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# 2017 Caltech Space Challenge – Lunarport: Lunar Extraction for Extraterrestrial Prospecting (LEEP)

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## Abstract

**Results from this paper were developed as part of the 2017 Caltech Space Challenge: Lunarport to design an autonomous lunar base intended to extract resources from the surface to convert to fuel in order to resupply shuttles in orbit. The proposal herein, Lunar Extraction for Extraterrestrial Prospecting, LEEP, represents the winning team's design for a "Lunarport" and all references can be found in the original paper. The development of space and human progress beyond our world is largely limited by the cost per kilogram to deliver a payload to orbit. Furthermore, the current most powerful launch vehicle, LV, in the world has a maximum deliverable payload to Low Earth Orbit, LEO, of about 29 mT. NASA is currently developing the next generation of heavy LV but access beyond the Earth will still be limited by existing LVs. What happens if a mission requires more performance and is it achievable without the exorbitant cost of developing ever larger launchers? Lunarport seeks to answer this question by going back to the moon. The ultimate goal is to explore the economic feasibility of refueling deep-space missions with propellant harvested from the moon. Working within a proposed budget of 1 billion dollars a year, a mining base is to be established on the south pole of the moon to extract water frozen just beneath the surface of a permanently shadowed crater. LEEP's proposal incorporates high Technology Readiness Level, TRL, systems and a highly robust, modular, fault-tolerant design to produce propellant for deep space missions at the lunar South Pole on a short time scale and with a low risk of mission failure. Every effort has been made to make LEEP both realistic and feasible and to design a mission that provides direct and indirect benefits in the most cost-effective ways possible. Nominal operating capacity is expected in the late 2020s; LEEP can resupply one mission to Mars per year, enabling a 27.6% increase in payload delivered to Trans-Mars Injection. The modular architecture could be expanded in the future to enable multiple missions per year, and its modular nature means that LEEP's expansion can be completed for a fraction of the cost of the initial system. One particularly interesting application of LEEP's architecture is in support of refueling missions to high-energy destinations. Early numbers indicate a 250% increase in payload delivered directly to a Trans-Saturn Injection compared to a mission that is not refueled, for example, and the more energetic the destination, the greater the benefit. This has direct applications for robotic exploration of the outer Solar System and for vastly expanded mission capabilities at very little additional cost.**

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## Nomenclature

EUS = Exploration Upper Stage
GNC = Guidance, Navigation and Control
HEEO = High Earth Elliptical Orbit
ISRU = In-Situ Resources Utilization
IVF = Integrated Vehicle Fluids
JPL = Jet Propulsion Laboratory
LEEP = Lunar Extraction for Extraterrestrial Prospecting
LEO = Low Earth Orbit
LLO = Low Lunar Orbit
LLS = Lunar Landing System
LRS = Lunar Resupply Shuttle
LUS = Large Upper Stage
LV = Launch Vehicle
NASA = National Aeronautics and Space Administration
PRS = Propellant Refueling System
SLS = Space Launch System
TMI = Trans-Mars Injection
TRL = Technology Readiness Level
ZBO = Zero Boil-Off

## I. Introduction

U.S. National Space Policy declares that NASA "will send humans to orbit mars and return them safely," a goal echoed in NASA's strategic plan. The funding follows: today, nearly 19% of the agency's budget supports SLS or Orion, the two most prominent elements of the journey to Mars architecture.[*] The United States is not alone in the goal of Mars. European and Indian satellites currently orbit Mars alongside American counterparts, and 2020 may see the first private departure to Mars in the form of SpaceX's Red Dragon.

To develop the technology and techniques necessary to get to Mars, NASA, in cooperation with international partners, has constructed a roadmap of three phases to prepare for Mars: 1) Earth Reliant missions, 2) Proving Ground missions, and 3) Earth Independent missions. Of these three, the phase of greatest relevance to lunar refueling is Proving Ground.

In late March 2017, NASA announced the Deep Space Gateway to support Mars mission learning objectives.[†] However, the cancellation of the Asteroid Return Mission (ARM) in NASA's FY18 Proposed Budget removes a substantial pillar of the "Proving Ground." At the same time, there is a tremendous opportunity in the commercial space sector by providing the infrastructure that is needed to support the businesses and ventures that drive the global economy. Interest in cis-lunar economy is demonstrated by the interest in the Google Lunar X-Prize, the many private start-ups and proposals, and the tremendous opportunities and wealth of resources found on the moon. Doing a sustained mission on the moon over decades provides an infinite amount of information about how to operate in a harsh environment not only for a two week mission, but for a long duration and sustained presence. Numerous ideas have been proposed, but what is missing is the real, in-situ experience and increased TRL levels.

The Lunar Extraction for Extra-planetary Prospecting (LEEP) mission is the key to unlocking deep space missions, beginning with Mars. LEEP will help NASA, partner agencies, and the private sectors develop critical deep space technologies, starting with in-situ resource utilization, ISRU, and robotics. For NASA, LEEP would provide a “lifeboat” for the first long-duration Orion mission and could enable a 30% increase in payload to Mars for the first human mission.

