Final Report

For

Development of the Volatile Organic Compound (VOC) Removal System

For

The Moon to Mars eXploration Systems and Habitation (M2M X-Hab) 2024 Academic Innovation Challenge

Project Leads:
Andrew Bahlmann, Noah Vogel

Project Members:
Adam Bertrand, Maria Chamieh, Erin Clingerman, Erika Hathaway, Megha Jacob, Aishan Jupudy, Parker Kern, Hana Koehr, Alex Kripfgans, Angel Lin, Jeffrey Li, Colin Lavery, Nate Maceri, Caleb Ng, Grace Pizzini, Daniela Rabassa, Joel Sawyer, Edith Shear, Rishi Tappeta, Sarah Waldman, Andrew Ward, Lowen Walter

Project Sponsor (NASA Ames):
Grace Belancik

Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Project Overview

The United States, along with other countries around the world, is preparing to return humankind to the Lunar surface. This endeavor will require the development of new technologies if a human presence beyond the Earth's sphere of influence is to be maintained. Indeed, during the space race of the 20th century, a mere twelve astronauts traveled to the Moon and returned to Earth. Now, in the 21st century as we prepare to travel back to the Moon and on to Mars a more substantial effort will be needed to develop how astronauts can sustain themselves for long duration. Among the technologies that need further development are CO_2 and removal along with the removal of volatile organic compounds (VOCs). Long-term human exploration necessitates CO_2 and VOC removal systems which require little to no maintenance, i.e., no sorbent materials. Currently, NASA AMES is developing a CO_2 Deposition System (CDep) which does not rely on sorbent materials. Rather, by chilling the incoming air the system is able to "freeze-out" the CO_2 while allowing oxygen and nitrogen to pass through the system. However, this system in its current configuration is unable to filter out all VOCs. Therefore, it is necessary to further develop this system with the addition of a VOC removal element to provide a complete solution to the long-term problem of air revitalization in a safe and reliable manner.

1.1.1 A Brief Introduction to VOCs

VOCs constitute a diverse set of chemical compounds that possess the ability to volatilize into the air under normal atmospheric conditions. These compounds are characterized by their propensity to easily evaporate into the gaseous phase at room temperature, and they play a substantial role in various natural and anthropogenic processes, affecting both indoor and outdoor air quality. VOCs encompass an extensive array of chemical species, comprising hydrocarbons and their derivatives, which can originate from diverse sources such as biological organisms, vegetation, industrial activities, and combustion processes.

While many VOCs are innocuous, some pose significant health and environmental concerns. For instance, certain VOCs can participate in chemical reactions in the atmosphere, contributing to the formation of ground-level ozone and smog, which have detrimental effects on human health and ecosystems. Moreover, prolonged exposure to specific VOCs may result in adverse health effects, including respiratory and neurological issues.

Now imagine these VOCs trapped in a small room with nowhere to escape. In the context of spacecraft and confined environments, the presence of VOCs can be particularly problematic. The closed nature of spacecraft, coupled with the potential off-gassing of materials and the necessity of maintaining a controlled atmosphere, underscores the importance of addressing VOCs to ensure the well-being of astronauts and the functionality of sensitive instruments and equipment.

This project aims to address this challenge by pioneering the development of an advanced VOC removal system tailored to the unique conditions of space.

Our endeavor revolves around the creation of a cutting-edge system that effectively eliminates VOCs from the spacecraft's atmosphere. VOCs, emitted from various sources, pose potential risks to both human health and sensitive instrumentation. Therefore, the success of space missions hinges on the ability to deploy a reliable and efficient solution to cleanse the spacecraft environment of these volatile compounds.

1.2 Team Breakdown

The project team is organized into four subteams: chemical engineering, electrical engineering, mechanical engineering, and systems engineering. The systems engineering team is composed of the SPACE 583 project members.

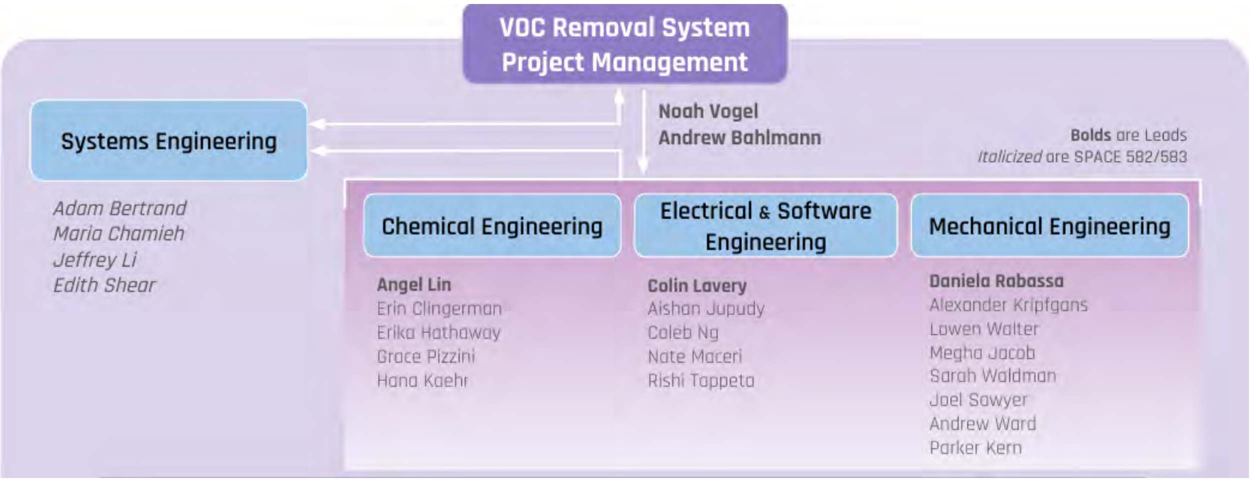


Figure 1: Project team structure.

2 Problem Definition

2.1 NASA Ames Carbon Dioxide Deposition System

The Carbon Dioxide Deposition (CDep) system developed by NASA Ames Research Center enables long-duration human space exploration by selectively depositing CO_2 onto a cold surface directly from cabin air via phase change temperatures of air constituents. The primary operations involve extracting moisture from the air saturated with CO_2, then depositing the CO_2, and ultimately rehumidifying the air. The rehumidified air, now essentially free of CO_2, is then recirculated back into the cabin. A full-scale schematic of the CDep system can be seen below in Figure 2:

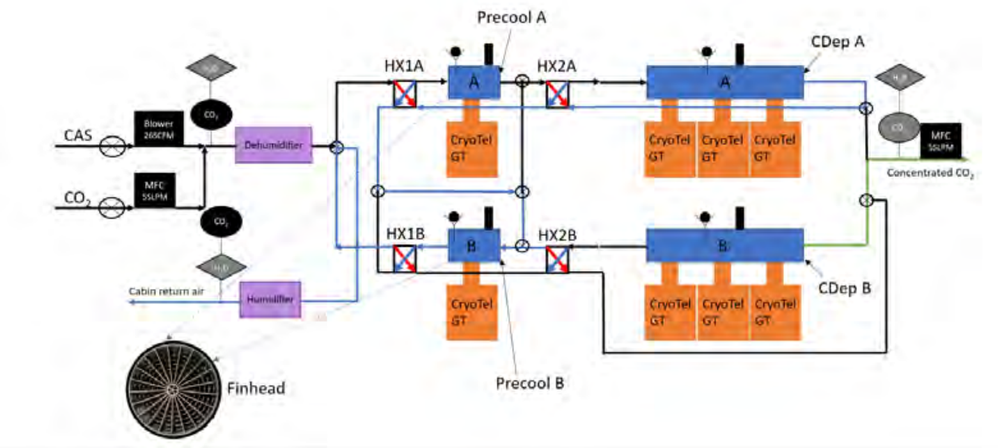


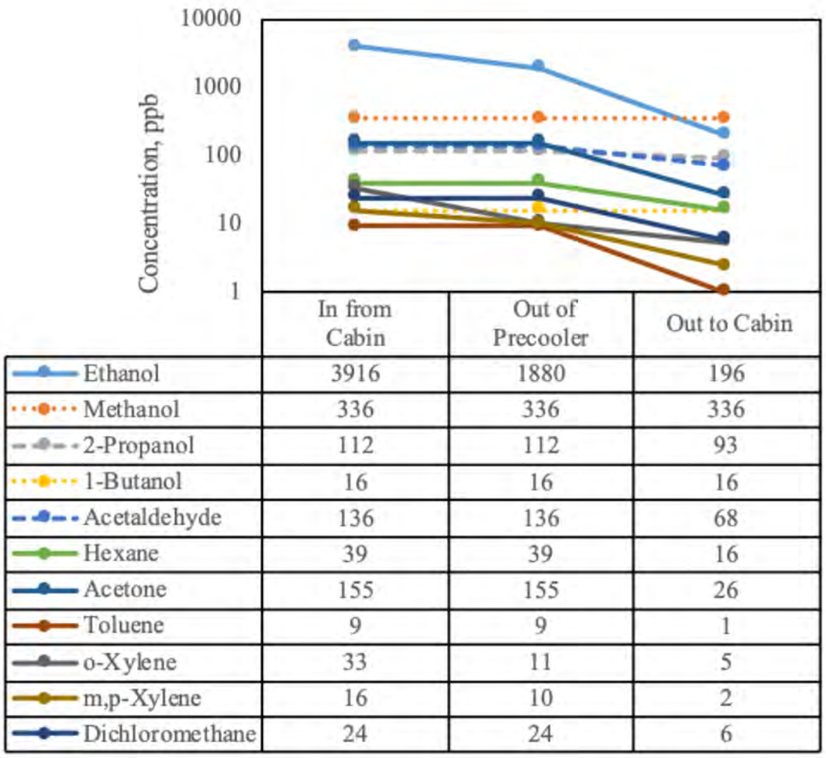
Figure 2: Schematic of full-scale CDep System

The first step of this system involves intaking CO_2 laden air from the environment and passing it through a hollow fiber membrane where moisture is pulled out of the air. Once the desired humidity level is reached, the system splits into two sections, denoted in Figure 1 as A and B. Each side works in conjunction with the other and is responsible for either depositing or sublimating. Both sides are operationally identical, and will consistently alternate their function from CO_2 deposition to sublimation and vice versa.

The section responsible for deposition will be defined as section A. Section A intakes the dehumidified air and feeds it through the first heat exchanger denoted at HX1A from Figure 2 and through a precooler (Precool A) bringing the temperature of the air down to 190K to capturing any remaining humidity. The air then travels through a deposition heat exchanger labeled HX2A, bringing the temperature of the incoming air down to 142 K, where the CO_2 can then be deposited into the deposition chamber (CDep A). Airflow transitions to side B, passing through the corresponding precooler (Precool B) and precool heat exchanger (HX1B) to eliminate any remaining humidity from its previous role as the deposition side. Subsequently, the air stream is guided through a humidifier, utilizing a second hollow fiber membrane. Here, water vapor diffuses back into the CO_2-free air, before circulating back into the cabin.

Simultaneously with the deposition process, the opposite side (CDep B and HX2B) sublimates CO_2. The sublimation process is dictated by the temperature of the sublimation chamber, resulting in a CO_2 output with pressure exceeding or equal to 20 psia. This pressure output obviates the necessity of a compressor to supply downstream CO_2 processing. Additionally, the system contains sensors that continuously measure humidity, CO_2 concentration, temperature, and pressure. These sensors provide real-time data on the diverse conditions within the system.[1]

The CDep system employs cryogenic coolers to eliminate CO_2 from the air stream by depositing it onto a cold surface, however, VOCs present in the spacecraft, with condensation or deposition temperatures within the temperature range (>130K), are also captured.



	In from Cabin	Out of Precooler	Out to Cabin
Ethanol	3916	1880	196
Methanol	336	336	336
2-Propanol	112	112	93
1-Butanol	16	16	16
Acetaldehyde	136	136	68
Hexane	39	39	16
Acetone	155	155	26
Toluene	9	9	1
o-Xylene	33	11	5
m,p-Xylene	16	10	2
Dichloromethane	24	24	6

Figure 3: VOC concentrations throughout CDep system

Of the 12 VOCs tested, 10 were confirmed to be captured by the system in some capacity. The objective is to eliminate these VOCs before directing the CO2 stream to a CO2 conversion system, preventing contamination. This can be achieved either upstream of the CO2 deposition process or by extracting them from the sublimed CO2 product. The primary challenge in designing this system is integrating it into the existing CDep architecture while minimizing mass, volume, and power requirements.

2.2 Customer Needs

One drawback to the CO_2 Deposition System is that it cannot completely remove all VOCs from the environment. Therefore, it is possible that VOCs can build up over time. To mitigate this problem, the scientists at NASA Ames tasked BLiSS to develop a system that can be integrated into the CDep system and provide a complete solution. In discussion with scientists and engineers at NASA Ames and Marshall Space Flight Center, we obtained the following needs for such a system:

CN1 : The system must remove VOCs from the environment.

CN2 : The system must quantify performance.

CN3 : The system must interface with the CDep system.

CN4 : The system must not negatively impact nominal CDep operation.

CN5 : The system must be maintainable.

CN6 : The project must cost no more than $50k.

CN7 : The project must be completed by the end of the 2024 academic year.

CN8 : The system must be scalable.

2.3 Scoping the Project

An important customer need is the interface between the VOC and CDep systems. Given certain restrictions on the project, it would be impossible to write interface requirements for the VOC system which could be verified. Therefore, the BLiSS VOC project team had to descope the project to deliver a prototype to NASA which could then be used as a basis for the future development of the CDep system capable of removing VOCs from the environment.

To descope the project we proposed making a smaller prototype of equivalent throughput, i.e., approximately equal gas speed in the system. This decision was based on the idea that, regardless of the VOC removal mechanism, the speed of the air coming into the system would be most important for a comparison with the CDep system. A gas flow speed for the VOC system equal to the CDep system results in an “analogous” flow rate.

2.3.1 CDep Mass Flow Rate

To determine the flow rate of the VOC system, we first consider the CDep system flow rate for four astronauts: 26 scfm. Converting to slm:[1]

$$\dot{q}_{\text{CDep}} = \left(\frac{26\ \text{ft}^3}{\text{min}}\right) \cdot \left(\frac{1\ \text{m}}{3.28\ \text{ft}}\right)^3 \cdot \left(\frac{1000\ \text{L}}{1\ \text{m}^3}\right) \tag{1}$$

$$\dot{q}_{\text{CDep}} \approx 736.8\ \text{slm} \tag{2}$$

Converting to kg/s, where relationship between volumetric and mass flow rate: $\dot{m} = \rho_n \dot{q}$, $\rho_n = \frac{p_n M}{Z_n R_u T_n}$ and subscript n refers to standard conditions:[2]

$$\dot{m}_{\text{CDep}} = \rho_n \dot{q} = \frac{p_n M}{Z_n R_u T_n} \dot{q} \tag{3}$$

$$\dot{m}_{\text{CDep}} = \frac{101325\ [\text{Pa}] \cdot 0.0280\ [\text{kg}\cdot\text{mol}^{-1}]}{8.314\ [\text{m}^3\cdot\text{Pa}\cdot\text{K}^{-1}\cdot\text{mol}^{-1}] \cdot 273.15\ [\text{K}]} \cdot 0.7368\ \left[\frac{\text{m}^3}{\text{min}}\right] \cdot \left[\frac{1\ \text{min}}{60\ \text{s}}\right] \tag{4}$$

$$\dot{m}_{\text{CDep}} \approx 0.0153\ \left[\frac{\text{kg}}{\text{s}}\right] \tag{5}$$

For one astronaut the flow rates are: $\dot{q}_{\text{CDep}} = 184.2$ slm and $\dot{m}_{\text{CDep}} = 0.0038$ kg/s. Compared with the flow rates of off-the-shelf mass flow controllers/meters.

---

[1] scfm: standard cubic centimeters per minute; slm: standard liters per minute.

[2] Use molar mass of nitrogen for calculation: $M_{\text{N}_2} = 0.0280$ kg/mol. Assume ideal gas: $Z_n = 1$. Standard conditions: $p_n = 101325$ [Pa], $T_n = 273.15$ [K]. Gas constant: 8.314 [J·K^{-1}·mol^{-1}] = 8.314 [m^3·Pa·K^{-1}·mol^{-1}] = 8.314 [kg·m^2·s^{-2}·K^{-1}·mol^{-1}].

mass flow rate (slm)	equiv. no. of astronauts
20	0.1086
40	0.2172
50	0.2714
60	0.3257
100	0.5429

Table 1: Mass flow rate comparison. The current mass flow controller flow rate is highlighted

2.3.2 Cross-Sectional Area Considerations

From the images of CDep in the papers provided by sponsors, the system used ConFlat (CF) components with diameter = 2 in ≈ 50.8 mm. The diameter of the components for the benchtop system is 1/2 in. For area comparison $R = 1$ in, $r = \frac{1}{4}$ in $\implies R = 4r$:

$$A_{\text{CDep}} = \pi R^2 = \pi(4r)^2 = 16\pi r^2 \qquad A_{\text{VOC}} = \pi r^2 \tag{6}$$

Assuming the density of the gas remains constant and equal for both cases $\rho_1 = \rho_2 = \rho$ along with a uniform velocity:

$$\dot{m}_{\text{CDep}} = \int_{\partial\Omega_1} dA\rho v \qquad \dot{m}_{\text{VOC}} = \int_{\partial\Omega_2} dA\rho v \tag{7}$$

$$\implies \dot{m}_{\text{CDep}} = A_{\text{CDep}}\rho v_{\text{CDep}} \qquad \implies \dot{m}_{\text{VOC}} = A_{\text{VOC}}\rho v_{\text{VOC}} \tag{8}$$

$$\implies \dot{m}_{\text{CDep}} = 16 A_{\text{VOC}}\rho v_{\text{CDep}} \tag{9}$$

Taking the ratio will provide an approximate velocity:[3]

$$\frac{\dot{m}_{\text{VOC}}}{\dot{m}_{\text{CDep}}} = \frac{\dot{q}_{\text{VOC}}}{\dot{q}_{\text{CDep}}} \tag{10}$$

$$\implies \frac{\dot{q}_{\text{VOC}}}{\dot{q}_{\text{CDep}}} = \frac{A_{\text{VOC}}\rho v_{\text{VOC}}}{16 A_{\text{VOC}}\rho v_{\text{CDep}}} \tag{11}$$

$$\implies \frac{v_{\text{VOC}}}{v_{\text{CDep}}} = 16\frac{\dot{q}_{\text{VOC}}}{\dot{q}_{\text{CDep}}} \tag{12}$$

For a mass flow rate of 50 slm:

$$\frac{v_{\text{VOC}}}{v_{\text{CDep}}} = 16 \cdot \frac{50 \text{ slm}}{736.8 \text{ slm}} \approx 1.0858 \tag{13}$$

mass flow rate (slm)	vel. ratio $\frac{v_{\text{VOC}}}{v_{\text{CDep}}}$
20	0.4343
40	0.8686
50	1.0858
60	1.3029
100	2.1716

Table 2: Mass flow rate comparison. The current mass flow controller flow rate is highlighted

---

[3] Mass flow and volume flows are proportional ($\dot{m} \propto \dot{q}$)

More generally $R = \kappa r$:[4]

$$\frac{v_{\text{VOC}}}{v_{\text{CDep}}} = \kappa^2 \frac{\dot{m}_{\text{VOC}}}{\dot{m}_{\text{CDep}}} \tag{14}$$

Velocity ratio of unity for $R = 4r$:

$$1 \frac{v_{\text{VOC}}}{v_{\text{CDep}}} = 16 \cdot \frac{\dot{q}_{\text{VOC}}}{736.8 \text{ slm}} \tag{15}$$

$$\implies \dot{q}_{\text{VOC}} \approx 46.05 \text{ slm} \tag{16}$$

Operating at 60%, requires ≈ 76.75 slm. If $R = 8r$:

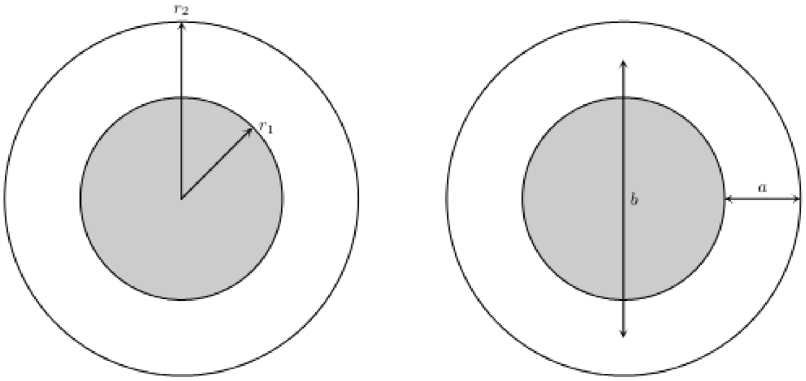
$$1 \frac{v_{\text{VOC}}}{v_{\text{CDep}}} = 64 \cdot \frac{\dot{q}_{\text{VOC}}}{736.8 \text{ slm}} \tag{17}$$

$$\implies \dot{q}_{\text{VOC}} \approx 11.5125 \text{ slm} \tag{18}$$

Operating at 60%, requires ≈ 19.1875 slm.

