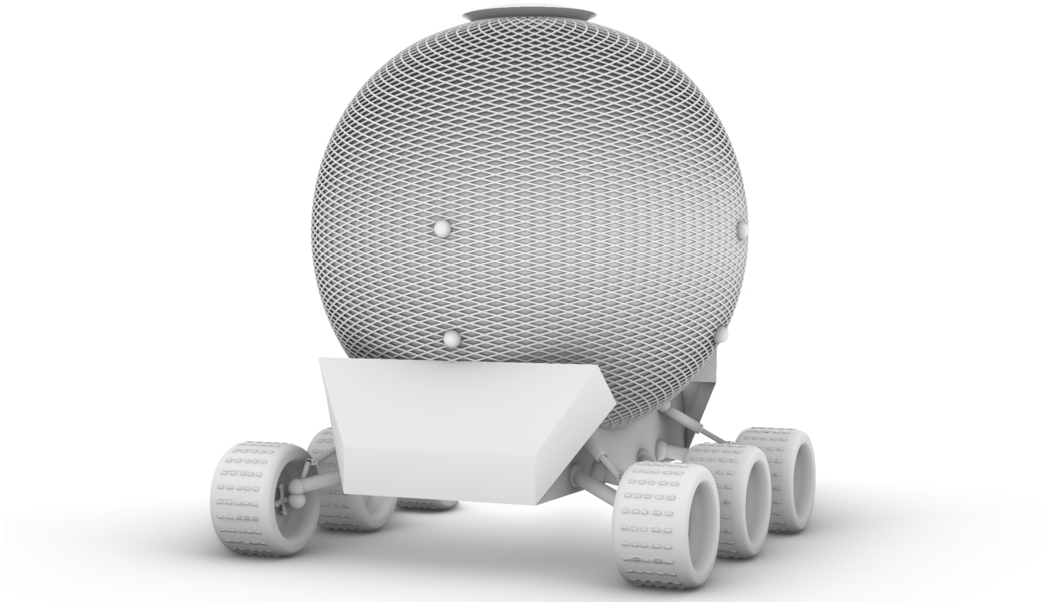
Revolutionary Aerospace Systems Concepts - Academic Linkage

# PROJECT MEPSA

## Methane Production and Storage Architecture

Theme 3: Mars Water-Based ISRU Architecture
2022 Proposal

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**Columbia University**

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# Acknowledgements

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# Quad Chart

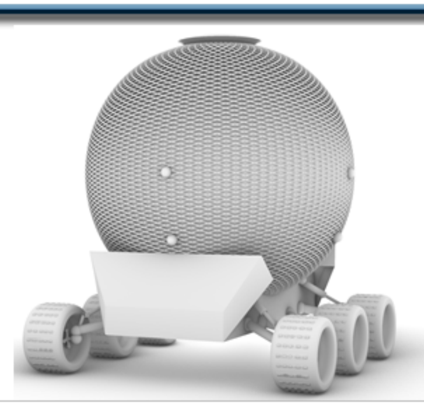
***Columbia University – Project MEPSA***

**Theme: Mars Water-based ISRU Architecture**

**Objectives & Technical Approach:**

- Objectives
  - Sustainable extraction of water from subsurface ice reserve and CO2 from atmosphere
  - Utilize raw materials to generate 50 tons of methane propellant/year, 200 tons of LOX/year
  - Store raw materials safely and securely
- Description of technical approach
  - Identify subsurface water extraction mechanisms, methane generation mechanisms and CO2 extraction mechanisms, giving weightage to novelty, feasibility, safety and effectiveness

**Image:**



**Key Design Details & Innovations:**

- We will be using a MMRTG, capable of generating 110 W of electrical power
- We use a silica aerogel sheet to melt the subsurface ice reserves and efficiently extract the water using vacuum pumps
- We utilize a MOXIE-style system for CO2 extraction; the CO2 used for Sabatier reaction and
- Innovative Sabatier reactor that works on a small scale and avoids catalyst degradation; based on PCI's Microlith-based Sabatier reactor
- We have a spherical storage container to weather Martian conditions optimally, concentric LOX and CH4 storage containers

**Schedule:**

- Project lands on Mars
- Silica aerogel dome deployed
- Water extraction begins, vacuum pumps supply water to rover
- Reactor and storage system on rover start functioning

