MITHRIL
Mars Ice Thermal Harvesting Rig and ISRU Laboratory
NASA Revolutionary Aerospace Systems Concepts - Academic Linkage (RASC-AL) 2022
Theme 3: Mars Water-based ISRU Architecture

The Illinois Space Society in Collaboration with Honeybee Robotics
Department of Aerospace Engineering
Grainger College of Engineering
University of Illinois, Urbana-Champaign

Project Manager: Alec Auster, Junior, Aerospace Engineering
Faculty Advisors: Michael F. Lembeck, Ph.D. & Zachary R. Putnam, Ph.D.
Graduate Student Advisor: Linyi (Tiger) Hou

Team Members

Alec Auster  
Junior  
Aerospace Engineering

Alonzo Arostegui  
Junior  
Aerospace Engineering

Ishaan Bansal  
Freshman  
Aerospace Engineering

Ana Bojinov  
Freshman  
Aerospace Engineering

Grant Davis  
Sophomore  
Aerospace Engineering

Gautam Dayal  
Freshman  
Math & Computer Science

Madison Frankenthor  
Freshman  
Aerospace Engineering

Shikhar Kesarwani  
Freshman  
Aerospace Engineering

Jack Kosciarz  
Freshman  
Aerospace Engineering

Ariana Kulesar  
Freshman  
Aerospace Engineering

Brody Lauer  
Junior  
Aerospace Engineering

Eugene Lim  
Freshman  
Aerospace Engineering

Sara McCarthy  
Freshman  
Aerospace Engineering

Zoe Mihevc  
Sophomore  
Mat. Science Engineering

Katharine Moy  
Freshman  
Chemical Engineering

Madeline Odeen  
Sophomore  
Aerospace Engineering

Komol Patel  
Junior  
Aerospace Engineering

Atishi Porwal  
Freshman  
Aerospace Engineering

Avinash Raju  
Sophomore  
Aerospace Engineering

Fuad Samhouri  
Junior  
Aerospace Engineering

Riya Shah  
Freshman  
Aerospace Engineering

Galen Sieck  
Freshman  
Aerospace Engineering

Alan Wang  
Freshman  
Computer Science
Objectives & Technical Approach:

- Provide at least 50 tons a year of methalox propellant to support future Mars systems.
- Advance the maturity of in-situ resource utilization technology to support human spaceflight and expand NASA’s ability to perform more ambitious exploration of the Martian surface.
- Adapt "Rodwells” for use on Mars.

Key Design Details & Innovations:

- STING provides abundant quantities of water for a proportionally small power requirement.
- Rodwell used as heat sink for surface fission systems.
- Scaled up Microlith Sabatier reactors to meet production requirements.
- Inflatable cryogenic storage tanks with insulation panels to optimize volume and reduce mass.
- Robotic set-up and maintenance for autonomous operations.
- Readily scaled for increasing propellant demand.

Schedule:

- Design and Development begins in FY 2023.
- Technological maturity achieved in FY 2030.
- Fabrication, Integration, and Testing FY 2030-2035.
- Final assembly and launch FY 2035.

Cost:

$21.1 Billion
(Includes operational cost through 2042)
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I. Introduction

The fourth planet from the Sun, Mars has captured the human imagination over the annals of history, and represents humanity’s next step through the stars. With a thin atmosphere and a third of Earth’s gravity, the austere, dusty red planet houses a secret buried 2 billion years ago: water ice. In compliance with the NASA RASC-AL 2022 Mars Water-based ISRU theme requirements, the University of Illinois and Honeybee Robotics present the Mars Ice Thermal Harvesting Rig and ISRU Laboratory (MITHRIL) to extract and leverage this water in order to manufacture and store at least 50 t of liquid methane and liquid oxygen per year. MITHRIL has a total mass of 21.6 t, a total volume of 97.2 m$^3$, and a total power of 58.47 kW; each increasing to 24.8 t, 111.81 m$^3$, 67.23 kW respectively with the addition of a 15% margin. This enables the architecture to be delivered on a single lander, reducing mission complexity while still meeting the Theme Requirements outlined in Table 1.

Table 1 Theme Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>MR-01</td>
<td>The architecture shall produce $\geq$ 50 t/year of propellant for future Mars systems</td>
<td>II.A, III.B, IV, V, VI.A</td>
</tr>
<tr>
<td>MR-02</td>
<td>The architecture shall store $\geq$ 50 t of liquid propellant for future Mars systems</td>
<td>VI.B, VII.A</td>
</tr>
<tr>
<td>MR-03</td>
<td>The architecture shall be packaged into units of $\leq$ 45 t</td>
<td>II.C, III.A</td>
</tr>
<tr>
<td>MR-04</td>
<td>The architecture shall be packaged into units of $\leq$ 300 m$^3$</td>
<td>II.C, III.A</td>
</tr>
<tr>
<td>MR-05</td>
<td>The architecture shall operate without human intervention</td>
<td>III.A, VII.A, VII.B, VII.C</td>
</tr>
<tr>
<td>MR-06</td>
<td>The architecture shall operate for $\geq$ 5 years</td>
<td>II.A, II.B, VII.A, VII.B, VII.C</td>
</tr>
</tbody>
</table>

These requirements have been decomposed and collected into a hierarchy of Level 1 Requirements in Appendix XII.A, each corresponding to a physical system within the architecture. Decision matrices and detailed technology trades weighing characteristics such as mass, power, and technology readiness level (TRL) are provided in Appendix XII.D.

II. Mission Overview

A. Subsurface Ice and Architecture

Many prospective sources of water ice exist on Mars, and the decision of which to tap into is integral to any potential water-based ISRU. The poles offer vast quantities of ice; the North revealing massive glaciers in summer after the overlying CO$_2$ sublimes away, the South permanently hidden. Both, however, are unsuitable for human exploration due to long periods of seasonal darkness during local winter and the unfavorably low visibility due to subliming CO$_2$ during local summer, thus making sites closer to the equator more attractive [2, 3]. The Martian atmosphere also contains trace amounts of water vapor:

![Fig. 1 Architecture Trade Tree](image1)

![Fig. 2 Prospective Sites Analyzed](image2)
approximately 1 kg per 250,000 m$^3$. Leveraging this supply is theoretically possible, but would require an air-handling system on the same order of magnitude as the largest air compressors on Earth (65 MW, 250 m$^3$) to produce 5 t/year of water, which is far below feedstock requirements for MITHRIL and therefore impractical for delivery to Mars [4]. The two most promising sources of water are ice sequestered in regolith and buried ice glaciers. These reserves occur throughout the mid latitudes, closer to the equator, and offer substantial quantities of water to fulfill requirement MR-01. The former was detected by the Mars Reconnaissance Orbiter’s (MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) and Mars Express’ Infrared Mineralogical Mapping Spectrometer (OMEGA). These deposits consist mostly of phyllosilicates (clay minerals), chlorites, and sulfates, and typically carry 2-9% water by weight. Initial research determined that excavating enough regolith to extract the necessary amount of water would require multiple football fields worth of regolith per year at 3% water content at a depth of 5 cm [4, 5]. This was deemed unsustainable in order to meet MR-06 due to the sheer real estate such an excavation effort would require, and the complex planning necessary to map out where it would occur. For subsurface glaciers, evidence of ice sheets have been found between latitudes of 20-55° North and South in the form of Lobate Debris Aprons (LDAs), Lineated Valley Fills (LVFs), and Concentric Crater Fills (CCFs), representing distinctive geomorphic landforms with creep and deformation of ice-rich debris [6]. Impact craters in these regions have also revealed clear ice. Mars Reconnaissance Orbiter’s (MRO) Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) measured <1% regolith content in these formations [7, 8]. The MRO Shallow Subsurface Radar also collected data consistent with hundreds of meters of relatively pure ice (>90%) roughly 0.5-10 m below the surface [9]. To identify potential extraction sites of near-surface glacial ice, data from the Subsurface Water Ice Mapping (SWIM) tool was analyzed using the Java Mission-planning Analysis for Remote Sensing (JMARS) platform [1, 10]. Fifteen prospective locations between latitudes of 28-47° North and South were analyzed in Table 18 in Appendix XII.D to establish bounds on climate and proximity to ice. The location of these sites can be seen in Fig. 2. From this information, a vertical profile of the Martian surface is assumed and provided in Fig. 3 [2, 10]. In the coming decade, a new round of analysis, the Subsurface Water Ice Mapping on Mars for the "International Mars Ice Mapper" (SWIM4IMIM), will focus on determining the southern limit of accessible water ice. SWIM4IMIM is a part of the International Mars Ice Mapper mission (IMIM), a greater effort that will identify the location, depth, spatial extent, and abundance of near-surface ice deposits, which can be leveraged to further refine assumptions regarding ice access during mission development [10, 11].

One method of accessing subsurface ice, Rodwells, quickly surpassed any other option in scalability, sustainability, and reduced size. Developed by Army engineer Raul Rodriguez, Rodwells are a type of water well used to create a cavity deep under a glacier’s surface to melt and collect water [2]. Such a well would only require approximately 30 m$^3$ of ice, about a third the size of a semi-truck, per year to meet theme requirements. As a result of the geometry of the well, Rodwells are easily scalable in volume through the addition or reduction of heat flux, all while maintaining a single stationary access point; providing Rodwells a clear advantage in meeting an increasing propellant demand as NASA expands surface exploration efforts on Mars. Rodwells have been in service in polar regions, a relevant analog, for over 60 years on Earth as well, which has provided sufficient experience with this technology to raise it to TRL 6 [2, 13]. Furthermore, work by Honeybee Robotics has bolstered the robustness of a Rodwell approach with the TRL 5 Redwater system. End-to-end testing in the option period will raise this to TRL 6 [14].
these reasons, Rodwells were selected as the method of water-based ISRU for MITHRIL. A comprehensive trade tree for this choice is provided in Fig. 1.

Fig. 5 MITHRIL Development Timeline

B. Timeline

MITHRIL Design and Development begins in fiscal year (FY) 2023 with a Mission Concept Review to define the mission architecture and evaluate concepts to meet the stated objectives. System Requirements and Mission Design Reviews take place in FY 2024 and 2026 to validate mission requirements and ensure compliance of the proposed architecture. Through Preliminary and Critical Design Reviews, the design is matured, followed by fabrication of mission elements. Assembly, Integration, and Test takes place from FY 2029 to FY 2035. Delivery of MITHRIL to the Martian surface is provided by NASA’s Launch Services Program. The details of the procurement for delivery services are expanded on in Sections II.C and VIII. Qualification is completed in FY 2035, with launch slated for mid-year. MITHRIL arrives and begins mission operations in FY 2036Q1, ready to fuel future Mars systems by FY 2037Q1. Autonomous sustainment efforts continue through at least FY 2042 to meet Requirement MR-06 and justify the program costs outlined in Section VIII. Future analysis aligns MITHRIL’s mission with the launch cadence and arrival of future Mars systems, and Section IX describes how the architecture can be scaled to meet and increasing propellant demand through the introduction of resupply missions, or by leveraging spares.

C. Delivery

In accordance with MR-03 and MR-04, MITHRIL is compatible with any rocket and lander with a cylindrical 300 m$^3$ envelope and 45 t payload capability. Currently, the only launch vehicles capable of carrying cargo of this size to Mars are Starship/Super Heavy and SLS block 1B or later, both with a diameter of 8 m [16, 17]. For the landing system, Starship is also capable of delivering MITHRIL, whereas only conceptual Mars landers have been identified within the SLS-based architecture as of this date [18, 19]. A range of cost estimates is provided for each delivery system in Section VIII. Upon delivery to the surface, the lander is assumed to be capable of arriving within the mid-latitudes between 20-50° North or South. Current Entry, Descent, and Landing (EDL) accuracy, as demonstrated by Perseverance, is a landing ellipse 7.7 km by 6.6 km [20]. By 2035, landing precision is expected to have improved to 200 m [21]. From Section II.A, the distance between two prospective glaciers is assumed to be at most 10 km apart from one another, thus well within reach of the transportation system outlined in Sections II.D and III.
D. Concept of Operations

MITHRIL is composed of 4 major systems: The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) rover, the Subsurface Targeted Ice miniNG (STING) system, the SABatier and water Electrolysis Refinement (SABER) unit, and inflatable cryogenic storage tanks. Following touchdown, the architecture is unloaded to the surface, and ATHLETE immediately begins searching for prospects for a suitable glacier using ground penetrating radar (GPR). Once a location is identified, ATHLETE transports and deploys all surface elements. Water ISRU operations then commence with STING, which drills through the overburden and starts melting subsurface ice with a heater integrated into the drill bit to initiate a Rodwell. The water is pumped out of the well and into an insulated water tank, which is heated with waste heat from a nearby, highly radiation-shielded, Kilopower Reactor Using Stirling TechnologY (KRUSTY) fission surface unit. Once enough hot water has accumulated in the tank, it is jetted and pumped cyclically through the well and reactor heat exchanger, and takes over as the primary heat delivery mechanism. Once in steady state operation, a portion of extracted water is sent to SABER, where it is distilled, filtered, and electrolyzed to produce oxygen and hydrogen. The hydrogen is fed to a set of Sabatier reactors, where it reacted with carbon dioxide from the atmosphere to produce methane and water. The latter is sent back to the electrolyzer for further processing, while the methane and oxygen are sent to storage. The storage system consists of a pair of inflatable tanks, each under a set of panels using Multi-Environment Multiple Layer Insulation (MEMLI) and using Reverse Turbo-Brayton Cryocoolers (RTBC) with Broad Area Cooling. An array of six additional low-shielded KRUSTY units power the architecture from afar, and communication links ensure cohesive operations and links to Earth. MITHRIL is designed to operate for a minimum of 5 years, and can leverage spares and resupply missions to meet increasing propellant demand if additional capacity is desired.

Fig. 7 MITHRIL Concept of Operations

III. Surface Deployment

A. Martian Surface Transport

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) is used for surface transportation (see Fig.8) and positioning cargo directly on the surface [22]. This TRL 6 rover has a pallet supported by six independently attached legs which can function as lifting arms capable of deploying cargo from the lander [15]. As an alternative to lifting cargo onto itself with a crane, ATHLETE can separate into two "Tri-ATHLETE" components [23]. These components can connect to a pallet which lowers itself down.
desired payload is then placed on the pallet, then lifted upwards [15]. For small components and precision positioning, ATHLETE utilizes a 5 degree-of-freedom, 2 pronged end-effector with a length of 1 m and a carrying capacity of 34 kg [24]. Throughout the deployment process, cables and tubing will be set up using ATHLETE’s 2 pronged end-effector, while larger components will be placed using ATHLETE’s crane arm capabilities. ATHLETE is sized for a payload capacity of 2105 kg, not including 790 kg of batteries operating at 60% Depth of Discharge (see XI.D) and 20 kg of support equipment. The rover itself has a stowed volume of 10.8 m$^3$, a mass of 1770 kg, and a power requirement of 8.371 kW [15, 24, 25]. The ATHLETE battery pack contains rechargeable lithium-ion batteries with specific energy of 117 Wh/kg and a TRL of 9 [26]. ATHLETE has a range of 20 km and a maximum speed of 1 m/s along an established transport route. Once the allotted battery capacity has been exhausted, ATHLETE will be recharged by KRUSTY reactors [27].

To meet production requirements, ATHLETE must deliver and deploy the entire architecture up to 10 km from the landing site to the production site in $\leq$ 65 days. First, ATHLETE identifies a suitable glacial access point for Rodwell operation and deploys the STING subsystem there. Next, it deploys the SABER refinement system near STING and connects them together with flexible tubing at a distance $\geq$ 5 m between the subsystems to allow for maintenance. This spacing is consistent between all subsequent subsystems as they are deployed. Following this, ATHLETE lays down a KRUSTY power unit near STING so that water collection may begin after melting. Subsequently, the communication dishes are placed in a location providing unobstructed visibility of the architecture. After this, ATHLETE deploys two propellant storage units in the configuration described in VLB and connects them to SABER using insulated propellant-compatible tubing. Finally, ATHLETE places the remaining 6 KRUSTY power units 100 m away from the rest of the architecture to avoid radiation damage [28, 29]. Power and coaxial data transfer cables are connected between architecture elements during each step of the deployment process. To mitigate the risk of a complete ATHLETE failure, a second assembled set of ATHLETE components are brought and kept in a crouched position (to reduce exposure to dust) until utilization is required. Additional spares are carried for components with relatively low MTBFs (Table 16). To protect all reserve components when not in use, they are stored under a protective cover.

**B. Ice Prospecting**

To confirm the presence of a sufficiently large ice deposit, a Ground Penetrating Radar (GPR) system is carried by ATHLETE on the first excursion from the landing site. While potential locations of subsurface ice have been established in Section II.A, the use of GPR is necessary to confirm the presence of such a glacier before starting drilling operations. Building on heritage systems such as the Radar Imager for Mars’ Subsurface Experiment (RIMFAX), a combination of high and low frequency radio waves are used for deep and shallow prospecting respectively, emitted from a single Frequency Modulated Continuous Wave antenna positioned 60 cm above the surface [30, 31]. To locate subsurface ice glaciers, the prospecting system resolves a boundary where the dielectric constant decreases to between 3.0 and 3.2, and attenuation of the ground decreases, which is an indication of a transition from soil to ice [30, 32]. Once a site is identified, ATHLETE begins transporting the architecture from the landing site to the identified drilling site.

**IV. Carbon Dioxide Capture**

The carbon dioxide acquisition system acquires, filters, and compresses 101.553 kg/day of atmospheric CO$_2$ for use in propellant production, borehole clearance, and borehole pressurization, satisfying requirements CDA-01, CDA-02, and CDA-03. After removing atmospheric dust and particulate matter with a consumable High-Efficiency Particulate Absorbing (HEPA) filter, the air is mechanically compressed through a scroll pump directly to the necessary subsystems. All systems consuming the compressed atmospheric gases are
tolerant of trace compounds such as N\textsubscript{2} and Ar in the quantities present [33, 34]. Housed within SABER, the carbon dioxide acquisition system has a mass of 71 kg and draws 9.9 kW of power during operation.

V. Subsurface Targeted Ice miniNG (STING)

The University of Illinois at Urbana-Champaign presents STING (TRL 5), the descendant of the Honeybee Robotics Redwater architecture, which drills through the Martian overburden and creates a Rodwell for water extraction, satisfying MR-01 and MR-02 [14]. STING evolves the Redwater approach through the use of hot water jetting, leveraging water as the delivery mechanism of waste heat from a nearby KRUSTY reactor [2, 35, 36]. To model the Rodwell, the U.S. Army Corps of Engineers’ Rodwell FORTRAN code has been re-organized and translated successfully into C. Additional adjustments were made to the values of specific heat and latent heat inputs derived through in-house calorimetry experimentation with Martian regolith simulant (MMS-1).

