AIAA SPACE Forum
12 - 14 Sep 2017, Orlando, FL
AIAA SPACE and Astronautics Forum and Exposition

10.2514/6.2017-5376

Enabling Deep Space Exploration with an In-Space Propellant Depot Supplied from Lunar Ice

Sophia Casanova[1], Jack Henry de Frahan[2], Vinicius Guimaraes Goecks[3], Sumudu Herath[4], Mercedes Herreras Martinez[5], Nicholas Jamieson[6], Therese Jones[7], Sung Wha Kang[8], Sydney Katz[9], Gary Li[10], Donal O'Sullivan[11], Daniel Pastor[12], Nathan Sharifrazi[13], Bryan Sinkovec[14], Joseph Sparta[15], Matthew Vernacchia[16]

Deep-space missions are heavily constrained by the amount of payload mass the launch vehicle can carry. Furthermore, the amount of payload mass the launch vehicle can carry is limited by the delta-V losses of escaping both Earth's gravity well and its atmosphere. Instead of launching the propellant mass to be used for trajectories to deep-space, if the propellant can be delivered in-space, the vehicle may carry a significantly larger payload from the surface of the Earth to the destination. Such an architecture is a paradigm shift for space exploration, enabling spacecraft to fly to the furthest reaches of the Solar System with more mass and/or in less time. An international team of sixteen students met at the 2017 Caltech Space Challenge to design Lunarport: a station which provides vehicles traveling to destinations around the solar system with propellant created from water ice extracted at the lunar south pole. A complete system concept design and architecture was produced, entitled 'Ice Rush', which leverages mostly TRL 6+ technology and is capable of refueling crewed Mars missions by 2032 at a total cost of $17B. A detailed analysis of in-situ resource utilization methods, propellant depot design, lunar site selection, and prospects for decreasing costs/increasing payloads of future deep-space missions is included. With the Ice Rush architecture, launching an SLS Exploration Upper Stage (EUS) to Lunarport's L_1 depot and refueling, the payload mass may be tripled for a mission to Europa or doubled for a free-return trajectory to Mars. A solar electric space tug concept is also presented, which would triple the Mars free-trajectory payload mass using Lunarport.

All authors contributed equally to this work at the 2017 Caltech Space Challenge.

[1] Graduate Student, University of New South Wales, s.casanova@unsw.edu.au.
[2] Graduate Student, ISAE-SUPAERO, jack.henry-de-frahan@student.isae-supaero.fr
[3] Graduate Student, Texas A&M University, vinicius.goecks@tamu.edu, AIAA Student Member.
[4] Graduate Student, University of Cambridge, sthh2@cam.ac.uk.
[5] Graduate Student, Arizona State University, mherre15@asu.edu.
[6] Graduate Student, University of Cambridge, npj24@cam.ac.uk.
[7] Graduate Student, Pardee RAND, tjones@prgs.edu, AIAA Student Member
[8] Undergraduate Student, Rhode Island School of Design, skang02@risd.edu.
[9] Undergraduate Student, Washington University in St. Louis, sydney.m.katz@wustl.edu.
[10] Graduate Student, University of California, Los Angeles, g.li@ucla.edu.
[11] Graduate Student, California Institute of Technology, dosulliv@caltech.edu.
[12] Graduate Student, California Institute of Technology, dpastorm@caltech.edu.
[13] Undergraduate Student, University of California, Irvine, nsharifr@uci.edu.
[14] Graduate Student, California Institute of Technology, sinkovec@caltech.edu, AIAA Student Member.
[15] Undergraduate Student, Georgia Institute of Technology, spartajoey@gatech.edu, AIAA Student Member
[16] Graduate Student, Massachusetts Institute of Technology, mvernacc@mit.edu.

Nomenclature

ACES	Advanced Cryogenic Evolved Stage
ALHAT	Autonomous Landing Hazard Avoidance Technology
ATHLETE	All-Terrain Hex-Limbed Extra-Terrestrial Explorer
Caltech	California Institute of Technology
COTS	Commercial off-the-shelf
DSG	Deep Space Gateway
DST	Deep Space Transport
DTE	Direct to earth
EUS	Exploration Upper Stage
FAA	Federal Aviation Administration
GALCIT	Graduate Aerospace Laboratories of the California Institute of Technology
GEO	Geosynchronous equatorial orbit
HEO	High Earth orbit
ISRU	In-situ resource utilization
ISS	International Space Station
JPL	Jet Propulsion Laboratory
L_1	First Earth-Moon Lagrange point
LAVA	Lunar Advanced Volatile Analyzer
LCROSS	Lunar Crater Observation and Sensing Satellite
LEO	Low Earth orbit
LH_2	Liquid hydrogen
LIDAR	Light Detection and Ranging
LLO	Low Lunar orbit
LM	Lunar Module
LO_2	Liquid oxygen
LRS	Lunar resupply shuttle
LTV	Lunar Transfer Vehicle
NASA	National Aeronautics and Space Administration
OGS	Oxygen Generation System
OVEN	Oxygen and Volatile Content Extractor
P-POD	Poly Picosatellite Orbital Deployer
PSR	Permanently shadowed region
PVEx	Planetary Volatiles Extraction
RCS	Reaction control system
RTG	Radioisotope thermoelectric generator
SEP	Solar electric propulsion
SKG	Strategic Knowledge Gap
SLS	Space Launch System
TLI	Trans-lunar injection
TMI	Trans-Mars injection
TRL	Technology readiness level
ULA	United Launch Alliance

I. Introduction

The desire for deep space missions that advance the current state of knowledge regarding the solar system and beyond has created a demand to launch heavy payloads on high energy trajectories. In particular, the drive to send humans to Mars has maintained a strong presence in space planning over the past few decades. In order to achieve these momentous tasks, it is important to consider architectures that break down deep space mission design into smaller stepping stones that both demonstrate new technology and lay a framework for a sustainable launch architecture to locations in deep space. While attempting to identify such a stepping stone, the Moon surfaces as a prime candidate due to both its proximity and abundance of resources that can be utilized in-situ.

The energy required to launch through the Earth's atmosphere and escape its large gravity well hinders the ability to send heavier payloads into deep space. Each unit of mass launched from Earth comes at a great cost and the total mass that may be launched to the final destination is capped by the performance of the launch vehicle. Earth's closest neighbor, the Moon, has no atmosphere and its gravity well is significantly smaller than the Earth's. For this reason, architectures that utilize resources from locations away from the Earth, such as the Moon, to launch payloads on deep-space trajectories may provide multiple benefits. These benefits include significantly increased payload mass to the final destination and higher energy deep-space trajectories which allow for shorter transit times and greater access to the entire solar system. This study specifically looks at using the Moon's resources to provide rocket propellants for vehicles bound for deep-space.

Recent lunar observation missions have revealed the potential of lunar resources, having identified water ice, methane, ammonia, and other exploitable volatiles near the Moon's poles.[1] These materials suffice to produce the propellant and infrastructure on the Moon required to create a refueling station in cis-lunar space. With this knowledge in mind, this study outlines a preliminary design and architecture for a launch and supply station in cis-lunar space, referred to as 'Ice Rush'. A complete lunar base and refueling architecture is laid out and considered in the context of a human Mars mission. In addition to the development and demonstration of technology, Ice Rush creates a framework for refueling deep space missions that intends to push the limits of human exploration capability further than ever before.

This study was performed by an international team of sixteen students known as team Voyager during the 2017 Caltech Space Challenge. The 2017 Caltech Space Challenge was a 5-day intensive mission design study held at the California Institute of Technology in which two international teams of students were given the mission design problem of 'Lunarport', a station which extracts and utilizes lunar resources to provide rocket propellant for deep-space bound vehicles. The teams attended lectures related to mission planning, systems engineering, lunar resource utilization, orbital mechanics, reusable launch vehicles, and in-space refueling and consulted with experts from government, academia, and industry.

II. Caltech Space Challenge Overview

A mission statement covering objectives, assumptions, and constraints for this study was provided by the 2017 Caltech Space Challenge to each research team. This mission statement is outlined below in Table 1 to provide greater context of this study. It is meaningful to keep in mind that all analyses, architecture trades, and final designs in this study were made over the remarkably short period of time of five days.

Table 1. Study Problem Statement, Objectives, and Constraints

Problem Statement
Provide a conceptual design and architecture for Lunarport, a system capable of supplying vehicles bound for deep space with propellants created from resources extracted from a lunar polar region.
Study Objectives
• Provide conceptual design and cost estimation for Lunarport construction, operation, and maintenance • Design self-sustainable ISRU station on lunar surface • Design ground support infrastructure on lunar surface, including lunar launch and landing station • Design a Lunar Resupply Shuttle (LRS) to shuttle lunar resources from surface to refueling location • Design refueling system for providing propellants to customer (the deep-space bound vehicle) • Provide detailed construction, operation, and maintenance plan including systems engineering, business plans, timelines, and lifetime estimates for the entire Lunarport system
Lunarport Design Requirements
• Lunarport shall provide propellant to a vehicle or set of vehicles traveling to deep-space (beyond Earth-moon system) • Lunarport shall provide propellants produced from resources extracted from the Moon • Costs for constructing and operating Lunarport shall be limited to $1B/year, with unused funds available to roll over to future years • Lunarport shall be a robotically operated and maintained system, yet capable of allowing human visitors • Once operating at full capacity, Lunarport shall provide sufficient propellant to support a crewed mission to Mars which includes cargo and crew • At full operating capacity, Lunarport shall be capable of sustaining the intended rate of crewed Mars missions • Lunarport shall be built and tested incrementally in order to reduce technical and financial risk • NASA shall be the initial funding source for Lunarport, with transition to the commercialization of the facility possible for long-term

The design of Lunarport is a large and intricate systems engineering problem. Such a concept touches upon several complex engineering problems currently being addressed today, such as reusability of space vehicles, in-space propellant transfer, and in-situ resource utilization. Moreover, many candidate architectures exist for Lunarport. The trades considered in this study are shown in Table 2 below.

Table 2. Trade Space for Lunarport Design

Trade	Options Considered
Customer propellant transfer location	Lunar surface; on orbit
Propellant transfer method	Pumped; tank swap
Location for electrolysis of water	Lunar surface; propellant depot
Propellant depot location	LEO; GEO; Earth-Moon L_1; LLO
Lunar pole for resource extraction	North pole; south pole
Lunar base location	Considered entire polar region by studying surrounding geography and geology
Surface transportation of extracted H_2O from mining location to launch pad / H_2O storage location	Piping system; ice trucker robot; elastic/electromagnetic launch system; direct delivery by mining robots
Mining rover power	Nuclear; batteries; power cable; reflected solar; beamed microwave/optical from solar
Space tug propulsion system	Chemical propulsion; electric propulsion

III. Lunarport Justification

As an Executive Branch agency, the strategic goals of NASA are subject to changes in both presidential administrations and congressional budget constraints. The 2017 NASA Transition Authorization Act[2] prioritizes cis-lunar exploration as a first step to a crewed Mars mission, stating, "the United States should have continuity of purpose for the Space Launch System (SLS) and Orion in deep space exploration missions, using them beginning with the uncrewed mission, EM–1, planned for 2018, followed by the crewed mission, EM–2, in cis-lunar space planned for 2021, and for subsequent missions beginning with EM–3 extending into cis-lunar space and eventually to Mars [in the 2030s]." These objectives are consistent with NASA's Evolvable Mars Campaign, first announced in 2014 as a path to utilize near-Earth space assets to create Earth-independent crewed missions to Mars of 2-3 years in length.[3]

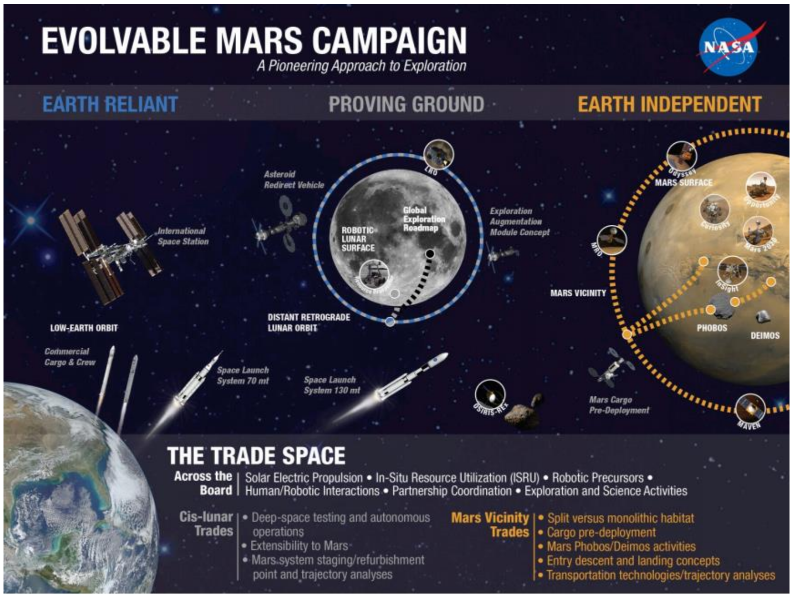


Figure 1. ***NASA's Evolvable Mars Campaign.***[4]

This plan establishes a human path to Mars by 2033 via three phases of development, supported by crewed SLS missions. Phase 1 establishes a Deep Space Gateway (DSG) in cis-lunar space, from approximately 2022-2026, gradually building up the gateway in four stages delivered by SLS: 1. 40kW Power/Propellant Bus, 2. Habitation module, 3. Logistics, 4. Airlock. The DSG is intended to be human-tended, rather than a consistently inhabited station. From 2027-2033, six SLS missions would establish the Deep Space Transport (DST), with an initial delivery of the transport vehicle followed by alternating logistics and refueling payloads (delivered by SLS crewed and cargo missions, respectively). The entire architecture assumes one crewed SLS/Orion launch per year beginning in 2023 plus one cargo SLS launch per year beginning in 2027.[5]

The in-situ resource utilization (ISRU) technologies used in a Lunarport mission are a follow-on to the Lunar Resource Prospector, acting as a bridge to future crewed missions in cis-lunar space or on the lunar surface. The present roadmap to the DSG and DST do not presently include a fuel source; a robotic ISRU mission is a logical and cost-effective mechanism to enable Mars transportation. The modular structure of the DSG and DST allow for the Lunarport to gradually ramp up propellant production as the Mars-bound vehicle is completed. In the event of a Lunarport failure, it may be possible to service the Lunarport using DSG as a staging ground.

