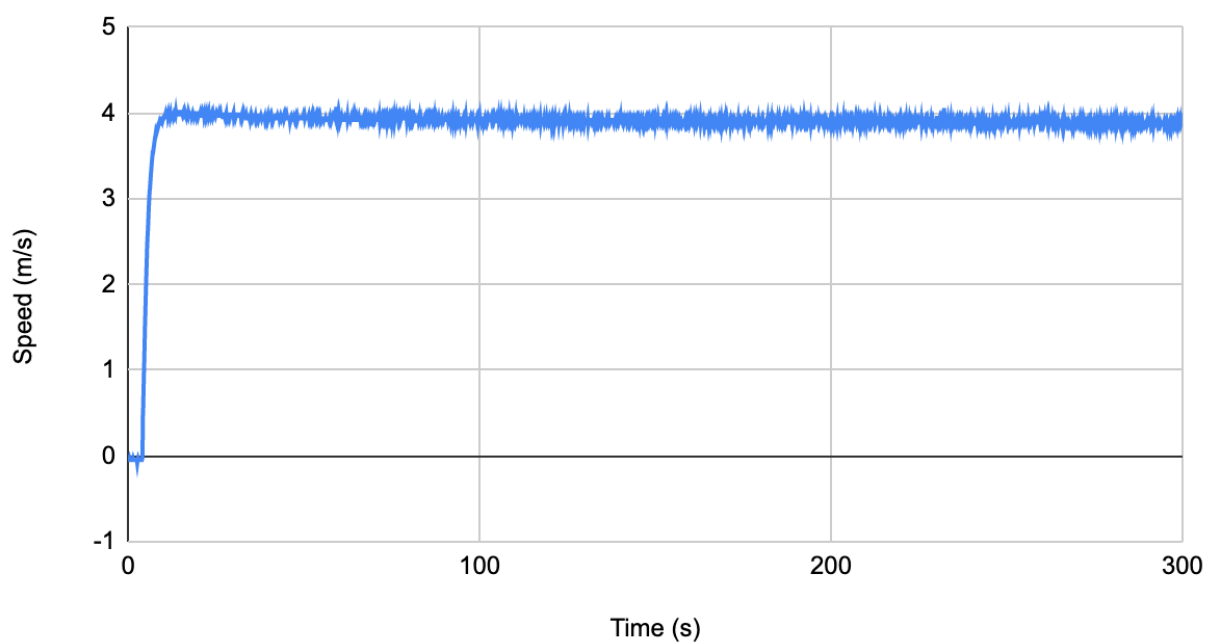
Speed (m/s) vs. Time (s)



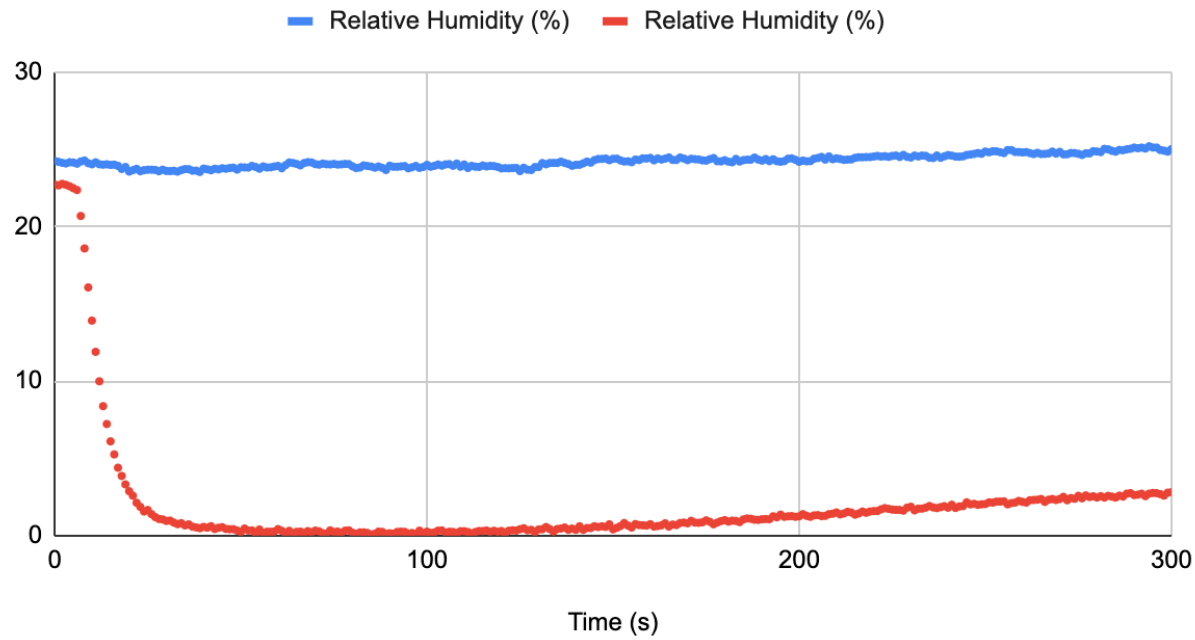
Flow rate tests.

Testing conditions: steel wool, no sorbent, desiccant, ran for 300s

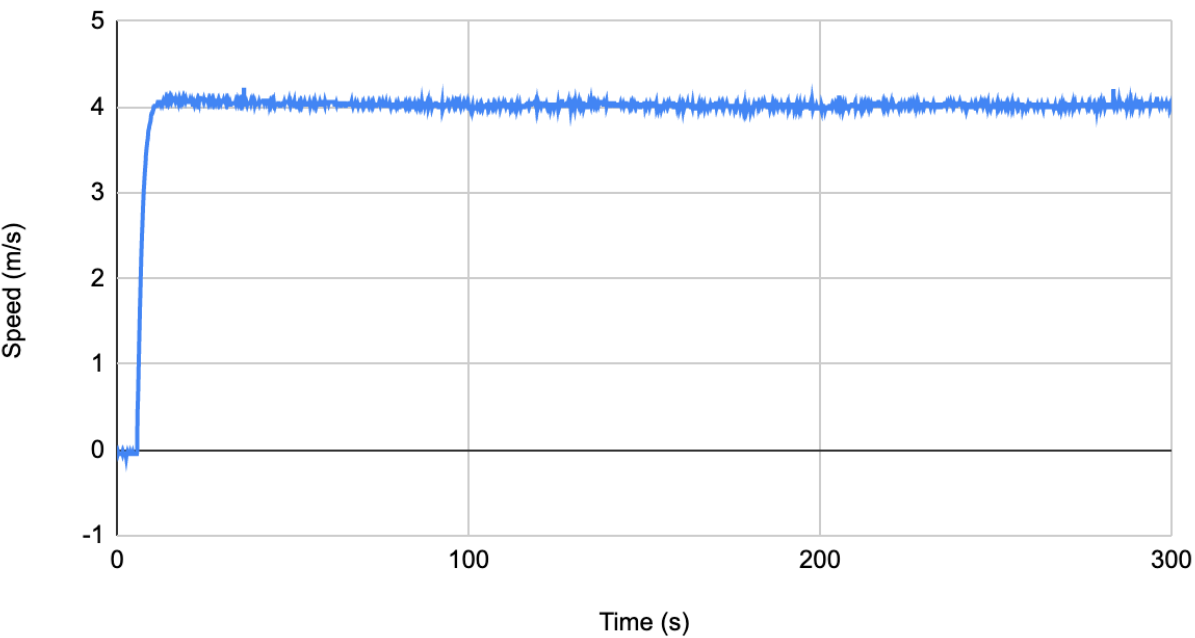
Speed (m/s) vs. Time (s)



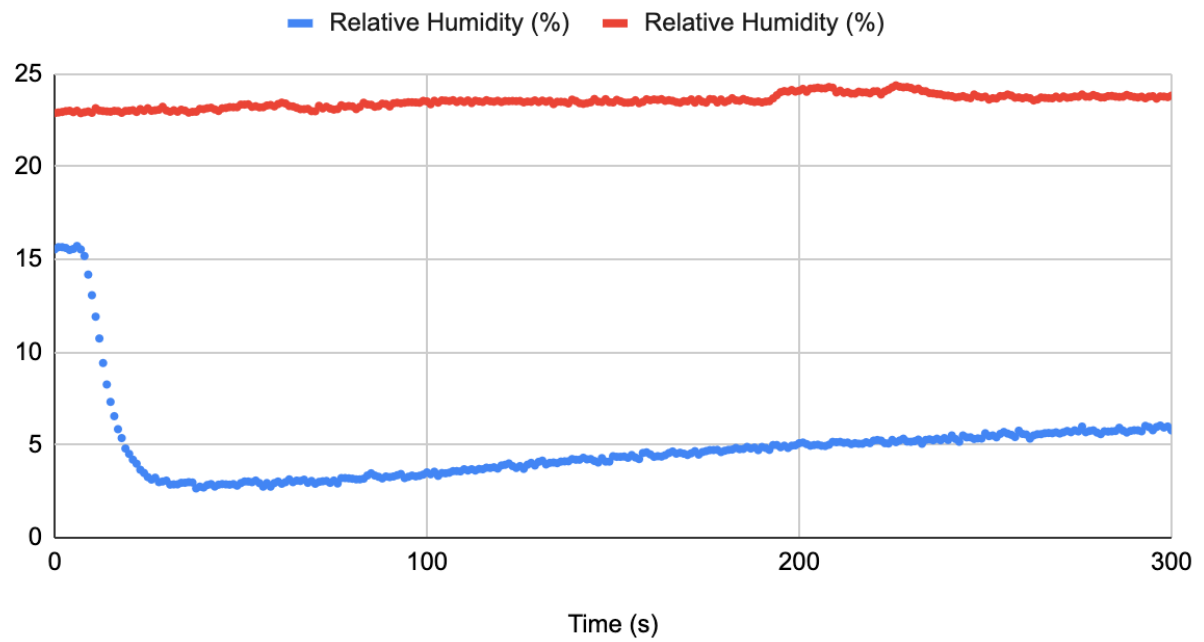
Relative Humidity (%) and Relative Humidity (%)



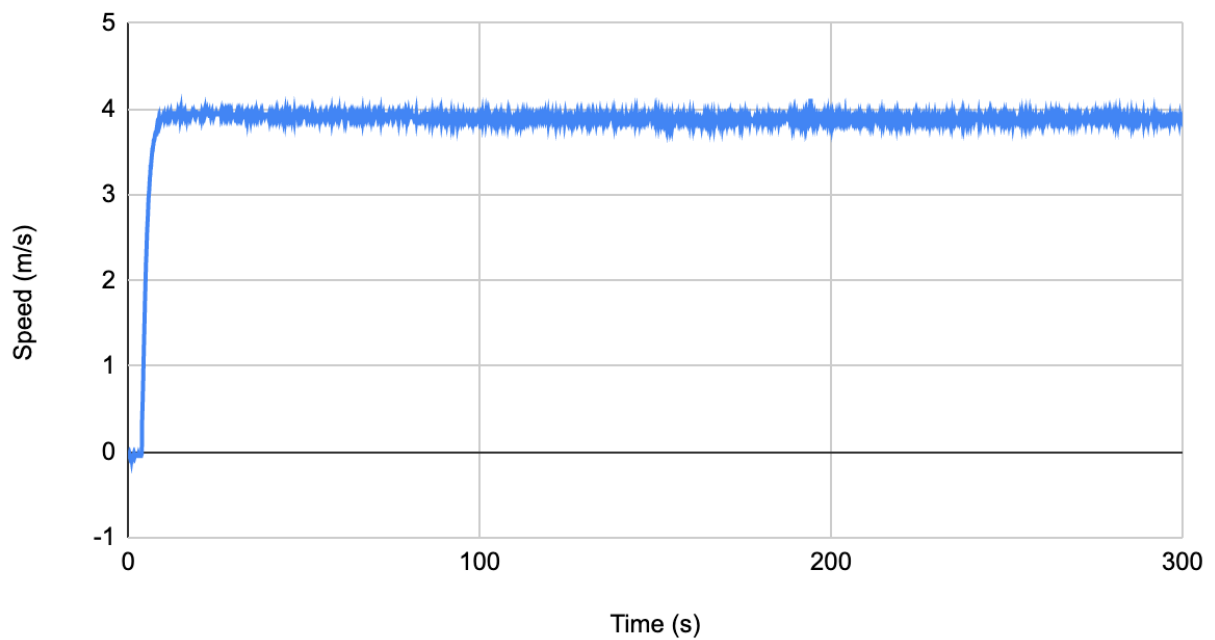
Speed (m/s) vs. Time (s)



