MARRS
Martian Airborn Residue Remediation System: Dust Mitigation on Mars via Electrostatic Precipitation

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments.

1 Introduction

Background

Dust mitigation is a key component of successful human exploration on Mars. Martian regolith, or dust, presents unique hazards to human health. It contains toxic compounds and when kicked up by a dust storm, it can remain suspended in the air indefinitely due to Mars' low gravity and thin atmosphere (Levy, 2022). Not only is it a hazard to human health, but it can also reduce the longevity of equipment by entering internal components and causing damage (Wang et al, 2025). As humans colonize Mars, systems need to be in place to mitigate these hazards caused by Martian dust.

The Martian Airborne Residue Remediation System (MARRS) is designed to prevent dust from entering habitats, labs, or other structures where crew members may not be wearing protective suits or breathing apparatus and/or where equipment that is sensitive to dust damage will be placed. Much like a mudroom that we use on Earth, MARRS consists of a chamber that attaches to the entryways of the habitats and structures that require dust mitigation measures. Unlike an Earth-based mudroom, however, MARRS contains a wind tunnel, an electrostatic precipitator (EP), a channel for dust removal, and moving doors which work together to remove the dust from the chamber and the objects and crew within. Once the dust has been removed, the crew can safely move through to the habitat without bringing harmful levels of Martian dust with them.

Electrostatic precipitation was chosen as the primary method of dust removal. It works by passing dust particles through a charged mesh. The particles acquire that charge and then flow towards plates of opposite charge. The particles stick to the plates, effectively containing them. A wind tunnel was designed to create the flow needed to remove dust particles from cargo and crewmembers and pass them through to the EP.

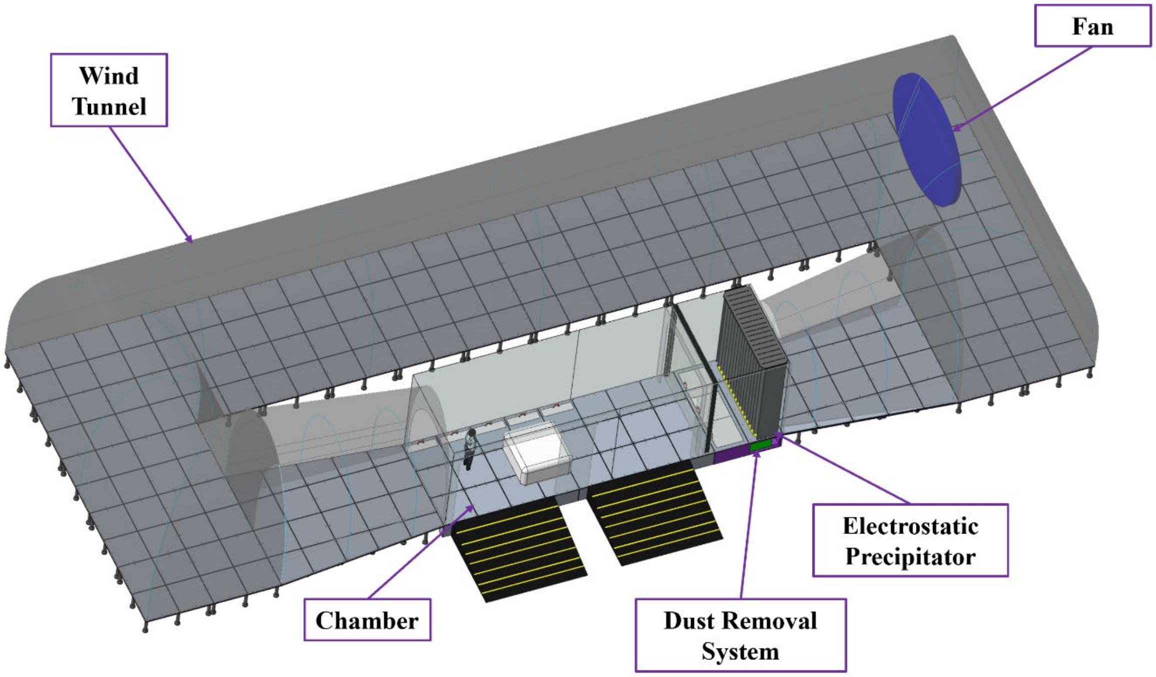


Figure 1: MARRS, isometric view

MARRS, as shown in Figure 1, is approximately 28 meters long and 10 meters wide. The wind tunnel is four meters tall and necks down to the height of the chamber – three meters. The chamber itself has two entrances, not including passageways to the wind tunnel. These entrances allow for different configurations with attachments to other structures. One entrance should be the loading point for contaminated cargo and crewmembers. The other entrance would be connected to clean structures, such as pressurized living habitats or laboratories. This design allows for the entrances to connect directly to the airlock of a habitat or to a tunnel that can route to a structure farther away. The entrances are identical, so the final configuration would depend on the colony's layout.

This project was inspired by NASA's Revolutionary Aerospace Systems Concepts Academic Linkage (RASC-AL) competition. RASC-AL is a design competition in which students select a theme and design accordingly. The Advanced Science Missions and Technology Demonstrators for Human-Mars Precursor Campaign theme was chosen for our mission concept. The first requirement of this theme was to reduce technology/operational risks to crew. MARRS fulfills this requirement by reducing the potential exposure human crew will have to Martian dust and by protecting equipment. Mitigating the human health risk associated with dust inhalation not only helps safeguard crew health but it also can eliminate operational slowdowns due to crew illness or injury caused by the dust. By preventing dust contamination of equipment meant to operate indoors, MARRS also reduces the risk of equipment malfunction and its associated mission objective risk.

Mission Statement

To develop the technical skills of aerospace engineering students and to help advance the technologies required for humans on Mars missions, the MARRS seeks to design a chamber that removes Martian dust from crewmembers and items placed inside. This dust removal system will help mitigate the risks posed by dust particles to human health, equipment malfunction, and science experiment contamination.

Mission Objectives

(1) Reduce Chamber Dust Levels to Less Than 1.0 mg/m3

Dust inside the chamber must be reduced to a level recommended by the NASA-commissioned Committee on Precursor Measurements Necessary to Support Human Operations on the Surface of Mars (NASA, 2024). Dust is abundant in the Martian atmosphere and will pose a risk to both human health and mission hardware. Different dust mitigation techniques were analyzed to create a final product that has the highest likelihood of success.

(2) Develop Actionable Design Concepts for Future Mars Mission Planning

The goal is to contribute feasible, scalable, and cost-conscious solutions that could be implemented by NASA or partner agencies in upcoming mission architectures. The design promotes the use of EP in dust mitigation attempts for future Mars missions. Analysis for the overall habitat entry chamber was conducted to prove the feasibility of EP technology combined with a large structure and wind tunnel under Martian conditions.

(3) Foster Undergraduate Experience in Engineering Practices

The educational objective of the design project is to give undergraduate students experience in project management, product design, and other engineering technical skills. It is important to get hands-on experience in these skills and document the process along the way. The project had an emphasis on problem solving, starting off with the goal of examining a shortfall in crewed Mars mission plans. Every step of the project requires high critical thinking and open mindedness to reach the product.

Concept of Operations

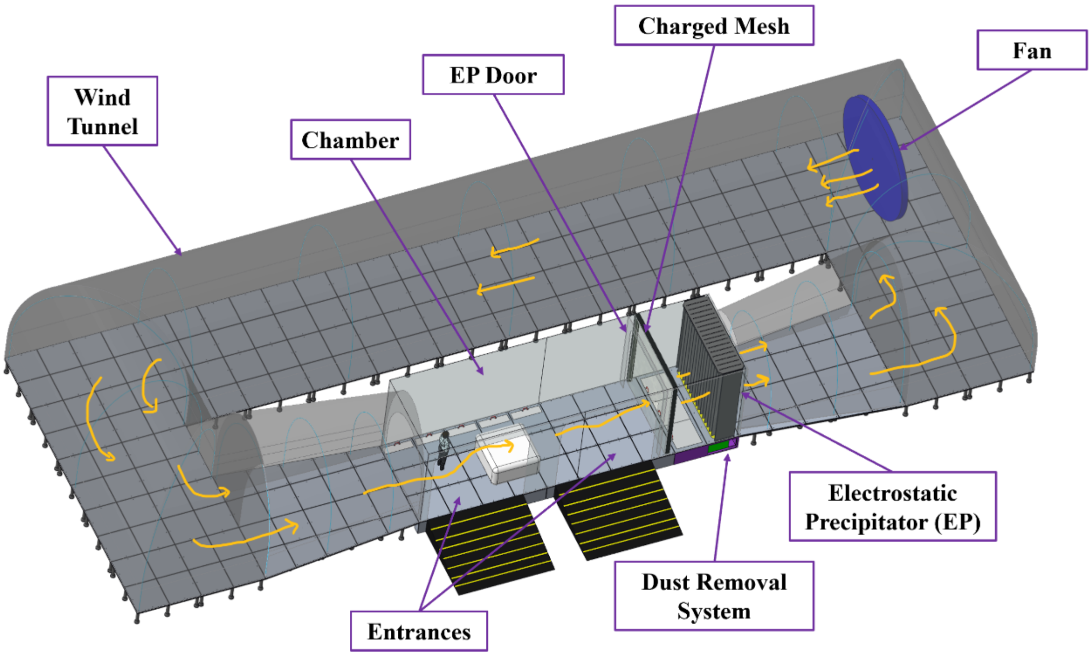


Figure 2: MARRS CONOPS

The Concept of Operations for MARRS is as follows:

Stage One: Loading

Crewmembers load cargo into the chamber. Both entrances are sealed to prevent contamination from the outside environment. The EP door is opened.

Stage Two: System Activation

Sensors inside the chamber detect current dust levels. The EP is turned on. The plates and mesh are charged. The wind tunnel is turned on. Air begins to flow through the tunnel.

Stage Three: Cargo Decontamination

As the air crosses the cargo and crewmembers, it blows dust off and pushes it through the charged mesh. The particles, now containing a charge, continue to flow past the mesh and between the oppositely charged plates. The dust sticks to the plates. The air passes through the EP to the other side of the wind tunnel where it continues to cycle. This process continues until either the dust sensors detect acceptable levels of dust or until the plates have reached capacity.

Stage Four: Dust Removal from Electrostatic Precipitator Plates

The wind tunnel is turned off. To prevent recontamination of the main chamber, the EP door is closed, preventing any wayward particles from flowing back into the chamber. The EP is then turned off, losing its charge. The dust removal system is activated. First, a door underneath the EP plates is opened. Over time, the dust particles fall from the plates into a channel below the floor. Once this has happened, the door below the plates will close, again preventing recontamination. The channel is equipped with another fan and a door to the outside. The fan is turned on and the dust is blown outside the chamber. If the primary chamber was not fully decontaminated due to plates being at capacity, the crew members would revert back to Stage Two and repeat this process as necessary. The crew can then move through to the clean structures.

Stage Five: System Maintenance

It is expected that the EP plates will not be fully decontaminated during every removal process. Should there be dust build-up, crewmembers would simply brush the plates manually. The dust removal channel would also require periodic cleaning.

2 Design Requirements and Constraints

Functional Design Requirements

Detect dust level within chamber – Detection within ± 0.1 mg/m3 (NASA, 2024)

Verification Method: Test

For laboratory conditions on Earth, the EP should be tested under simulated Martian surface atmospheric conditions. This requires a pressure vessel that can maintain a near vacuum in its interior. In this vessel, the pressure should be reduced to 610 Pa, which is the pressure of the atmosphere on the surface of Mars, and a gas mixture approximated by carbon dioxide (95%), nitrogen (2.7%) and argon (1.9%) should be used. Testing at this stage does not require incorporation with the fan assembly, and the target values should be the Paschen coefficients, described in the EP technical study section of this technical report, tested over a target range of voltages, relating directly to E/p (electric field divided by pressure, where pressure is constant). A secondary target should be the voltage required to generate a coronal discharge around the mesh. There is already an equation directly providing the required voltage for a given mesh or wire, so this can be confirmed experimentally. For ease of testing, it has also been shown experimentally that there is little difference in data between pure carbon dioxide and Martian gas conditions (Calle et al., 2013).