Lunarport additionally fulfills a number of Lunar Human Exploration Strategic Knowledge Gaps (SKGs) related to ISRU, lunar surface exploration, and power, as detailed in Table 3.[6] These SKGs are also integral to further Mars exploration. NASA proving ground objectives for Mars include utilizing Lunar Distant Retrograde Orbit as a staging ground to Mars, utilizing ISRU in microgravity, and operations with reduced logistics capabilities.

Lunarport may also be used for other solar system probes. Additionally, a number of stakeholders have expressed interest in both crewed and un-crewed lunar missions. The European Space Agency's Moon Village concept or Bigelow's proposed lunar habitat could be good candidates for future customers of the Lunarport. The United Launch Alliance (ULA), has also been promoting an architecture, CisLunar-1000, which seeks to have 1000 people living and working in cis-lunar space within the next 30 years,[7] suggesting ULA may develop commercial technologies that may be used by NASA in Lunarport construction and be a potential long-term stakeholder in a cis-lunar propellant depot.

Table 3. Lunar human exploration Strategic Knowledge Gaps addressed by Lunarport (LP)

Strategic Knowledge Gap		LP Relevance
I. Understand the Lunar Resource Potential		
D-3	Physical characteristics of entrained volatiles	Very High

D-4	Understand slopes, elevations, block fields, cohesiveness of soils, trafficability	Very High
D-5	Landed missions to understand the charge reservoirs (plasma or ground) in the low conductivity environment	Very High
D-6	Determine the form, concentration and distribution of volatiles, how they vary from depths 0-3 m over distances of 10-100 m scales.	Very High
E	Understand the volatile contents of RDMDs, as well as their depth and distribution	Low
G	Measure the actual efficiency of ISRU processes in the lunar environment.	Medium
II. Understand How to Work and Live on the Lunar Surface		
A-1	Collect raw materials; create trenches, roads, berms, etc.; enables ISRU, surface trafficability, and ejecta plume mitigation.	Very High
A-2	Load, excavate, transport, process, and dispose of regolith; enables ISRU, surface trafficability, and ejecta plume mitigation.	Very High
A-3	Crush, grind regolith; understand effects of comminution; enhances ISRU process efficiency.	Very High
B3	Ability to remotely traverse over long distances enables a) prepositioning of assets, and b) robust robotic precursor missions.	High
B4	Autonomous landing capability for robotic missions similar to that demonstrated by Chang'e-3 lander.	Very High
C2	Characterization of geotechnical properties and hardware performance during regolith interactions on the lunar surface.	High
D4	Multiple landings at the same location on the lunar surface may scour or damage systems and equipment already emplaced at that location. Ejected regolith velocity, departure angles, and energy in engine plume exhaust need to be measured in situ to better understand mitigation strategies	Medium
F2	Polar missions may be in areas with extended solar availability; blackouts may extend to 3-5 days requiring 100 s of kW-hours; batteries will be prohibitively expensive.	Very High

IV. 'Ice Rush' – Lunarport System Design

As an Executive Branch agency, the strategic goals of NASA are subject to changes in both presidential administrations This section covers the system design of Lunarport, dubbed 'Ice Rush', produced by team Voyager of the 2017 Caltech Space Challenge. Inspired by the discovery of gold in the Sacramento Valley of California in 1848, a flood of prospective gold miners flocked to California, expanding its population by a hundredfold in just under three years. History has shown, as in the California Gold Rush and other gold rushes, that the discovery of valuable resources can be a powerful driver of human expansion, technological advancement, and societal prosperity. In the harsh vastness of space, water represents life, energy, and hope – perhaps there is no better analogy to gold on Earth than water in space. This system design of Lunarport is performed in hopes that someday, a new kind of rush, an 'Ice Rush' may emerge, one in which humankind first learns to leverage resources from an extraterrestrial world, fostering international collaboration in cis-lunar space, and empowering us to make the next great leap – to the red planet and beyond.

A. Lunar Site Selection

The approach taken for site selection and the development of full scale mining operations on the Moon has been adapted from the traditional terrestrial mining life cycle model. By taking this phased approach, the hope is to reduce geological uncertainty through detailed prospecting and exploration, which may increase initial cost and take additional time in order to complete a thorough exploration program, but will aim to reduce financial and engineering risk in the longer term.

Recent discoveries by the Lunar Reconnaissance Orbiter (LRO) and the Lunar Crater Observation and Sensing Satellite (LCROSS) impactor suggest the possibility of significant water ice deposits on the surface and the upper subsurface of the shadowed regions of the south Lunar poles where temperatures may be as low as > 40 K. Modelling suggests that subsurface water is likely present in temperature conditions of <100K and less than < 70 K for other volatiles such as carbon dioxide and hydrogen sulfide. Figure 2 below shows reconnaissance data and modeling predictions of the lunar south pole which were used to select the lunar sites.

The selection of the proposed mining site is based on a number of factors. The primary target is the extraction of water, so the initial analysis focused on locations where water ice could be stable within the top 10-20 cm (red, Fig. 2) with regions of possible stable water on the surface (white, Fig. 2) representing the most prospective regions. Stable water ice on the surface coincides with the permanently shadowed regions of the lunar surface. Thus far there has only been one in-situ measurement of water in the south lunar pole which was derived from the LCROSS impactor in the Cabeus Crater.

The number of days of light visibility at the site has implications for power requirements. The number of days of direct to Earth communication has impact on communication capability, and slope is constrained by requirements for rover mobility and a landing site for the resupply shuttle. Thus it is imperative that a site be selected based on meeting the engineering requirements for landing and operation as well as be co-located with prospective water ice resources.

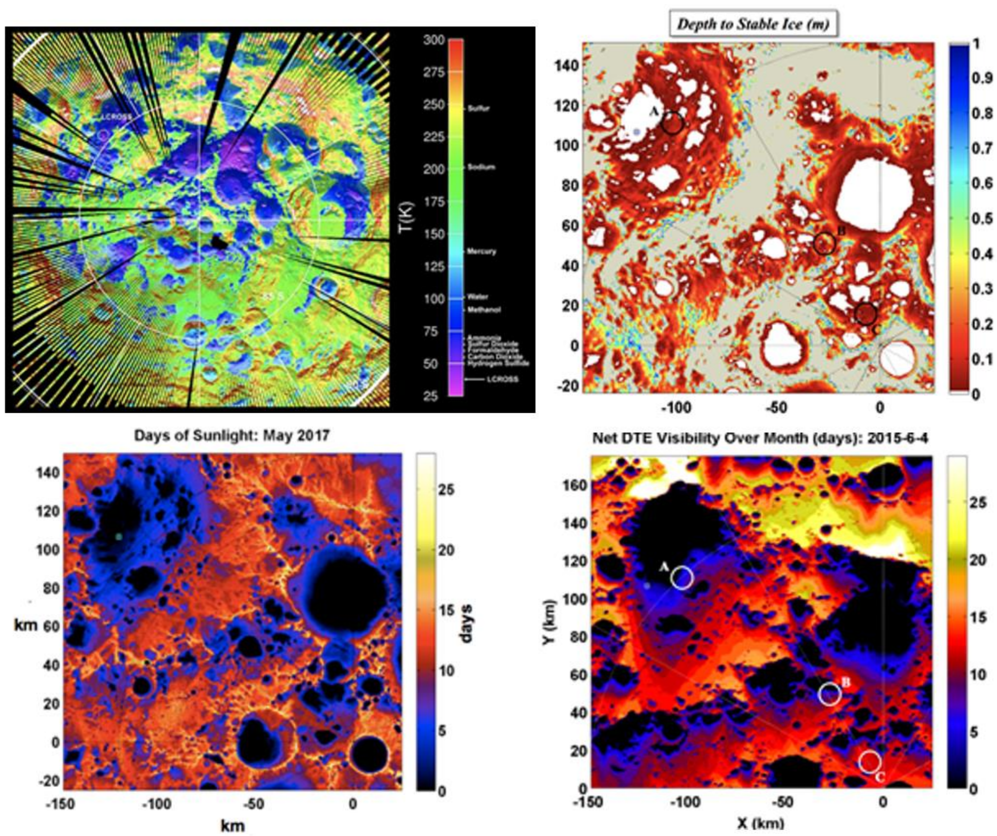


Figure 2. ***Top left*** **– Surface temperature map of the Moon's south polar region (LRO Diviner Lunar Radiometer Experiment).[8]** ***Top Right*** **- Depth to stable ice (m) and proposed Lunar Resource Prospector Landing Sites.[9]** ***Bottom Left*** **– Number of Earth days of sunlight per lunar day (~29 Earth days)[9].** ***Bottom right*** **– Number of Earth days of net Direct-to-Earth (DTE) visibility per lunar day. [9]**

Requirements for a suitable base site (landing site/launch pad facilities, storage, and power facilities), transportation route, and mining site have been identified. The criteria are summarized in Table 4. Based on these criteria, the team located a number of potential sites. The final selection was chosen on the basis of being the most favorable in meeting both selection criteria for geological factors as well as engineering design and operational constraints.

Table 4. Base site selection, transportation route, and mining site criteria

Base Site Selection Criteria	Transportation Route Criteria	Mining Site Criteria
• Slope ~5 degrees or less • Sunlit >75% lunar day • Landing ellipse > 500 m • Absence of identifiable hazardous terrain	• Slope <20 degrees • Traversable terrain • Minimal distance to mining site (<1 km ideal, 2-3 km possible, 5+ km unideal)	• Slope < 10 degrees • Depth to stable water <10 cm • Temperature < 100 K • Limited identifiable hazardous

The selected site is located in the lunar south pole approximately 50 km north-west of Shackleton crater, as shown in Fig. 3. Cabeus Crater was considered as a potential target location as it is favored from a geological uncertainty standpoint, being the only location where water has been definitively proven thus far, as shown by the LCROSS impactor results. However; the current site is preferable over Cabeus crater on the basis of landing and operational constraints which made Cabeus unsuitable due to long travel distances required between sunlit areas and the PSRs and the extreme temperatures in the central part of the crater (< 40 K) which would make operations, given current technology, extremely difficult and expensive. Prospecting missions will sure up resource estimates and ensure that they are appropriate for long-term mining operations. Therefore, the mining site locations and prospects within may change as more scientific information becomes available.

Three potential prospects have been selected all of which are located within permanently shadowed regions. These prospects are shown in Fig. 3. Prospect A is located in close proximity to the landing site (~500 m) however the approximate areal extent of the prospect is relatively small. This would be a good first prospect to test operations. Prospect B is located within less than 2 km of the landing site at its closest point and 15 km at its furthest point. Prospect C is located much further away from the landing site. To mine this site would either require moving the base operations or redesigning the mining rover power design. If the resource prospector identified resources in this area but current technology constrained its extraction then this prospect may be considered a contingent resource until new technologies to operate in this environment are developed. Table 5 outlines the key parameters of the landing site location and the three prospect areas.

For the purposes of this study, it is presumed that the resource prospector / scouting mission was successful and an in-situ discovery of an economic deposit was made at the proposed site. The exploration stage would then be followed by a detailed feasibility analysis and mine planning phase in which an assessment of the costs and equipment requirements will be made and a mine design plan developed. Assuming the site is found to feasible and a go-ahead decision is made, the mine construction stage would then be entered in which the power, communications, storage, and electrolysis facilities will be delivered to the site and the construction/sintering rover will begin preparing the site for future mining operations. The mine development and operation stage will begin when the mining rovers are sent to the site and begin their mining / water extraction operations. As the site is further developed attention will turn to locating new prospects. The lunar prospecting rovers will be sent to new locations and the mining life cycle will begin again.