A. Overburden Penetration

As shown in Fig. 9, STING must penetrate 10 m of regolith to reach subsurface ice. Leveraging development from the Honeybee Robotics Planetary Deep Drill, STING uses a tungsten carbide drill bit, due to its reliable performance in analog Earth environments [37, 38]. To remove cuttings during operation, 5.5 kg of pressurized CO\textsubscript{2} is ejected in bursts through pneumatic tubing, removing debris out through the annular clearance of the borehole where an aluminum deflector shield redirects the plume away from hardware [14, 39]. 50 m of titanium Coiled Tubing (CT), a proven terrestrial drilling technology (TRL 5), houses pneumatic lines for the CO\textsubscript{2}, in addition to hydraulic tubing for water transport, a 3.5 kW cable heater, power cables, and signal cables to transmit telemetry. With the ability to be wound around a compact drum assembly in a single continuous length of tube, CT eliminates the complexity of assembling threaded tubes during operation, acting as the drill sting and connection between the bottom of the hole and the surface [40]. To unwind and straighten the CT, as well as provide appropriate weight-on-bit for drilling, an injector subsystem, consisting of dual drive/preload rollers, pinchers and pushes the CT down the borehole [14, 40]. A brushless DC motor, chosen for its high efficiency and control, is integrated into the Bottom Hole Assembly (BHA) and provides the 630 N m of torque needed to drive the injector. Starting at the bottom edge, the BHA contains the aforementioned carbide drill bit, brushless DC motor, heated fluid lines (to move carbon dioxide and water and prevent a freeze-in scenario), peristaltic pump, an inflatable packer assembly, and a CT to BHA coupling [14]. Upon BHA contact with ice, the packer assembly and coupling detach from the rest of the BHA, where the packer then inflates to seal off the borehole from the low ambient pressure of Mars [41]. For five years of operation, a total of 110.67 kg of CO\textsubscript{2} is injected over time through the nozzles in the bit to maintain well pressure at 25 kPa, allowing the melted water to remain a liquid for extraction [14, 40]. The entire rig is supported by a lightweight adjustable derrick made from fiber-reinforced polymer composite [42]. Figure 10 summarizes the STING system, while a breakdown of each subsystem can be found in Appendix XII.D.

<table>
<thead>
<tr>
<th>Drilling Performance</th>
<th>Rate of Penetration (ROP)</th>
<th>3 m/hr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Max Time to Reach Ice</td>
<td>3.5 hr</td>
</tr>
<tr>
<td></td>
<td>CO\textsubscript{2} Required</td>
<td>5.5 kg</td>
</tr>
<tr>
<td></td>
<td>Power</td>
<td>0.42 W</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rodwell Performance</th>
<th>Melt Depth</th>
<th>14 m</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Duration of Well</td>
<td>1,850 days</td>
</tr>
<tr>
<td></td>
<td>Water Extracted</td>
<td>220 t</td>
</tr>
<tr>
<td></td>
<td>CO\textsubscript{2} Required</td>
<td>111 kg</td>
</tr>
<tr>
<td></td>
<td>Thermal Power</td>
<td>7.5 kW</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>System Mass</th>
<th>BHA subsystem</th>
<th>7.25 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CT subsystem</td>
<td>39.4 kg</td>
</tr>
<tr>
<td></td>
<td>Injector subsystem</td>
<td>24.6 kg</td>
</tr>
<tr>
<td></td>
<td>Drum subsystem</td>
<td>72 kg</td>
</tr>
</tbody>
</table>
B. Calorimetry Experiment

To characterize the impact that the purity of subsurface ice has on thermal energy requirements for melting, a calorimetry experiment was conducted using Martian regolith simulant (MMS-1), regent-grade sodium chloride, and distilled water [43]. The specific heat capacity and latent heat of a variety of mixture combinations were computed through two separate stages of experimentation and data collection. Utilizing styrofoam calorimeters, thermometers, and 2x2 inch copper cups, various concentrations of regolith, salt, and water were mixed and frozen as ice cubes at around -20 degrees Celsius. For the first part of the experiment, the initial temperatures of distilled hot water in the base of the calorimeter and the freezer temperature of the ice samples were taken before every trial. The ice cube was placed in the copper containers to allow maximum heat transfer with the hot water, and then sealed within the calorimeter. The final temperatures of the cold mixture and the hot water were taken once stabilized. The second stage of the experiment involved cooling the previously melted sample, and placing it back into the calorimeter to measure initial and final temperatures. These data points were then used in specific and latent heat equations shown in Appendix XII.B. The results demonstrate that lower water purity mixtures have lower specific and latent heats, thus indicating that increased debris presence will not increase heat requirements. However, such debris, especially Perchlorate salts, will adversely affect the refinement process. Because there is a high concentration of Perchlorate salts in martian soil, the filtration process will need to chemically address the chlorine from these salts to prevent water impurity [44]. Another issue is the physical attributes of regolith, rock, or dirt. These substances tend to be sedimentary and settle at the bottom of the ice and water once melted. A coarse filtration system is thus required for any regolith or rocky substance in the subsurface ice. Figure 11 displays the final results. Equal concentrations (triangle, green) move from 1.4 g of regolith and salt each, with the arrow indicating the direction of increasing debris concentration; unequal concentrations vary from 5.3 g of regolith, and 2.4 g of salt. The 90% purity results were used in the Rodwell thermal model described in Section V.C. A full experimental procedure is reported in Appendix XII.B.

C. Water Extraction

To meet feedstock requirements outlined in Table 3, STING collects water at 29 gal/day (109 kg/day), accounting for any losses throughout the production process and the 60 days of set-up reserved for year one operations. Once through the overburden, STING drills roughly 1 m into the ice where an integrated heater in the drill bit initiates the melt. During the first phase of operation, STING melts 350 gallons of water over the course of 3 days. The behavior of this initial melt has been modeled with the Honeybee Rodwell thermal
A peristaltic pump then draws water out and into a 350 gallon (1.32 m³) surface reservoir seed tank over the course of 13 days to begin the transition to water jetting. During this phase of water withdrawal, extraction rates are optimized to match the rate of new melt water to ensure the well does not collapse: a condition in which water extraction rates exceed melting rates and the well dries up [2]. The water in the seed tank is heated with waste heat from a nearby KRUSTY unit, and ultimately jetted into the Rodwell at 68°F to transfer 7.5 kW of waste heat. At this point, the integrated heater is powered down, and hot water from the seed tank takes over as the primary heat delivery mechanism [2]. Inducing convective currents, the injected water increases melt efficiency when compared to the use of a non-rotary resistive heater, all while using the otherwise wasted heat from the KRUSTY unit. The Rodwell is also used as in-situ water storage, with the pump consistently cycling water between the Rodwell and seed tank to melt ice, while 29 gal/day is siphoned off to SABER to produce propellant [45]. A thermal model of a Rodwell using water jetting was created in FORTRAN by the U.S. Army Corps of Engineers, and later adapted for Mars conditions by NASA. The University of Illinois has reorganized, rewritten, and debugged this code into C for Rodwell analysis in Appendix XII.C [36, 45]. The simulations produced with this model helped to determine optimal Rodwell operation, such as dimensions of the Rodwell over time, required thermal power, and the flow rate of the water from KRUSTY, all of which are shown in Appendix XII.C. To better visualize the data, Python code, also in Appendix XII.C, was written to interface with the outputs of the C code. Cross sectional views of the well overtime from this program are shown in Fig. 12, where special attention was paid to make sure the depth did not exceed the length of Coiled Tubing.

VI. Propellant Production

A. SABatier and water Electrolysis Refinement (SABER)

<table>
<thead>
<tr>
<th>Feedstock Requirements</th>
<th>Input</th>
<th>Mass (kg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>101.4</td>
<td></td>
</tr>
<tr>
<td>H₂O</td>
<td>97.85</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Products</th>
<th>Output</th>
<th>Mass (kg/day)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂</td>
<td>147.46</td>
<td></td>
</tr>
<tr>
<td>CH₄</td>
<td>36.95</td>
<td></td>
</tr>
</tbody>
</table>

Complying with requirement MR-01, the architecture produces ≥ 50 t of cryogenic propellant per year. CH₄ and O₂ propellant were selected for ease of storage, desirable feed requirements, and fuel performance compared to alternatives such as liquid hydrogen, as justified using a selection matrix in Sec. XII.D. Feedstock requirements of H₂O and CO₂ with corresponding outputs are calculated in Appendix XII.D and summarized in Table 3.

The H₂O obtained from STING is stored in an aluminum buffer tank, separate from the seed tank, and is heated and insulated with Multi-Environment Multiple Layer Insulation (MEMLI) [46]. To remove contaminants and avoid electrolyzer degradation, liquid H₂O is processed through a distillation chamber to remove acidic and basic components, and filtered through an Ionomer-membrane Water Processor (IWP) to remove volatiles and reduce H₂O conductivity to ≤ 1 μS [47]. Nafion membranes in the IWP are selected for their applicability to the purification of glacier-bound water and a high water recovery rate of 99% [48]. To increase the Mean Time Between Failure (MTBF) of the distillation chamber and IWP, the chamber is periodically flushed with clean water and aqueous HCl and the membrane bundles are replaced [by ATHLETE]. The subsequent MTBF values are 260,000h and 10,000h for the distillation chamber and IWP respectively [49].
Filtered and distilled H₂O is then fed into an electrolyzer to produce gaseous H₂ reactant for the Sabatier process and gaseous O₂ oxidizer. A Polymer Electrolyte Membrane (PEM) electrolyzer is selected for its high TRL of 8-9, high energy efficiency, and high H₂ production rates and purity of gases [50]. The electrolyzer stack is mounted for easy access and replacement by ATHLETE on account of the relatively high electrode degradation rate. The electrolyzer utilizes 18.3kW of power and produces O₂ and H₂ at 353.15 K [51]. The O₂ is produced at 101kPa, which is insufficient for it to be transported to storage. Consequently, it is sent to storage by increasing its pressure using a gas booster pump, and cooled to cryogenic temperatures.

For fuel production, SABER reacts atmospheric CO₂ and gaseous H₂ produced by the PEM electrolyzer in the Sabatier reaction (CO₂ + 4H₂→CH₄ + 2H₂O). Demonstrated in orbit aboard the International Space Station, Sabatier reactors have a TRL of 9 [52]. The combined Sabatier/Electrolysis (SE) reaction produces sufficient oxidizer without the need for a Sabatier/Reverse Water Gas Shift (S/RWGS) reaction (CO₂ + H₂→CO + H₂O). To produce CH₄ at the desired rate, the Sabatier reaction requires a catalyst to ensure high selectivity of the product and optimal kinetic rates. Traditionally, nickel and ruthenium monolith pellets are utilized; however, these are prone to catalyst deactivation due to sintering [53, 54]. Instead, Precision Combustion Inc’s Rhodium Microlith reactors are used to reduce maintenance [54]. Microlith catalysts allows the reactor to run at temperatures up to 673.15K without the risk of catalyst deactivation and has a CH₄ reaction selectivity of >99% [54]. The prototype developed by PCI occupies 100cm³ and produces 0.09442kg/h of CH₄, whereas the required production rate is 1.8498kg/h, in accordance with requirement MR-01. The proposed solution is to develop a reactor with thrice the radius, causing the reactor volume to increase to 900cm³, and the CH₄ production rate to 0.8498kg/h. Three of these scaled up reactors are included in SABER to exceed the minimum required production rate. Leveraging multiple reactors also enables CH₄ to be produced at a reduced, but consistent rate, regardless of degradation or failure of a single reactor. Each reactor has a MTBF of 13 000 h. From this, it is necessary to bring 20 spares to meet the reliability standards of the architecture, detailed more in section XII.D. Hence, ATHLETE will need to replace each Sabatier reactor after failure to achieve the required production rate. The products are then cooled using a condenser, causing the H₂O to be liquefied. It is then separated from the CH₄ in a gas/liquid Separator [33]. Similar to the oxidizer, CH₄ is sent to storage to be cooled to cryogenic temperatures, while the water produced is recycled through the electrolyzer as shown in Fig. 13. Figure 14 illustrates the SABER architecture in a process flow diagram [5, 33, 55].

SABER operates for 20 h a day with 4 h of daily downtime, that can be used for maintenance. The production rates for CH₄ and O₂ are calculated in order to produce 50t of propellant in the first year. This takes into account the downtime and the 65 days reserved for architecture set-up. In subsequent years, SABER can produce up to 61 t of propellant a year due to the additional 65 days of operation available. SABER uses 38.759 kW at peak power consumption and is sized without spares at a total mass of 731.8 kg and a volume of 1.82 m³. SABER’s sizing including spares is included in section XII.D.

B. Propellant Storage

Compliant with MR-02, the architecture stores more than 50 t of liquid propellant. At mixture ratios between 3.5 and 3.8 of O₂:CH₄, propellants at saturation temperatures, and a pressure of 30 kPa, 50 t of propellant requires 33.14 m³ for O₂ and up to 25.16 m³ for CH₄ [56, 57]. After the first year of operation, MITRHIL is capable of producing up to 61 t of propellant per year and the required storage volume grows
to 40.44 m³ for O₂ and up to 30.70 m³ for CH₄ [56, 57]. To store these quantities of propellants, a pair of inflatable dome propellant tanks are deployed, with a structure and thermal control system at TRL 4 [58, 59]. Inflated, the tanks have a diameter of 5.5 m and a height of 2.75 m, resulting in a volume of 42.8 m³ and a surface area of 60 m².

The internal liner of each tank is a 3.3 mm thick membrane of PTFE (Teflon) and PTFE FEP (Teflon FEP). This configuration limits leaks, does not rupture under small deflections at cryogenic temperatures, and uses materials approved for service with O₂ in Ground Support Equipment [60–62]. This liner is supported by a narrow Kevlar webbing, selected for its high strength, manufacturability, and heritage in inflatable structures [63, 64]. At the storage pressure, the mass of the restraint and liner are 1.5 kg/m² and 7.25 kg/m² respectively, for a total mass of 543 kg and a compacted volume of 1.2 m³ per tank [65–69].

To keep the O₂ and CH₄ at temperatures of 79 K and 98 K respectively, both passive and active thermal control systems are used [56, 57]. For passive thermal control, the tanks are surrounded by a dome made of 10 layer Multi-Environment Multiple Layer Insulation (MEMLI) panels [70]. To prevent damage to the insulation during transport and assembly, each panel is wrapped in 3 kg/m² of composite reinforcement, with additional insulation along the edges between panels. Supporting the weight of the tank, the insulating panels on the ground use 13 layers of Load Responsive Multiple Layer Insulation (LRMLI), as well as 0.2 kg/m² of UHMWPE (Ultra-High Molecular Weight Polyethylene) to protect from damage and mitigate effects of irregular terrain under the tanks [41, 71–74]. The mass for panels per tank is 350 kg, and so for one CH₄ tank and one O₂ tank used in MITHRIL, the total insulating panel mass is 700 kg.

To remove heat flux through the insulation, maintain the necessary cryogenic temperatures, and liquefy incoming propellants, the active thermal control system on each tank consists of a set of Reverse Turbo-Brayton Cryocoolers (RTBC, TRL 4) using broad area cooling (BAC, TRL 5) [75–77]. This method interfaces the cryocooler loop to the storage tank with a flexible hose along the wall of the tank, with the working fluid of the cryocooler being pumped through the hose to remove heat from the propellant volume. The hot side of the cryocooler loop then radiates heat away using the exterior of the insulating panels as the radiator surface. Assuming an environmental solar flux of 650 W/m² and a surface temperature of 280 K, the heat leak from the environment reaches a maximum of about 40 W through the panels, and an additional 20 W through the gaps between panels [70, 78]. Additionally, the liquefaction of incoming propellants in the tank require an extra 335 W and 185 W of heat removal capacity for O₂ and CH₄, respectively. To reach this level of cooling capacity, the CH₄ storage tank uses a pair of cryocoolers with 100 W and 150 W of heat lift capacity, while the O₂ storage tank uses the same configuration with an additional 150 W cryocooler [75, 79]. This configuration draws 8.5 kW of power in total, and allows spares to be kept common between the two systems while lowering the size of the individual cryocooler units. Figure 16 shows the thermal control loop with temperatures and pressures at the outlets of the radiator and BAC lines for both O₂ and CH₄, and a more detailed loop is given in Appendix XII.D.

To transfer propellant, each tank is connected to a centrifugal pump with the inlet submerged under the fluid level of the propellant. When unloading propellant from the tanks to other systems, the tanks are pressurized to 60 kPa, which means the pumps must have an inlet pressure drop of less than 20 kPa to prevent cavitation, which corresponds to a net-positive suction head (NPSH) of about 2 m. The O₂ and CH₄ pumps
selected each have an NPSH of 0.6 m and 1.8 m, respectively [80]. These pumps have flow rates of 1.5 L/s for O₂ and 1.25 L/s for CH₄. At this rate, each tank can be unloaded in under 10 hours while drawing <15 kW of power per tank [80]. Furthermore, with a pump inlet diameter of <12 cm, the propellant residuals, which are kept in the tank to prevent cavitation, are less than 2.2 m³ of liquid propellant [80]. Additionally, a pressure regulation system is located at the top of each tank to monitor and maintain liquid conditions using a suite of temperature sensors, pressure sensors, pressure relief valves, flow regulation valves, and a rotary vane vacuum gas pump connected to a high pressure buffer tank. This buffer tank can also be used to unload propellant residuals if needed.

With this configuration, the total reliability for the entire storage system is modeled using a gamma distribution based on MTBF, with a failure rate of less than 1 in 4000 over the mission duration (corresponding to a reliability of 0.9997), making it the most reliable component system in the architecture. A more detailed breakdown of spares and their respective technology reliability is provided in the Appendix XII.D. In order to deploy the storage tank system, the panels are first connected to each other using mechanical snap-fit connections to ensure a strong connection. Each tank is then inflated with its respective propellant gas at ambient temperature. Finally, the tanks are gradually chilled to cryogenic operating temperatures. A grid of sensors to measure pressure, temperature, and deflection is installed around the tank and is used to monitor conditions during inflation and nominal usage. These sensors are also capable of detecting conditions consistent with pinhole tears in the bladder.

VII. Support Systems

A. Power

MITHRIL has a peak power consumption of 58.46kW, corresponding to 20 hours a day of full system operation. The remaining 4 hours require a minimum safe operating power of 6.3kW. In addition to electrical power, STING requires a constant influx of 7.5 kW of thermal power to maintain the Rodwell. To meet this demand, MITHRIL employs seven Low Enriched Uranium (LEU) Kilopower Reactor Using Stirling TechnologY (KRUSTY) units (TRL 6) [27]. Each KRUSTY unit generates 10 kW of electrical power from 43.3 kW of thermal power, leaving approximately 30 kW of waste heat from each KRUSTY unit. A portion of this heat can be routed to STING, and the rest is shunted into KRUSTY’s radiator [27]. Figure 17a breaks down the duty cycle for an average day (24 h). One Highly Shielded KRUSTY (HS KRUSTY) sits close to STING and has heavy shielding to reduce the radiation exposure of nearby systems. The other six units are Lightly Shielded KRUSTYs (LS KRUSTY) and have less shielding to reduce mass, and thus sit farther away from the architecture. The shielding on HS KRUSTY is sufficient to reduce the level of output radiation to \(10^{11}\) n/cm² over 15 years [28]. This is below the \(10^{14}\) n/cm² over 5 years radiation limit of electronics in STING [29]. All reactors utilize a B₄C control rod mounted through the core, which can be used to throttle the amount of power released [27]. Figure 17b summarizes the power set-up and integration on the surface.