To reach the criterion of particulate level <1.0 mg/m3 (NASA, 2024) post-operation of the EP, the design could be tested at Martian conditions by using carbon dioxide gas at 610 Pa. The temperature may be adjusted to match the conditions of the proposed landing site. Ideally, a wind tunnel with an EP should be constructed, with a known amount of particulate matter, and efficiency should be calculated from the amount that is collected on the plates.

Electric fields can only form around current-carrying wires and parallel plates. Given the level of clearance between the main chamber and the EP, there is no possible harmful effects from the electric fields generated by the wires and plates.

ID	Function	Qualitative Performance Requirement	Validation Method
FN-1	Detect dust density in air within chamber	Detection within ± 0.1 mg/m^3	Inspection, Test
FN-2	Remove dust from chamber to sufficient levels	Particulate level < 0.1 mg/m^3 post-operation	Test
FN-3	Electric field should be contained to a buffer zone around the EP.	Electric field shall remain in a 0.25m buffer zone around the EP	Design, Analysis
FN-4	Air must be moving at a sufficient velocity to disperse the particles continuously in the chamber	Particulate level > 0.1 mg/m^3 pre-operation	Test, Analysis
FN-5	Voltage must be high enough to capture particles as they pass between the plates	EP performance ~90%	Design, Analysis
FN-6	Plates must have enough distance to prevent arcing between them	Voltage does not exceed breakdown voltage	Design, Test, Analysis
FN-7	Voltage is high enough to cause coronal discharge and charge particles as they pass through	Voltage is minimum at coronal discharge	Design, Analysis

Operational Design Requirements

The system must operate under Martian surface conditions. First, pressurizing and temperature-controlling the system is energy-intensive. Second, pressurizing the system is time-intensive. Theoretically, the crewmembers could stack cargo in a clean tunnel after decontamination and continue more rounds of decontaminating cargo without having to pressurize the system every time. Thus, the system shall be operational under Martian surface conditions to conserve energy and time spent on decontamination tasks. For verification, various components of the assembly that are sensitive to this change in pressure and temperature will be tested under Martian conditions, which is 610 Pa and –153 to +20 degrees Celsius. The relevant components are the EP, structural frame, fans, and individual electrical parts. Specifically, the breakdown voltage and coronal discharge voltage will need to be evaluated under the appropriate Martian pressure and temperature conditions. In summary, the main operational design requirements are given as follows, with appropriate testing and validation methods:

ID	Function	Qualitative Performance Requirement	Validation Method
OP-1	Operates under Martian surface pressure	Operational at 610 Pa	Analysis
OP-2	Operates under Martian surface temperature	Operational between –153 to 20 C	Material Properties

Mission Constraints

ID	Function
C-1	Large structure size to accommodate a minimum 1.5 cu. Meter payload
C-2	EP collects dust and mitigates to necessary density without losing efficiency
C-3	Maximum mass budget of 5 metric tons for payload
C-4	Maximum power budget of 30kWh
C-5	Maximum financial budget of $3 million

3 Ethical Considerations

Fission Surface Power is proposed as the leading candidate for Martian surface power because of the prevalence of dust storms, which would severely impact solar power generators. Although solar power may have a lower per unit cost, fission power suits the environment better because it can produce energy regardless of weather, landing site, and time of day. Furthermore, it requires less mass and volume when compared to solar power. They are overall better suited and a more sustainable choice for the Martian environment.

4 Technical Approach

Given the theme of advancing technologies to be used in human crewed Mars missions, we first referenced NASA's Technology Shortfalls List (Civil space shortfall ranking July 2024, 2024) and selected some shortfalls we felt aligned with our expertise. This list of shortfalls is a document containing a variety of technologies in need of advancement or development in order to meet NASA space, science, and technology priorities. Using our design to aid in the retirement of a shortfall would help further the advancement of technologies needed for early human missions to Mars. Then, we cross-referenced this shortlist with the current shortfall rankings (Civil Space Shortfall Descriptions July 2024, 2024). We identified the shortfall, "Active Dust Mitigation Technologies for Diverse Applications," ranked 56 out of 187, as the best candidate to guide our design project. MARRS conceptually helps to retire this shortfall by addressing dust mitigation efforts on Mars head-on.

Next, we conducted a literature review to determine the known and unknowns of dust mitigation efforts on Mars. This literature review helped design subsequent trade studies we performed to determine the optimal methods for dust mitigation on Mars, airflow on Mars, EP configuration, materials, and equipment, such as dust sensors.

We conducted preliminary analysis on various aspects of the design, such as structural integrity for chamber frames, wind speed for jet nozzles, and the force required to get dust particles to stick to EP plates. We made preliminary design decisions and then iterated the design details with further analysis. Then, we performed our final analysis and created our final design.

5 Program Management

Work Breakdown Structure

The work breakdown structure for the MARRS project, as shown in Figure 3, started with defining the requirements and constraints. From there, the work was broken down into three major elements: design, testing and validation, and deliverables. The design element was further broken down into subteams, as described in Appendix A. The design process was iterative, so much of the work performed within its subelements was repeated several times. The testing and validation element was broken down into system level work and component work. Ensuring that individual components work is important for overall function of the system. However, ensuring that those components work together as a system is equally important. Integration of the systems is listed under the design element because it was also part of the iterative design process – i.e., when one component changed, it was likely that something else would be changed because of it. System level testing and validation work exists to make sure the integration was successful. Finally, each of the deliverables elements had its own set of specific work requirements which were scheduled throughout the design process, not only ensuring documentation of the work completed, but also to gain feedback and make recommended modifications to the design as necessary.

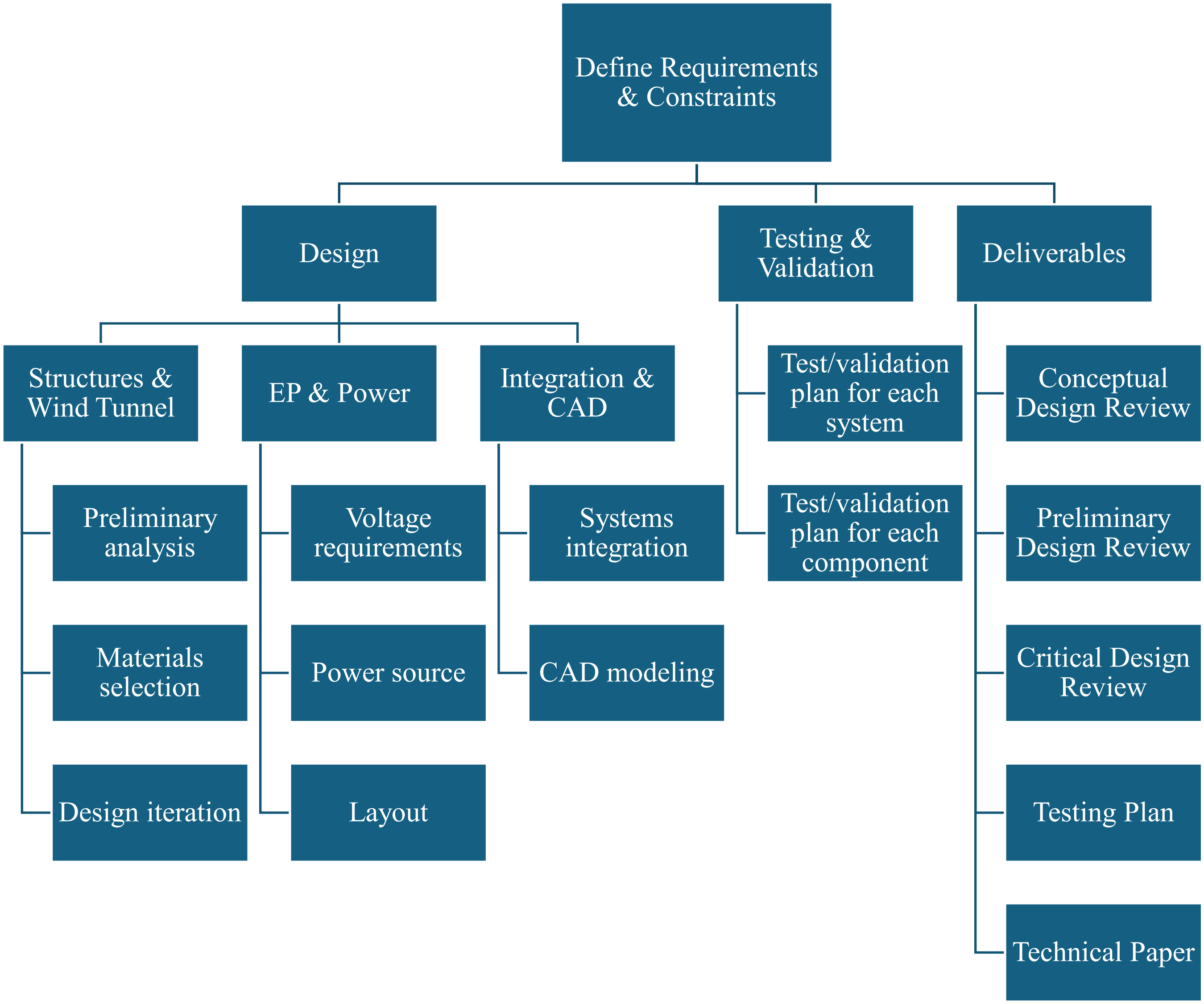


Figure 3: High Level Work Breakdown Structure

Tools

Because this project was conceptual, the tools we required to produce this design were fairly simple. We used Microsoft Excel to assist with some of the analysis, and we used Creo Parametric to model the design in CAD.

Risk Management

Again due to the conceptual nature of this design, the risks associated with this project were also conceptual. Early in the design process, we identified the risks and used a risk matrix to quantify them (Appendix C). These values highlighted where we needed to modify the design. Ultimately, we were able to walk down the risks from moderate to acceptable levels. The risks identified are as follows:

Risk 1: Dust not collecting in the EP

The likelihood of this occurring has dramatically decreased over the course of the overall design. At first jets were conceptualized to push the dust into the EP, however this did not consider how hard it would be to pressurize enough clean air to do this. In the final design, the fan and wind tunnel assembly has verified more than sufficient wind speeds to keep all dust circulating. This design choice was made to decrease the chances of failure compared to a jet array concept. Should this solution not lead to the collection of all dust, it would be reintroduced into the chamber and enter habitat. This would defeat the whole purpose of the design and introduce harmful dust particles into the Martian habitat. If more and more dust accumulates in the habitat, it would negatively affect the health of astronauts and the hardware being used for vital operations. With the final wind tunnel design, the probability of failure has dropped dramatically and would most likely not ruin the future mission. To mitigate the risk, analysis was conducted on certain fans being used in the structural design to produce high velocity wind. The wind speed generated should theoretically carry the dust into the EP plates and have them collected over time. Next steps to mitigating the risk would be to experimentally confirm the effectiveness of the fan and wind tunnel area chosen.

Risk 2: High voltage from EP shocking astronauts

The operation of EP technology requires high voltage which is not completely contained and has a field that could meet the astronauts. The EP subteam has verified that arcing from the EP should not be a concern as long as the astronauts do not stand overly close to it. It has been conceptually evaluated to not be a serious concern as long as they stand .25 meters from it. Should this analysis be wrong then the astronaut would be shocked from the arcing, however it is not always fatal making it not the worst possibility. To mitigate the chance of this happening, it was evaluated that arcing should not be an issue unless the astronaut is standing right next to the EP. A visible indicator for the safety line chosen will stop the astronauts from being that close by accident. It should be part of a safety debrief for them to understand this risk and follow the simple instructions to avoid any complications from it.