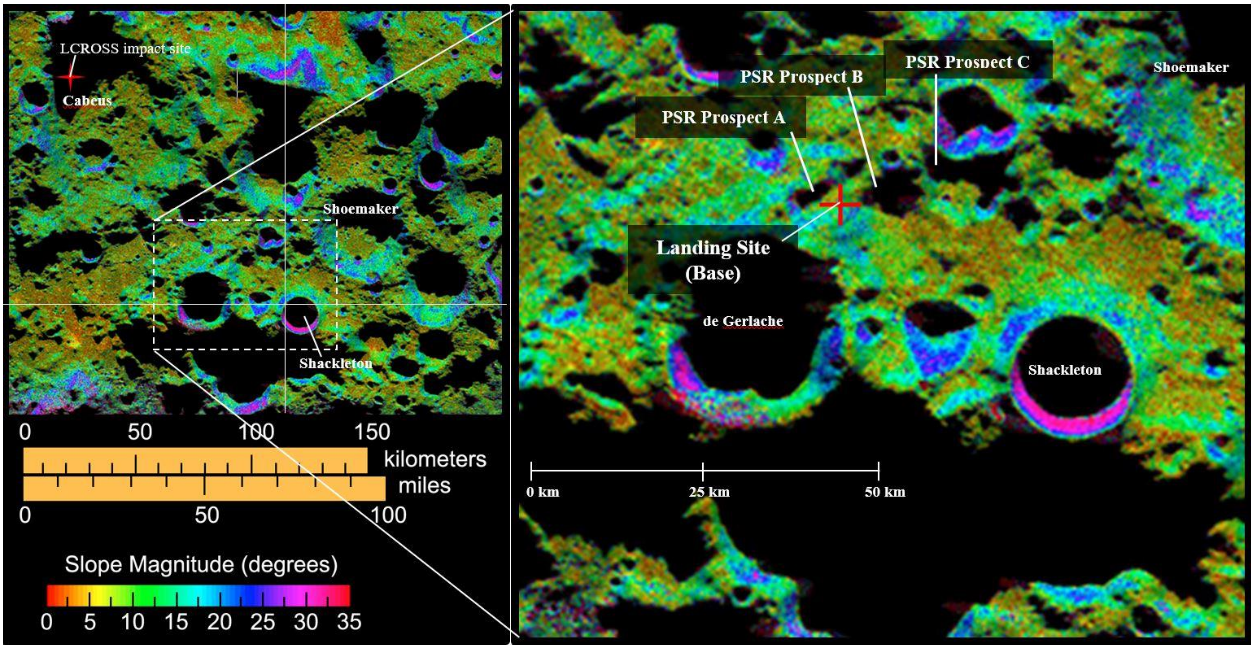


Figure 3. Enhanced radar imagery of the lunar south pole taken with the Goldstone Solar System Radar by NASA and JPL showing relative slope magnitudes.[10] The LCROSS impact site in Cabeus crater is overlaid. The selected landing site and three PSR prospects are overlaid and shown in close detail.

Table 5. Geological and Engineering Parameters of the Site Selection

	Distance from Landing Site	Depth to Stable Water	Temperature	Slope	% of Lunar Day with Sunlight	% of Lunar Day with Direct to Earth Communication
Landing Site	0 km	< 20 cm	~ 180 K max ~ 90 K min	< 5°	~ 75%	60 %
Prospect Site A	0.5 km	Surface - 10 cm	~ 100 K	10°	0 - 20%	< 20%
Prospect Site B	~ 2 km	Surface	~ 40-100 K	< 10°	0	0
Prospect Site C	~ 12 km	Surface	~ 40-100 K	< 10°	0	0

B. System Architecture

1. Lunar Surface Systems

The main surface systems are the lunar prospector, sintering robot, and mining robots. These surface elements are described in detail in Table 6. The infrastructure of the proposed surface system is fully scalable. A fully functional system is achieved with the shipment of four cargo landers to the lunar surface. Additional shipments of mining rovers are required to scale the system to meet Mars mission propellant demand rates.

The first launch to the Moon consists of four CubeSats and a lunar prospector to scout the proposed site and finalize site selection. The second shipment will arrive two years later bringing a sintering robot capable of building roads and protective berms, preparing for the arrival of the mining rovers. This sintering robot is powered by the lander via beamed microwave energy. The third lander will bring mining rovers so water extraction can begin. All landers are powered by solar panels and contain batteries as well as a thermally protective space for their robots to be stored during the lunar night. Within two years the electrolysis unit, LH_2, LO_2 and the water tanks arrive with the final shipment to enable fuel and water delivery to the depot.

Lunarport surface operations begin with a scouting mission. This activity will be conducted over a 2-year period to assess one or two potential mineable prospects in close proximity to the landing site. Prospecting will continue after mining operations begin to continue assessing new mining locations which will be developed at a later date. The Scout will operate similarly to the NASA Resource Prospector but over a more extended period. The Scout will use the Neutron Spectrometer System (NSS) to detect hydrogen in the sub-surface down to a concentration of 5% by weight and a depth of 1 meter. When hydrogen is detected in large enough concentrations near the surface (i.e. <10 cm) a drill sample will be taken to test for the presence of water. The Oxygen and Volatile Content Extractor (OVEN) will heat the sample to high enough temperatures to evolve the volatile gases which are then transferred to the Lunar Advanced Volatile Analyser (LAVA) for analysis. LAVA has the capability to measure water at concentrations above 0.5% by weight. To be considered a discovery the sample must contain water at a concentration greater than 4% by weight. Deposits on the order of 6-12% by weight will be considered high graded targets and will be the focus of initial mining operations. Once an area of interest is identified by the prospecting instruments the option to map the area in greater detail to delineate the deposits continuity, areal extent, quantity and quality will be decided upon by the science team. This will form the basis of a preliminary resource estimate. Once feasibility studies of the resource are undertaken incorporating engineering, mine planning and cost estimate studies it may be possible to convert the resource to a reserve signaling an intent to mine in the very near future.

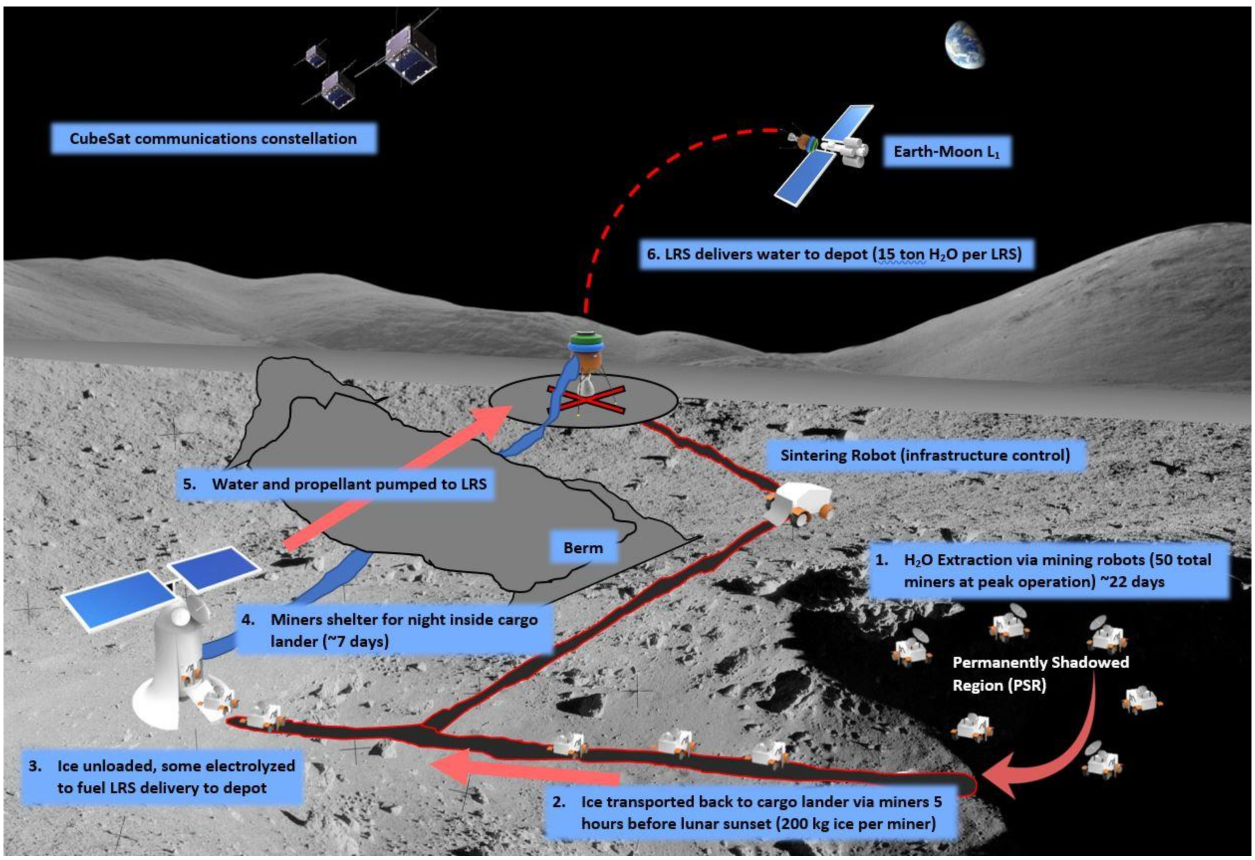
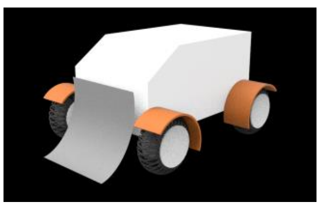
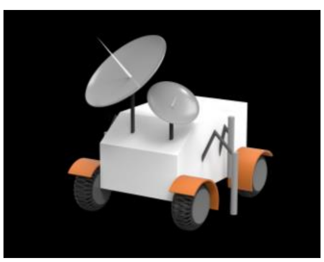


Figure 4. Concept of Operations for Lunar Surface Systems

Table 6. Surface System Elements

Lunar Prospector	
	The purpose of Lunar Prospector robot is to understand the distribution, concentration and extent of lunar volatiles in the polar regions of the Moon. This allows for feasibility studies, generating geological models, estimating resources, and provide valuable terrain information for mine planning and construction. The design of the Lunar Prospector is based primarily on the NASA Lunar Resource Prospector,[10] but powered by a radioisotope thermoelectric generator (RTG) and equipped with a LIDAR system for simultaneous localization and mapping (SLAM). It is assumed the reactors deteriorate by 10% over 14 years based on Zacny et al. (2015).[11]
Sintering Robot	
	The sintering robot is a multipurpose robot whose overall function is to control infrastructure at the surface base. It will construct roads on the surface by use of microwave sintering. It will be similar to the robot known as ATHLETE[12], which was developed and tested by NASA JPL and with improved automated docking systems to attach and detach construction equipment.[10] Essential construction equipment are proposed to have an automated docking systems that can detach and attach to the main sintering robot so it can perform multiple tasks simultaneously. The sintering robot will also perform propellant and water umbilical connections to the LRS on the pad.
Mining Robot	
 Mining Rover  Honeybee PVEx Corer[14]	The mining robots will extract and process volatiles from the lunar regolith. The proposed mobility system of the lunar miner is based Apollo lunar roving vehicle (TRL 9). This design decision was made on the basis of its load carrying capacity (490 kg), high roving speed (~13 km/hr or 3.6 m/s), and that it is proven technology in a lunar environment. This design will allow the mining rover to carry an approximately 200 kg payload of ice before transporting it back to the storage facility. For the coring and processing system the Honeybee Robotics Planetary Volatiles Extraction (PVEx) Corer[12] (TRL 5) will be used. Each mining rover will carry four core drills each capable of drilling 1 core per hour with each core produced about 1 kilogram of water ice. The rover receives power via microwave beams, which is addressed in the subsequent power section. Each mining rover will have a self-contained regolith processing unit aboard based on the Honeybee Robotics PVEx Corer. The PVEx corer drills a core into the lunar soil and heats the regolith in-situ. Volatiles are sucked out of the ground followed by the deposition of ice into a cold trap. Although this will require higher power requirements, it reduces the need to transport large amounts of regolith waste rock back to a central processing unit. This has a significant impact on production rate and is necessary to meet the production rate targets.

Lunarport mining operations will begin with the robotic mining rovers being delivered to the base site located in a relatively well sunlit location. They will then navigate to the identified resource locations within the permanently shadowed regions (PSRs). Upon arrival at the mining sites, the mining rovers will use their four Honeybee Robotics Planetary Volatile Extractor Corer systems to drill directly down into the icy regolith. The drill system will heat the regolith inside the captured cores, sublimating the ice out of the soil into water vapor. The vapor is then transferred into a cold-trap where it is then deposited into an ice storage tank on the vehicle. The mining rover will drill cores at a rate of one core per hour for approximately 20 hours per (Earth) day, giving it a total ice collection rate of about 10 kg of ice per day per rover. After approximately 22 Earth days of mining and just before the end of the lunar day, the mining rover's ice tank will be full with approximately 200 kg of ice. At this time, the mining rovers will collectively head back to the base, arriving no later than five hours before lunar sunset. The mining rovers will unload their mined ice at the ice storage facility and then head inside the landers that originally brought them down to the surface. Here they will be take shelter for the lunar night in the insulated and actively heated interior of the lander. The mining process restarts at lunar sunrise approximately eight Earth days later.

The mining rovers are equipped with approximately 24 hours of contingency battery power in case they lose access to the beamed power. In this circumstance the rover will enter an emergency mode, mining operations will cease and the rover will attempt restore access to the beamed power source. If unsuccessful, the mining rover can be commanded to head back to the base.

After the ice has been delivered successfully to the storage tanks and has undergone a final filtration some of the water is transferred to the electrolysis unit to produce propellant for the LRS. The electrolysis unit is powered by the solar panels at the site and produces the 20 tons of LH_2 and LO_2 propellants. This is required to deliver a 15 ton payload of water/ice up to the L_1 orbital depot. An additional LRS will return to the base approximately 2 weeks later to reload for another water delivery back up to the depot.