Nuclear fission is selected to power MITHRIL for three reasons: it provides thermal energy to STING for Rodwell creation and maintenance; it is simple to deploy; and it provides a dependable power level (in comparison to solar panels) [82]. KRUSTY is selected against other nuclear reactors for its mass efficiency and relatively high TRL. Figure 17c breaks down the mass efficiency of different power systems. Using seven reactors is more efficient than solar panels, however a more mass efficient system would be to employ five KRUSTYs paired with a battery pack that discharges during peak load times. In this setup, the battery pack would discharge, providing 14kW of electrical power, for 20 hours a day. During the 4 hour base load period, the battery pack would be recharged by the reactors. However, this system was not selected because the mass savings (1513 kg) is outweighed by the increase in complexity, especially given the fact that the total mass of MITHRIL is safely under mass budget constraints MR-03.
B. Communications

MITHRIL requires communication links to Earth for remote operation and to transmit telemetry. In accordance with the International Communication System Interoperability Standards (ICSIS) recommendation for Direct-to-Earth communication from Mars, these links operate in the X-Band regime [83]. The Earth side of the link consists of the 34 m Deep Space Network (DSN) antenna. The 34 m dish was selected over the larger 70 m antenna due to its lower demand, and consequently, lower cost [84]. The Martian side of the link consists of a JPL Universal Space Transponder (UST) and a 2.4 m antenna. The UST is a software-defined radio that sends and receives both X and UHF frequency bands, and has a TRL of 6 [85]. The UST is paired with the General Dynamics X-Band Solid State Power Amplifier (SSPA), which boosts its power output to 17 W. The SSPA is currently deployed on the Perseverance rover, and therefore has a TRL of 9 [86]. The antenna is a rigid parabolic high-gain satellite antenna that is based on hardware with established heritage. Similar to the UST, the antenna can transmit and receive both UHF and X-Band communications [87]. A TRL of 6 is estimated for the antenna on the basis that it is a proven Earth technology that must be adapted to Mars. Telemetry is transmitted at 22 kb/s, which reduces required transmission power while sending data efficiently. Commands are sent at 256 kb/s to allow for greater control of the architecture. If an emergency occurs when Earth and MITHRIL are not in a line of sight, the communications terminal can use its UHF capabilities to communicate with satellites in the Mars Relay Network [85, 87]. Figure 18 gives a breakdown of the communications system. Surface-to-surface communications for non-mobile elements utilizes coaxial cable running in parallel to the power lines. ATHLETE has a UHF antenna and a backup UST to allow for both surface-to-surface communication and for emergency UHF communication to the Mars Relay Network. A full link budget is available in Appendix XII.D.

C. Automation

To meet MR-05, MITHRIL must operate without direct human intervention. Statically positioned subsystems such as STING and SABER use fixed automation to accomplish their objectives. Fixed automation systems are pre-programmed to accomplish a specific, rigid set of tasks [88]. Examples of these tasks include opening and closing valves and turning on and off electrical systems. Fixed automation is implemented through Programmable Logic Controllers (PLCs), packages of computer chips that allow a system to be pre-programmed with specific tasks [89]. Since PLCs have been used for robotic manufacturing and other purposes on Earth for years, and all that is required for them is Mars hardening, a TRL of 6 is estimated for this technology.
The ATHLETE rover, which must accomplish the most diverse set of mission objectives, will employ autonomous driving capabilities, along with NASA JPL’s FootFall Planning System [90]. For the former, ATHLETE builds upon heritage software such as the Enhanced AutoNav (ENav) system used on the Perseverance rover [91]. On Perseverance, ENav uses stereo cameras to create and update an elevation map of the terrain and displays the tilt, roughness, and the time needed to move across it. ENav then creates candidate paths consisting of fixed-curvature arcs that do not require the rover to steer while driving, assigns them total costs, and then sorts them by that metric. The algorithm then evaluates whether those paths meet the specified clearance, attitude, and suspension angle limits. ENav then returns the lowest-cost path found and Perseverance takes that path [91, 92]. A similar, but more advanced, system will be employed on ATHLETE to allow it to drive autonomously. The latter software suite, FootFall, allows an operator on Earth to control ATHLETE’s leg placement, increasing ATHLETE’s ability to extract itself from a stuck position, or maneuver over rough terrain [90, 93]. To support set-up and maintenance tasks, a quick-disconnect tool adapter is attached at the end of each limb to equip a wide variety of tools. Each tool is locked over a rotating power take-off and powered using the wheel drive actuator [94]. During operation, these complex end-effectors are remotely controlled by ground controllers on Earth. Figure 19 gives an overview of the whole automation system.

D. Dust Mitigation

MITHRIL utilizes an Electrodynamic Dust Shield (EDS) to mitigate build-up of Martian dust on exposed equipment, specifically mechanical joints and optical sensors. ATHLETE is also outfitted with an electrodynamically charged brush to clean off any surfaces that the EDS system fails to or cannot protect on its own [95]. Spare parts are kept in clean, sealed containers to avoid any harmful contamination and ensure reliable operation when entering service.

VIII. Cost Analysis

Using heritage Mars missions and terrestrial analogs as a baseline, an in-house cost estimation tool was built using Python. Reported in Appendix XII.D, the program allows a user to choose which assumptions to operate under, and returns a cost within a range of 12.6 to 21.1 billion USD. The estimate is split into four categories: design and development, fabrication, operations, and services. Design and development and fabrication represent costs associated with developing and producing MITHRIL, operations cover the labor costs during mission duration, and services include launch and communications expenditures. Figure 20 displays the sand chart for the maximum estimated cost of 21.1 billion USD. This section details the assumptions made, and explains in-depth why greater specificity cannot be reasonably provided. Also, in line with recent testimony from NASA Administrator Bill Nelson that signaled a shift from cost-plus to fixed price contracts, the cost analysis of MITHRIL assumes a fixed-pricing model where design and fabrication are performed by contractors [96, 97].

The first section of the cost analysis is for launch services, which represent the largest contributor to the cost uncertainty. The Space Launch System (SLS) is considered first. According to the 2022 Inspector General report, one launch of the SLS, which is sufficient to carry MITHRIL to Mars, will cost $4.1 billion [98]. Alternatively, SpaceX’s Starship has been quoted to be as low as $1 million per launch, per Elon Musk’s own statement [99]. Unlike SLS, however, Starship would require multiple propellant tanker launches to reach Mars, with current estimates ranging between 8 and 14 launches [100]. Other systems such as Blue Origin’s New Glenn are examined as well, but their prices fall in between the above extreme cost estimates of Starship and SLS [101]. This yields a range for launch costs of $8 million to $4.1 billion. Since MITHRIL...
will launch in 2035, we cannot further speculate on the actual costs of launching a rocket to Mars in 13 years. The costs for maintaining communications with Earth are based on the formula provided in the DSN Services Catalog [84]. In addition, the DSN Mission Support Definition and Commitments Office was contacted to determine the Contact Dependant Hourly Rate for the use of one 34m satellite dish, as well as any associated fees (e.g. DSN Network Access Fee). The cost of operational facilities and personal for MITHRIL while it is on Mars is based on the operational costs of the Perseverance rover, approximately $150 million per year [102]. This is a fair comparison since the largest operational cost of MITHRIL will be driving and operating ATHLETE. To account for increased human supervision during set-up, the operational costs were scaled up by 150% during the first year of the mission.

The design and development and fabrication costs for element of MITHRIL are estimated in different ways depending on the nature of each subsystem. The cost for ATHLETE is based on the total cost of Perseverance Mission since it is a comparable system and because Perseverance already served as a baseline for the operational cost, which came to $3 billion [102]. The price estimate for MITHRIL’s automation system is based on the Bureau of Labor Statistics average yearly salary for a software engineer, $110 140 [103]. It is also assumed that it would take 30 developers 6 years to complete software development. The cost for the 4 other major subsystems: power, storage, STING, and SABER is identified using price points for terrestrial analogs, and scaling those up for Martian development. A Mars scaling factor captures the cost increase associated with the extra development needed to adapt technology for Mars. To accomplish this, the scaling factor is the ratio between the known cost of a Martian system and the known cost of a Terrestrial system. The systems picked were the Ingenuity Helicopter, $80 million, and a high performance terrestrial drone, $28 000 [102, 104]. Using this method, a Mars systems costs $2 857 for every $1 needed for a terrestrial application. To account for any error a 20% margin in both directions is applied to each price. The price for the power system is estimated to be $1.1 billion. This is based on a price of $5 500 per kW for terrestrial nuclear reactors [105]. This is then scaled to MITHRIL’s seven 10kW reactors, and the Mars scaling factor is applied. Storage is similarly estimated; the cost per gallon for a terrestrial cryogenic propellant tank is found to be $1.65, this is scaled to MITHRIL’s tank size and multiplied by the Mars factor [106]. This renders a final cost of $2.9 billion. The price point for STING is based on the cost of vertical drilling on land. On average, drilling costs $663 000 [107], which after applying the Mars factor becomes $1.9 billion. For SABER, the cost of setting up an oil refinery is $25 000 per gallon of oil produced in a day [108]. This is then converted to cost per kilogram and multiplied by the ratio of the average cost of a kg of methalox and the cost of a kg of oil. Methalox on average costs $1.55 per kg [109, 110], and oil costs $.82 per kg [111]. This number represents the cost of per kg of fuel per day. This is then scaled by the Mars scaling factor which returned a total cost of $1.8 billion for one SABER.

IX. Scalability

At 50 t/year of propellant production, MITHRIL may be able to support either one or two Mars Ascent Vehicles (MAVs) per year [45]. If NASA or private industry is to fully commit to a permanent human presence on Mars, the demand for propellant will increase drastically [112]. In this scenario, ease of scalability becomes a top-level functional requirement - a requirement that MITHRIL is in compliance with. Figure 21 summarizes sizing of the architecture with respect to an increasing propellant demand from 50 to 300 t/year, in increments of 50 t. Leveraging the Rodwell thermal model described in Section V, a single STING, provided adjustments to the heat exchange process with KRUSTY to extract more thermal energy, can meet water feedstock requirements over this entire range for 5 years. The inputs and outputs of these simulations

![Fig. 21 Scalability of MITHRIL](image_url)
can be found in Appendix XII.C, where special attention was paid to ensure wider, as opposed to deeper, wells, while not exceeding the maximum mass flow rate of the peristaltic pump. The remaining key systems in the architecture such as ATHLETE, SABER, storage, and power are designed to be modular, where either spares or resupply missions can be used to match propellant demand. The python script referenced in Section VIII for cost analysis includes an option for such resupply missions to determine how MITHRIL’s budget would be altered.

X. Risk Analysis

![Risk Matrix](image)

<table>
<thead>
<tr>
<th>ID</th>
<th>Risk</th>
<th>Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Given that STING is required to extract water from subsurface ice, there is a medium risk that the composition of the ice is less than 90% pure. This would result in elevated debris quantities in the Rodwell, thereby increasing the chance for clogging of STING and SABER systems.</td>
<td>The presence of a drill bit in the BHA allows for reactivation of drilling should there be a large layer of sediment. A coarse mesh filters out large particulates before entering the BHA and pump, and all water sent to SABER is distilled and filtered through Nafion membranes to ensure finer detritus is extracted.</td>
</tr>
<tr>
<td>2</td>
<td>Given the high stress concentrations at corner folds of flexible storage liners, there is a high risk that the propellant storage tank will develop pinhole tears, adversely impacting the ability to store cryogenic liquids, thereby leading to failure of mission objectives.</td>
<td>Inflation of the propellant pressure vessel and all operations which are expected to result in deformation are conducted at ambient temperature or with warm gas. Additionally, large deformations only occur once per mission during inflation, reducing fatigue.</td>
</tr>
<tr>
<td>3</td>
<td>Given that STING ejects cuttings from the borehole, and SABER expels filtered detritus, there is a medium risk that debris will accumulate and contaminate the architecture.</td>
<td>The injector on STING is sealed off to prevent cuttings from damaging the motor. Moreover, ATHLETE can use its limbs to bulldoze any significant build-up of debris.</td>
</tr>
<tr>
<td>4</td>
<td>Given that the autonomous assembly system that guides ATHLETE during the setup process is at a low maturity, there is a schedule risk that the system will not be developed prior to the mission. This would result in a requirement for human ground control which would increase the costs and timeline of the initial setup.</td>
<td>Set a date by which the autonomous assembly system shall have reached a maturity threshold. Should it not be matured prior to the selected date, the primary control of ATHLETE will transfer to manual operation from Earth. Moreover, the insulation panels on the storage tanks will have carbon fiber reinforcement to withstand applied forces from ATHLETE.</td>
</tr>
<tr>
<td>5</td>
<td>Given the high temperatures and extended operation of the Sabatier reactors, there is a medium risk of reactor failure. This would render MITHRIL incapable of producing CH₄.</td>
<td>Microlith based reactors are used to minimize the generation of local heat spots, as they have high heat transfer coefficients. Additionally, the reactors are cycled through active and idle states to reduce heating stress. Furthermore, additional technology development will result in more reliable reactors.</td>
</tr>
</tbody>
</table>

XI. Conclusions

Just one tonne of propellant produced in-situ represents an opportunity for NASA to deliver one more crew member, one more scientific payload, or one more set of life saving consumables. Adapting Rodwells for Mars using the revolutionary STING system, MITHRIL extracts hundreds of tonnes of water using otherwise wasted energy from KRUSTY, allowing for the production of not just one, but fifty or more tonnes of propellant a year. With custom scaled Microlith Sabatier reactors in SABER, an innovative inflatable storage tank design, and array of robotic capabilities, MITHRIL easily bolsters NASA’s ability to perform more ambitious surface exploration of the red planet, all while in direct compliance with the Mars Water-based ISRU Theme requirements set forth for the NASA 2022 RASC-AL competition.
Acknowledgments

The team would like to thank Dr. Stephen Hoffman (NASA JSC) and Alida Andrews (Aerospace Corp) for participating as reviewers in the SRR and PDR, and CDR; as well as providing technical assistance in translating the U.S. Army Corps of Engineers CRREL Fortran code [36] into C. The team would also like to acknowledge the 2019 UIUC RASC-AL project manager Linyi Hou (University of Illinois at Urbana-Champaign) for participating as a reviewer in the aforementioned design reviews, as well as Fuad Samhouri’s Unreal Engine team members: Richard Pryzbek, Shellyn Tunggara, and Siddhant Sharma, who helped create "RASC-AL: The Video Game" (University of Illinois at Urbana-Champaign). In addition, the team would like to express appreciation to Jeff Lasater (Kinetic Upstream) for providing information on the applications of oil drilling technologies on Mars. We also thank Dr. Ariel Ekblaw (Director of the Space Exploration Initiative, Massachusetts Institute of Technology) for lending insight into "TESSERAE": Tessellated Electromagnetic Space Structures for the Exploration of Reconfigurable, Adaptive Environments, and specifically the applications of geodesic tile/panel architectural design for space [113]. Last, but certainly not least, the team would like to give a huge thanks to Kris Zacny (Honeybee Robotics) and Joey Palmowski (Honeybee Robotics) for facilitating a collaboration between the University of Illinois at Urbana-Champaign and Honeybee Robotics, and for the invaluable information and data they provided [14].

XII. Appendices

A. Level 1 Requirement Compliance

The mission requirements prescribed in Table 1 have been decomposed and collected into a hierarchy of system designations.

Table 4  STING Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>STN-01</td>
<td>STING shall be capable of extracting water from subsurface ice</td>
<td>V.C</td>
</tr>
<tr>
<td>STN-02</td>
<td>STING shall be capable of penetrating regolith to reach subsurface ice</td>
<td>V.A</td>
</tr>
<tr>
<td>STN-03</td>
<td>STING shall remove regolith cuttings from the borehole</td>
<td>V.A</td>
</tr>
<tr>
<td>STN-04</td>
<td>STING shall melt subsurface ice</td>
<td>V.A, V.C</td>
</tr>
<tr>
<td>STN-05</td>
<td>STING shall maintain a liquid state of water during extraction</td>
<td>V.C</td>
</tr>
<tr>
<td>STN-06</td>
<td>STING shall extract ≥ 32.9 t/year of water from subsurface ice</td>
<td>V.C</td>
</tr>
<tr>
<td>STN-07</td>
<td>STING shall be capable of penetrating ≥ 10 m of regolith</td>
<td>V.A</td>
</tr>
<tr>
<td>STN-08</td>
<td>STING shall be capable of a total H₂O melt mass of ≥ 164.5 t</td>
<td>V.C</td>
</tr>
<tr>
<td>STN-09</td>
<td>STING shall maintain a borehole pressure of ≥ 10 kPa</td>
<td>V.C</td>
</tr>
</tbody>
</table>
### Table 5  SABER Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAB-01</td>
<td>SABER shall produce liquid methane</td>
<td>VI.A</td>
</tr>
<tr>
<td>SAB-02</td>
<td>SABER shall produce liquid oxygen</td>
<td>VI.A</td>
</tr>
<tr>
<td>SAB-03</td>
<td>SABER shall produce propellant with reactants taken only from Mars</td>
<td>VI.A</td>
</tr>
<tr>
<td>SAB-04</td>
<td>SABER shall distill water collected from STING to remove physical impurities</td>
<td>VI.A</td>
</tr>
<tr>
<td>SAB-05</td>
<td>SABER shall filter water collected from STING</td>
<td>VI.A</td>
</tr>
</tbody>
</table>

### Performance Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
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<tr>
<td>SAB-06</td>
<td>SABER shall produce $\geq 11 ,\text{t/year}$ of liquid methane</td>
<td>VI.A</td>
</tr>
<tr>
<td>SAB-07</td>
<td>SABER shall produce $\geq 39 ,\text{t/year}$ liquid oxygen</td>
<td>VI.A</td>
</tr>
<tr>
<td>SAB-08</td>
<td>SABER shall maintain an oxidizer to fuel ratio of $3.54:1 &lt; \text{Fuel} \text{ Ratio} &lt; 3.8:1$</td>
<td>VI.A</td>
</tr>
<tr>
<td>SAB-09</td>
<td>SABER shall reduce the water conductivity to $\leq 1 \mu \text{S}$</td>
<td>VI.A</td>
</tr>
</tbody>
</table>

### Table 6  Carbon Dioxide Acquisition Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDA-01</td>
<td>The CO$_2$ acquisition system shall collect carbon dioxide</td>
<td>IV</td>
</tr>
</tbody>
</table>

### Functional Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>CDA-02</td>
<td>The CO$_2$ acquisition system shall collect $\geq 30 ,\text{t/year}$ of carbon dioxide for SABER</td>
<td>IV</td>
</tr>
<tr>
<td>CDA-03</td>
<td>The CO$_2$ acquisition system shall collect $\geq 40 ,\text{kg/year}$ of carbon dioxide for STING</td>
<td>IV</td>
</tr>
</tbody>
</table>
## Table 7  Storage Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>STO-01</td>
<td>The storage system shall store liquid methane</td>
<td>VI.B</td>
</tr>
<tr>
<td>STO-02</td>
<td>The storage system shall store liquid oxygen</td>
<td>VI.B</td>
</tr>
<tr>
<td>STO-03</td>
<td>The storage system shall provide an interface for fuel extraction</td>
<td>VI.B</td>
</tr>
<tr>
<td>STO-04</td>
<td>The storage system shall provide an interface for fuel feed</td>
<td>VI.B</td>
</tr>
</tbody>
</table>

### Functional Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>STO-05</td>
<td>The storage system shall store $\geq 11$ t of liquid methane</td>
<td>VI.B</td>
</tr>
<tr>
<td>STO-06</td>
<td>The storage system shall store $\geq 39$ t of liquid oxygen</td>
<td>VI.B</td>
</tr>
<tr>
<td>STO-07</td>
<td>The storage system shall maintain cryogenic temperatures for liquid methane</td>
<td>VI.B</td>
</tr>
<tr>
<td>STO-08</td>
<td>The storage system shall maintain cryogenic temperatures for liquid oxygen</td>
<td>VI.B</td>
</tr>
<tr>
<td>STO-09</td>
<td>The storage system shall maintain a boiloff rate of $\leq 0.2%$ of maximum storage mass per year</td>
<td>VI.B</td>
</tr>
<tr>
<td>STO-10</td>
<td>The storage system shall maintain a leak rate of $\leq 0.2%$ of maximum storage mass per year</td>
<td>VI.B</td>
</tr>
</tbody>
</table>
### Table 8  Transportation Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRA-01</td>
<td>The transportation system shall carry payload</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-02</td>
<td>The transportation system shall lift payloads from ground level to a designated point above ground level</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-03</td>
<td>The transportation system shall deploy payloads</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-04</td>
<td>The transportation system shall provide energy to auxiliary systems</td>
<td>III.A</td>
</tr>
<tr>
<td><strong>Performance Requirements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TRA-05</td>
<td>The transportation system shall carry $\geq 1600$ kg of payload</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-06</td>
<td>The transportation system shall have a range of $\geq 10$ km</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-07</td>
<td>The transportation system shall have a maximum speed of $\geq 0.7$ m/s</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-08</td>
<td>The transportation system shall provide 1 kWh to auxiliary systems</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-09</td>
<td>The transportation system shall have a payload volume of $\geq 12$ m$^3$</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-10</td>
<td>The transportation system shall transfer payloads between ground level and $\geq 0.5$ m above ground level</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-11</td>
<td>The transportation system shall position objects with a tolerance of $\pm 10$ cm in the lateral-direction</td>
<td>III.A</td>
</tr>
<tr>
<td>TRA-12</td>
<td>The transportation system shall position objects with a tolerance of $\pm 1$ cm in the vertical-direction</td>
<td>III.A</td>
</tr>
</tbody>
</table>