**Cost:**

- Total proposed budget (1 launch + 1 iteration of ISRU) – ~$200 million

# 1 Introduction

In the future, interplanetary travel between the Earth and Mars will become more and more common, and the fuel demands of such missions will soon surpass what Earth can provide. For this reason, the concept of in-situ resource utilization is incredibly important and a major focus of Martian research today. Specifically, the ability to harvest and use subsurface water ice to synthesize propellant on the Martian surface, without any human interaction, will revolutionize the future of space industry. Highlighting sustainable solutions, renewable systems, and available on-site resources gives humanity a chance to avoid anthropocentric problems that inevitably arise in the future. With an innovative approach to this growing issue, the Columbia Space Initiative, RASC-AL presents MEPSA: Methane Production and Storage Architecture.

# 2 System Overview

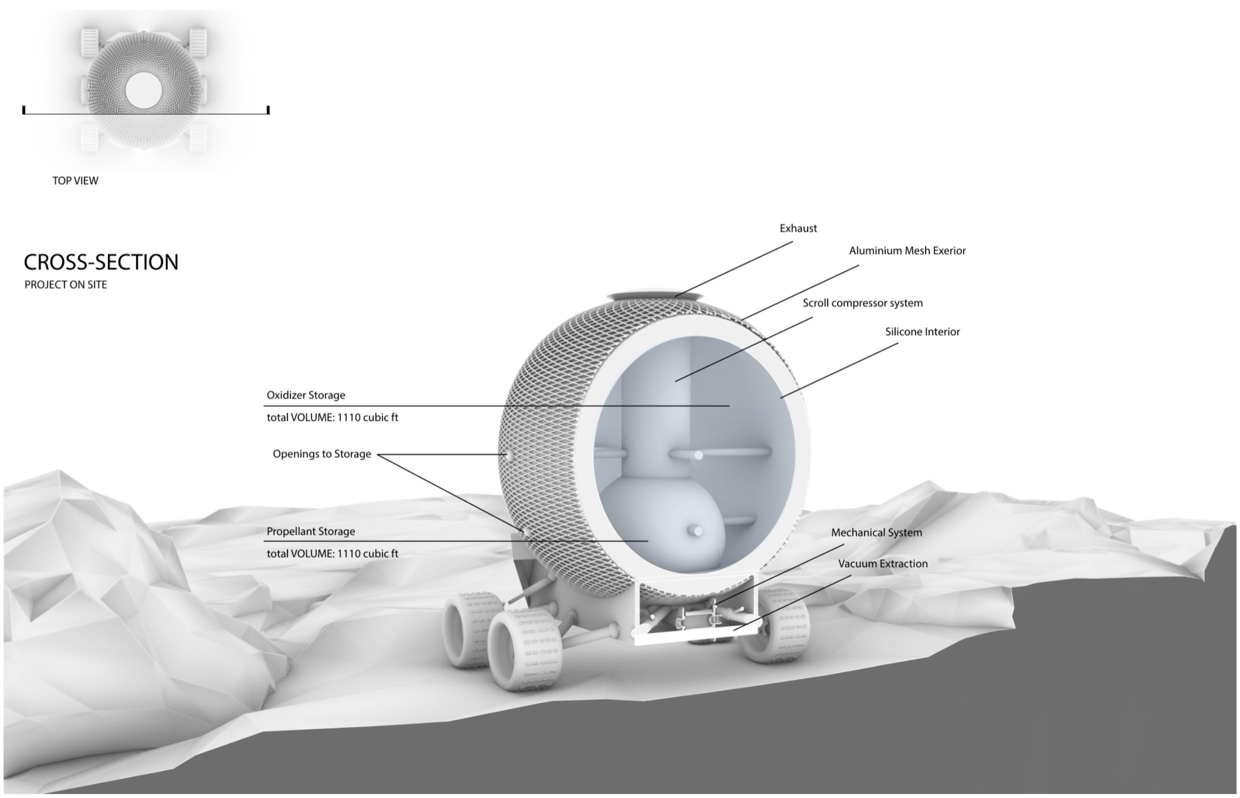



**Figure 1:** Drawing of proposed architecture.

Our fully autonomous and self sustainable proposal consists of elements that are coherently working together to maximize productivity and volume efficiency. The overall morphology of our structures is serving as a pressure vessel. The larger volume serves as a storage facility for oxidizer, protected by 2” the layer of silicone on the inside, while its core hosts a smaller volume for methane storage and a scroll compressor system. At the top of the structure, an exhaust as well as navigational mechanical systems allow full on-site supervision over the movement and condition of our structure. The material for exterior is aluminum, and a carefully designed mesh-like looking exterior facade allows the fully volumetric intake of CO2 from Martian Atmosphere, directly into the scroll compressor system. The bottom of the structure holds silica aerogel sheets used for vacuum H2O extraction, and mechanical systems for a fully autonomous movement of our proposal. Moreover, the location of energy units of the exterior, with wiring relatively close to the bottom surface of our project, allows us to project the generated heat into our advantage of H2O extraction.