Power:

The site for the surface base was chosen so as to receive sunlight for at least 21 out of the 29 Earth days (~75%) of the lunar day. The main power consumption at the Lunarport is due to the mining activities in Permament Shadowed Regions (PSR). Lower temperatures (~50 K) at the PSR and the volatile extraction from the cold regolith requires around 71 kW-h per day of energy for continuous operation, per mining robot.[12] Since direct sunlight is only present outside of the PSR, energy was required to be transferred in some manner to the mining robots, to be explained below. To achieve a modular architecture, each subsystem was designed to have its own power source. Different solutions were considered for transferring the power from the top of the crater (illuminated by the Sun) to the bottom (PSR), including nuclear reactors, batteries, reflected solar, and direct cable connection. Since it is expected to have more than 50 mining robots during Lunarport's peak operation, the main power decisions were centered around powering the miner robots. Powering 50+ robots with nuclear power sources was deemed too costly and too burdensome (nuclear power reactors are very difficult to obtain). Reflected solar power suffers from R^2 losses, so the energy received is degraded heavily the further the transmission becomes. Direct cable connection was seriously considered, but was deemed too risk prone and cumbersome. Should a cable break, come disconnected, that particular rover is at high risk of dying. Further cable routing makes for a challenge while roving in dark, unknown and potentially hazardous terrain of a PSR. It was decided to transfer the power from the solar panels to the rover using wireless power transmission. The energy collected by the solar panels on the lander at the top of the crater is converted and transferred as 5.8 GHz microwaves to the bottom of the crater. According to Jaffe and McSpadden, efficiencies of 17 to 19% can be achieved over the total sun energy available.[15] Fortunately, enormous amounts of solar energy fall on the lunar south pole, so this inefficiency is not quite so detrimental if extra solar energy can be harnessed (larger solar arrays).

Wireless power transmission, according to Jaffe and McSpadden, most of the proposed concepts is well understood, and techniques for the safe retro-directive control of the microwave beam have been developed and demonstrated.[15] However, the system still has yet to undergo testing in space. This would classify the microwave power transfer as TRL 5. The use of solar panels and nuclear does not present significant technology development risks. According to Sasaki et al., the microwave power transfer concept was proposed in 1968.[16] This technology was already demonstrated in controlled environments but still need to be proven is space. Operational risks include the deployment of the solar arrays and microwave transmitter from the lander. Transmission of energy can be decreased in case of block of line of sight, but rovers are equipped with emergency batteries to handle this risk. The use of this technology in the Lunarport architecture offers a great opportunity to mature wireless power transmission, a technology that could hold wide benefits for society as a whole.

Support Infrastructure: Launch Pad, Road Networks, and Shielding:

Using the sintering robot and its attachments, a permanent reusable launch and landing pad for the LRS will be constructed in a selected and cleared site. The pad will be constructed 500 m away from any lunar infrastructure to keep the infrastructure safe from debris thrown away by shuttle landings. The top sintered layer will improve the durability, dust ejection, stability and hence, the overall performance.

The unique properties of lunar regolith make for the extreme coupling of the soil to microwave radiation. It is possible to sinter lunar soil at 1,200–1,500°C in minutes in a normal kitchen-type 2.45-GHz microwave. Doing so would lead to a relatively fast construction of a road with good quality for rover movements. A 4-m wide road network is proposed for the transportation in the lunar base and beacons are located on the roads to navigate the rovers.

The covering berm is proposed to be constructed to keep the lunar infrastructure safe from the dust and debris which are ejected away by shuttle landings and launches. Moreover, a covering berm will act as a shield against radiation and asteroid impacts on lunar structures and rovers. A 5-m tall and 50-m long berm will be constructed using the excavation and filling attachments of the sintering robot. Construction process will allow propellant transfer pipes to be embedded in the berm.

Once the landers land on the temporary landing pads on the moon, they will be used as solar energy harvesters and communication centers. Hence it is important to keep these structures safe from radiation and asteroid impacts. As a remedy, landers will initially be covered by a carbon fiber deployable structure and its openings for rover movements will be controlled by Z-type origami components. Subsequently it will be covered by a regolith layer for protection against asteroid impacts, temperature fatigue and radiation.

Environmental Protection and Control:

It is very important to take into consideration the environmental risks of an autonomous lunar port as it is highly prone to uncertain and extreme environmental conditions at the surface of the lunar south pole. There are three main impacts, namely the regolith, radiation, and asteroid impacts for which protection designs are necessary to be implemented. Furthermore, it is essential to control the extreme thermal environment so that all operations will function well as expected.

Influence of regolith can be identified in two main aspects, abrasive lunar dust and high speed ejection of regolith while landing. Both of these impacts on permanent structures can be mitigated by having first, a deployable structure to cover from dust, and second, a regolith layer covering the structure which can absorb external regolith impacts. Dust affecting the rovers, solar panels, and communication systems would be protected by electromagnetic vibration systems attached to each of these components.

Radiation onto the lunar surface takes two main forms, electromagnetic and ionizing radiation. Ionizing radiation can penetrate up to a few centimeters in depth with severe magnitude. Ionizing radiation takes three forms, solar wind, solar cosmic rays, and galactic cosmic radiation, all of which can be avoided by the use of regolith layers up to several meters of thickness. Previous research work has estimated that a roughly 2.5m thick regolith layer is sufficient to limit the annual radiation dosage of 5 rem into the structure, which is the limit for radiation workers.[17] A structure designed for non-human operation would require a significantly thinner regolith layer, given the significantly lower radiation requirements on non-human system components.

Asteroid and meteoroids are naturally occurring solid bodies traveling through space at very high speeds. Most likely, a layer of compacted regolith will be placed atop the structure for protection against all of those hazards. It provides shielding against most micrometeoroid impacts because the relatively dense and heavy regolith absorbs the kinetic energy. Furthermore, a relatively tall, covering berm will also protect the surrounding structures by shielding against asteroids and meteoroids.

Thermal Protection and Control:

Temperatures at the south pole at the Moon are among the lowest temperatures ever recorded in the solar system due to areas being permanently shadowed from the Sun. Data from the Lunar Reconnaissance Orbiter (LRO) indicate that south-pole temperatures range as low as 25 K (-250 °C) in permanently shadowed regions to as high as 300 K (27 °C) in areas receiving sunlight greater than 70% of the lunar day.[7] Most systems are strategically placed out of the permanently shadowed regions to avoid the extreme cold. These systems will still require active heating, especially during the lunar night (approximately seven Earth days at the chosen site), so power has been budgeted to keep these systems warm during these times. Just before the sun sets, the mining robots will drive back to the site, drop off their ice loads, and drive into a thermally controlled environment. This thermally controlled environment will be the lunar lander that each respective mining robot was originally delivered to the surface in. Groups of six mining robots will spend the lunar night in this insulated and actively heated environment in a low power state until the sun rises approximately seven Earth days later. Once the sun has risen, the mining robots will drive back to the cold regions and restart their mining operations.

2. Space Systems

The space systems consist of the Lunar Resupply Shuttle (LRS), orbital propellant depot used for docking and refueling, a Solar Electric Propulsion (SEP) tug, Lunar Transfer Vehicle (LTV), and lunar lander. In this study in particular, the LRS and depot systems are discussed extensively. A major trade in the study determined whether to have a depot at all. Without a depot, refueling of the customer would require upwards of 30 dockings with LRS which increases complexity, risk and time. Additionally, the customer vehicle would need to have its own zero boil-off technology to avoid significant propellant loses. Thus, including a depot decreases risk to the customer and can provide state-of-the-art technology for propellant storage in space.

Figure 5 shows the configuration of the LRS. A 17-ton oxygen tank rests on top of a three-ton hydrogen tank with a 15-ton inflatable bladder for water storage wrapped around their junction. A docking port to fit the propellant depot is on top of the oxygen tank and contains interfaces for propellant and water exchange. The entire vehicle rests on four landing legs. The overall height of the LRS is 15 m with the legs unfolded. The landing legs fold up and the RL10 nozzle extension telescopes for stowing. During launch, the water bladder is deflated to fit within the launch vehicle fairing. The docking adapter doubles as a hardpoint to attach the LRS to the launch vehicle. The total dry mass of the LRS is approximately five tons. The orbital fuel depot is designed for the addition of successive modules. Table 7 details these stages. The overall dry mass of the fully assembled depot is approximately 70 tons.

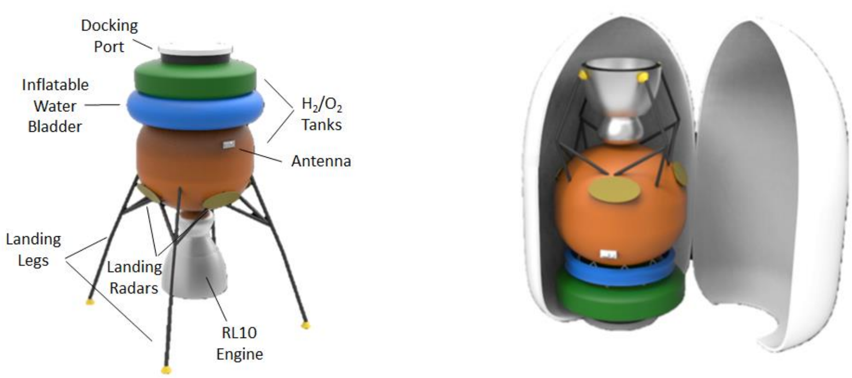
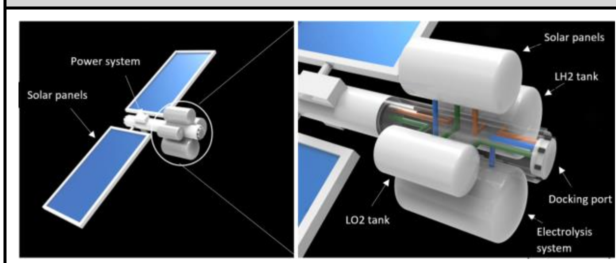
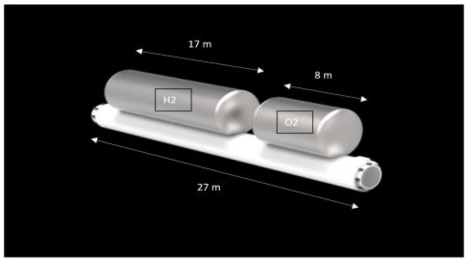


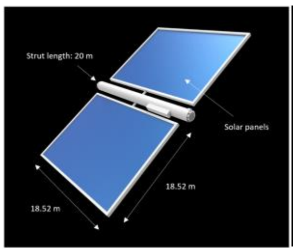
Figure 5. LRS Configuration. Operational configuration with parts labeled (left) and stowed configuration (right).

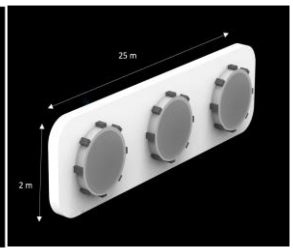
Table 7. Depot Module Specifications

Module 1: Demonstrator Module	
	• First module to be launched (SLS EUS) • Proof of concept and first step towards fully operational depot • Tanks for water, LO_2, and LH_2 • Electrolysis system to convert water to propellant • Two solar panels • Tanks weigh 25% less than the aluminum counterparts

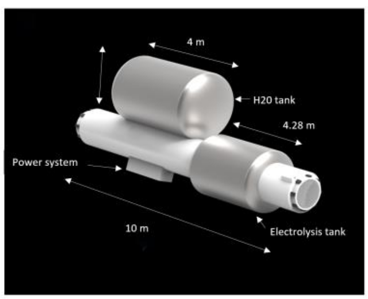
<table>
<tr><th colspan="2">Module 2: Propellant Tank Extension Module</th></tr>
<tr><td>
</td><td>

- Docks with existing demonstrator module
- Larger storage facilities to enable customer Mars mission of up to 600 tons
- Two modules used in final depot design
- Contains thermal control necessary to maintain cryogenic temperatures in large tanks

</td></tr>
<tr><th colspan="2">Module 3: Solar Panel Extension Module and Additional Docking</th></tr>
<tr><td>


</td><td>

- Docks with Module 2
- Enough power for electrolysis of 800 tons of propellant over a 24 month period
- Miura foldable solar panels[18]
- Additional docking ports to accommodate multiple LRS dockings at once

</td></tr>
<tr><th colspan="2">Module 4: Electrolysis Extension Module</th></tr>
<tr><td>
</td><td>

- Docks with existing refueling depot
- Allows for electrolysis of 800 tons of propellant over a 24 month period
- Larger water storage system and electrolysis plant

</td></tr>
</table>

A number of the components in both the LRS and depot have mid- to high-TRLs, requiring little further development, while others are not quite as far along. Table 8 outlines the LRS components and their corresponding technological development, while Table 9 shows the same data for the depot. Figure 6 shows the concept of operations for the LRS.

Table 8. Component breakdown and required technology development of the LRS

Component	Off-the-shelf Solution or Analogous Systems	Modifications from Analogous Solution	TRL
Main engine, ~100 kN, liq. H_2/O_2	RL10	Increase lifetime from one to three hours	9
H_2/O_2 tanks	e.g. Centaur	Change dimensions, reduce boil-off	9
Landing legs	e.g. Apollo LM	Design to support loads on impact for our particular vehicle	9
Power	H_2/O_2 fuel cell	Determine configuration on vehicle	9

Communications	S-band radio	Size antenna	9
RCS thrusters, ~100 N, gas. H_2/O_2	ULA ACES thrusters; Various prototypes for Space Station Freedom	Reconfigure for LRS	6
GNC for precision landing	JPL's ALHAT Mighty Eagle Lunar Lander	Refine algorithms for particular mission	6
Flexible bladder for water storage	e.g. TransAstra's APIS	Needs further lab testing Modify shape to fit LRS	4

Table 9. Component breakdown and required technological development of the propellant depot.