LEEP is also the first power plant for the solar system. While the costs today are high, it is likely the forerunner for a new industry of providing fuel as a service on orbit. This is the exact same model seen in cloud computing. Physics remains cruel; it takes fuel to lift fuel. Why not outsource? As more entities move into orbit, offering flexible energy and logistics services will be big business, just like it is here on earth. Now is the time and place to learn those skills.

This project’s focus on heritage hardware and increasing TRL-6 level projects to TRL-8 and TRL-9 opens up the options for groups who have made various proposals. From the table below and the entrants to competitions such as the Google Lunar X-Prize, it is clear that no one nation owns interest in going back to the moon. As ESA has suggested with Moon Village, it will take all of humanity to go back and set up permanent off-Earth habitation.

In addition to the mining capabilities that are demonstrated and developed in the LEEP project, capabilities are

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[*] "National Aeronautics and Space Administration FY 2016 Spending Plan for Appropriations Provided by P.L. 114-113," NASA, September 2016. Available online at tps://www.nasa.gov/sites/default/files/atoms/files/fy16_operating_plan_4sept_update_0.pdf.

[†] "Deep Space Gateways to Open Opportunities for Distant Destinations," NASA, March 28, 2017. Available online at https://www.nasa.gov/feature/deep-space-gateway-to-open-opportunities-for-distant-destinations.

enabled for other nations or missions to take part in. There has been tremendous interest in the South Pole as a place for radio astronomy, infrared missions, a test bed for teleoperation, and sustained instrumentation[‡]. This project would set up the infrastructure and raise TRL levels for a wide variety of technologies both on the lunar surface and in orbit. Once assets like communications infrastructure and launch pads start to develop, other missions have an easier time with their early stages and benefit from the lessons learned.

Mars is coming. The research accomplished by the LEEP mission will move humans on the Red Planet from science fiction to science.

## II. Methodology

### A. Mission Statement

LEEP delivers an in-space refueling service to enable deep-space exploration and commercial missions. Fuel is produced from lunar resources using autonomous extraction. The Lunarport also affords to gain knowledge and experience as well as foster international partnerships with institutions and private companies.

### B. Mission Requirements

Table 1 lists the high-level requirements and limitations considered for the mission. Most of the following requirements originate from the statement of work delivered at the beginning of the Caltech Space Challenge.

**Table 2. Mission Requirements.**

| Id. | Objective | Requirement | Type | Origin | Wt. | Rationale |
|---|---|---|---|---|---|---|
| **1.1 Concept & Development** | | | | | | |
| 1.1.1 | Budget | The design, construction and maintenance of the LEEP shall be under $1 billion per year (with unused funds of one year available the next) | Constraint | Originating | 100 | Statement of Work: "The design should include a detailed construction and operation/maintenance plan for the ISRU station, main hub, and refueling subsystems, under the constraint of an annual budget of $1billion (with unused funds of one year available the next)" |
| 1.1.2 | Desirability | The LEEP shall deliver value to the identified beneficiaries | Programmatic | Originating | 100 | Statement of Work |
| 1.1.3 | Economic Viability | The LEEP shall be economically viable | Constraint | Originating | 100 | Statement of Work |
| 1.1.4 | Technical Feasibility | The LEEP shall be technically feasible | Constraint | Originating | 100 | Statement of Work |

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[‡] Davis, G.W. et al. "The Lunar Split Mission: Concepts for Robotically Constructed Lunar Bases." International Lunar Conference, 2005.

| | | | | | | |
|---|---|---|---|---|---|---|
| **1.2 Construction** | | | | | | |
| 1.2.1 | Gain knowledge for future Mars exploration | The LEEP shall help to gain knowledge and experience for future Mars exploration | Programmatic | Originating | 50 | Statement of Work: "Technologies and operation experiences for accessing and utilizing lunar resources are relevant to future Mars exploration." |
| 1.2.2 | Human lunar mission | The LEEP could allow a human mission to the Moon | Incentive Award Fee Criterion | Derived | 30 | |
| 1.2.3 | Time to operation | The LEEP shall be operational no later than 2039. | Constraint | Originating | 100 | Statement of Work |
| **1.3 Operation & Maintenance** | | | | | | |
| 1.3.1 | Commercial mining | The Lunarport could double as a commercial mining base to allow the moon's resources to be exploited. | Incentive Award Fee Criterion | Derived | 30 | Source: (MailOnline, 2016) |
| 1.3.2 | In space fueling competition | LEEP shall fuel the deep-space traveling rocket at a lower cost than a direct mission. | Constraint | Originating | 100 | Statement of Work |
| 1.3.3 | In space fueling for deep-space rockets | LEEP shall fuel deep-space traveling rocket in cis-lunar orbit. | Programmatic | Originating | 100 | Statement of Work |

### C. Concept of Operations and Mission Architecture

Table 2 lists the years and payloads of each launch meant to send the initial equipment for the establishment and construction the lunar base for the LEEP Lunarport. The four different launches are made using Falcon Heavy rocket.

**Table 2. Concept of operations details for LEEP.**

| Launch Year | Deployment |
|---|---|
| 2024 | Power System for $H_2O$ Electrolysis;<br>Station on Rim meant to beam power into the dark crater for extractor units. |
| 2026 | Prospector and Multipurpose Constructor Rovers;<br>Delivery of equipment into a permanently shadowed crater region to prepare for ISRU |
| 2027 | Landing of H2O Extractor Rovers and Electrolytic Processing Equipment |
| 2028 | Delivery of Remaining Extractors for Full Capacity |

Upon completion of the LEEP Lunarport by 2028, operations will ensue to begin fueling deep-space missions, depicted in Fig. 2.