2.3.3 VOC removal system cross-sectional area considerations

The flow rate must be conserved. Figure 4 illustrates the cross-section of the VRE chamber.



(a) (b)

Figure 4: Volatile Removal Element cross section.

For an inner radius, r_1, and outer radius, r_2, the cross-sectional area of the VRE chamber is:

$$A_{\text{VRE}} = \pi \left(r_2^2 - r_1^2\right) = \pi b d \tag{19}$$

Assuming the density of the gas remains constant and equal along with a uniform velocity:

$$\dot{m}_{\text{VOC}} = \pi r^2 \rho v_{\text{VOC}} \qquad \dot{m}_{\text{VRE}} = \int_{\partial\Omega_3} dA \rho v = A_{\text{VRE}} \rho v_{\text{VRE}} = \pi \left(r_2^2 - r_1^2\right) \rho v_{\text{VRE}} \tag{20}$$

---

[4] Refer to this calculation for future reference.

Enforcing the flow rates are equal, the ratio of the velocities is:

$$\dot{m}_{\text{VOC}} = \dot{m}_{\text{VRE}} \tag{21}$$

$$\implies \dot{q}_{\text{VOC}} = \dot{q}_{\text{VRE}} \tag{22}$$

$$\implies r^2 v_{\text{VOC}} = (r_2^2 - r_1^2) v_{\text{VRE}} \tag{23}$$

$$\implies \frac{v_{\text{VRE}}}{v_{\text{VOC}}} = \frac{r^2}{r_2^2 - r_1^2} \tag{24}$$

The velocity of the gas in the VRE chamber is:

$$\dot{m}_{\text{VOC}} = \dot{m}_{\text{VRE}} \tag{25}$$

$$\implies \rho \dot{q}_{\text{VOC}} = \dot{m}_{\text{VRE}} \tag{26}$$

$$\implies \dot{q}_{\text{VOC}} = \pi \left(r_2^2 - r_1^2\right) v_{\text{VRE}} \tag{27}$$

$$\implies v_{\text{VRE}} = \frac{\dot{q}_{\text{VOC}}}{\pi \left(r_2^2 - r_1^2\right)} \tag{28}$$

Alternatively, using $r_2^2 - r_1^2 = \pi b d$:

$$\implies v_{\text{VRE}} = \frac{\dot{q}_{\text{VOC}}}{\pi b d} \tag{29}$$

2.4 VOC Selection

D4, also known as octamethylcyclotetrasiloxane, is a common cyclic siloxane used in several health and self-care products such as antiperspirants, lotions, and more. We have decided to pursue D4 at NASA's suggestion and because D4 has been previously tested and oxidized into CO, CO_2, and silica (SiO_2). Concerns regarding D4 include that the by-product of CO has a freezing point lower than the temperature at which the CDep system operates. It is possible that when the PCO system runs on the ISS with an air sample containing O_2 the carbon monoxide may form CO_2. Additionally, the silica by-product of D4 siloxane will deposit on the surface of our TiO_2 catalyst and decrease its performance over time. We can expect at least a 60% decrease in the performance of the catalyst after 72 hours of system testing based on previous experiments. However, the catalyst can be cleaned and reapplied, so our design includes a method of removing the catalyst tube from the PCO tank.

Toluene is a chemical commonly used in paints and adhesives. It has a simpler structure than D4 and will produce only CO and CO_2 as byproducts if fully converted in the PCO tank. Without D4, it has been shown that Toluene can be fully oxidized using photocatalytic oxidation, at least at concentrations below 250 ppbv. Additionally, experiments from literature [2] have tested the ability to remove both D4 and Toluene from the same air samples. These experiments concluded that the amount of Toluene will decrease as the silica byproduct deactivates the catalyst, but the two compounds should not inhibit the oxidation of the other. It is also known that a wavelength of 365 nm provides enough energy to oxidize both compounds over a period of 3 days.

2.4.1 VOC Concentration

Based on initial data, we determined that the appropriate concentrations of D4 and Toluene at high and low concentrations are:
High Concentration of D4: 300 ppm (60 mg/m^3) (+/- 1 ppm)
Low Concentration of D4: 23 ppm (12 mg/m^3) (+/- 0.1 ppm)

High Concentration of Toluene: 300 ppm (60 mg/m^3) (+/- 1 ppm)
Low Concentration of Toluene: 4 ppm (15 mg/m^3) (+/- 0.1 ppm)

The low VOC concentrations were selected from NASA's 2020 SMAC [**<empty citation>**], which details the allowable concentrations of VOCs on board the ISS. The tolerable concentrations for 7 days were selected as this length will be approximately the amount of time that system tests are run. High concentrations were selected such that the minimum amount of CO produced should fall within the limitations of the CO sensor selected by the electrical subteam.

3 Top-Level Project Objectives and Requirements

3.1 Mission Objective and Deliverables

The overarching mission objective is to develop a comprehensive and scalable Volatile Organic Compound (VOC) removal system with the aim of integrating it seamlessly with the Carbon Dioxide Deposition System (CDep) currently under development by NASA Ames. This mission was a two-fold endeavor, consisting of design and implementation phases, with the ultimate goal of creating a fully functional VOC removal system prototype for rigorous testing by the conclusion of the 2024 academic year. Thus, the mission objective is as follows:

MO1: Design a scalable volatile organic compound (VOC) removal system for integration with the CO_2 deposition system (CDep) under development by NASA Ames.

In pursuit of this objective in the context of a student project team, expected deliverables were defined to establish a common understanding between the team and the customer. These deliverables are what are expected to be completed by the conclusion of the 2024 academic year. The deliverables are as follows:

D1: Deliver modeling results, experimental testing results, operational recommendations, and scaling expectations for future designs.

D2: Project milestone reviews and meetings: SDR/PDR/CDR (PASSED)

3.2 Functional Requirements

In alignment with the overarching mission objective of designing and implementing a scalable Volatile Organic Compound (VOC) removal system integrated with the NASA Ames-developed Carbon Dioxide Deposition System (CDep), a set of functional requirements and constraints has been delineated to guide the development process.

The constraints are as follows:

CON1: The system shall have a mass no greater than 30 kg.

CON2: The system shall have a volume no greater than 60 cm X 120 cm X 30 cm.

CON3: The system shall consume no more than 60 W of power.

CON4: The cost to design, develop, and test the system shall not exceed $50,000.

CON5: The time taken to design, develop, and test the system shall not exceed 8 months.

CON6: The system shall not change the ambient temperature by more than 2 deg. C.

CON7: The system shall not change the ambient humidity by more than 2%.

CON8: The system shall comply with University of Michigan safety regulations.

The top level (Level 1) requirements are the top level requirements and are entirely derived from the needs of the customer. These requirements govern what the system is required to do in order to achieve the overall mission. The top-level functional requirements are listed in the table below:

Top Level Requirements

Requirement ID	**Description**	**Verification Method**
FR1.1	The system shall reduce the amount of Octamethylcyclotetrasiloxane (D4) to within acceptable SMAC limits.	Test
FR1.2	The system shall reduce the amount Toluene within acceptable SMAC limits.	Test
FR1.3	The system shall measure the amount of Octamethylcyclotetrasiloxane (D4).	Test
FR1.4	The system shall measure the amount of Toluene.	Demonstration
FR1.5	The system shall meet key integration metrics with the CDep System as requested by stakeholders.	Demonstration
FR1.6	The system shall have a the ability to continuously operate for 1 hour.	Analysis

All design decisions should stem from the constraints and top level requirements. For this reason all requirements must be verifiable. The rationales and verification method behind each top level requirement is listed below:

FR1.1: The purpose of the system is to remove VOCs to a concentration safe for astronauts and low enough not to interfere with the efficiency of the CDep system. This requirement will be verified through Test.

FR1.2: The purpose of the system is to remove VOCs to a concentration safe for astronauts and low enough not to interfere with the efficiency of the CDep system. This requirement will be verified through Test.

FR1.3: Users need to be provided with data in order to gauge that the system is working. This requirement will be verified through Demonstration.

FR1.4: Users need to be provided with data in order to gauge that the system is working. This requirement will be verified through Demonstration.

FR1.5: The system must integrate seamlessly with the CDep system to meet the mission objective. BLiSS' system's integration with CDep translates to it removing its target VOCs first thereby enhancing CDep's efficiency in removing its respective target VOCs (CO_2). This allows for a complete VOC removal system. This requirement will be verified through Inspection.

FR1.6: Reasonable testing time given schedule constraint of this project. This requirement will be verified through Test.

The Level 2 requirements are the second level requirements based on what is necessary to achieve the customer derived Level 1 requirements. These requirements govern what that system is required to do in order to achieve the overall mission. All design decisions should stem from the constraints and top level requirements. For this reason all requirements must be verifiable. The Level 2 requirements are listed below:

Functional Requirements- Level 2

Requirement ID	**Description**	**Verification Method**
Sensors and Data		
FR2.1	The system shall measure the humidity of the sample to an accuracy of 0.5%.	Demonstration
FR2.2	The system shall measure the temperature of the sample to an accuracy of 0.5℃.	Demonstration
FR2.3	The system shall measure the concentration of Octamethylcyclotetrasiloxane (D4) to an accuracy of 0.25 ppm.	Demonstration
FR2.4	The system shall measure the concentration of Toluene to an accuracy of 0.25 ppm.	Demonstration
Structures and Interfaces		
FR2.1	The system shall have a mass flow rate of 11.5 slm with a tolerance no greater than 0.5 slm.	Test
FR2.2	The system shall be made of non-reactive materials.	Inspection
FR2.3	All sensors shall interface with the system to allow for characterization of air sample.	Inspection
Removal Mechanism		
FR2.1	The removal mechanism shall allow for the sample to pass through the system.	Demonstration
FR2.2	The removal mechanism shall be capable of reducing the concentration of Octamethylcyclotetrasiloxane (D4) to at most 23 ppm.	Test
FR2.3	The removal mechanism shall be capable of reducing the concentration of Toluene to at most 16 ppm.	Test

The Level 3 requirements are the third-level requirements based on what is necessary to achieve the Level 2 requirements. These requirements, representing core functionalities and performance criteria for the level 2 requirements, are listed below:

Functional Requirements- Level 3

Requirement ID	**Description**	**Verification Method**
Sensors and Data		
FR3.1	The system shall quantify the humidity every 30 seconds.	Demonstration
FR3.2	The system shall quantify the temperature every 30 seconds.	Demonstration
FR3.3	The system shall quantify the D4 concentration every 15 seconds.	Demonstration
FR3.4	The system shall quantify the Toluene concentration every 15 seconds.	Demonstration

These functional requirements serve as a blueprint for the development of the VOC removal system, ensuring that it fulfills its core purpose while adhering to key performance indicators. Simultaneously, the outlined constraints provide the necessary boundaries to guide the design and development process, ensuring the system's compatibility with space mission parameters and resource limitations.

4 Analysis of Alternatives

In the pursuit of developing an effective and sustainable solution for the removal of Volatile Organic Compounds (VOCs), our investigation delves into a comprehensive analysis of various state-of-the-art technologies. This section, aptly titled "Analysis of Alternatives," aims to scrutinize and compare different VOC removal processes, each offering unique advantages and challenges.

Our focus extends to five prominent VOC removal methods: activated carbon adsorption, thermal oxidation, plasma membrane technologies, biofiltration, and photocatalytic oxidation. By critically examining these alternatives, we aim to provide valuable insights that will guide decision-making toward the most efficient and feasible solution.

4.1 Activated Carbon

Activated carbon is a highly porous form of carbon characterized by a large surface area, created through a process that activates carbonaceous materials, such as coconut shells or wood, at high temperatures. The resulting material is composed of microscopic pores and an extensive network of crevices. This unique structure allows activated carbon to effectively adsorb and capture a wide range of impurities and contaminants from gases or liquids. The adsorption process involves the attraction and binding of molecules to the carbon surface, removing pollutants and creating a purified substance. Activated carbon is widely used in various applications, including air and water purification, gas masks, and industrial processes, due to its exceptional ability to trap and immobilize a diverse array of organic and inorganic substances through its adsorption mechanism. One significant drawback, however, is the potential for carbon saturation over time. In the confined environment of a spacecraft, where space and resources are limited, the activated carbon's adsorption capacity can become exhausted as it accumulates VOCs. Once saturated, the carbon must be replaced to maintain efficient pollutant removal. This process of periodic replacement poses logistical challenges and increases the demand for storage of replacement materials on the spacecraft, factors that can compromise the overall efficiency and practicality of activated carbon as a long-term VOC removal solution in space. As a result, alternative methods that mitigate the need for frequent replacement and address the constraints of space environments may need to be explored for more sustainable and space-efficient VOC control systems on spacecraft. [3]

4.2 Thermal Oxidation

Thermal oxidation emerges as a widely employed technique to remove VOCs, distinguished by its effectiveness in neutralizing organic vapors through high-temperature oxidation, resulting in the conversion of organic compounds into environmentally benign byproducts such as carbon dioxide, water, and inorganic gases. Thermal oxidation holds the advantage of safely and cleanly incinerating diverse gaseous organic streams when meticulously designed and operated. However, it is essential to acknowledge certain drawbacks associated with this method, particularly in contexts such as spacecraft applications. Safety concerns arise due to the elevated temperatures required for thermal incineration, which may pose challenges in ensuring the well-being of personnel and the spacecraft's structural integrity. Notwithstanding its high destruction efficiencies, often exceeding 99%, thermal incineration's intricacies involve subjecting contaminant-laden waste gas to temperatures surpassing 1000°F, initiating combustion in the presence of oxygen. Moreover, integration with a CO_2 deposition system necessitates a constant temperature, much lower than the necessary temperature for thermal oxidation, and this process may prove incompatible, limiting its effectiveness. This process is also energy-intensive, which is not ideal on board a spacecraft. [4]

4.3 Plasma Membrane

The plasma membrane method of removing VOCs works by subjecting them to a plasma field. One way to create this field is by means of dielectric barrier discharge. The dielectric barrier discharge process consists of three key stages: discharge breakdown, charge transfer, and particle excitation, with micro-discharge being a crucial component occurring during breakdown and charge transfer. In micro-discharge, electrons accumulate on the medium's surface, leading to an avalanche effect and the formation of micro-discharge channels. In the final stage, this micro-discharge generates a multitude of excited particles in the discharge area, forming the energy basis for material surface modification. When volatile organic compounds (VOCs) interact with these particles, they undergo breakdown.

It is noteworthy that the plasma field necessary for this process can be created not only through dielectric barrier discharge but also via microwave and coronal discharge. However, applying this method to spacecraft comes with challenges. Continuous high energy would be required for sustained operation, presenting a significant drawback in the resource-constrained environment of space. Additionally, the effectiveness of this technique might be limited to only a few types of VOCs, reducing its versatility. Safety is also a concern when working with plasma, emphasizing the need for careful consideration and precautionary measures in spacecraft applications. [5]

4.4 Biofiltration

Biofiltration involves passing a humid and contaminated airstream through a porous support material with immobilized pollutant-degrading cultures. This process relies on microbial catabolic reactions for the degradation of waste compounds, particularly effective for dilute, high-flow waste gas streams with odors or volatile organic compounds. Under optimal conditions, pollutants can be completely degraded to carbon dioxide, water, and excess biomass. However, implementing biofiltration on a spacecraft poses practical challenges. The theoretical nature of this method in the context of space applications is a significant disadvantage. The unique and confined environment of a spacecraft, with limited space and resources, makes it challenging to adapt and maintain the optimal conditions required for biofiltration. Additionally, the need for a specific biofilter for each individual VOC introduces complexity and logistical issues, as it may not be feasible to accommodate multiple specialized biofilters on a spacecraft. [6]

4.5 Photocatalytic Oxidation

Photocatalysis refers to a broad category of chemical processes that are set in motion by the influence of light-activated catalysis. These reactions typically involve oxidation, although there are cases where reduction can occur. The catalyst employed in this context is usually a metal oxide semiconductor, such as titania, chosen for its specific band gap energy. This band gap allows the semiconductor to absorb ultraviolet photons, generating electron-hole pairs that act as catalysts and initiate chemical changes. In simpler terms, photocatalysis utilizes the energy from light to drive chemical reactions, particularly oxidation, by employing semiconductors like titania that possess specific characteristics conducive to these transformations. [7]

Photocatalytic oxidation distinguishes itself by relying on light energy rather than thermal energy, enabling operation at ambient temperatures and pressures. This characteristic leads to lower construction and operating costs. The process's low-temperature operation not only reduces weight and expenses but also minimizes corrosion from acid gas products. Despite its advantages, careful control of operating conditions is necessary to prevent fouling or poisoning of the catalyst. The utilization of ultraviolet (UV) light, commonly supplied by fluorescent blacklights, facilitates the breakdown of toxic organic chemicals into non-toxic or easily treatable compounds like carbon dioxide, water, and simple mineral acids. In the context of spacecraft applications, photocatalytic oxidation emerges as the optimal choice for VOC removal. Its reliance on light energy, particularly UV light, aligns with the limited energy resources available in space, offering a cost-effective and sustainable solution. The lower construction and operating costs, coupled with the use of lightweight materials, make photocatalytic oxidation suitable for the confined and resource-constrained environment of a spacecraft. However, the photocatalyst wiill degrade over time and must be replaced, but it can be chosen such that the resistance of the photocatalyst ensures high durability and longevity in space conditions. [8]

5 System Design

5.1 Concept of Operations

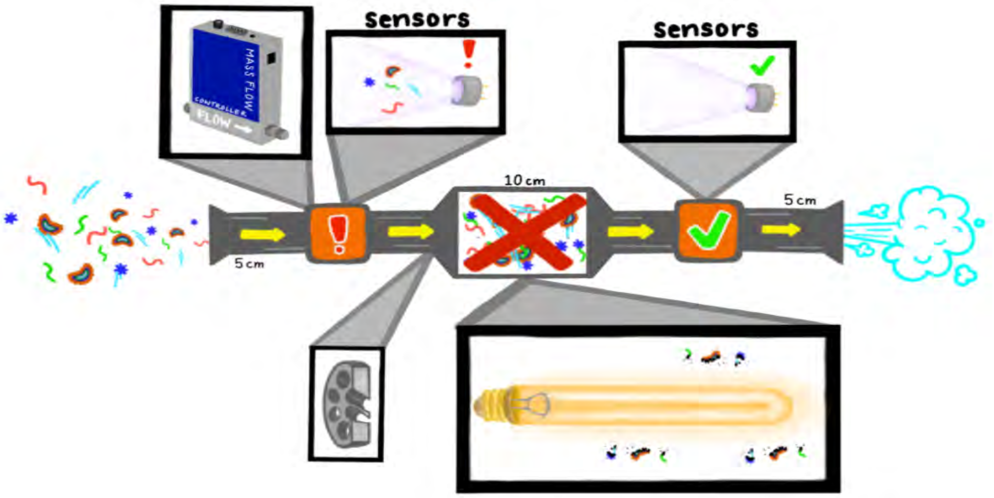


Figure 5: Generalized representation of the functionality of our system, or ConOps

This system aims to interface with the existing CDep system. The air will flow into the VOC removal system directly after it has had the CO_2 filtered from it by the CDep. It will then flow into the initial piping of the VOC system and then into the sensor bay. For the purposes of this prototype, a canister containing gas was inserted in the bench-top prototype via a mass flow controller.

This bay has an increased diameter to ensure that the flow is not corrupted by the sensors that exist here. The air is subject to sensors that will detect different VOCs that exist within it. Within this cavity, the VOCs are reacted on by our UV light and catalyst. The air then flows into a second sensor bay, which does a final evaluation of the air concentrations and airflow. Finally, the air flows out of the system via a duct the same diameter as the initial duct.

