Shackleton Energy Company's Propellant Depot and Space Transportation Architecture

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ABSTRACT

The aim of this article is to provide a review of the architecture and business for the first commercial propellant depots to be deployed in space within a decade. The capability to refuel spacecraft in low Earth orbit (LEO) underpins a paradigm shift that considerably decreases cost and increases the mass of spacecraft hardware possible per launch because of the reduction of onboard propellant requirements. This same refueling capability also enables repeated long-duration high-thrust missions for commerce, exploration, and security to be carried out at superior price-performance, resulting from extensive reuse of in-space vehicles and systems. Shackleton Energy Company is establishing initial propellant depots in LEO using propellants launched from Earth to commence sales and deliveries within 5 years from program start, followed by deliveries of water-derived propellants from the lunar poles within an additional 5 years. By sourcing the propellant from the Moon's lower energy gravity well, significant reductions in operating costs are possible, with additional infrastructure costs amortized over multiple sales cycles. The most readily accessible and operationally robust source of cryogenic liquid oxygen and liquid hydrogen is from the craters situated at the poles of the Moon, in the original form of water ice.

INTRODUCTION

Shackleton Energy Company (SEC) is embarking on an industrial program establishing propellant depots in space for commercial and governmental customers using fuel sourced from vast water ice deposits at the north and south poles of the Moon. Low-cost propellants in space will change the way space launch providers operate today, greatly reducing the cost to operate beyond low Earth orbit (LEO) and stimulating a new-age Gold Rush off of Earth not only for lunar ice but also for minerals and other resources that can be leveraged for financial and societal benefit. Gold opened the American West in the mid-19th century, and lunar ice will similarly open cislunar space by the early 2020s by fueling the space frontier.

The establishment of lunar-sourced propellant depots represents a significant business opportunity that will be implemented with private investment to ensure that cost, schedule, performance, and risk are managed effectively, providing the fastest delivery to market. The programmatic, technical, and regulatory risks are known, and successful implementation will lead to significant financial and societal rewards. SEC's detailed and proprietary enterprise model conservatively forecasts hundreds of billions of dollars in revenues over a 20-year operational timescale, with initial revenues from federal and commercial customers occurring within 36 months of program start.

A spacecraft maneuvering from LEO to geostationary transfer orbit will consume 42% of its initial mass in LEO as propellant.[1] For higher orbits, the propellant burden from LEO is even greater, as can be seen in *Table 1*. Therefore, the capability to refuel spacecraft in LEO underpins a paradigm shift that considerably increases the mass of useful spacecraft hardware possible per launch because of the reduction of onboard propellant requirements.

Table 1. Required Propellant Mass as a Percentage of LEO System Mass for Various Typical Missions Assuming State-of-the-Art LO_2/LH_2 Propulsion[1]

Final Orbit	% Propellant Mass
GTO	42
Trans-lunar injection	50
Trans-Mars injection	60
GSO	61
Lunar surface	75

GSO, geosynchronous orbit; GTO, geostationary transfer orbit; LEO, low Earth orbit; LH_2, liquid hydrogen; LO_2, liquid oxygen.

The combined advantages of cryogenic propellant refueling capability sourced from lower energy and operationally accessible locations mean that access to lunar-sourced water becomes an essential requirement for expanding infrastructure off Earth. Building upon early sales from first-generation depots, SEC will harvest this readily available, abundant supply of natural resource as the feedstock for extensive propellant production by building the world's first full-scale refueling stations at strategic locations in LEO and beyond to provide significant cost savings to customers operating in space.

Our extensive analysis shows that the business case closes profitably within a decade, with first revenues generated 36 months from program start. Following break-even, additional integrated business streams enable exponential growth as a purely commercial venture. As such, SEC is now actively engaging investors and strategic partners to undertake initial risk reduction activities as milestones on the path to program implementation. In order to achieve first-to-market

DOI: 10.1089/space.2013.0014

advantage, concurrent program planning and execution are essential, with the best talent and technology available worldwide.

This is a challenging undertaking that draws on existing best practices from the aerospace, mining, and energy industries. Current know-how in many technology fields will be utilized, and a number of proprietary new technologies currently at low technology readiness levels (TRL) will be developed throughout the course of the program. These will include developments in propulsion, communications, cryogenics production and fluid transfer, ultracold materials, electronics and fluids response, and biomedical and simulation technologies. New materials, remote mining methods in extremely cold operating temperatures, and life-support systems including teleassisted medicine for long-duration human space operations will also be utilized. The terrestrial spinoff opportunities arising from the intellectual property developed are likely to be numerous; the successful operation of propellant depots will underpin the creation of many new businesses in space providing additional economic growth and societal benefit.

PROGRAM OVERVIEW

SEC's team originates from exceptional engineering and expeditionary heritage and has laid the foundation for the establishment of an end-to-end supply chain for propellant provisioning (depots), supply (tankers and refineries), and source (lunar operations). The program is structured over four major risk reduction phases, each consisting of multiple success-driven milestones.

PHASE 1: PRELIMINARY DESIGN

This phase consists of detailed planning and design of all system elements, specific technology risk reduction, customer outreach and integration, regulatory coordination, and capital structuring. A highly detailed work breakdown structure has been constructed and team positions have been defined. The results from this 18-month foundation phase will be directly driven into the Phase 2 Prospecting and Phase 3 Infrastructure programs on concurrent fast tracks. SEC's design philosophy is to build robust, resilient, and redundant modular components on an industrial production line, minimizing clean room fabrication where possible; extraction vehicles on the lunar surface or depots undertaking many cycles of refueling will experience operational burdens usually found in the oil exploration and mining sectors. Therefore, a high degree of system redundancy is planned with a plug-and-play architecture that allows modular components to be rapidly assembled in space to provide multiple spacecraft configurations for various mission profiles. Once operational in space, SEC will provide a full spectrum of capability and services for all spacefarers, including those new space asteroid mining and tourist companies now building hardware for launch. SEC intends to become the central hub for provisioning and transportation for all human expeditions beyond LEO.

