Economic Assessment and Systems Analysis of an Evolvable Lunar Architecture that Leverages Commercial Space Capabilities and Public-Private-Partnerships

Forward

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Executive Summary

This study's primary purpose was to assess the feasibility of new approaches for achieving our national goals in space. NexGen assembled a team of former NASA executives and engineers who assessed the economic and technical viability of an "Evolvable Lunar Architecture" (ELA) that leverages commercial capabilities and services that are existing or likely to emerge in the near-term.

We evaluated an ELA concept that was designed as an incremental, low-cost and low-risk method for returning humans to the Moon in a manner that directly supports NASA's long-term plan to send humans to Mars. The ELA strategic objective is commercial mining of propellant from lunar poles where it will be transported to lunar orbit to be used by NASA to send humans to Mars. The study assumed A) that the United States is willing to lead an international partnership of countries that leverages private industry capabilities, and B) public-private-partnership models proven in recent years by NASA and other government agencies.

Based on these assumptions, the our analysis concludes that:

- Based on the experience of recent NASA program innovations, such as the COTS program, a human return to the Moon may not be as expensive as previously thought.
- America could lead a return of humans to the surface of the Moon within a period of 5-7 years from authority to proceed at an estimated total cost of about $10 Billion (+/- 30%) for two independent and competing commercial service providers, or about $5 Billion for each provider, using partnership methods.
- America could lead the development of a permanent industrial base on the Moon of 4 private-sector astronauts in about 10-12 years after setting foot on the Moon that could provide 200 MT of propellant per year in lunar orbit for NASA for a total cost of about $40 Billion (+/- 30%).
- Assuming NASA receives a flat budget, these results could potentially be achieved within NASA's existing deep space human spaceflight budget.
- A commercial lunar base providing propellant in lunar orbit might substantially reduce the cost and risk NASA of sending humans to Mars. The ELA would reduce the number of required Space Launch System (SLS) launches from as many as 12 to a total of only 3, thereby reducing SLS operational risks, and increasing its affordability.
- An International Lunar Authority, modeled after CERN and traditional public infrastructure authorities, may be the most advantageous mechanism for managing the combined business and technical risks associated with affordable and sustainable lunar development and operations.
- A permanent commercial lunar base might substantially pay for its operations by exporting propellant to lunar orbit for sale to NASA and others to send humans to Mars, thus enabling the economic development of the Moon at a small marginal cost.

- To the extent that national decision-makers value the possibility of economical production of propellant at the lunar poles, it needs to be a priority to send robotic prospectors to the lunar poles to confirm that water (or hydrogen) is economically accessible near the surface inside the lunar craters at the poles.
- The public benefits of building an affordable commercial industrial base on the Moon include economic growth, national security, advances in select areas of technology and innovation, public inspiration, and a message to the world about American leadership and the long-term future of democracy and free markets.

An independent review team — led by Mr. Joe Rothenberg, former head of NASA human spaceflight — and composed of former NASA executives, former NASA astronauts, commercial space executives, and space policy experts — reviewed our analysis and concluded that *"Given the study scope, schedule and funding we believe the team has done an excellent job in developing a conceptual architecture that will provide a starting point for trade studies to evaluate the architectural and design choices."*

DISCLAIMER: This was a limited study that evaluated two specific technical approaches for one architectural strategy that leverages commercial partnerships to return to the Moon. We did not evaluate all alternatives for returning to the Moon, nor did we evaluate using similar partnership methods for alternative destinations or purposes. While funded by NASA, the conclusions in this study are solely those of the NexGen study team authors.

STUDY ASSUMPTIONS

The primary economic research question of this study was:

> *"Could America return humans to the Moon, and ultimately develop a permanent human settlement on the Moon, by leveraging commercial partnerships, within NASA's existing deep space human spaceflight budget of $3-4 billion per year?*

The key study assumptions for this analysis included:

1) Public Private Partnerships as Acquisition Strategy

A significant purpose of this study is to assess the utility of public-private partnerships — specifically the proven Commercial Orbital Transportation Services (COTS)/ ISS Cargo Resupply Service (CRS) model —for private-sector lunar development. These approaches have now been proven to be effective at significantly reducing costs. While the focus of this study was on returning humans to the Moon, these same methods could be used for alternative destinations.

In the last decade, NASA has transitioned from a government-owned and –operated cargo delivery system to the International Space Station (ISS) to a privately-owned and –operated cargo delivery system with multiple competitors. NASA achieved this major transition by creating a public-private-partnership. Instead of a traditional acquisition approach, NASA used a linked two-part acquisition strategy summarized as follows:

1. NASA first signed "funded Space Act Agreements" (fSAAs) with significant investments by both NASA and industry, to demonstrate new system level capabilities that did not exist before. This program was called COTS.

2. The NASA CRS program, used FAR part 12, commercial terms, firm-fixed price (FFP) contracts to acquire cargo delivery services after the partners had proven they had the capability in COTS.

The result was successful development of two brand new launch vehicles (SpaceX's Falcon 9 and Orbital's Antares), two new American ISS cargo delivery spacecraft (Dragon and Cygnus) — at costs much less than was possible using traditional acquisition approaches.

These two acquisition tools — the fSAAs and the FFP FAR part 12 (commercial terms) contracts — were critically linked. In this specific situation, each element worked together to achieve all of NASA's objectives. Further, NASA analysis demonstrates that the fSAAs saved NASA many billions of dollars as compared to traditional NASA development approaches.

These successes have helped NASA quickly replace critical functions previously provided by the Space Shuttle at a time of significant budget constraints.

Cost Savings from the COTS/CRS Acquisition Model

In 2010, NASA conducted a study[i] that compared SpaceX's actual costs to develop the Falcon 9 and Dragon spacecraft against what NASA's cost models predicted it would cost using traditional cost-plus methods under federal acquisition regulations (FAR). Using the NASA-AF Cost Model (NAFCOM), NASA estimated that it would have cost NASA $3.977 Billion to develop these systems using traditional contracting methods. The reported SpaceX cost was $443 million[ii], which would be an 89% (or 8-to-1) reduction in costs over NASA's estimated cost for the traditional approach.

Policy History of COTS/CRS

The CRS program was created in the aftermath of the Columbia Accident by the Bush (43) Administration as the "Commercial Crew/Cargo Program". However, COTS was created later, in 2005, by NASA Administrator Mike Griffin. Griffin decided to use NASA's "other transactions" authority (OTA) to fund development of commercial systems in a much more streamlined manner. Griffin explained[iii] his thinking about this innovative strategy to the NASA JSC Oral History project:

- *"The question was how to get that started. In my view, a good way to get that started would be to make available to successful commercial developers the government market, and even to provide them a little bit of seed money."*

- *Using the In-Q-Tel model, one could achieve valid public purposes with a little bit of public money, while not corrupting the market.*

- *The way we structured it, according to what I had in mind, was through Space Act Agreements which themselves would be competed for.*

- *The idea was that we would make available milestone payments to companies who were working on their own private goals to develop space transportation systems. If they met milestones of interest to us—and we published what those milestones were—then they would get payments.*

- *We would not be involved in reviewing the designs or the development practices of the companies involved. They would have to bring the products to market in their own way, in their own time, by their own means, according to their own standards.*

- *I think everybody knew that the industry had reached a maturation point where the technical and managerial skills to develop commercial spaceflight capabilities were out there, and that what was lacking was any form of market. No matter how you cut it, the initial market was going to have to be government. Then once you got over those barriers to entry, maybe other purely commercial markets could develop. No one knew what those were, and I don't know what those are today. But you would never have an opportunity to find out if you couldn't get over the initial barriers to entry, and government could help with that.*

Four Successes in a Row for COTS/CRS Model

What we call the COTS model — which uses the U.S. Government's "other transactions authority" (OTA) via funded Space Act Agreements — has now developed four (4) new American launch vehicles in a row, when you account for the Atlas V and

Delta IV. These launchers were developed using nearly identical commercial partnership methods.

The Atlas V and Delta IV were developed by Lockheed Martin and Boeing, respectively, with commercial methods and processes, large private investments, and a significant (but minority) government investment. The U.S. Department of Defense invested $500 million in each project using OTAs as true partners, with Lockheed and Boeing privately investing several billion dollars each. Since each firm invested significant amounts of capital, for which they would only earn a return if it succeeded and flew successfully and often, the interests of the partners were aligned. The U.S. Department of Defense was willing to accept a secondary role with insight, but minimal USG oversight and control during the development phase[iv].

Both of these new launch vehicles were developed in about four (4) years, which was the same amount of time required to develop the Falcon 9 and Antares launch vehicles. All of these launch systems succeeded on their first try.

SpaceHab Independently Validates COTS/CRS Model

NASA has used similar public private partnership methods in the past that resulted in great success, as well as savings to the American taxpayer. SpaceHab was a commercial microgravity firm that raised private venture financing to commercially develop its patented pressurized mid-deck Shuttle modules. Of that amount, about $150 million was spent on DDT&E and manufacturing two flight modules[v]. This private financing was substantially based on a contract to sell commercial mid-deck locker services to NASA, and augmented by the potential of other commercial markets.

The U.S. Congress mandated that NASA conduct an independent cost assessment of what it would take NASA to develop the SpaceHab system using traditional government procurement practices. Price Waterhouse worked with MSFC and used MSFC's standard cost model tool to estimate[vi] that it would have cost NASA $1.2 Billion, which was 8 times more than SpaceHab spent using commercial practices and methods. SpaceHab demonstrated the same nearly order of magnitude cost savings that SpaceX demonstrated almost two decades later.

Implications for Cost Assessment

The NexGen study team had access to the data described above, as well as significant additional technical and cost information from many other space projects during the conduct of this study. This is discussed in much greater detail in the section on Life Cycle Cost Estimation starting on page 30.

2) 100% Private Ownership of Lunar Infrastructure and Assets

We assume private ownership of lunar infrastructure and systems. We did not identify any requirement for USG ownership of any of the lunar infrastructure elements. Private ownership and responsibility for infrastructure is critical to driving market-based incentives, decision-making, and efficiencies. NASA can achieve its public purposes and meet NASA's needs by serving as customer of commercially-provided services.

NASA has stated that "We're going to spend a 10-year period of time between 2020 to 2030 in cis-lunar space, trying to establish an infrastructure in lunar orbit from which we can help entrepreneurs, international partners and the like who want to get down to the surface of the moon."[vii] This architecture assumes as a baseline that NASA will not lead a return to the Moon, as stated by current NASA leadership, although it may support entrepreneurial lunar surface activities in pursuit of its journey to Mars. This study investigates one particular approach, and implementation of, such NASA support.

3) International Lunar Authority to Reduce Business Risk

There are significant implications of the private ownership of assets, as it transfers the majority of the development risk to private industry. The cost and risk of developing a lunar base — even with NASA and other country's space agencies as anchor tenant customers — is far beyond that which conventional requirements for risk-adjusted return on investment will accept or allow. The combination of very large financial commitments, technical risk, and dependence of government's keeping their commitments, makes this an extra-ordinary risk.

More important than anything, industry must be convinced that NASA and other space agencies will honor and keep their long-term commitments for lunar-based services. It is imperative that the U.S. Government not change its mind and break its commitment 2, 4 or 8 years later when we get a change of Congress or a change in President and NASA Administrator. However, given recent history, it is difficult to imagine industry trusting that NASA can keep such a commitment without significant changes.

Effectively managing this risk is a critical priority for the success of this model. In the section on "Managing Business Risk", starting on page 63, we will provide analysis on various alternatives to mitigate this risk. Our recommended solution based on the analysis of alternatives is the creation of an International Lunar Authority that is modeled after a combination of CERN and traditional public infrastructure authorities used in airports and seaports around the world.

4) Evolvable Lunar Architecture

The evolvable lunar architecture, which leverages commercial partnerships, that was assessed by NexGen was a 3-phase, step-by-step development of a lunar base. To the maximum extent possible, it uses existing and proven technologies in the current phase of development, and in parallel developed key technologies necessary for the next phase. The key decision point for transitioning to the next phase was driven, in part, by a few key technology developments.

This step-by-step approach allows for the incremental development and insertion of reusable elements in a low-risk phased manner that minimizes cost and risk. This was a critical aspect of the ELA, which will be covered in more detail in which is discussed at length in a section focused on our strategy to mitigate technical risk starting on page 48.

There were three phases to the NexGen Evolvable Lunar Architecture (ELA):

Phase 1: Human Sorties to the Equator/Robotic Scouting of Poles

Phase 1 was designed with three independent activities taking place in parallel:

- The robotic segment would focus on characterizing the amount and nature of the water in the lunar poles, to enable later prospecting, and to identify the optimal site for a lunar base.

- The human transportation segment would focus on developing and demonstrating the key systems for returning humans to the Moon, including the in-space transportation (a reusable crew capsule for transporting humans to lunar orbit and returning them safely to Earth), and a lunar lander.

- The technology segment would develop the technologies needed in Phase 2, such as propellant storage and transfer.

The Key Decision Point (KDP) to begin Phase 2 is the successful demonstration of human landing at the equator and with the successful demonstration of propellant storage and transfer capability needed for transferring human systems to a lunar polar orbit in Phase 2.

Phase 2: Sorties at Poles & ISRU Capability Development

The focus of Phase 2 is human sorties at the lunar poles, and developing the key capabilities and technologies needed for Phase 3. This is a stepwise transition phase that includes:

- Development of lunar surface ISRU capabilities and technologies to mine the lunar ice, and convert the water into propellant

- Development of a large reusable LOX-H2 lunar lander, including reliable cryogenic LOX/H2 engines and propellant depots.

- Completion of the robotic scouting mission, and selection of the site for the permanent lunar mining base.

The KDP for Phase 3 is when lunar water ISRU, cryogenic LOX/H2 storage and transfer, and a large reusable lunar lander are all available. The reusable lunar lander will have the ability to transport propellant to the L2 depot and return, to transport large structures from lunar orbit to the lunar surface, and safely transport humans to/from the lunar surface.