5.2 Proposed Systems Architecture

For the schematic representation of our proposed project's architecture, we have created a comprehensive diagram. This illustration offers a portrayal of the operational framework of our system.

The system undergoes a comprehensive purification process, starting with a rotameter at the input, which regulates the airflow rate for proceeding through the system. From the controller, the air stream is directed into Sensor Manifold A, housing sensors for temperature/humidity and Volatile Organic Compound (VOC) concentration analysis. This stage involves recording the properties of the incoming air stream to create an input air stream record for reference.

Subsequently, the air stream passes through the Volatile Removal Element (VRE), a pivotal component designed to convert volatile elements into non-toxic compounds. The VRE employs a chamber exposed to UV light, effectively transforming volatile elements into non-harmful compounds. The air then splits such that half passes through Sensor Manifold B and half passes through the CO sensor. The air cycles back through the VRE by the power of the air pump, passing through another rotameter on the way to record mass flow. Once a certain VOC concentration has been met, the air is taken out of the loop and is emptied from the system.

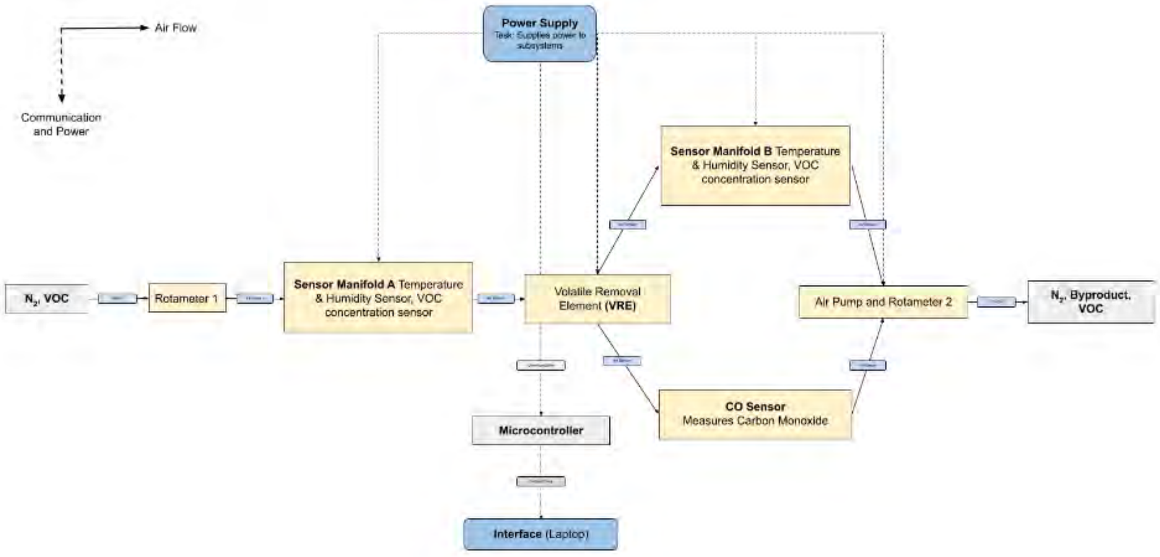


Figure 6: Proposed System Architecture

The data outputs from sensors A and B are routed to the microcontroller in real time. Here, the microcontroller performs a comparative analysis by executing a simple subtraction operation between the input and output records. This analytical approach enables us to discern real-time changes in various parameters measured as the air progresses through our system.

The results obtained from this stage of the process are indicative of the system's performance. For instance, minimal temperature fluctuations, typically less than 1°C, are expected. The pressure sensor readings will essentially affirm the absence of any leaks or structural weaknesses within the system. Furthermore, the VOC concentration sensor will register a decline in the overall concentration of volatile organic compounds following their treatment in the removal chamber.

To provide real-time visibility into these measurements and system progression, all recorded data is conveniently displayed on a user interface. This interface serves as a monitoring platform, facilitating immediate observation and evaluation of the system's operational dynamics. It is worth noting that the entire system is powered by a dedicated power supply unit, ensuring seamless and continuous operation.

5.3 Volatile Removal Element

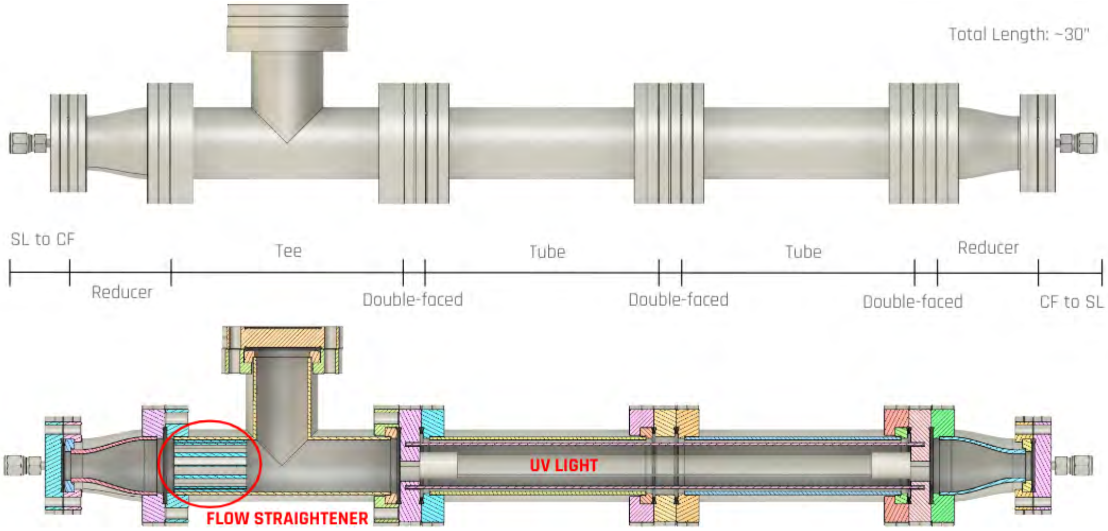


Figure 7: Volatile Removal Element Design

The VRE is composed of multiple ConFlat (CF) flanges that together, house the UV light, flow straightener, and glass tube. The only modified components include two machined CF double-faced flanges that hold the UV light and glass tube in place, as well as a tapped CF tee flange used to feed the UV light wires out of the system. The hole that the wires were fed through was closed using Torr Seal to retain an air-tight system. Finally, the material types of additional components such as the printed flow straightener were carefully selected to avoid UV degradation and offgassing.

5.3.1 Plan for Integration

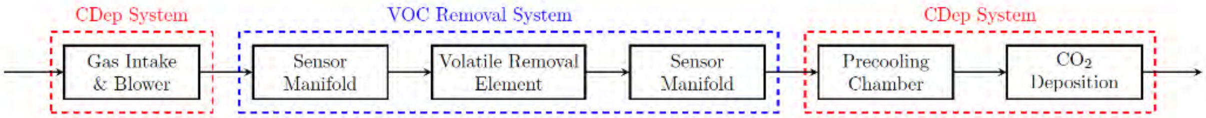


Figure 8: Plan for Integration with CDep System

From the design of a scaled-down prototype, a larger system can be made to interface with the CDep system. The VOC removal system would ideally sit between the gas intake and precooling chamber of the CDep system. In the case of our prototype, we are conducting an independent test campaign since integration with CDep is not feasible.

5.3.2 Flow Straightener

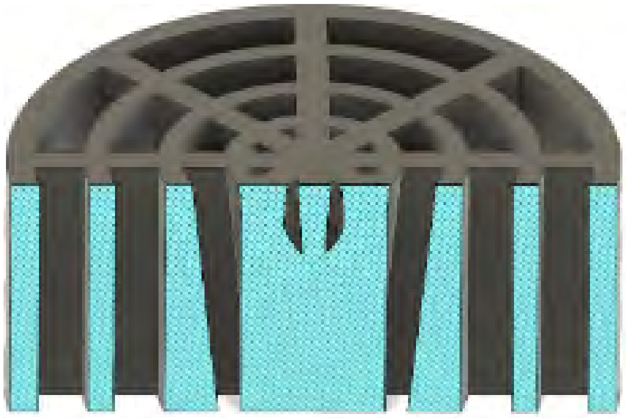


Figure 9: Flow straightener cross-section

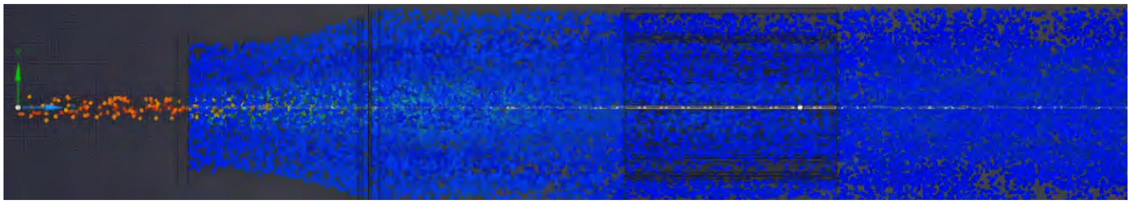


Figure 10: Flow straightener fluid dynamics simulation

To maximize the accuracy of our sensor data and PCO effectiveness, we aimed to prevent disturbances in the airflow. Therefore, we designed and printed a flow straightener that would allow for uniform velocity and distribution of airflow within the VRE. Figure 9 shows how the sudden diameter change on the left leads to an airflow with higher velocity concentrated in the center. After passing through the straightener, the airflow assumes a uniform velocity and slightly slows down: a state ideal for sensor readings and PCO. The flow straightener is placed in the tee flange, upstream of both the UV light and second sensor manifold as seen in Figure 6.

5.3.3 UV/Glass Tube-Holding Apparatus

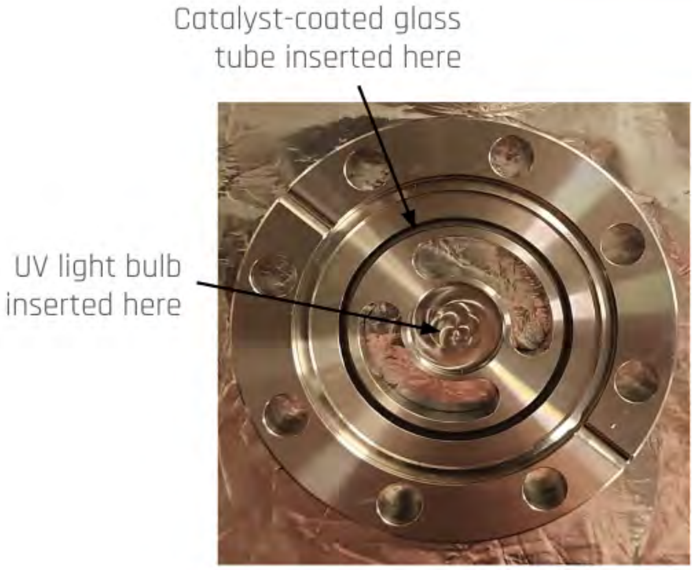


Figure 11: UV/glass tube-holding flange

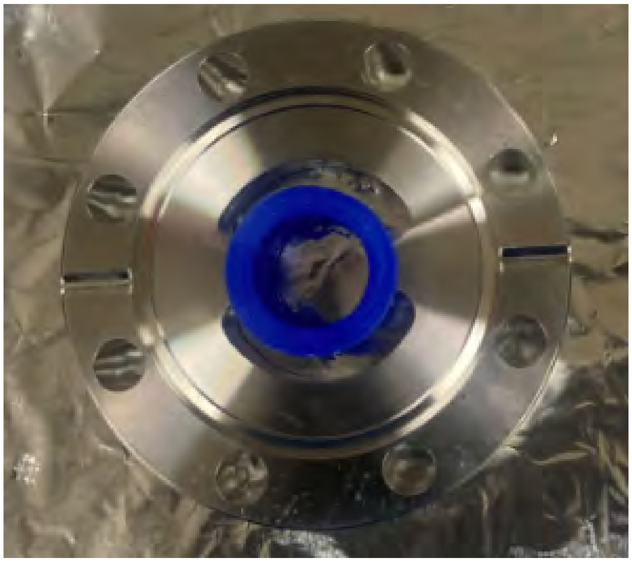


Figure 12: Wired UV/glass tube-holding flange

The UV bulb and glass tube were held in place by a ConFlat flange manufactured such that the UV light sits in the center of the glass tube. For the left side of the UV bulb, we had to utilize a flange with a nylon-print insert to minimize the risk of arcing and allow the wires that power the bulb to be fed through the system.

5.3.4 Catalyst Coating

Figure 13: Catalyst coating procedure

To coat our glass tubes, we utilized a baking procedure. We began by mixing the coating solution of ethanol, water, and Titanium (IV) Isopropoxide and preparing the fiberglass sheets for dip coating. After soaking the fiberglass sheets in our mixture, we added them to the glass tubes and heated them at 400°C so that the catalyst would adhere to the glass.

5.4 Sensor Manifold

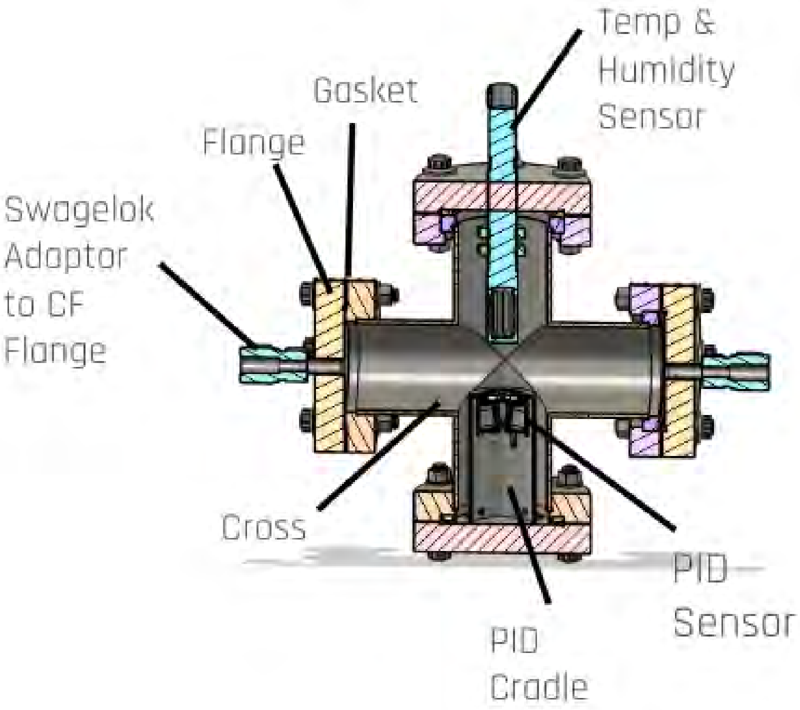


Figure 14: Sensor manifold design

We used a cross joint to integrate our temperature and humidity sensor and PID into our system. The design allows air to flow through the cross while the two sensors sit just outside the airflow. This way, they can detect concentrations but are not hit with the full force of the flow, which could lead to sensor damage.

5.4.1 Photoionization Detector Cradle

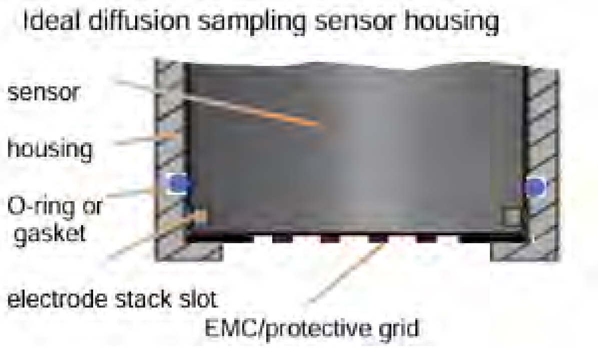


Figure 15: Suggested photoionization detector integration

Figure 16: Photoionization detector cradle

Under the guidance of the user manual, we decided to design a cradle for the PID to sit in and be extruded into the airflow. We printed the cradle design out of nylon and used o-rings to help both the PID fit into the cradle and the cradle fit into our flange for integration into the sensor manifold. The bar at the bottom of the PID cradle was added because the fit of the cradle into the flange was so tight that it was difficult to pull the cradle out without a handle.

5.4.2 Photoionazation Detector Calibration

Figure 17: Calibration chamber

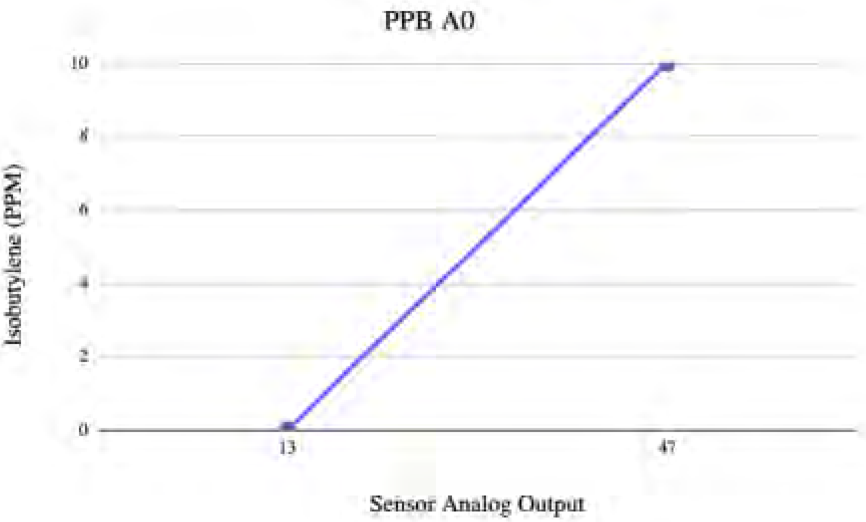


Figure 18: Isobutylene concentration vs. sensor analog output

```
Serial.println(((analogRead(0) * 0.2941) - 3.8235) * 0.56);
```

Figure 19: Arduino code converting analog output to PPM concentration of Toluene

We calibrated the PID by flowing known concentrations of Isobutylene gas, a common calibration VOC through the sensor using a calibration chamber and recording the corresponding analog outputs. Then, we graphed the correlation between Isobutylene concentration and sensor analog output. It is important to note that due to the high correlation factor of the line of best fit, this calibration can relate analog output to concentrations beyond the 10 ppm limit of the graph.

5.5 Design Iterations

5.5.1 Revolution 1

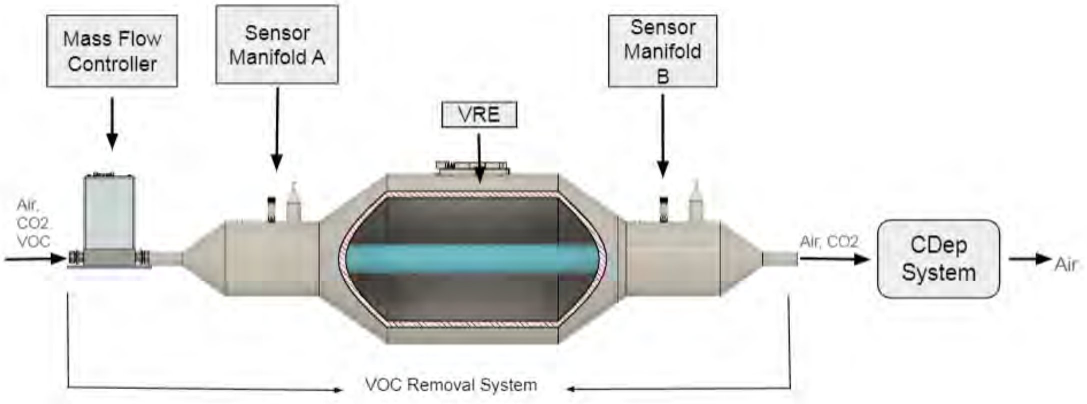


Figure 20: Revolution 1

The first iteration of our system had many flaws. The two most prominent flaws were that it was not conducive to manufacturability or serviceability. We initially envisioned a welded infrastructure, which would prove difficult for replacing components and troubleshooting system errors. The system adequately incorporated most of our sensing components that were included in the final design. However, this iteration focused only on the system's general architecture and failed to delve into the details of the VRE and surrounding subsystems. Additionally, the system was further idealized as a single-pass setup, which we quickly realized would allow reaction time to recycle all of the introduced VOCs.