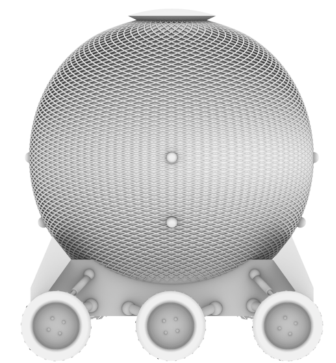


**Figure 2:** Model front view

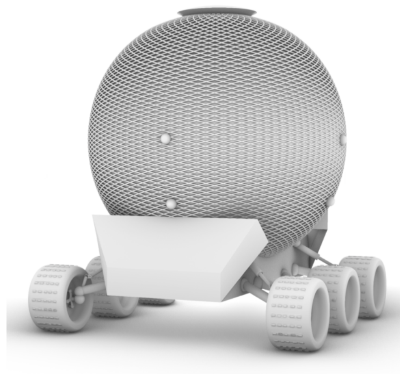


**Figure 3:** Perspective view 1

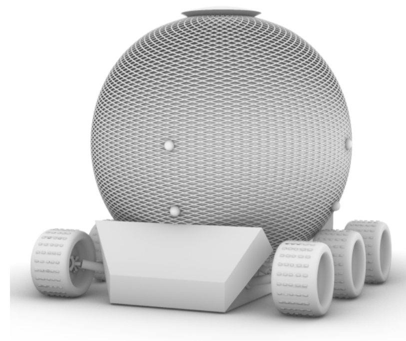


**Figure 4:** Perspective view 2

In the case where more than a singular structure is created, two systems are able to autonomously connect under careful management of structures' alignment. A total of 8 openings (2 on each side) to the storage facility are able to link together in order to maximize storage volume's efficiency and overall structures' stability.

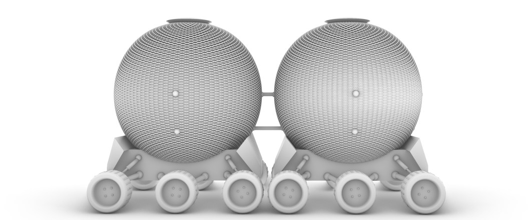


**Figure 5:** Front-to-back connection

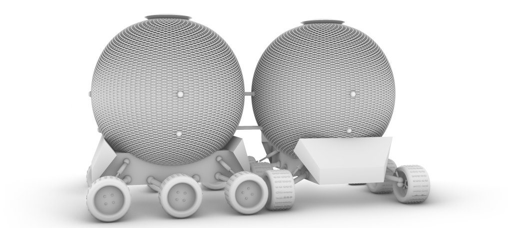


**Figure 6:** Back-to-side connection

## 2.1 Region of Interest

### 2.1.1 Identified Potential Location A: Oxia Palus Quadrangle

Other than Martian North and South Poles, our studies have shown that mid-northern latitudes are more suitable and feasible for our proposal. Research from NASA JPL, relying on Mars Climate Sounder (MRO) and the Thermal Emission Imaging System (THEMIS) camera on Mars Odyssey, has shown that water in the state of ice is locked away underneath the regolith. Our team selected and focused on the Northern Martian Hemisphere, to identify the best potential location. With information gathered from multiplicity of resources and scientific studies, Oxia Palus Quadrangle has shown the most promising data. One of the key features is the presence of a dense soil, which would allow for a successful landing of an aircraft, and would prevent our architecture from sinking or being stuck at any point of its movement, or working processes. At the same time, this region, once rich with rivers and lakes, has shown vast amounts of water presence right underneath the regolith. Importantly, regions from this quadrangle were selected by NASA, as one of the potential future human landing sites.