Phase 3: Permanent Lunar Base transporting propellant to L2

The focus of Phase 3 is the operations of a large-scale mining lunar water, cracking of the water into lunar propellant, storage of the propellant, and transfer of 200 metric tons of propellant per year to a propellant depot at the Earth-Moon L2 station. To achieve this objective, a permanent lunar base for a crew of 4 is first developed using the lunar ISRU and reusable lunar lander. The purpose of the crew is to operate, maintain, and repair the mostly automated ISRU equipment.

Technical Analysis

General Technical Approach

For the three-phase Evolvable Lunar Architecture (ELA), space transportation systems and supporting infrastructure were designed and analyzed from initially providing access to the lunar surface to the development of a permanent human outpost supporting the production of lunar resource propellant for deep space exploration (Figure T-1). Phase 1 includes robotic prospecting for lunar ice at the poles to determine if exploitable ice does exist and human lunar equatorial surface access for demonstrating key space transportation systems and key life support systems. In addition technology will be developed for in-situ resource utilization (ISRU) mining and production of LOX/LH2 propellants, in-space propellant storage and transfer for lowering space transportation costs and safety risks. Phase 2 will test a human tended LOX/LH2 ISRU pilot plant and demonstrate routine lunar polar access to the lunar poles with the technologies developed in Phase 1. In order to evolve to Phase 3, technology development is required for reusable rocket propulsion for routine access to the surface and for delivering LOX/LH2 propellant to a depot in L2 with a reusable lunar module. In addition, an ISRU mining and production plant is developed for delivery and startup in Phase 3. Thus in Phase 3, LOX/LH2 is produced and delivered to L2 with a reusable lunar module and is being tended by a crew of 4 in a permanent lunar outpost. Although not studied, a similar evolvable Mars architecture can make use of space proven transportation, habitat, and ISRU systems and technology. Thus the next step of Mars human exploration requires the development of human and electronic radiation protection and entry/descent/landing of cargo and crew.

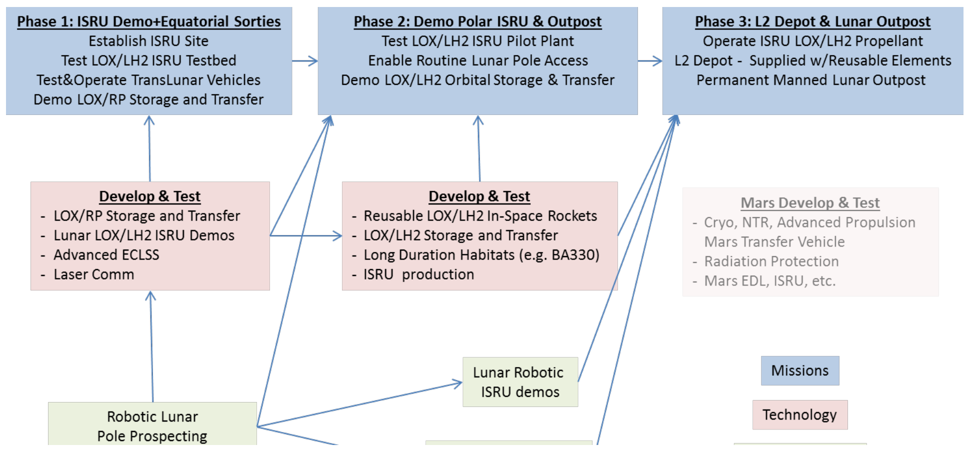


Figure T-1. Program Integration of Technology, Development, and Missions

At each phase, we use to the maximum extent existing systems and proven technologies as shown in Figure T-1. For new systems and technology, a measured approach was used — focused technology development, technology demonstrations, small scale pilot systems, full-scale systems development, and in-space systems testing to mitigate the initial risks to the crew and maximize mission success for each phase. High risk technologies and system demonstrations incorporate a number of planned failures, evolution development, and/or alternate strategies. Thus, each technology demonstration, system test, and phase completion milestone represents a key decision point in the program for continuation with risk, replan with reinvestment, or cancellation.

Analysis Methods

For the design and analysis of the space system architecture, various analysis methods were used. Because of the limited resources and time for this study, literature search provided much of the fundamental data and where appropriate conceptual design tools were used for vehicle sizing and geometry design.

Space system performance, deltaV, was defined for each leg of the space transfer as shown in Figure T-2. For Earth-moon transfer, the deltaV is taken the maximum actually used for the seven Apollo moon missions[viii]. However, for the Apollo descent trajectory, there was a flight path angle hold for the pilot to view the landing site for large boulders or small craters (7% penalty); and for the final approach, there were six hover maneuvers for pilot attitude and speed corrections. In addition, there were additional contingencies for engine-valve malfunction, redline low-level propellant sensor, and redesignation to another site (9% penalty). In this study, it was assumed that the landing sites are fully defined, advanced laser sensors for remote site debris and crater checkout, and modern propellant and engine sensors for measuring and establishing final engine performance. In addition, the final descent time was reduced from the 45 seconds baselined in Apollo to 30 seconds at a decent velocity of 0.1 m/s. For polar lunar missions, the cis-lunar performance was taken from NASA's Exploration Systems Architecture Study that provided the baseline systems for NASA's Constellation program[ix].

The performances of transfers from Earth to Earth-moon L2 and from there to Mars orbit were taken from various references[x], [xi], [xii], [xiii]. The selected data are for direct missions only. Performance can be optimized for specific dates of transfer using gravity turns but cannot be used in this study because specific missions and dates are not available.

Simple orbital mechanics defined the 1-body orbit around Earth to a periapsis of Earth-moon L2 to compute the periapsis deltaV and the atmospheric entry speed of 11km/s.

Finally for all deltaVs in Figure T-2, an additional 5 percent reserve is used.

For vehicle sizing and mass, the Georgia Tech Launch Vehicle and Space System Synthesis (LVSSS) was used.[xiv] This method uses the regression of historical components of space systems for mass properties and sizes the system to meet thrust-to-mass ratio and deltaV constraints. A statistical analysis was performed on the vehicle mass growth history from the initial mass estimate at program start to the final flight mass showing a growth range from 7 percent for families of similar vehicles to 53 percent for the Apollo lunar module. For this study, the mean of this data, 30 percent, was used as the growth factor on the estimated inert mass. The LVSSS mass estimate could be considered conservative because it overestimates the 0.04 inert mass fraction of the Falcon 9 launch vehicle by 35 percent because of the growth margin and the utilization of technology that ranges from 4 decades old to today.

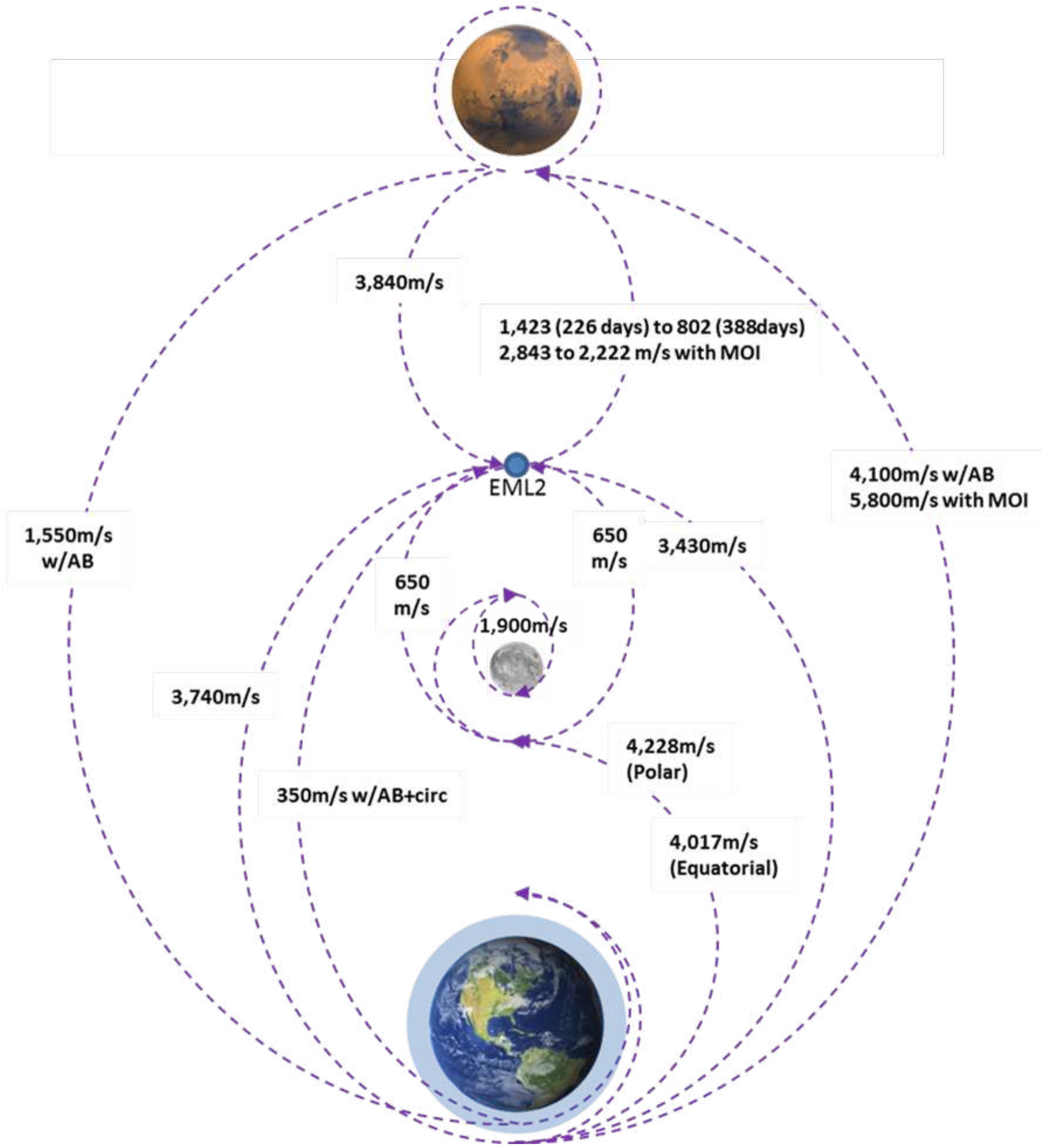


Figure T-2. Transfer Performance DeltaV

Phase 1A — Robotic Scouting, Prospecting, Site Preparation

Paving the Way with Robotics

Prior to establishing a commercially-operated ISRU facility and human arrival, various robotic systems would be preparing the way. These robotic systems would take on various tasks and responsibilities to include scouting, prospecting, and initial infrastructure build-up. As NASA's Ranger program and Surveyor program led the way to the manned Apollo program, automated planetary robotic systems will pave the way to lunar human settlement and resource production plants.

"The strategy on the Moon is to learn how to mine its resources and build up surface infrastructure to permit ever increasing scales of operation."

The Moon: Port of Entry to Cislunar Space, Paul Spudis

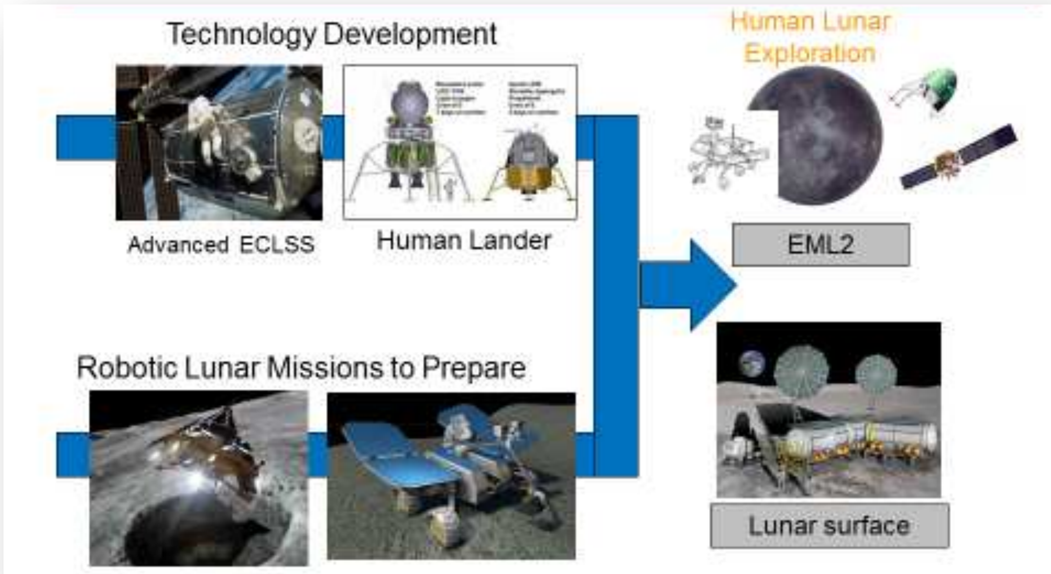


Figure T-3. Strategic Approach to Human/Robotic Operations on the Lunar Surface. Parallel technology development and robotic missions prepare base for human arrival

Scouting

Scouting is the first stage of resource reconnaissance of a targeted area (second is prospecting). Initially, precursor robotic surface scouting missions will follow present-day orbital assets to get a first-hand look at the surface. While lunar orbital data is important in establishing a large database of information about the lunar surface (topography, estimate of resources, etc.), it is imperative to get "ground-truth" from robotic surface systems both for resources, terrain and hazard assessment. Methods include ground-truth surface mapping and sampling, core drilling, and geochemical analysis of the water/ice resources. The objectives of this initial phase of operation is to:

1. Identify and prioritize specific sites, through surface operations, that show the best promise for follow-on prospecting. These robotic assets will search for both volatiles/water-ice deposits. This step is essential prior to spending time and energy in prospecting a given site location for water/ice.