Component	Off-the-shelf solution or analogous systems	Modifications from Analogous Solution	TRL
Propellent generation system (Electrolysis)	Scaled-up version of the Oxygen Generation System (OGS) onboard the ISS	Modified version of the ISS OGS specifically designed to produce propellants	7
Storage tanks	LH_2 / LO_2 storage in NASA Composite Cryogenic tank	A 5.5-m diameter version of the tank was demonstrated in 2015-16	6
Propellant transfer interface	COTS	Assuming expedited transfer method over next 5-10 years	9
Water-to-LH_2 and Water-to-LO_2 Liquefiers	COTS	Assuming efficiency increases over next 5-10 years	9
Docking / modular connector	COTS	Assuming improvements in computer vision docking technology over next 5-10 years	9
Solar array and power system	Foldable solar panels based on the Miura Fold	Assume current development of a 2.7-m side length to 25-m length foldable solar panel is successful	4
ADCS	Analogy - Moog ISP DST-11H Bi-Propellant thruster	Assume it is possible to modify the system to utilize LO_2 and LH_2 as the propellants	7
Strut	COTS	Standard satellite strut design	9

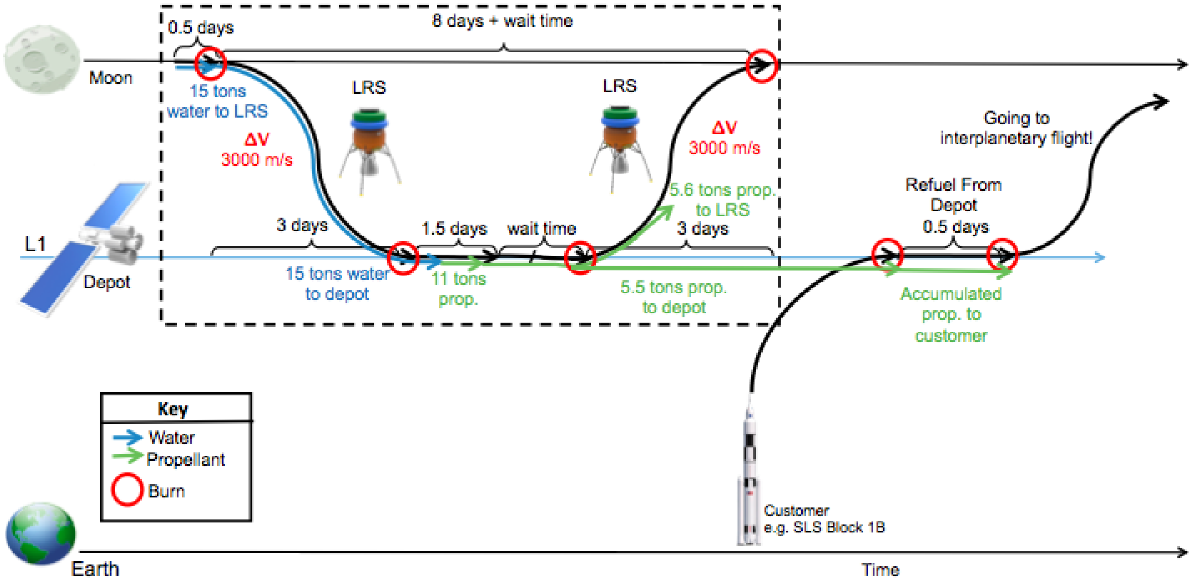


Figure 6. Concept of operation for the LRS.

The key performance metric for LRS operations is the mass leverage, shown in Figure 7.

$$Mass\ leverage\ =\ \frac{mass\ of\ propellant\ deposited\ at\ depot}{mass\ of\ water\ mined}$$

Figure 7. Mass Leverage Definition

The mass leverage is driven by the amount of propellant the LRS consumes in transporting resources to the depot.

The current architecture provides a mass leverage of 0.13. To reduce costs and launch requirements, each LRS is re-used for several cycles. To meet the required delivery rate and system uptime, there will be one active LRS and two in-space spares deployed at any time (once Lunarport is operating at full capacity). When first deployed, the LRS lands at the base on the moon surface. The LRS loads 15 tons of water and 20 tons of propellant into its tanks. The base needs to mine 42 tons of water to generate this much water and propellant. The LRS then burns these 20 tons of propellant to launch to the depot. Once docked to the depot, the LRS uses electrical power from the depot to melt the water ice in its bladder (Fig. 8), and pump liquid water into the depot's holding tank. The 15 tons of water from the LRS is electrolyzed by the depot to produce 11 tons of propellant over several weeks.

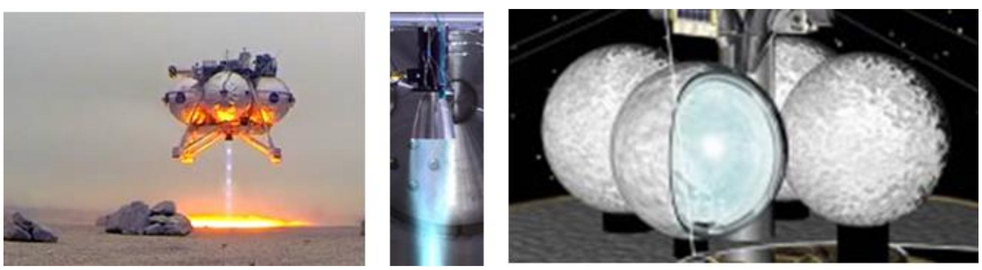


Figure 8. Technologies needed for the LRS are already under active development. JPL's ALHAT sensor demonstrates using terrain-relative navigation for precision landing (shown on left, in a test flight on the

Morpheus lander). ULA is test-firing H_2/O_2 reaction control thrusters for their Advanced Cryogenic Evolved Stage (ACES, middle). TransAstra is developing flexible water bladders under a SBIR contract (right).

The LRS waits at the depot until it needs to fly another cycle. Just before departure, the LRS withdraws 5.5 tons of propellant from the Depot and burns it when flying back down to the base. Table 10 summarizes the delta-V budget for the LRS refueling cycle.

Table 10. Delta-V budget for the LRS refueling cycle. Assumes 97% expulsion efficiency for water and propellant tanks. Delta-V figures include 500 m/s margin for maneuvering, attitude control, and boil-off of propellant. The mass leverage is 0.13. A net mass of 5.5 tons of propellant is deposited in the Depot by each LRS cycle.

Event	Delta-V (m/s)	I_{sp} (s)	Total mass before event (Mg)	Total mass after event (Mg)	Dry mass (Mg)	Δ water mass during event (Mg)	Δ prop. mass during event (Mg)	Water payload mass after event (Mg)	Propellant mass after event (Mg)	Burn time (s)
Depot to Base	3000	460	11.5	5.9	5	0	-5.6	0.45	0.45	229
On Base			5.9	40.7	5	15	19.8	15.45	20.2	
Base to Depot	3000	460	40.7	20.9	5	0	-19.8	15.45	0.45	811
At depot			20.9	11.5	5	-15.0	5.6	0.46	6.0	

After many LRS cycles, a large amount of propellant is deposited at the depot. This propellant is then transferred to a customer vehicle. When returning to the lunar base during each cycle, the LRS follows of special landing trajectory (Fig. 9) that is designed to minimize the risk to base infrastructure in the event of an LRS failure. It is important to minimize this risk because LRS spacecraft will be aggressively re-used, so failures near the end-of-life are likely.

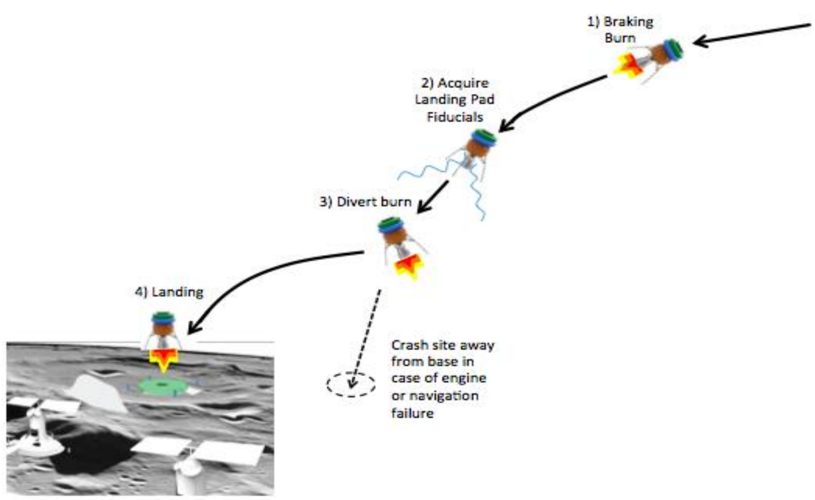


Figure 9. LRS Landing Sequence.

Figure 10 summarizes the concepts of operation for the refueling process at the depot. The ice in the LRS bladder is heated up and transferred to a water storage tank. The water is then transferred to an electrolysis plant for separation into hydrogen and oxygen. Gaseous hydrogen and oxygen are then transferred into their own respective tanks with intermediate liquefiers in order to store the spacecraft-usable propellants of LH_2 and LO_2. The depot stores the propellants until such a time that they can be transferred into a customer vehicle that docks with the depot.

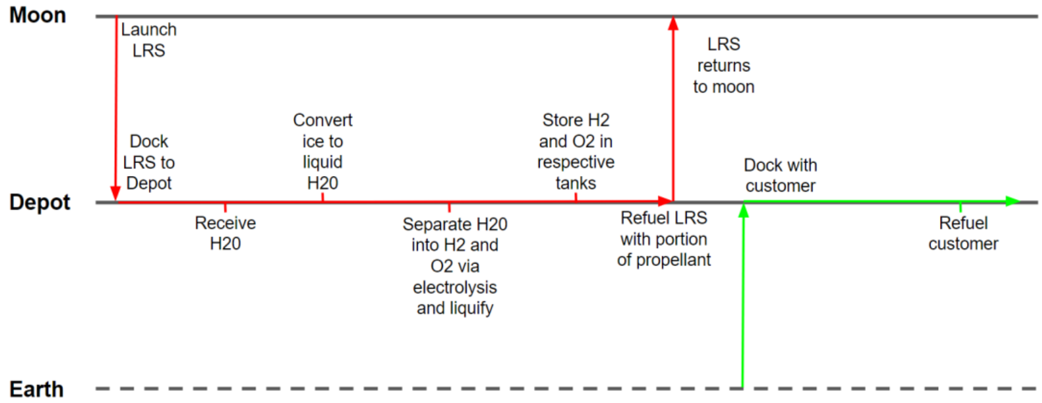
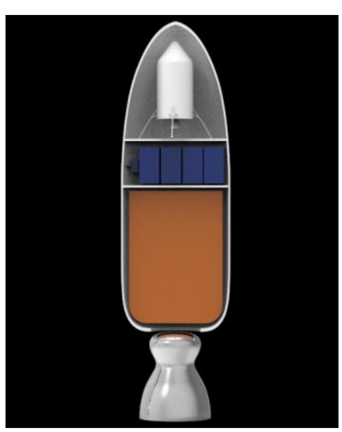


Figure 10. Concepts of operation for the depot refueling process.

In addition to designs of the LRS and depot which relate to the actual refueling process, designs for a SEP tug, LTV, and lunar cargo lander are required in order to transport cargo (especially mining robots) to cis-lunar space and ultimately to the lunar surface. The highlights of these designs are summarized in Table 11.

Table 11. SEP tug, LTV, and lunar cargo lander design highlights

Solar Electric Propulsion (SEP) Tug	
 SEP Tug model from Donahue et al.	• Delivers customers spacecraft via the SLS Block 1b EUD from LEO to L_1 refueling. • Solar array to provide 700-800 kW BOL • Three 200 kW concentric channel Hall thrusters with an Isp of 4000s, 60 mN/kW, and 2.27 trips/tank[19] • Round trip time of 2 years and 1 tank/round trip • Refueled by Falcon Heavy with tank delivery cap of 54 tons • Replace thrusters every six years
Lunar Transfer Vehicle	

	• Comes in 'compact' and 'plus' sizes
	• Used to carry cargo to various locations in cis-lunar space from TLI.
	• Launched on Falcon Heavy expendable or SLS B1b
	• Compact
	  ○ 1 Astrobotic lander and P-POD deployer with 6U Cubesats (payload mass of 2 ton)
	  ○ Transfer from LTI to LLO and deploy cubesats into communication constellation
	• 5T Plus
	  ○ 5 Astrobotic landers and ground deployment mechanism
	  ○ Transfer from LTI to LLO
	• 20T Plus
	  ○ Full 20 ton Depot
	  ○ Insert into L_1 Halo Orbit and deploy depot

Lunar Cargo Lander	
	● Lands 5 ton payload on the lunar surface ● Deploys mining robots and 40 kW solar arrays on the lunar surface ● Protects lunar surface assets during lunar night (internal temperature above 250 K) ● Can store up to 6 mining robots

C. Mission Design

1. Launch Vehicle Selection

The launch vehicle selection depends on the payload mass, dimension, cost, and timing needs of each phase of the mission. For this reason, the selection process is carried out individually for each payload. Table 12 shows the main parameters for each launch vehicle considered, with many of the parameters estimated based on existing technologies or company projections. Table 13 shows the characteristics for each payload along with the selected launcher.