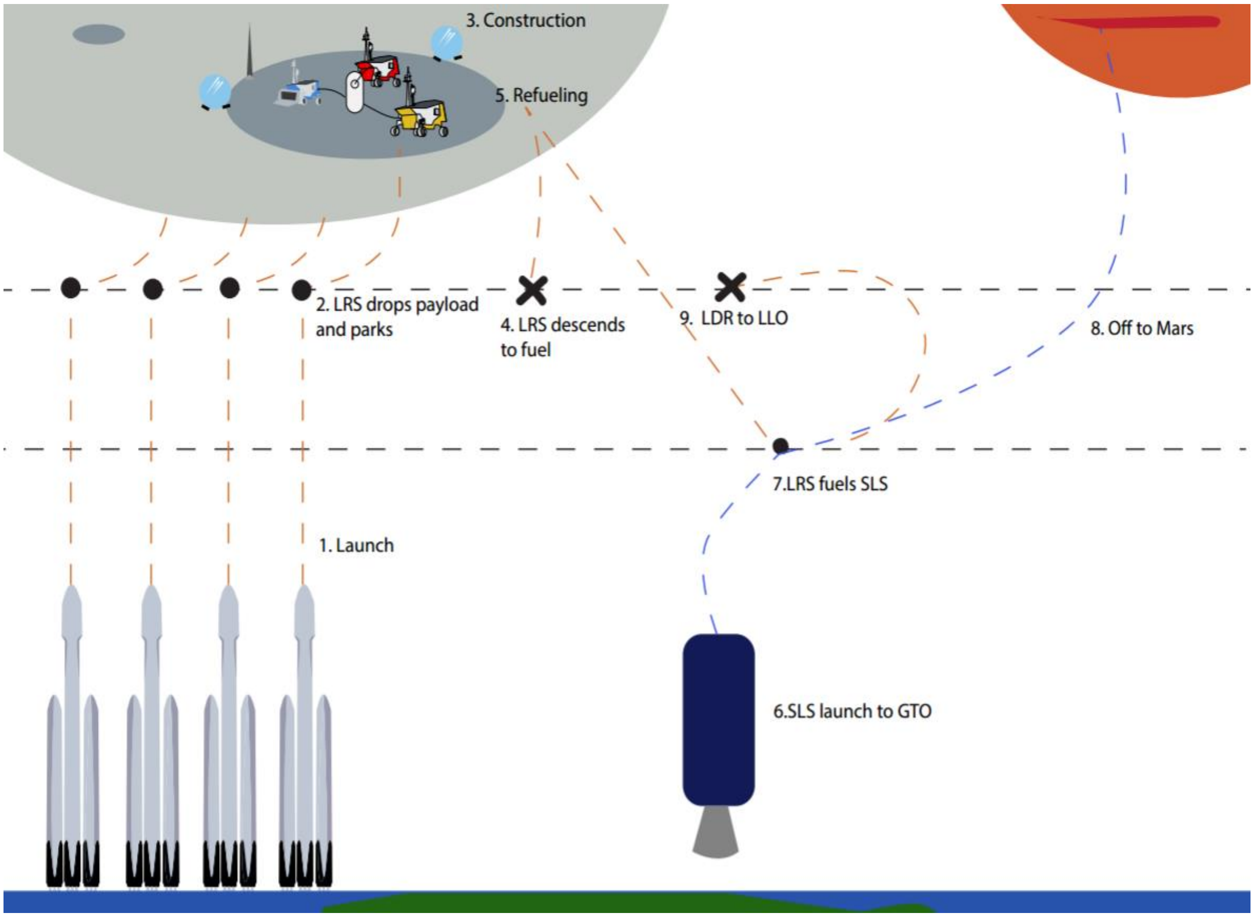


**Figure 2. Concept of operations for LEEP.**

### D. Mission Design Choices

Throughout this study, several trade-offs were considered. Indeed, with the assigned annual $1 billion budget coupled with technologies with varying TRLs, discussions led to comparing different options that were present on different levels of the mission. Table 5 lists the questions being addressed, various options considered and the final decisions chosen, which are bolded and underlined, for main mission design choices.

**Table 5. LEEP Main Trade-Offs**

| Design Decision | Description | Rationale | Option A | Option B | Option C | Option D | Option E | Option F |
|---|---|---|---|---|---|---|---|---|
| **1.** Resource Transfer to Orbit | What resource to transport from LEEP to Space? | Fuel for LRS | **$H_2$ / $O_2$** | $H_2O$ | Other Volatiles | Regolith | Metals | $N_2$ |
| **2.** Rendezvous | Where should LRS intersect with the space craft? | Multiple rendezvous locations; Suits customer; Flexibility | LEO | **High Earth Elliptical Orbit (HEEO)** | LLO | L1 | L2 | LRO |
| **3.** Transfer | What to transfer in orbit? | Second type of payload required for orbit; Simplified operations | **Propellant** | Tanks | Propulsion Stage | | | |
| **4.** Location | Where to locate the LEEP? | Presence of water in Cabeus crater | North Pole | **South Pole** | Equatorial | | | |
| **5.** Conversion | Where to convert H2O to propellant? | Surface temperature allow LOX ZBO - less water needs to be mined; Less mass lifted from lunar surface | Orbit | **Surface** | Orbit/ Surface | LRS | | |
| **6.** Storage | Where to store propellant? | Surface shades | Orbit | **Surface** | Orbit/ Surface | LRS | | |
| **7.** Maintenance Strategy | How to maintain the facility? | Solar panels limit lifetime to 15 years; Must be replaced | Dedicated | **Replacement** | Permanent | | | |