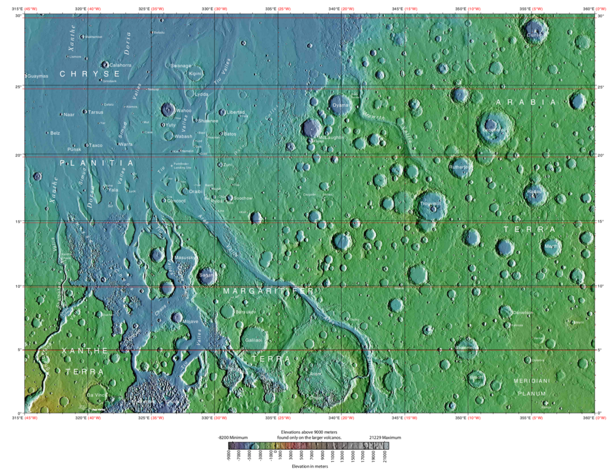



**Figure 7:** Map of Oxia Palus quadrangle from Mars Orbiter Laser Altimeter (MOLA) showing the lowest elevations in blue.

### 2.1.2 Identified Potential Location B: Condor Chasma in Valles Marineris

The second potential location for our proposal is Condor Chasma, situated in Valles Marineris' northern part. It is the largest canyon of Valles Marineris, and it is approximately 810 km long. Based on studies published by NASA JPL in late 2021, this region has also shown an extremely rich presence of water ice right underneath the regolith. Importantly, the location of this region is in low latitudes, hence the temperatures are not as low and severe as they are in regions close to North or South Martian Poles.

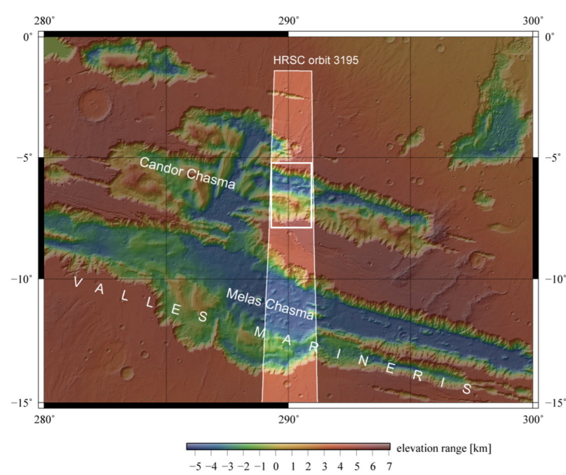



**Figure 8:** Candor Chasma.

# 3 Extraction System

## 3.1 Propellant Acquisition and Extraction

Instead of drilling for water using extensive/intrusive machinery, we propose an idea to simulate a greenhouse effect on Mars. Studies have shown that silica aerogel sheets could both block harmful radiation and insulate heat to successfully melt subsurface water ice. This water would mix with the Martian regolith to create a usable Martian soil for farming, as most studies suggest to use this method for, but we instead propose extracting the water directly from the soil to use as propellant. It is expected that over two Martian years, a usable water reservoir could form under these massive silica aerogel domes. Using a vacuum extraction method, the water could be extracted and then used for propellant.

Although this may seem like a long process, space exploration usually happens at a steady pace, and mining water from a planet will not be an overnight project. Unlike other extraction methods that involve drilling, this method is much more sustainable and multi-purpose, as the radiation-blocking aerogel domes could be used for habitation both on the Martian surface and en-route to Mars. The conventional purpose of farming and insulating heat in a Martian settlement would also play a role. Additionally, this method is far less intrusive to the planet, which ensures that it can be utilized in the long term without severe damage. Finally, silica aerogels are 97% air, so they weigh almost nothing and could be transported in large quantities without the need for heavy payloads or high cost missions.

What is unique about this proposal is how sustainable the water source is. Although the RASC-AL guidelines requires for the mission to collect 50 tons of water per year minimum, this yield will grow exponentially, as the simulated greenhouse effect continuously warms the surface and increases subsurface temperatures past the melting point of water. The following approximate calculations are based on data from the Harvard School of Engineering and Applied Sciences regarding temperature increase from aerogel greenhouse effect and an estimation from Arizona State University that concentrated areas on Mars contain 10% subsurface water ice.

From the Harvard data, it appears that after one year, regolith up to 1.7 meters deep will be past the melting point of water. If the dome is assumed to be one square mile (2.59 x 106 sq. meters) and the water concentration is expected to be 10%, the yield after one year would be 116,000,000 gallons of water, or 156,000 tons. This is over 3000 times the 50-ton/yr requirement.