6 Structures and Integration

Overall Assembly

Materials

The materials chosen for design can be used optimally under Martian temperatures and atmosphere. Lightweight, and strong materials were the main properties being assessed, leading to the main use of three commonly used materials from past space endeavors. Extruded 6061 Aluminum was chosen for square cross-section beams as they need to be strong, stiff, and long. Cold-rolled 6061 Aluminum is ideal for the thin plated floor tiles of structure. This process works best for flattening metals into plates that can be connected to create the chamber floors in the design. Thin, airtight Mylar sheets will be used to contain the internal environment of the structure, as proven effective by a previous NASA experiment maintaining a pressurized Mylar vessel in the vacuum of space. Low-carbon steel plates for the EP due to their strength, affordability, and conductivity. These plates are necessary to hold the EP to the required performance standards.

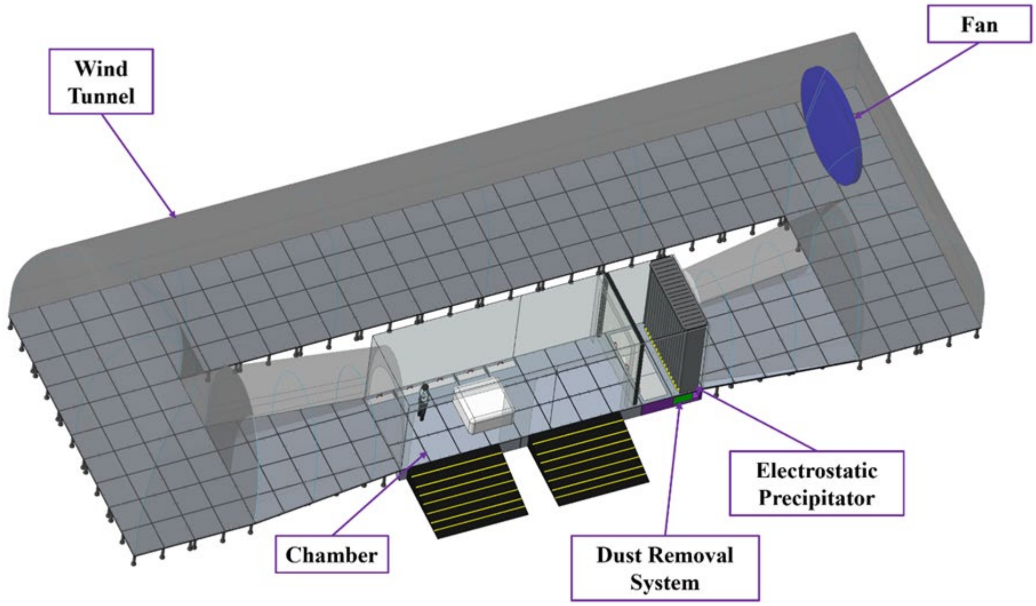


Figure 4: Overall Assembly

Chamber Subassembly

Description

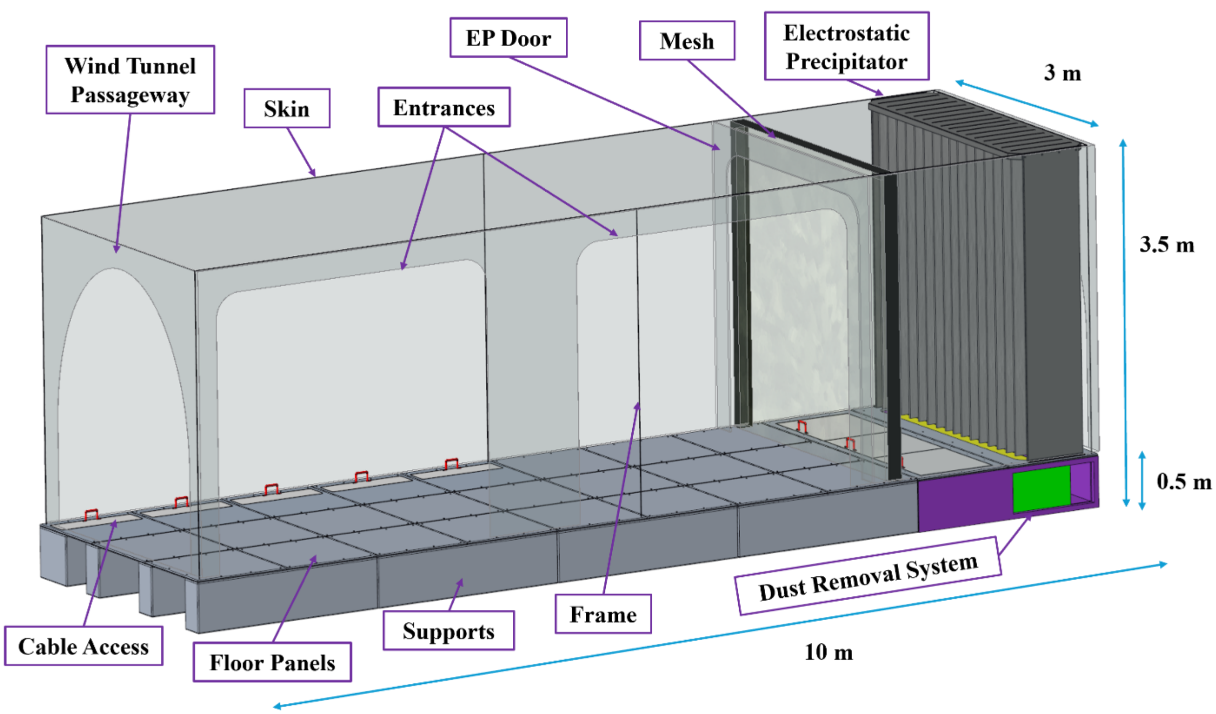


Figure 5: Chamber Subassembly

The chamber subassembly as seen in Figure 5 consists of supports, frame, Mylar skin, flooring panels, the EP subassembly, and the dust removal system subassembly. Interior chamber dimensions for cargo space is approximately three meters wide by eight meters long by three meters high. A control panel (shown in Figure 6), is mounted on a stand near the cable access ports on the left side of Figure 4.

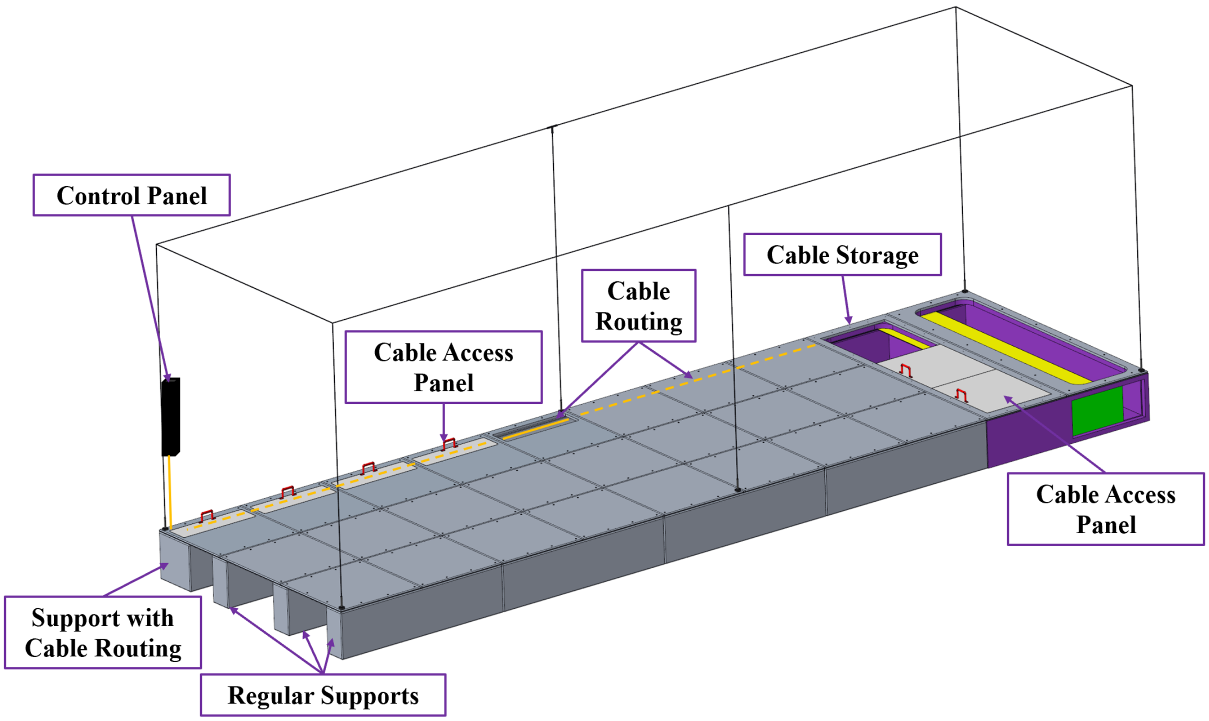


Figure 6: Simplified Chamber

The EP and dust removal doors require cable connections. These cables are stored in a chamber next to the dust removal assembly. The cables are then routed underneath the flooring panels in special supports, shown in Figure 7, and up to the control panel.

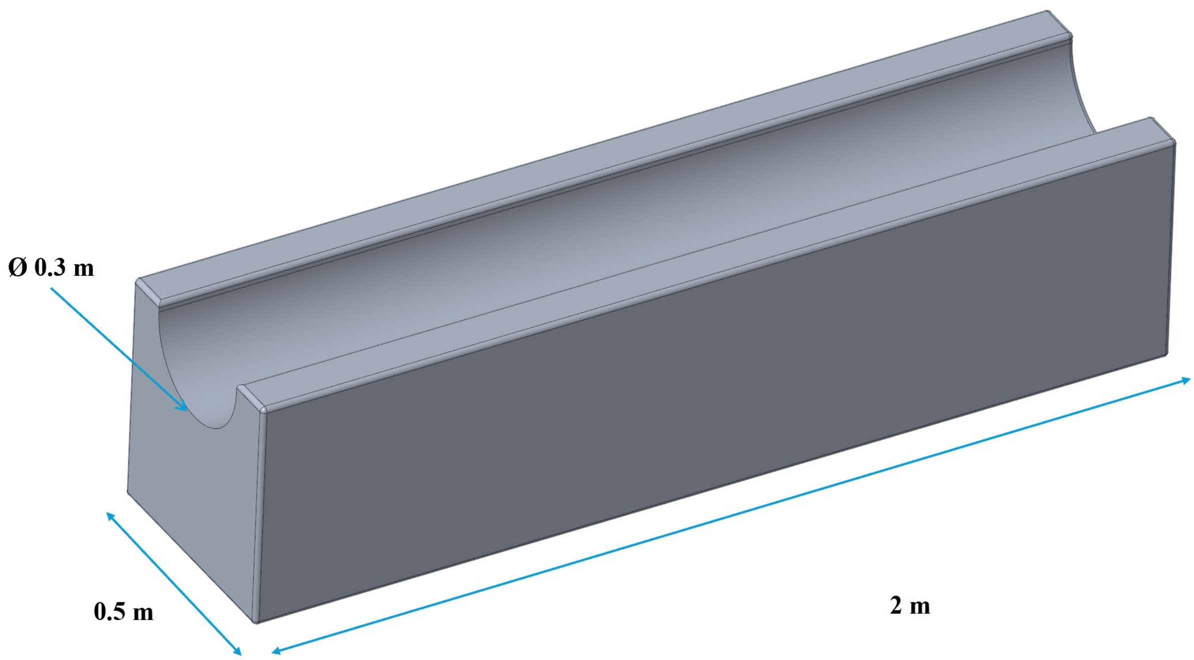


Figure 7: Floor Support with Cable Routing

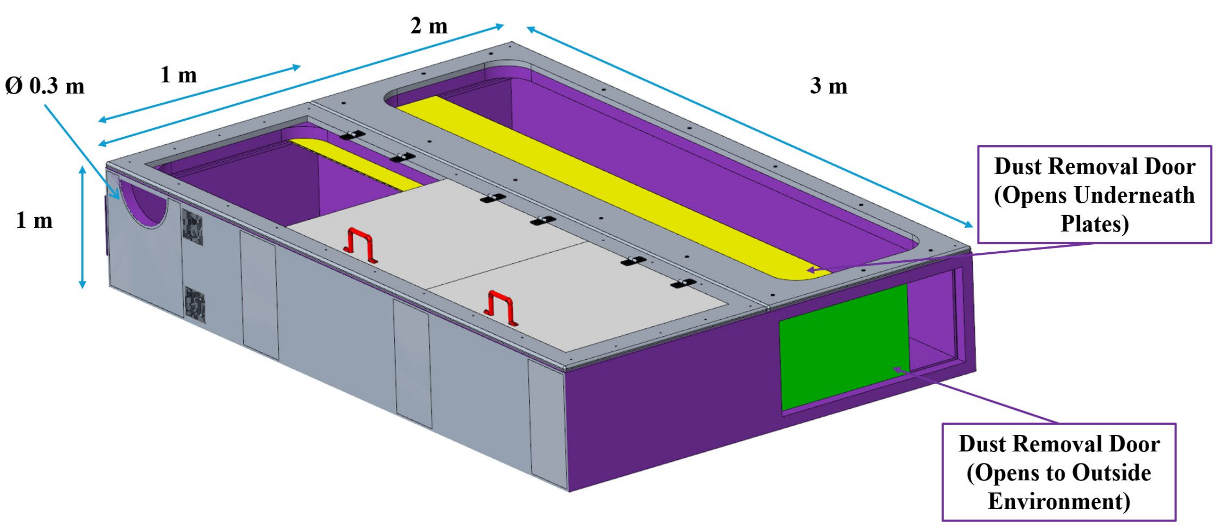


Figure 8: Dust Removal Chamber

The dust removal system has two doors – one which opens underneath the EP plate and the other that opens to the outside environment, shown in Figure 8. Electrical connections are contained within the cable storage section.