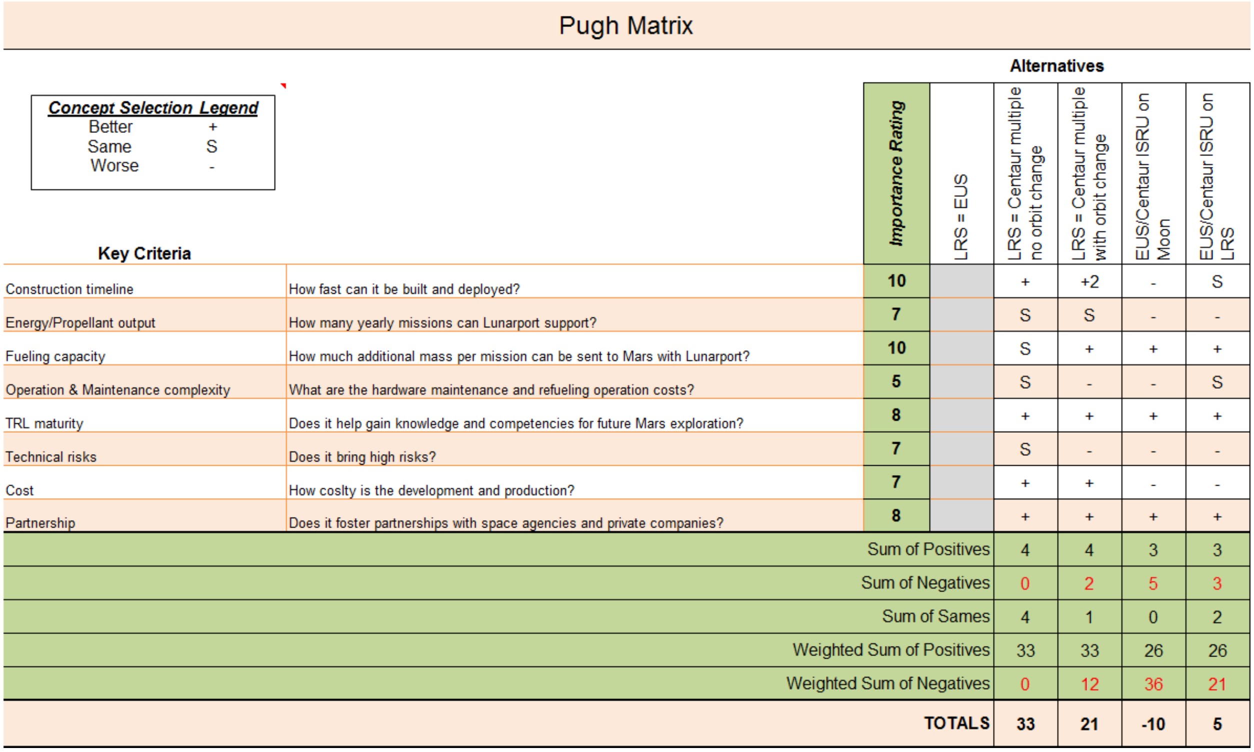
| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **8.** Contractual Arrangement | Which entity will bear the risk and costs of designing and operating LEEP? | Insufficient expected demand for lunar resource on reasonable timescale to entice private investment | **Public** | Public-Private | Private | | | |
| **9.** Power Production | Where to produce power? | Solar concentrators focus light into the dark crater for power | **Ground** | Orbit | | | | |

The criteria that was selected and used for the mission design selection were as follows:

1. **Construction timeline**: How fast can it be built and deployed?
2. **Energy/Propellant output**: How many yearly missions can LEEP support?
3. **Fueling capacity**: How much additional mass per mission can be sent to Mars with LEEP?
4. **Operation & Maintenance complexity**: What are the hardware maintenance and refueling operation costs?
5. **TRL maturity**: Does it help gain knowledge and competencies for future Mars exploration?
6. **Technical risks**: Does it bring high risks?
7. **Cost**: How costly is the development and production?
8. **Partnership**: Does it foster partnerships with space agencies and private companies?