2. Identify optimal locations for landing sites and base locations. This would include reconnaissance of areas best suited for locations of: solar power, landing pads, habitation, communications and processing equipment for the lunar volatiles.

Initially, five or more robotics surface assets could be combined in a single launch to 'scout' likely sites on the Moon's surface for resources and infrastructure placement. The robotic assets could be a combination of 'hoppers' and 'lander/rover' systems. The hopper technology allows the robotic scout to cover vast ranges by ‘hopping’ from one potential resource site to another. On the other hand, the land/rover allow a more detailed inspection of probable sites.

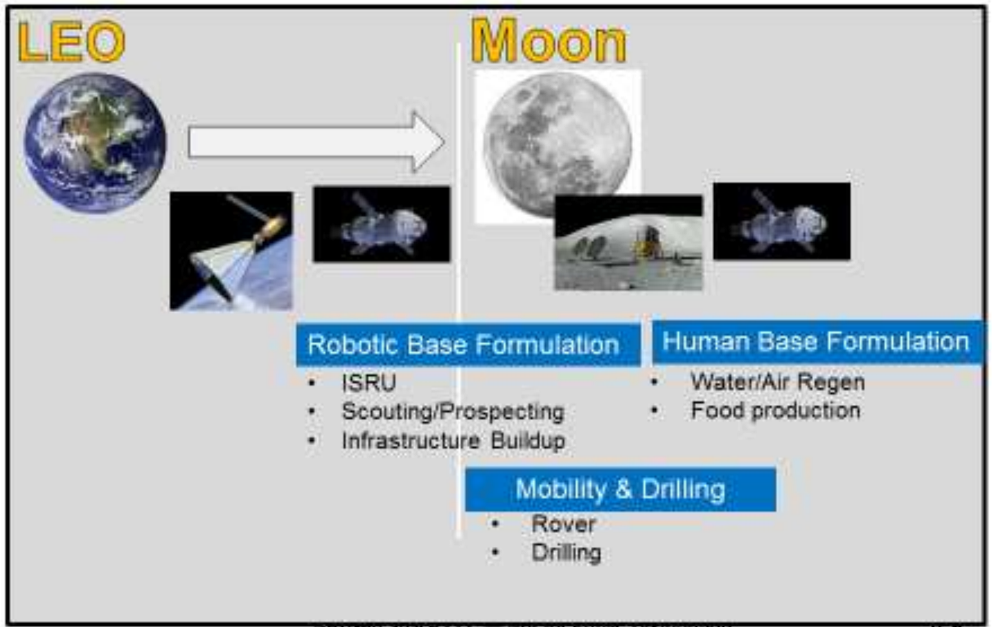


Figure T-4. Moving from Earth Reliant” to “Earth Independent”. Technology development required for robotic mobility, drilling and human life support prior to establishing long-term human operations on the Moon.

While we now know[xv] there is hydrogen, likely in the form of water, in the cold traps of the lunar polar craters, it is possible that the robotic scouting missions will not discover a source of hydrogen that enables the economical production of cryogenic (LOX/LH2) propellant. While we think this unlikely based on the data from multiple sources of hydrogen at the poles, the consequences would be significant. If this happens, the proposed strategy for lunar development will need to be amended, and the plans for prospecting and mining will need to be delayed and potentially cancelled. We have prioritized this as the number one strategic technical risk among all the identified technical risks (see “Technical Risk Assessment” on page 28).

Prospecting

The second phase of the robotic reconnaissance is analogous to the mining industry where key sites are down-selected from the scouting data for more intense resource prospecting. Prospecting is a much more intensive, organized and targeted form of scouting. This goal of the exploration phase is to: specifically qualify and quantify the lunar water/ice….ala “prospecting for gold”. This involves assessing the probable resource content both in vertical depth at the surface and also horizontally to ascertain thickness of the ice, physical state and levels of contamination within the water/ice. Robotic probes would perform chemical analysis on the water/ice. Area selection is a critical step of the prospecting phase and designed to find the highest quality of resources (water/ice) as easily, cheaply and quickly as possible. The goal is to define the specific strategy to be used in excavating/extracting the water resources at the site, i.e. – what area of the site is to be extracted first and how is the excavation to expand from the initial production area?

Establish Supporting Infrastructure

Following the prospecting phase, the robotics systems will begin to develop basic site infrastructure that will transform the site into an ISRU production facility. During Phase 2, the robotic operations will be supported by human sorties to the chosen site. Paramount to the successful operation is the concept of "living off the land". Unlike Apollo, we must learn to robotically manipulate the resources of the surface of the Moon (asteroids and Mars) by using the indigenous materials located in-situ…without having to transport materials and supplies from Earth at great expense.

Before ISRU equipment is to arrive, the site must undergo some basic capability development. A series of site-preparation missions follow to include the arrival of a 100KW solar power and communications infrastructure. This element would be launched and landed at the site. The robotic systems, further enabled by the newly arrives power/comm system, would begin constructing the basalt launch/landing pads at the site. Dust/regolith at the site is a major issue for robotics and site infrastructure. High velocity lunar dust particles, created by rocket engine exhaust during descent and ascent from the lunar surface, have the potential to decimate all hardware within line-of-sight. Hence, robotic systems will perform backblading, leveling operations, and surface stabilization of the regolith to create launch/landing pads to enable safety and routine transportation to/from the site. The lunar basalt can be sintered using microwaves to make pavers, bricks and/or strong sintered surfaces for the landing pads and roads. These robotic systems will operate autonomously and/or through tele-robotic operations from Earth.

Following the landing pad construction, stabilized roads will be created at the site for moving ISRU and crew equipment into place once it arrives.

ISRU Facility

After prospecting, site preparation, and mining excavation, setting up in-situ resource utilization facility is the next step in the operation. The goal is to robotically install various equipment necessary to begin water extraction operations. The ISRU facility – a 'systems-of-systems' - will perform four major functions:

1. Sorting / Beneficiation
2. Extraction / Reduction
3. Cleanup / Filtering
4. Capture and Storage

Estimates place the projected amount of water on the Moon at 10 billion cubic meters of water at the poles (equivalent to the Great Salt Lake in Utah). By collecting the water/ice on the Moon, system processors can separate the water from soils particles and then separate the remaining water into is elements: hydrogen and oxygen.

The oxygen and hydrogen produced in this ISRU cycle will provide the necessary consumables for operating fuel cells for the robotic systems, air to breathe, water to drink and of course…propellant.

This will be a complex operation requiring a period of growth, trial and error, failure, repair, and maintenance as the process matures in operations and procedures.

Consumables will be captured in storage containers that handle water, oxygen and hydrogen. But initially, water can be easily and safely stored. Later, the water can be separated into cryogenic hydrogen and oxygen. Robotic systems will play a main role of transferring consumables for propellant transfer for vertical takeoff/vertical landing (VTVL) systems, storage tanks on rovers for fuel cell supply and more.

Begin Operations - Propellant Tanker/Lander

Once propellant depot operations are underway on the surface of the Moon, a large reusable Lunar lander/tanker will arrive at the site and land at the previously built landing pads. Robotic rovers will connect the tanks to the storage facilities to allow the tank capacity of the lunar lander/tanker to be filled for transport to the depot at L2. The availability of the large reusable lunar lander, which is 100% refueled from lunar propellants, is the critical step to a permanent lunar base.

Establish Crew Outpost

Following completion of the ISRU production facility, and the arrival of the large reusable lunar lander, the site is ready for the delivery of habitats, and other infrastructure needed for the permanent crewed lunar base. The ELA is designed to launch a Bigelow BA-330 expandable habitat sized system via either a Falcon Heavy or Vulcan LV to LEO, which is then transferred from LEO to low-lunar orbit (LLO) by leveraging in-space propellant transfer in LEO. The large reusable lunar lander will then rendezvous with the habitat, and other large modules, in LLO and transport them to the surface of the Moon. These modules would be moved by robotic systems from the designated landing areas to the crew habitation area selected during the scouting/prospecting operation. The modules could be positioned into lava tubes, which provide ready-made, natural protection against radiation and thermal extremes, if discovered at lunar production site. Otherwise, the robotic systems will move regolith over the modules for protection. Additionally, the robotic systems will connect the modules to the communications and power plant at the site.

Human & Robot Interaction as a System:

Why are robotics critical? The reasons that the process begins with robotics instead of beginning with 'human-based' operations like Apollo includes:

1. Robotics offer much lower costs and risk than human operations, where they effective, which is amplified in remote and hostile environments.

2. Robotic capabilities are rapidly advancing to a point where robotic assets can satisfactorily prospect for resources and also for set up and prepare initial infrastructure prior to human-arrival.

3. Robotics can be operated over a long period of time in performing the prospecting and buildup phases without being constrained by human consumables on the surface (food, water, air, CO2 scrubbing, etc.).

4. Robotics can not only be used to establish initial infrastructure prior to crew arrival, preparing the way for subsequent human operations, but to also repair and maintain infrastructure, and operate equipment after humans arrive.

Why do robots need humans to effectively operate a lunar base? Why can't robotics "do it all"? Why do we even need to involve humans in this effort?

1. Some more complex tasks are better performed jointly by humans and robotics….or by humans themselves. This is an important area of research and testing.

2. Humans operate more effectively and quicker than robotic systems, and are much more flexible. Human are able to make better informed and timely judgments and decisions than robotic operations, and can flexibly adapt to uncertainty and new situations.

3. Robotic technology has not reached a point where robots can repair and maintain themselves. The robotic systems will need to periodic as well as unscheduled maintenance and repair….provided by humans.

Public Benefits of Investments in Advanced Robotics

U.S. government investments in advanced technologies such as robotics will have tremendous impacts on American economic growth and innovation here on Earth. The investments just by DARPA in robotic technologies are having significant spill-over effects into many terrestrial applications and dual-use technologies**.** Examples of dual-use technologies include:

a. Robotic systems performing connect /disconnect operations of umbilicals for fluid/propellant loading … could lead to automated refueling of aircraft, cars, launch vehicles, etc.

b. Robotic civil engineering: 3D printing of structures on the Moon with plumbing through industrial 3D printer robotics, could lead to similar automated construction methods here on Earth.

c. Tunnel inspections: Robotic operations for inspecting lava tunes on the Moon could lead to advanced automation in mine shafts on Earth. Advances in autonomous navigation, imagery, and operations for dangerous locations and places could save many lives here on Earth.

d. Remote and intelligent inspection of unsafe structures from natural disasters (tsunamis, radiation leakage, floods, hurricanes) could enable many more operations by autonomous robotics where it is unsafe to send humans.

Roadmap

The following roadmap outlines the program development and operations: *(dates are placeholders)*

Timeframe	Event Milestone
2017	Lunar lander demonstration
2015-2017	DDTE of scouting / prospecting technologies for the landers
2018	Deployment in phased sorties for scouting operations
2019-2020	Launch and deployment of robotic prospecting assets
2015-2019	DDTE on Earth of ISRU capability
2020	Site selection for ISRU operations and base plant, including "Go/No-Go" decision for production of flight systems for lunar ISRU propellant systems.
2021	Begin robotic construction phase for launch/landing pads, power systems and infrastructure at chosen lunar site
2021	Human Lunar Landing at Equator
2023	Robotic setup and testing of ISRU demo operations at selected test site
2025	Begin testing of integrated ISRU production systems on Moon
2031+	Initial polar facility (propellant production) operations

Phase 1B — Human Sorties to Lunar Equator

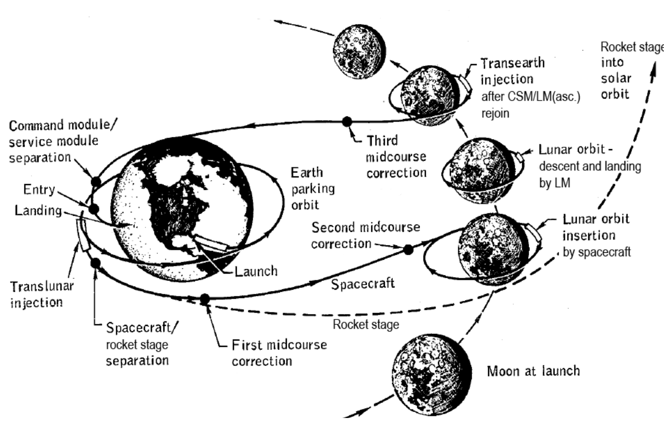


Figure T-5. Apollo System Architecture

For lunar sorties, the ELA system architecture has many similarities to the Apollo architecture, but is somewhat different because we use existing space systems, infrastructure and technologies. For Apollo, Earth orbit was achieved with the very large Saturn V launch vehicle to deliver all the lunar system architecture to orbit in one launch. The Saturn third stage (S-IVB) performed a suborbital burn to low-Earth Orbit (LEO), and also had enough propellant to perform a second burn TransLunar Injection (TLI) burn. As the system approached the moon, the Service Module performed the Orbit Insertion (LOI) burn. The astronauts transferred from the astronaut habitat Command Module capsule to the 2-stage Lunar Module for descent to and ascent from the lunar surface. After the sortie missions, later including the Lunar Rover for surface transportation, the crew performed a Lunar Orbit Rendezvous of the Lunar Ascent Module with the Command/Service Module in lunar orbit. For return to Earth, the Service Module performed the TransEarth Injection (TEI) burn; the Command module separated, entered the Earth's atmosphere and splashed down in the Pacific for recovery.

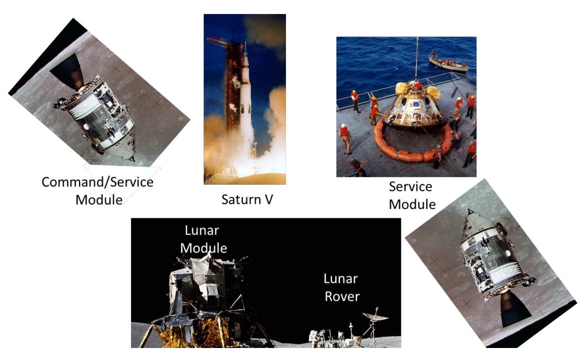


Figure T-6. Apollo System Elements

Today, there are several options for space system elements of repeating lunar sorties; however, today's smaller commercially available launch vehicles required more than one launch to low-Earth orbit and element assembly before continuing to the moon. The following analysis is focused only on SpaceX space systems, which is only one of many options available today; this selection is solely based on the availability of open source data for system performance, mass, cost, and technology.