In order to accomplish the program within a serviceable capital budget, all spacecraft within the architecture must be designed to be completely reuseable, which is much easier to accomplish for LEO and on the Moon than it is for Earth-to-LEO transport. High upfront costs will be required to construct the system with capital assets to include depots, tankers, power generation, transportation, habitation, and surface operations units forming a mining/exploration outpost with access to abundant sources of sunlight at the lunar poles. This cost will be amortized over a period of increasing sales of propellant. An investigation of trade spaces has shown that in-space refueling with a modular spacecraft structure utilizing refuelable tugs is the optimum architecture for servicing multiple missions and assembly tasks.[2]

PHASE 2: ROBOTIC LUNAR PROSPECTING

To build upon the data already obtained by international lunar orbiting missions, SEC will build, test, launch, and operate several rovers that will continuously prospect for water ice and other volatiles and then generate *in situ* assay maps in selected lunar craters for the duration of the prospecting missions. SEC intends to launch multiple rovers to the lunar poles, employing production design principles of the main architecture, to provide maximum prospecting coverage, while system and subsystem redundancy will be utilized to ensure fail-safe operations (*Fig. 1*). A seasoned mission-planning team with access to all known lunar data has already been assembled. Our team includes highly qualified and respected lunar scientists, engineers, and leaders who are veterans of previous NASA lunar missions ready to assist in the mission planning using the most current and relevant lunar data. Cooperation with NASA scientists and operators is being coordinated through a Space Act Agreement with all NASA centers.

PHASE 3: INFRASTRUCTURE DEVELOPMENT

In Phase 3 (*Fig. 2*), SEC will develop, test, and space-qualify mission-essential elements required in Phase 4 (Operations). These risk reduction elements include both in-space and lunar surface capabilities. Common system elements to be defined include power provisioning, lunar surface mining and processing equipment, in-space transport systems, life support systems with teleassisted medicine, and a LEO space operations center with inflatable systems for a variety of applications. Inflatable systems include both manned and unmanned transport spacecraft, space/lunar habitats, work facilities, staging areas, and fuel storage. Additionally, role-specific components will be developed, such as aerobraking systems to assist in orbital insertion as the large water tanker transporters arriving from the Moon rendezvous with LEO and other fuel depots, thus reducing the cost of operations and fuel consumption. Lunar to LEO aerobraking is absolutely essential to mission accomplishment and business case closure. Much of this infrastructure will share common components and systems enabling increased production engineering and consequently reducing individual vehicle costs.[3]

To create customer awareness, build confidence, and meet their mission needs, subscale prototype depots will be inserted into LEO to provide early propellant deliveries within 5 years from program start. This introductory system will provide early revenue streams to offset capital expenses. SEC will initially provide liquid oxygen (LO_2) and liquid hydrogen (LH_2) to the LEO depot to start operations. Thereafter,

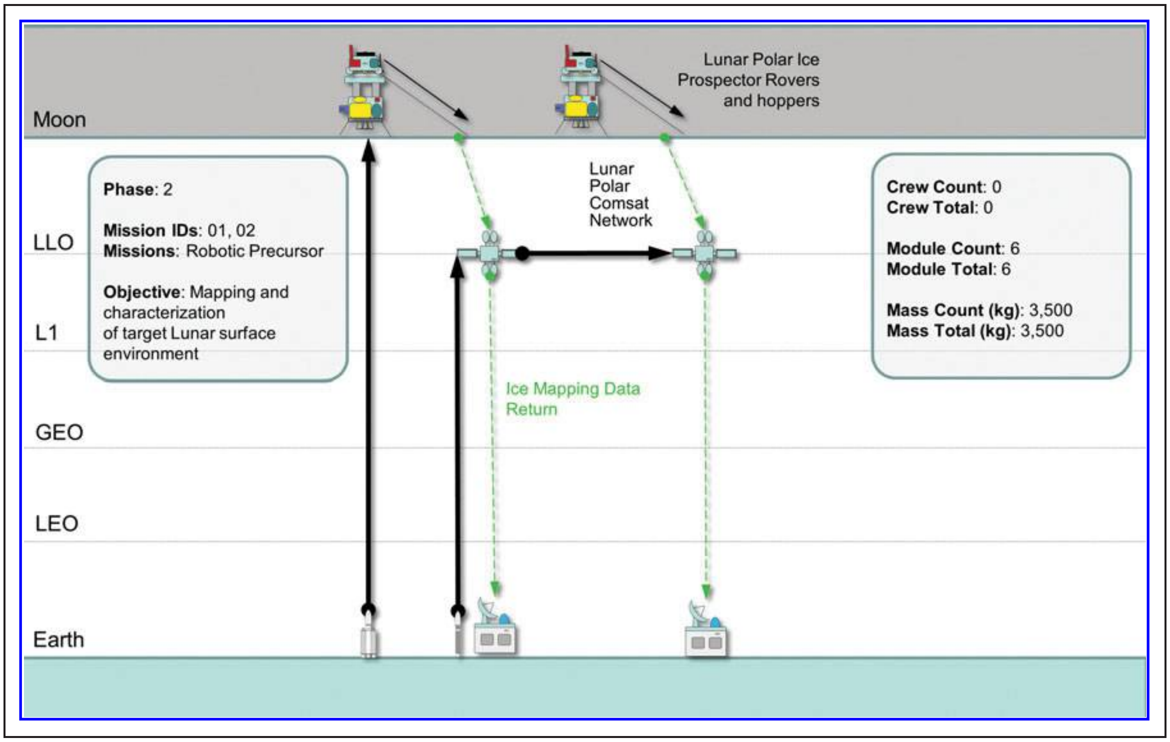

Fig. 1. Phase 2 Lunar Prospecting consisting of semi-autonomous rover missions for the identification of location and composition of highest yield ice deposits inside target lunar polar craters.