The major mission trade-off involves the selection of the location where to convert $H_2O$ to fuel and where to store fuel. The following 5 options were identified and a Pugh matrix was established, depicted in Fig. 3:

1. ISRU is located on the moon and the Lunar Resupply Shuttle, LRS, is an Exploration Upper Stage, EUS, on the moon. The refuel happens in space. This configuration +30% increase in payload mass.
2. Similar configuration to option 1 but instead of having one EUS, multiple (2 to 4) Centaur vehicles are used on the Moon. This configuration has a benefit of 45% of propellant.
3. In this option, the ISRU is in orbit. The Centaurs constitute the LRS system. They bring brings water into space. Electrolysis and fuel creation happen in orbit. This configuration has a negative balance.
4. This configuration is a mix of option 1 and option 2. Centaurs are on the surface and are launching to refuel an EUS which stays in orbit. The EUS tank is being refueled by those Centaur LRS. The EUS can be seen as a PRS, propellant refueling system. PRS is going to its rendezvous orbit to refuel the specified mission. +70% fuel but needs to extract 2 to 2.5 times faster.
5. This fifth option is mix of option 1, 2 and 3. The ISRU are located in the LRS (Centaurs). The rovers fill the LRS tanks and it prepares just enough propellant to launch. It brings water in orbit to a power station full of solar panels. Then, it starts creating the propellant for the refueling as well as for its return on the Moon. The benefit of this +70% of more fuel but triple the extraction rate. This solution also uses an EUS in orbit as well. Disadvantages: if a Centaur LRS breaks apart, you lose two systems. The main benefit is having no need of an ISRU on the Moon.



Pugh Matrix

**Concept Selection Legend**

| | |
|---|---|
| Better | + |
| Same | S |
| Worse | - |

| Key Criteria | | *Importance Rating* | Alternatives | | | | |
|---|---|---|---|---|---|---|---|
| | | | LRS = EUS | LRS = Centaur multiple no orbit change | LRS = Centaur multiple with orbit change | EUS/Centaur ISRU on Moon | EUS/Centaur ISRU on LRS |
| Construction timeline | How fast can it be built and deployed? | **10** | | + | +2 | - | S |
| Energy/Propellant output | How many yearly missions can Lunarport support? | **7** | | S | S | - | - |
| Fueling capacity | How much additional mass per mission can be sent to Mars with Lunarport? | **10** | | S | + | + | + |
| Operation & Maintenance complexity | What are the hardware maintenance and refueling operation costs? | **5** | | S | - | - | S |
| TRL maturity | Does it help gain knowledge and competencies for future Mars exploration? | **8** | | + | + | + | + |
| Technical risks | Does it bring high risks? | **7** | | S | - | - | - |
| Cost | How coslty is the development and production? | **7** | | + | + | - | - |
| Partnership | Does it foster partnerships with space agencies and private companies? | **8** | | + | + | + | + |
| | | Sum of Positives | | 4 | 4 | 3 | 3 |
| | | Sum of Negatives | | 0 | 2 | 5 | 3 |
| | | Sum of Sames | | 4 | 1 | 0 | 2 |
| | | Weighted Sum of Positives | | 33 | 33 | 26 | 26 |
| | | Weighted Sum of Negatives | | 0 | 12 | 36 | 21 |
| | | **TOTALS** | | **33** | **21** | **-10** | **5** |

**Figure 3. Pugh Matrix highlighting various mission trade-offs.**

LEEP's mission design choice was the 2nd option. However, if interest and investment in the Lunarport is present in the future, the chosen solution can be improved and evolved towards options 3, 4 or 5.

### E. Mission benefits

The primary mission benefits of LEEP for the main stakeholders is summarized in Table 6.

**Table 6. LEEP Primary Mission Benefits**

| Humans | Space Agency | Private Company |
|---|---|---|
| • Open up universe to humanity<br>• Search for life outside Earth | • Explore deep space and minimize launched mass from Earth<br>• Create international partnership with private companies and space agencies<br>• Gain knowledge and competencies on deep space exploration | • Test mining systems<br>• Develop new markets |

# III. Results and Discussion

## A. Ground-Based Operations

Ground operations are conducted to extract water from the icy lunar regolith and process it into cryogenic LOX/LH2 fuel for the refueling tankers. Ground operation deployment consists of four launches:

1. Power System for $H_2O$ Electrolysis (2024)
    - Station on rim to beam power into the dark crater for extractor units.
    - Electrolyzer unit must operate continuously at 70 kW to meet fueling requirements.
2. Prospector and Multipurpose Constructor Rovers (2026)
3. Electrolyzer Unit and Extractor Rovers (2027)
4. Remaining Extractors for Full Capacity (2028)

The first payload is launched in 2024 and deploys solar focusing equipment along the crater rim to illuminate the landing site and provide available power. The second payload delivers four rovers in 2026 into the permanently shadowed crater region, two of which are for construction and maintenance, and two for ice deposit prospecting. The construction/maintenance rover then deploys a solar farm within the crater region to power the in-coming Electrolyzer unit. In 2027 the third ground payload delivers the ISRU electrolysis unit and a first batch of extraction rovers. Water extraction and processing begins. Lessons learned are incorporated into the builds of the second batch of extraction rovers, which are delivered into the crater as the fourth lunar surface payload in 2028, bringing the total number of extraction rovers to twelve and the base to full propellant production capacity.

The delivery sequence of lunar surface equipment requires delivering multiple robotic rovers at once and in the same location. This is done with a larger version of a typical retrorocket descent rover deployment shell called the Lunar Landing System, LLS. The LLS consists of a platform, capable of receiving a modular payload that has an integrated hypergolic bipropellant propulsion system intended for one-time use and designed to be as versatile as possible when it comes to delivering equipment to the lunar surface. The propulsion system is an Aerozine 50/$N_2O_4$ hypergolic system. Three kinds of equipment are delivered. On the crater rim, two LLS's carrying 5 folded solar focusing mirrors each land in typically lit regions. These deploy to their determined locations and focus solar light into the crater. The used landing system then deploys a parabolic dish for direct-to-Earth communications.