Table 12. Launcher Comparison

Launch Vehicle	Payload mass to LEO (tons)	Payload mass to TLI (tons)	Payload Fairing Diameter (m)	Payload Fairing Length (m)	Volume (m^3)	Cost of Booster ($)	Cost per ton to TLI ($)
SLS 1B	105	39	10	31	2435	$1 B*	$26 M
Falcon Heavy (Reuseable)	20	6	4.6	11	183	$90 M*	$15 M
Falcon Heavy (Expendable)	54	16	4.6	11	183	$150 M*	$9.375 M
New Glenn 2-Stage	45	15	4.5	14	223	$150 M*	$10 M
New Glenn 3-Stage	62	20	6	18	509	$200 M*	$10 M
Delta IV Heavy	28	9	5	19	375	$440 M	$49 M

***estimated based on existing launch vehicles or company projections**

Table 13. Selected Launch Vehicles

Payload	Mass (tons)	Maximum orbit time	Selected launcher
LRS	20	Short, 1 month	Falcon Heavy
Lunar Lander	15	Long, several months	Falcon Heavy
Small Depot	30	Short, 1 month	Falcon Heavy
Solar Panels for Depot	25	Short, 1 month	SLS 1B
Scale Up Package	15	Short, 1 month	Falcon Heavy

2. *Orbit Selection*

The options considered for transportation from Earth to the lunar base and depot were an electric propulsion spiral orbit, a low energy orbit with chemical propulsion, and direct transfer with chemical propulsion. The trade study for the different trajectories in shown in Table 14. The selected orbit for cargo delivery is direct transfer with chemical propulsion based on the simplicity and low operational risk. The SEP spiral orbit was implemented for the advanced operational phase in which an SEP tug tows the customer from LEO to L_1. Low-energy chemical maneuvers showed promise for reduced delta-V, but required complex simulation to discern the necessary delta-V and trajectories; future architectures may implement low-energy transfers for optimized performance.

Table 14. Trajectory options

Trajectory Selection	Criteria					
	Transit Time	**Complexity**	**Operational Risk**	**TRL**	**Total Cost**	**Propellant Mass Ratio**
EP Spiral	**V. Slow**	**High**	**Moderate**	**5**	**Low**	**Very Low**
LE Chem	**V. Slow**	**Medium**	**Low**	**9**	**Medium**	**Medium**
D Chem	**Fast**	**Low**	**Low**	**9**	**High**	**Medium**

After considering multiple trades, the rendezvous orbit for the customer and therefore the location of the orbital depot was selected to be the Earth-Moon Lagrange Point 1 (EM-L_1). Initially, HEO was considered because of its lower delta-V requirement, but later it was realized that, given our limitations in the design of the LRS, using HEO would require the customer to wait more than one month per LRS delivery and requires precise timing. The customer will need to also traverse to L_1 from Earth, while the LRS will need to do so from the lunar surface. Each transfer maneuver is listed in Table 15 with its vehicle, location, initial orbit, destination orbit and delta-V.

Table 15. Delta-V budget

Vehicle	Location	Initial Orbit	Destination Orbit	Delta-V
Lunar Lander	Mid-course	TLI	TLI-Corrected	30 m/s
Lunar Lander	Moon	TLI-corrected	100km Polar Lunar Orbit	4 km/s
Lunar Lander	Moon	100 Polar Lunar Orbit	None	1.9 km/s
LRS	Moon	None	Insertion to L_1	2.4 km/s
LRS	L_1	Insertion to L_1 from the Moon	L_1 Halo	20 m/s
Small Depot	L_1	Insertion from Earth	L_1 Halo	3.8 km/s
Small Depot	L_1	Insertion from Earth	L_1 Halo	3.8 km/s
Customer	L_1	Insertion from Earth	L_1 Halo	3.8 km/s
SEP Tug	L_1	LEO	L_1 Halo	7 km/s

3. *Payload Optimization*

The payload delivered to deep space destinations must be optimized to ensure that the propellant depot allows for cheaper missions rather than adding cost and complexity.

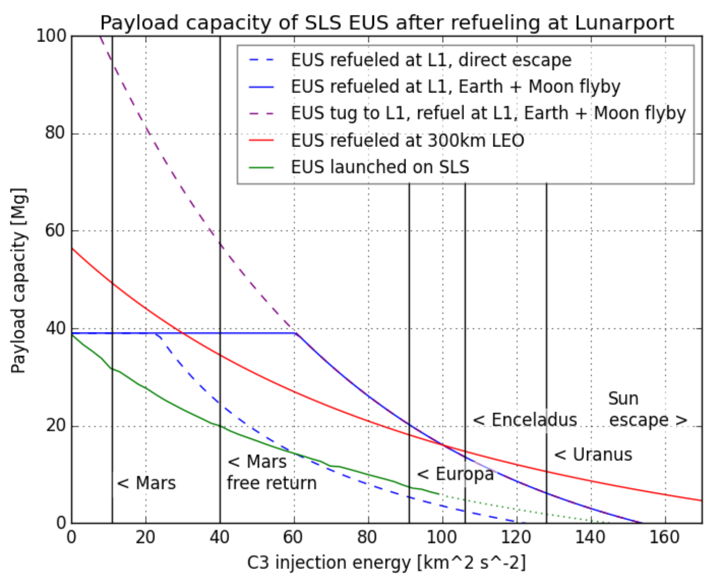


Figure 11. Refueling at Lunarport's L_1 depot increases the payload capacity of the Space Launch System's (SLS) Exploration Upper Stage (EUS).

In Fig. 11, the green curve shows the payload capacity of the EUS if launched directly onto an Earth-escape trajectory. The blue curves show the payload capacity of EUS after refueling at L_1. Leaving L_1 via Earth + Moon Oberth maneuvers is favorable. The blue curves are capped at 39 tons because the SLS/EUS can only bring 39 tons of payload mass to L_1. If an SEP tug pulls the EUS and payload to L_1, larger payloads are possible (purple curve). Payload capacity for an EUS refueled in LEO is shown for reference (red line); however our architecture does not allow this option because of the high energy cost of transporting propellant from the Moon to LEO. (Data for direct launch of EUS on SLS from Donahue and Sigmon.[20] L_1 departure Oberth Trajectories from Schaffer et al. [21]

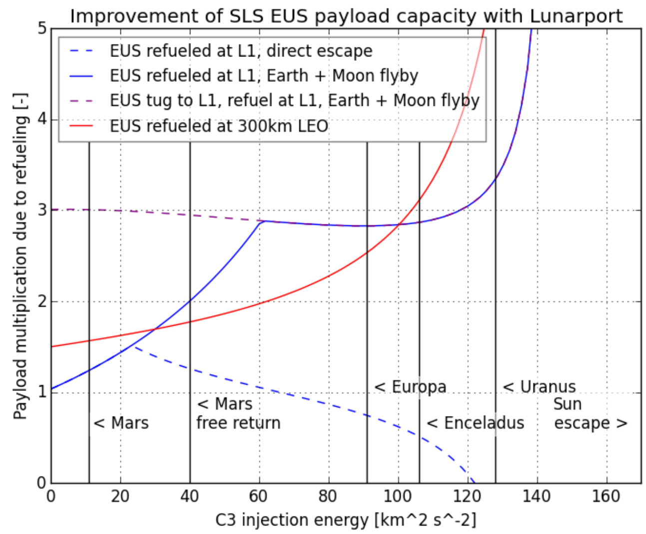


Figure 12. A threefold increase in the payload capacity of the Space Launch System's (SLS) Exploration Upper Stage (EUS) to many destinations can be achieved by using Lunarport.

For the icy moons (Europa and Enceladus), launching the EUS to L_1, refueling at Lunarport's depot, then departing Earth via Oberth maneuvers triples the payload capacity compared to a direct launch of the EUS. For Mars missions, very heavy payloads (~90 tons) can be injected by an EUS from the L_1 depot. However, EUS can only lift 39 tons to the L_1 depot, so a SEP tug is required to realize the full benefit of Lunarport for Mars missions. A first order cost savings can be performed with the following estimations:

1. SEP tug cost ~$2B (including materials cost, development, testing and evaluation, estimated based on ARM mission cost of ~$1.5B)
2. SLS Launch ~ $500M (76 kg to LEO, assuming cost decrease by 2040 and selling ~58% of the remaining payload mass)
3. Maintenance ~$1B (Hall thruster replacement, propellant resupply)
4. Operation costs ~$500M / year

Figure 12 shows that the payload to Mars can be increased by 200% resulting in an effective savings of two SLS launches or $2B. The total cost is reduced by performing multiple trips, specifically five round trips of the 102-ton wet mass EUS with 90-ton payload over the course of ten years before replacement of the entire SEP tug. The net income generation will be equal to the $2B cost savings minus the 2-year operating cost of Lunarport minus the SEP tug cost divided by five deliveries:

$$\$2B - \$1B - (\$3.5B / 5) = \$300M \text{ saved per year}$$

Therefore, the above calculation demonstrates that net positive revenue can be produced with the assumptions stated above. The above cost assumptions are highly dependent on the decreasing cost of SEP tug technology including > 100 kW solar arrays, large-area solar array deployment, high-powered electric propulsion with long lifetime, and overall cost estimation methodology. Overall, this result is very promising, showing that future deep space missions, particularly to Mars, can be strongly improved using an ISRU-supplied fuel depot with an SEP tug.

D. Lunarport Construction Sequence and Capability Ramp-Up

The first mission prior to construction is the prospector mission. This exploring phase will determine with greater detail the availability of the resources needed for Lunarport. Alongside the prospector robot a constellation of CubeSats will be launched. They will provide communication with Earth for the days when there is not line of sight between Lunarport and Earth.

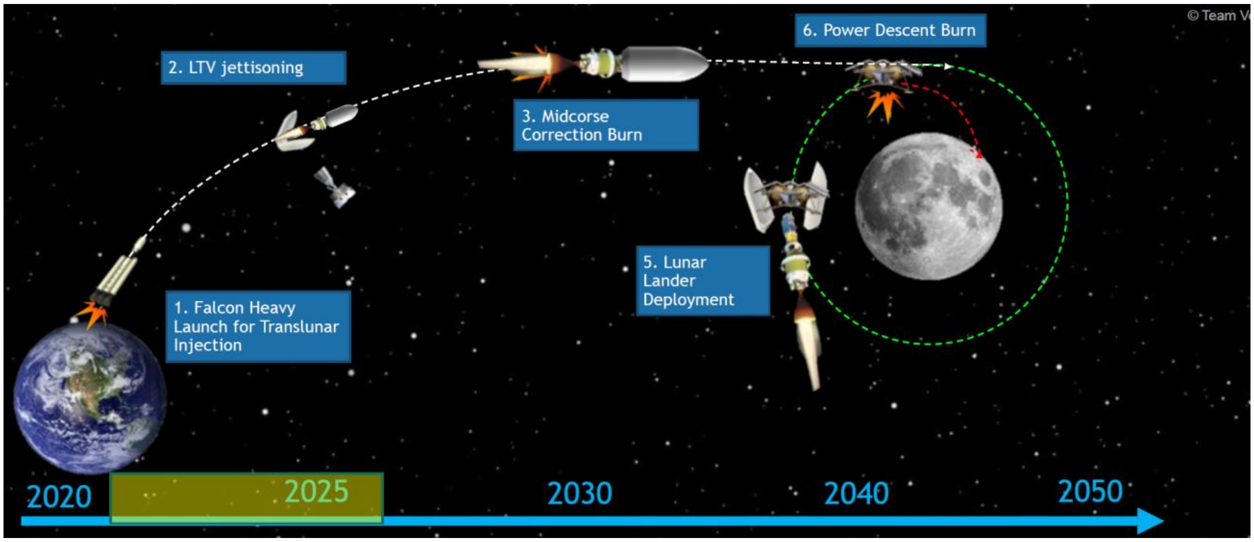


Figure 13. The first launch includes the prospector and communication CubeSats.

The next phase is the construction of the base. A Lunar Lander is launched with a sintering robot to build the necessary equipment. It will build the roads, the launching pad and the covering berm. This completion of this phase is expected by 2026. The launching pad will allow the landing of the first two LRS spacecraft. They will perform a simulated refueling operation between them to test the refueling operations.

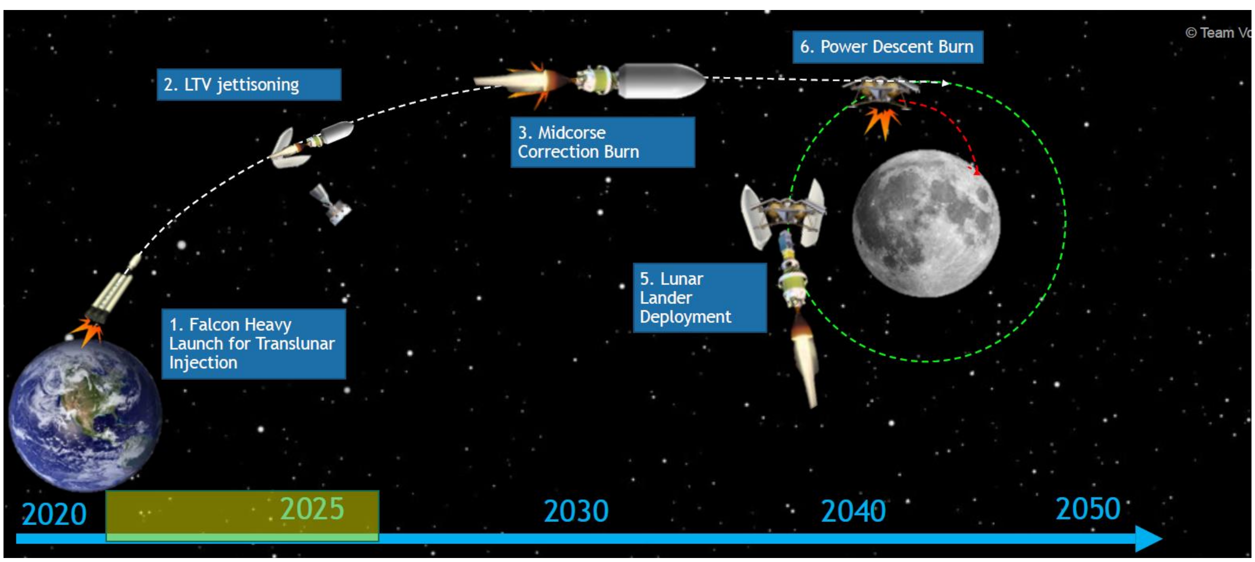


Figure 14. The general construction phase involves Falcon Heavy deliveries with various Lunar Landers providing the final descent burn to the surface.