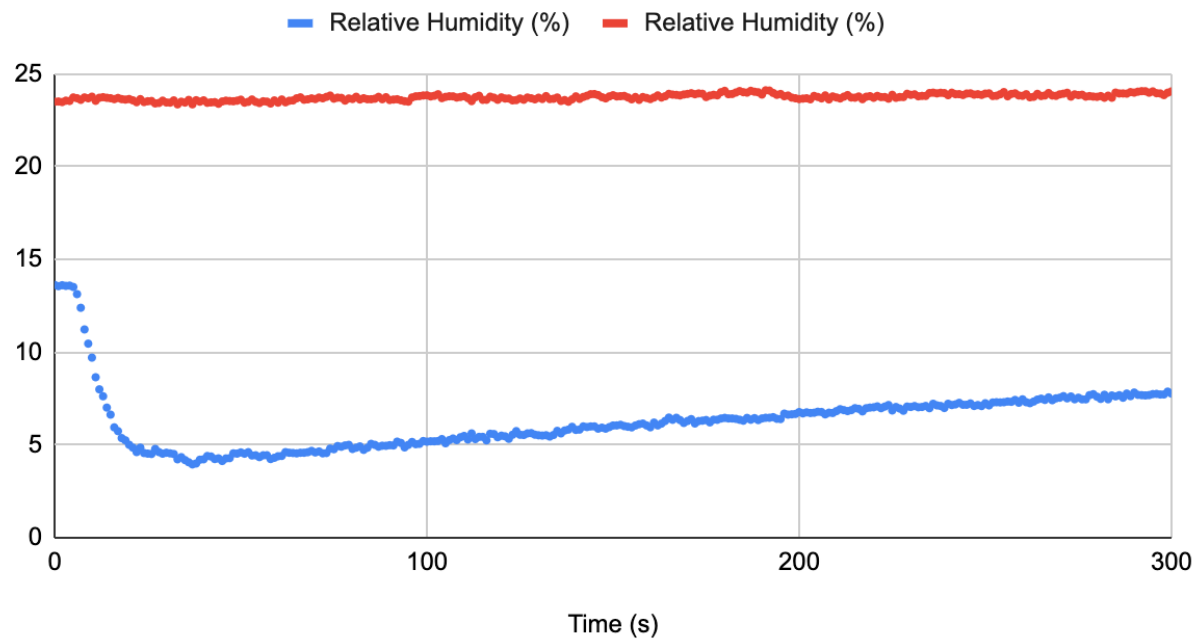
Relative Humidity (%) and Relative Humidity (%)



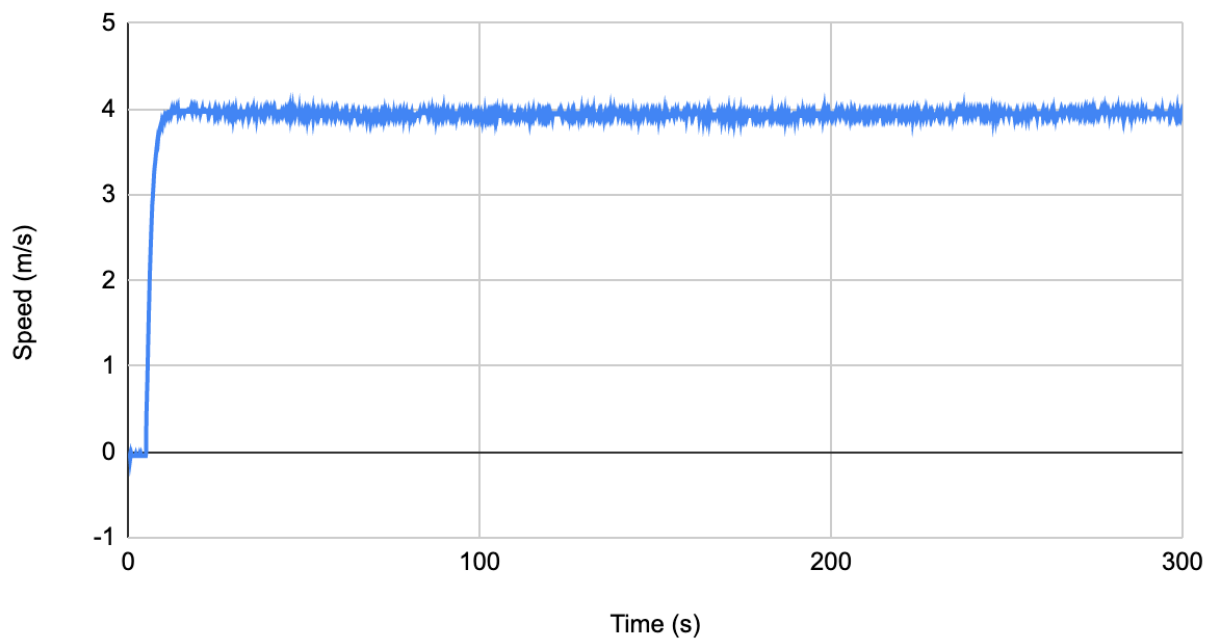
Speed (m/s) vs. Time (s)



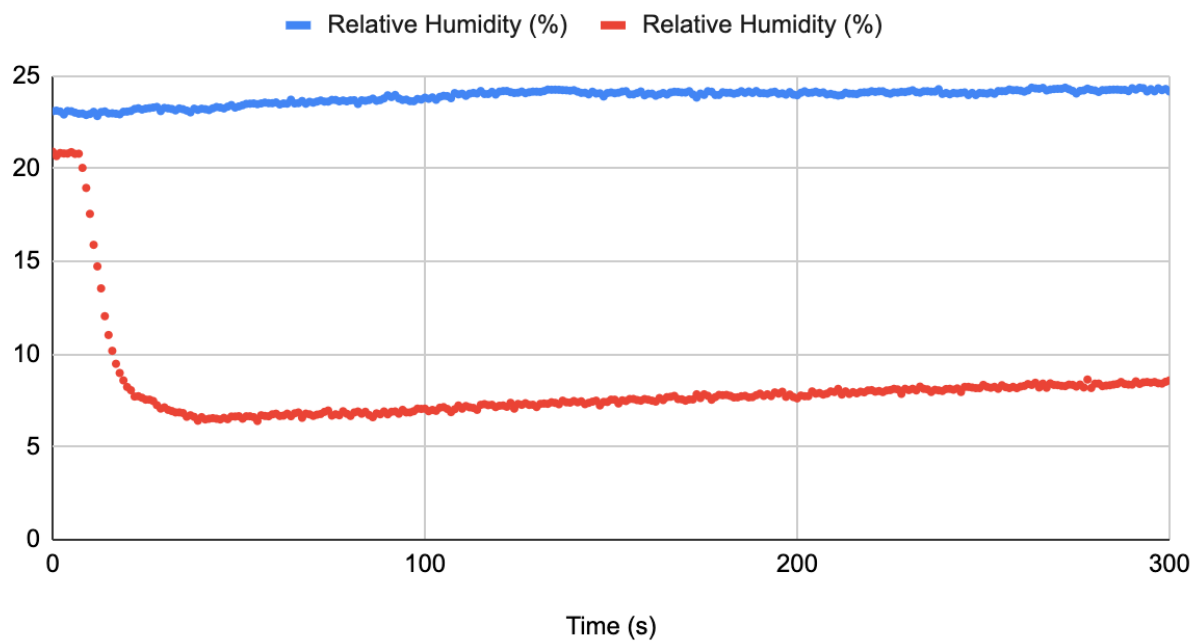
Relative Humidity (%) and Relative Humidity (%)



Speed (m/s) vs. Time (s)



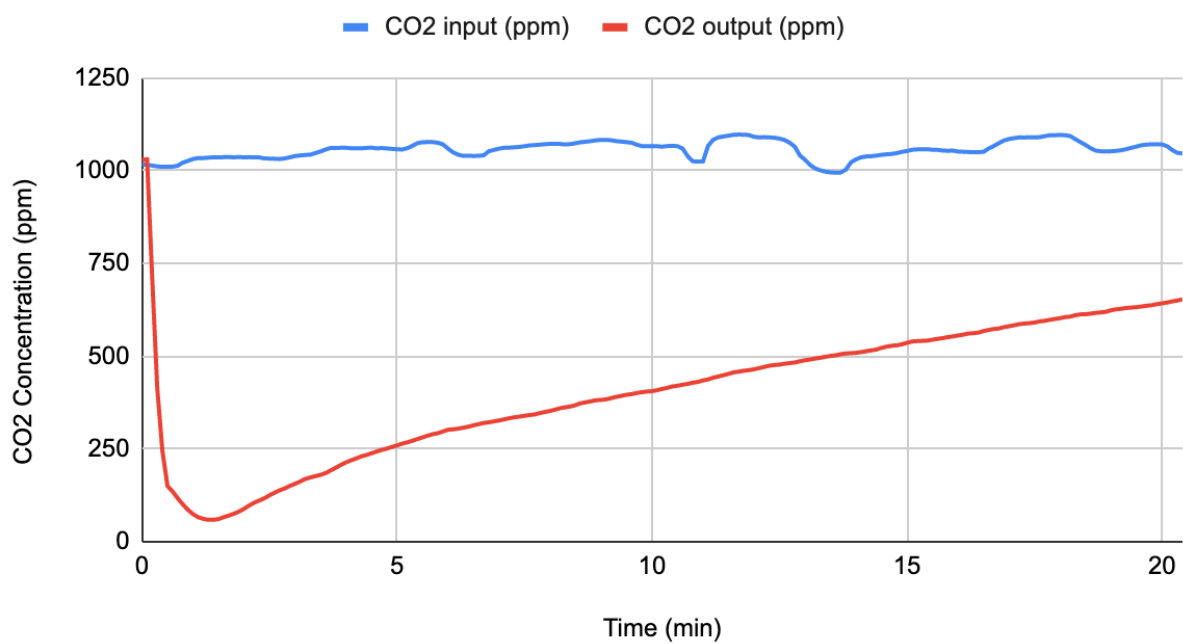
Relative Humidity (%) and Relative Humidity (%)



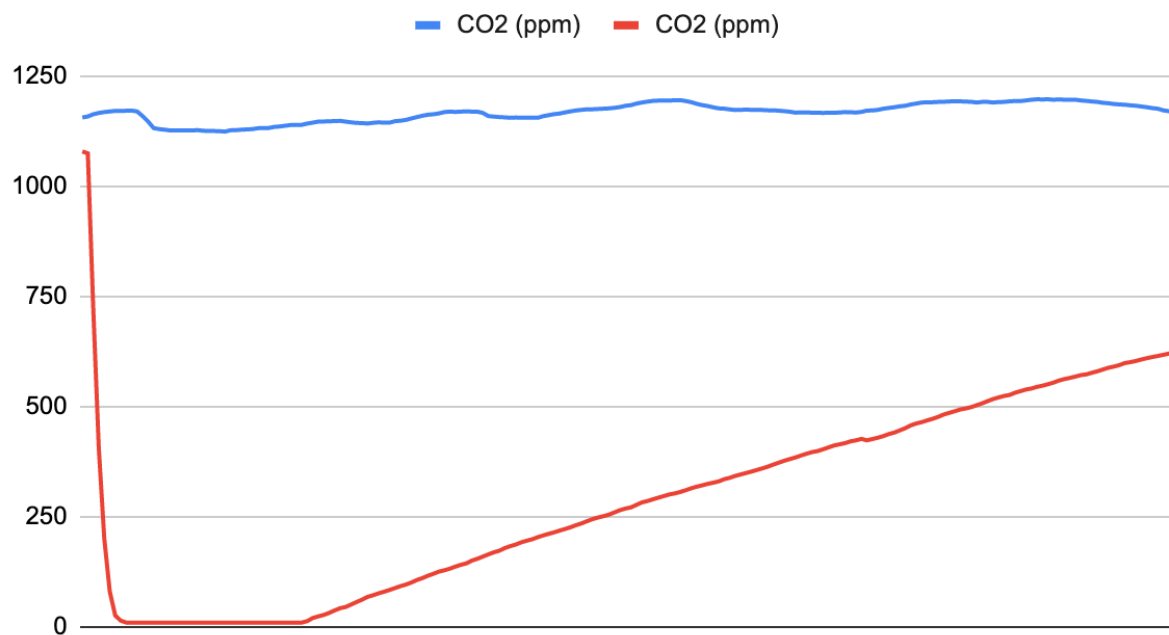
Desiccant tests.