It should be noted that the United Launch Alliance (ULA) released on April 2015 their technology roadmap for advanced programs that includes a distributed space system architecture for supporting cis-lunar, lunar, and deep space mission. This architecture has a next generation launch system, called Vulcan, doubles the payload capability of the Atlas V can be fitted with 6 solid rocket motors and an advanced cryogenic evolved stage (ACES) with a GTO payload of 32t. The Vulcan uses the Sensible Modular Autonomous Return Technology (SMART) to return the new low-cost BE-4 engines and avionic package. In addition, low-cost/fully reusable XCOR engines will replace six-decade old RL10 engines for in-space propulsion and upgrades to the Boeing CST-100 for cargo and human transport. This new capability is projected to be price competitive with SpaceX.

In addition, ULA has conducted experiments at NASA Marshall for cryogenic fluid transfer and advanced fluid management systems for utilizing any boiloff propellant for stationkeeping. Also, ULA has complete design of the dual thrust axis lunar lander using the Centaur/Delta IV upper stages and ACES for reliability and again low cost.[xvi] For this study that ends in Phase 3 using LOX/LH2 produced for the lunar surface, this new architecture would eliminate technology development costs of fully reusable LOX/LH2 engines and development costs of the Lunar Module. Unfortunately, the ULA announcement was too late to be incorporated into the first phase of this study.

Launch Vehicle and TransLunar Injection/Lunar Orbit Insertion. Historically, the human mission cost beyond Earth's orbit have been dominated by launch cost. However, the cost reduction revolution started by SpaceX with their Falcon launch vehicles and being matched by ULA's Vulcan launch vehicle development will usher in a new era for human exploration. Launch cost is dramatically being reduced and may become a fraction of the mission cost rather than the dominating cost factor. For this study, the Falcon 9 and Falcon Heavy were used as representative of the new trend in launch costs because of the violable prices on the SpaceX web site.

SpaceX currently operates the Falcon 9 that has a payload of 13.1t to LEO at 28.5° at a per launch cost of $62.1M ($4750/kg) as per there Web site. This compares to the Saturn V that delivered 130t at $46,000/kg. The economy of Falcon 9 is based on the large number of planned launches per year; as of 2016 there are 21 launches currently sold. In addition, SpaceX is actively developing a reusable Falcon 9 that should further reduce costs.

In addition, SpaceX is developing the Falcon Heavy using 3 modified Falcon 9 cores and the Falcon 9 second stage. Falcon Heavy has an advertised payload to LEO of 53t at a cost of $90M ($1700/kg). Because of the lack of maximum payload (53t) compared to the Saturn (120t), multiple launches of the Falcon Heavy (and Falcon 9s) are required for the lunar sortie as shown in Figure T-7. As will be shown in the Life Cycle Cost section, this is an excellent economical approach because the price of the Falcon Heavy and Falcon 9 launches on a dollars per kilogram basis are more than an order of magnitude lower cost than the Saturn V and Space Shuttle programs.[xiii]

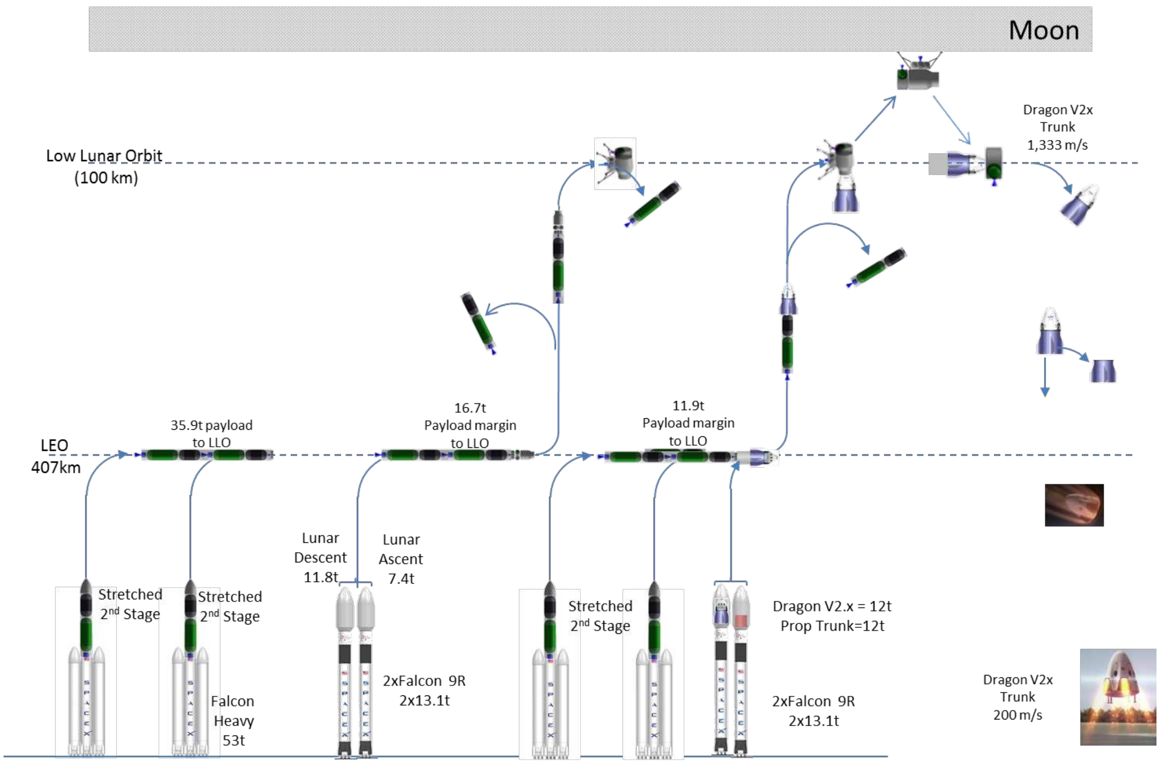


Figure T-7. Phase 1 Lunar Sortie

For this mission, the Falcon Heavy 2nd Stage is modified by extending the propellant tanks to deliver propellant in its tanks for the TransLunar Injection and Lunar Orbit Insertion (equatorial TLI=3,268 m/s and LOI=949m/s which includes a 5% margin). The mass of the tank barrel section extensions for the left over propellant is 586kg for the LOX tank and 366kg for the RP tank which is less than the 2500kg fairing. Thus, the extended 2nd stage can deliver 53.6t of propellant to orbit, slightly more than its stated payload of 53t. This tank extension is not a costly modification because all the Falcon stages are 3.66m in diameter and use the same manufacturing rig. In Phase 1, two stretched 2nd Stages are mated in orbit and can deliver 35.9t to low-lunar orbit, more than the required 24.6t Dragon V2.

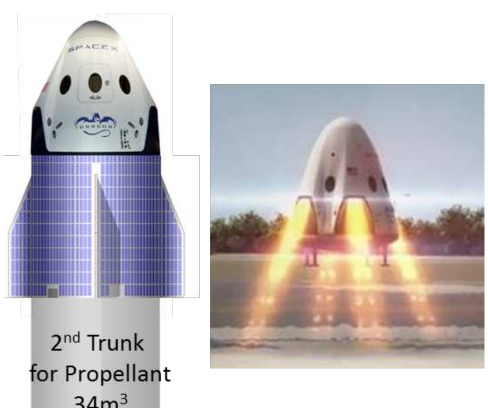
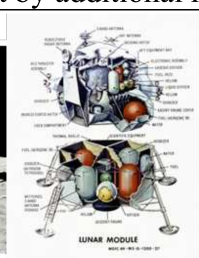


Figure T-8. Modified Dragon V2

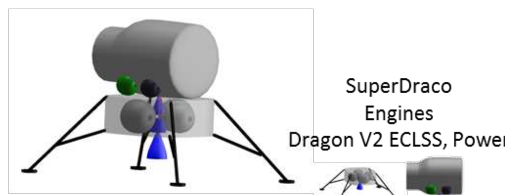
Command/Service Module: The Command Module/Service Module is a modification of the SpaceX Dragon V2 spacecraft designed for delivery of 7 astronauts to the space station (see Figure T-4). Its dry mass is 6.4t with a cargo capacity of 3.3t for a total of 9.7t plus 1,456kg for deorbit and landing. As opposed to using hydrogen fuel cells for power, the Dragon V2 uses solar cells deployed from the first trunk as shown in Figure T-8. In this study, the Dragon V2 was modified for 4 astronauts for up to 14 total days (8 to and from the moon with 6 day margin) for a total mass of 11t (plus 1.2 factor for ASE). In addition, a second trunk was added to the Dragon V2 to provide an additional 10,625kg of propellant for the TransEarth Injection (equatorial 1,061m/s). The total trunk mass was 12,752kg. It should be noted that the Phase 1 architecture only supported an equatorial mission with 2 astronauts on a 7 day sortie. However, with additional translunar mass payload capability in Phase 3, the modified Dragon V2 has the capability to support a crew of 4 to the lunar poles and the propellant for the transEarth injection.

The Super Draco engine uses hypergolic propellant (NTO-MMH) with a thrust of 68,169N at an estimated specific impulse of 324s vacuum.

Lunar Module: For Phase 1 minimum sorties, the lunar module is initially operated only for 2 crew for a 7-day mission to gain early experience with the new systems. As shown in Figure T-9, the lunar module was designed with the Super Draco engine and the life support from the Dragon V2. Although not shown, 2.1kW of power is provided by Ultraflex solar arrays rather than the 72hr batteries of Apollo. A straight descent to the lunar surface is planned differing from the Apollo lander where the astronauts were given time to seek an appropriate landing site while descending. Thus the ascent and descent deltaVs are 1,988m/s (includes 5 percent performance margin). Unlike Apollo, the use of a polar-capable design for early equatorial missions allows a significantly higher consumables margin for these early missions. Although the missions were very similar, the current Lunar Module has a total mass greater than Apollo module where new technology is offset by additional required design and performance margins.



	Lunar Module Descent	Lunar Module Ascent
Body Structure, kg	444	473
Induced Envir Protection, kg	149	155
Lnch Recov & Dkg, kg	218	23
Main Propulsion, kg	505	213
Orient Control Sep & Ullage, kg	6	156
Prime Power Source, kg	260	167
Power Conv & Distr, kg	30	210
Guidance & navigation, kg	20	35
Instrumentation, kg	3	58
Communication, kg	6	50
Environmental Control, kg	44	132
(Reserved), kg	150	277
Personnel Provisions, kg	24	44
Crew Sta Contrl & Pan, kg	1	108
Mass Growth Allowance, kg		
SUBTOTALS (Dry Weight), kg	1,859	2,102
Personnel, kg	-	325
Non Cargo, kg		
Cargo, kg	-	-
Ordnance, kg	12	12
Resid Prop & Serv Items, kg	122	54
Inflight Losses, kg	148	314
RCS Propellant, kg		
SUBTOTALS (Inert Weight), kg	2,141	2,808
Full Thrust Propellant, kg	7863	2258
TOTAL (Gross Weight), kg	10004	5066
Total with Payload, kg	15070	5066
Isp, s	315	315
DeltaV available, m/s	2278	1823



	Descent Lander	Ascent Lander
Body Structure	829	536
Induced Environmental Protection	35	19
Main Propulsion	409	219
Orient Control Separation	0	136
Prime Power	182	157
Power Conversion and Distribution	36	70
Guidance and Navigation	38	38
Instrumention	32	32
Communication	97	97
Thermal Control	170	166
Personnel Provisions	0	699
Crew Station Control Panel	0	141
Range Safety and Abort	71	71
Mass Growth Allowance	577	819
Personnel	0	325
Ordanance	23	23
SUBTOTALS (Dry Mass), kg	**2,499**	**3,549**
Residual Propellant	178	69
Reserves	178	69
RCS Propellant	0	263
SUBTOTALS (Inert Mass), kg	**2,856**	**3,950**
Cargo	**7,385**	
Full Thrust Propellant	8,906	3,435
Total (Gross Mass), kg	**19,147**	**7,385**
Total wo/Cargo, kg	**11,762**	**7,385**
Isp, s	324	324
DeltaV, m/s	1988	1988

Figure T-9. Lunar Module Comparisons

Technology: During Phase 1, technology will be developed to meet the requirements of an eventual permanent human outpost tending the lunar ice propellant plant.

First a more efficient TransEarth Injection Stage will need to be developed. Because the 2nd Stage is delivered to orbit with tanks that are 73 Percent empty (the tanks can accommodate 143t more propellant), technology will need to be developed to transfer and store in orbit for extended duration both LOX and RP in orbit. This TransLunar Injection Stage (modified Falcon 9 2nd stage) can be adjusted to a range of payload from 15t to 70t by the amount of refill propellant in orbit. Thus, the cheapest "payload to orbit" launch vehicle can be used such as a reusable Falcon 9 or any other new launch vehicle. As shown in Figure T-10, the amount of refill propellant can be adjusted to meet the payload needs. Thus, 2 Falcon 9 refills (24t) can be used to put 23t of payload to lunar orbit, which is more than needed for the lunar module.