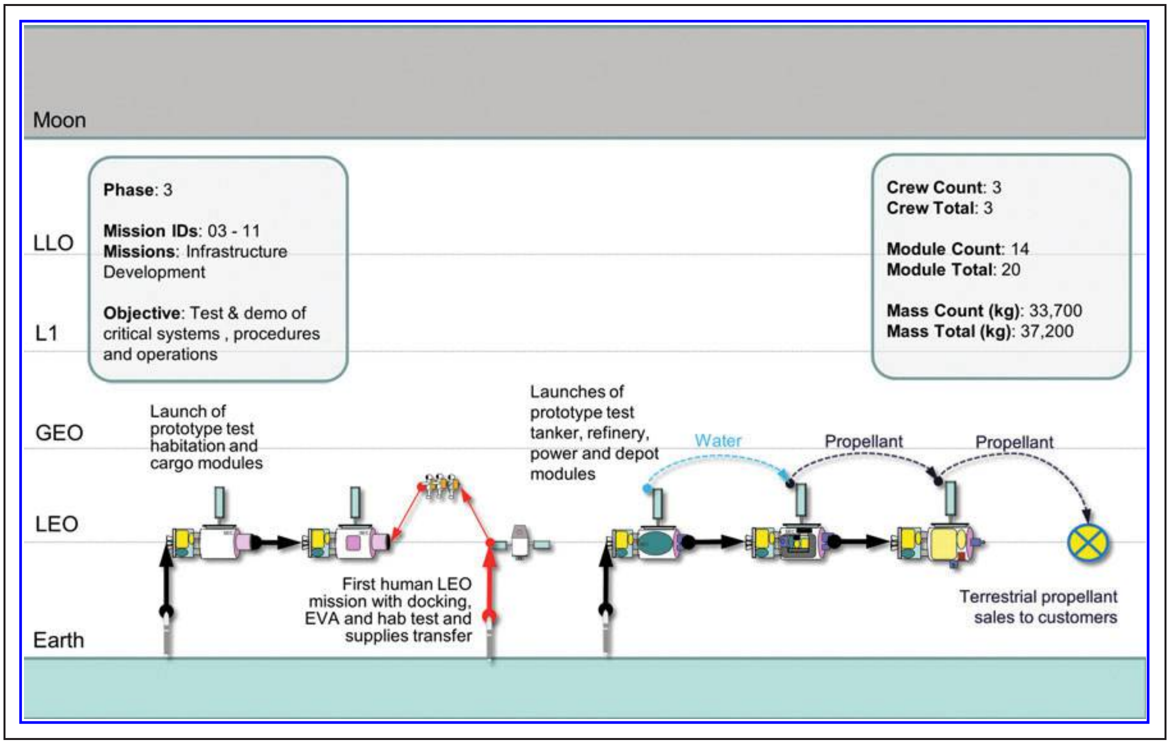

Fig. 2. Phase 3 Infrastructure deployment. Production line development of interchangeable spacecraft components will herald an industrial scale approach to space infrastructure.

water will be launched to LEO for conversion to LO_2 and LH_2 using prototype refining systems that will mature over time for industrial-scale production. The activities carried out in Phase 3 will raise TRLs for refining, storage, and transfer issues to a high level of confidence and safety, enabling SEC to conduct refining operations at scale when water is delivered from the Moon in Phase 4.

Several baseline studies for cryogenic depots have already been carried out by the industry, and NASA is undertaking risk reduction technology demonstration via the Cryogenic Propellant Storage & Transfer (CPST) program. CPST's objectives are to demonstrate the capability to store, transfer, and measure cryogenic propellants. In the same manner that SEC engages personnel and uses data from the LCROSS, LRO, and other NASA missions as precursor risk reduction for water ice location, CPST will also provide early data applicable to SEC's architecture. In coordination with the CPST program outcomes, SEC is also currently working with partners for the development of the first-generation depots in Phase 3, though details of these relationships cannot currently be disclosed.

Building upon the presence of first-generation depots in LEO, a fleet of spacecraft will then be developed to establish the full supply chain of low-cost propellant provisioning. Transport of water from the lunar surface to LEO via low lunar orbit (LLO) with or without tank exchange at LLO will be undertaken by modular tankers supplying refining vehicles that will process water liquefaction to constituent LO_2 and LH_2. With current technologies, boil-off rates for LH_2 can be reduced to around 0.1% per day.[1] Further reduction in boil-off of both LO_2 and LH_2 can be achieved at a system level by delaying the liquefaction of source water in the storage tankers. Sufficient thermal control for boil-off mitigation has already been demonstrated in preliminary ground system tests.[4] With active thermal control on second-generation depots, boil-off can be reduced to zero[5] although early mission scenarios can accommodate low boil-off rates.

PHASE 4: PRODUCTION, MINING, AND OPERATIONS

Once developed to satisfactory levels of readiness (which will include orbital testing in all cases), each vehicle module will be incorporated as a baseline system in Phase 4. Extensive use of existing capability (e.g., lessons learned, technology, safety procedures, human operations, test infrastructure) from NASA will reduce programmatic risk and defray investment costs in Phases 3 and 4.

The industrial architecture required for the establishment of a full propellant supply chain includes the establishment of significant in-space and lunar surface components (*Fig. 3*). By utilizing fully interchangeable common structures for basic spacecraft types, nonrecurring engineering costs can be drastically reduced as production engineering methods are increasingly utilized.[3]

Transportation and storage vehicles with common propulsion system units, inflatable cores, common power, and life support capabilities will be deployed ready for setup and utilization.