Testing conditions: steel wool, no sorbent, desiccant, ran for 20 min.

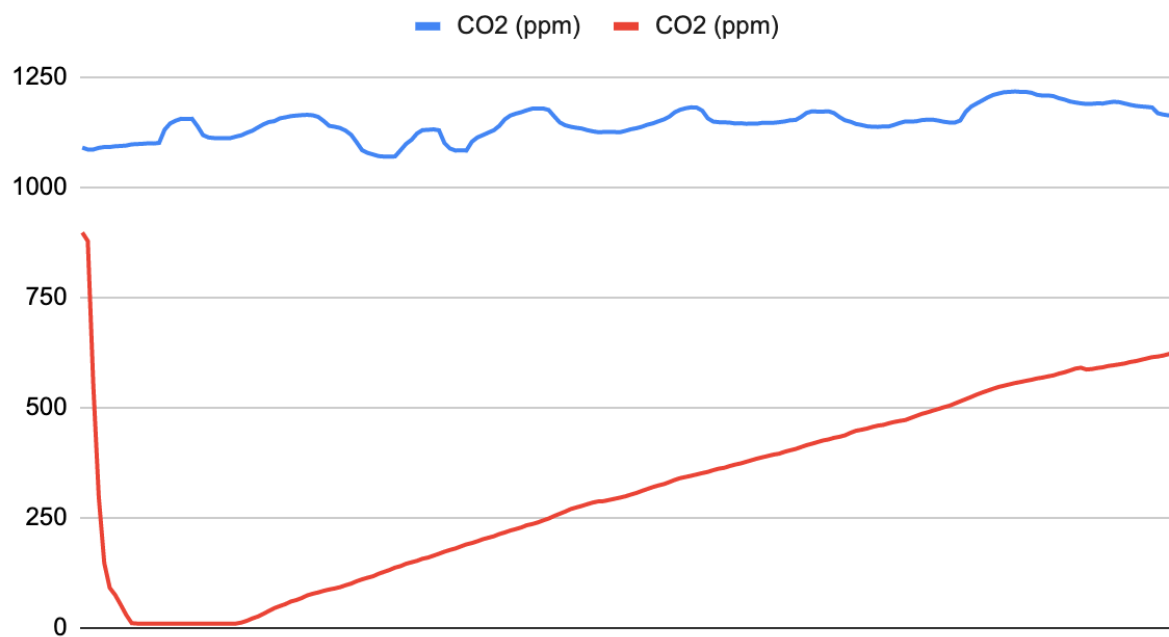
CO₂ concentration vs Time



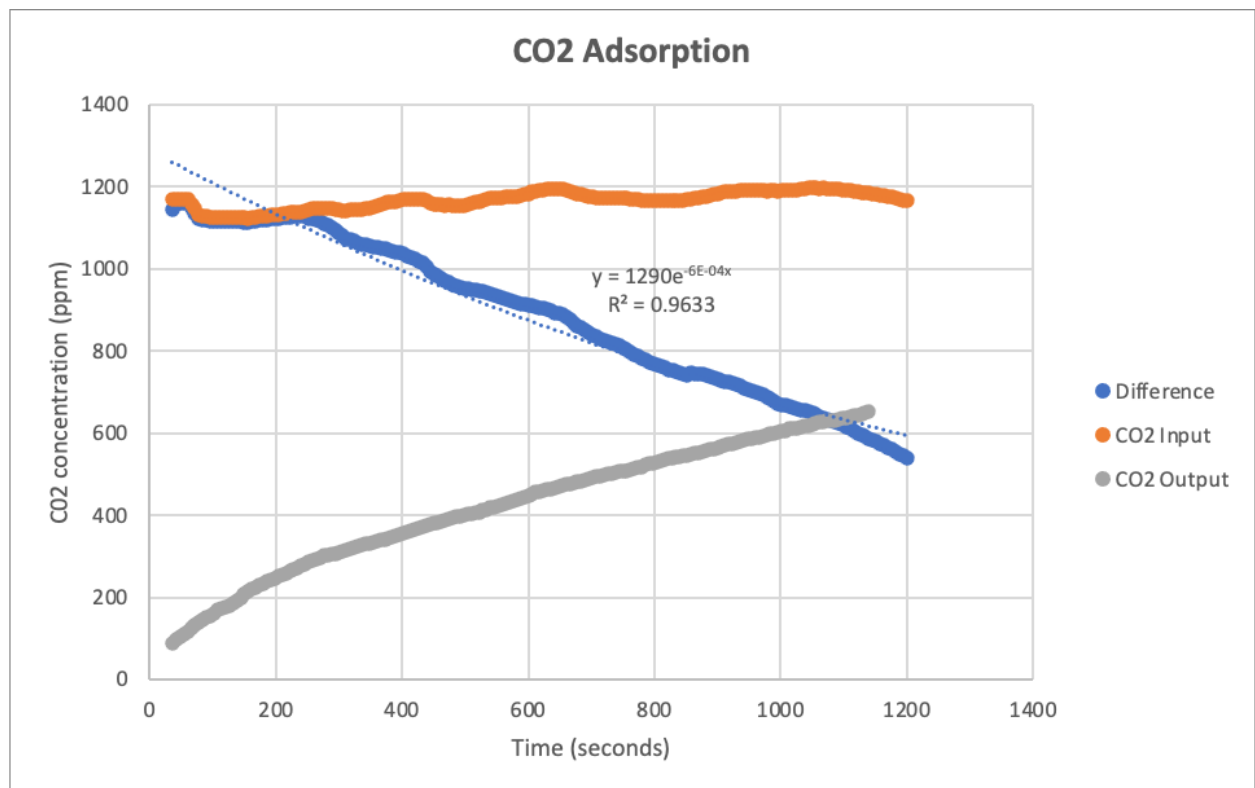
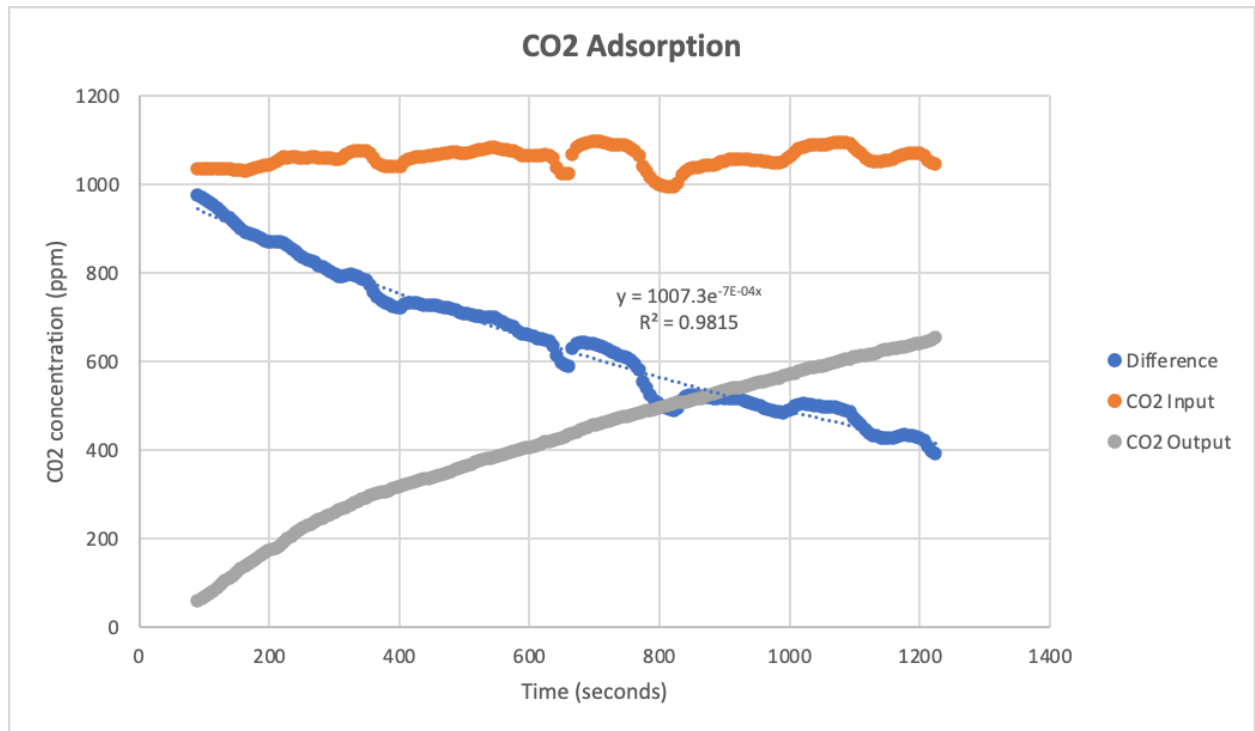
CO2 (ppm) and CO2 (ppm)

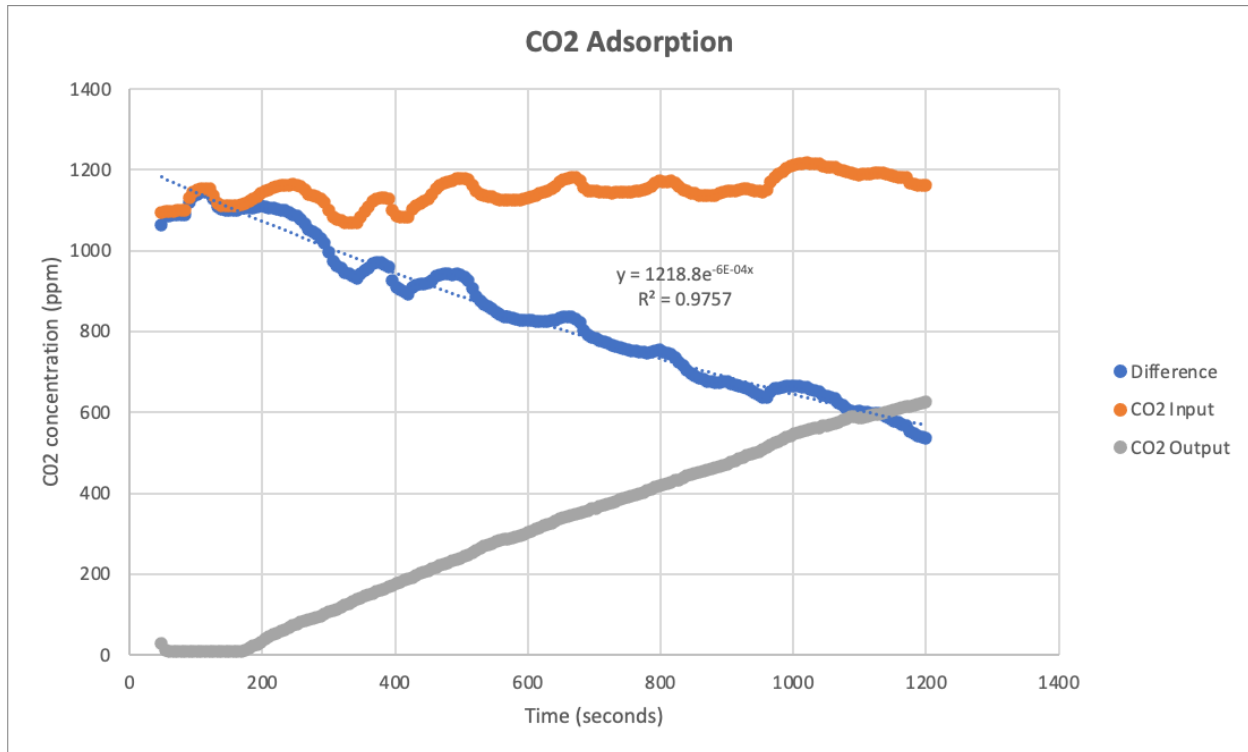


CO2 (ppm) and CO2 (ppm)



Sorbent tests.