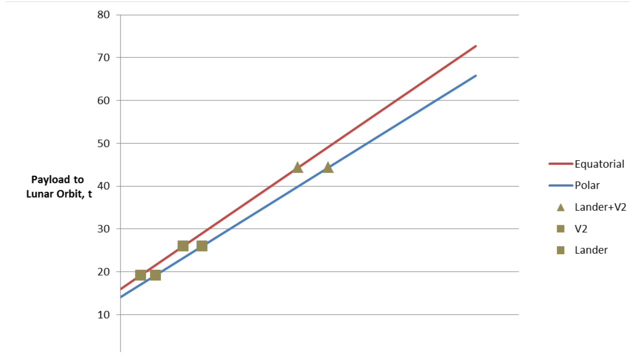


Figure T-10. Payload to Lunar Orbit from refilling the Falcon 2nd Stage

The second critical technology is to develop highly reliable and supportable life support, communications, power, data, mobility, and other subsystems for the permanent human outposts. Reliability, failure data, and spares for the space station will inform the requirements for each of the critical systems. However, for the ISS, maintainability optimization was to minimize crew time for maintenance, while mass for spares was not as constrained due to the relative close proximity to Earth. Reduction of spares mass will be needed for cost-effective lunar operations. Requirements for spares to be transported to the outpost will be based on reliability improvements and a supportability concept that is optimized for lunar rather than LEO operations.

Finally, the technology for ISRU LOX/LH2 production needs to be developed ending with a demonstration on the lunar pole in Phase 2. Included in the technology development and demonstration are excavators and loaders for mining the regolith, haulers for moving the regolith, hoppers for feed, extraction of water from regolith, electrolysis and liquefiers for oxygen and hydrogen production, and storage for water and zero-boiloff propellants, and the power for the plant either solar electric or nuclear.

Phase 2 — Human Sorties to Poles

In 2nd Phase the base of operations is moved from the lunar equator to the lunar poles to determine the best location for extracting lunar ice found in the robotic searches in Phase 1 and then operate a pilot production plant. The pilot plant has a maximum mass of 7.4t to support requirements to incrementally build up capacity using a modular approach as described in the Risk section and because this is the payload of the Lunar Descent Module is also sized to support this strategy.

As shown in Figure T-11, the system architecture is similar to Phase 1. However, with on-orbit refill technology, only a single Falcon 2nd Stage is required to reach the poles instead of 2 reducing the risk of assembly of the stages and staging. Shown in the figure are multiple reusable Falcon 9's for refilling the stage assuming that they will be the cheapest payload delivery launch vehicle. However with refill, the cheapest existing launch vehicle at that time is likely to be used to further reduce cost. In addition, a propellant depot could be used to accept propellant from any supplier, and would separate the multiple refills to the mission stage to just one to simplify operations. As shown for the Dragon V2 delivery, only 14t additional propellant is required for lunar transport but 2 Falcon 9Rs are used with a total capacity of 25t of propellant. Thus one of the launches has only a partial payload with propellant. While a depot would ensure that all flights

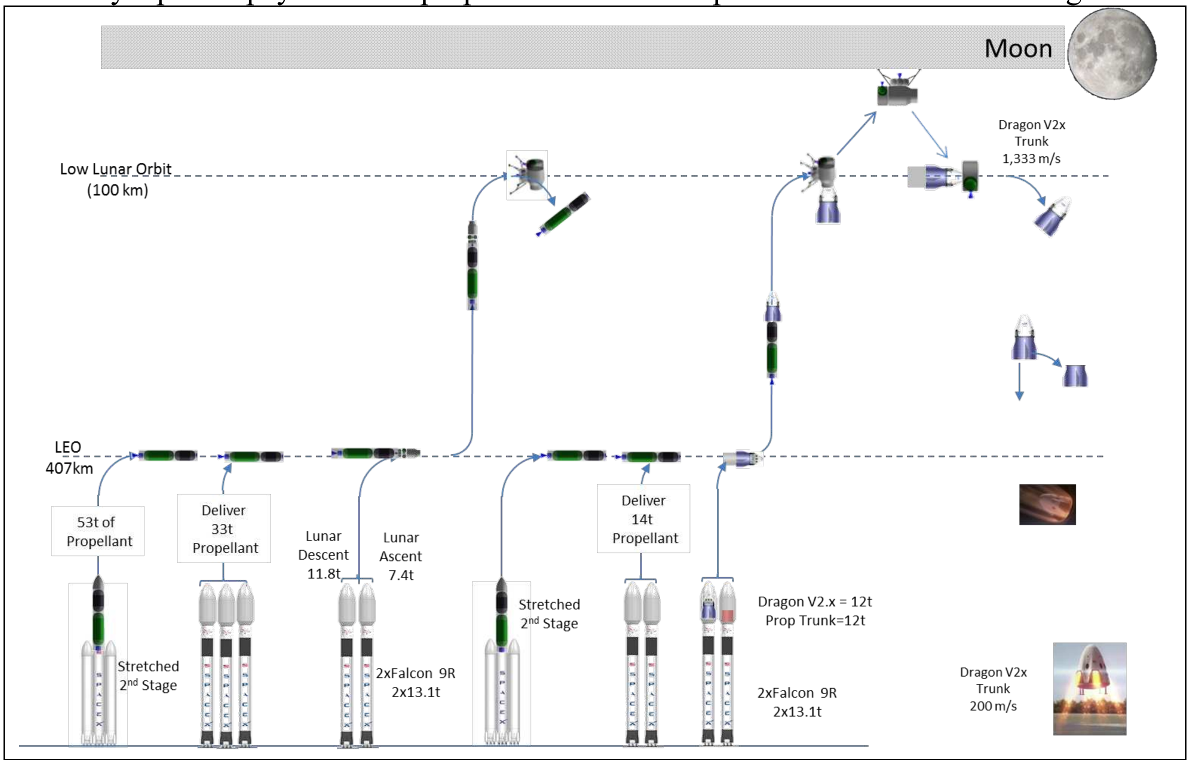


Figure T-11. Phase 2 System Architecture

had a full payload of propellant and might be justified on economics or for operational reasons, we assumed direct propellant transfers from the launcher to the TLI stage.

Phase 2 continues lunar transport operations and testing of LOX/LH2 ISRU propellant plant systems at the lunar poles. In parallel, technology development continues to develop the technology for Phase 3.

Technology: Phase 2 technology developments support the DDT&E of the ISRU production plant and the delivery system of the propellant to L2 for the Mars Transfer Vehicle in Phase 3. High risk developments include a highly reliable, supportable, and efficient ISRU system, reusable LOX/LH2 rockets to deliver the propellant to L2 and return to the lunar surface. Other medium risk technology developments include a cryocooler system for zero boil-off on the lunar surface and at L2, in-space storage and transfer of LH2 (LOX was demonstrated in Phase 1), lunar human and cargo rovers for ISRU operations, a large highly reliable human outpost for 4 crew.

Phase 3 — Propellant Delivery to L2 & Permanent Lunar Base

The Phase 3 system architecture is shown in Figure T-12. Transportation to the moon still assumes use of the Falcon Heavy with the 2nd stage refilled with Falcon 9Rs. The key differences are in the operation of the LOX/LH2 ISRU production plant and the transport of the propellant to a depot in L2 with a reusable LOX/LH2 Lunar module.

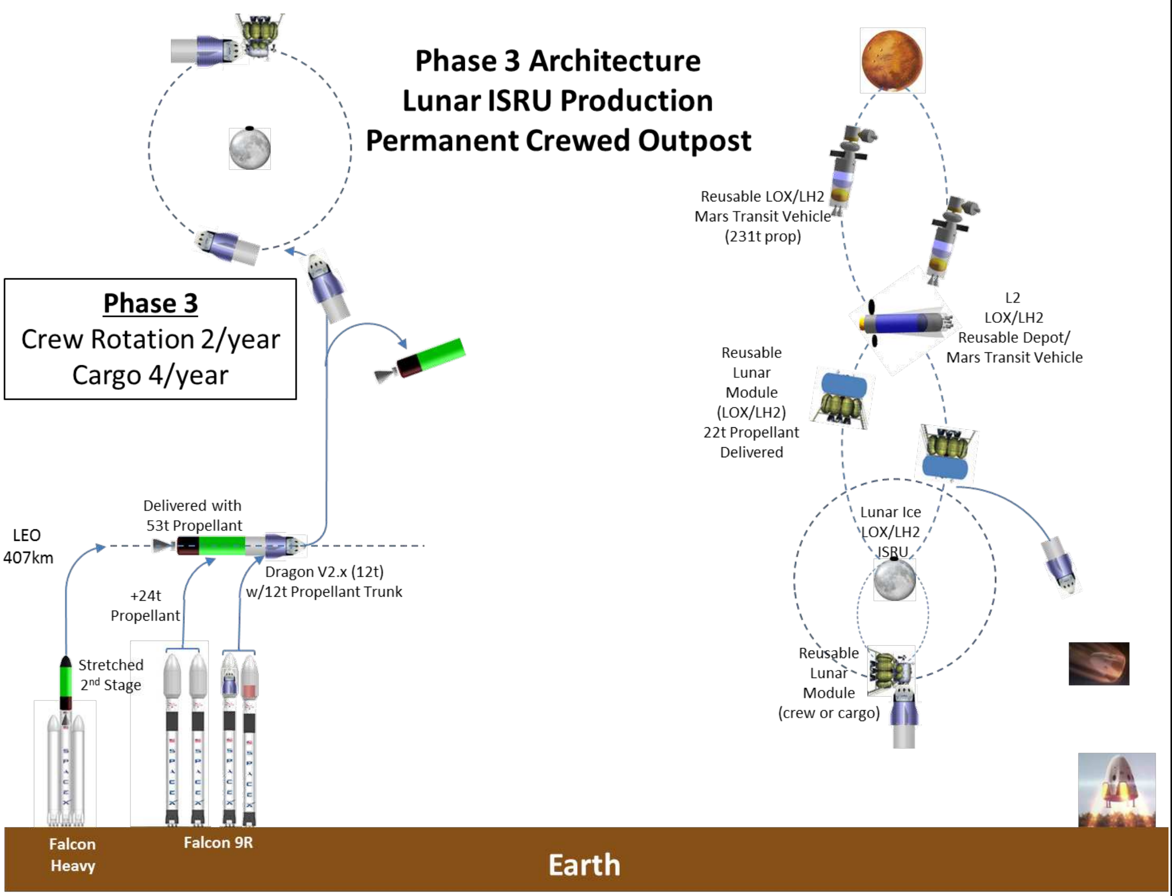


Figure T-12. Phase 3 System Architecture

Reusable Lunar Module (RLM). The RLM is designed to deliver the propellant to L2 and return. In addition, the RLM replaces the Phase 1 Lunar Module and delivers from low-lunar orbit to the surface the following: the ISRU plant, human and cargo lunar rovers, All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHELETE) for lifting and moving cargo, the large 4-crew habitat, and as well as crew as seen in Figure T-13. This is based on a NASA-designed lunar base buildup scenario.[xvii].

The RLM has reusable LOX/LH2 engines with performance similar to the RL10B-2 with a specific impulse of 465s. The RLM was designed for a low-lunar orbit to surface payload of 24.3t capturing the ISRU plant of 22t and the habitat of 20t. For propellant delivery to L2, 13 flights per year are required for the assumed LOX/LH2 Mars Transfer Vehicle with a propellant payload of 12.2t and tanks and airborne

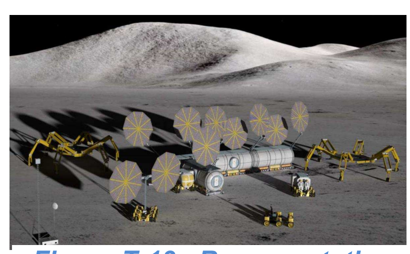


Figure T-13. Representative Lunar Outpost support equipment of 10 and 20 percent respectively. The RLM has an inert mass of 8.3t and propellant mass of 47t giving a propellant mass fraction of 0.90.

LOX/LH2 ISRU Plant. The ISRU plant was designed to produce LOX/LH2 for the LOX/LH2 Mars transfer Vehicle based on NASA's DRA 5.0 Mars Architecture.[xviii] The architecture supported two 103t cargo flights followed 26 months later by a 62.8t payload crew flight. A two-stage Mars Transfer Vehicle was conceptually designed using the same reusable LOX/LH2 engines as the RLM and a propellant mass fraction of 0.9 (same as the Saturn S-IVB). The total propellant required for each mission was 158t where the 103t cargo flights were one way to Mars and the crewed flight was round trip to L2. The Mars cargo payload is delivered to L2 in two increments and the crewed payload in one flight.

The RLM was designed to transport the propellant to L2 requiring 38t per flight and 13 flights per year. Thus the ISRU plant is designed to produce propellant for the RLM as well as the MTV propellant totaling 707t per year. Using a 10 percent margin, the ISRU plant was designed to produce 777t per year. Modularization of the ISRU systems to allow delivery and operation in increments is planned to allow initial production at 1/3 of total planned capacity with growth to full capacity in two additional increments. This allows for learning between increments to be implemented in the ISRU design, operation at partial capacity in the event part of the system is down for maintenance, and provides for future growth if needed.

Ice Concentration	1.00%
Annual Propellant Demanded	777,000 kg
Water (3.52kg/day; 4-crew; 20% margin)	6,167 kg
Oxygen (0.84kg/day; 4-Crew; 20% margin)	1,472 kg
Mining Equipment	
Front Loader	1,078 kg
Hauler	889 kg
Low Pressure Feed Hopper	13 kg
High Pressure Feed Hopper	88 kg
Regotith Thermal Processing	561 kg
Electrolysis	2,728 kg
Oxygen Liquefier	1,559 kg
Hydrogen Liquefier	566 kg
Water Tank	234 kg
Oxygen Tank	935 kg
Hydrogen Tank	2,306 kg
Nuclear Power System (SNAP-50 alpha)	10,764 kg
Total ISRU Plant	21,721 kg

Figure T-14. ISRU Production Plant

The ISRU model is similar to results presented in the Lunar Surface Construction & Assembly Equipment Study in 1988[xix]. It is assumed that the lunar pole regolith is 1% water ice being conservative of 1.4% from Chandrayann-1 and 5.6% from Lunar Reconnaissance Orbiter. The model consists of front loader, hauler, low and high-pressure hoppers, electrolysis, oxygen and hydrogen liquefiers and tanks, and power. The ISRU components and total mass are shown in Figure T-14. A nuclear power plant is assumed; however, with the plant at the poles, solar arrays could be used and the ISRU plant could be delivered in two trips.