As a result, the area of the dome can be sufficiently decreased, instead around 860 square meters. This would yield slightly over 50 tons of pure water after the first year. However, it is important to keep in mind that this number would only grow every year, causing an ever-increasing yield without needing to expand the dome or introduce new machinery to the area, making this proposal especially sustainable and plausible.

If the 860 square meter dome is to be pursued, the radius of the circular base would have to be slightly over 16 meters. As such, the surface area of the dome would require 1720 square meters of 2.5cm silica aerogel sheets. This corresponds to 43 cubic meters of silica aerogel, with an estimated density of only 1000g/m3. This means that all of the silica aerogel would only weight 43kg, which is nowhere near the allotted 45 tons of payload, nor 300 cubic meters of volume. Since the aerogel sheets will not take up as much space, there is now more space available for the vacuum extraction method to be implemented so that the water can be harvested and purified.

As for deployment, the dome would be autonomously set up, similar to a tent. Inspired by the space industry's recent exploration into inflatable habitats, the dome would be assembled as much as possible on Earth, wrapped up, and then set to deploy upon arrival to the surface. Since only the thin aerogel sheets are needed, no additional structural material will be necessary, except for a steel frame that is staked into the Martian regolith to keep the structure secure. For an estimated circumference of 100 meters, a 2 x 2 cm steel beam, the total weight, including the stakes, would only be around 350 kgs or 0.385 tons, which would not add significantly to the cost or size of the mission.

## 3.2 Propellant and Oxidizer

The most essential component of constructing the ISRU system is identifying the optimal propellant and oxidizer.

One of the most common oxidizers is liquid oxygen, also referred to as LOX. It is frequently used as an oxidizer for liquid/cryogenic propellants. LOX does not contain other inert elements which could dilute its effect, and it is suitable with a wide variety of fuels. $O_3$, ozone, is a higher energy form of LOX, but is extremely unstable, and hence cannot be used as a fuel. Another possible replacement for LOX is FLOX (contains 60-70%$F_2$); however, FLOX is extremely toxic. Cryogenic solid replacements for LOX - $OH_2, CO$, solidified $O_2$ - have been primarily restricted to the laboratory and are inconvenient and expensive. On the other hand, due to the widespread use of LOX as an oxidizer, space organizations have extensive experience with problematic scenarios and have performed extensive research on easier in-situ generation mechanisms. Hence, we chose LOX as our oxidizer of preference.

The choice of propellant is a significantly more complex decision to make. We have innumerable options - from RP-1 to $CH_4$ and 2,3-BDO - with each option having advantages of its own. We place emphasis on a few important conditions including, but not limited to specific impulse, higher heating value, mass of propellant required for a given $\Delta v$ and expected O/P ratio. If there is a point of confusion, we qualitatively evaluate the ease of generation of propellant on Mars' surface. The relevant information can be found in Table 1.

Any unknown propellant mass values were computed using the following formula, as in Kruyer et al. 2021:

$$m' = m_e e^{\frac{I_{sp}}{I'_{sp}} \log \frac{m}{m_e}} = 4.6\,tons$$

Here, $m_e$ is the mass of the empty Mars Ascent Vehicle, set to 8.542 tons for all propellant mass calculations for regularity (Kruyer et al. 2021); $m'$ is the required propellant mass we want to evaluate (in our case, the propellant for which we wanted to evaluate the required

| Criteria | Methane | 1,2-ethanediol | 2,3-butanediol | RP-1 | LH2 |
|---|---|---|---|---|---|
| Boiling point (deg $C$) | -162 | 197 | 184 | 216 | -253 |
| Melting point (deg $C$) | -187 | -12 | 19 | -10 | -259 |
| Specific Impulse (s) | 459 | 396 | 420 | 370 | 391 |
| O/P ratio (kg/kg) | 4:1 | 1.29:1 | 1.96:1 | 3.48:1 | 6:1 |
| HHV (MJ/kg) | 50.1 | 19.2 | 27.3 | 43.1 | 142 |
| Propellant mass (ton) | 6.4 | 12.1 | 8.4 | 7.1 | 4.6 |

**Table 1:** Table that compares data of probable fuels [2][3][4].

propellant mass is $LH_2$ - liquid hydrogen). $I'_{sp}$ is the specific impulse of $LH_2$. $I_{sp}, m$ are the specific impulse and required propellant mass of methane, respectively.