As soon as the primary operational architecture has been deployed, SEC's crew will be deployed in space to the LEO

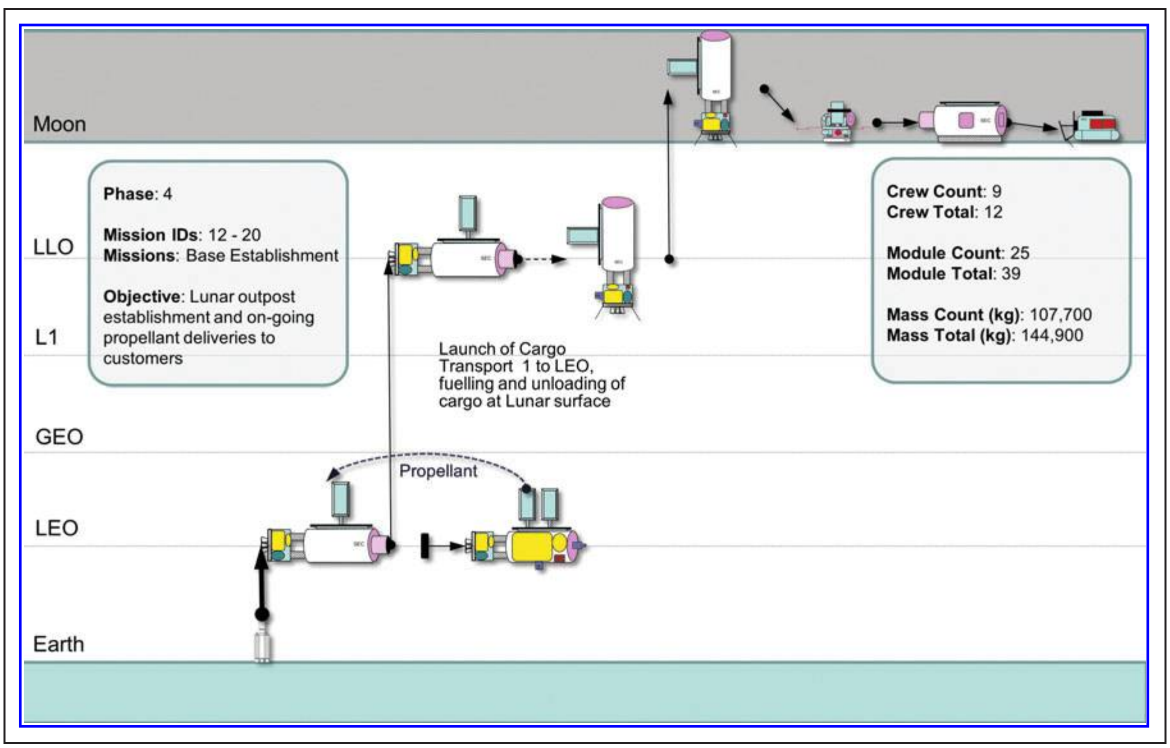

Fig. 3. Functional components of Phase 4 architecture will be deployed in space and on the lunar surface before industrial crew arrival.

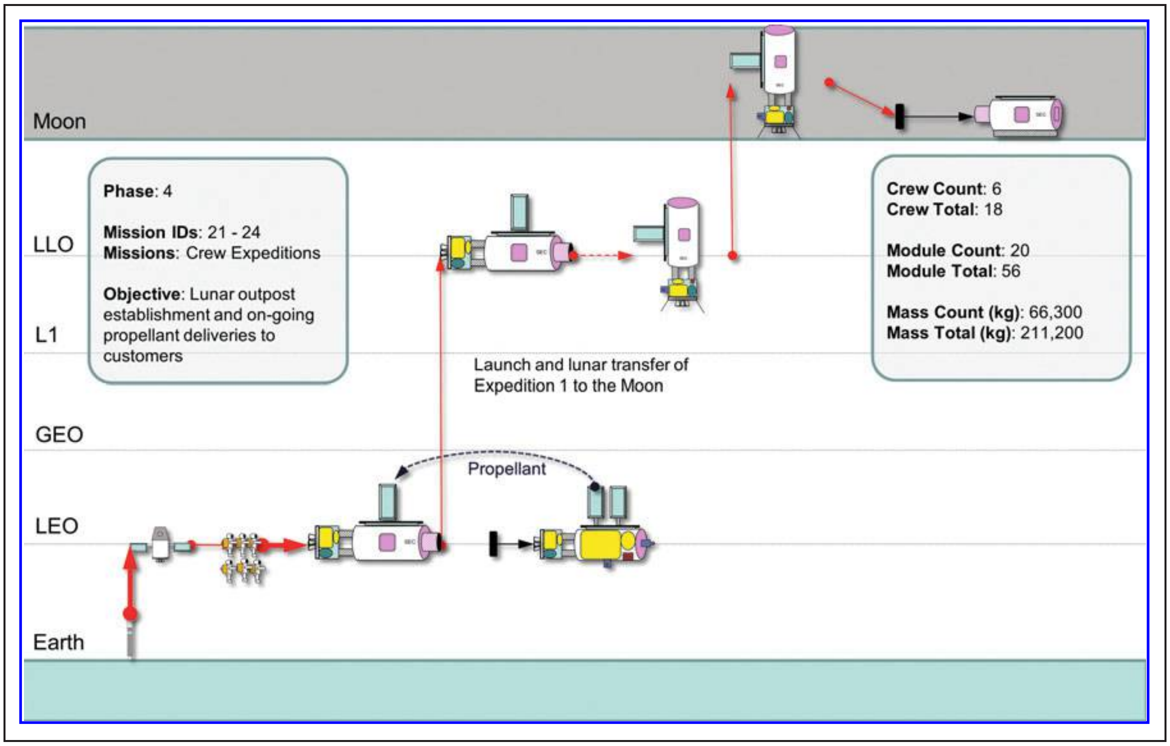

Fig. 4. Deployment of Shackleton Energy's industrial crew in space and on the lunar surface to begin and maintain production operations to schedule.

Operations Center and the first lunar outpost at the selected lunar pole (*Fig. 4*). Undertaking critical testing and checkout remotely further reduces program risk, enabling the crew to concentrate on operations once production is underway. For any industrial operation, real-time maintenance will be required on location. By maintaining a crew on location for mission critical repairs and addressing vehicle and equipment failures, the probability for successful delivery of water to the in-space depots is dramatically improved.