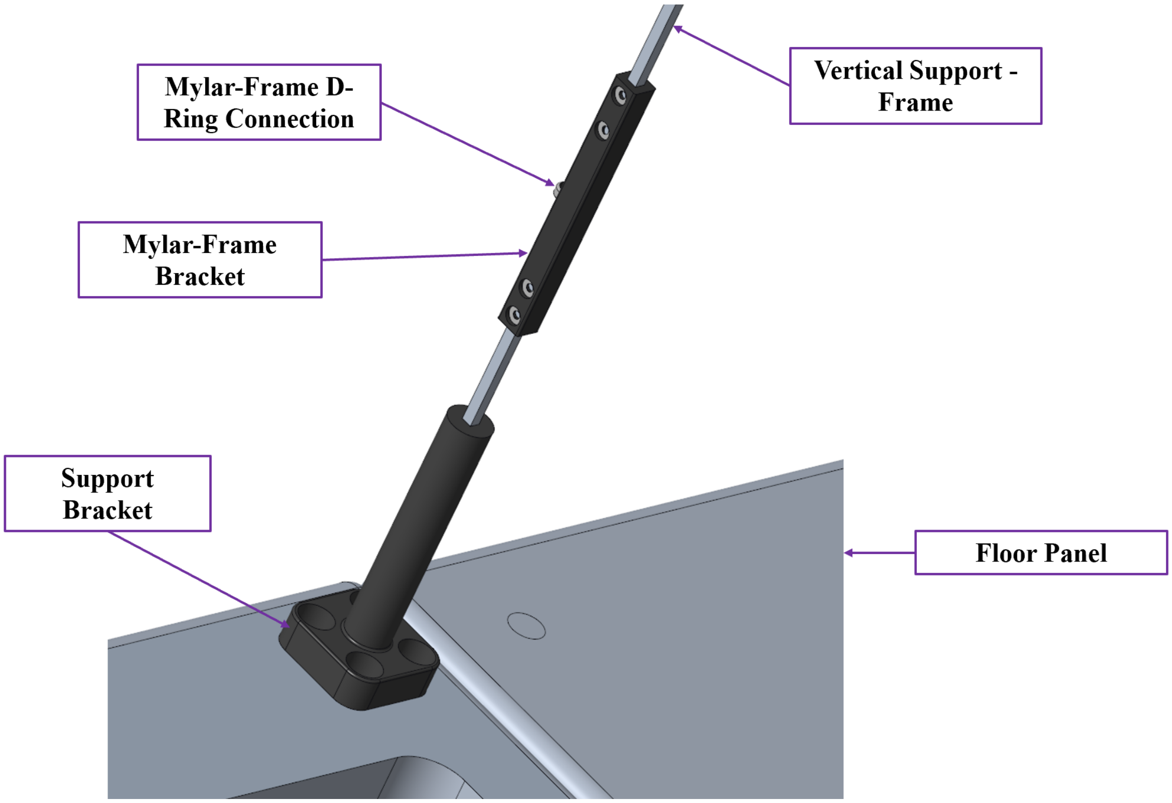


Figure 9: Vertical Support & Mylar Sheet Attachments

The vertical supports are held in place by a bracket that is bolted directly to the flooring. The Mylar skin has sewn in metal D-rings which clip into the Mylar-Frame D-Ring Connection bracket, as shown in Figure 8.

Analysis

The structure was designed to be spacious in order for the astronauts to fit comfortably with any payloads from outdoors missions. The outside shell was given dimensions of L=10 m, W=3 m, H=3 m. The frame will be made of 6 vertical supports and 8 horizontal beams (not pictured) with square cross-sections, t=5 cm. The mylar sheet around the structure will have the volume given by the outer shell with a thickness of .191 mm. A mylar sheet with similar thickness was used in a NASA experiment where it contained a pressure within it in space (Litteken, 2019). Only the top 4 beams and 5 faces of the structure will exert a force that will be supported by the 6 columns. The floor support beams will carry the weight of the floor tiles, astronauts, fans and hardware.

$$F_{column} = \left(\rho_{al}(2Lt_{al}^2 + 2Wt_{al}^2) + \rho_{my}\left(LWt_{my} + 2LHt_{my} + 2WHt_{my}\right)\right) g$$
$$F_{floor} = \left(m_{floor} + m_{astronauts} + m_{fan} + m_{hardware}\right) g$$

With the columns equally spaced 5 meters apart, they each carry an equivalent amount of force. An unrealistic high estimate for the floor force is chosen where all the mass exerted on the floor is localized to a small area on a support beam.

$$P_{column} = \frac{F}{6}$$
$$P_{floor} \sim F_{floor}$$

This force value can be compared to the critical buckling load to check for failure. With known Modulus of Elasticity of aluminum, and a moment of inertia calculation this load can be found.

$$\mathrm{I} = \frac{\mathrm{t}_{\mathrm{al}}^4}{12}$$

$$\mathrm{P}_{\mathrm{cr}} = \frac{\pi^2 \mathrm{EI}}{\mathrm{L}^2}$$

The critical load is significantly larger than the force acted upon the column supports, therefore it does not fail due to buckling. Next, we must check for max bending on the structure which occurs at the midway point between 2 supports. The weight of the beams can be simplified as a uniform load, w. The max moment can be then found with a given formula for a simply supported beam.

$$M_{max} = \frac{w\left(\frac{L}{2}\right)^2}{8}$$
$$\sigma_{max} = \frac{M_{max}c}{I}$$

The maximum bending stress on the top beams is also considerably less than the yield strength of aluminum as is the floor’s bending stress. Next the maximum deflection can be calculated from the given formula.

$$\delta_{max} = \frac{5w\left(\frac{L}{2}\right)^4}{384EI}$$

The maximum deflection of the top horizontal beams comes out to be around .7 mm which is acceptable. The maximum deflection of the floor is 1.1 mm, which is a little high, but should not theoretically be reached under normal operation.

The structural strength of the Mylar sheet has to be evaluated. The dust storms on Mars can reach 60 m/s, which is accompanied by pressure acting on the structure. This max pressure can be estimated from the drag force formula, assuming Martian air density and a high drag coefficient of 1.

$$P_{wind} = \frac{1}{2}\rho v^2$$

The pressure comes out to be 36 Pa which is negligible compared to the tensile strength of Mylar, 190 MPa. This is logical as the air density on Mars is significantly lower than that of Earth. The same wind speeds on Earth would cause damage to structures unlike on Mars.

Internally, the wind produced also acts as a shear force on the support columns. In a worst-case scenario, the force of an astronaut falling/hitting the column acts in the same direction as the wind, causing a maximum shear force to be enacted. A high estimate of a maximum of V = 1000 N was assumed in calculation. t = 5 cm, y = 2.5 cm.

$$Q = \frac{1}{2}t^2 y$$

$$\tau = \frac{VQ}{It}$$

This gives a max shear value of 1.2 MPa which is significantly less than the shear strength of 6061 aluminum, 207 MPa. Therefore, the structure does not fail to shear stress.

Wind Tunnel Subassembly

Description

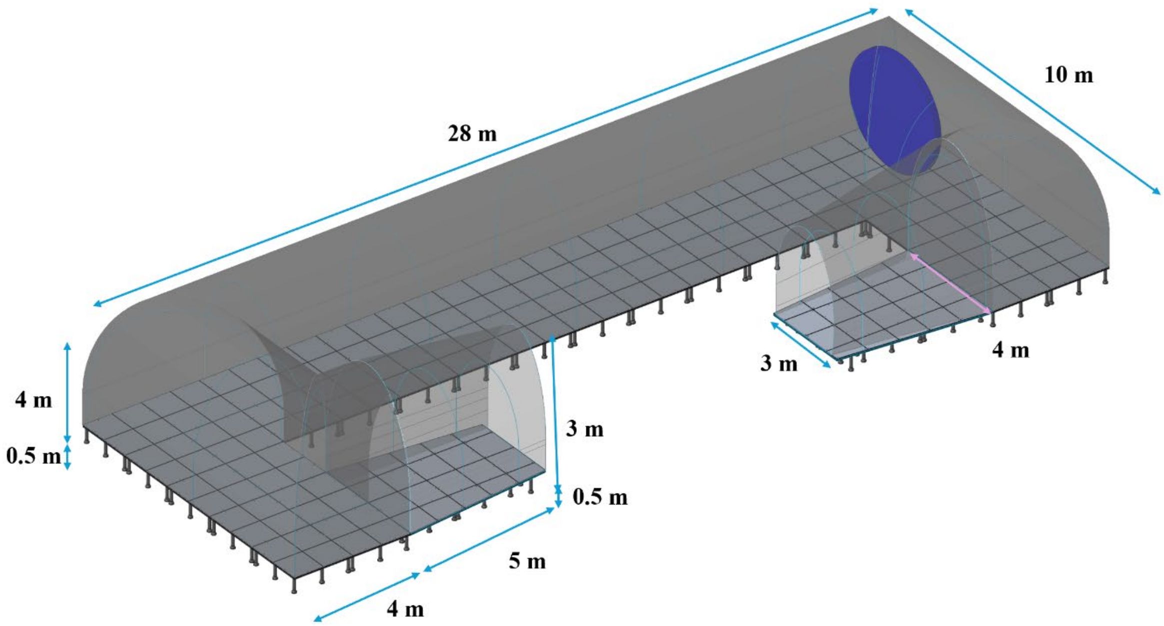


Figure 10: Wind Tunnel Subassembly

The wind tunnel subassembly, shown in Figure 10, consists of flooring panel subassemblies, Mylar skin, hoops for the frame, and a fan.