From the data in Table 1, we can clearly see that methane, 2,3-butanediol and $LH_2$ are the best possible choices for a propellant. It must be noted that $LH_2$ has a much lower melting point, and is thus harder to store than methane or 2,3-BDO. Furthermore, the LOX/$LH_2$ ratio is unfeasibly high, at 6:1. Secondly, although 2,3-BDO has a lower O/P ratio and somewhat favorable properties, generating 2,3-BDO (from glucose, Kruyer et al. 2021) is significantly harder than generating methane (using the Sabatier reaction), especially on the surface of Mars.

Hence, the propellant Project MEPSA will generate in-situ is $CH_4$, methane.

## 3.3 Raw Material Filtration and Transfer

We will transfer the water extracted from the vacuum pump to the section of the rover that deals with processing the $H_2O$. Before utilizing the water for propellant generation, we need to get rid of the raw material of pollutants that could hinder the propellant generation. For this, we shall use a filter relying on silver nanoparticles embedded in an aluminium-chitosan cage for an initial (possibly targeted, utilizing the nanoparticles) filtration (Sankar et al. 2013), proceeded by a small-scale electrolytic filtration system to eradicate remaining pollutants, and extract $H_2$ and $O_2$ from the water. The $H_2$ will be sent to the propellant generation center, and the $O_2$ will be cooled and directed to the LOX storage container. Therefore, using Sabatier reaction is imperative in this situation.

## 3.4 Propellant Generation

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

$\Delta H_0 = -165$ kJ/mol

The above is the Sabatier reaction, the reaction used to produce methane and water from carbon dioxide and hydrogen. For every mole of CH4 propellant needed (16g), 1 mole of water needs to be extracted (18g), and 1 mole of CO2 needs to be obtained from the Martian atmosphere (44g). The water output from the Sabatier reaction will be condensed and redirected to the electrolytic filtration unit to resupply for the Sabatier reaction. However, the Sabatier reaction is an industrial process with complexities like the Bosch process ($CO_2 + 2H_2 \rightarrow C(s) + 2H_2O$), which slows up the catalyst. We need to avoid such complexities while scaling down the Sabatier reaction to more feasible scales. We will therefore be using the Microlith-based small-scale Sabatier reactor - microlith is a technology patented by Precision Combustion, Inc. - PCI. PCI's approach to a small-scale exothermic Sabatier reaction achieves high $CO_2$ conversion and high $CH_4$ selectivity without catalyst degradation (Junaedi et al. 2011). We will be using a larger (corresponding to the $CO_2$ output we need) version of PCI's Microlith-based Sabatier reactor.

## 3.5 Carbon dioxide extraction

To perform the Sabatier reaction, and to obtain sufficient $O_2$ to have enough LOX, we need to extract $CO_2$ from the Martian atmosphere. This question has already been addressed by previous NASA ISRU-based projects like MOXIE, the Mars Oxygen ISRU Experiment. We will use a scroll compressor to extract $CO_2$ from the Martian atmosphere (as in MOXIE) and we will direct two-fifth of the extracted $CO_2$ to the Sabatier reactor and the remaining three-fifths through a solid oxide electrolysis unit (as in MOXIE) to convert the $CO_2$ to $O_2$ (Hecht et al. 2020).

## 3.6 Propellant Liquefaction and Refrigeration

There are several liquefaction methods in use currently - specifically, leading methods include conduction, broad area cooling, in-tank heat exchange, the Linde Cycle, the hydrogen Claude cycle, and in-line liquefaction. For ISRU use on the surface of Mars, a broad area system using reverse Turbo-Brayton cooling architecture, as seen in Figure 9 , is selected due to its small scale design being optimal for a ISRU propellant plant, as well as its performance in Desai et al. Broad area cooling works by circulating a fluid, in this case helium, through a network of tubes covering the cryogenic tank. The helium is used to absorb any heat that would otherwise get to the propellant. Reverse Turbo-Brayton architecture is unique in how it only requires one gas cooling loop and heat exchanger.