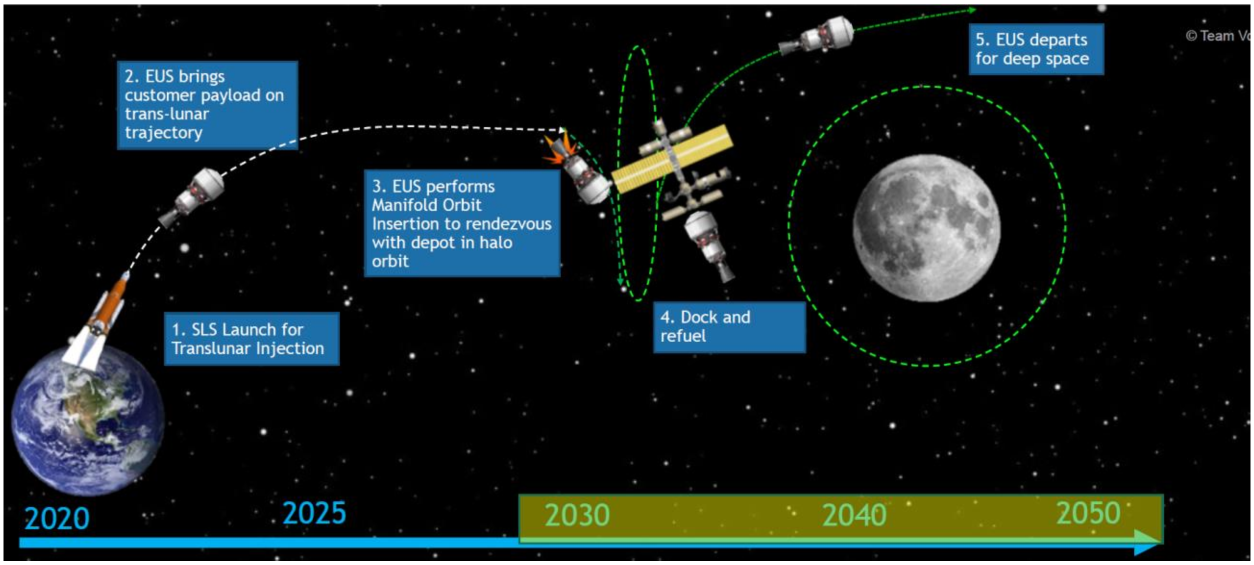


Figure 15. The operational phase above is reached when the depot begins reaching 120 t capacity with the required delivery cadence from the LRS.

After direct LRS-to-LRS refueling has been demonstrated and the depot has been fully completed with a capacity of 411 tons (11-ton depot + 400 tons tank module), the operational phase begins. In this phase, the customer can purchase up to 120 tons of propellant at the L_1 depot initially in 2023, and up to 400 tons around 2032. The production and delivery rate will continue to scale as an increasing amount of rovers and depot modules are delivered. The SLS Block 1b delivers 39 tons to TLI via the EUS which constrains the maximum payload possible during this phase. This constraint is removed in the tug-assisted operational phase described below.

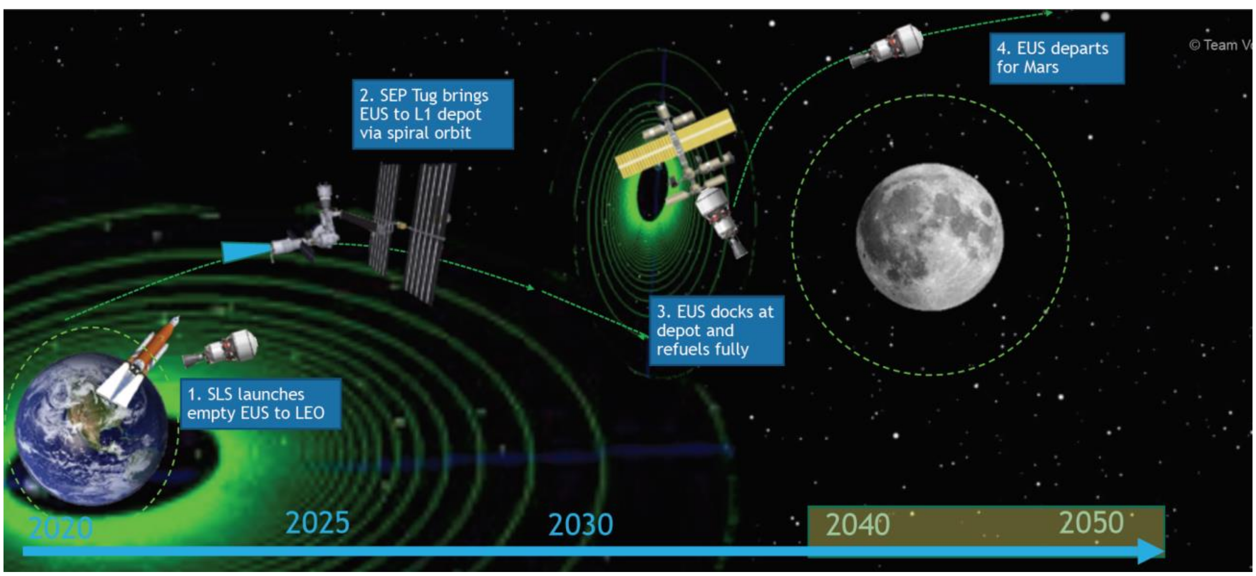


Figure 16. The schematic above describes the tug-assisted timeline operations once the fully operational phase is reached in the 2040s.

The final operational phase is reached once the production rate and LRS delivery capability can yield a total of 600 tons of propellant to the depot every four years. The SEP tug is utilized to tow the customer spacecraft (no crew) from LEO to L_1 as shown in Figure 7.2b. This savings in delta-V allows the customer to increase the payload mass delivered to Trans-Mars Injection (TMI) according to the tug-architecture shown in Fig. 15. The propellant production and depot propellant capacity are shown in Fig. 16.

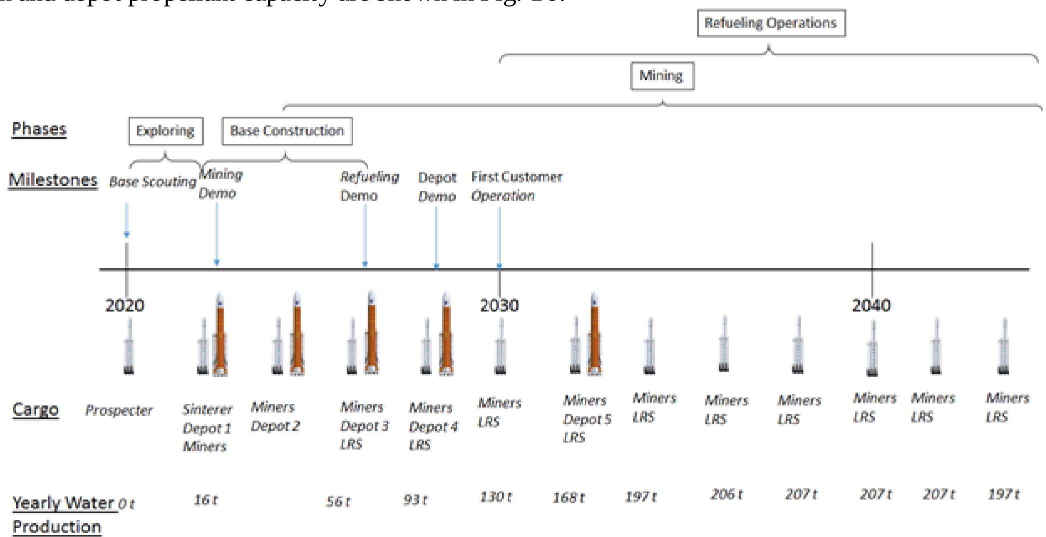


Figure 17. A detailed timeline highlighting the cargo delivery and yearly water production in their respective phases.

E. Risk Analysis

Figure 18 shows a risk analysis matrix for the construction and operation of the mission architecture presented in this study. During the design of the mission architecture and subsystems, care was taken to keep risks out of the 'red zone' of the matrix. For example, the LRS crashing into the base has significant consequences to the overall success of the Lunarport; however, the likelihood of this risk has been minimized through a carefully selected landing trajectory. A number of other consequential risks involve equipment failures. The likelihood of these risks is minimized to keep them in the 'green zone' or 'yellow zone' by using flight-proven technologies whenever possible and when not possible, allowing for significant technological development before flight. Some of the more likely risks include propellant boil-off and getting a mining drill stuck. Both of these risks are less consequential because their technology is currently being developed to minimize their effects (composite cryogenic tanks for boil-off and a mechanism to get drills unstuck).

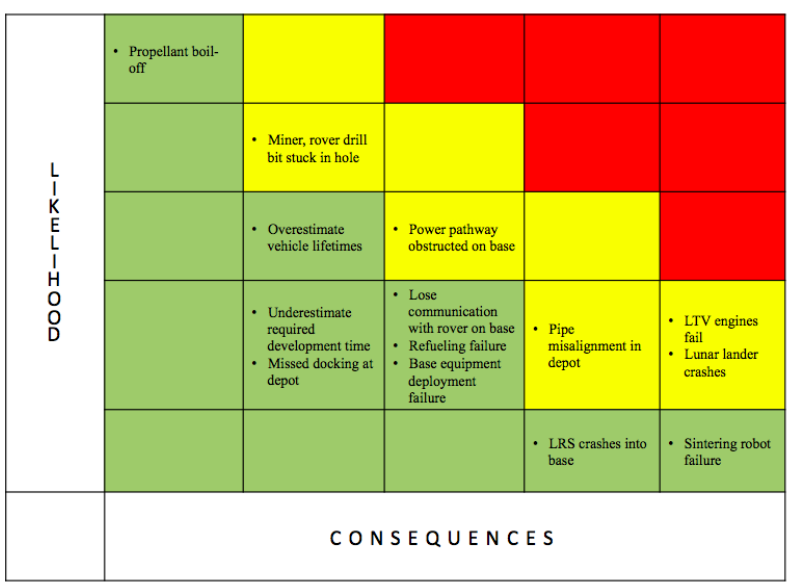


Figure 18. Risk Analysis Matrix.

F. Programmatic Considerations

1. Construction and Development Cost

The development and construction costs of the project are shown in Table 16, and represent the total costs for the initial project development starting in 2017 and ending when the first set of rovers are operational in 2022. It is found that total development costs for this initial mission amount to $4.6B. Analogous technologies were used when available, and scaled if necessary to accommodate for development. Approximate scaling factors were utilized for Project Management, Systems Engineering, Safety and Mission Assurance, Science and Technology, Mission Operations, and Ground Control that were suggested by the JPL Architecture team (A-Team).

Table 16. Development costs. Based on initial 2022 mission, with analog technologies listed. Recurring costs are listed in Appendix C.

System	Development and Construction Cost ($M)
Project Management, Systems Engineering, Safety and Mission Assurance	$102
Mission Operations and Ground Control	$114
Payload and Spacecraft	$2,405
Systems I&T	$200
Launch/Vehicle Services	$1,270
Science/Technology	$57
Reserves	$481
Total	$4,629

2. Operating Cost

Figure 19 shows the overall operating costs for the mission in the top panel, while the middle panel shows the total money available to the mission at any given time (annual budget plus rollover minus operating costs). Total costs through 2032 equal $17B. The bottom panel shows the yearly income from refueling missions and the $1B yearly budget. The initial operating cost is low, due to a lack of launches at the beginning of the mission. The $1B / year subsidy of the project ends in 2032, as the project then is making enough profit to be self-sustaining, assuming a sale of propellant for $5500/kg (in comparison to $10,000/kg in LEO). It is assumed that there are small refueling missions of 120 tons per year every four years as well as Mars-scale missions of 520 tons every four years at full operational capability.

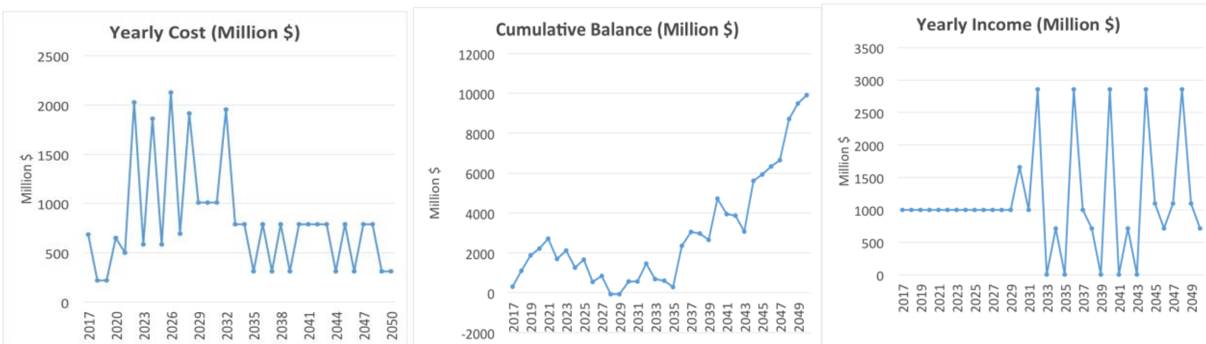


Figure 19. Yearly cost (top), cumulative balance (middle) assuming $1B per year funding through 2031, and yearly income (bottom) given the yearly cost of operations and nominal Mars refueling missions every four years beginning in 2032 and smaller customer refueling every two years beginning in 2030.