### Table 9  Set-Up and Maintenance Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAM-01</td>
<td>The set-up and maintenance system shall position objects within a specific radius from a designated point in space</td>
<td>III.A VII.C</td>
</tr>
<tr>
<td>SAM-02</td>
<td>The set-up and maintenance system shall lift objects.</td>
<td>III.A VII.C</td>
</tr>
<tr>
<td><strong>Performance Requirements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SAM-03</td>
<td>The SAM system shall position objects within a tolerance of 1 mm radius from a designated point in space.</td>
<td>III.A VII.C</td>
</tr>
<tr>
<td>SAM-04</td>
<td>The set-up and maintenance system shall lift objects of $\geq 10$ kg</td>
<td>III.A VII.C</td>
</tr>
</tbody>
</table>
### Table 10  Power Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>POW-01</td>
<td>The power system shall provide electrical power</td>
<td>VII.A</td>
</tr>
<tr>
<td>POW-02</td>
<td>The power system shall produce thermal power</td>
<td>VII.A</td>
</tr>
<tr>
<td>POW-03</td>
<td>The power system shall distribute electrical power across the architecture</td>
<td>VII.A</td>
</tr>
<tr>
<td>POW-04</td>
<td>The power system shall distribute heat to STING</td>
<td>VII.A</td>
</tr>
<tr>
<td>POW-05</td>
<td>The power system shall limit emitted radiation exposure at the propellant access point</td>
<td>VII.A</td>
</tr>
</tbody>
</table>

**Performance Requirements**

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>POW-06</td>
<td>The power system shall provide $\geq 50$ [kWe]</td>
<td>VII.A</td>
</tr>
<tr>
<td>POW-07</td>
<td>The power system shall produce $\geq 5$ [kWt]</td>
<td>VII.A</td>
</tr>
<tr>
<td>POW-08</td>
<td>The power system shall limit emitted radiation exposure at the propellant access point to $10^{14}$ [n/cm$^2$ per 5 years]</td>
<td>VII.A</td>
</tr>
</tbody>
</table>

### Table 11  Prospecting Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>PRO-01</td>
<td>The prospecting system shall identify subsurface glaciers</td>
<td>III.B</td>
</tr>
<tr>
<td>PRO-02</td>
<td>The prospecting system shall have an unobstructed view of the surface</td>
<td>III.B</td>
</tr>
</tbody>
</table>

### Table 12  Communications Requirements

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM-01</td>
<td>The communications system shall receive data from Mission Control</td>
<td>VII.B</td>
</tr>
<tr>
<td>COM-02</td>
<td>The communications system shall transmit data to Mission Control</td>
<td>VII.B</td>
</tr>
<tr>
<td>COM-03</td>
<td>The communications system shall relay commands to the architecture from Mission Control</td>
<td>VII.B</td>
</tr>
<tr>
<td>COM-04</td>
<td>The communications system shall collect telemetry from the architecture.</td>
<td>VII.B</td>
</tr>
</tbody>
</table>

**Performance Requirements**

<table>
<thead>
<tr>
<th>Identifier</th>
<th>Statement</th>
<th>Applicable Sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>COM-05</td>
<td>The communication system shall receive data from Mission Control at a rate of $\geq 256$ Kbps</td>
<td>VII.B</td>
</tr>
<tr>
<td>COM-06</td>
<td>The communications system shall transmit data to Mission Control at a rate of $\geq 22$ Kbps</td>
<td>VII.B</td>
</tr>
</tbody>
</table>
B. Rodwell Experiments

Phase 1a: Physical Demonstration

Using commercial off the shelf components (COTS), the team constructed a prototype Rodwell. After drilling two feet into the ground, ice was inserted to simulate a Martian subsurface glacier. A heater was lowered into the "well," melting the ice for subsequent extraction by a centrifugal pump. Finally, the water was used to power a fuel cell car science kit to demonstrate the final stage of MITHRIL: propellant production [114]. From the demonstration, the team identified major challenges to Rodwell operation as well as corresponding mitigations made; both of which are outlined in Table 13. To support NASA’s goals for educational outreach and STEM engagement, the Rodwell prototype was demonstrated live during the UIUC Engineering Open House (EOH), as a part of our "Life on Mars" exhibit.

Table 13 Rodwell Prototype Challenges & Mitigation

<table>
<thead>
<tr>
<th>Challenge</th>
<th>Prototype Mitigation</th>
<th>MITHRIL Mitigation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initiating drill operation was more difficult than anticipated, and the auger did not gain enough grip to penetrate the surface.</td>
<td>Two members applied downward force on the bit to prevent slippage.</td>
<td>Injector provides increased weight-on-bit force at the start of drilling operation.</td>
</tr>
<tr>
<td>Auger got stuck in the borehole, which halted drilling operations.</td>
<td>Pullout auger and manually clean, re-insert and repeat until requisite depth is met.</td>
<td>Utilize pressurized gas &quot;mud&quot; to blast pulverized cuttings out of the borehole. Mars low ambient pressure allows for efficient gas blasts (1 g gas to 3 kg cuttings), allowing continuous drilling operation [39].</td>
</tr>
<tr>
<td>Priming the pump was more difficult than anticipated, taking multiple attempts to operate.</td>
<td>Team manually primed pump before operation.</td>
<td>Use a positive displacement pump, specifically a peristaltic pump. Unlike the centrifugal pump used in the prototype, the peristaltic pump does not require priming.</td>
</tr>
</tbody>
</table>
Phase 1b: UIUC Engineering Open House

At UIUC, Engineering Open House was hosted on the engineering quad in order to provide educational outreach to children, adults, and future students. The RASCAL team demonstrated the physical prototype and the electrolysis car, and presented the design to hundreds of people over the course of two days.

Fig. 24   Educational Outreach Event: Engineering Open House

Phase 2: Rodwell Calorimetry

In phase two of the Rodwell prototype, the team aims to explore the effects of salt and regolith stimulant on the specific heat of water and latent heat of ice. To obtain these values, a calorimetry experiment is to be conducted. Using styrofoam cups and a conductive copper container, conservation of energy can be applied in the form \( Q = mc\Delta T \), where \( Q \) is heat in joules, \( m \) is mass in grams, \( c \) is specific heat in \( \frac{J}{g^\circ C} \) and \( \Delta T \) is the change in temperature in Celsius. The equation \( Q = \frac{m}{L} \), where \( L \) is latent heat in \( \frac{J}{g} \), will also be applied. Pure distilled water will act as a control, with three experimental groups: a salt water mixture; a regolith water mixture; and a salt, regolith, and water mixture. The anticipated outcome of the experiment is expressed in the hypothesis below:

Equipment

1) PASCO Styrofoam Calorimeters
2) Water thermometers (two for each calorimeter)
3) Conducive copper containers (one for each calorimeter)
4) 44 mL mixing glasses
5) Regend Grade Sodium Chloride and MMS-1 Simulant
6) Distilled Water
7) Kettle
8) Measuring Scale, Measuring Spoons, and Liquid Measuring Cup

The presence of salts and regolith stimulant will decrease both the specific heat of water and the latent heat of ice, thus decreasing the amount of thermal energy required to melt and maintain the Rodwell.

Procedure

1) Pour 26 grams of distilled water into each segment of an ice tray and freeze, this will act as the control group.
2) Record masses of copper test tubes.
3) Prepare debris sample by mixing various concentrations of grams of debris (salt, regolith, or both) with water to a maximum of 26 grams. Freeze.
4) Record debris mixture components.
5) Assemble Styrofoam cup calorimeter, and place a conductive copper test tube inside in order to separate the samples.
6) Quickly pour 75 g of heated distilled water into calorimeter and measure temperature.
7) Quickly take the debris sample from the refrigerator. Record temperature of freezer, seal, and place ice cube into calorimeter.
8) Seal calorimeter and wait until the temperature equalizes.
9) Open calorimeter, record temperature of both samples.
10) Remove water and clean calorimeter and test tube as needed.
11) After solving for \( c_{\text{sample}} \), pour 30 g of the liquid debris sample (does not need to be refrigerated any longer) into the calorimeter. Record Temperature.
12) Pull debris ice sample and place into calorimeter, seal and wait until temperature equalizes.
13) Open calorimeter, record temperature of both samples
14) Solve for specific heat of debris sample \( (c_{\text{sample}}) \), where \( c_{\text{water}} \) and \( c_{\text{copper}} \) is known:

\[
m_{\text{water}} c_{\text{water}} \Delta T_{\text{water}} = m_{\text{sample}} c_{\text{sample}} \Delta T_{\text{sample}} + m_{\text{copper}} c_{\text{copper}} \Delta T_{\text{copper}}
\]

15) Solve for latent heat of debris sample \( (L_{\text{sample}}) \), where \( c_{\text{sample}} \) is known:

\[
m_{\text{sample}} c_{\text{sample}} \Delta T_{\text{sample}} = m_{\text{sample}} c_{\text{sample}} \Delta T_{\text{sample}} + m_{\text{sample}} L_{\text{sample}}
\]

16) Repeat for remaining ice cubes of the same debris concentration until depleted.
17) Clean all items.
18) Repeat steps 3-17 for new debris samples for at least 3 additional trials (salt, regolith, or both). The samples should be created with just salt and water, just regolith and water, an equal mixture of regolith and salt mixed with water, and an unequal mixture of regolith and salt mixed with water.
Data Collection

Throughout data collection, there were sources of error that the team tried to mitigate, but in the end there were some trials that were outliers in the data. It was important that three minimum trials were completed to account for any of these discrepancies, which are highlighted in red as "outlier." Green highlights signify a value that is completed and takes into account collected data that did not have any produced error for maximum accuracy. The control was a set of 100 percent pure distilled water, followed by a 90 percent purity that mixed regolith and salt. The just regolith and just salt trials did not have any cross-mixtures and were used to determine each individual effect. The unequal concentrations used the same amount of water (19 grams) and varied the salt-regolith ratio as shown in Fig. 25. In the same table, equal regolith and salt is shown to have varying water masses, but the regolith and salt ratio is 1:1.

Fig. 25  Ratio of Concentrations

<table>
<thead>
<tr>
<th>Regolith</th>
<th>Water</th>
<th>Salt</th>
<th>Water</th>
<th>Regolith</th>
<th>Salt</th>
<th>Water</th>
<th>Regolith</th>
<th>Salt</th>
<th>Water</th>
</tr>
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<tbody>
<tr>
<td>6</td>
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<td>6</td>
<td>20</td>
<td>5</td>
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<td>1</td>
<td>25</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>63</strong></td>
<td><strong>63</strong></td>
<td><strong>405</strong></td>
<td><strong>63</strong></td>
<td><strong>405</strong></td>
<td><strong>42</strong></td>
<td><strong>42</strong></td>
<td><strong>228</strong></td>
<td><strong>30</strong></td>
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</tbody>
</table>

Fig. 26  Constants, 100 and 90 Percent Purity Data
### Fig. 27 Salt Only Data

#### CURRENT RATIO: 1s 25w

<table>
<thead>
<tr>
<th>Trial (Phase change process)</th>
<th>Water Ti</th>
<th>Water Tf</th>
<th>ΔT Water</th>
<th>Sample Ti</th>
<th>Sample Tf</th>
<th>ΔT Sample</th>
<th>Latent Heat of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>67.9</td>
<td>32.9</td>
<td>35</td>
<td>-13.1</td>
<td>32.8</td>
<td>45.9</td>
<td>267.867253</td>
</tr>
<tr>
<td>2B</td>
<td>77.1</td>
<td>39.4</td>
<td>37.7</td>
<td>-13.1</td>
<td>39.4</td>
<td>52.5</td>
<td>275.877859</td>
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<tr>
<td>3C</td>
<td>74.5</td>
<td>39.8</td>
<td>34.3</td>
<td>-13.5</td>
<td>39.6</td>
<td>53.1</td>
<td>234.193809</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trial (Liquid process)</th>
<th>Water Ti</th>
<th>Water Tf</th>
<th>ΔT Water</th>
<th>Sample Ti</th>
<th>Sample Tf</th>
<th>ΔT Sample</th>
<th>Specific Heat of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>57.3</td>
<td>46.6</td>
<td>10.7</td>
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<td>46.6</td>
<td>30.8</td>
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<td>57.7</td>
<td>47.1</td>
<td>10.6</td>
<td>16.3</td>
<td>47.1</td>
<td>30.8</td>
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<tr>
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<td>57.1</td>
<td>47.4</td>
<td>9.3</td>
<td>19.4</td>
<td>47.5</td>
<td>28.1</td>
<td>4.16624692</td>
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</tbody>
</table>

#### CURRENT RATIO: 2s 24w

<table>
<thead>
<tr>
<th>Trial (Phase change process)</th>
<th>Water Ti</th>
<th>Water Tf</th>
<th>ΔT Water</th>
<th>Sample Ti</th>
<th>Sample Tf</th>
<th>ΔT Sample</th>
<th>Latent Heat of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>66.4</td>
<td>31.2</td>
<td>35.2</td>
<td>-17.1</td>
<td>31.2</td>
<td>48.1</td>
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<tr>
<td>2B</td>
<td>70.9</td>
<td>35.9</td>
<td>35</td>
<td>-14.7</td>
<td>35.5</td>
<td>50.2</td>
<td>251.263988</td>
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<tr>
<td>3C</td>
<td>70.9</td>
<td>36</td>
<td>34.9</td>
<td>-15.4</td>
<td>35.9</td>
<td>51.3</td>
<td>245.586149</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Trial (Liquid process)</th>
<th>Water Ti</th>
<th>Water Tf</th>
<th>ΔT Water</th>
<th>Sample Ti</th>
<th>Sample Tf</th>
<th>ΔT Sample</th>
<th>Specific Heat of Sample</th>
</tr>
</thead>
<tbody>
<tr>
<td>1A</td>
<td>67</td>
<td>52.3</td>
<td>14.7</td>
<td>12.1</td>
<td>52.3</td>
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<td>4.41375341</td>
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<tr>
<td>2B</td>
<td>72.5</td>
<td>57.9</td>
<td>14.4</td>
<td>15.5</td>
<td>58.3</td>
<td>44.8</td>
<td>3.87959546</td>
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<tr>
<td>3C</td>
<td>68.1</td>
<td>53.5</td>
<td>14.6</td>
<td>15.1</td>
<td>53.6</td>
<td>38.5</td>
<td>4.57690309</td>
</tr>
</tbody>
</table>

#### CURRENT RATIO: 3s 23w

<table>
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<th>Sample Tf</th>
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Fig. 28  Regolith Only Data
### Fig. 29 Unequal Concentrations Data

#### UNEQUAL

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</table>

| **TRIAL (liquid process)** | Water Ti | Water Tf | ΔT Water | Sample Ti | Sample Tf | ΔT Sample | Specific Heat of Sample |
| 1A                | 58      | 44.9    | 11.1     | 12.3     | 44.5      | 31.9      | 4.199618293 Specific Heat AVG |
| 2B                | 63      | 50.8    | 12.2     | 12.2     | 50.8      | 38.6      | 3.84623742  |
| 3C                | 64.6    | 46.8    | 17.8     | 14.9     | 46        | 30.1      | 7.45602867  4.00132817 |

#### CURRENT RATIO: 5r, 2s, 19w

| **TRIAL (phase change process)** | Water Ti | Water Tf | ΔT Water | Sample Ti | Sample Tf | ΔT Sample | Latent Heat of Sample |
| 1A                | 58.7    | 28.8    | 29.9     | -13.9    | 28.8      | 42.7      | 212.3648673 Latent Heat AVG |
| 2B                | 66.5    | 35.8    | 30.7     | -13.9    | 35.8      | 45.7      | 193.4383463  |
| 3C                | 62.3    | 31.3    | 29.9     | -13.9    | 33        | 46.9      | 187.0313323  197.6115153 |

| **TRIAL (liquid process)** | Water Ti | Water Tf | ΔT Water | Sample Ti | Sample Tf | ΔT Sample | Specific Heat of Sample |
| 1A                | 68      | 54.5    | 13.5     | 14.2     | 54.5      | 40.1      | 4.043042565 Specific Heat AVG |
| 2B                | 63.6    | 48.3    | 15.3     | 12.2     | 48.3      | 36.1      | 5.087011151  |
| 3C                | 67.3    | 53.3    | 14.0     | 14.9     | 53.3      | 38.2      | 4.388811189  4.215928877 |

#### CURRENT RATIO: 3r, 4s, 19w

| **TRIAL (phase change process)** | Water Ti | Water Tf | ΔT Water | Sample Ti | Sample Tf | ΔT Sample | Latent Heat of Sample |
| 1A                | 62.3    | 31.3    | 30.3     | -19      | 33.3      | 50.3      | 217.9442022 Latent Heat AVG |
| 2B                | 65.1    | 34.7    | 30.4     | -19.8    | 34.7      | 54.5      | 203.4366887  |
| 3C                | 61      | 30.9    | 30.1     | -20.3    | 30.9      | 51.2      | 211.5115129  210.9655013 |

| **TRIAL (liquid process)** | Water Ti | Water Tf | ΔT Water | Sample Ti | Sample Tf | ΔT Sample | Specific Heat of Sample |
| 1A                | 48.6    | 41.1    | 7.5      | 14       | 41.1      | 27.1      | 3.340193017 Specific Heat AVG |
| 2B                | 68.6    | 50.5    | 18.1     | 15.6     | 50.5      | 34.7      | 6.29547721  |
| 3C                | 69      | 54.5    | 13.1     | 11.7     | 54.5      | 41.2      | 3.837546077  3.58809847 |

#### CURRENT RATIO: 4r, 3s, 19w

| **TRIAL (phase change process)** | Water Ti | Water Tf | ΔT Water | Sample Ti | Sample Tf | ΔT Sample | Latent Heat of Sample |
| 1A                | 60.1    | 30.2    | 29.9     | -20.1    | 30.2      | 50.3      | 217.19793 Latent Heat AVG |
| 2B                | 71      | 36.7    | 33.4     | -21.7    | 36.7      | 58.4      | 246.8256676  |
| 3C                | 67.6    | 36.1    | 31.5     | -21.6    | 36.1      | 57.7      | 212.8679490  225.5705158 |

| **TRIAL (liquid process)** | Water Ti | Water Tf | ΔT Water | Sample Ti | Sample Tf | ΔT Sample | Specific Heat of Sample |
| 1A                | 61.8    | 49.8    | 12       | 12.8     | 49.8      | 37        | 3.914391114 Specific Heat AVG |
| 2B                | 64.1    | 54.6    | 9.5      | 17       | 54.6      | 37.6      | 3.09406711  |
| 3C                | 66.7    | 54.0    | 12.3     | 11.6     | 54.0      | 42.6      | 3.484777859  3.482843241 |
### Fig. 30 Equal Concentrations Data

#### Equal Ratio: 3r, 3s, 24w

<table>
<thead>
<tr>
<th>Trial (phase change process)</th>
<th>Water Ti</th>
<th>Water Tf</th>
<th>$\Delta T_{\text{water}}$</th>
<th>Sample Ti</th>
<th>Sample Tf</th>
<th>$\Delta T_{\text{sample}}$</th>
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<th>Specific Heat of Sample</th>
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<th>Sample Tf</th>
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#### Equal Ratio: 2r, 2s, 22w

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<th>$\Delta T_{\text{water}}$</th>
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<th>Sample Tf</th>
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#### Equal Ratio: 3r, 3s, 20w

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#### Equal Ratio: 4r, 4s, 18w

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</table>
1. Freeze ice cubes of varying debris concentrations: regolith, salt, and both.
2. Use hot water in base of calorimeter and heat up copper cup to stabilize temperature.
3. Melt ice cube in calorimeter and find initial and final equalizing temperature.
4. Chill mixture and place in calorimeter again to determine change in temperature.