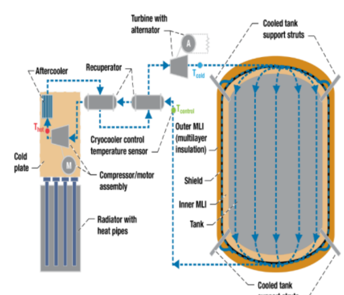



**Figure 9:** Broad Area Cooling (Desai et al. 2017)

## 3.7 Propellant Liquefaction and Refrigeration

Another reason to use broad area cooling architecture is that Reverse Turbo-Brayton systems are able to achieve zero-boiloff for storage of cryogenic rocket propellant over long periods of time . Parasitic heat causes liquid propellant to vaporize, which causes the storage tank pressure to increase, eventually to a dangerous level. In order to mitigate this pressure buildup, such tanks have to be adequately vented, which leads to a significant loss of propellant. This loss, in turn, leads to future missions having to carry more fuel, increasing mission mass. A 90 Kelvin, 500 Watt cryocooler from the company Creare will be used to power this system, as seen in Figure 10. Modeling was run on the proposed system by Desai et al. , and it was determined that to achieve an average net refrigeration of 500 W, the power required by the cryocooler was 4750 W.

Desai et al. also ran a simulation comparing the liquefaction rate for a tank that began with a 1% liquid fill level vs. a tank that began with a 90% liquid fill level (seen in Figure 10). In both cases, it was determined that the liquefaction rate oscillates around 2.2 kg/hr, although there is a sharp rate drop at 99% for the tank that began with 90% liquid fill level. It was determined by Desai et al. that usage of this architecture on Mars can potentially reduce cryocooler mass and power consumption by 20%.

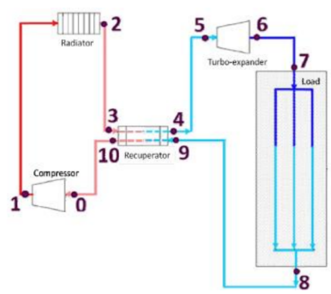



**Figure 10:** Single Stage Reverse Turbo-Brayton Cycle Cryocooler System (Desai et al. 2017)

### 3.8 Power System

For the power system of our project, we propose to use a multi-mission radioisotope thermoelectric generator, or MMRTG. This is RTGs most recent system, which generates about 110 watts of electrical power at launch.

## 4 Project Timeline

- Project lands on Mars
- Silica aerogel dome deployed
- Water extraction begins
- Vacuum pumps supply water to rover
- Reactor and storage system on rover start functioning
- LOX and $CH_4$ storage containers start getting filled

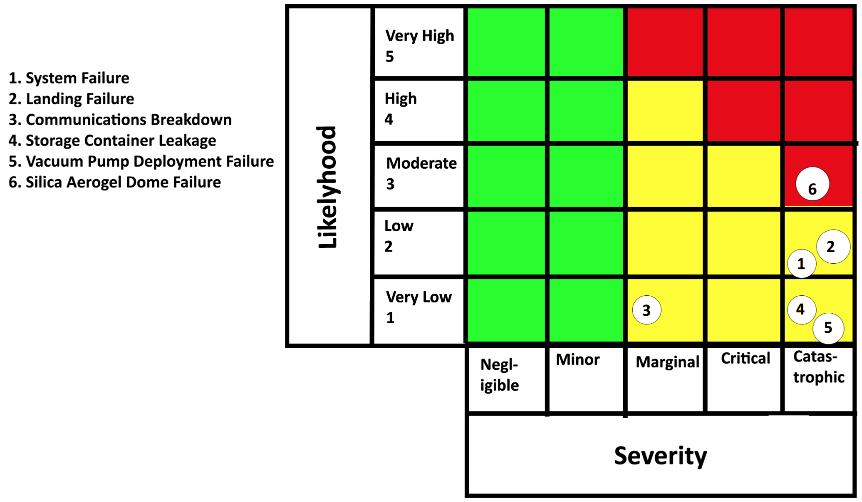



**Figure 11:** Risk chart

# 5 Risk and Budget Assessment

Based on a cursory analysis of costs of existing unmanned missions to Mars, excluding the travel costs, we estimate a net cost of almost 200 million dollars.

# 6 Conclusion

Part of space exploration requires an acknowledgement of intervention humanity is able to cause within the limitless boundaries of extraterrestrial space. The notion of limitlessness is conceptual, as any human intervention has a consequence, especially the long-term price humanity must pay. Project MEPSA, by Columbia Space Initiative is an innovative and sustainable approach to utilizing ISRU Resources, paving the way for humanity to settle on Mars, and further explore our solar system.

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