5.5.2 Revolution 2

Figure 21: Revolution 2

The second iteration of our system design was backed by numerous trade studies and marked the beginning of the building portion of our design cycle. Being able to physically put this system together allowed us to get a better understanding of what we had to build. Building off of the shortcomings of REV.1, we designed REV.2 to include an air-cycling element to allow the VOCs to be exposed to UV light for a longer period of time. Furthermore, we started focusing on airflow mechanisms and efficiencies; we were mindful of the varying flow rates through the system and how they would impact our sensors and VRE capabilities and we incorporated a pump to continuously move air through our closed loop. Ultimately, REV.2 was a huge learning opportunity for us, and it opened our eyes to the experimental nature of the project. We recognized that our system was much more scientific than we originally thought: we would have to go through a heavy testing phase which was not given much space in the initial outlining of the project. The scope of our project underwent a large shift at this stage of its life cycle as we realized this, pushing us into our third and final revolution.

5.5.3 Revolution 3

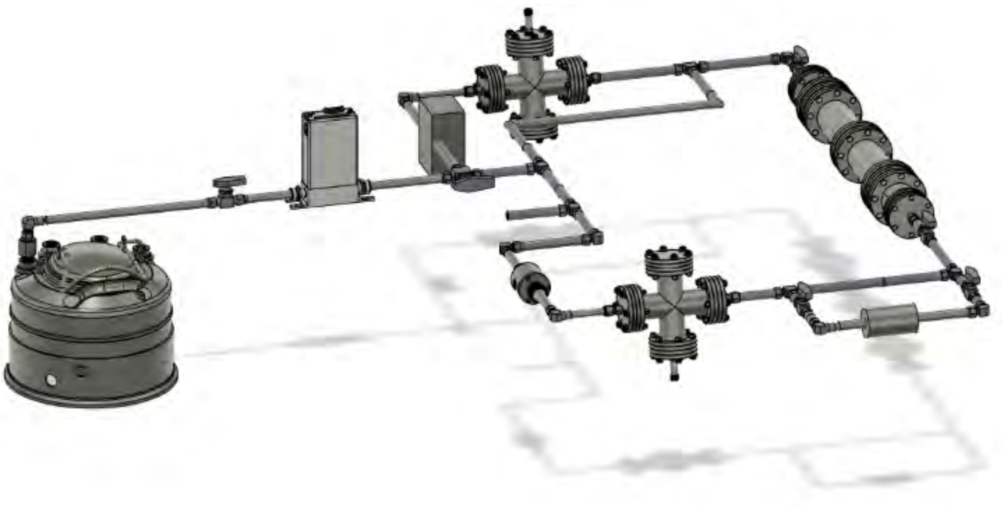


Figure 22: Revolution 3

Our final major iteration incorporated all of the lessons we learned in previous iterations and was ultimately much more serviceable and thus, easier to test and troubleshoot. Throughout our design of REV.3, we kept in mind the necessity of building a realistically testable system by prioritizing modular construction. Such a structure allowed us to easily make changes to our setup and evaluate subsystem failures. Though our final prototype underwent many small changes, its general idea and architecture were maintained throughout our testing phase. The specifications of our final design's reactor bay, (the portion of the design to be integrated with the CDep system), measured 11.41 kilograms in mass, and took up 0.1 square meters of volume, meeting both requirements as referenced in section 7.

6 Trade Studies

6.1 PID Sensor

Based on the trade study analysis, the MiniPID 2 PPB VOC Gas Sensor by IonScience was selected as the most suitable sensor for measuring linear siloxanes in the VOC removal system. It meets the essential requirements of detecting linear siloxanes (FR1.1) and measuring SMAC concentrations in the range of 50 to 600 ppm (FR1.5). The sensor uses a 10.6 eV light, which can measure decamethyltetrasiloxane at 10.24 eV and hexamethyldisiloxane at 9.6 eV. It has a wide measurement range of 0.1 to 40 ppm, a simple 3-pin interface for ease of use, and a high sensitivity of 30 mV/ppm. The MiniPID 2 PPB sensor's overall performance and features make it the most suitable choice for the VOC removal system.

6.2 Materials

Selecting the right material for the structure of the VOC removal system is crucial for achieving the desired functionality, durability, and cost-effectiveness of the system. It involves a thoughtful analysis of the specific requirements and constraints, considering factors that range from performance characteristics to economic considerations and environmental impact.

Based on a market availability survey as well as previous work by the BLiSS team, three material choices were identified that met the ”Must Haves” criteria: Aluminum 6061, Stainless Steel 316, and Stainless Steel 304. Each of these materials has its unique properties and potential for use in our context. However, after a thorough trade study considering all our must-haves and wants, we decided on Stainless Steel 304.

Following the summation of scores in a trade matrix analysis, Stainless Steel 304 scored highest in the total nominal and maximum score, only losing out in the total minimum to Aluminum 6016. Its corrosion resistance and strength set it apart from aluminum, while the extra resistance in Stainless Steel 316 comes at too large a cost in both money and density.

6.3 Assembly Connection

Our VOC system aims to assemble various components, particularly tubing, with a focus on selecting the appropriate connection type. Key selection factors include the ability to effectively seal components, the use of 304SS steel determined from the previous trade study, and adherence to industry standards for reliability, ease of procurement, and scalability. Additionally, other requirements are considered. Ranked in order of importance, and weighted accordingly, they are: ease of disconnection for assembly modifications, availability of relevant and scalable sizes, off-the-shelf non-reactive sealing materials availability (to not interfere with the system's internal chemistry), ease of integration with the NASA CDep, and assembly rapidity. The CF Flange emerges as the optimal choice due to its wide size range, seamless integration with NASA CDep, availability of non-reactive materials, and partially rapid ability for disassembly. The KF Flange and ISO (K/F) Flange also offer advantages but score lower due to limitations in size range or scalability. Welding, while circumventing certain issues, lacks the flexibility of disassembly. This qualitative assessment culminates in the selection of the CF Flange as the most suitable connection type for our project.

6.4 DC Brushless Pump

The DC brushless pump is an integral part of the CDep testing rig to recirculate air through the system for multiple pass testing. Requirements for this pump are sectioned into 4 detained wants. The pump connection is 1/4” in size to properly connect with the rest of the system setup. 1/4” tubing is the size required to feed into the system and as such the pump connection should first and foremost fit these specifications to avoid leakage of VOCs. Overall power consumption is initially constrained for the system at 60 watts. The system is meant to ruin in environments where large amounts of power are not readily available and as such lower power requirements for pumps will be ideal. The flow rate of the pump must be between 5 to 15 slm. The flow rate of the pump between these values is required for proper testing of VOCs based on specific sizing calculations of the CF flanges used. Finally, the pump must be a DC brushless motor. Brushless motors offer more efficiency as they are electronically driven and have a decreased risk of required maintenance. Other desires looked into were operational lifetime, corrosion resistance, and cost. KNF pumps in their N96 lab series were examined and the overall suitable option was the KNF N96 STDC-B-M. The only section it was not ideal for was its increased cost over other options.

6.5 Mass Flow Controller

To simulate the output flow from the NASA CDep and into our VOC system we need to create the corresponding mass flow calculated earlier in the report, 11.5 standard liters per minute, or SLM or SLPM. This is a very important and expensive component of our system so the right selection must be made. Our requirements for the Mass Flow Controller (MFC) are to cost less than \$5000 corresponding to CON4, operate in the desired flow rate range (11.5 slm) corresponding to FR1.2, operate at sea level, and operate at 40% +/- 5% humidity. To rank the options we looked for MFCs with low power consumption, low cost, high accuracy, and low response time.

The four options we looked at were the Red-y smart controller GSC-D, Burkert 8742, GC3 Series, and Brooks 5851E. The final scores, not including the cost factor, were 0.45, 0.62, 0.78, and 0.12. All options satisfied our requirements, but only the Burkert 8742 and GC3 Series mass flow controllers had sufficiently high scores for consideration. The GC3 Series, however, had a much lower power consumption than that of the Bukert 8742, so we decided on the GC3 Series.

6.6 Temperature and Humidity Sensor

To verify our customer's want of not increasing the temperature by more than 1°C and humidity by more than 5%, we need a way to measure the temperature and humidity. This led to the sensor threading requirements corresponding to FR2.1 and FR2.2, the ability to measure temperature between 10 deg C and 30 deg C corresponding to CON1, and the ability to measure humidity corresponding to CON2. To rank the options we looked for a small cross-sectional area, low cost, high accuracy, and low power consumption, with weights of 0.45, 0.10, 0.30, and 0.15 respectively.

Only one sensor met all our requirements, the M12FTH4Q Sure Cross Temperature and Humidity sensor. This sensor has a 0.25 W power consumption, costs \$300, has a 3.6 to 5.5 V DC supply voltage, measures 0 to 100% relative humidity (RH) with a 0.1% RH resolution and +/- 2% accuracy at 25 deg C and 10-90% RH, measure between -40 deg C and +85 deg C with a 0.1 deg C resolution and +/- 0.4% accuracy at 0 deg C to 60 deg C, using a simple 1-wire serial interface.

6.7 Pressure Sensor

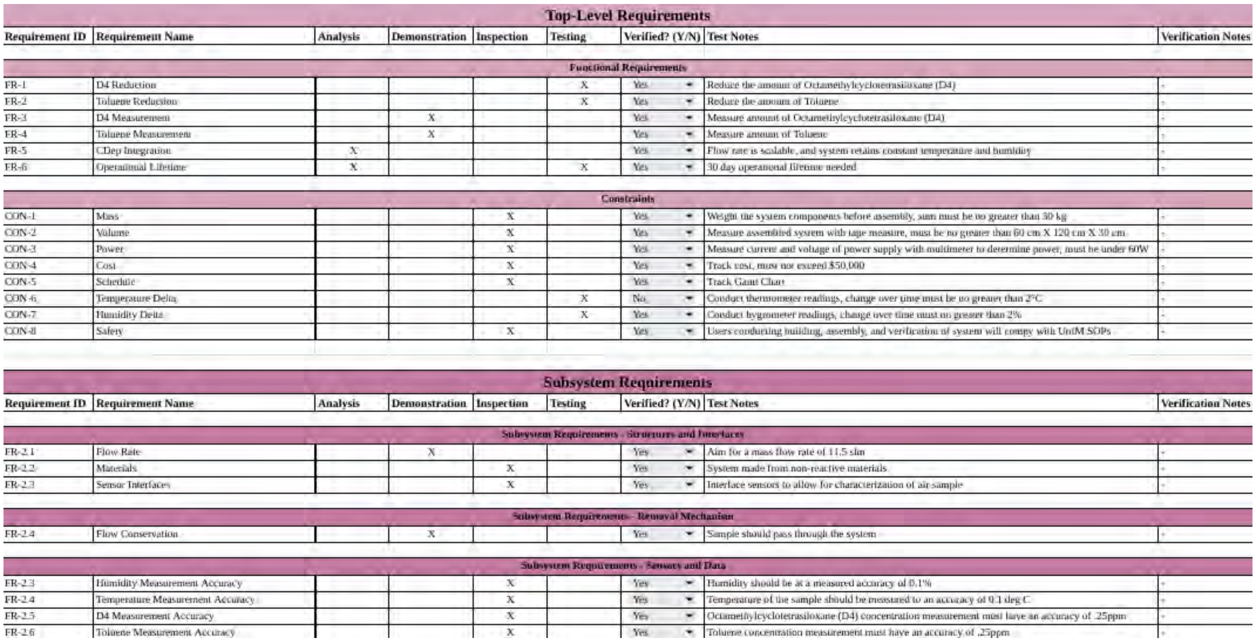
In order to determine if there is a leak system, a pressure sensor will determine a difference in pressure over time. If a dip in pressure is observed, we will know there is a leak that needs to be fixed. We set up a pressure decay test with our original system to confirm that the system was leak-proof. The sensor was threaded corresponding with FR2.5 and measured absolute pressure corresponding with FR1.2. The pressure sensor used was the Corrosion-Resistant Pressure and Vacuum Gauge, an analog-based dial that measures absolute pressure and can be integrated into the system via a custom, 1/4-inch threaded flange in the first sensor manifold. This pressure sensor proved to be incredibly useful during our static tests to identify leaks in our system.

7 Testing and Results

7.1 Testing Plan

The setup of our testing procedure began with setting up all appropriate values and purging the system with N_2 gas to clean it and flush out any particulates that may have gotten into our system during troubleshooting and maintenance and any VOCs that may have been introduced during the setup. Then, we prepared the VOC mixture for bubbling consisting of 1 μL of Toluene and 1 μL of D4 to a 100 mL volume of deionized water. We then placed this mixture into our system so that we could bubble its gaseous form into the VRE. We ran N_2 gas through the system both when the UV light was on and when it was off and recorded the data captured by our PID and temperature and humidity sensor. To wrap up the test, we purged the system with N_2 gas again until the PID recorded a 0 ppm concentration of VOCs.

7.2 Verification and Validation



Top-Level Requirements

Requirement ID	Requirement Name	Analysis	Demonstration	Inspection	Testing	Verified? (Y/N)	Test Notes	Verification Notes
Functional Requirements								
FR-1	D4 Reduction				X	Yes	Reduce the amount of Octamethylcyclotetrasiloxane (D4)	-
FR-2	Toluene Reduction				X	Yes	Reduce the amount of Toluene	-
FR-3	D4 Measuremen		X			Yes	Measure amount of Octamethylcyclotetrasiloxane (D4)	-
FR-4	Toluene Measuremen		X			Yes	Measure amount of Toluene	-
FR-5	CDep Integration	X				Yes	Flow rate is scalable, and system retains constant temperature and humidity	-
FR-6	Operational Lifetime	X			X	Yes	30 day operational lifetime needed	-
Constraints								
CON-1	Mass			X		Yes	Weight the system components before assembly, sum must be no greater than 30 kg	-
CON-2	Volume			X		Yes	Measure assembled system with tape measure, must be no greater than 60 cm X 120 cm X 30 cm	-
CON-3	Power			X		Yes	Measure current and voltage of power supply with multimeter to determine power, must be under 60W	-
CON-4	Cost			X		Yes	Track cost, must not exceed $50,000	-
CON-5	Schedule			X		Yes	Track Gantt Chart	-
CON-6	Temperature Delta				X	No	Conduct thermometer readings, change over time must be no greater than 2°C	-
CON-7	Humidity Delta				X	Yes	Conduct hygrometer readings, change over time must no greater than 2%	-
CON-8	Safety			X		Yes	Users conducting building, assembly, and verification of system will comply with UofM SOPs	-

Subsystem Requirements

Requirement ID	Requirement Name	Analysis	Demonstration	Inspection	Testing	Verified? (Y/N)	Test Notes	Verification Notes
Subsystem Requirements - Structures and Interfaces								
FR-2.1	Flow Rate		X			Yes	Aim for a mass flow rate of 11.5 slm	-
FR-2.2	Materials			X		Yes	System made from non-reactive materials	-
FR-2.3	Sensor Interfaces			X		Yes	Interface sensors to allow for characterization of air sample	-
Subsystem Requirements - Removal Mechanism								
FR-2.4	Flow Conservation		X			Yes	Sample should pass through the system	-
Subsystem Requirements - Sensors and Data								
FR-2.3	Humidity Measurement Accuracy			X		Yes	Humidity should be at a measured accuracy of 0.1%	-
FR-2.4	Temperature Measurement Accuracy			X		Yes	Temperature of the sample should be measured to an accuracy of 0.1 deg C	-
FR-2.5	D4 Measurement Accuracy			X		Yes	Octamethylcyclotetrasiloxane (D4) concentration measurement must have an accuracy of .25ppm	-
FR-2.6	Toluene Measurement Accuracy			X		Yes	Toluene concentration measurement must have an accuracy of .25ppm	-

Figure 23: Requirement verification and validation

Top-level system and subsystem requirements were verified through analysis, demonstration, inspection, and testing. All of the stakeholder's requirements have been met and verified.

7.3 Results

After extensive experimentation throughout the testing process, we were able to compile enough data to plausibly conclude that our VRE system removes VOCs. We showed this via two metrics: decaying VOC concentration and the creation of carbon monoxide. Further temperature and humidity data can be found in the appendix.

Figure 24 consists of two graphs showing the CO and VOC concentrations, respectively, throughout two hours of testing, both with and without the UV light being powered. As shown in the top graph, there was a large spike in CO concentrations when the UV light was turned on around the 1800-second mark, signifying that the reaction was successfully occurring. There is also a slight increase in CO concentration when the UV light is not on, which we did not expect. This could be due to unforeseen byproducts of certain components of our system, but we will need further testing to fully determine this.

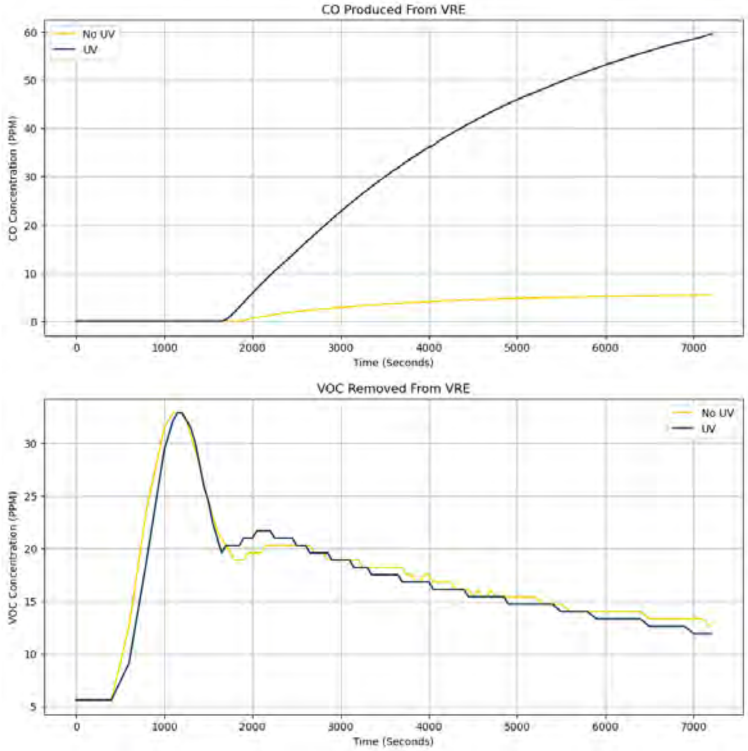


Figure 24: Data visualized

Looking at the bottom graph, we see that the VOC concentration increases with and without UV light before plateauing at 34 ppm and beginning to drop. This drop is likely representative of the dispersion of VOC throughout the system and a potential loss due to small imperfections in our airtight seals. The bell-like curve is abruptly disrupted at around 1800 seconds, the same point at which CO begins to be read by our sensor. At this mark, the VOC concentrations begin to rise before plateauing again, slightly higher with the UV light on than off. After the plateau, the concentrations begin to drop once again. We can directly compare the removal of VOCs with and without the UV light after this second peak. By comparing the values at the second VOC peak to the final values recorded at the two-hour mark, we found that the UV light removed 27.27% more VOCs in testing than when the test was run without the UV light. This, combined with a 1003% increase in CO concentration, is enough for us to conclude that the process of using photocatalytic oxidation as a VOC removal element can be viable, although further iterations and experimentation of our system will be required.

8 Testing Faults

8.1 Air Pump

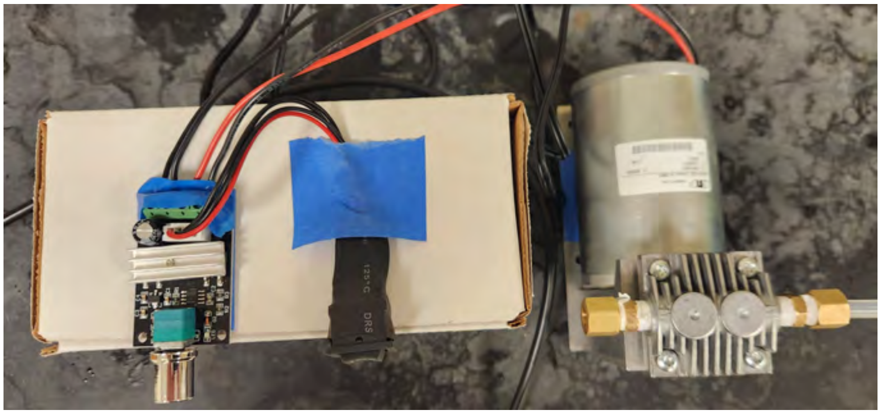


Figure 25: Air pump

During testing, we noticed that when we introduced VOCs into the system, the concentration levels dropped drastically within minutes, even when the UV light was not on. We hypothesized that this dramatic drop in concentration levels was due to a leak in the system, and through unit testing, we identified the air pump as the main contributor to this problem. The air pump itself was not airtight and was in fact leaking air from our main system loop out into the surrounding atmosphere. We then hypothesized that this effect created a pressure differential between our system and the surrounding environment, allowing for air to seep in through micro-leaks, diluting the VOC concentration of the air in our loop. This testing fault caused our VOC concentration to drop off dramatically, in the first few minutes of testing—regardless of UV light activation.