With production facilities in place at the lunar polar base, and the first propellant depots ready for operations, the full supply chain of water tankers between the lunar surface and orbital depots will commence (*Fig. 5*). Water extraction operations will occur based upon data received during Phase 2 of the program to ascertain the highest yields and composition of ice in the craters. Design of mining and processing facilities in Phase 3 will be undertaken by SEC's lunar mining operations in readiness for Phase 4 operations.

Water-carrying tankers will return to LEO on a 90-day aerobraking cycle to conserve propellant. As mentioned earlier, this capability is absolutely essential to close the SEC business case. Delaying refining of water to cryogenic propellant for as long as possible before customer delivery significantly reduces the operational impact of LO_2 and LH_2 boil-off. Once water has been transferred, the tankers return to LLO and the lunar surface. Every mission to and from the Moon to LEO will be optimized for provisioning, equipment transport, and other logistics support needs.

The tankers will be fueled in LEO and, following a trans-lunar injection burn, will be placed into an escape velocity trajectory. With minor midcourse corrections as necessary, a third burn will be required to enter into a circular, 100 km nominal altitude parking orbit from which the landing can be planned. A final sustained burn is required to deorbit and land the craft or transfer water tank to a lander depending on configuration. These maneuvers can be summarized with the following ΔVs from the rocket equation:

$$Q = M_{spacecraft+payload} \cdot \left(e^{\frac{\Delta V}{I_{sp} \cdot g_0}} - 1\right) \quad (1)$$

where
Q = propellant mass, kg
M = vehicle mass (unfueled), kg
I_{sp} = specific impulse (a measure of the effectiveness of fuels), seconds
g_0 = gravitational acceleration constant (9.807 m/s^2)
e = constant = 2.718
ΔV = velocity change increment (m/s)

The amount of propellant needed (Eq. 1) for the mission (which amounts to 80% of the mission mass budget) is related not only to the amount of ΔV needed, but also to the dry mass of the spacecraft and its nonstructural cargo, as well as to the energetics of the propellant (*Table 2*).

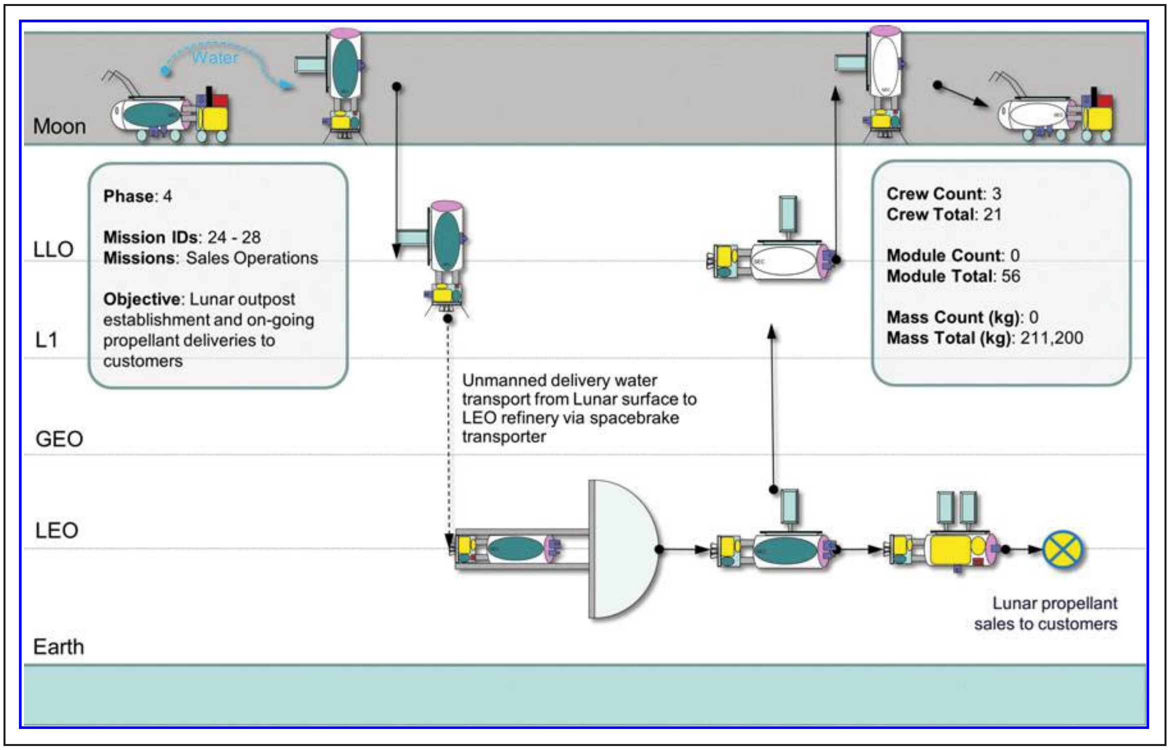

Fig. 5. Water tanker transportation supply chain and delivery to propellant depots.

The mission cost is directly controlled by the mass budget and the technology utilized, which is accounted for by the kilogram. A significant reduction in the system dry mass of the vehicle will have a linear effect also on the propellant mass. It is for this reason that inordinate amounts of effort are spent on lightweight composites and other advanced methods of structural optimization. The energetics of the propellant, on the other hand, have an *exponential* effect on the amount of propellant required. At present, the most optimum chemical mix that has been developed is LO_2 and LH_2. Not surprisingly, this combination was used on the *Apollo* upper stage boosters as well as in the space shuttle main engines. Its use for lunar cycling missions is unavoidable at this time. Consequently, the identification of over 1 billion tonnes of water ice at the lunar poles has dramatically validated the logistics (and profitability) of SEC's program architecture.