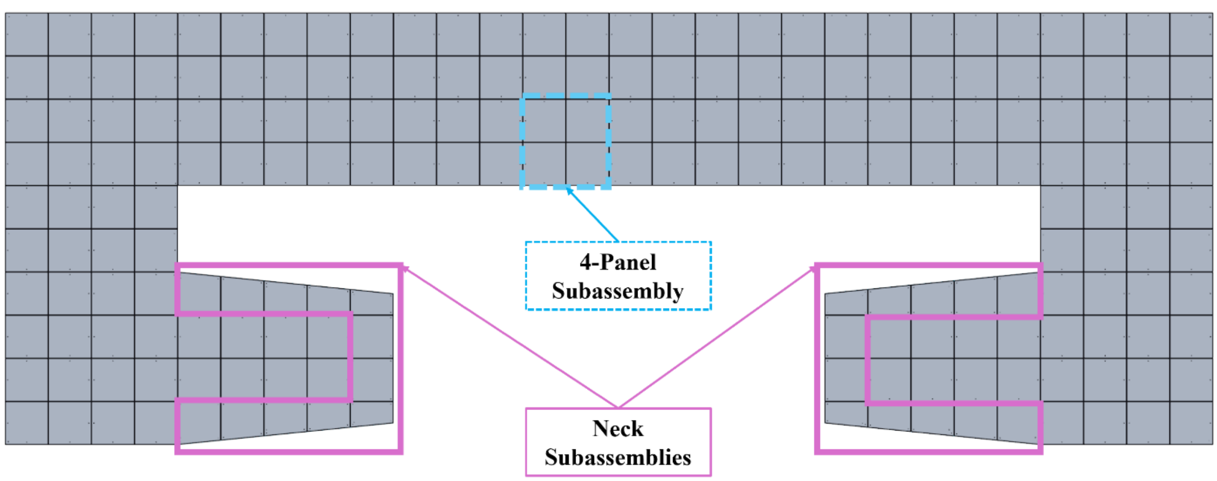


Figure 11: Wind Tunnel Flooring Layout

The flooring has two subassemblies, shown in Figure 11. They are a four-panel subassembly and a neck subassembly. The four-panel subassembly is composed of four one square meter panels, held together by a bracket, as shown in Figures 12 and 13.

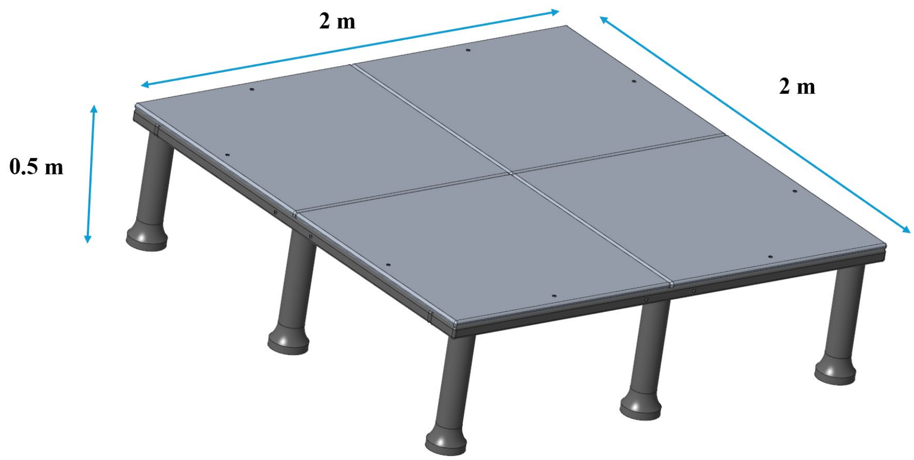


Figure 12: Wind Tunnel Floor Four Panel Subassembly

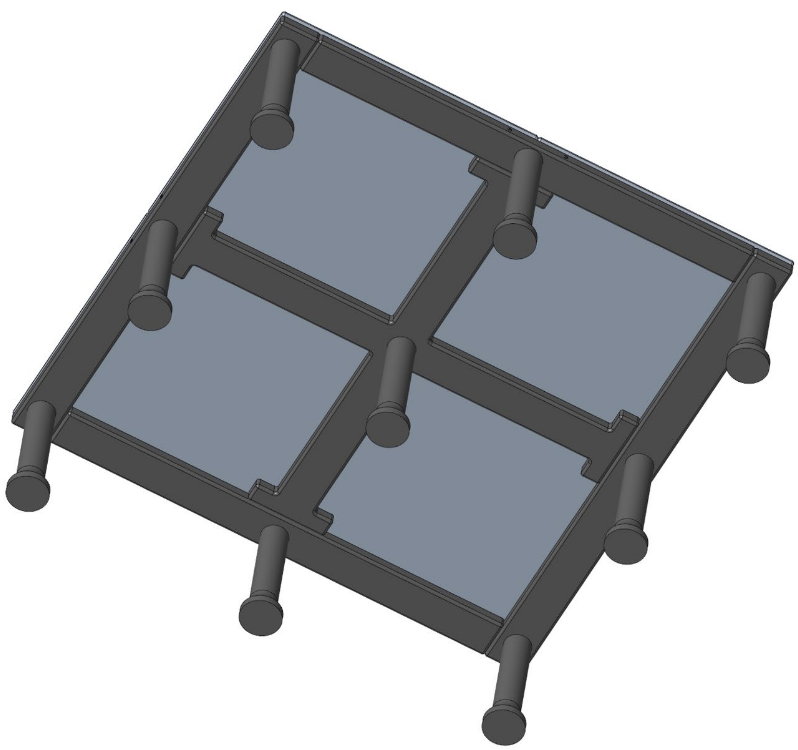


Figure 13: Wind Tunnel Floor Panel Subassembly, Bottom View

The neck subassembly, shown in Figure 14, has two one square meter panels and irregular shaped polygons for the remaining panels. Two four-panel subassemblies fit in the gaps between panels A-J through D-G.

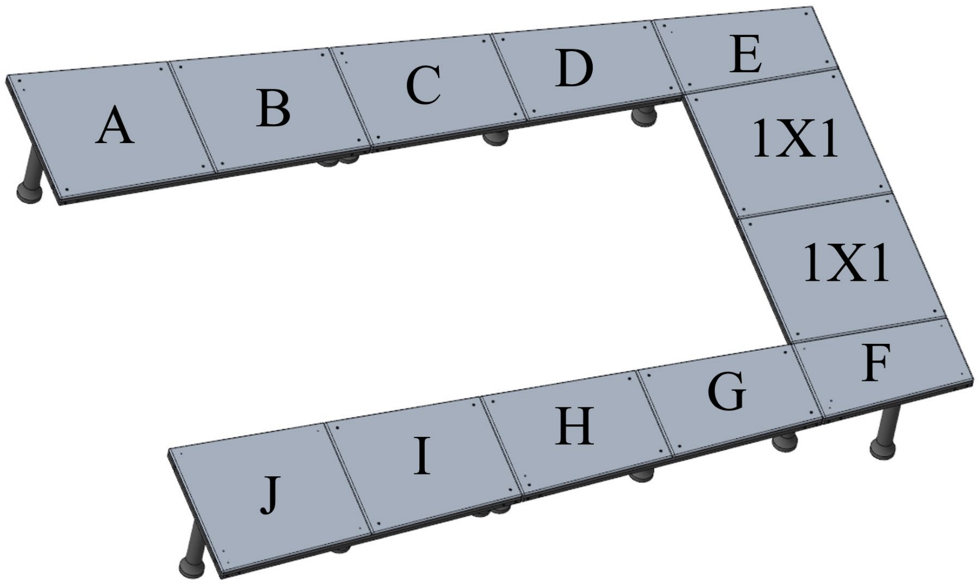


Figure 14: Wind Tunnel Floor Panel Neck Subassembly

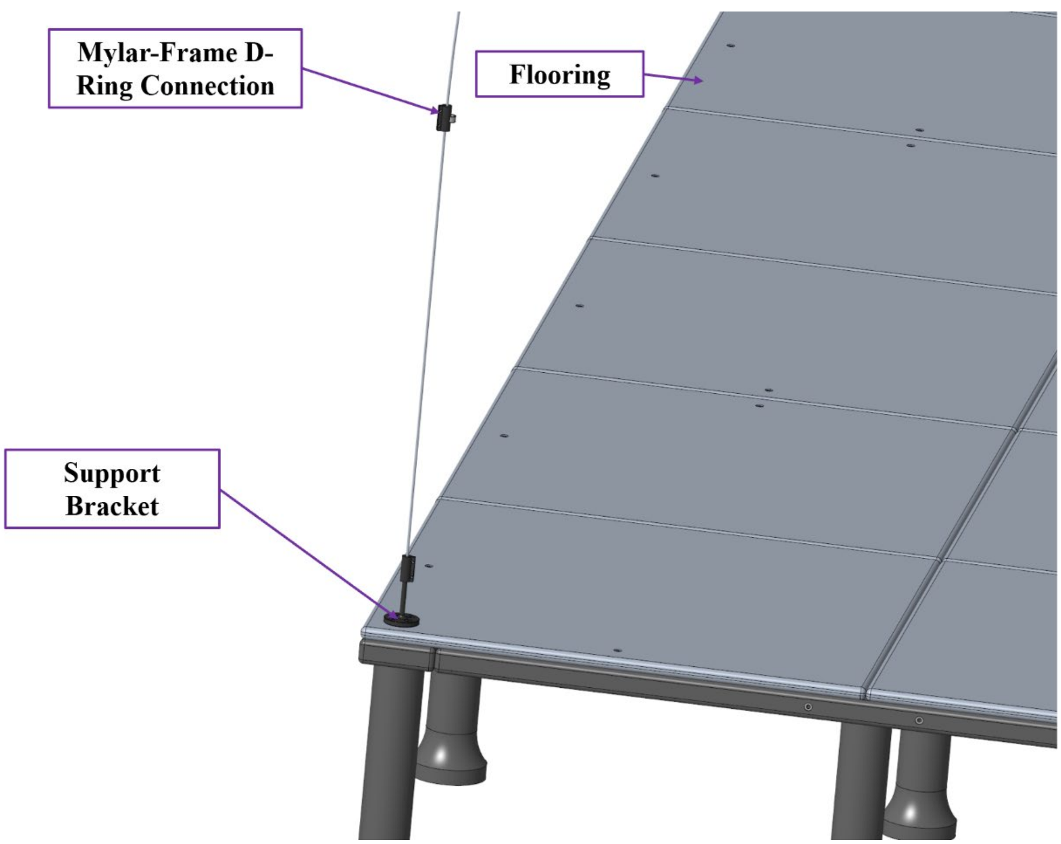


Figure 15: Wind Tunnel Frame and Mylar Skin Brackets

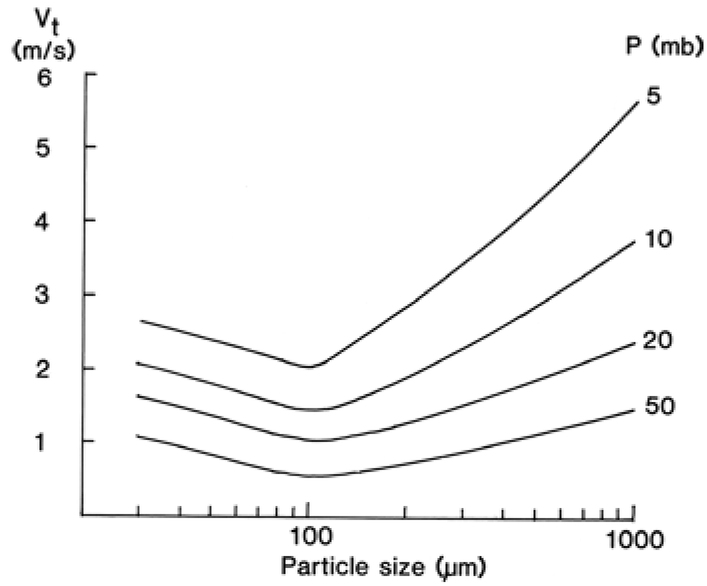
The hoops, which have a 5 cm diameter, are connected to the flooring panels by brackets similar in design to the chamber frame rackets. The Mylar Skin is connected to the frame in the same manner as in the chamber, as shown in Figure 15.