8.1.1 Air Pump Leak Mitigation

To mitigate this issue with our air pump, we first began by removing the faulty component from our system. We then proceeded to perform a series of static tests with our pressure sensor integrated into the sensor manifold. Results from this test showed that without an air pump to keep the sample cycling through our system, air was seeping out of the VRE chamber and tubing components through small micro leaks, undetectable by our numerous soap leak tests. We identified that the main leak in the system came from our PID cradle, which was the only place where soap leak tests weren't applicable, due to risks of the soapy solution interfering with sensor wires and electronic components. Our workaround to this had us remove the custom cradle from our system completely. A hole was bored into a blank flange, which was then attached using gaskets and bolts to one of the ends of the cross-shaped structure of the manifold. The PID rested inside the cross with no cradle, and the wires fed out of the manifold through the small hole created in the flange. This hole was then Torr-sealed, allowing us to conduct another static pressure decay test. The results of this new pressure decay showed that the system held pressure for a significantly longer time (on the order of hours rather than minutes) and that we could still read VOC concentration from our PID. The final architecture of this flange system resembled the integration of the wires for the UV light very closely, as is discussed in section 5.3 of this report. In mitigating this issue, we were now able to run full system tests with little to no air leakage.

8.2 Bubbling Procedure

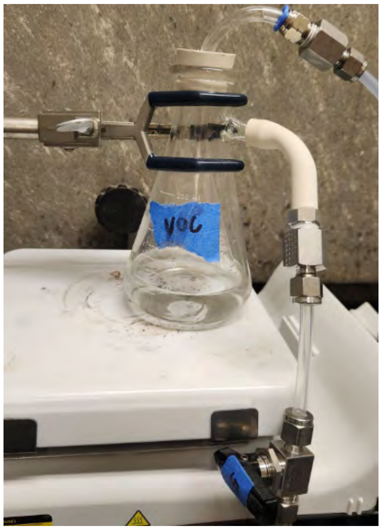


Figure 26: VOC bubbler

When introducing the VOCs into our system, we initially began by bubbling a 100% VOC solution by looping air through the top tube and into the bottom tube. This resulted in liquid VOC being thrown into the system, oversaturating our PID and requiring us to recalibrate.

8.2.1 Oversaturation Mitigation

We decided to incorporate the VOCs into our system without bubbling, but instead by blowing N_2 through only the bottom tube into a diluted VOC mixture. This mixture consisted of 1 μL of Toluene and 1 μL of D4 added to 100 mL of deionized water. The new solution was allowed to diffuse into the N_2 in the closed loop system via the CO sensor fan and then cut off when we reached our goal concentration. By introducing a diluted mixture of VOCs, we were able to keep the concentrations of Toluene and D4 low enough for our PIDs to read.

8.3 System Leaks

Despite initial soap tests, leaks were persistent in our system; we picked up a mass flow differential with our rotameters at the beginning and end of our system. We discerned several issues that would combine to cause this leaking. The Swagelok fittings are only designed to be used once, but we were forced to reuse some on multiple occasions. Additionally, when we were troubleshooting we had to undo and redo many fittings, which could have caused imperfect tightening. We also suspected the PID cradle-to-flange connection and the CO sensor of leaking due to the complexity of their integrations.

8.3.1 System Leak Mitigation

To decrease the risk of micro leaks from joints that we couldn't detect with our soap leak tests, we minimized the number of Swagelok fittings in our system. Furthermore, we closed off the loop to the CO sensor and only opened it on certain occasions to get interval readings instead of continuous data. This way, we could still obtain sufficient CO readings while minimizing leaking. Finally, we modified our PID integration to remove the cradle which we found to be the cause of major leaking due to the difference in materials of the cradle and the flange it is integrated with. Instead, we used a quick-drying sealant to cover a hole through which we fed the wires of the PID. Though not as secure, the PID could still gather sufficient data to track VOC concentrations.

These mitigation strategies succeeded in decreasing leaking in our system and allowing pressure to be held for a much longer period of time. This enabled us to run longer tests to get more complete data. In the future, we hope to further mitigate these leaks such that our data can be more accurate and we can run longer, more comprehensive tests.

9 Project Management

9.1 Work Breakdown Structure

The work breakdown structure (WBS) for the VOC project is illustrated in the figure below. The WBS is largely organized across all four subteams and the project leadership as shown in level 2. Level 3 includes the high-level responsibilities of each group.

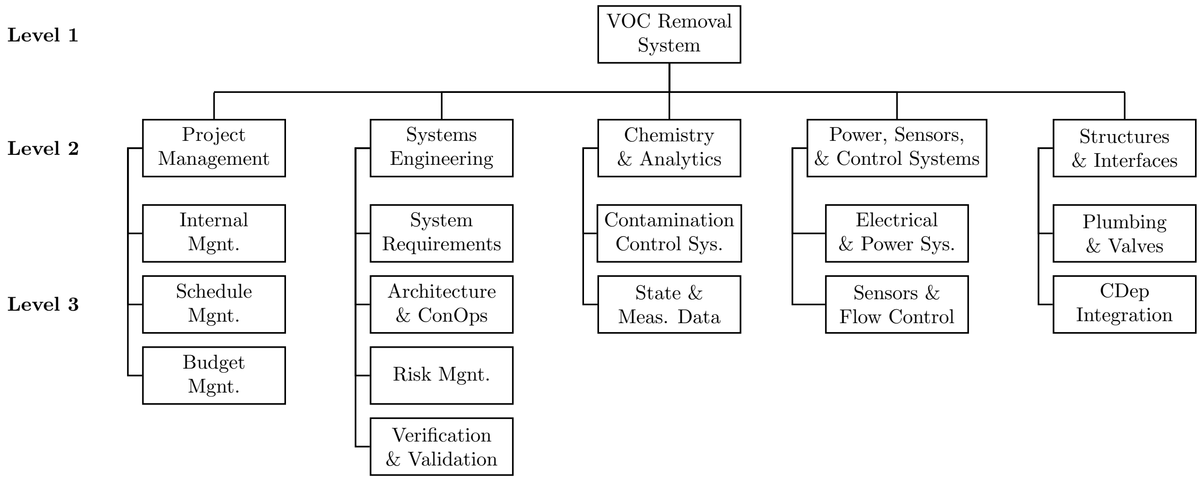


Figure 27: Work breakdown structure for VOC project.

9.2 Project Schedule

With a complex project, such as this one, an important aspect that needs to be accounted for is the project schedule. The success of this project will be dependent on the ability of our team to stay on course with the project schedule that has been predetermined.

There were key dates that our team ensured to abide by, and those dates are listed below:

- **October 19, 2023:** Requirements and System Definition Review
- **December 1, 2023:** Preliminary Design Review
- **February 13, 2024:** Critical Design Review
- **April 4, 2024:** Progress Checkpoint Review

- **May 6, 2024:** Project Completion and Evaluation

Our team designed a Gantt chart so that we could have the key milestones and dates depicted in an easy-to-view manner.

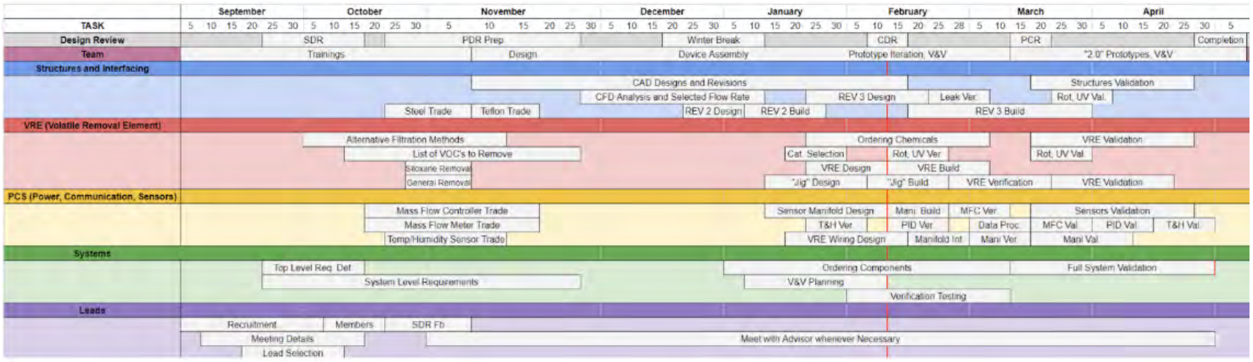


Figure 28: Gantt chart of timeline

The Gantt chart is broken down into 7 sub-tasks which are the following:

- Design Review
- Team
- Structures and Interfacing
- VRE (Volatile Removal Element)
- PCS (Power, Communication, Sensors)
- Systems
- Leads

Under each sub-task, there are various tasks listed underneath with the estimated time each should take. To note, winter break has been scheduled into the Gantt chart due to the majority of project team members being unable to meet in person and work on the project.

9.3 Project Cost

The cost for this project is a limiting factor that will define what materials our team will be able to utilize. The preliminary budget allocation is that of $47,245.00.

The budget breakdown is depicted below.

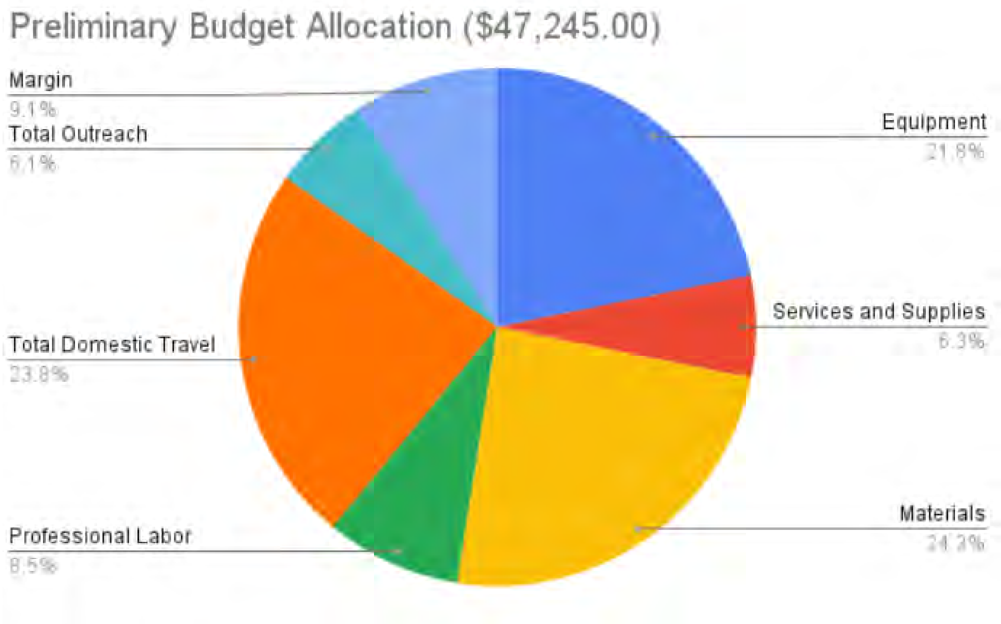
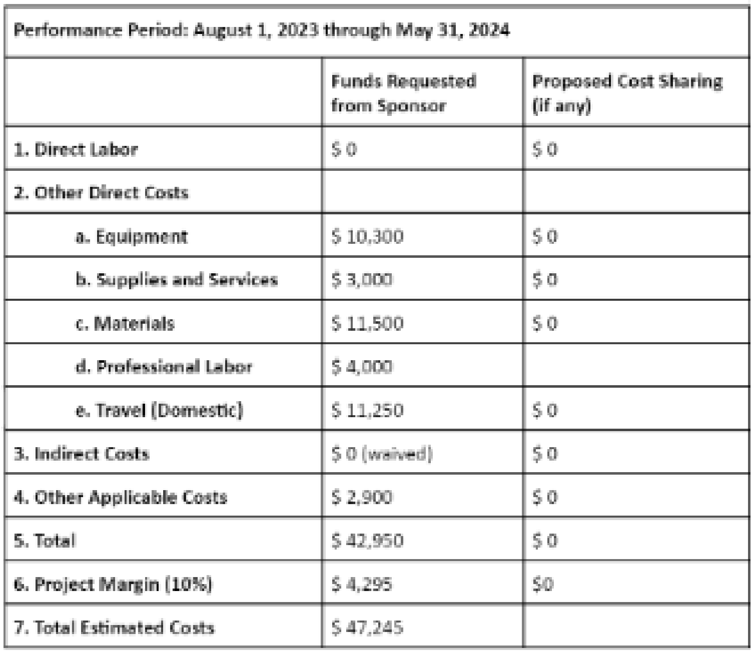


Figure 29: Preliminary budget allocation

Our team has also organized a table that outlines the funds we are requesting from the sponsor and what those funds will be allocated for the performance period that ranges from August 1, 2023, through May 31, 2024.



Performance Period: August 1, 2023 through May 31, 2024		
	Funds Requested from Sponsor	Proposed Cost Sharing (if any)
1. Direct Labor	$ 0	$ 0
2. Other Direct Costs		
a. Equipment	$ 10,300	$ 0
b. Supplies and Services	$ 3,000	$ 0
c. Materials	$ 11,500	$ 0
d. Professional Labor	$ 4,000	
e. Travel (Domestic)	$ 11,250	$ 0
3. Indirect Costs	$ 0 (waived)	$ 0
4. Other Applicable Costs	$ 2,900	$ 0
5. Total	$ 42,950	$ 0
6. Project Margin (10%)	$ 4,295	$0
7. Total Estimated Costs	$ 47,245	

Table 3: Project costs

To note, our team decided to go with a 10% cost margin.

9.4 Risk Analysis

Risk analysis involves a systematic process of identifying, assessing, and managing potential risks associated with space missions. The goal is to enhance mission success by understanding and mitigating potential challenges. The process typically includes:

- Risk Identification: Identifying potential events or conditions that could impact mission objectives. This involves considering technical, schedule, cost, and other factors.
- Risk Assessment: Evaluating the likelihood and consequences of identified risks. This step involves quantifying the probability and potential impact of each risk.
- Risk Mitigation: Developing strategies to minimize or eliminate identified risks. This may involve implementing design changes, contingency plans, or other measures to reduce the likelihood or impact of risks.
- Risk Communication: Effectively communicating risk information to stakeholders, ensuring that decision-makers and team members are informed about potential challenges and mitigation strategies.
- Risk Monitoring and Control: Continuously monitoring and reassessing risks throughout the project lifecycle. Adjusting mitigation strategies as needed and maintaining awareness of evolving risks.

Risks were assigned a score between 1-5 for their probability and severity of occurring and plotted on a risk matrix to visualize the risks. This plot will be updated as the risks are mitigated.

A list of all identified risks, along with a brief description and categorization according to whether they are considered technical, cost, or schedule risks, as well as corresponding action to mitigate, watch, or accept the risk, is presented below in Table 9.4.

Risks				
Risk ID	**Risk Item Title**	**Risk Description**	**Category**	**Action**
1	UV bulb arcing	High-voltage arcing within the UV bulb assembly can lead to complete loss of power to the UV bulb	Technical	Mitigate
2	Insulating material arcing	Electrical arcing through insulating materials can degrade performance and potentially cause system failure	Technical	Mitigate
3	System leaking	Leaking in the system could happen due to poor connection and proper sealing during initial construction process	Technical	Mitigate
4	Catalyst coating deterioration	Over time, the catalyst coating on reactor surfaces may degrade, reducing efficiency	Technical	Mitigate
5	Maintenance of 3D printed parts	Over time, the material properties can degrade due to exposure to UV light, heat, moisture, or chemicals, affecting the structural integrity and performance of the parts.	Technical	Mitigate
6	Sensor calibration error	Inaccurate sensor calibration can provide faulty readings, leading to improper system operation	Technical	Mitigate

Risk ID	**Risk Item Title**	**Risk Description**	**Category**	**Action**
7	System contamination	Introduction of contaminants into the system can degrade components and cause failures.	Technical	Mitigate
8	Manufacturing error of CF flanges	Improperly manufactured CF flanges may not seal adequately, leading to leaks and potential contamination	Technical	Mitigate
9	Connector failure	Connector failure inhibits function of electrical or data harnessing	Technical	Mitigate
10	Pressure build up	Excessive build-up within the system can lead to leaks or mechanical failures	Technical	Mitigate
11	Purity of gases	Impurities in the gases used can change the expected chemistry inside the system	Technical	Mitigate
12	Outgassing	Outgassing from materials can introduce contaminants and degrade system environment	Technical	Mitigate
13	UV light operation	Failure of the UV light to operate can impact system efficiency	Technical	Accept
14	Flushing system	Inadequate flushing between tests can lead to cross-contamination and inaccurate results	Cost Schedule	Watch
15	Unpredicted chemical reactions	Unforseen chemical reactions between materials/gases can produce undesirable effects	Technical	Accept
16	Power supply failure	Failure supplying power to system	Technical	Mitigate

Table 4: List of all identified risks

9.5 Risk Mitigation Strategy

This section describes detailed mitigation strategies planned for nine of the selected top risks and presents burn-down charts for each risk along with a timeline of risk burn-down.

9.5.1 UV Bulb Arcing

The total risk of high-voltage (HV) arcing in the UV bulb of the VOC removal system has been decreased to a low risk. This was necessary because HV arcing could lead to a complete loss of power to the UV bulb. If that happened, the UV bulb would no longer be able to perform its critical function of VOC breakdown. This loss of VOC removal capability could then jeopardize the air quality and environmental control of the overall system, as the VOCs would no longer be effectively broken down and removed. The mitigation steps are organized below in Table 5. The burn-down chart representing this mitigation strategy is depicted below in Figure 30.

Date	**Likelihood**	**Consequence**	**Risk**	**Step #**	**Mitigation**
4/10/24	5	4	20	1	
4/14/24	4	4	16	2	Implement HV-resistant coatings and insulation on critical components in the UV bulb assembly.
4/18/24	3	4	12	3	Redesign UV bulb housing and power supply to increase HV arcing protection.
4/22/24	2	4	8	4	Test prototype UV bulb assembly under simulated HV arcing conditions. Identify and resolve issues.
4/26/24	2	3	6	5	Implement real-time HV arcing detection and automatic shutoff capabilities. Prevent cascading failures within VOC Removal system.
4/30/24	1	3	3	6	Provision for redundant UV bulb and power supply systems within the VOC removal system.

Table 5: UV Bulb risk mitigation steps

Further explanation of mitigation steps:

- The first mitigation step is to implement HV-resistant coatings and insulation on critical components within the UV bulb assembly, such as the electrodes, wiring, and power supply connections. This decreases the likelihood of HV arcing by protecting against dielectric breakdown.
- The second step is to redesign the UV bulb housing and power supply to increase the physical separation and insulation between HV components. This also decreases the likelihood by limiting the potential for arc formation.
- The third step is to test the prototype UV bulb assembly under simulated HV arcing conditions, such as high-voltage testing chambers. This allows identification and resolution of potential arcing issues before deployment.
- The fourth step is to implement real-time HV arcing detection and automatic shutoff capabilities for the affected UV bulb. This will mitigate the consequence of an arcing event by quickly isolating the problem and preventing cascading failures within the VOC removal system.
- The fifth step is to provision for redundant UV bulb and power supply systems within the VOC removal system. This reduces the overall impact, as the failure of one UV bulb or power supply will not jeopardize the entire VOC removal capability.