Test 1

Velocity Flow Rate (m/s)	3.315497951	Vernier Flow Meter
Mass of Sorbent Used (kg)	0.288	Zeolite 13X
Mass of CO2 Adsorbed (kg)	0.002042717	Sum of Test 1
CO2 Adsorption Rate (kg/s)	1.80134E-06	Average of Test 1 per sec
CO2 Adsorption Rate (kg/kgs)	6.25464E-06	Rate per mass of sorbent
CO2 produced by 1 human (kg/day)	1	CO2 production rate
CO2 adsorption per day (kg/day)	0.155635548	Current prototype
Desired Scale	6.425267325	Desired increase in size

Cylinder Diameter (m)	0.15	Fixed by IMS
Cylinder Length (m)	0.2	
Volume (m ³)	0.003534289	
Scale, Adsorption Bed only	8.581464013	

Compression bed volume (m ³)	0.000883572
Adsorption bed vol given compression bed (m ²)	0.002650717
Scale, Adsorption including Compression	6.43609801

Test 2

Velocity Flow Rate (m/s)	2.702560425
Mass of Sorbent Used (kg)	0.282
Mass of CO ₂ Adsorbed (kg)	0.00237783
CO ₂ Adsorption Rate (kg/s)	2.04281E-06
CO ₂ Adsorption Rate (kg/kgs)	7.244E-06
CO ₂ produced by 1 human (kg/day)	1
CO ₂ adsorption per day (kg/day)	0.176498725
Desired Scale	5.665763314

Cylinder Diameter (m)	0.15
Cylinder Length (m)	0.2
Volume (m ³)	0.003534289
Scale, Adsorption Bed only	8.581464013

Compression bed volume (m ³)	0.000883572
Adsorption bed vol given compression bed (m ²)	0.002650717
Scale, Adsorption including Compression	6.43609801

Test 3

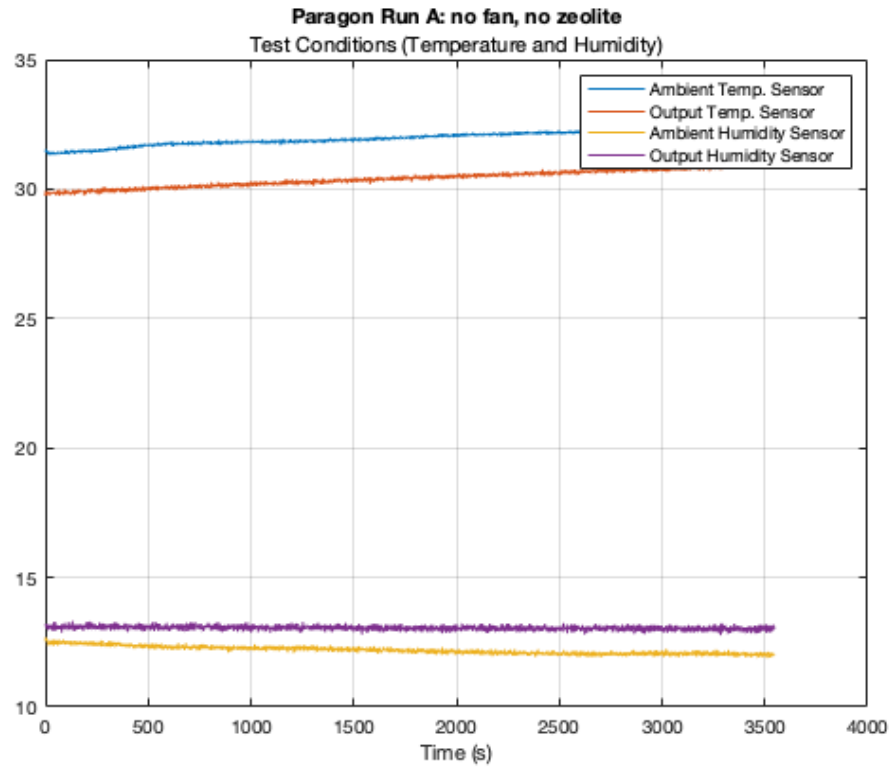
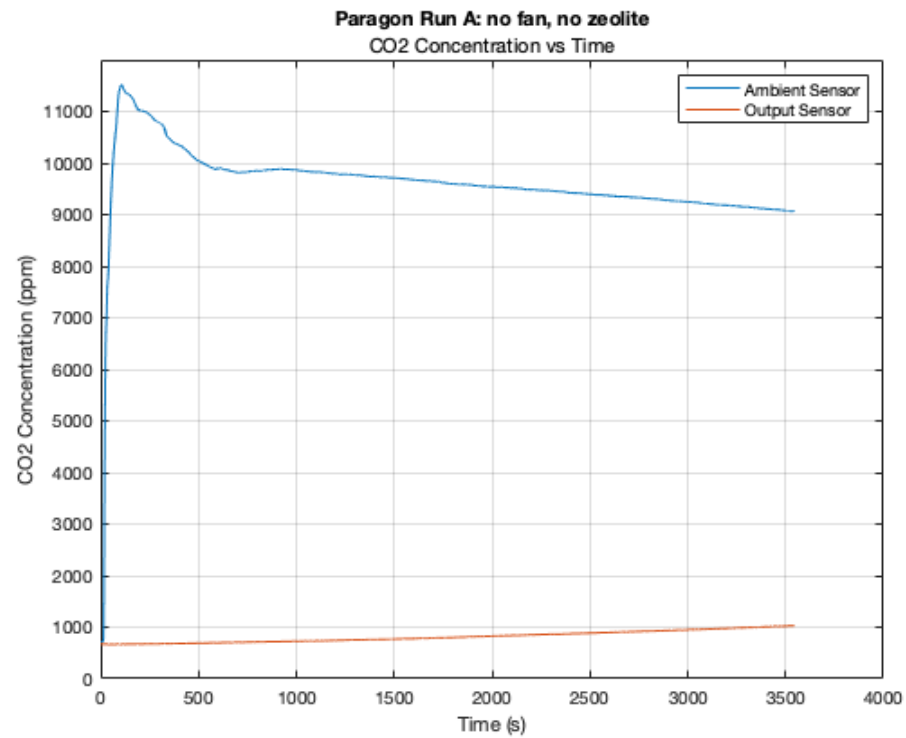
Velocity Flow Rate (m/s)	1.975631714
Mass of Sorbent Used (kg)	0.285
Mass of CO ₂ Adsorbed (kg)	0.001647084
CO ₂ Adsorption Rate (kg/s)	1.42976E-06
CO ₂ Adsorption Rate (kg/kgs)	5.0167E-06
CO ₂ produced by 1 human (kg/day)	1
CO ₂ adsorption per day (kg/day)	0.123531281
Desired Scale	8.095115622

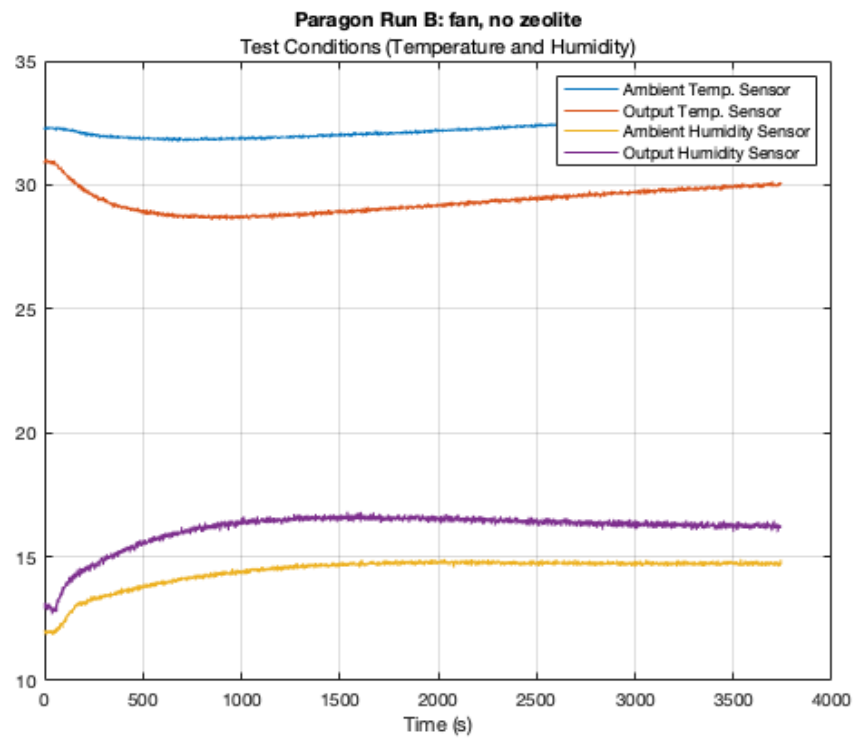
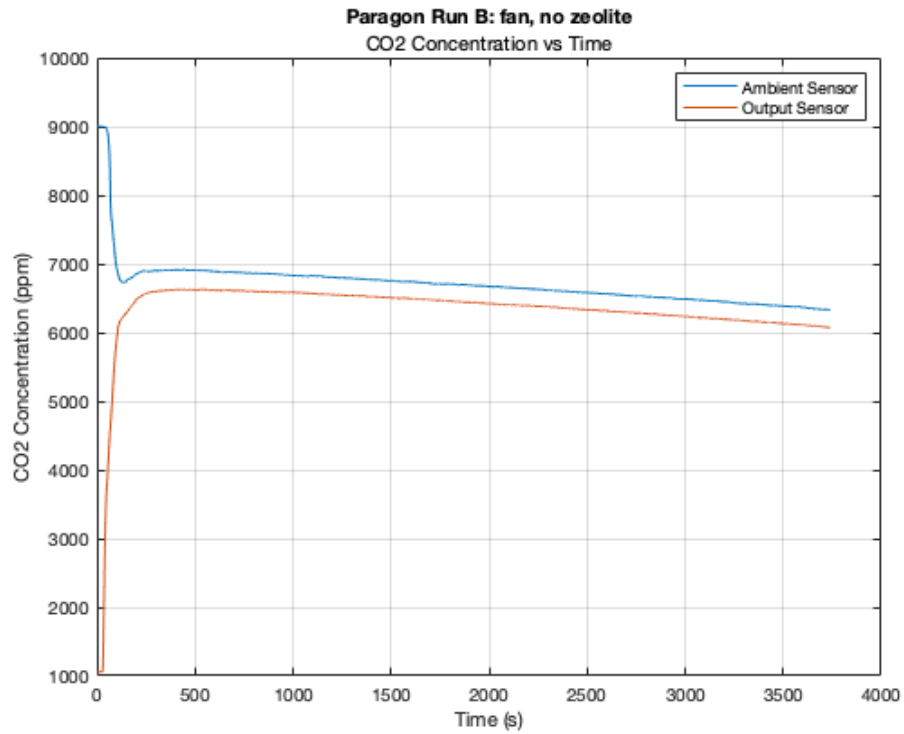
Cylinder Diameter (m)	0.17
Cylinder Length (m)	0.2
Volume (m ³)	0.004539598
Scale, Adsorption Bed only	11.02241378