An LLS with two prospecting rovers and two construction rovers land within the volatile-rich darkened region of Cabeus crater. The constructors prepare crater base for the LRS, to land by clearing loose regolith with a bulldozer. The ISRU $H_2O$ processing unit lands with retrorockets on a modified LLS without any rovers, and a total of twelve extractor rovers are deployed in two LLS runs. It's estimated that each extractor rover can mine and deliver to the Electrolyzer unit 40 kg/day of $H_2O$ when equipped with four Honeybee Robotics PVEx coring devices. Once the base is fully deployed in 2028 as described, it can extract and process 90 mT of $H_2O$ per year with an Electrolyzer unit operating at 70 kW (assuming 35 kW of water splitting power from 50% efficiency). This meets the 60 mT of propellant required for an EUS refuel mission with ample margin for problems with extractors and for $LH_2$ boil-off problems.

## B. Space Operations

LEEP's primary mission is to refuel spacecraft in cis-lunar space. To do so, it uses modified Centaur upper stages as LRSs. These Centaurs are modified with composite landing legs, enhanced GNC systems, United Launch Alliance's integrated vehicle fluids, IVF, system for reducing boil-off and vehicle complexity, and other modifications (e.g. solar panels) as necessary depending on the performance of the IVF system. These Centaurs are refueled on the lunar surface by an ISRU, then launch into LLO, transfer to a low-periapsis elliptical orbit around the Earth, rendezvous with a craft to be refueled, transfer their excess fuel, and then return to the lunar surface.

The use of Centaurs leverages a mature and proven technology to decrease development costs and increase reliability of the process, and the use of multiple smaller refueling vehicles adds redundancy and fault tolerance to LEEP's ability to conduct refueling operations, reducing the risk associated with putting a vehicle in orbit and trusting that LEEP will be able to resupply it. Using Centaurs and refueling the Large Upper Stage, LUS, of the SLS computational analysis tools were developed to determine the ideal rendezvous orbit. Figure 3 illustrates the results of optimizing rendezvous orbits for refueling an LUS using various numbers of Centaur LRSs.

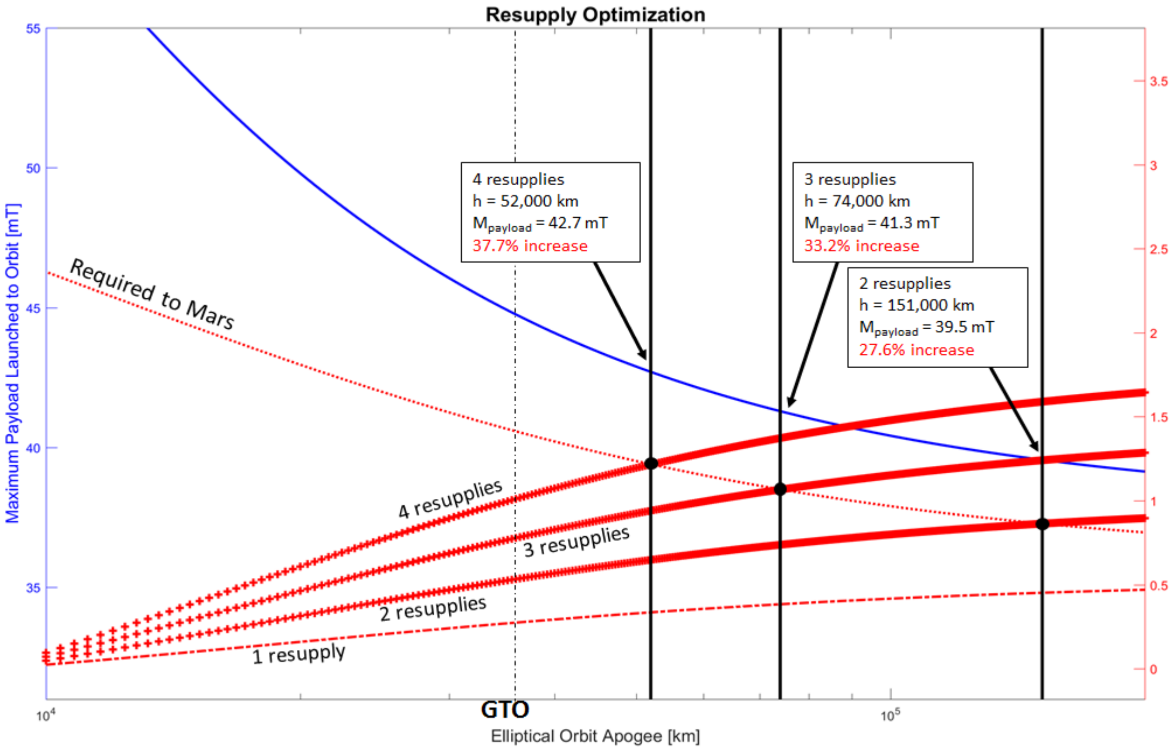


**Figure 3. Trajectory Optimization Analysis.**

The optimal solution is to send two refueling vehicles, because sending more LRSs represents a very large investment in propellant production operations but does not result in a comparably large increase in payload. This suggests that increase in mass sent to Trans-Mars Injection, TMI is approximately 28%. Keeping in mind that each payload mass includes the empty mass of the LUS, the increase in usable payload is over 45%. Sending smaller payloads to more energetic orbits more fully utilize LEEP's capabilities than sending large payloads to less energetic orbits.