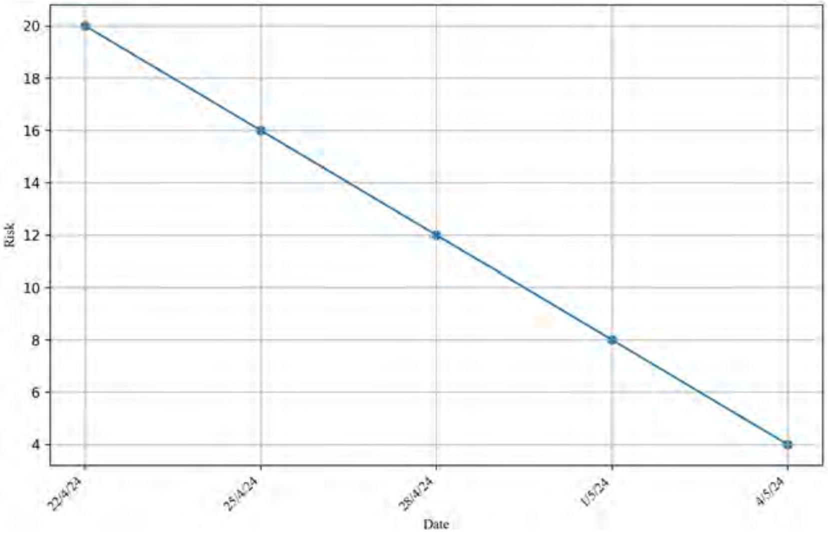


Figure 30: Burn-down chart of UV bulb arcing risk

9.5.2 Leakage

The total risk of a bit flip-induced failure has been decreased to a low risk. This is necessary as a single leak in the system could compromise all calibrations and measurements throughout the testing of the VOC chamber. The mitigation steps are organized below in Table 6. The burn-down chart representing this mitigation strategy is depicted below in Figure 32.

Date	Likelihood	Consequence	Risk	Step #	Mitigation
4/10/24	4	3	12	1	
4/10/24	3	3	9	2	ensure correct and new gasket usage
4/13/24	2	3	6	3	determine proportion torquing specs required for the system
4/15/24	2	2	2	4	ensure correct gasket tightening steps are followed. Tighten to ensure symmetrical gasket indentation throughout
5/4/24	2	2	2	5	run leak check after assembly

Table 6: Leakage risk mitigation steps

Further explanation of mitigation steps:

- The first mitigation step is to check proper gasket sizing and to ensure new out-of-package copper gaskets are only being used. It is important to not reuse prior gaskets as gaskets take the impression of CF flanges they are set in when they are first used. If improper tightening happens a gasket seal will imprint poorly and make any further resealing difficult. As such only new copper gaskets should be used during each assembly of the system.
- The second step is to ensure tightening happens in proportional torquing. If each bolt is not torqued to a specified amount, it is possible to tighten some bolts more than others thus creating uneven sealing on the copper gasket and allowing for leakage to slip through on a specific bolt or specific side of the CF flange.
- The third step is to ensure that the tightening of the copper gasket is symmetrical. This is achieved through tightening bolds opposite of each other at each turn and ensuring a ”star” pattern when each bolt is tightened. This allows for proper even pressure to be applied to all

sides of the gasket so one side is not tightened more than another allowing for a full complete seal around all sides.

- The fourth step is to leak-check systems before running. Leak checking by applying a soap and water mixture will help identify immediate leaks when running air through the system. Doing this initially ensures that materials and time are not wasted on testing before addressing situations that need to be fixed.

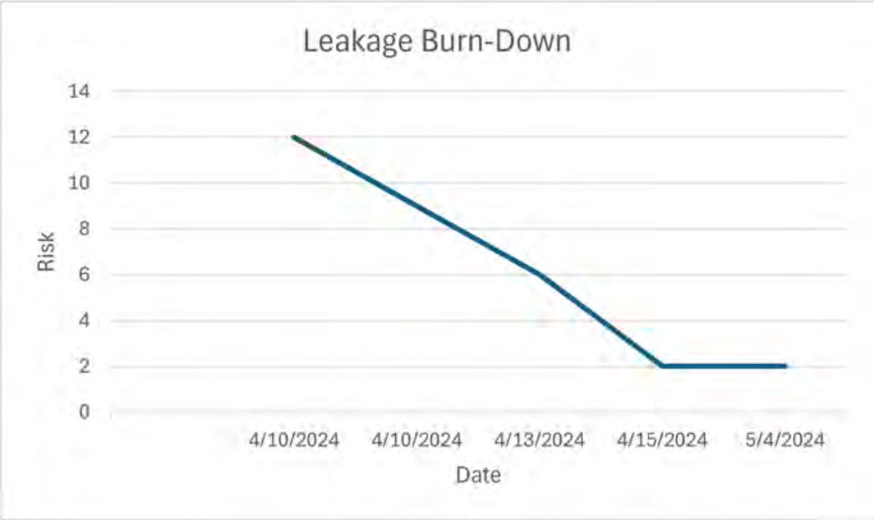


Figure 31: Burn-down chart of leakage risk

9.5.3 Soap Leak Testing

Figure 32: Soap bubble from soap leak test

We utilized soap leak testing to determine where VOCs were leaking from our system. To conduct the test, we made a solution of one part soap and three parts water and pressurized the system with air. We then used a paper towel soaked in this mixture to soap all the potential leak points of the system. If any leaks were present, then bubbles would form around the location of the leak. Once we identified these leaks, we made the necessary adjustments to minimize them.

9.5.4 System Contamination

The total risk of system contamination has been reduced to a low risk. This was crucial because any contaminants introduced into the system, whether particulates or chemical residues, could potentially degrade performance or cause complete failure of sensitive components.

The mitigation steps are organized below in Table 7. The burn-down chart representing this mitigation strategy is depicted below in Figure 33.

Date	Likelihood	Consequence	Risk	Step #	Mitigation
4/1/24	5	5	20	1	
4/8/24	4	5	15	2	Implement strict cleanroom protocols and procedures for all assembly, integration, and testing activities
4/15/24	2	4	11	3	Use high-efficiency particulate air (HEPA) filters and positive pressure environments
4/22/24	4	4	7	4	Conduct thorough cleaning procedures before final system integration
4/29/24	5	3	4	5	Implement redundant sealing mechanisms and contamination monitoring sensors

Table 7: System contamination risk mitigation steps

Further explanation of mitigation steps:

- The first step is to establish and enforce strict cleanroom protocols and procedures for all assembly, integration, and testing activities involving the system. This reduces the likelihood of contaminants being introduced.
- The second step is to utilize high-efficiency particulate air (HEPA) filters and positive pressure environments in the cleanrooms and work areas. This further decreases the likelihood of particulate contamination.
- The third step is to conduct thorough cleaning procedures on all components and subsystems before final integration. This removes any residual contaminants that may have been introduced earlier.
- The fourth step is to implement redundant sealing mechanisms, such as gaskets, O-rings, and protective covers, to prevent contaminant ingress after final assembly. This reduces the consequence of any residual contamination.
- The fifth step is to incorporate contamination monitoring sensors within the system to detect any contaminants that may have found their way in despite the other mitigation measures. This allows for early detection and potential corrective actions, further reducing the consequences.

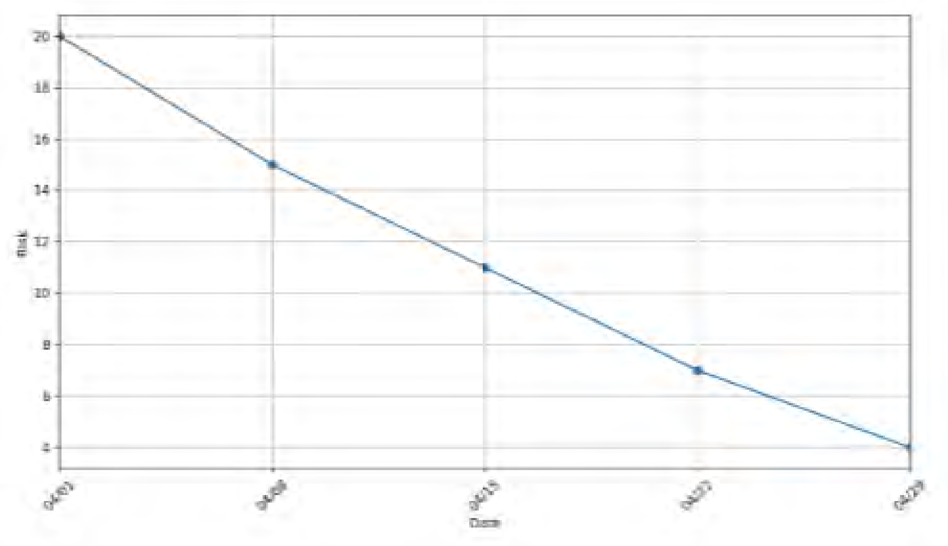


Figure 33: Burn-down chart of system contamination risk

9.5.5 Sensor Calibration Error

The total risk of sensor calibration error in the VOC system has been decreased to a low risk. This is crucial to ensure that measurements taken during operation can be used to accurately assess the performance of the VOC removal system. If the sensors are improperly calibrated, it will impact the ability to measure a delta of concentrations across the removal system, making a system performance characterization inaccurate and potentially misleading. It could also affect the temperature and humidity measurements, potentially leading the team to believe the temperature/humidity control requirements were met when they were not, or vice versa. The mitigation steps are organized below in Table 8. The burn-down chart representing this mitigation strategy is depicted below in Figure 34.

Date	**Likelihood**	**Consequence**	**Risk**	**Step #**	**Mitigation**
4/12/24	5	4	20	1	
4/18/24	4	4	16	2	Establish detailed calibration test procedures
4/24/24	3	3	9	3	Conduct regular calibration tests
4/30/24	2	2	4	4	Extensive documentation of calibration tests and sensor readings
5/4/24	1	2	2	5	Calibration equipment maintenance

Table 8: Sensor calibration error risk mitigation steps

Further explanation of mitigation steps:

- The first mitigation step is to create detailed, standardized calibration procedures for each sensor so that each step and all required equipment are clearly defined. The procedure should adhere to industry calibration standards like ISO 17025. This reduces the likelihood that errors will be made during the calibration process.
- The second step is to conduct regularly scheduled calibration tests throughout the life cycle of the system to ensure that the sensors are kept in proper operating condition. Consistent calibration will help reduce the effects of sensor drift, reducing the likelihood and impact of initial calibration errors.

- The third step is to extensively document all calibration tests and sensor readings. The process of documentation will help to catch errors after they happen, reducing the likelihood and impact of the risk.
- The fourth step is to conduct thorough maintenance of the calibration equipment. This will help reduce the likelihood of errors during the calibration process due to faulty equipment.

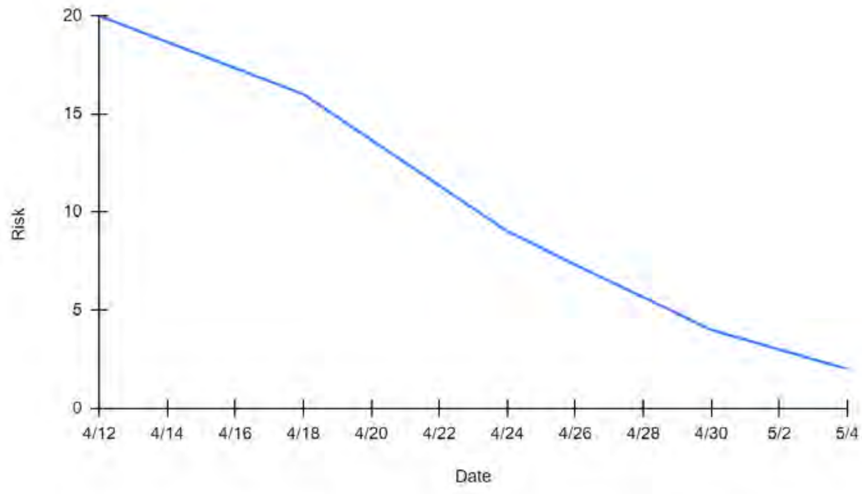
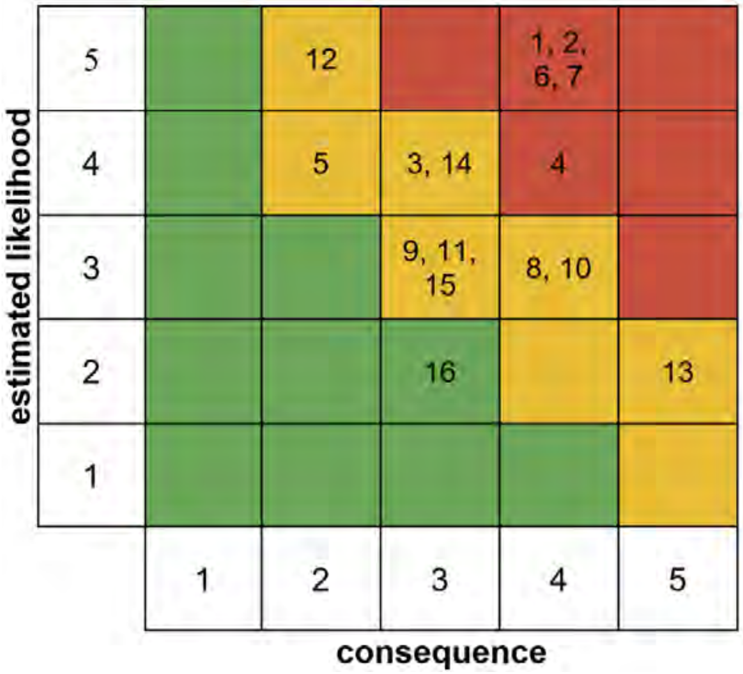


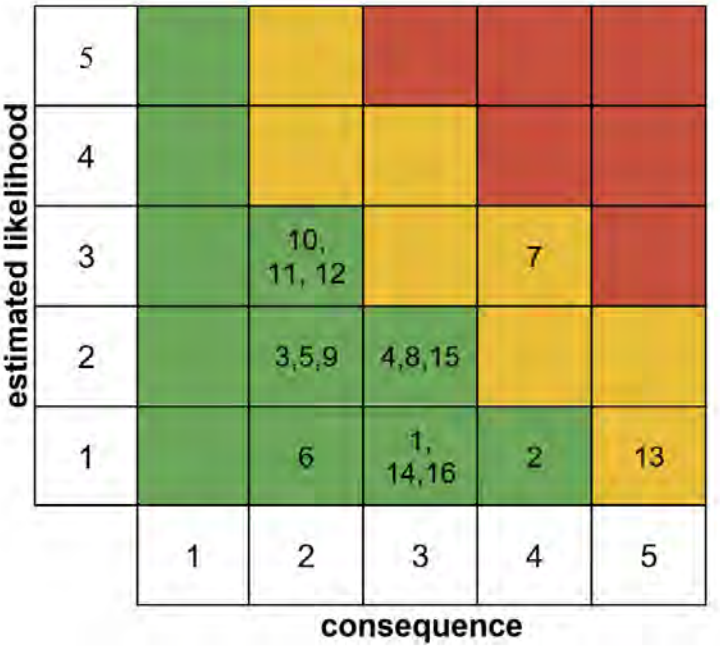
Figure 34: Burn-down chart of sensor calibration error risk

By the end of this project, all risks have been mitigated to a lesser risk value in our fever charts. No risks remain in the high-risk category.



	1	2	3	4	5
5	🟩	🟨 12	🟥	🟥 1, 2, 6, 7	🟥
4	🟩	🟨 5	🟨 3, 14	🟥 4	🟥
3	🟩	🟩	🟨 9, 11, 15	🟨 8, 10	🟥
2	🟩	🟩	🟩 16	🟨	🟨 13
1	🟩	🟩	🟩	🟩	🟨

Figure 35: Fever chart before mitigation



estimated likelihood 5	🟩	🟨	🟥	🟥	🟥
4	🟩	🟨	🟨	🟥	🟥
3	🟩	🟩 10, 11, 12	🟨	🟨 7	🟥
2	🟩	🟩 3,5,9	🟩 4,8,15	🟨	🟨
1	🟩	🟩 6	🟩 1, 14,16	🟩 2	🟨 13
	1	2	3	4	5
	consequence				

Figure 36: Fever chart after mitigation

10 Lessons Learned

This project has been an invaluable experience for not only project and subteam leads but also general members. Getting the chance to be with a project throughout the majority of its life cycle has taught us many things about engineering, leadership, teamwork, and scientific processes. Three major lessons have stuck out to us throughout the project.

10.1 Timing

At the beginning of the academic year, it was easy to think we had more than enough time for this project. However, as the months started to go by, we found that time was passing quicker than we thought. We underestimated how long it would take to outline the project, find involved members, and bring them up to speed. As a result, we did not start physically building anything until March of 2024. Furthermore, we underestimated lead times for components and how much time we would need to test our system, resulting in backups in putting the system together and getting data.

After the past year's experiences, we have found that always being one step ahead in planning is crucial to keeping the project moving. One needs to be aware of problems that may arise in the next stages of a project and be ready to deal with them. Additionally, setting harder deadlines for project stages can help move everyone along together, not just those in charge of the project. One of our biggest takeaways is that it is incredibly valuable to begin building and testing as early as possible, even if the system isn't the final prototype. Building multiple different system iterations can help sort out problems that may not be apparent in digital designing and brainstorming and help circulate new ideas.

10.2 Component Testing

While designing and building the system, it was difficult not to focus only on our system as a whole instead of honing in on the details of each subsystem. In theory, our system seemed to work well, but in practice, many small errors plagued each of our subsystems, causing system-wide problems and failures. This ultimately led to an inefficient use of time and likely caused some of our timing issues towards the end of the project.

Looking back, we acknowledge that unit testing our system from early on would have helped prevent these system-wide issues. By testing individual components and processes before we put them all together, it would have been easier to make these fixes. Additionally, such allocations among various team members would have allowed for more parallel work between subteams, streamlining the building and testing processes.

10.3 Data

As a result of the mid-year rescoping of the project, we did not put much thought into data simulation at the onset of the design process. Furthermore, we never anticipated how sources of error within our project could impact our gathered data. This led to difficulties with data analysis and system troubleshooting throughout the testing phase of the project.

In hindsight, it would have been beneficial to use process simulation software to visualize what our data was supposed to look like before we began testing. This would have allowed us to get a better understanding of what to expect from testing in advance. Additionally, this would have allowed us to anticipate errors and how they could impact our data. With this knowledge, we would have been better prepared for the testing phase of the project.

11 Future Work

We have made considerable progress on the project since the kick-off meeting in September 2023. We organized the project sub-teams and defined roles for each sub-team. In October 2023 we held and passed our System Definition Review with our NASA sponsors. We presented our initial level 1 requirements, analysis of alternatives, and project management practices. Based on the feedback from our sponsors and advisers we de-scoped the project to ensure the validation and verification test campaign can be executed by BLiSS. In early December 2023, we held and passed our Preliminary Design Review with NASA Ames project sponsors. We presented the updated project scope, level 1, and level 2 requirements. In addition, we presented the trade studies, performed by subteams, along with a REV.1 CAD design of the VOC removal system. From the feedback we received from sponsors and advisers after our PDR presentation, we revised and updated our functional requirements, finalized our trade studies, and started assembly on our REV.3 system design. Critical Design Review was passed with NASA sponsors and final engineering changes to our design were made, manufacturing, and verification and validation (V&V) test plans were completed. After completing our V&V we began organizing testing materials and spaces. In the week leading up to our final presentation, we ran tests and improved our system to gather the most accurate data we could. Unfortunately, due to leaks and other subsystem errors, we were unable to collect the data we would have liked to before our final presentation at NASA Ames.

11.1 Thermal Desorption for Gas Chromatography/Mass Spectrometry Analysis

To obtain more accurate data for the VOC concentrations in the air cycling through our system during and after testing, we propose the use of a desorption tube to gather samples. These samples can then be handed off to a professional lab to run a fuller analysis of not only VOC concentrations, but also temperature, humidity, or other potentially desired qualities of the air sample. To integrate this desorption tube, we recommend using another loop within the VRE loop that can be opened whenever a sample is desired. The tube should be made of glass, and utilize a Polydimethylsiloxane (PDMS) or Tenax® TA sorbent.

It is important to note that for the sorbent, due to the high (>100°C) boiling points of D4 and Toluene, it must be a porous polymer. Additionally, the sorbent should not be carbon-based so as not to add to the concentrations of CO produced by the system. This could cause confusion with the readings from the CO sensor. When integrating the desorption tube, it is important to be aware of the flow rate of air through the desorption tube; if the flow rate is not within the optimal ranges, it could break the tube or cause inaccurate readings. Therefore, we recommend using an additional rotameter in the desorption tube loop to make necessary adjustments to the airflow rate.