Analysis

To determine the properties of the fan necessary, a formula relating the wind speed generated, volumetric flow rate, and cross-sectional area of the airflow section was used. For compressible flow in wind tunnels, air density affects the wind speed. However, this would require pressure gauges, and the effect of this phenomenon is considered negligible for low-speed wind tunnels under 80 m/s (Glenn Research Center, n.d.). A high-powered axial fan was chosen to supply the high volumetric flow rate required for the design. The diameter of the fan, Howden Alphair Jetstream, is around 3.5 meters (SVL, 2023). The wind speed needed to be generated for Martian dust particles to remain airborne is a minimum of 1.4 m/s (NASA, n.d.). To avoid turbulent airflow, the wind tunnel is larger than the main chamber to allow for the structure to neck down. The volumetric flow rate on Mars would not be equivalent to that of Earth due to its substantially lower atmospheric pressure. The analysis assumes a 10-fold decrease in fan effectiveness resulting in Q = 47 $\frac{m^3}{s}$, $A_{chamber} = 9\,m^2$, $A_{tunnel} = 12.5\,m^2$.

$$v = \frac{Q}{A}$$

With the volumetric flow rate of the fan and cross-sectional areas of each section, the air velocity will be sufficient to carry the dust particles according to observational data from Martian dust storms. The velocity in the chamber is $v = 5.2\,\frac{m}{s}$ and the wind tunnel is $v = 3.7\,\frac{m}{s}$. The velocities were designed to be higher than the threshold to both increase the chance of particle motion and reduce mass in unnecessary structure size. With the pressure on mars being around 6-7 mb, the graph below shows the necessary wind speed to carry certain dust particles. The average wind speed on mars is below 7.5 m/s, therefore large dust particles should not be a common occurence and would be on the high side of the necessary wind speed.



The force that the wind and dust exert is important. As the atmosphere of Mars is significantly lower than that of Earth, the number of particles being blown in the same volume is less. What allows the design to work is the proven particle motion at the generated wind speed and the low force required for dust to attach onto the EP. The force of dust can be estimated from the drag force equation that relates force to air density, air speed, area of effect, and drag coefficient. $\rho = .02 \frac{kg}{m^3}, v = 52 \frac{m}{s}, A = 9\, m^2$, and $c_d \sim .5$.

$$F = .5\rho v^2 A c_d$$

This gives a force of 1.2 N and Pressure of 13.5 Pa, which is low enough to not risk blowing the dust off the plates.

Electrostatic Precipitator Subassembly

Description

The EP subassembly is composed of a frame which mounts to the flooring inside the chamber. The upper frame section holds the EP plates. There are 16 EP plates, spaced 15 cm apart. The plates are offset from the flooring by 2.8 cm to prevent damage from the door underneath them sliding. The mesh (Figure 5), has a similar exterior frame that is mounted to the floor. It is spaced 1.5 meters from the plates.

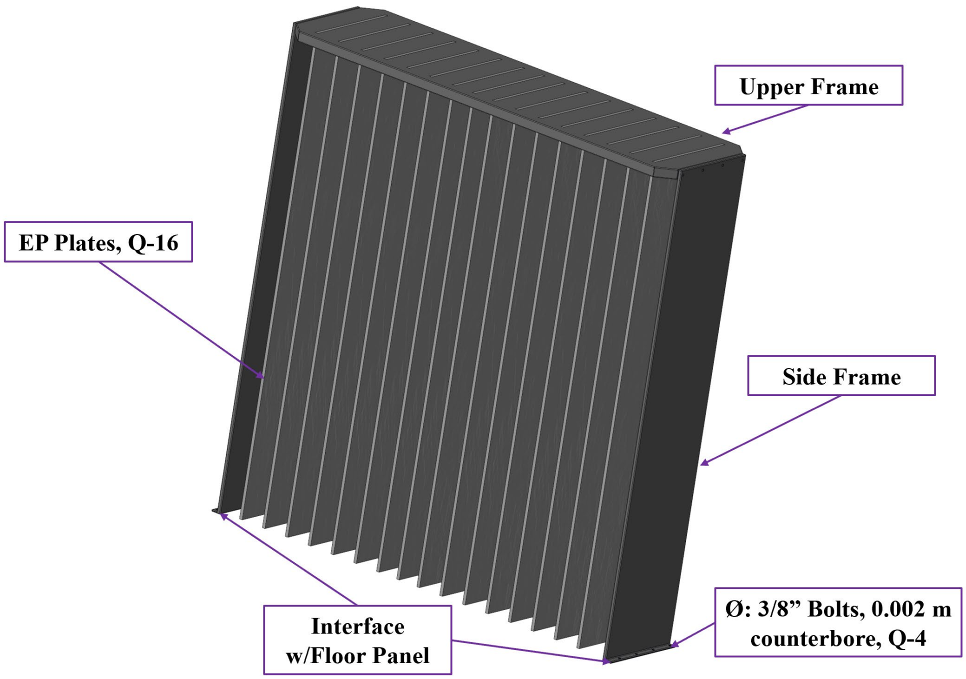


Figure 16: EP Subassembly, Mesh Not Shown

Analysis

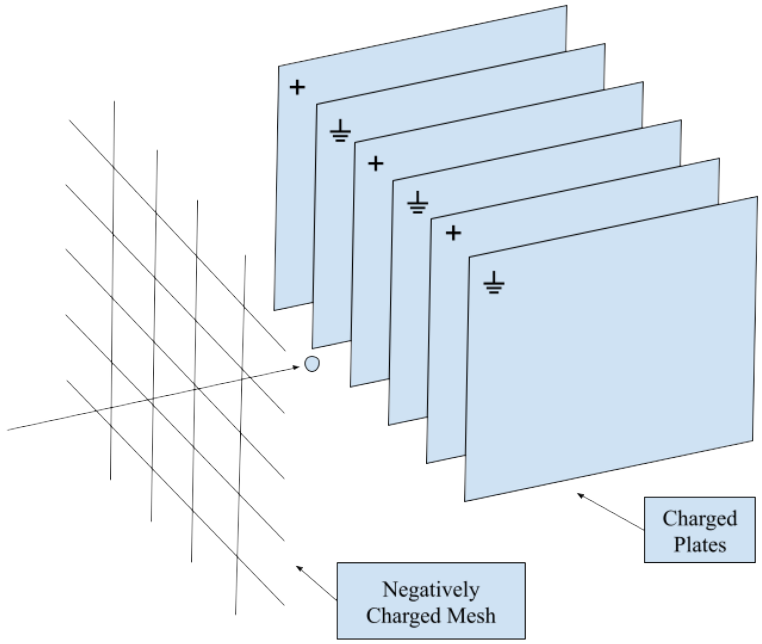


Figure 17: Visualization of Parallel Plate Electrostatic Precipitator

The design constraints of the EP are as follows: (1) The air must be moving at a speed high enough that it disperses the particles through the chamber continuously, (2) The voltage must be high enough to allow the particles to be captured by the plates as they pass between them, (3) the plates must be far enough apart so that there is no arcing between them, and (4) the voltage must be high enough that there is coronal discharge from the mesh charging particles that pass through.

To investigate the first two constraints, we pose the worst-case scenario for the EP: a massive, fast-moving particle with the charge of a single electron that starts its trajectory between the plates from close to the grounded plate. This imposes a relationship for the distance between the plates, the width of the plates, the voltage differential between the plates, and the initial velocity of the particle.

$$E = \frac{\Delta V}{d}, F_{plates} = q_p E \rightarrow F_{plates} = m_p a_p = \frac{q_p \Delta V}{d} \rightarrow a_p = \frac{q_p \Delta V}{m_p d} \quad (1)$$

First, the force acting on the particle from the plates can be determined from the electric field created by the voltage differential, as shown above. This allows us to find the acceleration acting on the particle from the electric field alone. (m_p) and (q_p) are mass of the particle and charge of the particle respectively.

$$\Delta x = v_0 t + 0.5at^2 \rightarrow t = \frac{w}{v_0}, \frac{d}{2} = 0.5a_p t^2 = \frac{q_p \Delta V w^2}{2m_p d v_0^2} \rightarrow \Delta V = \frac{m_p d^2 v_0^2}{q_e w^2} \quad (2)$$

Using kinematics, the above relationship can be found using d, the distance between plates, (v_0), the initial velocity of the particle, and (ΔV), the voltage difference between plates. (q_p) is exchanged for the charge of an electron in the last equation and w is the width of the plates. The above relation assumes that (v_0) is adjusted appropriately so that the particles remain within the length of the plates during flight.

The range of particle sizes carried in the Martian atmosphere is between 1-4 micrometers. The density of Martian particles was found to be approximately 800-1800 (kg/m^3) (Grott, 2021). Using the assumption that most particles can be modeled as spheres, the heaviest particle possible is (6.03e10^-14). Substituting this g_M and q_e into the equation gives an approximation of the minimum voltage required to capture the particle before it leaves the EP. Setting width to 0.75 m and distance between plates to 0.15 m, we get the following theoretical range of voltages based on a naive approach to the problem, depending on the lowest and highest velocities possible, 3.7 and 5.2 m/s respectively.

$$V_{min}, V_{max} = (2060\,V,\ 4070\,V) \ (3)$$

To satisfy the third constraint and set an upper bound on the voltage, we use Paschen's Law, which gives the breakdown voltage between two electrodes in a gas as a function of pressure and gap length. The breakdown voltage describes the voltage necessary to start a discharge arc across an insulator; in this case, it is specifically for gases.

$$V_B = \frac{Bpd}{\ln(Apd) - \ln\left(\ln\left(1 + \frac{1}{\gamma_{se}}\right)\right)} \ (4)$$

Constants A and B are dependent on the gas, p is pressure, d is distance between the plates, andγ_{se} is the secondary electron-emission coefficient. For Mars' atmosphere, primarily composed of CO2, A and B can be found by fitting the curve to data points used in a simulated Martian environment (Calle, 2011). A was found to be 1.71 and B was found to be 65.5 approximately, and γ_{se} equals 0.0088 for Aluminum Oxide surfaces (Chiang, 2016). At an air pressure of 4.75 torr and 150 mm, the breakdown voltage is 8,400 V. However, it is possible to get a better estimate by approximating the upper region of Paschen’s law as a line, so that the breakdown voltage can be found with the following equation (McDougall, 2016).

$$V_B = \alpha P d = 60kV \cdot d\ = 8910\,V (5)$$

Using these values, we can find a theoretical relationship between the breakdown voltage and the distance between the plates. Both are within the same range of values, so that a maximum of 8000 V should be used for the operation of the EP. However, in practice, it is best to find the values A, B, and γ_{se} experimentally for the desired E/p range.

For the fourth constraint, we impose another lower bound based on the minimum voltage required for coronal discharge. Coronal discharge is the luminous electrical discharge produced when a high voltage passes through a gas. For round wires, the relation between the electric field generated, radius of wire, and relative gas density (to 1 atm) is given in the following equation (EPA, 1999):

$$E_C = 3.126 \times 10^6 d_r \left(1 + 0.0301\sqrt{\frac{d_r}{r_w}}\right) \text{ (6)}$$

Then the corresponding voltage is:

$$V_C = E_C r_w \ln\left(\frac{d}{r_w}\right) \text{ (7)}$$

Using d = 15 cm, radius of wire of around 0.05 m, d_r =0.0059, we find the minimum voltage required for coronal discharge to be 1030 V.

Taking experimental voltages required to produce a corona for EPs, we take the voltage to be 4000 V approximately (Ziedan et al, 2010), with a separation of 15 cm to reduce the chance of arcing between plates, we find that the approximate force acting on a particle is:

$$F_p = \frac{q_p V}{d} = \frac{(1.6022 \cdot 10^{-19} C \cdot 4kV)}{0.15m} = 4.28 \cdot 10^{-15} N \text{ (8)}$$

The current required for the operation for the EP must also be calculated, and this is given by the following equation as a function of vacuum permittivity, ion mobility constant (for Carbon Dioxide at surface temperature conditions), voltage, and distance between plates and mesh (EPA, 1999). The ion mobility constant is given as 0.96 (Rokushika, 1986), and substituting in the equation, we get the following estimate for the current:

$$j = \mu\varepsilon_0 \frac{V^2}{L^3} = 0.0403\, A \text{ (9)}$$

Another consideration is for the fans that blow air towards the EP. Since there are no equations that dictate the dependence of airflow velocity on distance from the fan outlet, this is best found experimentally and adjusted accordingly so that it does not influence particles that are at the entrance of the EP's charged plates. This is further complicated by the low atmospheric pressure on Mars, which would drastically reduce the airflow for each fan, and also the initial velocity of the particle.