Table 2. LEO to Moon ΔV Budget

Trajectory	ΔV (km/s)
Trans-lunar injection from LEO	3.15
Mid-course correction	0.05
Lunar circularization at 100 km	0.85
Lunar landing	1.63
Total	5.68

The high probability identification of water ice at the lunar poles emerged in several stages. During the 1990s, two robotic science missions were sent to the Moon. Both involved the use of small orbiting spacecraft. These were the 1994 joint DoD-NASA Clementine mission and the 1998–1999 NASA Lunar Prospector mission. The former used an improvised radio experiment to infer the presence of ice at the South Pole of the Moon. The latter used a neutron spectrometer to infer the presence of hydrogen, particularly at the South Pole region of the Moon. Since that time, several new lunar polar orbiting science spacecraft have been launched, including Chandrayaan (India) and Lunar Reconnaissance Orbiter (LRO; United States). Experiments measured lunar polar lighting, surface temperatures, and other properties to map areas that could contain water ice. The LCROSS penetrator experiment launched with LRO was successfully deployed and impacted a permanently shadowed area near the South Pole. Combined data from these missions indicate approximately 1 billion metric tonnes of water ice at the South Pole of the Moon and 600 million metric tonnes at the North Pole. Since no *in situ* prospecting for ice has ever been undertaken on the Moon, this is undertaken in Phase 2 as described earlier in order to determine the character, quality, and yield of the ore, which in turn impacts system design of the mining and extraction systems developed in Phase 3 (infrastructure development) and deployed in Phase 4 (operations).

As outlined earlier, a component of the SEC risk reduction plan will involve sending industrial robotic rovers to the floor of

Shackleton crater and other polar craters to create proprietary 3D resource maps of the highest yield locations. SEC rovers will be designed for long-term presence, comprehensive characterization of each targeted crater, and the ability to transfer to neighboring high-priority craters. We anticipate, based on the analysis of C1 chondrite asteroidal material and comets and also the ejecta plume from the LCROSS Centaur stage impact in the lunar South Pole crater of Cabeus,[6] that water ice will be the predominate volatile present, but there very likely will also be present usable quantities of carbon dioxide (CO_2); carbon monoxide (CO); ammonia (NH_3); methanol (CH_3OH); and methane (CH_4), all of which will be useful building blocks for in-demand consumables. The concentration of water ice in the regolith at the LCROSS impact site is estimated to be over 5%.[6] The SEC lunar prospectors will be highly mobile, reliable, and equipped with sophisticated sensor suites to systematically and comprehensively prospect for volatiles of interest.

Once the tanker has been loaded with water for transport and its propulsion system fueled with LO_2 and LH_2 at the lunar surface, the vehicle will then lift off to a direct lunar-escape and earth-capture trajectory. As before there will be midcourse corrections. As Earth is approached, however, a different problem exists when going to the Moon: the excess velocity that was originally necessary to leave the Earth's gravity well, amounting to a significant 3.15 km/s. This energy has to be dissipated in any event to return to Earth. However, the objective at return is to align in a parking orbit with our depots to supply customers with propellant. One example of delivery points for propellant and water is the International Space Station (ISS). The ISS typically requires over 3 tonnes of propellant per year for maneuvering and reboost and about 1 tonne of water.[7] Although representing a small niche, using SEC spacecraft for reboosting ISS with lunar-sourced propellant would represent an anchor client for closing the delivery supply chain.

To rendezvous with the ISS on a return from the Moon, those 3 km/s need to be dissipated then followed by the necessary maneuvers to the ISS. The first operation can be done with aerobraking maneuvers saving significant amounts of propellant. This has been done since the inception of the space program, but is known more commonly as re-entry. However, for ΔV dissipation we are not reentering to the surface of the Earth in this case. The tanker will graze the Earth's atmosphere just long enough to dissipate those 3.15 km/s of excess velocity, whereupon the vehicle skips out the other side and back into orbit. It requires great precision and high-speed active control of the vehicle.

The aerobrake maneuver places the tanker in an eccentric orbit, with perigee coinciding with the low point of the atmospheric pass and apogee coinciding with the ISS. Such precise timing and positioning is achievable with today's onboard processors and positioning systems. At apogee the barge must fire its engines (the first time since the midcourse correction burn) in order to boost the perigee to ISS altitude. From that point on, only minor orbital maneuvering need be done to dock and/or park the barge in the vicinity of the ISS, completing the return trajectory. The energy balance for the return trip is as follows (*Table 3*):

Table 3. Moon to LEO ΔV Budget

Trajectory	ΔV (km/s)
Trans-earth injection from lunar surface	2.37
Mid-course correction	0.05
Aerobrake (−3.15 km/s)	No propellant cost
ISS circularization burn	0.11
LEO maneuvering and docking	0.05
Total	2.58

ISS, International Space Station.

Notice the difference between this number and the amount of propellant related ΔV needed to go from LEO to the Moon presented above (5.68 km/s), providing a significant resource and cost saving for the heavily laden return leg of the propellant supply chain.

SEC BUSINESS MODEL

Building up from these very simplest of calculations as illustrations, SEC has expanded the mission planning, mass modeling, and systems engineering for the entire architecture over a 30-year operational period modeling in great detail depots, transport vehicles, life support, lunar operations, and delivery. By aligning the production requirements of the architecture with detailed customer demand models for propellants, transportation, and other services, a complete econometric analysis has been developed spanning program development from the commencement of near-term revenue streams to long-term market expansion,

The key criteria for SEC's business success is to be able to privately produce and deliver propellants in space with cost margins at least an order of magnitude cheaper per kilogram than anything launched from Earth to LEO, thus enabling significant profit margin from sales as demand increases. SEC's internal integrated system model indicates multiple primary client opportunities from propellant sales offering significant returns with clear market needs identified. Preliminary modeling indicates revenues in the hundreds of billions of dollars up to 2040 for a total capital expenditure of approximately $22B. From conservative assumptions within SEC's model, deferred revenues commence 3 years from first investments escalating within 5–10 years with first deliveries of propellants to customers.