Fig. 31 Rodwell Calorimetry - Concept of Operations
C. Rodwell Code

Scalability Results

(a) 50 t Propellant, 7.5kW, 29 gal/day
(b) 100 t Propellant, 10kW, 58 gal/day
(c) 150 t Propellant, 15kW, 87 gal/day
(d) 200 t Propellant, 15 kW, 116 gal/day
(e) 250 t Propellant, 20kW, 145 gal/day
(f) 300 t Propellant, 25kW, 174 gal/day

Fig. 32 Rodwell Sizing for Increasing Propellant Demand
Python Rodwell Graphing Code

The following code reads the output text files produced by either the FORTRAN versions of the Rodwell model code. It can be used to extract the output data in anyway the user would like, and we specifically used it to generate plots and animations of our Rodwell design. This code, along with some other helper files can be accessed at the hyperlinked Github repository.

```python
# NON TABLE DATA
import numpy as np
import pandas as pd
import numpy.linalg as la
import matplotlib.pyplot as plt
from io import StringIO

# Helper Functions
def minusparse(line):
    newline = ''
    for i in range(len(line)):
        if line[i] == '− ':
            newline += '␣' + line[i]
        else:
            newline += line[i]
    return newline

def equalparse(line):
    temp = [x.strip() for x in line.split('="")]
    temp[-1] = temp[-1][:-1]
    return temp

# END HELPER FUNCTIONS

# Open file
def nontabledata(file_name):
    cnt = 0
    f = open(file_name, 'r')
    data = ''
    features = [str(i) for i in range(0, 14)]

    # Get non-tables
    for _ in range(22):
        prevline1 = ''
        prevline2 = ''
        line = f.readline()

        # Get position
        if len(line.split('()') == 0):
            line = 'NONE'
            while(line.split()[0] != 'TOTAL'):
                prevline2 = prevline1
                prevline1 = line
                line = f.readline()
        if len(line.split('()') == 0):
            line = 'NONE'

        # Get hours
        prevline2 = minusparse(prevline2)
        hours = [x for x in prevline2.split('␣') if x != ''][0]

        # Get non-table
        newline = minusparse(line)
        newline = equalparse(newline)
        data += str(hours)
        while newline[0] != '':
            # Add to data
            data += '␣' + newline[1]

        # Update
        newline = minusparse(f.readline())
        newline = equalparse(newline)
        cnt += 1
        data += '␣

    # Convert to pandas object
    TESTDATA = StringIO(data)
    df = pd.read_csv(TESTDATA, header=None)
    df.columns = features
    return df

# DF mapping
---
0 = hours
1 = TOTAL ENERGY INPUT BTU
2 = SEASONAL ENERGY INPUT BTU
3 = SEASONAL ENERGY INPUT GAL FUEL
4 = SEASONAL ENERGY RATE BTU/HR
5 = TOTAL ENERGY INPUT GAL FUEL
6 = AVERAGE LB. WATER PER LB. FUEL
7 = SEASONAL LB. WATER PER LB. FUEL
8 = ENERGY FROM AIR TO ICE BTU
```
9 = SEASONAL ENERGY LOSS, AIR TO ICE BTU
10 = TOTAL WATER WITHDRAWN GAL
12 = SEASONAL WATER WITHDRAWN GAL
13 = SEASONAL WATER LOSS GAL

#Graph data for each column vs hours
#for name in features:
#    plt.scatter(df["0"], df[name])
#    plt.xlabel("hours")
#    plt.ylabel(name)
#    plt.title(name + " vs. hours")
#    plt.show()
df = nontabledata("OUTPUT_MARS_CORRECT.DAT")
# df2 = nontabledata("3_10kW_68deg_10Gal_MF REDONE.DAT")
# df3 = nontabledata("4_15kW_68deg_10Gal_MF REDONE.DAT")
kWh_5 = df["1"] / 3412 * 10**9
# kWh_10 = df2["1"] / 3412 * 10**9
# kWh_15 = df3["1"] / 3412 * 10**9
plt.plot(df["0"], kWh_5, 'bo', label = '5kW')
# plt.plot(df2["0"], kWh_10, 'ro', label = '10kW')
# plt.plot(df3["0"],kWh_15, 'go', label = '15kW')
plt.xlabel("hours")
plt.ylabel("kWh")
plt.title("Energy Input Over Time")
leg = plt.legend()

# READING FROM TABLES
import numpy as np
import pandas as pd
import numpy.linalg as la
import matplotlib.pyplot as plt
from io import StringIO

# Helper Functions
def minusparse(line):
    newline = ""
    for i in range(len(line)):
        if (line[i] == '− '):
            newline += " " + line[i]
        else:
            newline += line[i]
    return newline
def dataparse(line):
    temp = [x for x in line.split(" ".) if x != ""]
    temp[-1] = temp[-1][:-1]
    string_temp = ""
    for item in temp:
        string_temp += " " + item
    return string_temp

# END HELPER FUNCTIONS

# Open output file from FORTRAN code
def tabledata(file_name):
    cnt = 0
    f = open(file_name, "r")
    for _ in range(15):
        __ = f.readline()  # eliminate beginning text
    __ = f.readline()  # Get first table
    data = ""
    features = [x for x in f.readline().split(" ".) if x != ""]
    features[-1] = features[-1][0:2]
    for _ in range(29):
        newline = minusparse(f.readline())
        temp = [x for x in newline.split(" ".) if x != ""]
        temp[-1] = temp[-1][:-1]
        string_temp = ""
        for item in temp:
            string_temp += " " + item
        data += str(cnt) + string_temp + "\n"
    cnt += 1
    # Get tables
    for _ in range(21):
        line = f.readline()
        if (len(line.split()) == 0):
            line = "NONE"
        while (line.split()[0] == "START"):
            line = f.readline()
        if (len(line.split()) == 0):
            line = "NONE"
line = f.readline()  # eliminate empty line
line = f.readline()

newline = minusparseline
while newline != ""):
    data += str(newline) + dataparse(newline) + "n"
newline = minusparseline

# Convert to pandas object
TESTDATA = StringIO(data)
df = pd.read_csv(TESTDATA, names=features)

return df

df1 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df2 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df3 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df4 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df5 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df6 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df7 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df8 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df9 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

df10 = tabledatabab(50.5kW_68_33gal_AB.DAT)  Your file name here

H = (df1[HWC]) / 60) / 3.281  # Grab height of well
D = (df1[D]) / 3.281  # Grab diameter of well

fig = plt.figure(figsize=(8, 6), tight_layout=True)  # Create figure
ax1 = fig.add_subplot(221)  # Create optional subplotting functionality
ax1.plot(df1['TIME'], H, label='Height')  # Plot Height
ax1.plot(df1['TIME'], D, label='Diameter')  # Plot Diameter
ax1.set_xlabel('Time (hrs)')  # label
ax1.set_ylabel('Size (m)')  # label
ax1.set_title('Height vs Diameter')  # title
ax1.legend()  # legend

# function to create A, B, C values of equation of parabola: Ax^2+Bx+C

def calc_parabola_vertex(x1, y1, x2, y2, x3, y3)
    denom = (x1-x2) * (x1-x3) * (x2-x3)
    A = (x3*y2-y1) + x2 + (y1+y3) + x1 + (y3-y2) / denom
    B = (x3+4) * (y1-y2) + 2*x2*x3 + (y3+y1) + x1+x1 + (y2+y3) / denom
    C = x2 * x3 * y1 + 1 + y3 * x1 + x1 + (x3-x1) + y2 + y3 + x2 * (x1-x2) + y3 / denom
    return A, B, C

# initialize arrays to store data from Rodwell code
x1 = np.array([])  # Store x of the right x-intercept
x2 = np.array([])  # Store x of the left x-intercept
x3 = np.array([])  # Store x of the y-intercept
y1 = np.array([])  # Store y of the right x-intercept
y2 = np.array([])  # Store y of left x-intercept
y3 = np.array([])  # Store y of the y-intercept

# loop through Rodwell data to extract diameter and height of well at each time step
for i in range(len(x1)-1):
    x1 = np.append(x1, x1[i]+1)
    x2 = np.append(x2, x2[i]+1)
    x3 = np.append(x3, x3[i]+1)
    y1 = np.append(y1, y1[i]+1)
    y2 = np.append(y2, y2[i]+1)
    y3 = np.append(y3, y3[i]+1)

# initialize arrays to store A, B, C
A = np.array([])
B = np.array([])
C = np.array([])

# regenerate A, B, C for each time step
for i in range(len(x1)-1):
    a, b, c = calc_parabola_vertex(x1[i], y1[i], x2[i], y2[i], x3[i], y3[i])
    A = np.append(A, a)
    B = np.append(B, b)
    C = np.append(C, c)

# start plotting
import matplotlib.pyplot as plt
import matplotlib
import numpy as np
import time

# allow for "Animation"
from IPython.display import clear_output

# loop through x steps
x = 10
for i in range(len(x)-1, x):
    # clear last plot
    clear_output(wait=True)
    # create new plot
    fig = matplotlib.pyplot.gcf()
fig.set_size_inches(18.5, 10.5)
fig.set_dpi(100)
plt.clf()

# Determine how fast to animate
time.sleep(0.01)

# Create x values of parabola based on dimensions of well at each time step
x = np.linspace(x2[i], x1[i], 100)

# Generate the parabola
y = (A[i] * x^2) + (B[i] * x) + C[i]

# Plot the parabola
plt.xlim([-10, 10])
plt.ylim([y3[i] - 1, 0])
plt.xlabel("Depth (m)", fontsize=20)
plt.ylabel("Width (m)", fontsize=20)
plt.grid()
plt.plot(x, y, c='r', linewidth=6)
plt.show()

# Extract radius and height
Radius = x1[i]
Height = -y3[i]

# Compute volume of well
v = np.pi * Radius^2 * Height / 2

# Print values
print("Final Radius:", str(Radius))
print("Final Height:", str(Height))
print("Final Volume:", str(v))

Makefile Code to Compile C Code

This is the Makefile code to compile the following C code. It contains commands that run the main.c and main.h files to produce the output text file, and is functionally identical to the CRREL fortran code, the primary difference is that the C code is more accurate due to rounding differences between the coding languages. This file along with the other files needed to run the C code can be found at the hyperlinked Github repository.

C Code: main.c

This is the main.c C code. User inputs can be prescribed here, and it contains all of the constants needed to run the code, along with key computations.
```c
#include "main.h"

int main(void) {
    int i, J, JJ;
    double T3, MEO, QBC, MF, T34, QBC1, MUG1, MF1, T3E;
    double T25, MEG2, QBC2, MF2, T35, QBC4, QBC5, DEPTH;
    double AL, ALPHAI, BO, CPA, CPI, CPW;
    double DT, EIT, E, FI, GAM, H, HA, HI, HS, HBN, HSN, ISO, K1, MU, MUG, MUGS, MUGW;
    double MPS, MPW, MUGS, MUGW;
    double MEW, N, OMEGA, PI, PL, PM, PLT, PWT, Q5, QT, QIT, QT, RA, RH02, RH03;
    double ROW, RO, TAU, T, T1, T2, TP, TPI, TPIW, T31, T32, TF, TICE, TWB, TA, TS, TZ5, TZ6, TPIW_SET_N1;
    double D, MPA, MMG, HMB, MUGA, LE, AB, MW, AL, VA;
    double MEW, MU, ZP, RH03, ZPS, ASP, ML, DELH, HP, DP, HWPB;
    double TWP, MMW, HF, VWP, DF, EP, PMP, L, VAP, AIP;
    double Q, Q1, QB, TAU, RH04, TAP, FB, FHP, B, BZ, TPW;
    double E1, ESR, PRW, EKT, PMG, PLG, EF, EFC, QITI;

    FILE *fptr;

    printf("Hello␣RASC−AL␣World \n") ;
    char path[200];
    getcwd(path, 200);
    printf(" Current␣working␣directory :␣%s \n" , path);

    // if ((fptr = fopen(" input . txt " , " r ") == NULL) {
    // printf("Error : opening file for read \n") ;
    // Program exits if the file pointer returns NULL.
    // return (1) ;
    //}
    // if you want to update this later to rapidly change the input data without recompiling .
    // list the input variables here per the example below

    fscanf(fptr,"% lf ",&TZ3) ; // hrs
    fclose(fptr);

    // ******** PUT YOUR INPUTS HERE *******
    TZ3=216.0; // First table time end , then becomes large number (maybe full stop time)
    TZ3E=88000.0;
    T34=2064.0; // T34 increment for T31
    T35=96.0; // T35 increment for T32
    T36=5088.0; // T36 increment unknown what for
    TPIW_SET_N1=8.0; // Sets TPIW (increment for table time print) after first table
    MEO=350.0;
    MEG2=29.0;
    MEGS=29.0;
    MF=660.0;
    MF1=660.0;
    MF2=660.0;
    MFS=660.0;
    MFS=660.0;
    MUG=29.0;
    MUGS=29.0;
    MUGW=29.0;
    MUGW=29.0;
    QBC=25591.06;
    QBC1=25591.06;
    QBC2=0.0;
    QBC3=25591.06;
    QBC4=25591.06;
    QBC5=25591.06;
    DEPTH=160.0;
    TICE=−80.0;
    TWB=68.0;
    // ******** END YOUR INPUTS HERE *******

    // ******** DEFAULT PARAMETERS DO NOT CHANGE *******
    AL = 0.30; // Firn loss parameter 40
    ALPHAI = 0.0446; // ft2/hr 41
    BO = 1.1; // old value 0.199; // BTU/lbf−F. Cp ice 43
    CPA = 0.199; // Cp ice 44
    CPI = 0.5; // Cp water in btu/lbf
    CPW = 0.97; // hres (30 secs) 47
    DT = 8.333001E−03;
    EIT = 0.0;
    E = 0.0;
    FI = 0.90;
    GAM = 1.0;
    HA = 0.458; // Original 0.725;
    HB = 60.0;
    HI = 0.725; // original 0.725;
    HS = 32.5; // BTU/hr−ft2−F 56
    HBN = 24.0;
    HSN = 32.5;
    ISO = 32.5;
    J = 1;
```

KI = 1.28; // BTU/hr-ft-F, ice/firm conductivity 61
ME = 0.0;
MED = 0.0;
MMG = 0.0; // gallons, bulb water volume in gallons
MEN = 1106533.0;
N = 1;
OMEGA = 5.399;
PI = 3.141593;
PL = 0.0;
PM = 0.0;
PMF = 0.0;
PRT = 0.0;
QS = 0.0;
QT = 0.0;
QTT = 0.0;
QIT = 0.0;
RA = 1.5; // ft, drill radius
RHOIS = 45.0; // lbm/ft³, start close-off density of firm
RHOIM = 57.54; // lbm/ft³, max firm density
RHOW = 62.6; // lbm/ft³, water density (VERIFIED)
RO = RA; // ft

// TIME PARAMETERS
TAUP = 0.0;
TI = 0.0;
TIS = 0.0;
TP = 8.0;
TPI = 8.0;
TPIW = 8.0;
TZ1 = 8760.0; // 8760 hours is 1 earth year
TZ2 = 240.0; // 240 hours is 10 earth days
TZS = TZ1 - TZ6;

// TEMPERATURES
TF = 32.0;
TA=TICE; TA=TS;
TW=TWB; // ...

// MORE PARAMETERS
ZS = H; // ft, diameter of bulb
MFS = MF ;
MW = PI * RA * RA * H * RHOW ; // lbm, water mass
MMG = MW /
HW = H;
HWB = DEPTH + H; // ft, depth to well bottom
HWB = DEPTH + H; // ft, depth to well bottom
HWB = DEPTH + H; // ft, depth to well bottom
HWB = DEPTH + H; // ft, depth to well bottom

// Open output file
if ((fptr = fopen ("./output.txt", "w")) == NULL) {
    printf ("Error : opening file for write
") ;
    return (1) ;
}

// Print initial parameters
fprintf ( fptr , "WITHDRAWAL RATE = 100 gal/day
") ;
fprintf ( fptr , "BOILER WATER TEMP DEG F = %f
") , TWB ) ;
fprintf ( fptr , "BOILER WATER FLOW RATE lbm/hr = %f
") , MF ) ;
fprintf ( fptr , "CONVECTIVE COEFFICIENT BTU/HR-FT²-FT = %f
") , HS ) ;
fprintf ( fptr , "INITIAL DRILL RADIUS PT. FT = %f
") , RA ) ;
fprintf ( fptr , "DEPT TO TOP OF WATER AT START FT. = %f
") , DEPTH ) ;
fprintf ( fptr , "AIR WATER INTERFACE AREA FT² = %f
") , D ) ;
fprintf ( fptr , "WATER VOLUME IN BULB = %f
") , HWB ) ;
fprintf ( fptr , "AIR VOLUME = %f
") , VA ) ;

// Loop
for (i =1; i <=11250000; i++) {
    // Statements jump back here
}

// Program exits if the file pointer returns NULL.
return(1);
if (TI < TAUP) {
    // not sure what taup is
    MF = 0.0;
    MG = MGA;
    MU = MUD;
} else {
    MF = MFA;
    MG = 0.0;
    MU = 0.0;
}

L280:
ZP = HWB-1/2.0;  // ft, average bulb depth
RHOI = 20.18 + 2.4996 * pow(ZP,0.45);
if (ZP > 394.0) RHOI=RHOIM;
// compute the change in water depth, h (eq. 7)
DELH = 16.0 * H * (HS * (TW - TF) - QS) * DT / (RHOI * LE * 3.0 * (2.0 * GAM * H + D) ) ;
HP = H+DELH;
DP = D+GAM*DELH;
HWBP = HWB+DELH;
// assumes full shut-off of water leakage into firn at ZS
ZPS = HWB-ZS;
ASP = 2.0 * PI * D * H / 3.0;
if (ZPS > H) {
    ASP=0.0;
} else if (HWB > 25.0) {
    ZPP = (ZS+HWB-H) / 2.0;
    ASP = 2.0 * PI * D * H * (1.0 - pow((ZPS/H),1.5)) / 3.0;
    RHOI = 20.18 + 2.4996 * pow(ZPP,0.45);
}
// water mass lost to rn
MUL = AL * ASP * (RHOIS - RHOI) ;
if (MF != 0.0)
    TWB = QBC/(CPW * MF) + TW;
// Unknown what this is doing
TWP = TW+(MF * (TWB - TW) - HS * AS / LE - MU - MUL) * DT;
MWP = MW+(((TW - TF) * HS - QS) * AS/LE - MU - MUL) * DT;
MWG = MWP / (.134 * RHOW) ;
VWP = MWP / RHOW;
HF = sqrt (8.0 * VWP * HP / PI ) / DP;
DF = DP * sqrt (HF / HP) ;
HW = HF;
EP = CPW * (TWB - TWP) * MF * DT;
E = E + EP;
PMP = MU * DT;
PM = PM + PMP;
PLP = MUL * DT;
PL = PL + PLP;
AIP = AI+PI * ((DP*DP) - (D*D)) / 4.0 + PI*(DP+HP) / H;
VAP = VA + PI * ((DP*DP) - (HP*HP)) / 8.0;
H = HF;
D = DF;
TI = DT + TI ;
Q = HI - (TA - TS) ;
Q = Q + DT * AL;
QT = QT + Q * DT ;
QIT = QIT + QI ;
QB = QT / TI ;
TAU = ALPHA1 + TI / (BO + BO) ;
RHEA = 0.4758 / (TA + 460.0) ;
TAP = TA+HS*AB*(TW-TA)+HI+AI*(TS-TA) + DT/(RHEA*VA*CPA) ;
// Unknown what the loop does
while(1) |
    FB = (5.0*(BO+BO)+BO)/36.0 - BO/4.0 + 0.0*(1.0/3.0 - BO/2.0) + log(BO) - TAU*(BO-1.0)*log(BO) ;
    FBP = (5.0*(BO+BO))/12.0 - 0.25 - log(BO) / 2.0 + (1.0/3.0 - BO/2.0) / BO - TAU*(1.0 + 1.0/BO) ;
    BP = BO - FB / FBP ;
    BZ = fabs(BP - BO) ;
    if (BZ < .0001) break ;
    BO = BP ;
}
// Unknown what this does
B = BP ;
BO = BP + 1.0 ;
TS = TICE+GR*BO*(B-1.0)+log(B) / (KI*(B-1.0)+log(B)) ;
if (J == 1) {
    if (TI > TP) |
        fprintf(fptr,"%4.1f,%t4.2f,%t4.2f,%t4.2f,%t4.2f,%t4.2f,%t4.2f,%t4.2f,%t4.2f\n",TI,TWP,TAP,TS,MWG,D,HW,HWBP,AIP,VAP);
        TP = TP + TP1 ;
        TPW=TP ;
    }
    else {
        fprintf(fptr,"%4.1f,%t4.2f,%t4.2f,%t4.2f,%t4.2f,%t4.2f,%t4.2f,%t4.2f,%t4.2f\n",TI,TWP,TAP,TS,MWG,D,HW,HWBP,AIP,VAP);
        TPW = TPW + TPW ;
    }
}
if (TI > TP) {
    TP = TP + TPI;
    TAUP = TP + MUGA * .134 * RHOR/MUD - TPI;
}