### C. Economics & Schedule

The total non-recurring cost for LEEP is approximately \$10.2B and the estimated average recurring annual cost is \$80M per year. The development of the system is spread over 12 years. The break-even point when only considering single-launch SLS missions to TMI is 37 launches, or ~1200 mT, depicted in Fig. 4. However, the benefit to missions to the outer planets could see significantly larger increases in payload capacity and increased value.

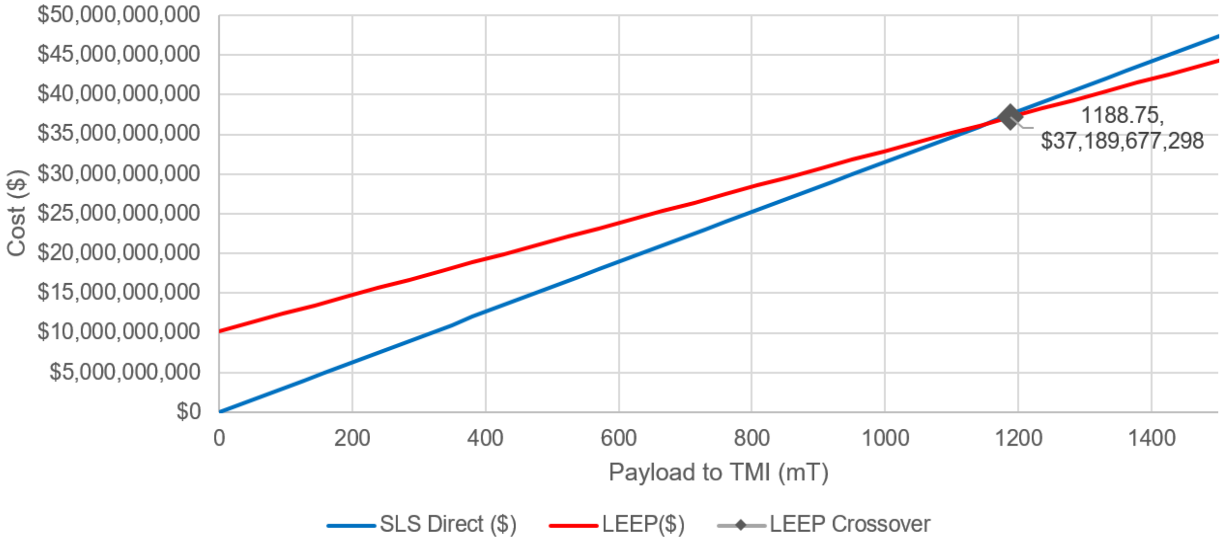


**Figure 4. Cost vs Payload to TMI.**

The development of technologies and hardware takes place over 12 years. The cost has been spread over this period to meet budget constraints and realistic development times. System reviews have been scheduled during this period, as portrayed in Fig. 5.