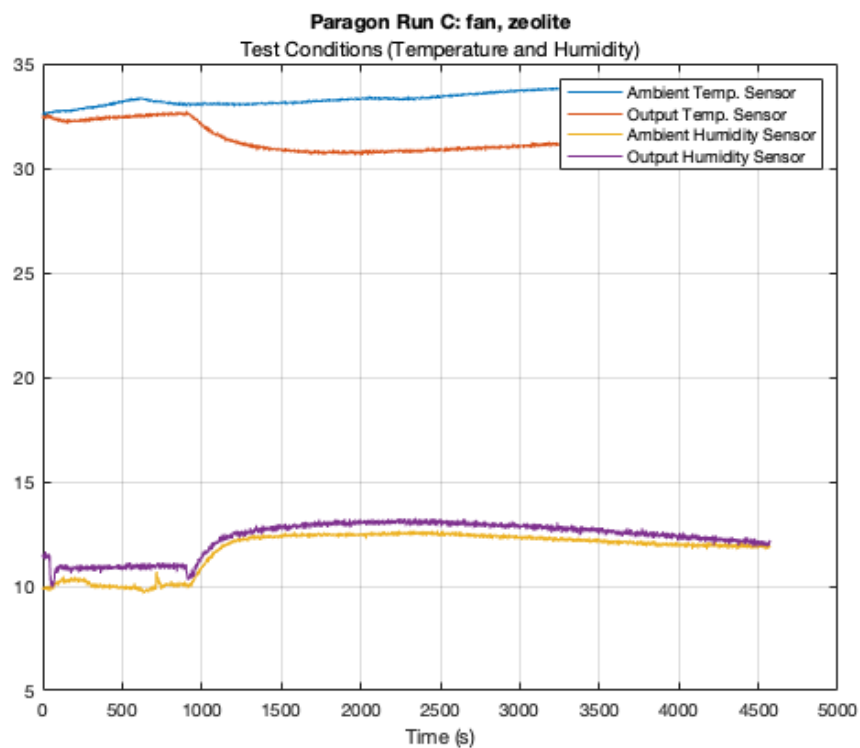
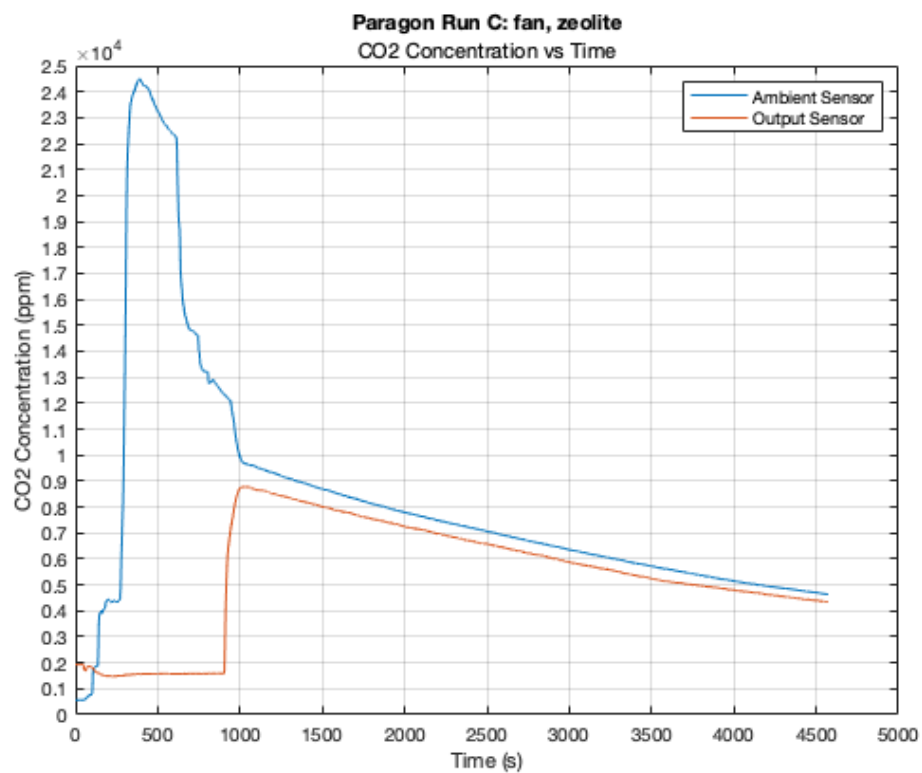
Compression bed volume (m ³)	0.001134899
Adsorption bed vol given compression bed (m ²)	0.003404698
Scale, Adsorption including Compression	8.266810333

Tables used for canister dimension calculations.

Final System Tests - PARAGON





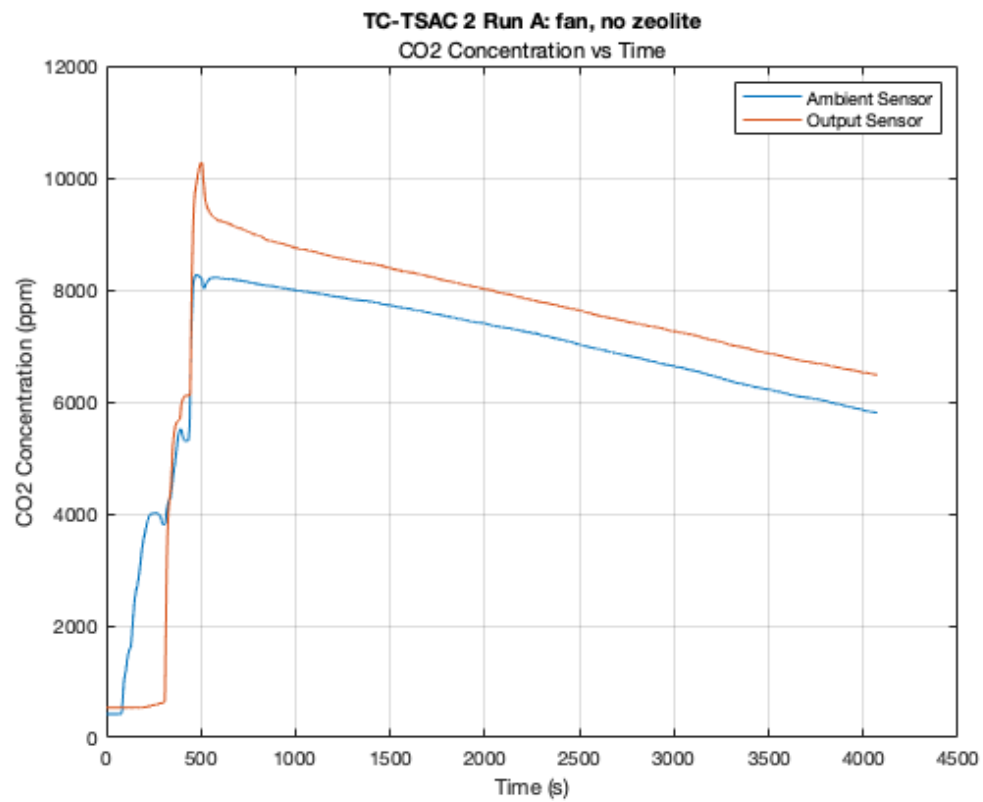


Test	CO ₂ diff (ppm)	Mass of CO ₂ adsorbed/lost (kg)
A (no fan)	3099.83	

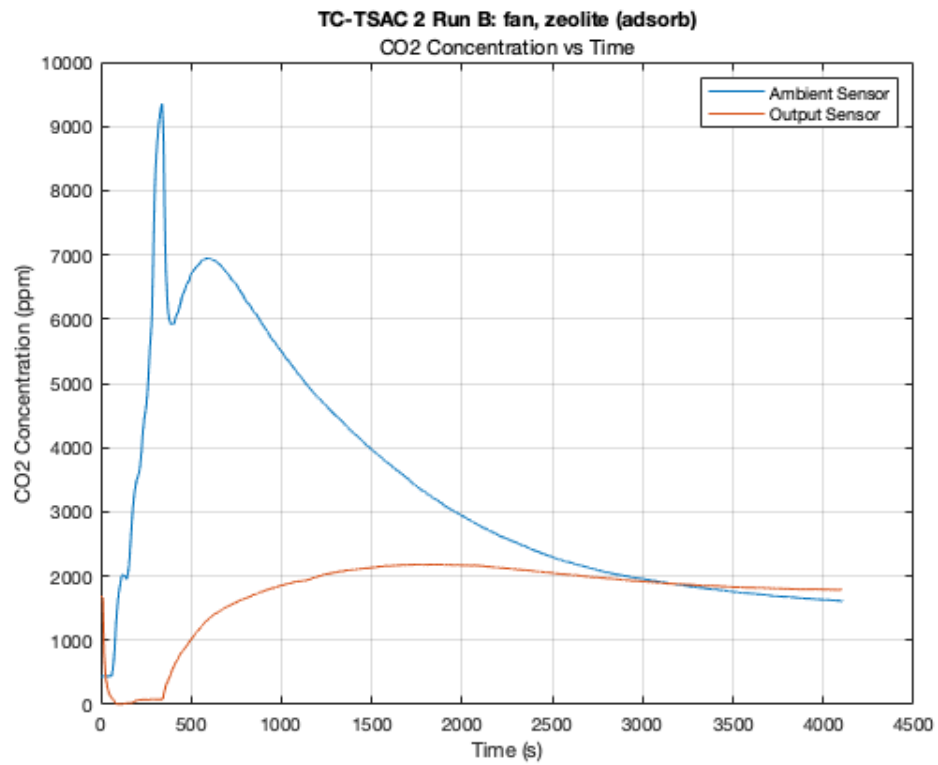
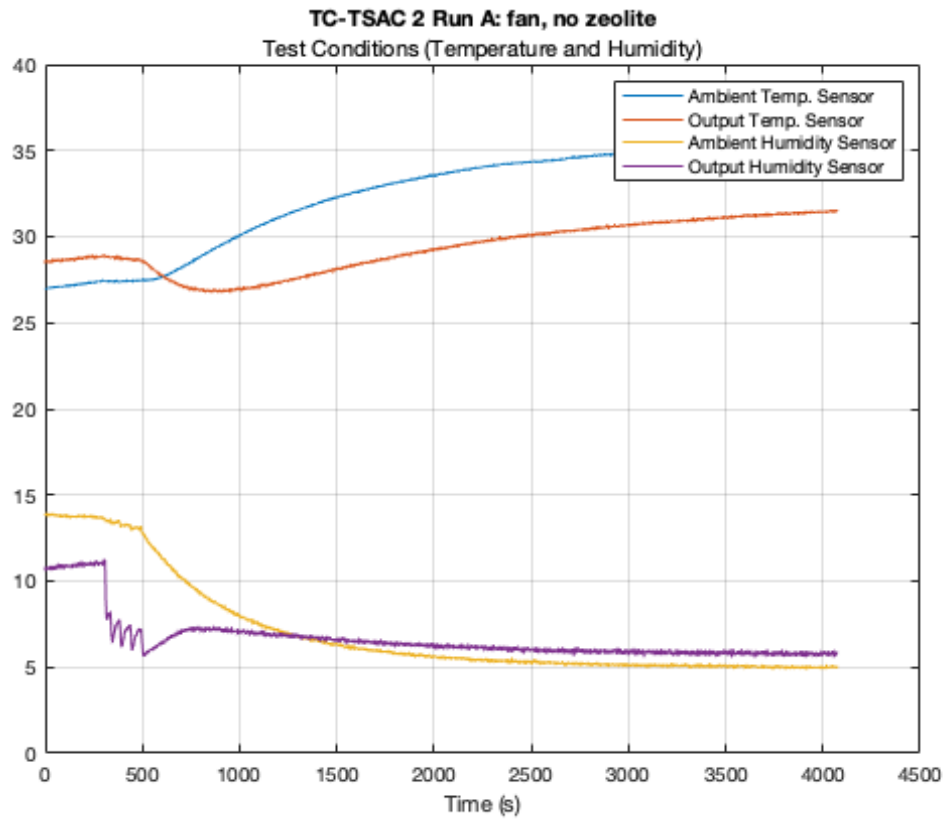
B (fan)	2677.5	0.008221965
C (fan, zeolite)	19913	0.013080483
C w/ leaks	17235.5	0.004858518

Velocity Flow Rate (m/s)	0.568631282
Mass of CO2 Adsorbed (kg)	0.004858518
CO2 Adsorption Rate (kg/s)	1.06267E-06
CO2 produced by 1 human (kg/day)	1
CO2 adsorption per day (kg/day)	0.091814513
CO2 adsorption per day (kg/day)	0.000697732