// Unknown what this does
HWB = HWBP;
TW = TWP;
TA = TAP;
MW = MWP;
AS = 2.0 * PI * D * H / 3.0;
AB = (PI * (D * D)) / 4.0;
VA = VAP;
if (D > 60.0) {
    HS = HSN;
} else {
    HS = HS0;
}
if (TW < 32.0001) TW = 32.0; // TW drops to low, reset it
if (TI > TZ2 || TI > TZ1) goto L1220;

//***************END OF LOOP***************
goto L1760; // Jump to finished output
L1220: // Print item in table and year dispatch
fprintf ( fptr, "%4.1f ,	%4.2f ,	%4.2f ,	%4.2f ,	%4.1f ,	%4.2f ,	%4.2f ,	%4.2f ,	%4.2f \n" ,TI , TWP , TAP , TS , MWG , D , HW , HWBP , AIP , VAP);
EI = E - EIT;
ESR = EI / (TI - TIS);
EIT = E;
PRW = MW - MWO + PM;
PRWT = PRWT + PRW;
PLT = PLT + PL;
PMT = PMT + PM;
EKT = PRWT * 19500.0 / EI;
EK = PRW * 19500.0 / EI;
PMG = PM / (.134 * RHOW);
PM = 0.0;
PLG = PL / (.134 * RHOW);
PL = 0.0;
MWO = MW;
EF = E / 140000.0;
EFI = EI / 140000.0;
QITI = QITI - QTT;
QTT = QIT;
fprintf ( fptr, "\n") ;
if (N == 1) { // Year 1
    N1
} else {
    N2
}
if (N == 3) { // Year 1
    N3
} else {
    N4
}
if (N == 5) { // Year 2
    N5
}
if (N == 6) goto L1520;
if (N == 7) goto L1500;
//CCC
338
if (N == 8) goto L1520;
if (N == 9) goto L1500;
//CCC
341
if (N == 10) goto L1520;
if (N == 11) goto L1500;
//CCC
344
if (N == 12) goto L1520;
if (N == 13) goto L1500;
//CCC
∗∗∗∗
END OF YEAR 6
∗∗∗∗
347
if (N == 14) goto L1520;
if (N == 15) goto L1500;
//CCC
∗∗∗∗
END OF YEAR 7
∗∗∗∗
350
if (N == 16) goto L1520;
if (N == 17) goto L1500;
//CCC
∗∗∗∗
END OF YEAR 8
∗∗∗∗
353
if (N == 18) goto L1520;
if (N == 19) goto L1500;
//CCC
∗∗∗∗
END OF YEAR 9
∗∗∗∗
356
if (N == 20) goto L1520;
if (N == 21) goto L1500;
/*
if (N == 22) goto L1760; // After year 10
N1 // Years that aren’t list above
// ******** Ending Output *******
L1760:
fprintf ( fptr , "\n") ;
fprintf ( fptr , "TOTAL␣ENERGY␣INPUT␣BTU␣=␣%e \n" ,E) ;
fprintf ( fptr , "TOTAL␣ENERGY␣INPUT␣GAL␣FUEL␣=␣%f \n" ,E/140000.) ;
fclose ( fptr ) ;
printf ("END\n") ;
return 0;
}
}
C Code: Inputs

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description</th>
<th>50T propellant</th>
</tr>
</thead>
<tbody>
<tr>
<td>MG0</td>
<td>Initialized bulb volume in gallons</td>
<td>12186.0*</td>
</tr>
<tr>
<td>MUG1, MUG2, MUG3, MUGS, MUGW</td>
<td>Water extracted in gal/day</td>
<td>29.0**</td>
</tr>
<tr>
<td>MF, MF1, MF2, MFS, MFW</td>
<td>Mass flow rate in lbm/hr</td>
<td>660.0</td>
</tr>
<tr>
<td>QBC, QBC1, QBC2, QBC3, QBC4, QBC5</td>
<td>Power in btu/hr</td>
<td>25591.06**</td>
</tr>
<tr>
<td>DEPTH</td>
<td>Depth to ice in ft</td>
<td>160*</td>
</tr>
<tr>
<td>TICE</td>
<td>Temperature of ice in Fahrenheit</td>
<td>-80*</td>
</tr>
<tr>
<td>TWB</td>
<td>Temperature of the water leaving the boiler in Fahrenheit</td>
<td>68*</td>
</tr>
</tbody>
</table>

*Values are unchanged from values given by Dr. Hoffman.

**When scaling the architecture these values change. 100T propellant: 58 gal/day and 10kW, 150T: 87 gal/day and 15kW, 200T: 116 gal/day and 15kW, 250T: 145 gal/day and 20kW, 300T: 174 gal/day and 25kW
C Code: Changes to Original Code

<table>
<thead>
<tr>
<th>Change</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Translating into C</td>
<td>As C is a lowlevel language, it is closer to the binary system used by computers which allows for more accurate computing. Also, as C supports the use of GOTO statements it was a primary candidate to translate the FORTRAN code into.</td>
</tr>
<tr>
<td>Removal of as many GOTO statements as possible</td>
<td>GOTO statements are acknowledged as bad practice in the CS community since they allow you to jump in and out of loops which creates complexity. These statements decrease efficiency and make it harder for future readers to understand the code. Therefore, the University of Illinois eliminated as many GOTO statements as possible along with adding comments to the code to make it easier to understand.</td>
</tr>
<tr>
<td>Integrating the input file into main.c</td>
<td>Having a separate input file requires implementing code to call and read that file. Those that are unfamiliar with coding can run into issues if they do not change the C code to accept their input file. Therefore, to increase simplicity the inputs are included in the main file.</td>
</tr>
<tr>
<td>Overriding the output file every time the code is compiled</td>
<td>To optimize the outputs the user of the code will need to run the program multiple times with various inputs. Rather than needing to delete or rename every single output file, the user can simply rerun the code and it will override the current output file. If the user wishes to keep an output file they simply have to rename it.</td>
</tr>
<tr>
<td>Changing only some variables to match the Rodwell Experiment Final Report</td>
<td>We found that some of the changes that were made to the U.S. Army Corp FORTRAN code in order to adapt it to Mars conditions broke the code, therefore we changed each variable individually and checked if it broke the code, those that worked were kept as can be seen in the comments of the code.</td>
</tr>
<tr>
<td>Using a value of 4.0366 J/gK for the specific heat of the water</td>
<td>In the code the variable CPW delineates the specific heat of water, this value was calculated using the data from the calorimetry experiments in order to use a CP of water that assumes unpure ice that contains regolith and salt deposits.</td>
</tr>
</tbody>
</table>

**STING/KRUSTY Heat Exchanger Python Code**

```python
import math

TMars = 222  # In Kelvin, equal to ~60 Fahrenheit, check with mining to insure this stays constant
e = math.e
pi = math.pi

# inputs
pipeLengthSurface = 10  # change this at will
pipeLengthSting = 60  # change this at will; represents maximum heat loss in Sting

TemporalKrustyWater = 305  # in Kelvin, ~32 Celsius, this variable should be changed at will as long as it is feasible for transfer from KRUSTY (Beneath 50C)

MassFlowrate = 0.832  # kg/s, from mining

ThermalAtKrusty = MassFlowrate * 191.83  # kW, from Fundamentals of Engineering Thermodynamics

#Step 1: pipe from krusty to sting

#Properties of Mars

TempMars = 150  # In Kelvin, from Mars Climate Database with coldest temperature;
TempRodwell = 211  # converted from fahrenheit in rodwell code

TempSky = 100  # In Kelvin, from Preliminary Thermal Surface Design of the Mars 2020 Rover

PressureMars = 0.00750062  # atm, or .760 kPa from Mars Climate Database, near 45 lat

GMars = 3.721  # km/s
	
rhoMars = 2.4  # kg/m^3  #From Mars Climate Database, corresponds to atmosphere

cpMars = 37.35  # J/mol K, assuming same as specific heat of CO2 as a gas

HeatTransferGround = 6/77.335 = 10e-4  # from Note on thermal properties of Mars, converted into watts per meter squared

DensityWater = 3.7854  # kilograms per gallon
```

---

*Krusty Heat Loss Code*

*Thermo Bible — Heat Transfer: A practical approach, first edition by Yunus Cengel*

Page 417 has a worked example of a pipe.

**Assumptions list**

- Steady operating conditions
- Cold winter night on Mars
- Air is an ideal gas
- Local atmospheric pressure is as stated
- Using cold measures of Mars — assuming behavior around 45-60N latitude
- Specific heat of Mars air is a big assumption — Used gas mix from [https://ntrs.nasa.gov/api/citations/19700003481/downloads/19700003481.pdf](https://ntrs.nasa.gov/api/citations/19700003481/downloads/19700003481.pdf)

Excess heat entering the rodwell will create extra melted water — will make rodwell wider, but will not have a significant performance impact.

---

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Math 41
pressureRodwell = .5 atm
rhoRodwell = (rhoRodwell / pressureMars) * rhoMars

#calculating Rayleigh number for convection
x = 1/39.37 #meters, characteristic length/outer diameter of pipe
beta = 1/tempMars #thermal expansion coefficient, ideal gas assumption
tempDif = tempKrustyWater - tempMars
#calculating Rayleigh number to understand heat loss in pipe
grashof = tempKrustyWater * beta * (tempDif)**3
prandtl = 7 #from Transport Properties at High Temperatures
rayleigh = grashof * prandtl
#from Heat Transfer
nusselt = 0.6 + (3.87*rayleigh**0.16)/(1 + (0.559/prandtl)**3 + 4/27)**2
h1 = kMarsAir / x * nusselt
Al = pi * x * pipeLengthSurface
QConv1 = h1*Al*tempDif
print("The heat lost from, convection in the outer, stretch of, pipe, per, second, is")
print(QConv1)

#Calculating heat lost from radiation
stefanBoltzmann = 5.67 * 10**(-8)
epsilonTitanium = 0.5 #https://www.omega.co.uk/literature/transactions/volume1/emissivitya.html, rough estimate for a titanium alloy
QRad1 = epsilonTitanium * Al * stefanBoltzmann * (tempKrustyWater + tempSky + 4)
print("The heat lost from, radiation in the outer, stretch of, pipe, per, second, is")
print(QRad1)

# this number is the largest of heat losses, it could be reduced further by adding an aerogel or other material with low emissivity to the outer shell.
tempStingWater = tempKrustyWater - 2 # this requires manual adjustment based on above values with a chart of water heat. This is roughly the amount of thermal energy lost (Engineering Thermodynamics) and the corresponding temperature

#Heat Transfer in upper part of sting in worst case scenario
#calculating new Rayleigh
x = 1/39.37 #meters, characteristic length/outer diameter of pipe
beta = 1/39.37 #thermal expansion coefficient, ideal gas assumption
tempDif = tempStingWater - tempRodwell
#calculating Rayleigh number to understand heat loss in pipe
grashof = tempStingWater * beta * (tempDif)**3
prandtl = 65 #from Transport Properties at High Temperatures
rayleigh = grashof * prandtl
#from thermo book
nusselt = 0.6 + (3.87*rayleigh**0.16)/(1 + (0.559/prandtl)**3 + 4/27)**2
h1 = kMarsAir / x * nusselt
A2 = pi * x * pipeLengthSurface
QConv2 = h1*A2*tempDif
print("The heat lost from, convection, inside of, Sting, pipe, at, full extension, per, second, is")
print(QConv2)

#Calculating heat lost from radiation in Sting
stefanBoltzmann = 5.67 * 10**(-8)
epsilonTitanium = 0.5 #https://www.omega.co.uk/literature/transactions/volume1/emissivitya.html, rough estimate for a titanium alloy
QRad2 = epsilonTitanium * A2 * stefanBoltzmann * (tempKrustyWater + tempSky + 4)
print("The heat lost from, radiation in, the, Sting, pipe, per, second, is")
print(QRad2)

#This analysis predicts a maximum of 1132 watts of heat loss, which is 15% of the heat needed to power the rodwell, but only 3.77% of the total heat energy produced by KRUSTY.
#Additionally, over 82% of this heat loss is in the Rodwell, where a fraction of it will be used to expand the rodwell.
The final consideration is the effects of adding a water storage tank associated with KRUSTY, and any conduction that might occur between the pipes and the ground of Mars.

Works Cited

Millour, E., â€œThe Mars Climate Database (MCD version 5.3)â€‌, p. 12247, 2017.
Cost Analysis

Fig. 33 Low Cost Estimate SAND Chart

Cost Analysis Python Code

```python
import numpy as np

# initializes cost categories
operations_pro = np.zeros(20)
operations_total = 0
services_pro = np.zeros(20)
services_total = 0
design_pro = np.zeros(20)
design_total = 0
fabrication_pro = np.zeros(20)
fabrication_total = 0

# fixed price values
STARSHIP_LAUNCH_COST = 11*10**6 #10 launches multiplied by the quotes price of $1,000,000
SLS_LAUNCH_COST = 4.1*10**9 #1 launch at the IG price of $4.1 Billion
DRILL_PRICE = 663000
OP_COST_BASELINE = 1.5*10**8
AMOUNT_METHANE = 11086 #kg
AMOUNT_LOX = 39130 #kg
STORAGE_TANK_SIZE = 34 #m^3
ATHLETE_PRICE = 3*10**9 #based on the price of the Perseverance Rover
DSN_HOURS = 450
DSN_BASE_RATE = 1792 #The Rb quoted price from the DSN Mission Support Definition and Commitments Office.
TTC_COST = 300000
NETWORK_ACCESS_FEE = 2700
MIM_COST = 290000
RF_TEST_COST = 120000

mars_factor = (800000000/28000)

"""Type in 'low' for the low estimate, 'high' for the more expensive one, or 'mean' for the average."
"The calculator will automatically return the total cost, inflation is taken into account."

"This script calculates the price for the MITHRIL ISRU. The calculator will ask for several inputs corresponding to cost assumptions, e.g. the cost of the launch system."
"Inflation is taken into account."

# determines price of communications
services_pro[10]+=MIM_COST+RF_TEST_COST+NETWORK_ACCESS_FEE
```

43
def main():
    # Determine the total yearly cost for DSN usage based on a 2% inflation rate
    af = DSN_BASE_RATE * (1 + 10/10)
    yearly_cost = DSN_HOURS * af + NETWORK_ACCESS_FEE
    services_pro += yearly_cost

    # Determine the cost to develop software
    CS_LABOR_COST = 110140 + 100000  # Average salary from BLS + a bunch for other costs
    NUM_CS_WORKERS = 30
    total_software_cost = CS_LABOR_COST * NUM_CS_WORKERS * 5
    total_software_cost_pro = total_software_cost / 8
    for i in range(8):
        design_pro[i] += total_software_cost_pro

    # Determine the cost for operations
    op_cost_modifier = 1.8
    for i in range(12, 20):
        operations_pro[i] = OP_COST_BASELINE * op_cost_modifier
        op_cost_modifier = op_cost_modifier - .1
    # Determine launch costs
    launch_cost = 0
    launch_vehicle = input('SLS is estimated to cost $4.1 Billion, while Starship is presumed to cost $10 Million.
')
    launch_vehicle = launch_vehicle.upper()
    if launch_vehicle == 'LOW':
        launch_cost += STARSHIP_LAUNCH_COST
        print('Using the LOW estimate.
')
    elif launch_vehicle == 'HIGH':
        launch_cost += SLS_LAUNCH_COST
        print('Using the HIGH estimate.
')
    else:
        launch_cost = (STARSHIP_LAUNCH_COST + SLS_LAUNCH_COST) / 2
        print('Using the MEAN cost.
')
    launch_cost_pro = launch_cost / 3
    launch_cost_pro = launch_cost_pro / 8
    for i in range(9, 12):
        services_pro[i] += launch_cost_pro

    # Determine cost of KRUSTY
    krusty_price = 5500
    krusty_total_cost = 0
    krusty_choice = input('The estimated range for power is between $880 Million and $1.3 Billion.
')
    krusty_choice = krusty_choice.upper()
    if krusty_choice == 'HIGH':
        krusty_total_cost = 7 * krusty_price * mars_factor * 1.2
        print('Using the HIGH estimate.
')
    elif krusty_choice == 'LOW':
        krusty_total_cost = 7 * krusty_price * mars_factor * .8
        print('Using the LOW estimate.
')
    else:
        krusty_total_cost = 7 * krusty_price * mars_factor
        print('Using the MEAN cost.
')
    krusty_total_cost_fab = krusty_total_cost * .75
    krusty_total_cost_design = krusty_total_cost * .25
    krusty_total_cost_fab_pro = krusty_total_cost_fab / 8
    krusty_total_cost_design_pro = krusty_total_cost_design / 6
    for i in range(8):
        design_pro[i] += krusty_total_cost_design_pro
    for i in range(6, 12):
        fabrication_pro[i] += krusty_total_cost_fab_pro