3. Long-term Operations and Business Plan

Ice Rush has a present budget allocation of $1B per year for the lifetime of its mission. As NASA's mission has transformed from one responsible for all U.S. space activity to one that primarily enables the development of non-commercially viable scientific and technological missions, unless NASA's cost structure changes, the Lunarport will have to transition to another business model once profitable. Several options could exist for the long-term future of Ice Rush:

- No-cost NASA refueling station
  - NASA could aim to keep operations of Ice Rush at a level that only meet NASA or U.S. government requirements for space missions. The refueling station may also be of interest to NOAA and DoD missions that require station keeping, particularly for expensive GEO satellites. The propellant depot reserve could also provide risk-mitigation for end-of-life satellite operations/refueling scenarios.
- No-cost international collaboration refueling station
  - NASA may exchange free refueling to other space agencies for utilization of other resources of said space agencies; e.g., in exchange for using the Moon Village
- No-cost commercial and NASA refueling station for solar system exploration:
  - In order to promote the U.S. space industry (currently a mission of FAA AST), NASA could provide propellant at cost to U.S. commercial ventures if in excess of U.S. government need. This would effectively subsidize the commercial industry, and encourage space companies to incorporate within the U.S. If demand were too high for the Lunarport production rate, some form of cost-sharing structure between the private industry and NASA could be utilized
- Sale of Ice Rush to net $0 cost
  - NASA, once Ice Rush enters full operational phase and is deemed a 'proven' technology/business, could offer the sale of Lunarport to a commercial entity to amortize the the total cost to NASA. It could be continuously offered on the free market for the total outstanding 'debt' NASA has for the project, until purchased by a commercial entity, who would be able to develop it as they saw fit. The sale would likely have to be to a U.S. company due to International Traffic in Arms Restrictions (ITAR).
- Sale of Ice Rush in exchange for future NASA utilization
  - NASA could also contract with a commercial company for the sale of Ice Rush in exchange for refueling use for further NASA missions. ITAR would again likely restrict the sale to a U.S. company

4. Political Considerations

The United Nations Treaty on Principles Governing the Activities of States in the Exploration and Use of Space, Including the Moon and Other Bodies, or Outer Space Treaty, ratified by 105 nations, including all major space powers, was enacted in 1967 after nearly a decade of negotiations on space law post Sputnik launch. This treaty, in addition to three other space treaties, form the basis of international space law.

Article II of the United Nations Outer Space Treaty of 1967, asserts that “Outer space, including the moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.” While there was an effort to create a follow-on Moon Treaty, the Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, in 1979 to more carefully define lunar activities, this effort failed, with only 17 countries party to the treaty (including no spacefaring countries). The Moon Treaty likely failed for several reasons, including Article XI, which required that “neither the surface nor the subsurface of the moon, nor any part thereof or natural resources in place, shall become property of any State, international intergovernmental or non-governmental organization, national organization or non-governmental entity or of any natural person”. Because of the failure of the United Nations Committee on the Peaceful Uses of Outer Space to coalesce on a narrower version of “claim of sovereignty”, the utilization of extraterrestrial resources is at present a legal gray area.[22]

Both the United States and Luxembourg have chosen to adopt the perspective that resource extraction does not violate the Outer Space Treaty, with Luxembourg partnering with Planetary Resources for asteroid mining, and approvals by the Federal Aviation Administration Office of Commercial Space Transportation (FAA AST) for both the Moon Express probe as well as the Bigelow Aerospace lunar base.[23] Though Bigelow has no immediate plans for a lunar base, the AST payload review was seen as a step to measure the regulatory uncertainty for lunar property rights.[24] The approval was viewed by many as a U.S. government endorsement for commercial activities on other celestial bodies, suggesting that permanent lunar fixtures, not just short-term probes such as Moon Express, are likely viable for commercialization.[25]

While it may be possible to receive AST authorization for commercial lunar activities, the process is presently ad hoc for missions that are not standard (e.g., launches of communications satellites), and may involve approval from other agencies, including the State department, National Oceanic and Atmospheric Administration (NOAA), and the Federal Communications Commission (FCC) depending on the mission payloads. Though this creates complexity in the mission approval process for commercial activities, AST is required by the Commercial Space Launch Act (HR. 3942) to make licensing decisions within 180 days.[24]

5. Planetary Protection

Article IX of the Outer Space Treaty requires that states party to the treaty conduct operations on the moon and other celestial bodies to avoid harmful contamination. Under NASA’s Planetary Protection guidelines, non-returning lunar missions fall under Category II.[26] This project will request a preliminary Planetary Protection Office categorization, and will provide the Planetary Protection Plan at the end of Phase B (the Conceptual Study). In addition the Pre-Launch Planetary Protection Report, Post-Launch Planetary Protection report, and End of Mission Report will be provided in coincidence with our mission timeline.

V. Conclusion

A viable space-based propellant depot is critical to deep space exploration. Both NASA and the commercial sector recognize the importance of in-situ resource utilization for this purpose; NASA’s Deep Space Gateway requires the refueling of its Deep Space Transport vehicle to Mars in cis-lunar space, and companies such as ULA (CisLunar-1000) are eager to exploit the lunar economy for both the refueling of deep space missions as well as satellite life extension. Recognizing the requisite architecture for exploration in cis-lunar space and beyond, the week-long 2017 Caltech Space Challenge asked an international team of undergraduate and graduate students to design Lunarport, a refueling depot in cis-lunar space supplied from ice extracted at the lunar south pole, with a $1B/year budget. Lunarport was designed to be able to provide 600 tons of LH_2-LO_2 propellant for a crewed Mars mission by 2032, in concurrence with NASA’s timeline.

The final design of the Lunarport, called ‘Ice Rush’, is presented here in detail, including all major lunar surface systems, space systems, mission designs, operations, construction, and programmatic considerations. Ice Rush utilizes ISRU at the lunar south pole to provide ice to a Lunar Resupply Shuttle (LRS), which then transports ice to a propellant depot at the Earth-Moon L_1 point. At the depot, ice is then converted to LH_2-LO_2 propellant, and made available to customers. The Ice Rush architecture utilizes state-of-the-art or emerging space technology for ISRU (Honeybee Robotics Planetary Volatiles Extractor Corer), power (wireless power transmission), propulsion (solar electric), space vehicle design (reusability), and propellant storage (composite cryogenic tanks).

The architecture of this mission is modular and scalable. As such, it is flexible to incorporate new technologies, adjust to any technical or programmatic challenges, and provide refueling capabilities to a wide range of missions. Ice Rush slowly builds up, sending six Curiosity-size mining rovers every two years beginning in 2022, and every year starting in 2026, as well as two Lunar Resupply Shuttles annually beginning in 2028. This enables the modular depot to supply 120 metric tons of propellant in 2031 and 520 tons in 2032. With this continuous cadence of mining rovers and LRSs supplied to Ice Rush, the supply scales up to 630 tons of propellant available to refuel a customer at the depot every four years after 2032.

Following the first Mars mission of two cargo and one crew vehicle by 2032, Ice Rush can supply propellants to send a crewed mission to Mars every four years. Payload capacity for deep-space missions is also drastically improved. Specifically, the Ice Rush architecture can triple the payload mass capacity to the icy moons, Europa or Enceladus.

Lunarport may present an opportunity to enable public-private partnerships in the space industry. NASA has shifted its position over the last several decades from the only actor in the U.S. space industry to one of many, suggesting that their main purpose has become to enable non-economically viable or costly emerging space technologies, rather than develop commercially viable technology. As such, a conceptual Lunarport may be best financed by NASA during initial development, and then transitioned to a more commercial long-term model.

Ice Rush was designed using technology at almost exclusively TRL-6 and above, for a total cost of $17B through its financial independence in 2032. At this time, we find that the depot will be self-sustaining, if able to resupply missions at a cost of $5500/kg or greater.

Acknowledgments

The authors (team Voyager) would like to thank the California Institute of Technology (Caltech), the Graduate Aerospace Laboratories of the California Institute of Technology (GALCIT), and the NASA Jet Propulsion Laboratory (JPL) for hosting the 2017 Caltech Space Challenge. The authors would also like to thank the sponsors of the event for allowing such an incredible event to take place (Airbus Defence and Space, Microsoft, Keck Institute for Space Studies, Orbital ATK, Northrop Grumman, Moore-Hufstedler Fund, Blue Origin, Boeing, Lockheed Martin, Schlumberger, and Honeybee Robotics). The authors are also extremely grateful to Ilana Gat and Thibaud Talon, the student organizers, as well as the several other student experts who helped make the event a reality. Finally, the authors thank the many technical experts who gave relevant lectures and graciously committed their time to provide their technical advice on the many challenges faced during the week of the competition.

References

[1] Colaprete, A., et al., "Detection of Water in the LCROSS Ejecta Plume", Science, Vol. 330, Issue 6003, 22 Oct. 2010, pp. 463-468.
[2] NASA Transition Authorization Act, S. 442, 115th Congress, 2017
[3] NASA Exploration Forum, NASA, 29 Apr. 2014, https://www.nasa.gov/content/nasa-exploration-forum-details-human-path-to-mars/
[4] Crusan, Jason, "Evolvable Mars Campaign", NASA Advanced Exploration Systems Division Human Exploration and Operations Mission Directorate, 2014, https://www.nasa.gov/sites/default/files/files/NextSTEP-EMC-Reference.pdf
[5] Smith, Marcia S., "NASA Continues Journey to Mars Planning", SpacePolicyOnline.com, 28 Mar. 2017, http://www.spacepolicyonline.com/news/nasa-continues-journey-to-mars-planning
[6] NASA, "Strategic Knowledge Gaps", 29 Aug. 2016, https://www.nasa.gov/exploration/library/skg.html
[7] Kutter, B., "Cislunar-1000: Transportation supporting a self-sustaining Space Economy", AIAA SPACE 2016, AIAA SPACE Forum, (AIAA 2016-5491)
[8] NASA, "Lunar Reconnaissance Orbiter," 10 Oct. 2010, https://www.nasa.gov/mission_pages/LRO/news/lro-lcross-impact.html
[9] Sanders 2016, https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20110014548.pdf
[10] NASA (2017). https://www.nasa.gov/exploration/home/022708.html. [image]
[11] Picard, M., et al., Resources Prospecting & Mobility Beyond Earth, ISAIRAS 2014, http://robotics.estec.esa.int/i-SAIRAS/isairas2014/Data/Session%207a/ISAIRAS_FinalPaper_0050.pdf
[12] Zacny, K., Indyk, S.; Luczek, K.; Paz, A, "Planetary Volatiles Extractor (PVEx) for In Situ Resource Utilization (ISRU)", Earth Sp. Conf., 2015.
[13] NASA Jet Propulsion Laboratory, "The ATHLETE rover", https://www-robotics.jpl.nasa.gov/systems/system.cfm?System=11
[14] Honeybee Robotics (2017). https://www.honeybeerobotics.com/portfolio/planetary-volatiles-extractor/. [image]
[15] Jaffe, B.P., and McSpadden, J., "Energy Conversion and Transmission Modules for Space Solar Power," *Proceedings of the IEEE*, Vol. 101, no. 6, 2013, p. 1424-1437
[16] Sasaki, S., Tanaka, K., and Maki, K.I. "Microwave power transmission technologies for solar power satellites," *Proceedings of the IEEE*, vol. 101, no. 6, pp. 1438–197, 2013.
[17] Ruess, F., Schaenzlin, J., and Benaroya, H. "Structural design of a lunar habitat." *Journal of Aerospace Engineering* 19.3 2006, p. 133-157.
[18] Miura, K., Method of Packaging and Deployment of Large Membranes in Space, Institute of Space and Astronautical Science, Vol. 618, 1985, p. 1-9
[19] Brown, D., Beal, B., Haas, J., "Air Force Research Laboratory High Power Electric Propulsion Technology Development", IEEEAC, 2009.
[20] Donahue, B., and Sigmon, S., "Space Launch System Capabilities with a New Large Upper Stage", AIAA SPACE 2013 Conference and Exposition, AIAA SPACE Forum, (AIAA 2013-5421)
[21] Schaffer, M., St. Germain, B., and Bradford, J., "Cryogenic Propulsive Stage (CPS) Mission Sensitivity Studies Earth-Moon L1 Departure Results", 4 Oct. 2012, http://www.ulalaunch.com/uploads/docs/Published_Papers/Exploration/Cryogenic_Propulsive_Stage_Mission_Sensitivity_Studies_-_Earth-Moon_L1_Departure.pdf
[22] Agreement Governing the Activities of States on the Moon and Other Celestial Bodies. Resolution 34/68, 18 Dec. 1979, http://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties/intromoon-agreement.html
[23] Planetary Resources, "Planetary Resources And The Government Of Luxembourg Announce €25 Million Investment And Cooperation Agreement", 3 Nov. 2016, http://www.planetaryresources.com/2016/11/planetary-resources-and-the-government-of-luxembourg-announce-e25-million-investment-and-cooperation-agreement/
[24] Commercial Space Launch Act, HR. 3942, 98th Congress, 1984
[25] Foust, Jeff, "FAA Review a Small Step for Lunar Commercialization Efforts", 6 Feb. 2015, http://spacenews.com/faa-review-a-small-step-for-lunar-commercialization-efforts/#sthash.IG6jQL5a.dpuf
[26] NASA, "Planetary Protection Provisions for Robotic Extraterrestrial Missions", NPR 8020.12D, 20 Apr. 2011 https://nodis3.gsfc.nasa.gov/displayDir.cfm?Internal_ID=N_PR_8020_012D_&page_name=main