In addition to the primary business of propellant sales, SEC's business model identifies revenue-generating market channels from secondary infrastructure re-use, leveraging significant commercial opportunities with no additional infrastructure cost. Further to that, tertiary business units are scheduled that become commercially viable once SEC's primary business is underway, requiring additional infrastructure production with little additional nonrecurring engineering costs. The combination of these secondary and tertiary business streams that are enabled through SEC's primary model provides the potential for many multiples of returns of the propellant depot financial model outlined.

SEC's financial models indicate significant return on investment for early stage investors. By adopting a milestone-based risk reduction investment approach, high leverage, early stage investment can yield significant returns. Perceived risks are high because of the historic familiarity of government space programs being subject to political uncertainties. For SEC, programmatic, technical, regulatory, and financial risks are controllable and definable within an industrial commercial context.

SEC has undertaken several years of prudent and thorough architecture and business modeling with inputs from dozens of team members on SEC's program and enterprise model. This has enabled SEC to develop a coherent industrialization roadmap, which remains independent of the budget-constrained political mandates of space agency programs. SEC also attempts to avoid the pitfalls of traditional New Space company business forecasts that tend to overestimate short-term development and underestimate long-term potential, resulting in significant marketing efforts in the early stage to compensate immediate shortfalls in viable business planning combined with little or no scalable business model.

As with any analysis, SEC's enterprise model is subject to a series of market, engineering, and regulatory assumptions, the uncertainty of which defines the extent of the investment risk profile. By focusing on existing, latent, and future markets with a combination of sensitivity variations for pricing fluctuation, program delays, engineering overruns, demand variations, and many other variable factors, we can not only identify best-case scenarios (which historically have been presented as baseline economic models for many other programs[8]) but also highlight critical risk factors and scenarios that affect the program. Several members of SEC's team involved in the construction of the model and its underlying engine originate from the mining and energy sectors and are fully versed in resource econometric analysis for decadal term business planning. Although the details of SEC's enterprise model and the target customers and markets remain confidential, a presentation of the model is possible by arrangement for qualified investors.

By combining industrial capital structuring and production engineering principles to a space infrastructure program beyond LEO,

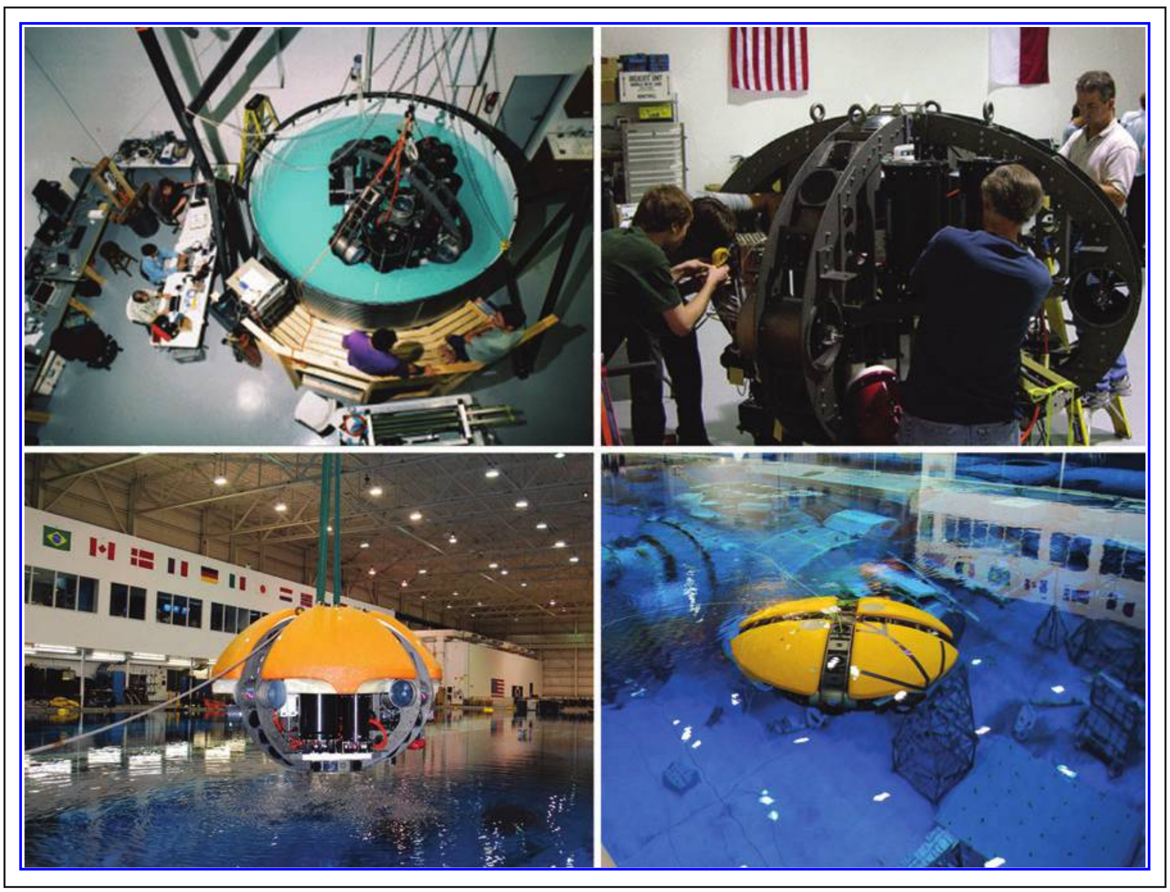

Fig. 6. Extensive engineering heritage. Top row: Design and construction of the fully autonomous Endurance extreme environment robotic vehicle as test prototype for NASA's Europa mission. Bottom row: Undergoing underwater testing at NASA's Neutral Buoyancy Facility at Johnson Space Center.

SEC is uniquely placed to build an integrated business that truly leverages advantage of scale. SEC is intentionally modeled as an energy venture rather than a traditional space enterprise with the entire business model structured to build early revenues by integrating the spinoff opportunities offered by transportation, propellant, communications, exploration, biomedical, and several additional market niches.