Habitat. The largest payload for the RLM is the Bigelow 330 inflatable space habitat. It has a mass of 20t and a 330 m3 volume (13.5 m long by 6.7 m diameter). It is designed to have two solar arrays and thermal radiators and life support systems to support a crew of 6.

Outpost Infrastructure. The pressurized crewed and cargo rovers were taken from the MARS DRA 5.0 study with masses of 9.6t and 0.5t.

For lifting and moving large components like the ISRU plant and habitat, the JPL ATHLETE was selected. Based on analysis by Brian Wilcox of NASA JPL,[xx] the ATHLETE was sized for the lunar surface carrying a 25t payload resulting in a total mass of 4.8t including a 30% mass margin.

L2 Propellant Depot. The LOX/LH2 L2 propellant depot was selected from previous analysis on propellant depots[xxi] for the required propellant mass storage of 230t. The depot has an empty mass of 18.2t thus in the same payload class of the IRU plant and habitat. The depot is designed for zero boiloff with a cryocooler system mass of 2.2t requiring a power of 2.6kW that was designed by Dr. David Chato at NASA Glenn. The depot has propulsion for station keeping at the Earth-moon Lagrange points (EML1 and EML2) that require 50m/s of deltaV.

Phase 4+ (Optional) — Reusable OTV between LEO and L2

One of the major remaining cost drivers in Phase 3 is the transport of payloads from LEO to lunar orbit. This is a significant cost of permanent lunar operations, as well as the delivery of the Mars payload from low-Earth orbit to L2 for integration on the Mars Transfer Vehicle. One potential next evolution in the ELA is the development of a reusable Orbital Transfer Vehicle (ROTV) that is optimized for transporting large payloads between LEO and lunar orbit. This OTV could be refueled either in LEO or from the Moon.

In NASA's Mars DRA 5.0 study[xxii], one complete mission requires three trips to Mars. The first two trips deliver the required 103t of payload for each cargo delivery and the third trip, taking place 26 months later, delivers the crew to Mars. The cargo mainly includes the aerobreak shell (2x43.7t), descent stage (2x23.3t), surface habitat (16.5t), nuclear power (7.3t), ascent stages (21.5t w/RP propellant), ISRU plant (1.3t), rovers and power (10.6), crew consumables (6t) and miscellaneous smaller items. The crew system consists of the transit habitat (32.8t) and a backup Command Module (13.2t, Dragon V2x in this study).

The initial transfer to L2 of the Mars cargo uses the expendable filled Falcon 2nd stage for transfer requiring the delivery of the stage and one-way propellant requiring 8 Falcon 9Rs or 2 Falcon Heavys.

We specifically studied the concept of an ROTV that is filled with lunar LOX/LH2 at L2 and completes a TEI burn with no payload and a trans-L2 injection burn with payload. To maintain a reasonable size for the ROTV, a payload of 27t was selected (one-quarter of each cargo payload mass). For an ROTV that uses propulsion for the entire round trip, the performance requirement is 6,967 m/s (deltaV= 3,692 m/s for TransL2 Injection and L2 Insertion, 49m/s TransEarth Injection, and 3,226 m/s for Earth Orbit Insertion). The resulting ROTV vehicle has a gross mass of 229t with an inert mass of 34t and propellant mass of 194t per trip.

However, if Earth aerocapture is employed (Figure T-15), the performance requirement is reduced to 4,041 m/s (deltaV= 3,692 m/s for TransL2 Injection and L2 Insertion, 49m/s TransEarth Injection, and 300 m/s Earth orbit correction). The analysis assumed the same ballistic coefficient as the Apollo Command Module (capsule) and the same structural and thermal protection system fraction. A 20 percent mass savings can be

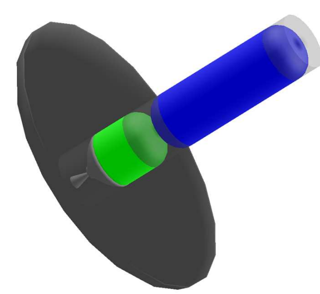


Figure T-15. Aerocapture Reusable OTV Module obtained using the SpaceX Dragon heatshield with composite load bearing structure and modern PICA thermal protection material. The resulting ROTV has a gross mass of 154t, with inert mass of 48t (including the 34t aeroshield), and propellant mass of 106t.

With the aerocapture ROTV, a reusable heatshield has to be developed to eliminate the need to deliver a heatshield to L2 for each roundtrip. Options include a larger area (lower ballistic coefficient) to reduce heating for a non-ablative heatshield possibly using an inflatable concept or use the "free" lunar water for transpiration cooling to further reduce the surface heating.

The resulting impact on the system architecture is an additional same-size ISRU plant and an additional Reusable Lunar Module for delivering the propellant to the ROTV.

Technical Risk Assessment

The main technical risks of the system architecture are the following:

ISRU Processing & Exploitable Lunar Ice	(High)
Reliable LOX/LH2 ISRU system	(High)
Long Life (100+ uses) Cryo Rockets	(High)
LOX/LH2 Storage and Orbit Transfer	(Med)
Long Life (years) Commercial Habitats	(Med)
Long Duration Dragon V2.1/CST-200 w/prop	(Low)

> ***The most significant system-level technical risk of the ELA is the possibility we will not find abundant enough levels of accessible hydrogen, which is critical to enabling economical production of lunar propellant.***

The most significant system-level technical risk of the entire ELA is the possibility we will not find abundant enough levels of accessible hydrogen, which is critical to enabling economical production of lunar propellant. While we have proven that there is hydrogen trapped in lunar polar craters, we do not know how deep the water/hydrogen is buried, or if it is locked up in some form that is uneconomical to release. To mitigate this risk, rovers and prospecting systems need to be developed, tested, demonstrated, and validated. The availability of readily and economically available water, or hydrogen, at the lunar poles needs to be proven before significant investments can be made in all the other ISRU systems and the reusable lunar module that depends on lunar propellant. To the extent national decision-makers value the economical production of propellant at the lunar poles, this objective needs to be a top priority.

Next, although the physics of harvesting and processing lunar ice into water and liquid oxygen and hydrogen are well known, a key technology to develop is an extremely reliable and autonomous system for mining the water/hydrogen. While these systems must be designed to be reliable and autonomous, they must also be remotely repaired by robots and/or humans on the surface of the Moon. The primary economic purpose of humans of the Moon is repairing and maintaining the autonomous systems. Just as we at ISS, but even more so, astronaut time is going to be the most rare and precious resource. Spares and line replace units are planned, but a constant transfer of ISRU subsystems or complete systems from Earth would destroy the economics of propellant supply. Related to this, the ability to rapidly manufacture replacement parts on the Moon using local materials and additive manufacturing will be a critical technology.

The final high-risk technology is long-life cryogenic rocket engines for the Earth-moon and moon-L2 transfer modules. In the Phase 3 operational scenario, every year there are six trips from LEO to the moon for crew and cargo delivery, plus 13 trips from the surface of the moon to L2 for propellant delivery. A fully reusable lunar landing system is mandatory in this architecture, with the primary technical challenge being highly-reliable and reusable cryogenic rocket engines.

The cryogenic propellant storage and orbit transfer is rated at a medium risk. Propellant transfer has been shown to be viable through the many Russian Progress, Automated Transfer Vehicle (ATV)/space station and the DARPA Orbital Express demonstration. But these propellants are storables; with cryogenics the key areas of concern are no-leak connectors and low-boiloff transfer. The transfer may be completed by mechanical means, circular momentum, or by low-g fluid settling.

For zero boiloff, there are existing Earth-based cryocoolers such as the Cryomech Gifford-McMahon Cryorefrigerator that has the capacity and size required for the ISRU plant and propellant depot. The AL325 requires only 11.2 kW of power, weighs 22 kg, small volume (122 x 102 x 150 cm) and costs $43k. Technology development requires changing the cooling liquid from water and 0-g operation. The other medium risk technology is long-life human habitats. The key is to reduce maintenance and spares to enable economical long-life operations.

Life Cycle Cost Estimates

NexGen's life cycle cost (LCC) analysis of the evolvable lunar architecture (ELA) addresses key factors beyond the cost of the elements (launchers, landers, spacecraft, etc.) These factors include: (1) modeling and uncertainty, (2) a NASA budget context, and (3) integrating innovative ways of doing business. This economic assessment of the ELA, devised using public-private partnerships to create an affordable and sustainable approach, used a combination of system engineering, economic modeling and analysis, and a NASA budget context to assess life cycle alternatives.

The maturity and value of an estimate in making decisions among various options depends on certain factors. These include a clear purpose to the estimate, the expertise of the estimators, the availability of suitable historical data, and understanding uncertainties. NexGen's team included subject matter experts (Wilhite and Zapata) with over six decades of experience in space systems cost estimation and economic modeling, and leveraged access to many decades of historical cost data, including relatively new data about the cost efficiencies of commercial partnerships.

Basis of Estimate

NexGen's LCC estimates for the ELA reduced traditional cost estimation models over-emphasis on weight-based cost estimation — which loses significant context in the data. We focused on the development of an integrated, comprehensive LCC (development, manufacturing, flight and ground operations, procurement and government), all within a proper NASA budget context, and incorporated non-technical acquisition approaches alongside traditional technical/design factors.

For this Basis of Estimate (BOE), the LCC model applied estimates of all life cycle costs consistent with NASA budget practice. For the ELA assessment, we included:

- Non-recurring and recurring costs
- Development, manufacturing, ground operations & launch costs, and
- Direct and indirect costs:
  - Industry / procurement (contractor, partner, support contractors, and related)
  - Government (civil servants, government management and related)
    - Program Management (i.e., Level 1 NASA at HQ, etc.)
    - Project Management (i.e., Level 2/3 NASA at centers, by element, etc.)

Ground Rules

As described in the Study Assumptions (see page 6), the NASA budget into which the ELA cost estimates must be phased is limited to slightly less than $3B per year. This is the amount below the blue-dashed-line in Figure LCC-1.

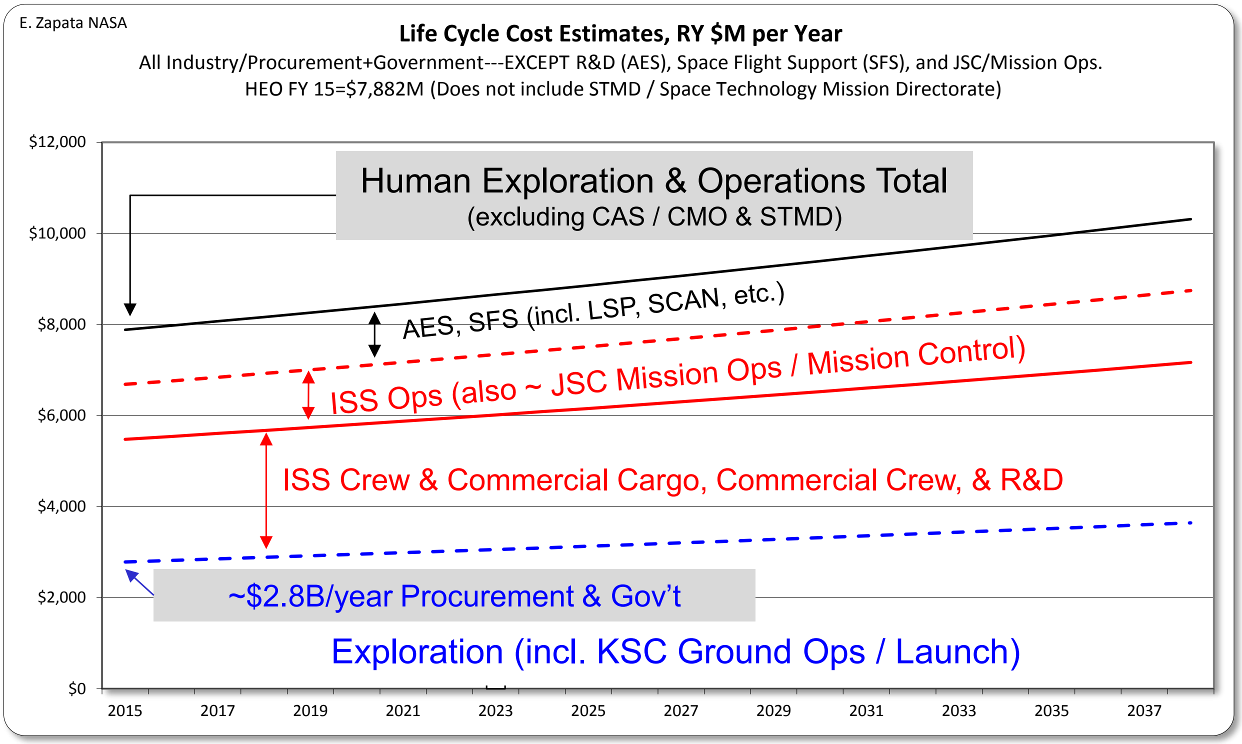


Figure LCC-1. The NASA Human Exploration & Operations budget splits.

Additional ground rules for the ELA include:

- Address the concurrence of the architecture with other NASA projects and elements (e.g., cargo/crew to ISS) and any cost effects, such as using these available elements or elements derived from these.
- Use year 2017 as year 1 / Authority to Proceed.
- Target 2 crew flights per year to lunar surface locations.
  - Cargo support flights linked.