    # Determine SABER costs
    price_per_barrel_oil = 25000
    price_per_gallon_oil = price_per_barrel_oil / 42
    price_per_kg_oil = price_per_gallon_oil * 3.45
    price_per_kg_methalox = price_per_kg_oil * (1.55 / .82)
    saber_price_base = price_per_kg_methalox * (AMOUNT_METHANE + AMOUNT_LOX) / 300 * mars_factor
    saber_price_low = .8 * saber_price_base
    saber_price_high = 1.2 * saber_price_base
    saber_cost = 0
    saber_choice = input('The price points for SABER are between $1.5 and $2.3 Billion.
')
    saber_choice = saber_choice.upper()
    if saber_choice == 'HIGH':
        saber_cost_design = saber_price_high * (1057 / 1656)
        saber_cost_fab = saber_price_high * (619 / 1656)
        print('Using the HIGH estimate.
')
    elif saber_choice == 'LOW':
        saber_cost_design = saber_price_low * (1057 / 1656)
        saber_cost_fab = saber_price_low * (619 / 1656)
        print('Using the LOW estimate.
')

if __name__ == '__main__':
    main()
```python
else:
    saber_cost_design = (saber_price_high+saber_price_low)/2*
    1037/1656
    saber_cost_fab = (saber_price_high+saber_price_low)/2*
    619/1656
    print("Using the MEAN cost.")
    saber_cost_design_pro = saber_cost_design /8
    saber_cost_fab_pro = saber_cost_fab /6
    for i in range(8):
        design_pro[i]+=saber_cost_design_pro
    for i in range(6,12):
        fabrication_pro[i]+=saber_cost_fab_pro

#determines storage cost
storage_tank_gallons = 2*STORAGE_TANK_SIZE
tank_cost_per_gallon = 1380000/835958
storage_cost = storage_tank_gallons*tank_cost_per_gallon+mars_factor
storage_choice = input( 'The costs for storage are $2.3 and $3.5 Billion, respectively.' )
storage_choice = storage_choice.upper()
if storage_choice == "HIGH":
    storage_cost设计 = storage_cost*(1057/1656)=1.2
    storage_cost_fab = storage_cost*(619/1656)+1.2
    print("Using the HIGH estimate.")
elif storage_choice == "LOW":
    storage_cost_design = storage_cost*(1037/1656)+.8
    storage_cost_fab = storage_cost*(619/1656)+.8
    print("Using the LOW estimate.")
else:
    storage_cost_design = storage_cost*(1037/1656)
    storage_cost_fab = storage_cost*(619/1656)
    print("Using the MEAN cost.")
    storage_cost_design_pro = storage_cost_design /8
    storage_cost_fab_pro = storage_cost_fab /6
    for i in range(8):
        design_pro[i]+=storage_cost_design_pro
    for i in range(6,12):
        fabrication_pro[i]+=storage_cost_fab_pro

#determines STING cost
sting_cost = DRILL_PRICE
sting_choice = input( 'STING is estimated to cost between $1.5 and $2.3 Billion.' )
sting_choice = sting_choice.upper()
if sting_choice == "HIGH":
    sting_cost_design = sting_cost*(1105/1739)=1.2
    sting_cost_fab = sting_cost*(634/1739)+1.2
    print("Using the HIGH estimate.")
elif sting_choice == "LOW":
    sting_cost_design = sting_cost*(1105/1739)+.8
    sting_cost_fab = sting_cost*(634/1739)+.8
    print("Using the LOW estimate.")
else:
    sting_cost_design = sting_cost*(1105/1739)
    sting_cost_fab = sting_cost*(634/1739)
    print("Using the MEAN cost.")
    sting_cost_design_pro = sting_cost_design /8
    sting_cost_fab_pro = sting_cost_fab /6
    for i in range(8):
        design_pro[i]+=sting_cost_design_pro
    for i in range(6,12):
        fabrication_pro[i]+=sting_cost_fab_pro

#determines ATHLETE cost
athlete_cost_design = ATHLETE_PRICE
athlete_cost_fab = ATHLETE_PRICE
athlete_cost_design_pro = athlete_cost_design /8
athlete_cost_fab_pro = athlete_cost_fab /6
for i in range(8):
    design_pro[i]+=athlete_cost_design_pro
for i in range(6,12):
    fabrication_pro[i]+=athlete_cost_fab_pro

#apply a 2% inflation factor
for i in range(20):
    inf_factor = 1.02**i
    design_pro[i] = design_pro[i]*inf_factor
    fabrication_pro[i] = fabrication_pro[i]*inf_factor
    services_pro[i] = services_pro[i]*inf_factor
    operations_pro[i] = operations_pro[i]*inf_factor

#determines total cost in each category
operations_total = sum(operations_pro)
services_total = sum(services_pro)
design_total = sum(design_pro)
fabrication_total = sum(fabrication_pro)
total_cost = operations_total+services_total+design_total+fabrication_total
print("The total calculated cost for MITHRIL is $", np.round(total_cost), ")
```
D. Calculations

*MITHRIL* Sizing Breakdown

### Table 14  Detailed Breakdown

<table>
<thead>
<tr>
<th>Subsystem/Component</th>
<th>Quantity</th>
<th>Unit Mass (kg)</th>
<th>Total Mass (kg)</th>
<th>Power (kW)</th>
<th>Stowed Volume (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>1.0 STING</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.1 Derrick</td>
<td>3</td>
<td>172.5</td>
<td>517.5</td>
<td>X</td>
<td>12.09</td>
</tr>
<tr>
<td>1.2 Drum</td>
<td>3</td>
<td>52</td>
<td>156</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>1.3 Coiled Tubing</td>
<td>4</td>
<td>39.40</td>
<td>157.6</td>
<td>3.5</td>
<td>X</td>
</tr>
<tr>
<td>1.4 CT Injector</td>
<td>4</td>
<td>24.6</td>
<td>98.4</td>
<td>0.4</td>
<td>X</td>
</tr>
<tr>
<td>1.5 Bottom Hole Assembly</td>
<td>7</td>
<td>5.6</td>
<td>39.2</td>
<td>3</td>
<td>X</td>
</tr>
<tr>
<td>1.6 Peristaltic Pump</td>
<td>10</td>
<td>1.65</td>
<td>16.5</td>
<td>2.1</td>
<td>X</td>
</tr>
<tr>
<td>1.7 Seed Tank</td>
<td>2</td>
<td>17</td>
<td>34</td>
<td>0.045</td>
<td>3.2</td>
</tr>
<tr>
<td>1.8 Surface Tubing</td>
<td>3</td>
<td>19.7</td>
<td>59.1</td>
<td>1.75</td>
<td>X</td>
</tr>
<tr>
<td><strong>2.0 SABER</strong></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2.1 Recycle Pump</td>
<td>2</td>
<td>26</td>
<td>52</td>
<td>9.4</td>
<td>0.07</td>
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<tr>
<td>2.2 IWP Filter</td>
<td>13</td>
<td>3</td>
<td>39</td>
<td>0.231</td>
<td>0.5</td>
</tr>
<tr>
<td>2.3 H₂O Buffer Tank</td>
<td>1</td>
<td>17</td>
<td>17</td>
<td>0.045</td>
<td>0.05</td>
</tr>
<tr>
<td>2.4 CO₂ Pump</td>
<td>2</td>
<td>70</td>
<td>140</td>
<td>9.936</td>
<td>0.25</td>
</tr>
<tr>
<td>2.5 Gas/liquid Separator</td>
<td>5</td>
<td>8</td>
<td>40</td>
<td>0.138</td>
<td>0.755</td>
</tr>
<tr>
<td>2.6 Electrolyzer</td>
<td>5</td>
<td>25</td>
<td>125</td>
<td>18.33</td>
<td>1.51</td>
</tr>
<tr>
<td>2.7 Adsorption Heaters</td>
<td>2</td>
<td>8</td>
<td>16</td>
<td>0.69</td>
<td>0.02</td>
</tr>
<tr>
<td>2.8 Flow controllers</td>
<td>13</td>
<td>1</td>
<td>13</td>
<td>0.025</td>
<td>0.01</td>
</tr>
<tr>
<td>2.9 Sabatier Reactors</td>
<td>23</td>
<td>2.4</td>
<td>55.2</td>
<td>X</td>
<td>1.23</td>
</tr>
<tr>
<td>2.12 Miscellaneous parts</td>
<td>2</td>
<td>162</td>
<td>324</td>
<td>X</td>
<td>0.5</td>
</tr>
<tr>
<td>2.13 SABER Case</td>
<td>1</td>
<td>375</td>
<td>375</td>
<td>X</td>
<td>1.82</td>
</tr>
<tr>
<td><strong>3.0 Propellant Storage</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3.1 Common Storage Bladder</td>
<td>2</td>
<td>543</td>
<td>1084</td>
<td>X</td>
<td>2.88</td>
</tr>
<tr>
<td>3.2 Cryocooler 150 W</td>
<td>6</td>
<td>116</td>
<td>696</td>
<td>5.64</td>
<td>0.37</td>
</tr>
<tr>
<td>3.2 Cryocooler 100 W</td>
<td>4</td>
<td>110</td>
<td>440</td>
<td>2.85</td>
<td>0.37</td>
</tr>
<tr>
<td>3.3 Insulation Panels</td>
<td>2</td>
<td>350</td>
<td>700</td>
<td>X</td>
<td>3.14</td>
</tr>
<tr>
<td><strong>4.0 Transportation</strong></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4.1 ATHLETE</td>
<td>2</td>
<td>1770</td>
<td>1770</td>
<td>8.371</td>
<td>23.38</td>
</tr>
<tr>
<td>4.2 Li-on Batteries</td>
<td>60</td>
<td>28.02</td>
<td>789.6</td>
<td>X</td>
<td>0.78</td>
</tr>
<tr>
<td><strong>5.0 Power</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5.1 HS KRUSTY</td>
<td>1</td>
<td>2105</td>
<td>2105</td>
<td>X</td>
<td>5.83</td>
</tr>
<tr>
<td>5.2 LS KRUSTY</td>
<td>6</td>
<td>1863</td>
<td>11178</td>
<td>X</td>
<td>34.98</td>
</tr>
<tr>
<td>5.3 Ground Cables (30m)</td>
<td>6</td>
<td>61</td>
<td>305</td>
<td>X</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Table 15 Detailed Breakdown

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.0 Communications</td>
<td>X</td>
<td>X</td>
<td>251.02</td>
</tr>
<tr>
<td>6.1 FlyAway 2.4m</td>
<td>1</td>
<td>236</td>
<td>236</td>
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<tr>
<td>6.2 JPL UST</td>
<td>2</td>
<td>6.77</td>
<td>13.54</td>
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<td>6.3 Co-Axial Cable</td>
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<td>.17</td>
<td>.82</td>
</tr>
<tr>
<td>6.4 NanoAvionc UHF</td>
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<td>0.33</td>
<td>0.66</td>
</tr>
<tr>
<td>Total</td>
<td>X</td>
<td>X</td>
<td>21595.52</td>
</tr>
<tr>
<td>Total w/ 15% Margin</td>
<td>X</td>
<td>X</td>
<td>24834.85</td>
</tr>
</tbody>
</table>

* Total power does not include ATHLETE so as to reflect peak power loads during the duty cycle.

**MITHRIL Spares and Reliabilities**

Table 16 Detailed Spares and Reliabilities

<table>
<thead>
<tr>
<th>Subsystem/Component</th>
<th>MTRF (hours)</th>
<th>Number Installed</th>
<th>Spares</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Refining</td>
<td>X X</td>
<td>X X</td>
<td>0.9988</td>
<td></td>
</tr>
<tr>
<td>Sabatier Reactor</td>
<td>14,000</td>
<td>3</td>
<td>20</td>
<td>0.9999</td>
</tr>
<tr>
<td>IWP Filter</td>
<td>10,000</td>
<td>1</td>
<td>12</td>
<td>0.9999</td>
</tr>
<tr>
<td>Electrolyzer</td>
<td>65,000</td>
<td>1</td>
<td>4</td>
<td>0.9997</td>
</tr>
<tr>
<td>Distillation Chamber</td>
<td>260,000</td>
<td>1</td>
<td>2</td>
<td>0.9996</td>
</tr>
<tr>
<td>Gas/Liquid Separator</td>
<td>84,000</td>
<td>1</td>
<td>4</td>
<td>0.9999</td>
</tr>
<tr>
<td>Valves</td>
<td>100,000</td>
<td>5</td>
<td>8</td>
<td>0.9999</td>
</tr>
<tr>
<td>Cooling Heat Exchangers</td>
<td>170,000</td>
<td>3</td>
<td>5</td>
<td>0.9999</td>
</tr>
<tr>
<td>Propellant Storage</td>
<td>X X</td>
<td>X X</td>
<td>0.9998</td>
<td></td>
</tr>
<tr>
<td>Cryogenic Fuel Pumps with Inducers</td>
<td>4,000</td>
<td>2</td>
<td>4</td>
<td>0.9999</td>
</tr>
<tr>
<td>Temperature Sensors</td>
<td>2,300,000</td>
<td>6</td>
<td>4</td>
<td>1.0000</td>
</tr>
<tr>
<td>Pressure Sensors</td>
<td>1,000,000</td>
<td>6</td>
<td>4</td>
<td>1.0000</td>
</tr>
<tr>
<td>Rotary Vane Vacuum Gas Pumps</td>
<td>195,000</td>
<td>2</td>
<td>4</td>
<td>0.9999</td>
</tr>
<tr>
<td>Gas Compressor (Booster)</td>
<td>30,000</td>
<td>2</td>
<td>8</td>
<td>1.0000</td>
</tr>
<tr>
<td>Cryocooler</td>
<td>105,000</td>
<td>5</td>
<td>5</td>
<td>0.9993</td>
</tr>
<tr>
<td>Transportation</td>
<td>X X X</td>
<td>X X</td>
<td>0.9995</td>
<td></td>
</tr>
<tr>
<td>Wheels</td>
<td>1,389</td>
<td>6</td>
<td>12</td>
<td>0.9999</td>
</tr>
<tr>
<td>Leg Joint Actuator</td>
<td>197,100</td>
<td>6</td>
<td>9</td>
<td>0.9999</td>
</tr>
<tr>
<td>Lithium Ion Batteries</td>
<td>72,197</td>
<td>28</td>
<td>32</td>
<td>0.9996</td>
</tr>
<tr>
<td>Processor</td>
<td>43,000,000</td>
<td>7</td>
<td>1</td>
<td>0.9999</td>
</tr>
<tr>
<td>Wheel Actuator</td>
<td>120,000</td>
<td>6</td>
<td>9</td>
<td>0.9999</td>
</tr>
<tr>
<td>Mining</td>
<td>X X X</td>
<td>X X</td>
<td>0.9994</td>
<td></td>
</tr>
<tr>
<td>Derrick</td>
<td>500,000</td>
<td>1</td>
<td>2</td>
<td>0.9999</td>
</tr>
<tr>
<td>Drum</td>
<td>400,000</td>
<td>1</td>
<td>2</td>
<td>0.9998</td>
</tr>
</tbody>
</table>
Table 17  Detailed Spares and Reliabilities

<table>
<thead>
<tr>
<th></th>
<th>Quantity</th>
<th>Quantity Installed</th>
<th>Quantity Used</th>
<th>Reliability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coiled Tubing (x50 m)</td>
<td>250,000</td>
<td>1</td>
<td>3</td>
<td>0.9999</td>
</tr>
<tr>
<td>CT Injector</td>
<td>60,000</td>
<td>1</td>
<td>3</td>
<td>0.9999</td>
</tr>
<tr>
<td>BHA</td>
<td>40,000</td>
<td>1</td>
<td>6</td>
<td>0.9999</td>
</tr>
<tr>
<td>Peristaltic Pump</td>
<td>15,000</td>
<td>1</td>
<td>9</td>
<td>0.9997</td>
</tr>
<tr>
<td>Total Reliability</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.9964</td>
</tr>
<tr>
<td>Refining</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.9981</td>
</tr>
<tr>
<td>Mining</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.9930</td>
</tr>
<tr>
<td>Storage</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.9999</td>
</tr>
<tr>
<td>Transportation</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.9995</td>
</tr>
<tr>
<td>Power*</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.9995</td>
</tr>
<tr>
<td>Communications*</td>
<td>X</td>
<td>X</td>
<td>X</td>
<td>0.9995</td>
</tr>
</tbody>
</table>

*Power and Communications equipment are assumed to have a reliability of 0.9995

Governing gamma distribution:

\[
\text{Reliability} = \prod_{i=1}^{n_{\text{system}}} \prod_{j=1}^{n_{\text{component}}} 1 - \Gamma(\alpha = n_{\text{spare}_{ij}} + 1, \theta = \frac{\text{MTBF}_{ij}}{\text{quantity}_{\text{installed}_{ij}}}, x \leq t_{\text{final}})
\]

Total Chance of Failure = \((1 - \text{Reliability}_{\text{Total}}) \times 100\% = 0.36\%\)
Landing Site Analysis

Table 18  Landing Site Candidates

<table>
<thead>
<tr>
<th>Region*</th>
<th>Location</th>
<th>Ice Consistency**</th>
<th>Temp (K)***</th>
<th>Pressure (Pa)</th>
<th>Solar Flux (W/m2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EM</td>
<td>39.89 N, 192.09 E</td>
<td>0.50</td>
<td>167-279</td>
<td>690-950</td>
<td>171-473</td>
</tr>
<tr>
<td>AP</td>
<td>39.80 N, 202.10 E</td>
<td>0.53</td>
<td>169-278</td>
<td>700-960</td>
<td>170-475</td>
</tr>
<tr>
<td>PM</td>
<td>35.23 N, 163.95 E</td>
<td>0.5</td>
<td>166-283</td>
<td>650-809</td>
<td>226-488</td>
</tr>
<tr>
<td>AP</td>
<td>40.02 N, 203.35 E</td>
<td>0.75</td>
<td>168-278</td>
<td>700-960</td>
<td>168-476</td>
</tr>
<tr>
<td>DM</td>
<td>39.11 N, 23.20 E</td>
<td>0.5</td>
<td>170-278</td>
<td>670-930</td>
<td>190-479</td>
</tr>
<tr>
<td>AP</td>
<td>46.16 N, 188.80 E</td>
<td>0.93</td>
<td>163-273</td>
<td>710-970</td>
<td>114-449</td>
</tr>
<tr>
<td>EM</td>
<td>39.0 N, 192.1 E</td>
<td>-0.2</td>
<td>167-280</td>
<td>700-970</td>
<td>182-476</td>
</tr>
<tr>
<td>AF</td>
<td>39.8 N, 220.6 E</td>
<td>0.5</td>
<td>167-277</td>
<td>700-970</td>
<td>182-476</td>
</tr>
<tr>
<td>IC</td>
<td>33.5 N, 17.0 E</td>
<td>0.5</td>
<td>159-284</td>
<td>630-870</td>
<td>262-495</td>
</tr>
<tr>
<td>PM</td>
<td>39.0 N, 172.0 E</td>
<td>0.5</td>
<td>170-279</td>
<td>690-960</td>
<td>172-477</td>
</tr>
<tr>
<td>NF</td>
<td>28.88 S, 300.29 E</td>
<td>0.5</td>
<td>166-308</td>
<td>410-520</td>
<td>280-650</td>
</tr>
<tr>
<td>NT</td>
<td>37.33 S, 350.65 E</td>
<td>0.1</td>
<td>150-308</td>
<td>430-560</td>
<td>207-617</td>
</tr>
<tr>
<td>AC</td>
<td>31.97 S, 96.55 E</td>
<td>0.5</td>
<td>163-306</td>
<td>650-850</td>
<td>213-613</td>
</tr>
<tr>
<td>HP</td>
<td>35.35 S, 94.02 E</td>
<td>0.5</td>
<td>162-304</td>
<td>650-850</td>
<td>179-605</td>
</tr>
<tr>
<td>PT</td>
<td>40 S, 104 E</td>
<td>0.5</td>
<td>151-305</td>
<td>530-670</td>
<td>163-601</td>
</tr>
</tbody>
</table>

* Ausonia Cavus (AC), Hellas Planitia (HP), Promethei Terra (PT), Phlegra Montes (PM), Erebus Montes (EM), Noachis Terra (NT), Protonilus Mensae (PM), Nectaris Fossae (NF), Deuteronomium Mensae (DM), Ismenius Cavus (IC), Acheron Fossae (AF) Arcadia Planitia (AP).

** SWIM provides the ice consistency at different depths for a selected region on a scale of -1 to 1, where -1 indicates that data is inconsistent with ice, and 1 is consistent with ice. All but two locations had consistencies of > 0.5 for depths > 5 m within a 10 km radius, corroborating the findings in Dundes et al. [115].