Software and Controls

The electrical system accomplishes the following tasks: (1) the use of the EP at the desired range of voltages, (2) the opening and closing of the airlock from inside the chamber and in the connecting hallway to the habitat, and (3) the operation of components that can be connected in series to the main power source, such as the fans or dust sensor. To accomplish this goal, there are three main circuits central to the use of the design, which are the circuits for the EP, the airlock, and the components in series. These circuits are all put in parallel with a 12V source so that they can be powered simultaneously but toggled via the control panel individually.

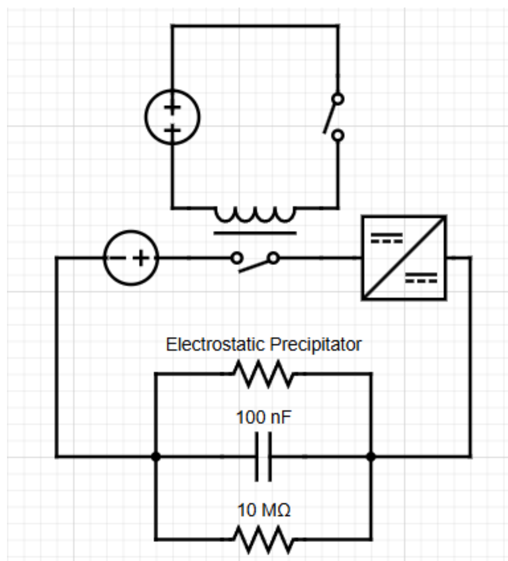


Figure 18: Circuit Diagram for Electrostatic Precipitator

The above diagram shows the circuit diagram for the EP; the top portion shows the circuit connected to the control panel, and the bottom portion shows the circuit controlling the EP. The control panel circuit has a switch toggling the EP on and off, and a relay that completes the circuit for the EP when activated. Since the operating current ranges from 0.01 to 0.16 A (dependent on the voltage source from 2-8 kV), in the EP circuit, there must be low-voltage source at 12V with a switch immediately following it, before it is converted to the desired voltage via the DC-DC converter. Then, the EP is in parallel with the capacitor and bleeder resistor, where the capacitor is necessary for attenuating noise and bleeder resistor provides surge protection. This produces a net kWh of 7.35 with the main contributor being the EP; the control panel produces a trivial amount of 0.00192 kWh.

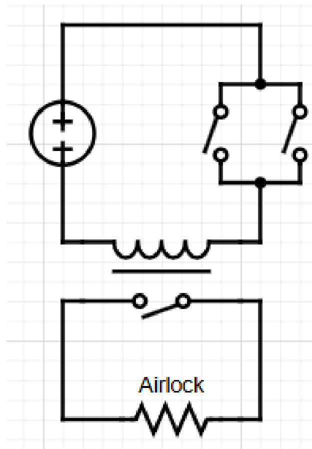


Figure 19: Circuit Diagram for Airlock

This is the airlock circuit. This airlock would be the interface between MARRS and the clean habitat destination. It can be looped into the system for MARRS. In the top portion of the circuit, there are two SPST switches representing the switch on the inside of the chamber and the switch on the connecting tunnel between the chamber and the habitat. This makes it possible to toggle the airlock from both locations, as desired. Both switches toggle the relay, which turn powers the solenoid for the airlock.

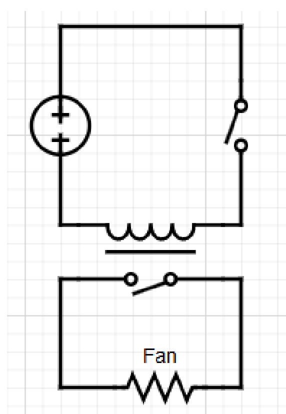


Figure 20: Circuit Diagram for Fan/Dust Sensors

This circuit works for the fan as well as the dust sensor. Similar to the EP circuit, there is only one switch turning on the lower circuit, which powers the fan. The relay completes the circuit when the switch is closed, so that the component in series with the fan is activated. In the case of the dust sensor, it should have no switches at all, and should only have the sensor and an LCD display in series, so that the current particulate levels can be displayed on the screen.

For dust level detection, we employ the Seeed Studio 101020012 dust sensor, which is capable of detecting dust particles in a chamber that are larger that 1 micrometer in diameter, at a relative humidity below 95%, which the Martian atmosphere satisfies (Seeed Tech, 2015). In our design, two of these sensors will be situated opposite the EP, to avoid any damage from the electric field of the EP, used to cross-verify the dust level in the chamber, and checked until the dust concentration in the air meets a safe level.

In total, the power consumed comes out to 4 kWh, because the EP will draw the most power, but also be used for short intervals of time. Assuming that at most, it is used for a total of an hour every day, it will consume around 4 kWh in the worst-case scenario, at maximum voltage, current and duration. With the contributions from other components, it comes out to around 4.1 kWh maximum.

Power, Thermal and Environment

For the environment of the chamber, it is not necessary to pressurize or control the temperature of the chamber, because Martian environment would theoretically widen the range of acceptable voltages by raising the breakdown voltage, ideally should be ready for use as fast as possible, and would require more energy and resources to compress air and produce heat.

The main source of power will be provided by the fission reactors proposed (NASA, 2025). The maximum power level of 30 kWh allowed for the operation of the assembly informs the design of the circuits and the control panel. The combined power usage of the assembly is 11.4 kWh. Based on the KRUSTY fission power test for simulating fission power generation in space, which produced 5.5 kW, we assume that there are multiple reactors available to draw power from on Mars.

7 Conclusion

The design and development of the Martian Airborne Residue Remediation System helped our team of three undergraduate aerospace engineering students hone our technical engineering skills and expand our range of knowledge. The scope of our project was large, ambitious, and required us to apply all of the knowledge we have gained at our time at the University of Virginia. At a conceptual level, MARRS successfully helped us adhere to our mission statement and fulfill our mission objectives.

Based on our design and analysis, MARRS meets the functional and operational requirements within its constraints. This supports meeting our first objective to reduce dust levels within the chamber. Our second objective to develop actionable design concepts for future Mars mission planning has also been met. Successful deployment of MARRS can provide actionable data for the use of electrostatic precipitation as an effective dust mitigation on other small bodies of scientific interest. Finally, the design of MARRS gave our team firsthand experience in project management and product design while requiring us to use all of our skills to identify a problem and then solve that complex problem.

8 References

Axial fans: Howden: SVL, Inc.. Minneapolis, MN & Fargo, ND. SVL. (2023, April 13). https://www.svl.com/manufacturer/howden/axial-fans/

Baglin, V., Bojko, J., Scheuerlein, C., Gröbner, O., Taborelli, M., Henrist, B., & Hilleret, N. (2000). *The secondary electron yield of technical materials and its variation with surface treatments* (No. LHC-Project-Report-433).

Calle, C., Clements, J., Thompson, S., Cox, N., Hogue, M., Johansen, M., & Williams, B. (2011, September). Dust removal technology for a Mars in situ resource utilization system. In *AIAA SPACE 2011 Conference & Exposition* (p. 7348).

Chiang, C. L., Zeng, H. K., Li, C. H., Li, J. Y., Chen, S. P., Lin, Y. P., ... & Juang, J. Y. (2016). Secondary electron emission characteristics of oxide electrodes in flat electron emission lamp. *Aip Advances*, *6*(1).

Civil Space Shortfall Ranking July 2024. (n.d.-a). https://www.nasa.gov/wp-content/uploads/2024/07/civil-space-shortfall-ranking-july-2024.pdf?emrc=7dbadc

Civil Space Shortfall Descriptions July 2024. (n.d.-b). https://www.nasa.gov/wp-content/uploads/2024/07/civil-space-shortfall-descriptions-july-2024.pdf?emrc=622753

Civil space shortfall ranking July 2024. NASA. (2024). https://www.nasa.gov/wp-content/uploads/2024/07/civil-space-shortfall-ranking-july-2024.pdf?emrc=7dbadc

Electrostatic Precipitators (1999). In EPA.gov. Retrieved May 7, 2024, from https://www.epa.gov/sites/default/files/2020-07/documents/cs6ch3.pdf

Glenn Research Center. (n.d.). *Wind tunnel aerodynamics*. NASA. https://www.grc.nasa.gov/www/k-12/VirtualAero/BottleRocket/airplane/tunnel1.html

Grott, M., Spohn, T., Knollenberg, J., Krause, C., Hudson, T. L., Piqueux, S., ... & Banerdt, W. B. (2021). Thermal conductivity of the Martian soil at the InSight landing site from HP3 active heating experiments. *Journal of Geophysical Research: Planets*, *126*(7), e2021JE006861.

James Dillon Cobine. Gaseous Conductors: Theory and Engineering Applications. New York: McGraw-Hill, 1941

Kahre, M. (2024, April 17). *Dust storms on Mars*. Oxford Research Encyclopedia of Planetary Science. https://doi.org/10.1093/acrefore/9780190647926.013.119

Levy, R. (2022). *Dusty differences between Mars and Earth*. NASA. https://earthobservatory.nasa.gov/images/149926/dusty-differences-between-mars-and-earth

Litteken, D. A. (2019). *Inflatable technology: using flexible materials to make large structures*. NASA. https://ntrs.nasa.gov/api/citations/20190001443/downloads/20190001443.pdf

Martian Dust Storms and Their Effects on Propagation. NASA. (n.d.). https://descanso.jpl.nasa.gov/propagation/mars/MarsPub_sec5.pdf

McDougall, M. O. (2016). *Martian Environment Electrostatic Precipitator* (No. KSC-E-DAA-TN34471).

NASA, Exploration Systems Development Mission Directorate. (2025, April). *Moon to Mars architecture definition document*. National Aeronautics and Space Administration.

NASA's Space Technology Mission Directorate. (2024, July). *Stakeholder Webinar: Civil Space Shortfall Ranking* [Webinar]. NASA. https://www.nasa.gov/wp-content/uploads/2024/07/shortfall-ranking-results-july-2024-508-tagged.pdf?emrc=fd191e

Rokushika, S., Hatano, H., & Hill, H. H. (1986). Ion mobility spectrometry in carbon dioxide. *Analytical Chemistry*, *58*(2), 361-365.

Seeed Technology Inc. (2015). Grove - Dust Sensor User Manual. Retrieved from https://www.mouser.com/datasheet/2/744/Seeed_101020012-1217636.pdf

Wang, J. L., Rosenbaum, J. J., Prasad, A. N., Raad, R. R., Putman, E. J., Harrington, A. D., Aintablian, H., & Hynek, B. M. (2025). Potential Health Impacts, Treatments, and Countermeasures of Martian Dust on Future Human Space Exploration. *GeoHealth*, *9*(2), e2024GH001213. https://doi.org/10.1029/2024GH001213

Ziedan, H., Sayed, A., Mizuno, A., & Ahmed, A. (2010). Onset voltage of corona discharge in wire-duct electrostatic precipitators. *International Journal of Plasma Environmental Science and Technology*, *4*(1), 36-44.