Assumptions

Given the importance of assumptions to a cost estimate, NexGen's analysis made assumptions across all major Human Exploration & Operations budget items. The most significant of NexGen's assumptions include:

- Assume the ISS is operational concurrent with the architecture
  - ISS R&D, cargo transport to ISS, and crew transport to ISS continues. ISS funding is generally not available for other purposes throughout the life of the project.
  - Exception: ISS Operations as ~ equivalent to Mission Operations (see ahead).
  - Exception: Lunar architecture possibly indirectly reducing costs of cargo & crew missions to ISS, and/or to a post-202x (TBD) ISS end-state or ISS follow-on.
  - Most Human Spaceflight areas not affected – Mission Operations, AES, SFS, Space Technology

    - Exception: Additional capabilities & costs due to certain in-space operations to be addressed separately (“Other In-space Operations”).
    - Exception: Address potential NASA Spacecraft Communications and Network (SCaN) budget shortfalls, whereby existing capabilities may be adequate to support cis-lunar operations, but using these capabilities would incur costs.
        - Additional SCaN capabilities offer new opportunities via a NASA commercial acquisition.
- Assume NASA budget growth vs. aerospace cost inflation factors – per assorted scenarios (NASA inflation index, usual OMB or agency guidance, etc. or other scenarios; some scenarios lose purchasing power over time)
- Assume NASA Civil Service levels persist. No ability to convert any government program/project management savings into procurement / partner $.
- According to the Acquisition Entity, assume effects on prices consistent with prior experience applies – key consideration affecting prices from providers / partners (prices = costs to NASA)
    - Phase 1 NASA acquisition approach is analogous to the Commercial Orbital Transportation Services / Cargo Resupply Services (COTS/CRS) development & acquisition partnerships
    - Phase 2 & 3 NASA acquisition approach is a series of development & acquisition partnerships with a “Lunar Authority” analogous entity (covered separately)
- Other customers / business case impacts
    - Integrate the amortization effect of the Acquisition Entity procuring elements that are also common with other non-NASA customers or business cases (unit volume dependency, etc.)
    - Investment business cases
    - The effect of a providing partner investing X % private capital in development that is not recovered by the partner until later in recurring operations (smoothen phasing).

Historical Data

While ground rules and assumptions (GR&A) set the stage for a cost estimate, historical data provides a foundation. NexGen’s estimate of the ELA’s LCC required estimates of elements from spacecraft to launchers to unique space systems, including related operations, atop which would rest any government program and project management.

Given that many ELA space system elements are cargo or crew spacecraft of some type, and given that this study’s purpose was to explore public-private partnerships, recent hard data from partnerships that are developing cargo and crew spacecraft was preferred in developing cost estimates. Figures LCC-2 and Figure LCC-3 show data across a range of spacecraft, from (1) space to surface, from (2) much older to very recent programs, from (3) cargo to crew applications, and from (4) cost-plus ownership to commercial partnership acquisitions.

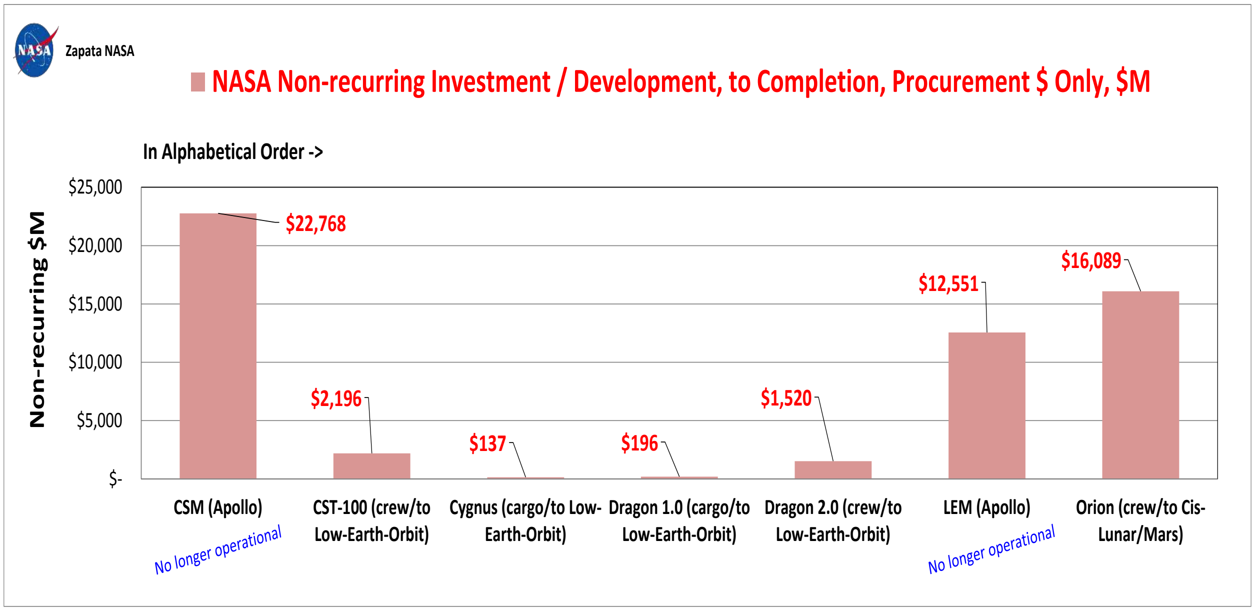


Figure LCC-2. NASA NRC development costs of spacecraft, procurement only, assorted

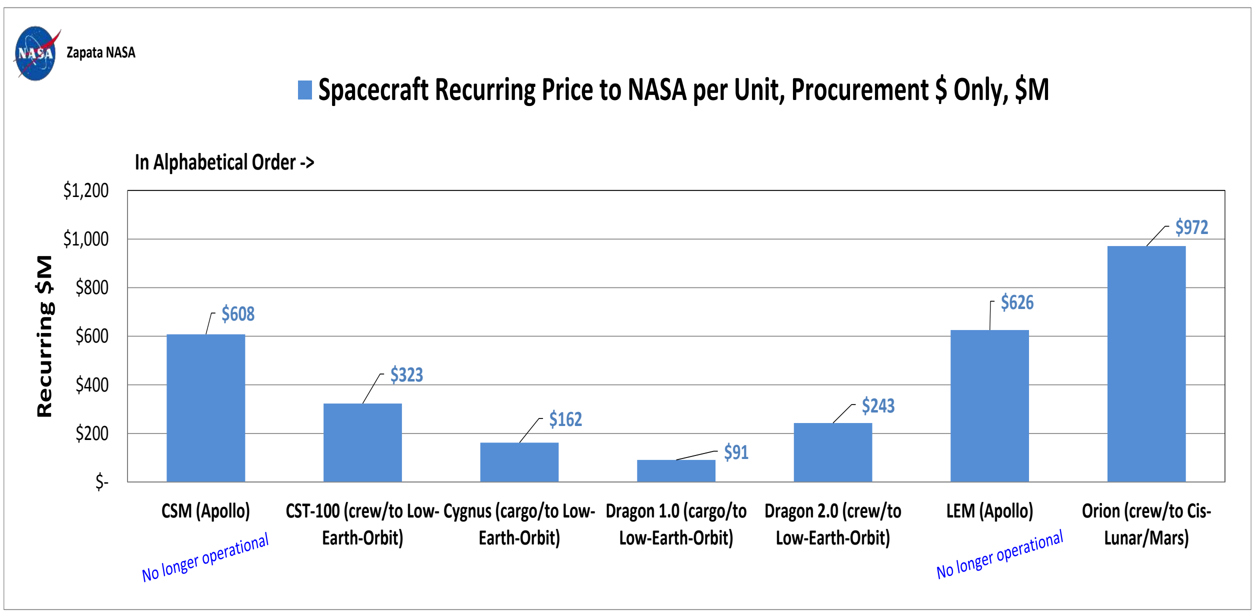


Figure LCC-3. NASA RC price per unit, costs of spacecraft, procurement only, assorted

For launch services, recent NASA contract price data was preferred for estimating the costs of acquiring launch services in the ELA. The launch price (specifically, the price to NASA) can be characterized not just according to class of payload, but also according to block purchases of launches. The ISS, through the ISS Space Transportation Office, or the Commercial Crew Office has made bulk multi-year purchases, vs. purchases of just one launch through the Launch Services Program (LSP). Where data was not available, the cost estimate used a cost estimating relationship consistent with the extent of what data was available. For example, NASA has procured Falcon 9 launchers as block-buys (within ISS cargo and crew services) and as one only (for science missions). The cost estimating applied additional costs and premiums for NASA acquiring the services of a Falcon Heavy fully consistent with Falcon 9 acquisition data.

Ground and mission operations are additional costs beyond the cost of acquiring spacecraft and launch systems. According to the scenario, cost-estimating relationships applied consistent with both historical data (usually the upper bound) and the partnership approach (the lower bound).

To be conservative, the estimate calculated government program and project management across all phases and elements of the ELA at traditional levels. These estimates may be extremely high and inconsistent with a partnership approach, but consistent with the NASA budget whereby any savings here do not easily convert into additional procurement dollars. The conservative approach was preferred, consistent with the NASA budget, if not the partnership approach.

Lastly, for estimating the cost of unique items, for example a propellant depot, the process relied on a combination of past studies, subject matter experts and conservatism again applied atop any values.

To address uncertainty at steps along the basis of estimate, the process created a three-point estimate across any points of departure as well as within adjustments and extrapolations. This is consistent with the level of assessment of this study, as an "architecture" or concept level LCC profile.

Modeling & Analysis - Scope

Figure LCC-4 summarizes what is included in a cost estimate, the "itemized bill", and what is not, and what is addressed in some way other than being included as a cost estimate (an assumption for example).

Phase 1

Non-recurring Costs:
- Prospectors
- Landers for Prospectors
- LO/RP Storage/Transfer Demo
- ALL Launchers for Prior
- ISRU Demo (6.5t) Development
- Mods of 2nd Stages, Stretch
- Mods of LEO spacecraft to Cis-lunar Capable
- Crewed Lunar Lander Development (Expendable, 2 Partners)
- Test Flight Unit Items
  - Prior Spacecraft
  - Prior Lunar Landers
  - Launchers for Prior

Recurring Costs:
- Crew Spacecraft
- Landers
- Launchers for Prior
- In-space Ops (see FAQ)

Phase 2

Non-recurring costs:
- Carrier Tanks Development
- Mod of 2nd Stages, to Fillable
- Launchers for Test Flights of Prior
- Launcher for ISRU Demo (from Ph. 1)
- LH2 storage Transfer Demo, Hosted

Recurring Costs:
- Carrier Tanks
- Crew Spacecraft
- Crew Landers
- Launchers for Prior
- In-space Ops (see FAQ)

Phase 3

Non-recurring Costs:
- Crewed Lunar Lander Development (Reusable, 2 Partners)
  - + 1st Unit
- ISRU Plant Development (Full Scale)
- LLO Refueling Station Development
- Rovers Development + 2 Units
- Equipment Development ("ATHLETES") + 2 Units
- Habitat Development + 2 Units
- Launchers for Prior (per Ph. 2, 2nd Stg Fillable)
- Carrier Tanks for Prior Launchers

Recurring Costs

Cargo
- Cargo / Canisters (& Lander / Descent Portion)
- Launchers for Prior

Crew
- Crew Spacecraft
- Launchers for Prior (per Ph. 2, 2nd Stg Fillable)
- Carrier Tanks for Prior Launchers
- Crew Use / Ops of Lander (Reused)

Operations
- In-space Ops, +More Surface Ops of Prior

Replacement
- Continuous Replacement Costs - Life Limited Items (Reusable Lander, ISRU Plant, etc.)

+ $ Across All Phases > Government Program Management, Project Management, KSC Ground Ops

+ What $ are elsewhere @ existing NASA budget levels > Space Flight Support (incl. SCaN, LSP), JSC Mission Control & Ops (see FAQ), and R&D & Technology (AES, STMD)

Figure LCC-4. Scope of the LCC of the ELA.

Modeling & Analysis – Drivers

Some of the cost drivers of particular interest in the ELA are primarily non-technical.

- Phase 1 operates under a COTS/CRS acquisition model
  - Assume slightly more efficient than Commercial Crew acquisition model
  - Crew Spacecraft - some reusability (crew module portion)
  - Launchers - expendable
  - Lunar landers – new / expendable
    - Two developments as w. commercial partnership acquisitions; with two providers, for dissimilar redundancy and competition.
- Phase 2 & 3
  - "Lunar Authority" partnership / acquisition model improves prices (costs) to NASA over Phase 1
  - Launchers - some reusability
- Phase 3
  - Lunar lander – new / reusable (additional in-space ops, etc.); two as before for dissimilar redundancy and competition.
  - Rovers, equipment, habitats
  - Additional replacement costs of life limited items
    - Esp. ISRU facility, landers, and L2 refueling station, rovers, etc.

Modeling & Analysis – Context, the NASA Budget

The basis of estimate receives its context from within NASA budget scenarios based on hard empirical data. We assumed a budget increase based on the average budget growth of NASA's budget over the last 13 years (at 1.175% per year), and assume this will be exceeded by the level of cost inflation in the system (estimated at 2.5% per year, per the official NASA Inflation Index). This conservative baseline scenario assumption reduces the purchase power available to NASA over time. Figure LCC-5 shows NASA budget data since 2003, arranged to show a flow of funds of like items. For example, Shuttle "operations" (red) segue into Commercial Cargo and Crew –again "operations". This data shows that NASA's actual top line budget has grown by 1.175% per year, but NASA's real purchasing power has decreased because of inflation.