*** Ranges of temp, pressure, and solar flux are seasonal. Data is from the Mars Climate Database [78].

![Grey-scale overlay indicates presence of ice](image_url)

**Fig. 34  Prospective Sites Analyzed Wide View**
**SABER Calculations**

Fig. 35 Interface For SABER calculations

<table>
<thead>
<tr>
<th>Comparison of Reactions</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Inputs</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Type</td>
<td>Input Value</td>
</tr>
<tr>
<td>Total Propellant</td>
<td>51000</td>
</tr>
<tr>
<td>Oxygen</td>
<td>39913.04348</td>
</tr>
<tr>
<td>Methane</td>
<td>11086.95652</td>
</tr>
<tr>
<td>Water Concentration</td>
<td>8</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs From Chen et al. *</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction</td>
<td>Water Required (kg)</td>
</tr>
<tr>
<td>SR/E</td>
<td>24904.17977</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Outputs based from Sanders et al. **</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Reaction</td>
<td>Water Required (kg)</td>
</tr>
<tr>
<td>SR/E</td>
<td>24904.17977</td>
</tr>
</tbody>
</table>

* Specific Mass of 72.2 kg and Specific Power of 0.68 kW with reference to 1 kg/h of CH₄, and Specific Mass of 83.3 kg and Specific Power of 5.83 kW with reference to 1 kg/h of O₂ [5]

** Specific Mass of 140.71 kg and Specific Power of 10 kW with reference to 1 kg/h of O₂ [55]

*** Regolith calculations are an artifact of initial trades between targeting subsurface ice or water sequestered in regolith.

Fig. 36 Sabatier and Electrolysis Mass Balance

Sabatier Reaction (SR) / Electrolysis

\[ 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]
\[ \text{CO}_2 + 4\text{H}_2 \rightarrow \text{CH}_4 + 2\text{H}_2\text{O} \]
\[ 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]

Net: \[ 2\text{H}_2\text{O} + \text{CO}_2 \rightarrow 2\text{O}_2 + \text{CH}_4 \]

Instructions: Do not touch unless you're troubleshooting

Only change input values

Check to see which calculation is correct

Highlighted orange is your required reactants

<table>
<thead>
<tr>
<th>Inputs</th>
<th>Input Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oxygen</td>
<td>39913.04348</td>
<td>kg</td>
</tr>
<tr>
<td>Methane</td>
<td>11086.95652</td>
<td>kg</td>
</tr>
<tr>
<td>Water Concentration</td>
<td>8</td>
<td>% mass</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sabatier Process WRT Methane</th>
<th>Reactants Required (kg)</th>
<th>Actual Production (kg)</th>
<th>Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>30420.00976</td>
<td></td>
<td>Process must be done WRT Methane</td>
</tr>
<tr>
<td>Water</td>
<td>24904.17977</td>
<td></td>
<td>Mass Conserved</td>
</tr>
<tr>
<td>Regolith</td>
<td>311302.2471</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td></td>
<td>44238.77882</td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td></td>
<td>11086.95652</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sabatier Process WRT Oxygen</th>
<th>Reactants Required (kg)</th>
<th>Actual Production (kg)</th>
<th>Check</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon Dioxide</td>
<td>27446.4538</td>
<td></td>
<td>Process must be done WRT Methane</td>
</tr>
<tr>
<td>Water</td>
<td>22469.7962</td>
<td></td>
<td>Mass Conserved</td>
</tr>
<tr>
<td>Regolith</td>
<td>280872.4524</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oxygen</td>
<td></td>
<td>39913.04348</td>
<td></td>
</tr>
<tr>
<td>Methane</td>
<td></td>
<td>10002.20652</td>
<td></td>
</tr>
</tbody>
</table>
Peristaltic Pump Calculations

Equations describing head loss and required hydraulic power are provided in Equation 1. Shaft power:

\[ P_s = \frac{P}{Efficiency} \]

where pump efficiency is 0.75. Installed power:

\[ P_i = P_i \times CIP \]

\[ Re = \frac{UD_h}{v} \quad \Delta p = f_d \frac{L}{D_h} \frac{\rho V^2}{2} \quad \Delta H = \frac{\Delta p}{\rho g} \quad \Delta h = \frac{U^2}{2g} \quad P = \rho g (\Delta H + \Delta h) \] (1)

Table 19 Coefficient for Installed Power

<table>
<thead>
<tr>
<th>Installed Power (kW)</th>
<th>Coefficient for Installed Power (CIP)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( P_i &lt; 1 )</td>
<td>1.5</td>
</tr>
<tr>
<td>( 1 &lt; P_i &lt; 5 )</td>
<td>1.2-1.5</td>
</tr>
<tr>
<td>( 5 &lt; P_i &lt; 50 )</td>
<td>1.15-1.2</td>
</tr>
<tr>
<td>( P_i &gt; 50 )</td>
<td>1.1</td>
</tr>
</tbody>
</table>

Fig. 37 Moody Diagram for Reynolds Number

Table 20 Pump Calculations: Range of Operations

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Max Operation</th>
<th>Nominal Operation</th>
<th>Min Operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds Number (( Re ))</td>
<td>Unitless</td>
<td>37520</td>
<td>17055</td>
<td>4093</td>
</tr>
<tr>
<td>Mean Velocity (( U ))</td>
<td>m/s</td>
<td>10.29</td>
<td>4.68</td>
<td>1.1227</td>
</tr>
<tr>
<td>Hydraulic Diameter (( D_h ))</td>
<td>m</td>
<td>0.0047</td>
<td>0.0047</td>
<td>0.0047</td>
</tr>
<tr>
<td>Kinematic Viscosity (( v ))</td>
<td>m²/s</td>
<td>1.3E-06</td>
<td>1.3E-06</td>
<td>1.3E-06</td>
</tr>
<tr>
<td>Pressure Loss (( \Delta p ))</td>
<td>kPa</td>
<td>15492</td>
<td>3795</td>
<td>317</td>
</tr>
<tr>
<td>Darcy Friction Factor (( f_d ))</td>
<td>Unitless</td>
<td>0.0234</td>
<td>0.0275</td>
<td>0.040</td>
</tr>
<tr>
<td>Length (( L ))</td>
<td>m</td>
<td>60</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Density (( \rho ))</td>
<td>kg/m³</td>
<td>999</td>
<td>999</td>
<td>999</td>
</tr>
<tr>
<td>Major Head Loss (( \Delta H ))</td>
<td>m</td>
<td>4167</td>
<td>1020.97</td>
<td>85.277</td>
</tr>
<tr>
<td>Gravitational Constant (( g ))</td>
<td>m/s²</td>
<td>3.721</td>
<td>3.721</td>
<td>3.721</td>
</tr>
<tr>
<td>Minor Head Loss (( \Delta h ))</td>
<td>m</td>
<td>28.5</td>
<td>5.88</td>
<td>0.338</td>
</tr>
<tr>
<td>Loss Coefficient (( k ))</td>
<td>Unitless</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Power (( P ))</td>
<td>kW</td>
<td>2.89</td>
<td>.318</td>
<td>.0064</td>
</tr>
<tr>
<td>Volumetric Flow (( Q ))</td>
<td>m³/s</td>
<td>1.8E-04</td>
<td>8.3E-05</td>
<td>2E-05</td>
</tr>
<tr>
<td>RPM</td>
<td>rpm</td>
<td>600</td>
<td>280</td>
<td>75</td>
</tr>
<tr>
<td>Shaft Power (( P_s ))</td>
<td>kW</td>
<td>3.85</td>
<td>0.467</td>
<td>0.053</td>
</tr>
<tr>
<td>Installed Power (( P_i ))</td>
<td>kW</td>
<td>4.63</td>
<td>.70</td>
<td>.078</td>
</tr>
<tr>
<td>Installed Power X3* (( P_i ))</td>
<td>kW</td>
<td>13.88</td>
<td>2.10</td>
<td>0.236</td>
</tr>
</tbody>
</table>

*3 hydraulic tubes in use to SABER/KRUSTY in the CT (maximum). Maximum power is **only** used for an emergency.
**Propellant Tank Heat Flux Calculations**

\[ P_{\text{out}} = A e \sigma (T^4 - T_{\text{sky}}^4), \text{ Stefan-Boltzmann Law} \]

\[ P_{\text{in}} = A (1 - r) S_{\text{flux}} = A e S_{\text{flux}} \]

\[ S_{\text{flux}} = \sigma (T^4 - T_{\text{sky}}^4) \]

\[ T = \left( \frac{S_{\text{flux}}}{\sigma} + T_{\text{sky}}^4 \right)^{1/4} \]

\[ T = \left( \frac{650 \text{ W/m}^2}{5.67 \times 10^{-8} \text{ W/(m}^2 \text{K}^4)} + (180 \text{ K})^4 \right)^{1/4} \]

\[ T = 334.5 \text{ K} \]

\[ \frac{\dot{Q}}{A} = \frac{\dot{Q}_{\text{ref}}}{A_{\text{ref}}} \left( \frac{\Delta T}{\Delta T_{\text{ref}}} \right) \]

\[ \frac{\dot{Q}}{A} = 0.19 \text{ W/m}^2 \left( \frac{334.5 - 89}{210 - 105} \right) \]

\[ \frac{\dot{Q}}{A} = 0.44 \text{ W/m}^2 \]

\[ \dot{Q} \leq \frac{\dot{Q}}{A} A = (0.44 \text{ W/m}^2)(86 \text{ m}^2) \]

\[ \dot{Q} \leq 38 \text{ W} \]

**Detailed Propellant Storage Thermal Loop Diagram**

- **Insulated Dome - Oxygen Storage**
  - Oxygen from SABER
  - 2.05 g/s
- **Insulated Dome - Methane Storage**
  - Methane from SABER
  - 0.51 g/s

**Key:**
- Propellant Line
- Coolant Line

Fig. 38  Temperatures and Pressures for Propellant Storage Thermal Loop [81]
ATHLETE Power Calculations
Assumptions:
1) ATHLETE will be powered by lithium-ion batteries at 60% Depth of Discharge (DOD)
2) The lithium-ion batteries will degrade to 85% of their original capacity in 5 years
3) The average ground grade on Mars is 5%
4) ATHLETE will travel at an average speed of 0.5 m/s or 1.8 km/h
5) ATHLETE will need to travel a maximum of 10 km in a single trip

Design [15, 24, 25]:
1) ATHLETE’s payload capacity is 2619 kg
2) ATHLETE will require 8371 W of operational power
3) The lithium-ion batteries will have a specific energy of 117 W h/kg

The maximum amount of time ATHLETE will travel in a single trip according to assumptions 4 and 5, is

\[ \frac{10 \text{ km}}{1.8 \text{ km/h}} = 5.6 \text{ h}. \]

The battery capacity required, according to assumptions 1 and 2 and design items 2 and 3, is found by

\[ \frac{8371 \text{ W} \times 5.6 \text{ h}}{0.85} \times \frac{1}{0.6} = 91,916.86 \text{ W h}. \]

To find the total mass of batteries required, the battery capacity is divided by the specific energy of the battery:

\[ \frac{91,916.86 \text{ W h}}{117 \text{ W h/kg}} = 786 \text{ kg}. \]

Communications Summary

Table 21  X-Band Command Link Budget Direct from DSN

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link Margin (dB) (Eb/No Method)</td>
<td>80.7</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>7150</td>
</tr>
<tr>
<td>Spacecraft Antenna Gain (dB)</td>
<td>43.9</td>
</tr>
<tr>
<td>Ground Station Antenna Gain (dB)</td>
<td>68.3</td>
</tr>
<tr>
<td>Transmitter Output Power (dB W)</td>
<td>110</td>
</tr>
<tr>
<td>Data Rate (kb/s)</td>
<td>256</td>
</tr>
</tbody>
</table>

Table 22  X-Band Telemetry Link Budget Direct to DSN

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Link Margin (dB) (Eb/No Method)</td>
<td>8.2</td>
</tr>
<tr>
<td>Frequency (MHz)</td>
<td>7150</td>
</tr>
<tr>
<td>Spacecraft Antenna Gain (dB)</td>
<td>43.9</td>
</tr>
<tr>
<td>Ground Station Antenna Gain (dB)</td>
<td>68.3</td>
</tr>
<tr>
<td>Transmitter Output Power (dB W)</td>
<td>12</td>
</tr>
<tr>
<td>Data Rate (kb/s)</td>
<td>22</td>
</tr>
</tbody>
</table>
Decision Matrices

Where possible, all final decisions are made using custom decision matrices derived from [116], which weighs qualitative and quantitative data to inform technology selection. Characteristics of the entity under evaluation are listed, and then weighted out of 100%. These weights are then normalized to take into account any difference in units between characteristics. The equation that describes this procedure is outlined in Eq. 2, where the weight of the characteristic is divided by the max value of that characteristic from the chosen technology candidates. For quantitative data, values are assigned based on actual measurable characteristics such as density, mass, etc. Qualitative data is reported by rankings. Finally, a gross merit is calculated with the sum of the scores for each characteristic, and selected systems are indicated with a green highlight.

\[
\text{Normalized Weight of Characteristic} = \frac{\% \text{Weight}}{\text{Max (Value)}}
\]

(2)

Table 23  Water Deposit Selection Matrix

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Weight</th>
<th>Normalized Weight</th>
<th>Value</th>
<th>Score</th>
<th>Value</th>
<th>Score</th>
<th>Value</th>
<th>Score</th>
<th>Value</th>
<th>Score</th>
<th>Value</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>0.25</td>
<td>0.188</td>
<td>3</td>
<td>0.1875</td>
<td>4</td>
<td>0.25</td>
<td>4</td>
<td>0.25</td>
<td>3</td>
<td>0.188</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>0.25</td>
<td>0.125</td>
<td>3</td>
<td>0.1875</td>
<td>4</td>
<td>0.25</td>
<td>3.5</td>
<td>0.219</td>
<td>2</td>
<td>0.125</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Location</td>
<td>0.50</td>
<td>0.5</td>
<td>4</td>
<td>0.5</td>
<td>1</td>
<td>0.125</td>
<td>2</td>
<td>0.25</td>
<td>4</td>
<td>0.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Gross Merit:</td>
<td></td>
<td></td>
<td>0.875</td>
<td></td>
<td>0.625</td>
<td></td>
<td>0.719</td>
<td></td>
<td>0.813</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 24  ISRU System Selection

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### Table 25  Power System Decision Matrix

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<th>Pylon Value</th>
<th>Pylon Score</th>
<th>UltraFlex Array Value</th>
<th>UltraFlex Array Score</th>
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<tr>
<td>Mass (kg)</td>
<td>-0.6</td>
<td>-6.36×10⁻⁵</td>
<td>6468</td>
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<td>0.2</td>
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### Table 26  Antenna Decision Matrix

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<th>GATR 1.2m Value</th>
<th>GATR 1.2m Score</th>
<th>Mars2020 X-Band Value</th>
<th>Mars2020 X-Band Score</th>
<th>FlyAway 2.4m Value</th>
<th>FlyAway 2.4m Score</th>
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<tr>
<td>Mass (kg)</td>
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<td>-0.004</td>
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<td>-0.323</td>
<td>0.125</td>
<td>-0.003</td>
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<td>Gain (dBi)</td>
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<td>0.598</td>
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<td>0.326</td>
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<td>.7</td>
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<td>0.001</td>
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### Table 27  Propellant Selection Decision Matrix

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<th>Ethylene Value</th>
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<th>Hydrogen Value</th>
<th>Hydrogen Score</th>
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<td>( I_{sp} ) (s)</td>
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<td>-3.17×10⁻²</td>
<td>24.5</td>
<td>-0.778</td>
<td>39.2</td>
<td>-1.244</td>
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<td>CO₂ Required (t)</td>
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<td>-2.10×10⁻²</td>
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<td>-0.629</td>
<td>47.7</td>
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<td>Power Required (kW)</td>
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<td>-0.04</td>
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<td>Fuel Density (kg/m³)</td>
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<td>4.40×10⁻³</td>
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### Table 28  Transceiver Decision Matrix

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<th>Value</th>
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<tr>
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Gross Merit: 1.069

### Table 29  Methane Production Reaction Decision Matrix

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<td>0.222</td>
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<td>0.778</td>
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<td>Specific Mass (kg)</td>
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<td>72.2</td>
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<td>CO₂ Required (t)</td>
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<td>-3.35 × 10⁻²</td>
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<td>29.8</td>
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Gross Merit: -2.14

### Table 30  Filtration System Decision Matrix

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Gross Merit: 7.56
### Table 31 Storage Tank Construction Decision Matrix

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<td>Volume</td>
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### Table 32 Insulation Decision Matrix

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<td>Heat Flux (W/m²)</td>
<td>-0.35</td>
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</tr>
<tr>
<td>Durability</td>
<td>0.05</td>
<td>1.25</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>2.5</td>
</tr>
<tr>
<td>Cost</td>
<td>-0.05</td>
<td>-1.67</td>
<td>2</td>
<td>-3.33</td>
<td>3</td>
<td>-5</td>
</tr>
<tr>
<td>Gross Merit:</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

### Table 33 Transportation Decision Matrix

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Weight</th>
<th>Normalized Weight</th>
<th>ATHLETE Value</th>
<th>Score</th>
<th>Rocker-Bogie Value</th>
<th>Score</th>
</tr>
</thead>
<tbody>
<tr>
<td>Top Speed (m/s)</td>
<td>0.05</td>
<td>0.180</td>
<td>2.78</td>
<td>0.5</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Volume (m³)</td>
<td>-0.25</td>
<td>-0.056</td>
<td>15.1</td>
<td>-0.849</td>
<td>17.8</td>
<td>-1</td>
</tr>
<tr>
<td>Specific Power (W/kg)</td>
<td>-0.2</td>
<td>-0.473</td>
<td>5.3</td>
<td>-2.5</td>
<td>0.1</td>
<td>-0.05</td>
</tr>
<tr>
<td>Turning Radius (m)</td>
<td>-0.1</td>
<td>-12.7</td>
<td>0</td>
<td>0</td>
<td>0.16</td>
<td>-2</td>
</tr>
<tr>
<td>Rover Mass Fraction (%)</td>
<td>-0.4</td>
<td>-0.133</td>
<td>20</td>
<td>-2.67</td>
<td>30</td>
<td>-4</td>
</tr>
<tr>
<td>Gross Merit:</td>
<td></td>
<td></td>
<td>-5.51</td>
<td></td>
<td>-7.04</td>
<td></td>
</tr>
</tbody>
</table>
Detailed STING Breakdown

Fig. 39  STING Bottom Hole Assembly, Courtesy of Honeybee Robotics
Flight Forward Configuration: Folded bilayer
- Gas tight fluoropolymer bladder layer
- Durable Vectran/Kevlar abrasion layer

Fig. 40  STING Bottom Hole Assembly continued, Courtesy of Honeybee Robotics
Fig. 41  STING Coiled Tubing and Injector, Courtesy of Honeybee Robotics
TRL 5 Redwater Testing

Fig. 42  TRL 5 Redwater Testing courtesy of Honeybee Robotics
RASC-AL: The Video Game

In order to create a virtual prototype of the MITHRIL architecture for the NASA 2022 RASC-AL competition, a video game was created to allow for an immersive experience of MITHRIL on the surface of Mars. Players can freely navigate the Martian surface and interact with a few pieces of the architecture. This environment was also used for cinematic purposes, first presented in the proposal video, and soon to be displayed in the upcoming con-ops video that will debut at the UIUC RASC-AL Forum Presentation. Sporting two levels, users can opt for a more engineering based experience and take a tour of the architecture, or a game version that sees you fight off evil aliens during the Martian night (note the latter mode is purely for fun). At the poster session, all are welcome to play the game!
References


[110] Dinkin, S., “Increasing the profit ratio,” https://www.thespacereview.com/article/2893/1#text=Liquid%20methylene%20costs%20about%20241.35, the%20December%202022% spot%20price, 2016.