11.2 Catalyst Deactivation Solution

We noticed while testing that the PCO efficiency decreased after three days of irradiation, revealing a deactivation of TiO_2 catalyst accompanied by a yellowish coloration of the media. This indicates that the D4 concentration affected the photocatalytic degradation efficiency due to SiO_x buildup. To counteract this degradation, we propose using activated carbon as an absorbent filter in the system or treating the catalyst coating with an alkaline solution such as NaOH so that it can be cleaned of silica buildup. [2]

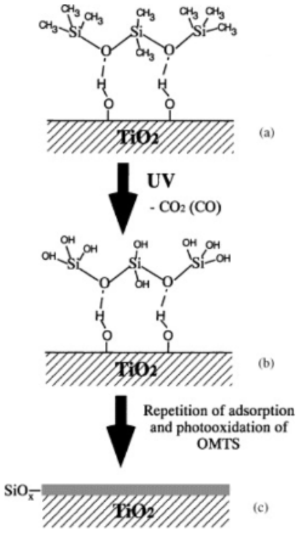


Figure 37: Accumulation of SiO_x

11.3 VRE Suggestions for Future Exploration

To maximize the amount of VOCs that the VRE can react on we suggest scaling the system up. We propose two potential methods to support this maximization: increasing the number of VREs in parallel to one another and increasing the length of the VRE. In both cases, increasing the VRE capacity would decrease the amount of cycle time needed to react on all of the VOCs. Though scaling the system would increase its volume and mass, it would allow VOC removal to occur at a faster rate. [9]

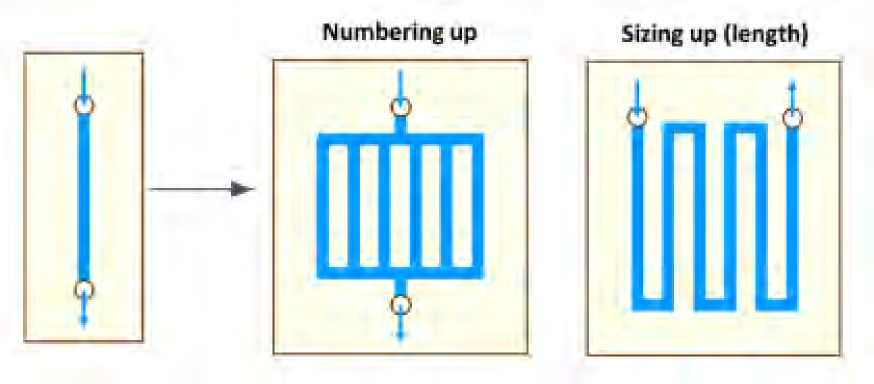


Figure 38: VRE scaling suggestions

For further testing, we propose the use of various VOCs beyond D4 and Toluene, such as Methanol, Ethanol, or Acetaldehyde. There are thousands of VOCs present in the ISS, so it would be valuable to test a PCO system on a wide variety of compounds. To react on these different VOCs, the PCO system would need to utilize various new catalysts.

References

[1] Pranav Jagtap et al. "Spacecraft Carbon Dioxide Deposition Full-Scale System: Design, Analysis, Build and Test". In: (2023). URL: https://hdl.handle.net/2346/94760.

[2] L. Lamaa et al. "Photocatalytic oxidation of octamethylcyclotetrasiloxane (D4): Towards a better understanding of the impact of volatile methyl siloxanes on photocatalytic systems". In: *Applied Catalysis B: Environmental* (2014).

[3] H. Marsh. *Activated Carbon*. 2006. URL: https://www.sciencedirect.com/book/9780080444635/activated-carbon.

[4] Lawrence K. Wang, Wei Lin, and Yung-Tse Hung. *Thermal Oxidation*. Ed. by Lawrence K. Wang, Norman C. Pereira, and Yung-Tse Hung. Totowa, NJ: Humana Press, 2004, pp. 347–367. ISBN: 978-1-59259-778-9. DOI: 10.1007/978-1-59259-778-9_8. URL: https://doi.org/10.1007/978-1-59259-778-9%5C_8.

[5] Yi Xing et al. "The Bibliometric Analysis and Review of the Application of Plasma in the Field of VOCs". In: *Catalysts* 12.2 (2022). ISSN: 2073-4344. DOI: 10.3390/catal12020173. URL: https://www.mdpi.com/2073-4344/12/2/173.

[6] Webster T. S. Devinny J. S. Deshusses M. A. "Biofiltration For Air Pollution Control". In: (2017). URL: https://doi.org/10.1201/9781315138275.

[7] Stephen O. Hay et al. "The Viability of Photocatalysis for Air Purification". In: *Molecules* 20.1 (2015), pp. 1319–1356. ISSN: 1420-3049. DOI: 10.3390/molecules20011319. URL: https://www.mdpi.com/1420-3049/20/1/1319.

[8] Gratson D. Lyons C. Turchi C. "Solving Widespread Low-Concentration VOC Air Pollution Problems: Gas-Phase Photocatalytic Oxidation Answers the Needs of Many Small Businesses." In: (1995). URL: https://www.osti.gov/biblio/58061.

[9] Zhengya Dong et al. "Scale-up of micro- and milli-reactors: An overview of strategies, design principles and applications". In: *Chemical Engineering Science* (2021).

APPENDICES

A Additional Data

All raw data gathered during our testing campaign for this project can be accessed in this Google Drive folder: https://shorturl.at/TiusH

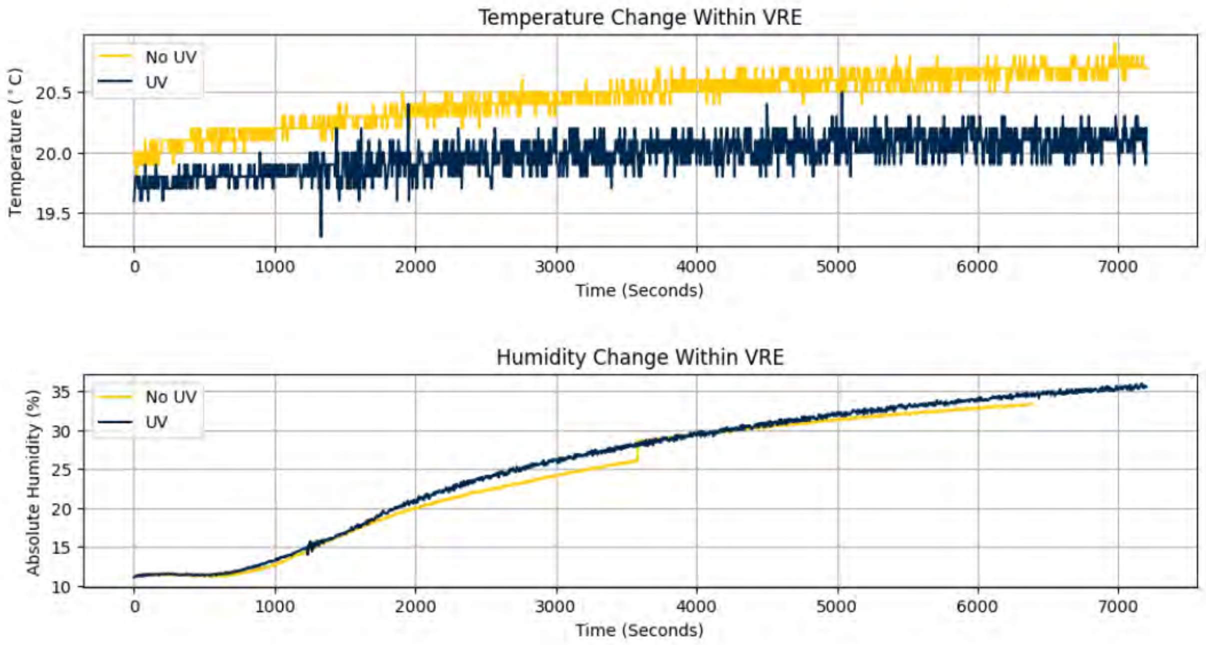
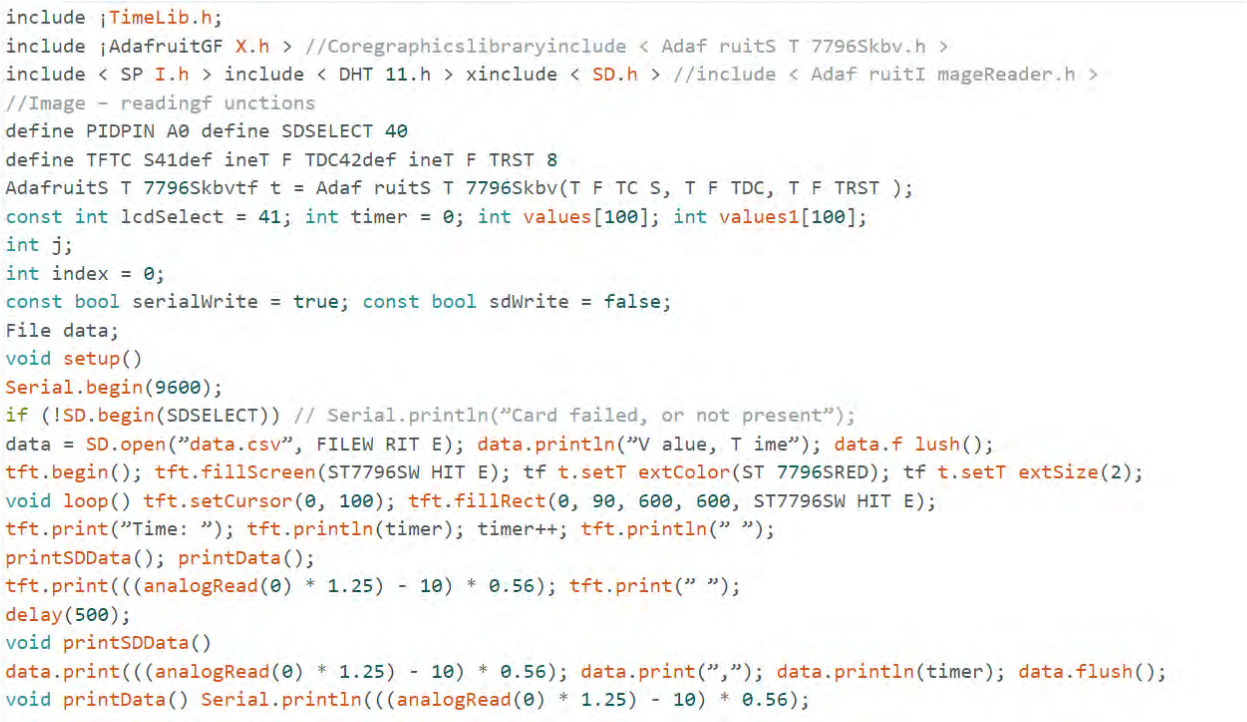


Figure 39: Temperature and humidity data visualized

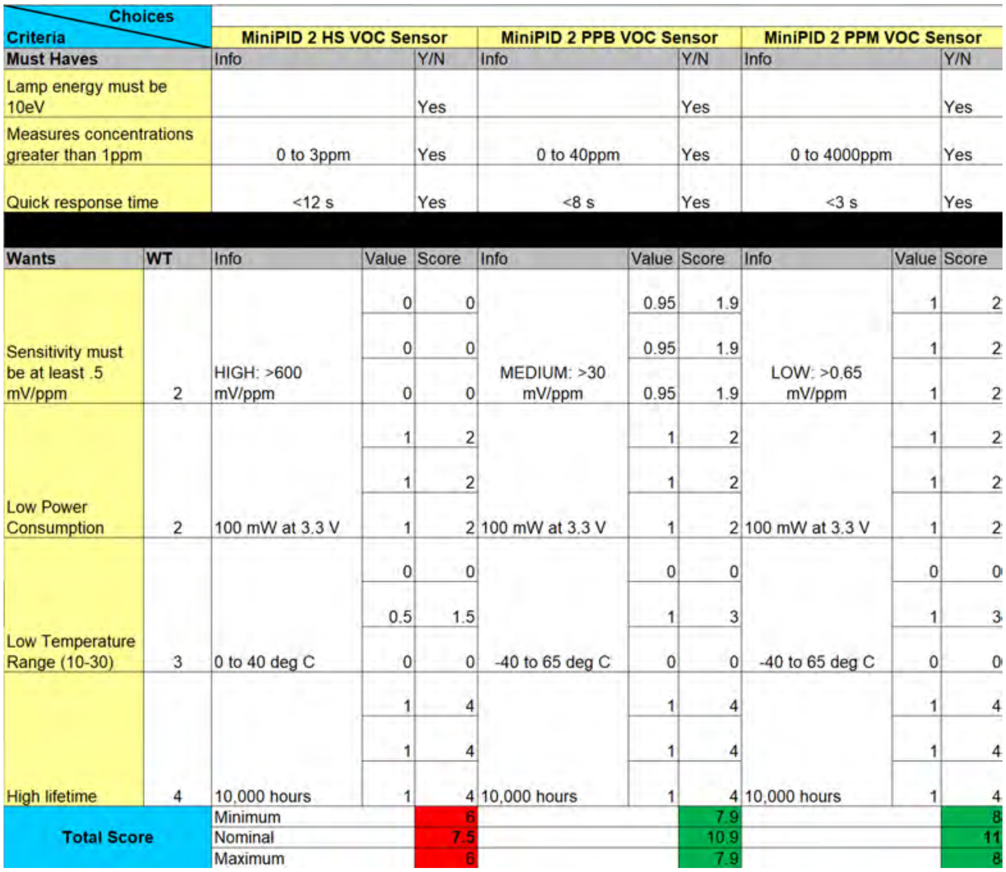
B Code



```
include ¡TimeLib.h;
include ¡AdafruitGF X.h > //Coregraphicslibraryinclude < Adaf ruitS T 7796Skbv.h >
include < SP I.h > include < DHT 11.h > xinclude < SD.h > //include < Adaf ruitI mageReader.h >
//Image - readingf unctions
define PIDPIN A0 define SDSELECT 40
define TFTC S41def ineT F TDC42def ineT F TRST 8
AdafruitS T 7796Skbvtf t = Adaf ruitS T 7796Skbv(T F TC S, T F TDC, T F TRST );
const int lcdSelect = 41; int timer = 0; int values[100]; int values1[100];
int j;
int index = 0;
const bool serialWrite = true; const bool sdWrite = false;
File data;
void setup()
Serial.begin(9600);
if (!SD.begin(SDSELECT)) // Serial.println(”Card failed, or not present”);
data = SD.open(”data.csv”, FILEW RIT E); data.println(”V alue, T ime”); data.f lush();
tft.begin(); tft.fillScreen(ST7796SW HIT E); tf t.setT extColor(ST 7796SRED); tf t.setT extSize(2);
void loop() tft.setCursor(0, 100); tft.fillRect(0, 90, 600, 600, ST7796SW HIT E);
tft.print(”Time: ”); tft.println(timer); timer++; tft.println(” ”);
printSDData(); printData();
tft.print(((analogRead(0) * 1.25) - 10) * 0.56); tft.print(” ”);
delay(500);
void printSDData()
data.print(((analogRead(0) * 1.25) - 10) * 0.56); data.print(”,”); data.println(timer); data.flush();
void printData() Serial.println(((analogRead(0) * 1.25) - 10) * 0.56);
```

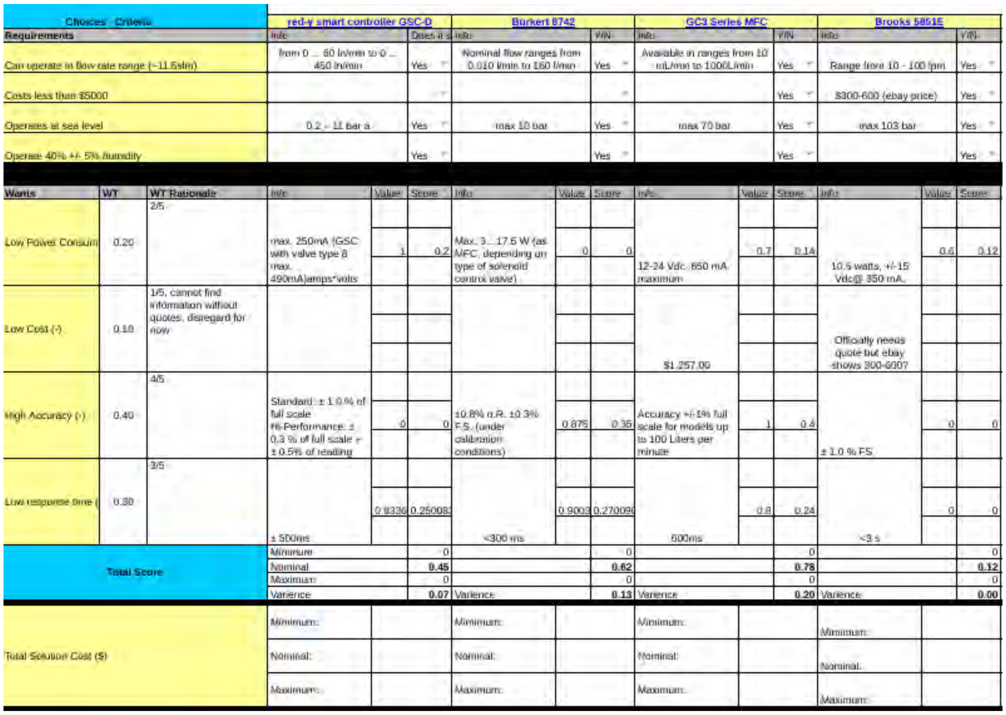
Figure 40: Code used to gather data, write to SD card, LCD screen, and serial output

C Trade Matrices



Criteria / Choices		MiniPID 2 HS VOC Sensor			MiniPID 2 PPB VOC Sensor			MiniPID 2 PPM VOC Sensor		
Must Haves		Info		Y/N	Info		Y/N	Info		Y/N
Lamp energy must be 10eV				Yes			Yes			Yes
Measures concentrations greater than 1ppm		0 to 3ppm		Yes	0 to 40ppm		Yes	0 to 4000ppm		Yes
Quick response time		<12 s		Yes	<8 s		Yes	<3 s		Yes
Wants	**WT**	Info	Value	Score	Info	Value	Score	Info	Value	Score
Sensitivity must be at least .5 mV/ppm	2	HIGH: >600 mV/ppm	0	0	MEDIUM: >30 mV/ppm	0.95	1.9	LOW: >0.65 mV/ppm	1	2
			0	0		0.95	1.9		1	2
			0	0		0.95	1.9		1	2
Low Power Consumption	2	100 mW at 3.3 V	1	2	100 mW at 3.3 V	1	2	100 mW at 3.3 V	1	2
			1	2		1	2		1	2
			1	2		1	2		1	2
Low Temperature Range (10-30)	3	0 to 40 deg C	0	0	-40 to 65 deg C	0	0	-40 to 65 deg C	0	0
			0.5	1.5		1	3		1	3
			0	0		0	0		0	0
High lifetime	4	10,000 hours	1	4	10,000 hours	1	4	10,000 hours	1	4
			1	4		1	4		1	4
			1	4		1	4		1	4
Total Score		Minimum		6			7.9			8
		Nominal		7.5			10.9			11
		Maximum		6			7.9			8

Figure 41: PID Trade Study



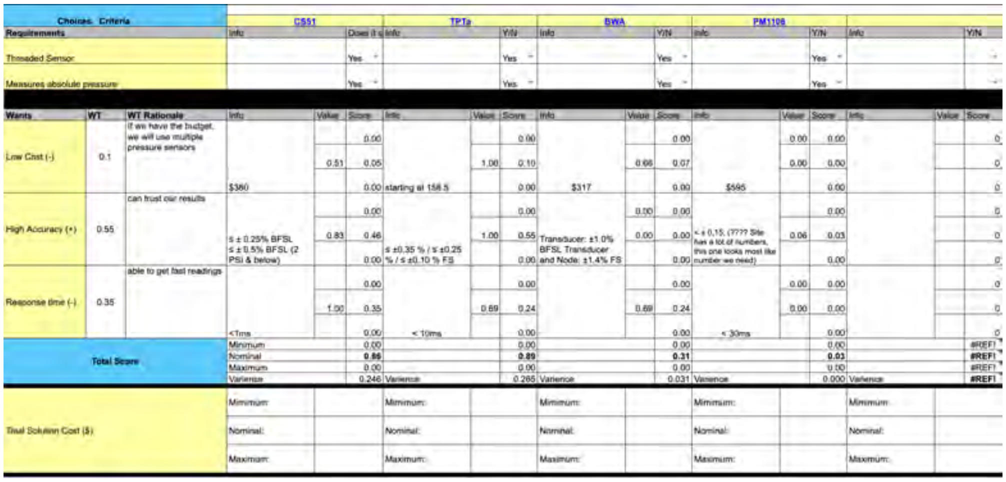
Choices Criteria	red-y smart controller GSC-D		Burkert 8742		GC3 Series MFC		Brooks 5851E	
Requirements	Info	Does it s	Info	Y/N	Info	Y/N	Info	Y/N
Can operate in flow rate range (~11.5slm)	from 0 ... 60 ln/min to 0 ... 450 ln/min	Yes	Nominal flow ranges from 0.010 l/min to 160 l/min	Yes	Available in ranges from 10 mL/min to 1000L/min	Yes	Range from 10 - 100 lpm	Yes
Costs less than $5000						Yes	$300-600 (ebay price)	Yes
Operates at sea level	0.2 - 11 bar a	Yes	max 10 bar	Yes	max 70 bar	Yes	max 103 bar	Yes
Operate 40% +/- 5% humidity		Yes		Yes		Yes		Yes