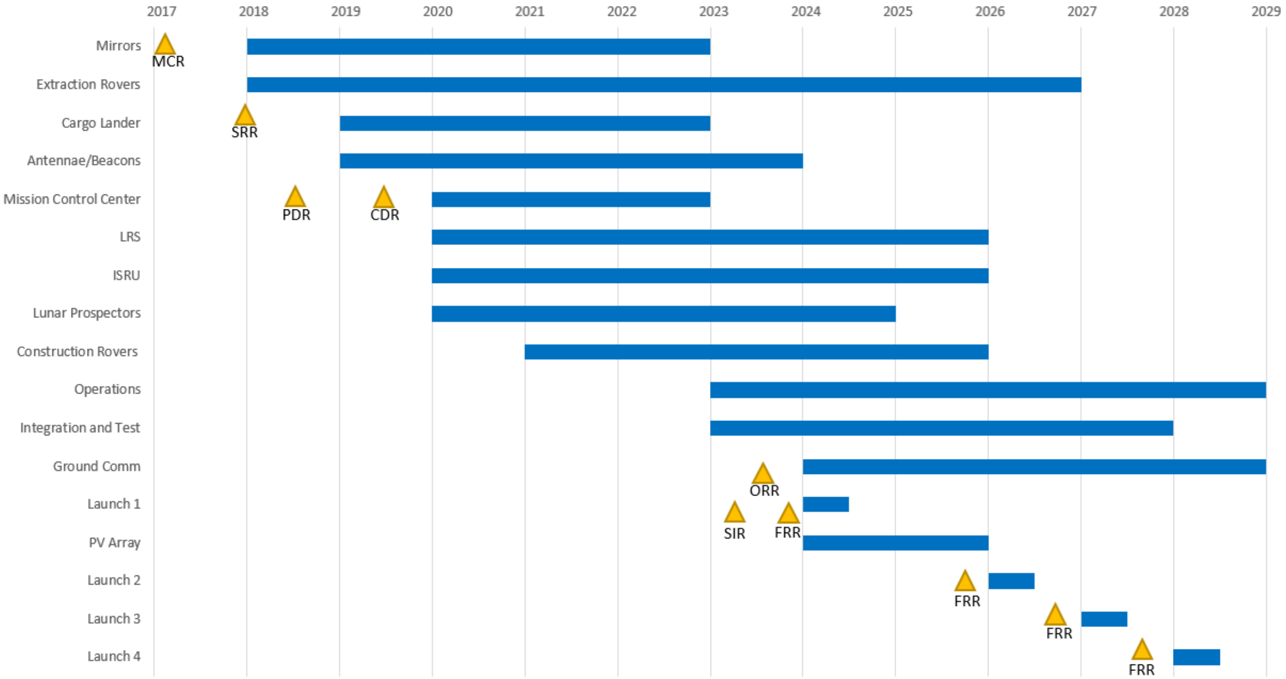


**Figure 5. Design Schedule.**

## D. Future expansion

LEEP was conceptualized in the context of a tight schedule (boots on Mars by the end of the 2030s) and a small budget ($1 billion per year). Because of these constraints, prospective innovations were not taken advantage of innovations such as electric propulsion, small modular nuclear reactors, nuclear thermal rockets, and similar technologies. However, LEEP could be upgraded with these technologies as they become available and costs decrease. Its modular architecture makes LEEP an excellent platform for continual improvement as new technologies become available, and provides an already-in-place infrastructure that allows for easy deployment and utilization of new technologies.

### E. Concept Feasibility and Risk Analysis

The LEEP annual cost is capped at $1B, but extra funds can be saved for future year's development. This is a significant benefit because it allows cost spreading without losing efficiency so that resources are allocated appropriately for early concept development through fabrication, testing, and assembly. The LEEP team determined the total system lifecycle cost using engineering build-up phasing based on the lunar emplacement schedule and required development to meet it.

The program cost will peak in 2024 at $1.67B when the first deployment mission happens. By 2029 LEEP only requires continuing steady-state operations where the program will also prepare for resupply missions which may cause relatively small increases.

The cumulative cost over time, starting in 2018, does not match the available budget due to the spending peak. The figure above shows both the LEEP cumulative cost and the maximum possible cost ($1B x years). While the annual budget is underutilized in the early years of development, by 2026, the banked resources will be accounted for. The difference for future projects can then be used for alternative projects as the annual costs are only a fraction of the $1B. Cumulative costs over the duration of LEEP operations are depicted in Fig. 6.

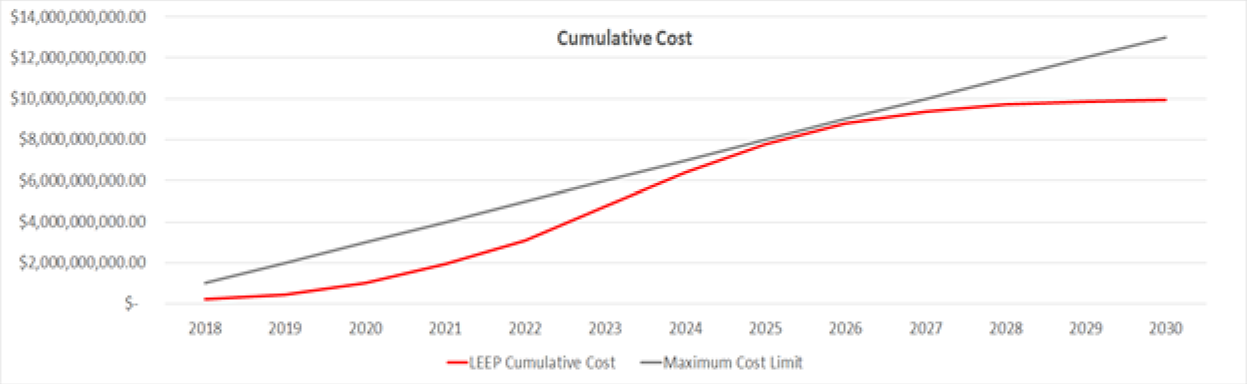


**Figure 6. Cumulative Cost over the years.**

## IV. Conclusion

LEEP is able to provide fuel as a service for deep space missions. This fueling service serves as an integral step towards future manned missions to Mars but can also provide a leap into the outer solar system and beyond. Our modular system can accommodate various supply needs. It also allows for various upgrades and advances in technology to be easily installed into the LEEP infrastructure, if any were made during the duration of operations.

Both the public and private sector can benefit from our service. The initial mission for LEEP was to prove our system could improve current methods on getting to Mars by the 2030's, which was accomplished. The overall mission, however, can be expanded upon by the private sector to fuel various types of missions in space. LEEP can also help to promote public-private partnerships. Thus, if public and private sectors utilize our system, they can expand the capabilities of the system allowing it to provide services for a wide range of applications in space.

Our solution to the problem given is to provide a practical system comprised of high-TRL technologies and devices while staying under budget throughout the entire process.

## Acknowledgments

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## Reference

The final paper, which includes all of the references properly cited for this work, and presentation from this competition can be found at: http://www.spacechallenge.caltech.edu/final-results.