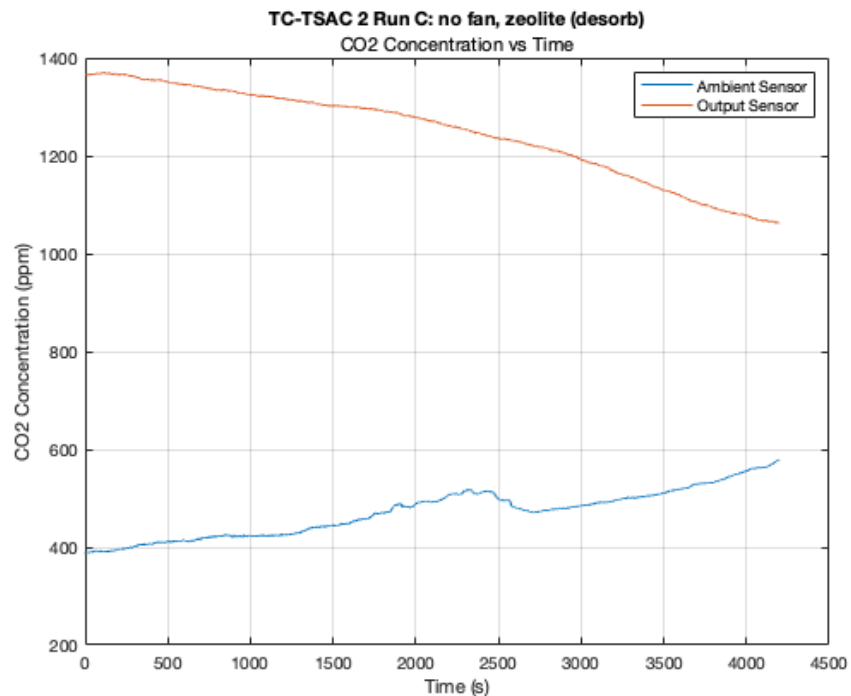
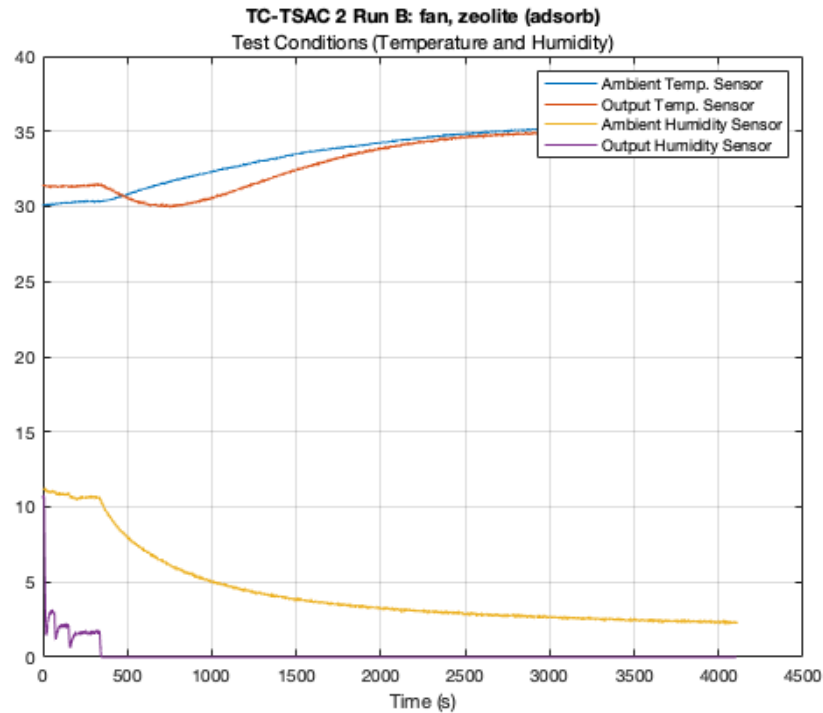
Final System Tests - TC-TSAC RE-DESIGN



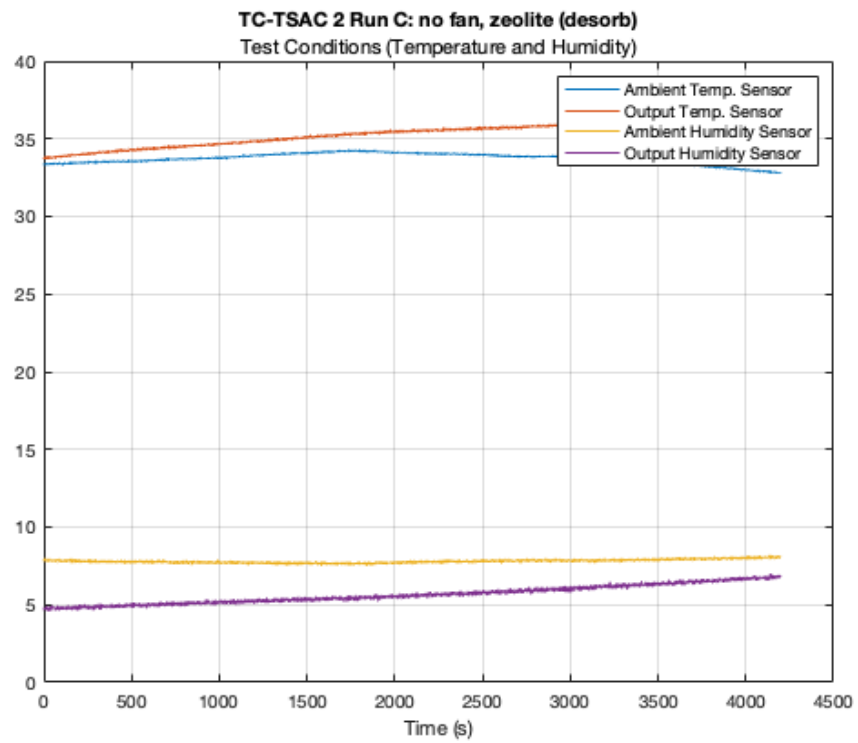
- Shows leakage rate of system.

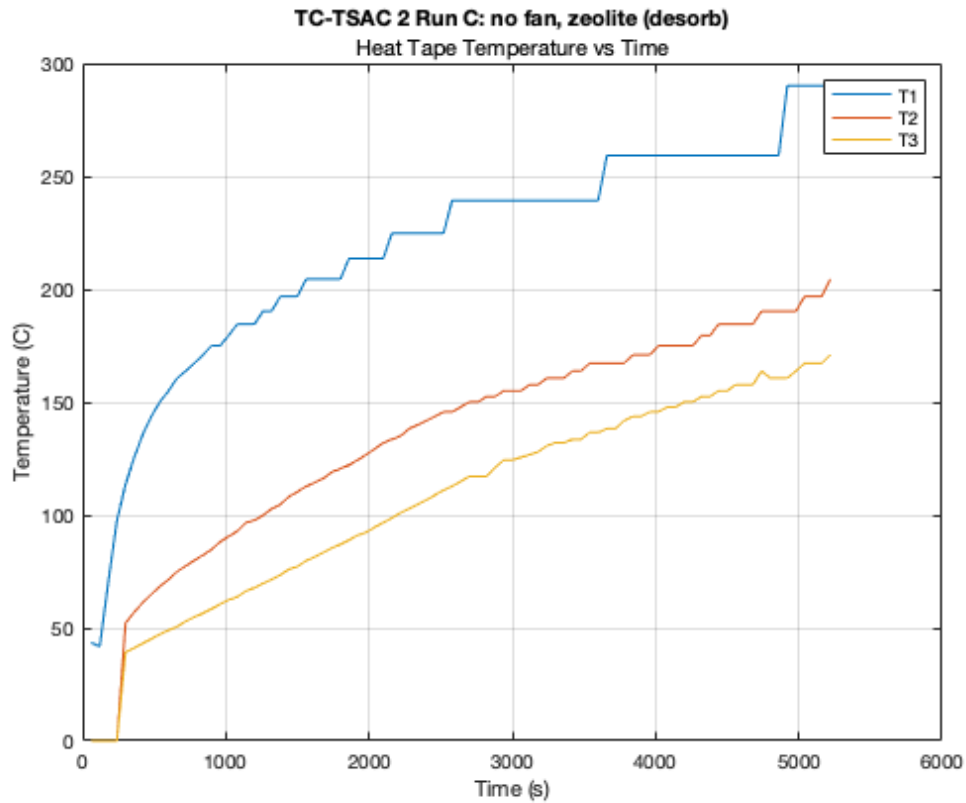


- The dips towards the start of the curve are due to the fan being kicked on. This allowed the air in the system to mix which explains why it looks like there is a sudden drop in the carbon dioxide concentration. The flattening shows when the zeolite gets saturated. Looking at the humidity graph, it may be due to the fact that excess water is causing the system to saturate faster.

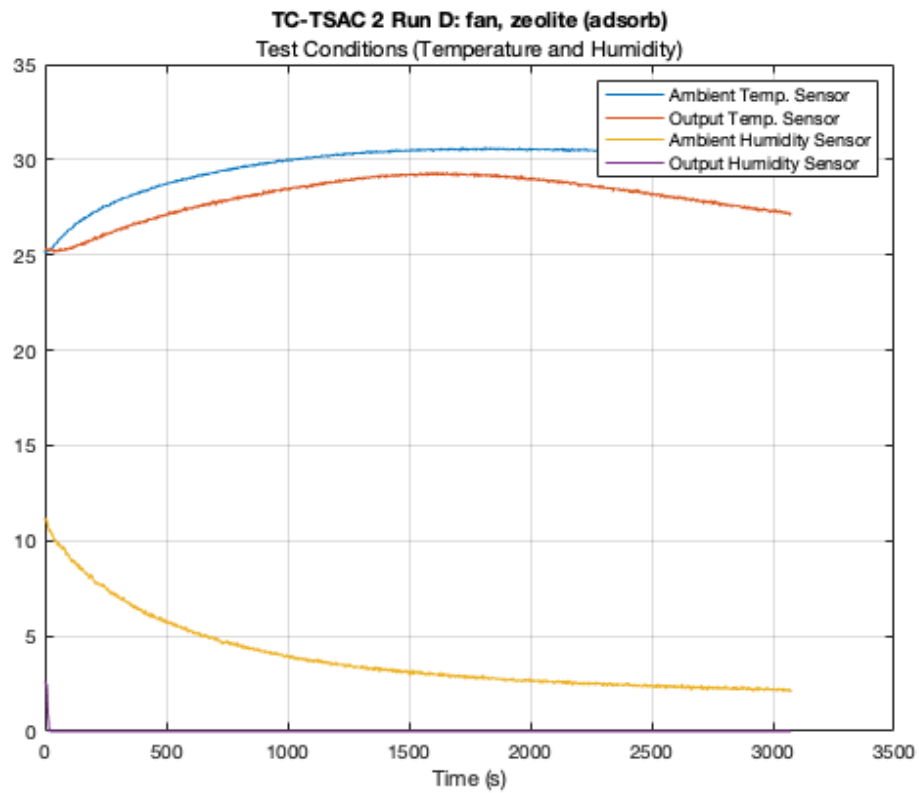
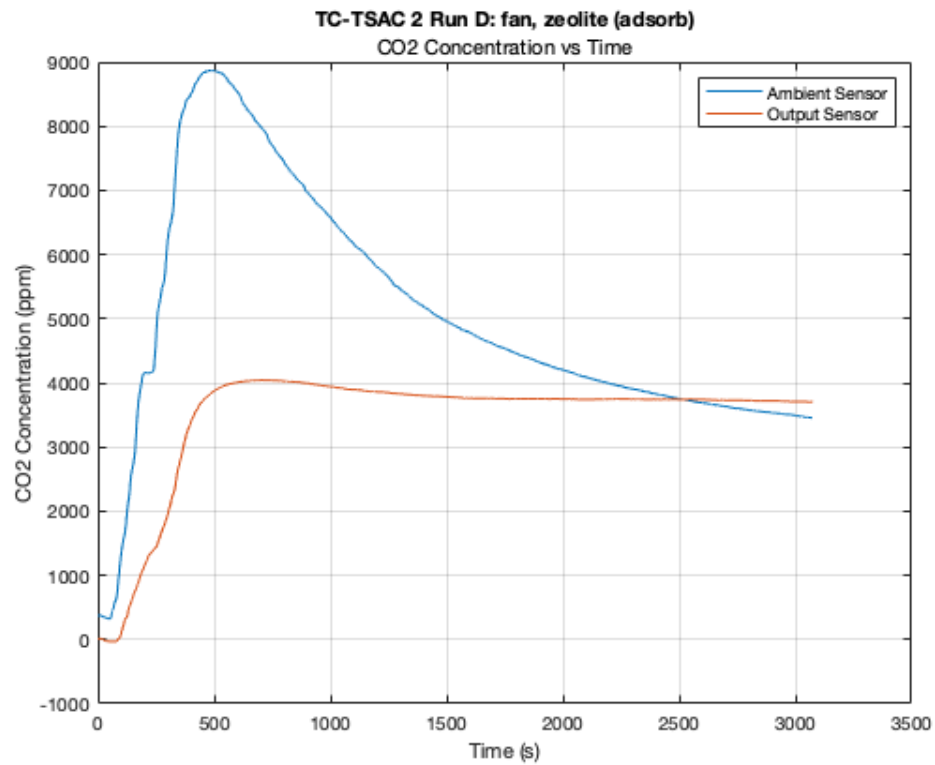