9 Appendices

Appendix A: Teams and Roles

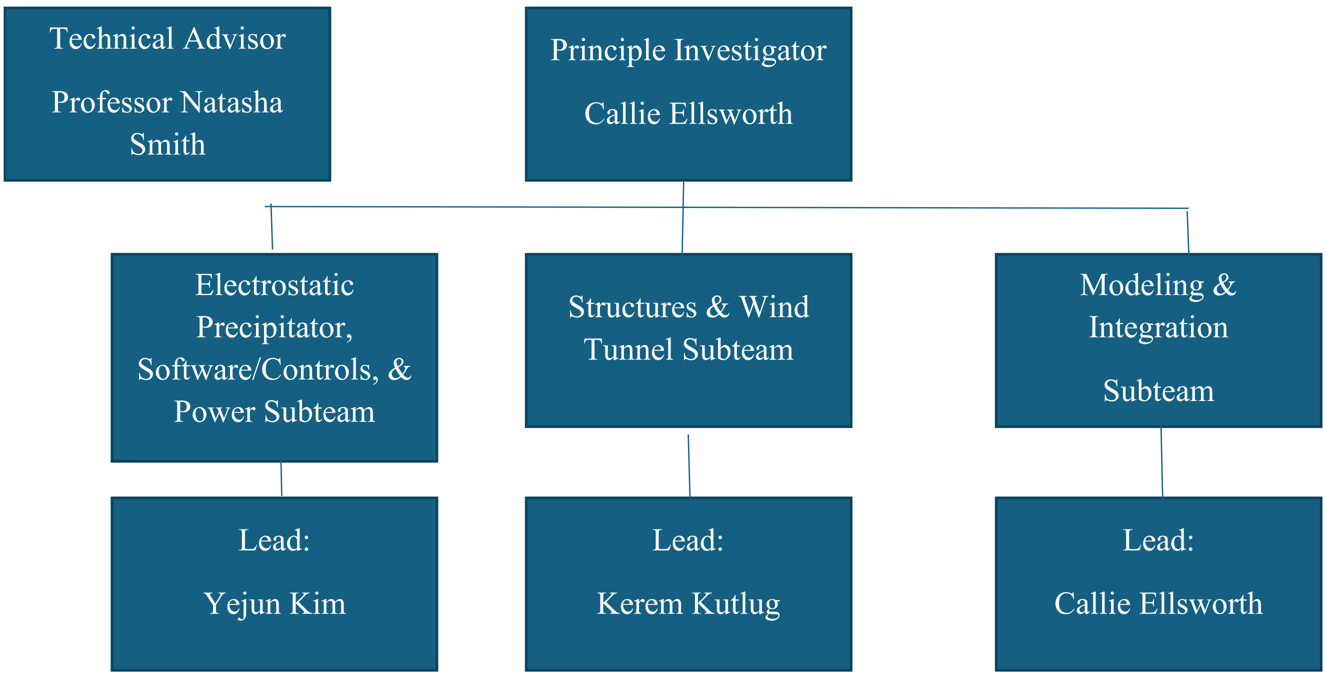


Figure 21: Team Structure

The Electrostatic Precipitator, Software and Controls, and Power subteam analyzed the voltage requirement of the EP as well as examined safety precautions necessary to operate the technology. They found all the software that would be required to have the EP operate successfully in the design. Finally, they examined all the different equipment and the power that it would require to operate.

The Structures and Wind Tunnel subteam determined the best physical design of the external structure would not fail to any forces and accommodate all the internal technology, astronauts, and payloads. They examined the necessary airflow conditions required to have a working wind tunnel that circulates the dust particles into the EP.

The Modeling and Integration sub team modeled the system in CAD and examined the connections of all the different equipment in the design.

Appendix B: Financial Budgets

Conceptual Budget for Production and Operation

Component	Cost ($)
Aluminum Supports	11,500
Mylar Sheets	155
Electrostatic Precipitator	50,000
Fan Assembly	500,000
Dust Sensor	200
Payload	1,000,800
Total	1,562,655

Prototype Budget Spent*

Component	Cost ($)
Dust Sensor	12
Vacuum Pump	55
Fans	36
Total	113

**Initial prototyping efforts were descoped due to time and resource constraints*

Appendix C: Risk Management

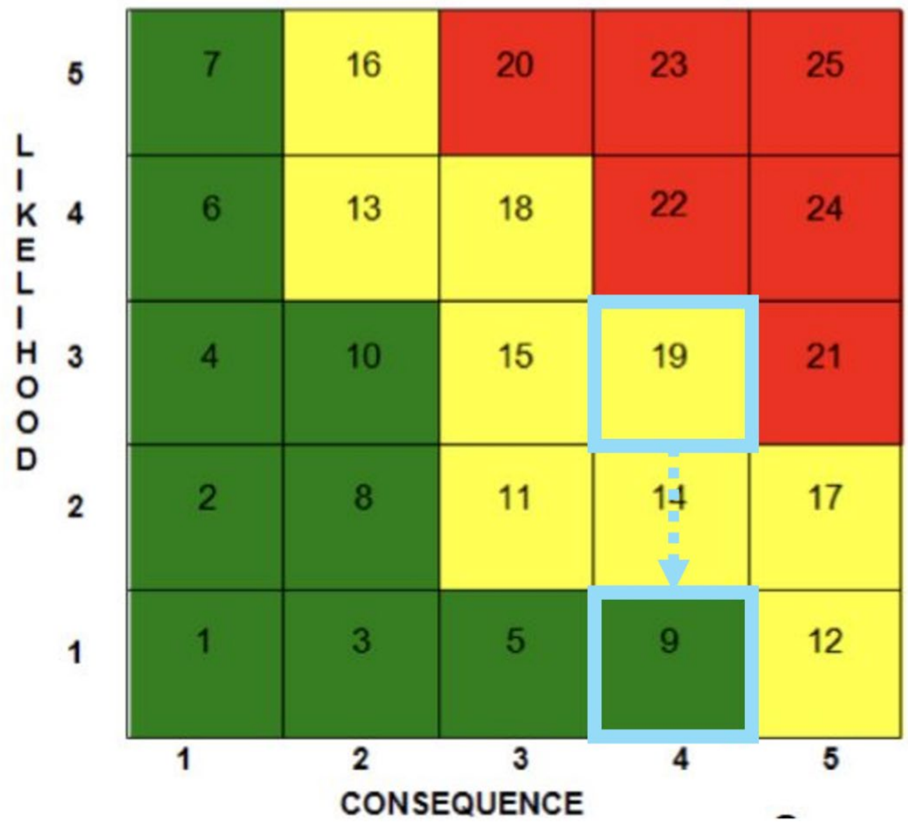


Figure 22: Risk Matrix Walkdown for Risk 1

Risk 1: Dust not collected in EP

Initial:

Likelihood: 3

Consequence: 4

Priority Score: 19

Mitigation: Adjusted design to wind tunnel, verified sufficient wind speeds through analysis

Final:

Likelihood: 1

Consequence: 4

Priority Score: 9

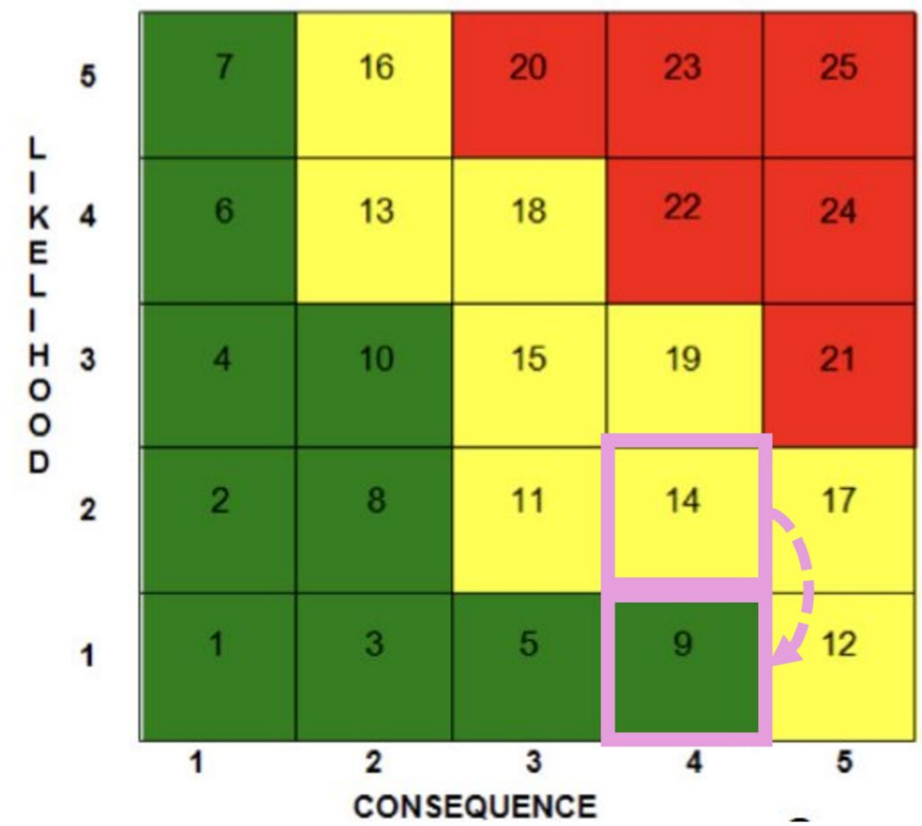


Figure 23: Risk Matrix Walkdown for Risk 2

Risk 2: High voltage from EP shocking astronauts

Initial:

Likelihood: 2
Consequence: 4
Priority Score: 14

Mitigation: Adjusted layout, verified safety zone through analysis, safety process described

Final:

Likelihood: 1
Consequence: 4
Priority Score: 9

Appendix D: Power Budget

Component	Power (kWh)
Fan Assembly	7.35
Dust Sensor	0.04
EP	4
Total	11.39

Appendix J: Mass Budget

Component	Mass (kg)
Mylar Sheets	37
Aluminum Supports	475
Floor	2,065
Floor Supports	51
Fan Assembly	230
EP	50
Wind Tunnel	67
Dust Sensors	1
Hardware (Nuts, Bolts, D-Rings)	135
Total	3,111

Appendix K: Structural Analysis Calculations

1	material properties/knowns				mass calcs		failure calcs (chamber frame)			
2	density (Al)	2710	kg/m^3		474.25	kg (Al)	buckling (cr)		42174.66209	N
3	density (My)	1390	kg/m^3		36.54171	kg (My)	Pcr>P	no buckling		
4	length	10	m		Force calcs		bending (max)		1364620.5	Pa
5	width	3	m		106.6700178	N (My)	bending check	no bending		
6	height	3	m		657.0395	N (Al)	deflection (max)		0.000741642	m
7	E (Al)	6.9E+10	Pa		763.7095178	N (total)	SF (buckling)		331.3406035	
8	t (My)	0.000191	m		127.2849196	N (support)	SF (bending)		202.2540333	
9	t (Al)	0.05	m		75.81225	N (square face)				
10	N (supports)	6					frame bending calcs			
11	gravity	3.73	m/s^2				I (Al)		5.20833E-07	m^4
12	w	25.27075	N/m				M (Al)		28.42959375	N*m
13	yield strength	2.76E+08	Pa				c		0.025	m
14					mass/load calcs					
15	failure calcs (chamber floor)				2065.02	kg (floor)	failure calcs (inner structure)			
16	length	10	m		50.8125	kg (supports)	buckling (cr)		5675022.531	N
17	width	3	m		121.95	kg (columns)	Pcr>P	no buckling		
18	height	3	m		2237.7825	kg (total)	SF (buckling)		20870.70826	
19	t (floor)	0.0254	m		8157.3981	N (total)				
20	t (supports)	0.05	m		271.91327	N (support)	failure calcs (shear stress)			
21	N (supports)	30					V		1000	N
22	h (support)	0.25	m				Q		0.00003125	m^3
23	load force	3189.15	N	buckling (cr)	5675022.531	N	I		5.20833E-07	m^4
24	I (support)	5.21E-07	m^4	Pcr>P	no buckling		t		0.05	m
25	I (floor)	1.37E-06	m^4	SF (buckling)	1779.478084		Max Shear		1200000	Pa
26	M (floor)	398.6438	N*m	bending (max)	3707394.29	Pa				
27	w (floor)	3189.15	N/m	bending (check)	no bending					
28	c	0.0127	m	SF (bending)	74.44581785					
29				deflection	0.001155489	m				

Appendix L: Wind Tunnel Calculations

	A	B	C
1	wind tunnel calcs		
2	density martian air	0.02	kg/m^3
3	Q Earth	470	m^3/s
4	Area wind tunnel	12.56637	m^2
5	Area chamber	9	m^2
6	Q Mars	47	m^3/s
7	drag coefficient	0.5	
8	force (EP)	1.227222	N
9	velocity (chamber)	5.222222	m/s
10	pressure (EP)	0.136358	Pa
11	velocity (tunnel)	3.740141	m/s
12	max external wind	60	m/s
13	external wind pressure	36	Pa
14			