Wants	WT	WT Rationale	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Low Power Consum	0.20	2/5	max. 250mA (GSC with valve type 8 max. 490mA)amps*volts	1	0.2	Max. 3...17.5 W (as MFC, depending on type of solenoid control valve)	0	0	12-24 Vdc. 650 mA maximum	0.7	0.14	10.5 watts, +/-15 Vdc@ 350 mA.	0.6	0.12
Low Cost (-)	0.10	1/5, cannot find information without quotes, disregard for now							$1,257.00			Officially needs quote but ebay shows 300-600?		
High Accuracy (-)	0.40	4/5	Standard: ± 1.0 % of full scale Hi-Performance: ± 0.3 % of full scale + ± 0.5% of reading	0	0	±0.8% o.R. ±0.3% F.S. (under calibration conditions)	0.875	0.35	Accuracy +/-1% full scale for models up to 100 Liters per minute	1	0.4	± 1.0 % FS	0	0
Low response time (	0.30	3/5	± 500ms	0.8336	0.25008	<300 ms	0.9003	0.27009	600ms	0.8	0.24	<3 s	0	0

Total Score								
	Minimum	0		0		0		0
	Nominal	0.45		0.62		0.78		0.12
	Maximum	0		0		0		0
	Varience	0.07	Varience	0.13	Varience	0.20	Varience	0.00

Total Solution Cost ($)								
	Minimum:		Minimum:		Minimum:		Minimum:	
	Nominal:		Nominal:		Nominal:		Nominal:	
	Maximum:		Maximum:		Maximum:		Maximum:	

Figure 42: Mass Flow Controller Trade Study



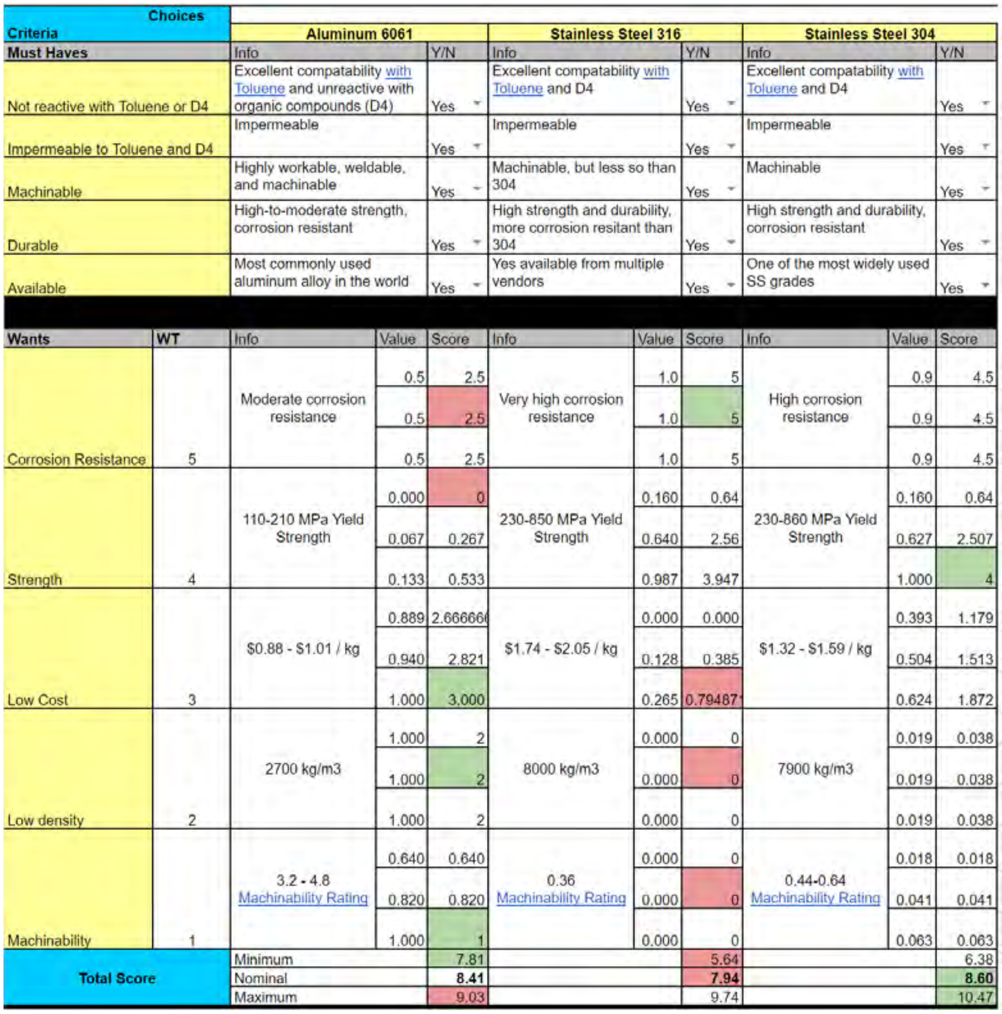
Choices Criteria	CS51		TPTa		BWA		PM1106			
Requirements	Info	Does it s	Info	Y/N	Info	Y/N	Info	Y/N	Info	Y/N
Threaded Sensor		Yes		Yes		Yes		Yes		
Measures absolute pressure		Yes		Yes		Yes		Yes		

Wants	WT	WT Rationale	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Low Cost (-)	0.1	If we have the budget, we will use multiple pressure sensors			0.00			0.00			0.00		0.00	0.00			0
				0.51	0.05		1.00	0.10		0.66	0.07		0.00	0.00			0
			$380		0.00	starting at 158.5		0.00	$317		0.00	$595		0.00			0
High Accuracy (+)	0.55	can trust our results			0.00			0.00		0.00	0.00			0.00			0
			≤ ± 0.25% BFSL ≤ ± 0.5% BFSL (2 PSI & below)	0.83	0.46		1.00	0.55	Transducer: ±1.0% BFSL Transducer and Node: ±1.4% FS	0.00	0.00	< ± 0.15, (???? Site has a lot of numbers, this one looks most like number we need)	0.06	0.03			0
					0.00	≤ ±0.35 % / ≤ ±0.25 % / ≤ ±0.10 % FS		0.00			0.00			0.00			0
Response time (-)	0.35	able to get fast readings			0.00			0.00			0.00		0.00	0.00			0
				1.00	0.35		0.69	0.24		0.69	0.24		0.00	0.00			0
			<1ms		0.00	< 10ms		0.00			0.00	< 30ms		0.00			0

Total Score										
	Minimum	0.00		0.00		0.00		0.00		#REF!
	Nominal	0.86		0.89		0.31		0.03		#REF!
	Maximum	0.00		0.00		0.00		0.00		#REF!
	Varience	0.246	Varience	0.265	Varience	0.031	Varience	0.000	Varience	#REF!

Total Solution Cost ($)										
	Minimum:		Minimum:		Minimum:		Minimum:		Minimum:	
	Nominal:		Nominal:		Nominal:		Nominal:		Nominal:	
	Maximum:		Maximum:		Maximum:		Maximum:		Maximum:	

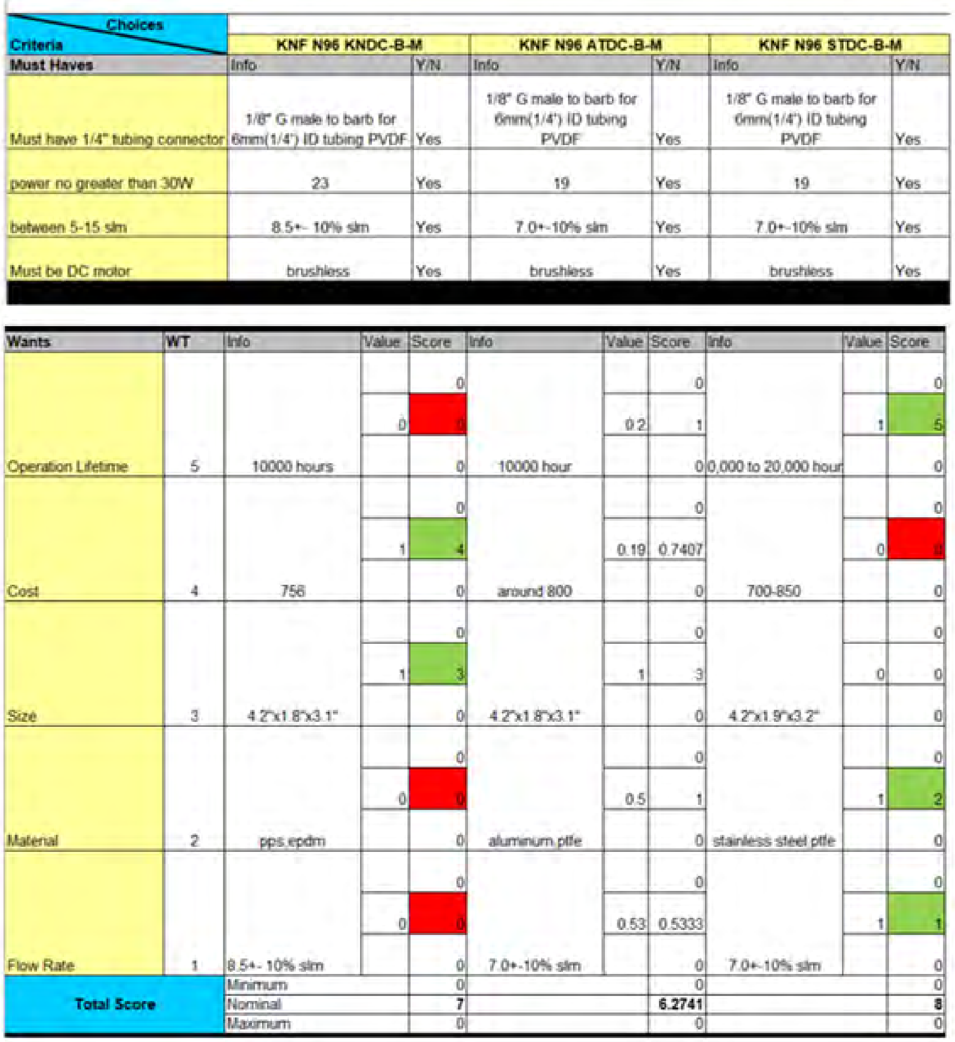
Figure 43: Absolute Pressure Sensor Trade Study



Choices Criteria	Aluminum 6061		Stainless Steel 316		Stainless Steel 304	
Must Haves	Info	Y/N	Info	Y/N	Info	Y/N
Not reactive with Toluene or D4	Excellent compatability with Toluene and unreactive with organic compounds (D4)	Yes	Excellent compatability with Toluene and D4	Yes	Excellent compatability with Toluene and D4	Yes
Impermeable to Toluene and D4	Impermeable	Yes	Impermeable	Yes	Impermeable	Yes
Machinable	Highly workable, weldable, and machinable	Yes	Machinable, but less so than 304	Yes	Machinable	Yes
Durable	High-to-moderate strength, corrosion resistant	Yes	High strength and durability, more corrosion resitant than 304	Yes	High strength and durability, corrosion resistant	Yes
Available	Most commonly used aluminum alloy in the world	Yes	Yes available from multiple vendors	Yes	One of the most widely used SS grades	Yes

Wants	WT	Info	Value	Score	Info	Value	Score	Info	Value	Score
Corrosion Resistance	5	Moderate corrosion resistance	0.5	2.5	Very high corrosion resistance	1.0	5	High corrosion resistance	0.9	4.5
			0.5	2.5		1.0	5		0.9	4.5
			0.5	2.5		1.0	5		0.9	4.5
Strength	4	110-210 MPa Yield Strength	0.000	0	230-850 MPa Yield Strength	0.160	0.64	230-860 MPa Yield Strength	0.160	0.64
			0.067	0.267		0.640	2.56		0.627	2.507
			0.133	0.533		0.987	3.947		1.000	4
Low Cost	3	$0.88 - $1.01 / kg	0.889	2.666666	$1.74 - $2.05 / kg	0.000	0.000	$1.32 - $1.59 / kg	0.393	1.179
			0.940	2.821		0.128	0.385		0.504	1.513
			1.000	3.000		0.265	0.79487		0.624	1.872
Low density	2	2700 kg/m3	1.000	2	8000 kg/m3	0.000	0	7900 kg/m3	0.019	0.038
			1.000	2		0.000	0		0.019	0.038
			1.000	2		0.000	0		0.019	0.038
Machinability	1	3.2 - 4.8 Machinability Rating	0.640	0.640	0.36 Machinability Rating	0.000	0	0.44-0.64 Machinability Rating	0.018	0.018
			0.820	0.820		0.000	0		0.041	0.041
			1.000	1		0.000	0		0.063	0.063
Total Score		Minimum		7.81			5.64			6.38
		Nominal		**8.41**			**7.94**			**8.60**
		Maximum		9.03			9.74			10.47

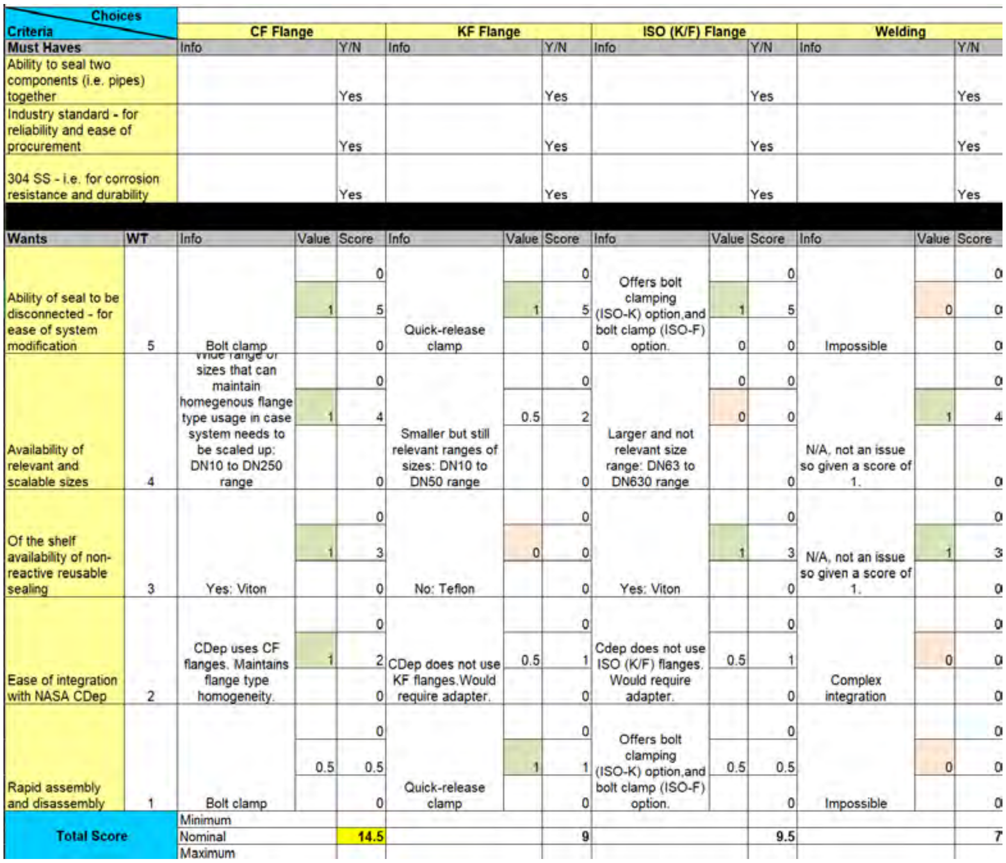
Figure 44: Materials Trade Study



Choices / Criteria	KNF N96 KNDC-B-M		KNF N96 ATDC-B-M		KNF N96 STDC-B-M	
Must Haves	Info	Y/N	Info	Y/N	Info	Y/N
Must have 1/4" tubing connector	1/8" G male to barb for 6mm(1/4") ID tubing PVDF	Yes	1/8" G male to barb for 6mm(1/4") ID tubing PVDF	Yes	1/8" G male to barb for 6mm(1/4") ID tubing PVDF	Yes
power no greater than 30W	23	Yes	19	Yes	19	Yes
between 5-15 slm	8.5+- 10% slm	Yes	7.0+-10% slm	Yes	7.0+-10% slm	Yes
Must be DC motor	brushless	Yes	brushless	Yes	brushless	Yes

Wants	WT	Info	Value	Score	Info	Value	Score	Info	Value	Score
Operation Lifetime	5	10000 hours		0	10000 hour		0	0,000 to 20,000 hour		0
			0	0		0.2	1		1	5
				0			0			0
Cost	4	756		0	around 800		0	700-850		0
			1	4		0.19	0.7407		0	0
				0			0			0
Size	3	4.2"x1.8"x3.1"		0	4.2"x1.8"x3.1"		0	4.2"x1.9"x3.2"		0
			1	3		1	3		0	0
				0			0			0
Material	2	pps,epdm		0	aluminum,ptfe		0	stainless steel ptfe		0
			0	0		0.5	1		1	2
				0			0			0
Flow Rate	1	8.5+- 10% slm		0	7.0+-10% slm		0	7.0+-10% slm		0
			0	0		0.53	0.5333		1	1
				0			0			0
Total Score		Minimum		0			0			0
		Nominal		**7**			**6.2741**			**8**
		Maximum		0			0			0

Figure 45: DC Pump Trade Study



Choices Criteria		CF Flange			KF Flange			ISO (K/F) Flange			Welding		
Must Haves		Info		Y/N	Info		Y/N	Info		Y/N	Info		Y/N
Ability to seal two components (i.e. pipes) together				Yes			Yes			Yes			Yes
Industry standard - for reliability and ease of procurement				Yes			Yes			Yes			Yes
304 SS - i.e. for corrosion resistance and durability				Yes			Yes			Yes			Yes
Wants	**WT**	Info	Value	Score	Info	Value	Score	Info	Value	Score	Info	Value	Score
Ability of seal to be disconnected - for ease of system modification	5	Bolt clamp		0	Quick-release clamp		0	Offers bolt clamping (ISO-K) option,and bolt clamp (ISO-F) option.		0	Impossible		0
			1	5		1	5		1	5		0	0
				0			0		0	0			0
Availability of relevant and scalable sizes	4	Wide range of sizes that can maintain homegenous flange type usage in case system needs to be scaled up: DN10 to DN250 range		0	Smaller but still relevant ranges of sizes: DN10 to DN50 range		0	Larger and not relevant size range: DN63 to DN630 range	0	0	N/A, not an issue so given a score of 1.		0
			1	4		0.5	2		0	0		1	4
				0			0			0			0
Of the shelf availability of non-reactive reusable sealing	3	Yes: Viton		0	No: Teflon		0	Yes: Viton		0	N/A, not an issue so given a score of 1.		0
			1	3		0	0		1	3		1	3
				0			0			0			0
Ease of integration with NASA CDep	2	CDep uses CF flanges. Maintains flange type homogeneity.		0	CDep does not use KF flanges.Would require adapter.		0	Cdep does not use ISO (K/F) flanges. Would require adapter.		0	Complex integration		0
			1	2		0.5	1		0.5	1		0	0
				0			0			0			0
Rapid assembly and disassembly	1	Bolt clamp		0	Quick-release clamp		0	Offers bolt clamping (ISO-K) option,and bolt clamp (ISO-F) option.		0	Impossible		0
			0.5	0.5		1	1		0.5	0.5		0	0
				0			0			0			0
Total Score		Minimum											
		Nominal		14.5			9			9.5			7
		Maximum											

Figure 46: Assembly Connection Type Trade study