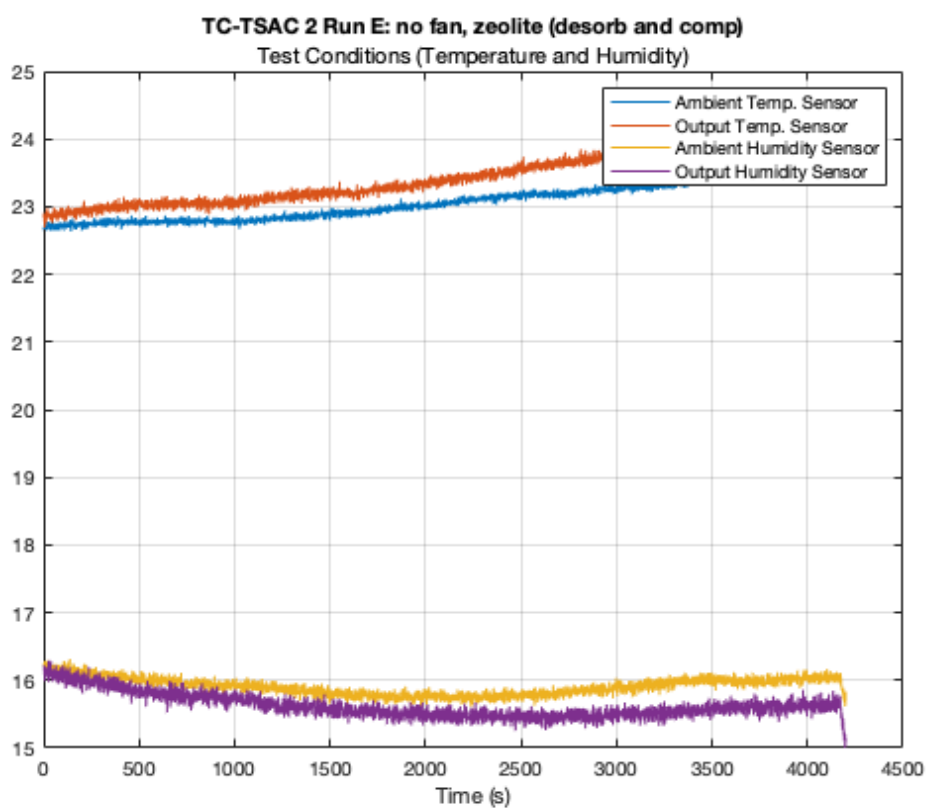
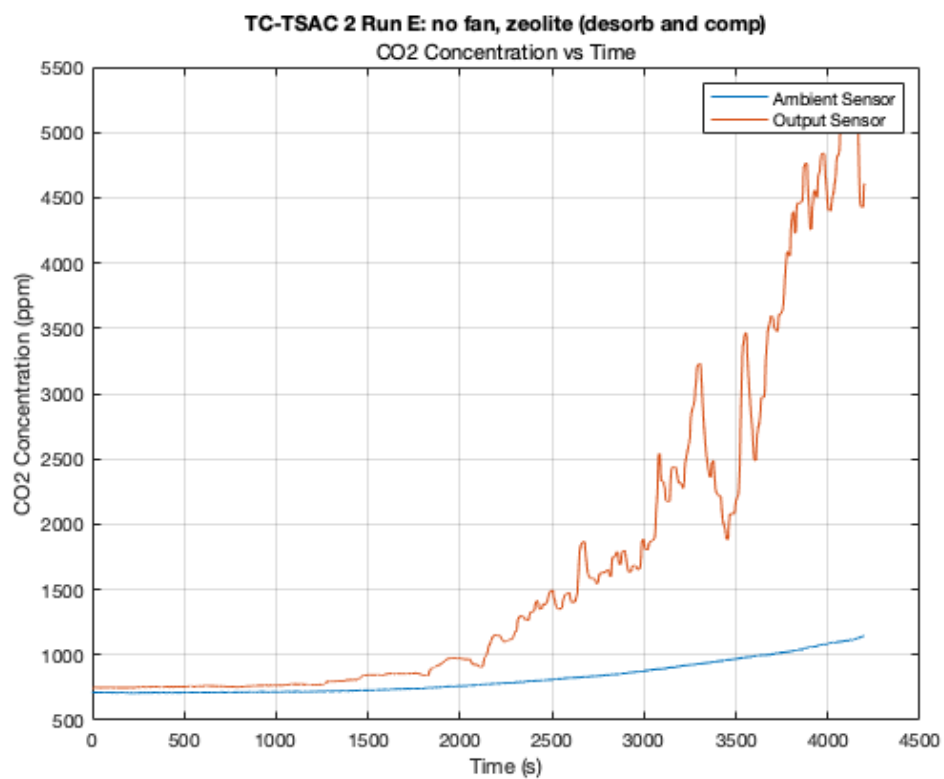
- Desorb test did not release as much carbon dioxide as desired since it took awhile for the heat tape to reach the ideal temperature.

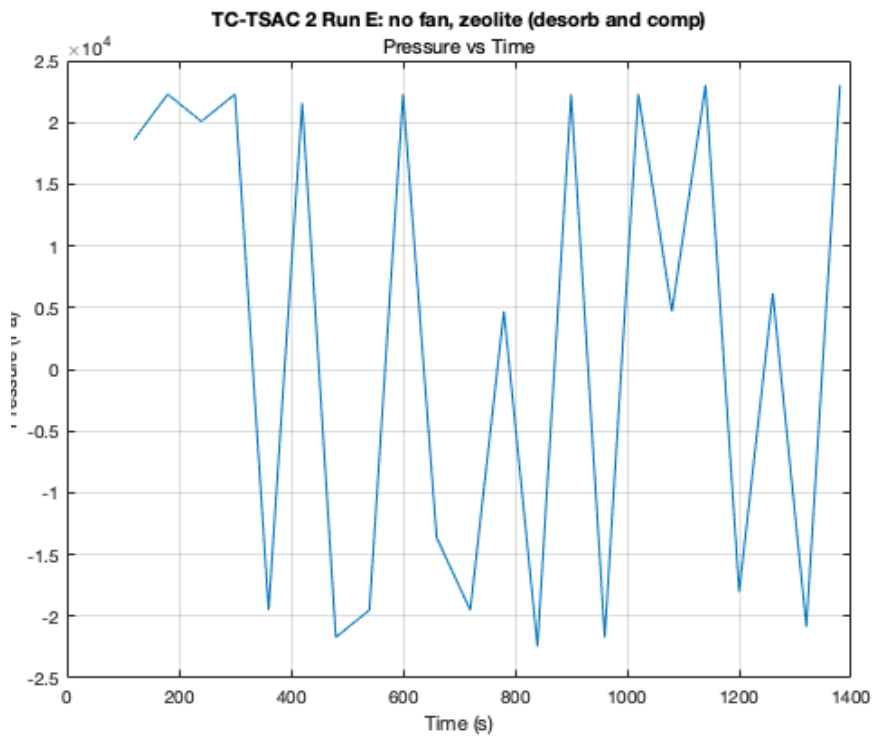
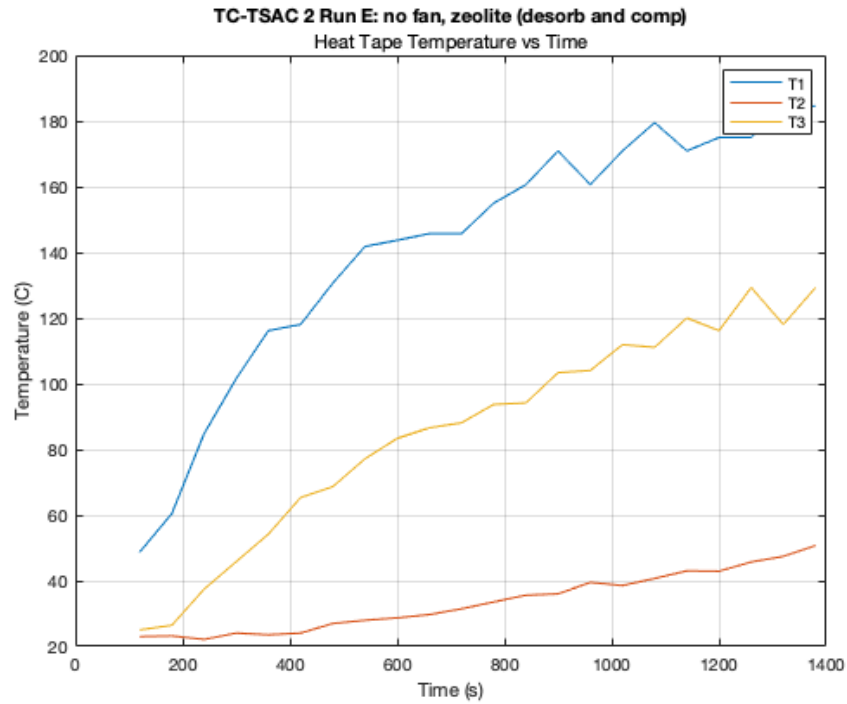




- The step pattern originated from the fact that the microcontroller could perform an analog to digital conversion with 10 bits. With large values it causes the difference between bits to be represented as having large differences. Something to consider in the future is using a separate analog to digital converter that uses more bits to convert and that way the latter pattern will be reduced.







- Compression bed had leaks so the pressure sensor did not accurately capture data. Data was not fully captured for the whole time due to the data acquisition corrupting the data past the 1400 second mark. The temperature data did however follow similar trends as the desorb test.

Test	CO2 diff (ppm)	Mass of CO2 adsorbed/lost (kg)
A (fan)	2870.89	0.009432683
B (adsorb)	7738.67	0.021775147
B w/ leaks	4867.78	0.012342464
C (desorb)	191.33	0.000735572
D (adsorb)	5413	0.019489519
D w/ leaks	2542.11	0.010056837
E (desorb comp)	437.83	0.002122267

B (adsorb)	
Velocity Flow Rate (m/s)	4.03
Mass of CO2 Adsorbed (kg)	0.012342464
CO2 Adsorption Rate (kg/s)	3.00449E-06
CO2 produced by 1 human (kg/day)	1
CO2 adsorption per day (kg/day)	0.259588345
CO2 adsorption per day (kg/day)	0.004320711

D (adsorb)	
Velocity Flow Rate (m/s)	4.82
Mass of CO2 Adsorbed (kg)	0.01005684
CO2 Adsorption Rate (kg/s)	2.4481E-06
CO2 produced by 1 human (kg/day)	1
CO2 adsorption per day (kg/day)	0.21151672
CO2 adsorption per day (kg/day)	0.00352058

To calculate mass of carbon dioxide adsorbed, the following Excel formula was applied (example). dM/dt is the difference multiplied by the density, flow rate, and cross-sectional area. The final mass of adsorption is the sum of the calculated integration.

Time (s)	CO2 (ppm)	CO2 (ppm)	Difference divided by 1000000	density of co2 (kg/m ³)	flow rate (m/s)	A (m ²)	dM/dt	dt (s)	dM/dt * dt	mass of co2 (kg)
0	437	1678	-0.001241	1.64033361	-0.0534058	0.00050671	5.5087E-08	1	5.5087E-08	0.02177515
1	437	1678	-0.001241	1.64033361	-0.0534058	0.00050671	5.5087E-08	1	5.5087E-08	

This was done for as much time as the data collected.

For calculating how much was desorbed, the following was calculated in Excel (example). The ppm loss total is the sum of all of the ppm losses, the mass of carbon dioxide loss is the ppm loss total multiplied by the density divided by 1,000,000, multiplied by the volume of the system.