Several dozen revenue streams stem from an end-to-end propellant depot architecture. Although details of these near-term markets and customers necessarily remain proprietary, it can be stated that the scale and diversity of business opportunity arising provides for a fully integrated economy with significant early revenue and long-term profitability.

ENGINEERING & EXPEDITIONARY HERITAGE

SEC's team maintains a 30-acre industrial compound in Austin, Texas, that includes a main laboratory with an additional high bay clean room with 2-ton overhead crane plus engineering design facilities. Several technologies relating to power system, robotics, advanced artificial intelligence, and autonomous control and navigation have already been designed and prototyped (*Fig. 6*).

Deep-water exploration vehicles have been developed, built, and deployed in Antarctica to characterize enclosed underwater lakes covered by ice. The engineering technology subsystems and onboard intelligence software developed provide a test bed of capability and methodology of rapid prototyping and development and management of complex engineering programs.

Additionally, SEC has taken the technology developed and deployed it in extreme environments on several dozen expeditions to some of the most remote regions on Earth. These include technology testing operations in Antarctica and long-duration expeditions deep into some of Earth's most complex cave systems isolated from extended logistics and supply chains. Several of these missions have characterized the psychological requirements for SEC's industrial crew operating in isolated craters in the polar regions of the Moon and provide us with preliminary data on our industrial astronaut selection processes (*Fig. 7*).

By developing advanced life support, automation, and robotics technologies in-house and applying them in logistically isolated missions, we have established a unique combination of advanced robotics and systems technology combined with some of the most challenging human endurance expeditions.

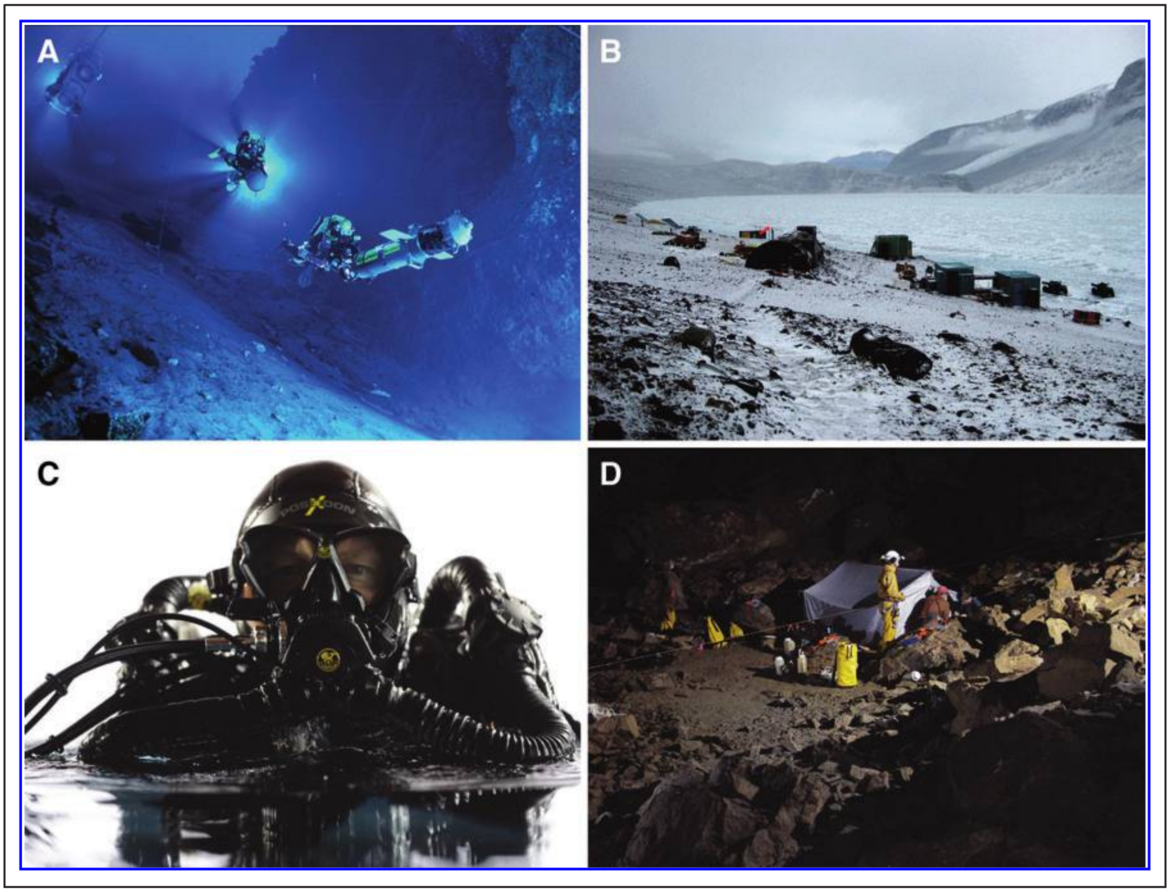

Fig. 7. **(A)** Underwater transport and propulsion vehicles. **(B)** Scientific and experimental operations in Antarctica. **(C)** Advanced closed-cycle life support systems. **(D)** Long-duration expeditions deep into extreme cave complexes.

CONCLUSIONS

SEC has established a world-class team and consortium of strategic partners ready to open new space-based markets at high rates of growth and rapid investor return. By integrating multiple industrial services around a propellant depot architecture, with the bold leadership necessary to open a new frontier, SEC's proven team is establishing the platform for an entire space-based economy beginning operations and sales this decade. With exceptional net present values, the program provides a clear and robust investment proposition offering new market growth of the scale of the industrialization of the mid-1800s. The establishment of this fully commercial program will generate billions of dollars in profit, early return on investment, stimulate thousands of jobs, underpin national economic growth, and provide a resilient platform for addressing the significant challenges that will affect the populations of our planet throughout this century as we open up Earth's economic frontier for the benefit of all.

AUTHOR DISCLOSURE STATEMENT

No competing financial interests exist.

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