Time (s)	CO2 (ppm)	CO2 (ppm)	V (m ³)	density of co2 (kg/m ³)	mass co2 (kg)	change in mass (kg)		ppm diff	ppm loss	ppm loss total	mass co2 lost		mass released (kg)
0	387.5	1365	2.1955388	1.5697816	0.0013355	0.0006594		-34.49	0.0037238	-22.0914335	7.614E-05		0.0007356
1	388.25	1365	2.1955388	1.5697816	0.0013381			-33.74	0.0036428				
2	388.50002	1365	2.1955388	1.5697816	0.001339			-33.489985	0.0036158				

Appendix D

Software Design Document

Sub-scale Adsorption and Compression CO₂ Removal System Re-design Team #22014

Joaquin Pesqueira
Brianna Otero
William Fowler
Kenneth Werrell
Grace Halferty

Requirements:

There are some requirements which can be found in the system requirements document that rely on this software to work properly. Those requirements are the following:

4.1.3 User Interface: The system shall display carbon dioxide levels, humidity, and temperature. (D/I)

This is addressed via the use of an PlatformIO in VS Code which outputs all the values to a serial monitor. The temperature sensors are thermistors who's resistances are measured while the other values are measured by vernier sensors.

4.3.1 Emergency Shutoff Button: The system shall have a shutoff button in order to shut down all components at once in the case of an emergency. (D)

The microcontroller has the ability to shut everything down in the case of an emergency. Turning off the controller will shut everything down as all the relays used are in the "normally off" mode.

4.4.2 Adsorbed CO₂ compressed to 1000 torr: The system shall compress the carbon dioxide to 1000 torr. (T)

The controller will have a pressure reading which is read from a pressure sensor.

4.4.5 CO₂ capture rate: the system shall measure the rate that CO₂ is captured: The system shall measure the carbon dioxide capture rate and display it on the sensor. (A)

This is done via the vernier sensors that display their data on a display.

Architecture/Design:

The parts of the system that are computer controlled are the heater, and sensors. The heater works via a relay that takes a signal from an arduino to supply power or no power to the heaters. If the heater is below a target temperature, the relay closes and supplies power to the heater. Once the temperature reaches the target, the switch opens thereby turning the heater off. This process repeats as long as needed.

The sensor array includes temperature and pressure sensors. The temperature sensor is a thermal resistor where the temperature changes the resistance. A voltage divider is used to measure the resistance using an analog data read. The resistance is then calculated. With that value the temperature can be calculated with use of the Steinhart equation where B is provided by the supplier:

$$\frac{1}{T} = \frac{1}{T_0} + \frac{1}{B} \left(\ln \frac{R}{R_0} \right)$$

The pressure sensor outputs a linear output from 1V to 5V where the pressures range from 0-600kPa. The arduino measures it with an analog input pin. The code fits a line to the relationship between and gets the pressure from the voltage reading. The resulting equation is $P = (600000/4)(V - 1)$ or $P = (150000)(V - 1)$.

Code:

Software Test Plan/Description:

Testing the thermistors is done by comparing the display to another source. In our case we first compared it to the verniers in the case of room temperature. For higher temperatures we tested them in boiling water where the temperature is known. The values had an error of 5%.

Testing the relay would be done via observing the temperature and the behavior of the heater. A lower target temperature is set. In our case the behavior was as expected and was able to maintain the specified temperature.

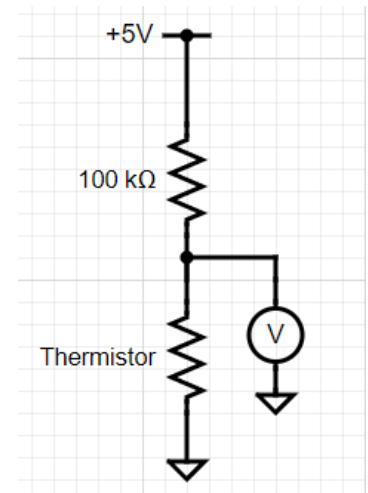
For pressure we were going to attach the sensor to a vertical pipe and fill it with water. The weight of the water would have added pressure to the sensor where it should have displayed a rise in pressure that could have been calculated and compared. We were not able to test the sensor as the resolution was too poor and it was not able to be used properly during the final testing.

Users Manual:

To use each temperature sensor a circuit needs to be used where the thermistor is connected in series with a $100\text{k}\Omega$ as shown. The analog probe should be connected in between the two components where the voltage reading can be used in the code above.

For using the heaters the relays are connected to the specified pins on the microcontroller. The relay should be normally open. The heaters can be directly connected to the relay. In the system the relay is connected to an extension cable and the heater is connected to that.

The pressure sensor must be connected to a power supply. Then it is connected to an analog input on the microcontroller and ground.



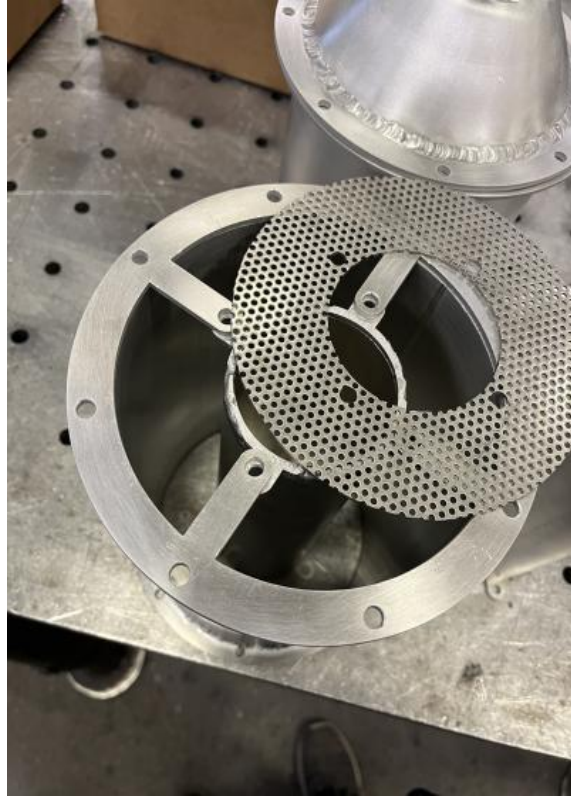
Appendix E: Images of System



Outer view of canister



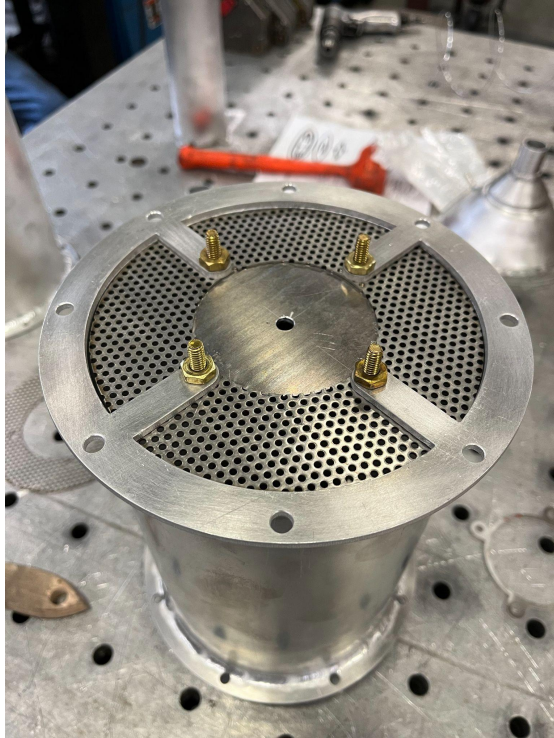
Compression and adsorption beds



Bed placement and mesh



Canister outer view



Mesh



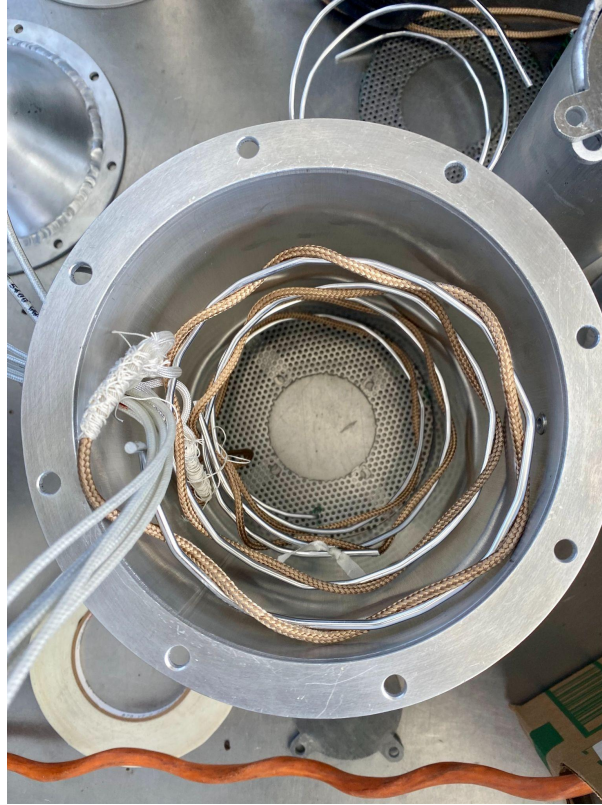
Cone top and hose barb for pipe fitting



Full system design



Paragon CO₂ Scrubber



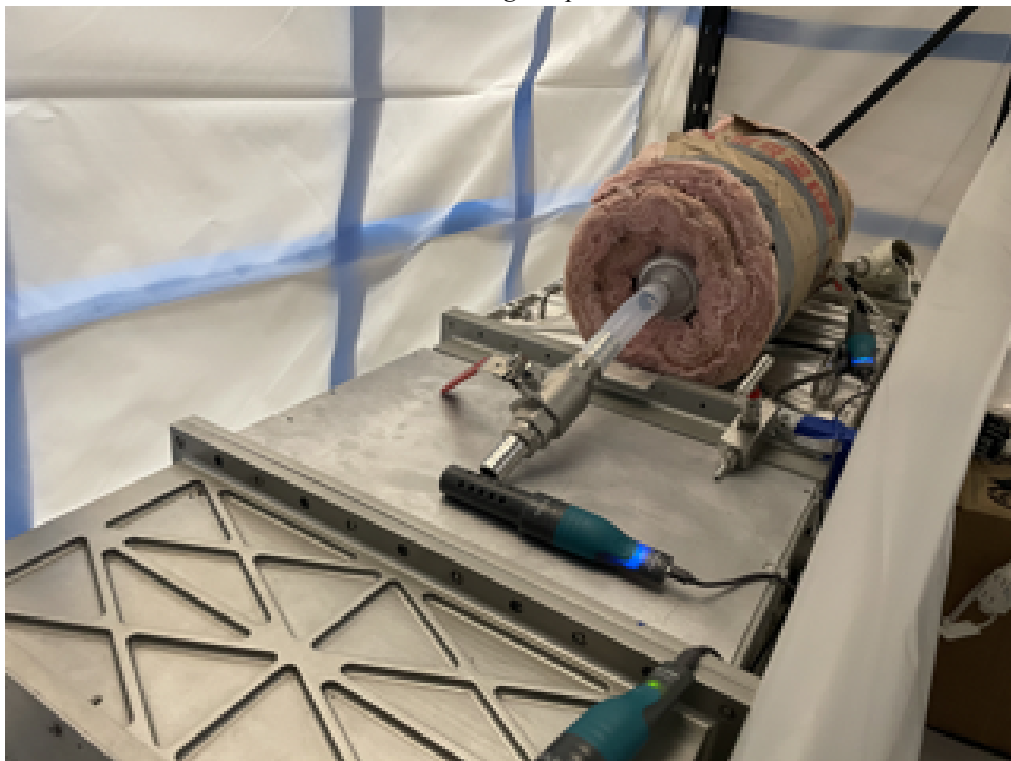
Inside bed with heat tape



Electronics for sensors



Testing setup



Desorb and compression test with insulation

Appendix F: Final Budget

Item(s)	Total Cost (\$)	Vendor(s)	Funding Left (\$)	Purchasing Methods	Purchase Dates
Pre-PDR Build		Amazon, Target, Lowes, Delta Adsorbents		Reimbursement and Purchasing Request Form	10/14/21 - 11/08/21
Benchtop Design		Ace Hardware, Graingers, Amazon, Elliott Electronic Supply		Reimbursement and Purchasing Request Form	1/11/22 - 2/5/22
Final Design		ATO, IMS, Amazon, Home Depot, Discover Valve, Gringers, University of Arizona		Reimbursement and Purchasing Request Form	1/11/22 - 4/7/22
Miscellaneous		Ebay, FedEx, Airgas		Reimbursement and Purchasing Request Form	2/24/22, 4/8/22, 4/27/22

The final negative amount was covered through supplemental funding through the project program managers.