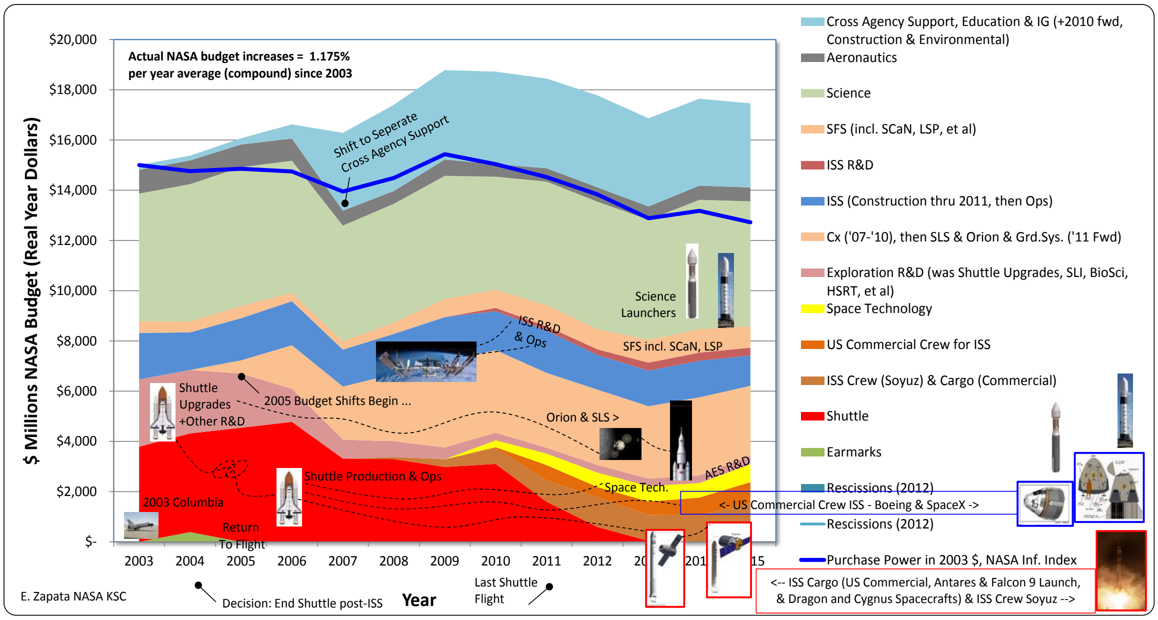


Figure LCC-5. The NASA budget since 2003. *All data from public NASA budget documents, "actuals" 2003 to 2013. 2014 and 2015 from public documents estimating costs (actuals pending).*

Life Cycle Cost Assessment - Results

The assessment placed the component costs of elements of the lunar architecture in a schedule, with development leading to manufacturing and operations, and later phases overlapping a prior phase of operation. The study goal was to remain (roughly) below a yearly budget constraint and above a certain flight rate tempo. The baseline case shown in Figure LCC-6 has the following characteristics:

- **Partnerships Driven**

-NASA COTS/CRS-like acquisition drives Phase 1
-NASA Partnership with a Lunar Authority drives Phase 2 & 3
-Landers and ISRU developments drive Phase 1 then 3 (Phase 2 transition less so)

- **Conservative, Margin**

-Uses the historical NASA budget growth since 2003
-Cost Inflation 2017 forward per the NASA Inflation Index
-Loses purchasing power over time

- **A slight overshoot in Phases 1 & 2**

-But having margin in Phase 3
-Consistent with ISS improvement, "future" ISS & post-2024 ISS
-Further optimizing would easily address and eliminate any overshoot

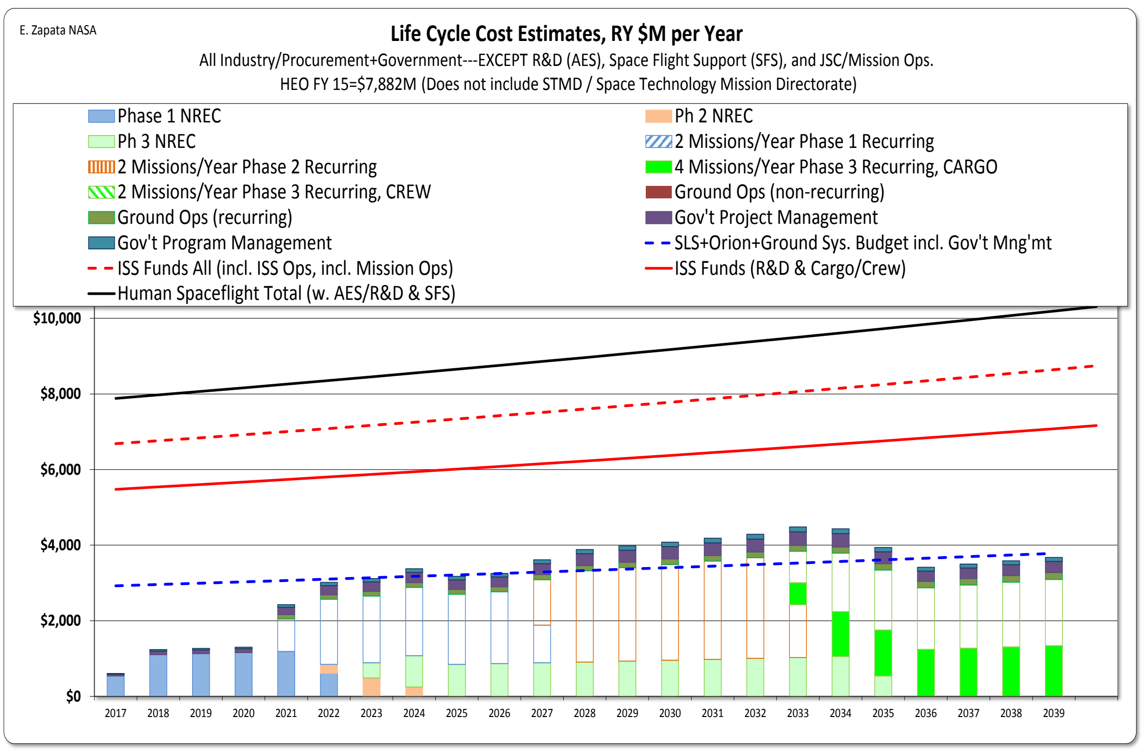


Figure LCC-6. Initial Conservative Scenario. Estimated costs across time for the baseline Evolvable Lunar Architecture.

In close-up, Figure LCC-7 shows the same results as Figure LCC-6 (putting aside funding within the ISS and other spaceflight budget lines).

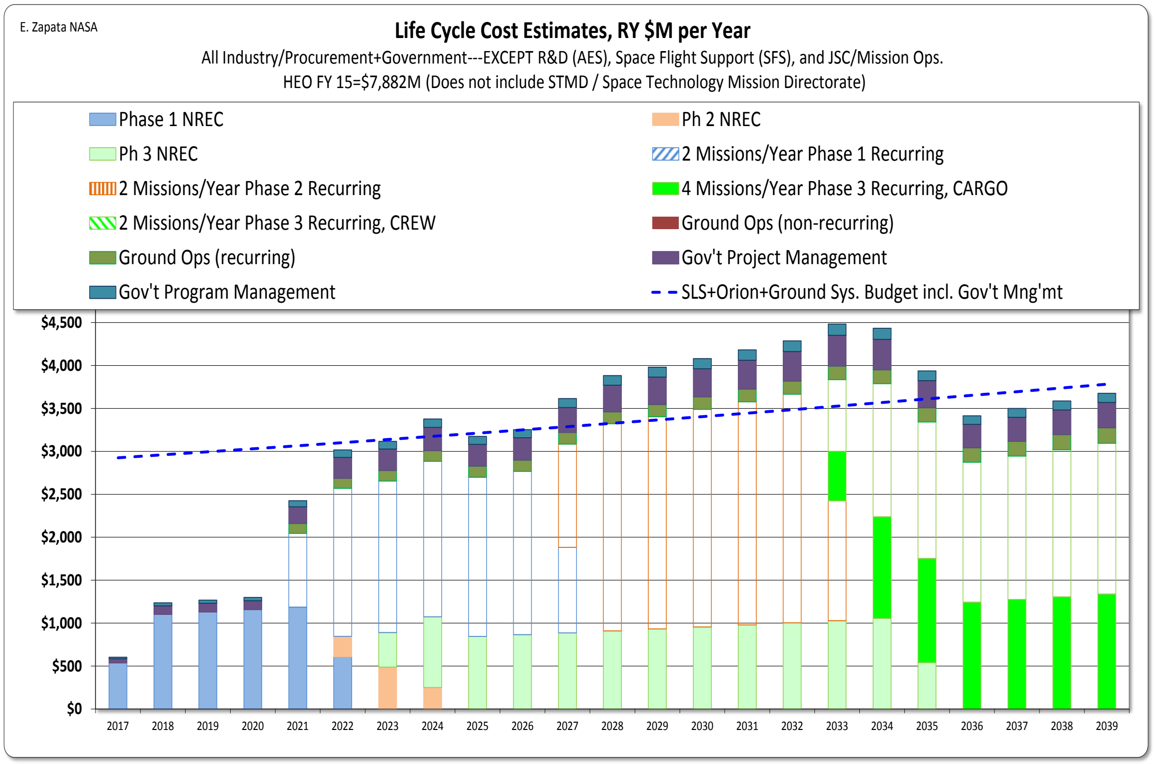


Figure LCC-7. Initial Scenario. *Close-up of estimated costs across time for the baseline ELA.*

This scenario results in:

- First boots on the Moon in 2021
- Two human sorties per year to the lunar surface during development
- A permanent lunar outpost, with delivery of propellant to an L2 depot, beginning in 2032.

However, as mentioned earlier this scenario slightly overshoots the budget constraint.

To understand a baseline life cycle profile, we need to understand its sensitivity to various factors. To do so, we can vary assumptions for (1) the NASA budget, (2) the mission rate for the architecture, and (3) the number of providers (partners).

For example, typical guidance in NASA cost estimation (either internal guidance, or external, as from the Office of Management & Budget/OMB) is that any rate of growth of the NASA budget precisely matches any cost inflation. Making one change, to using a baseline ELA life cycle cost assumption of a budget growing at the rate of inflation, results in Figure LCC-8. All the favorable characteristics of the baseline previously observed still apply, only improved, by virtue of less budget stress and no loss of purchase power over time.

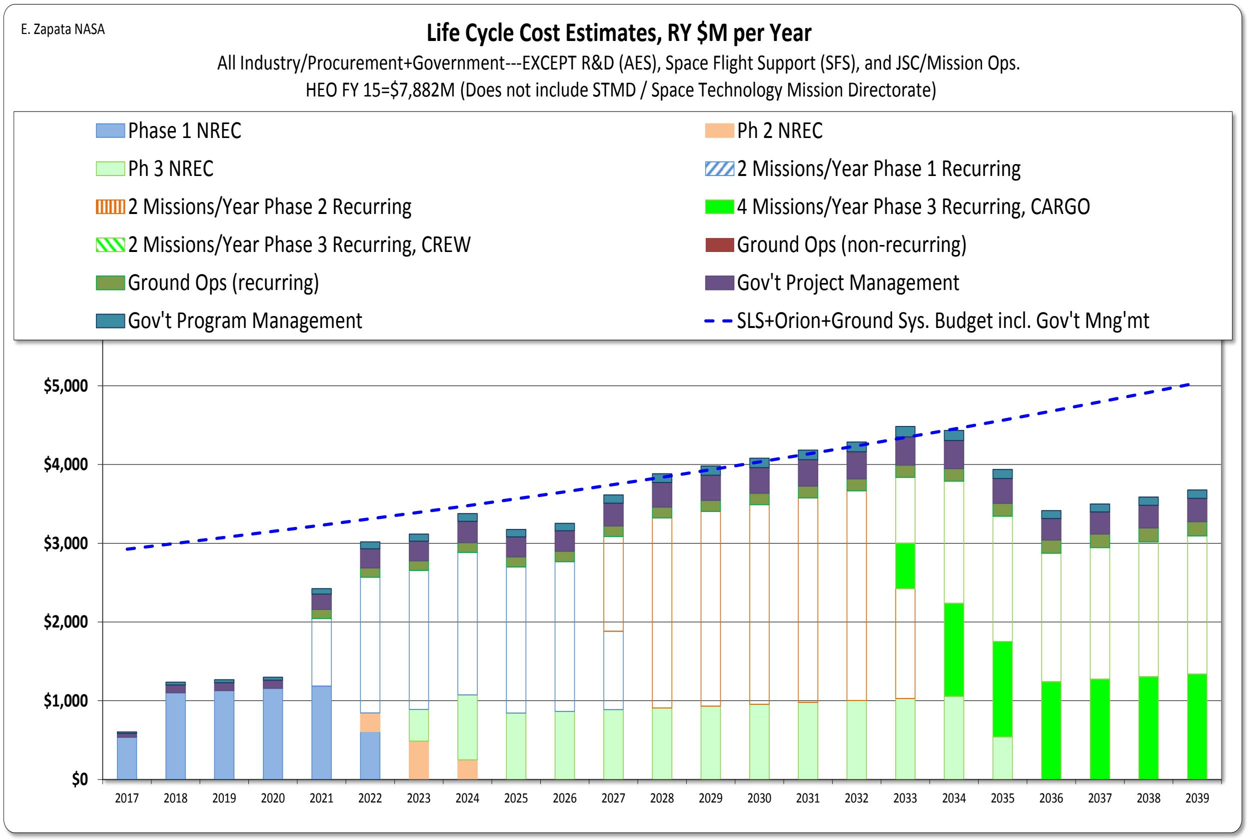


Figure LCC-8. Scenario with budget growth at rate of inflation. ***The baseline life cycle cost of the ELA within a context where budget increases match the rate of cost inflation.***

Since NASA cannot control inflation, nor can it control its budget, the ability of an agency to control costs by other means could be critical. An alternative approach to bring the LCC budget within the budget caps is to alter the mission rates (or flights to the lunar surface per year.) The baseline ELA life cycle with a variation for the mission rate is in Figure LCC-9. We do not believe that reducing the flight and mission rate from the target goals is strictly necessary as we expect that there is likely to be an improvement in the costs based on NASAs continued presence in LEO post-ISS. This scenario shows the extreme where no such improvement occurs and the baseline ELA must live strictly within its yearly budget. As Phase 3 had ample margin, it is able to reach the mission rate goal as before, but Phase 1 and 2 see a slightly lower mission rate indicated.

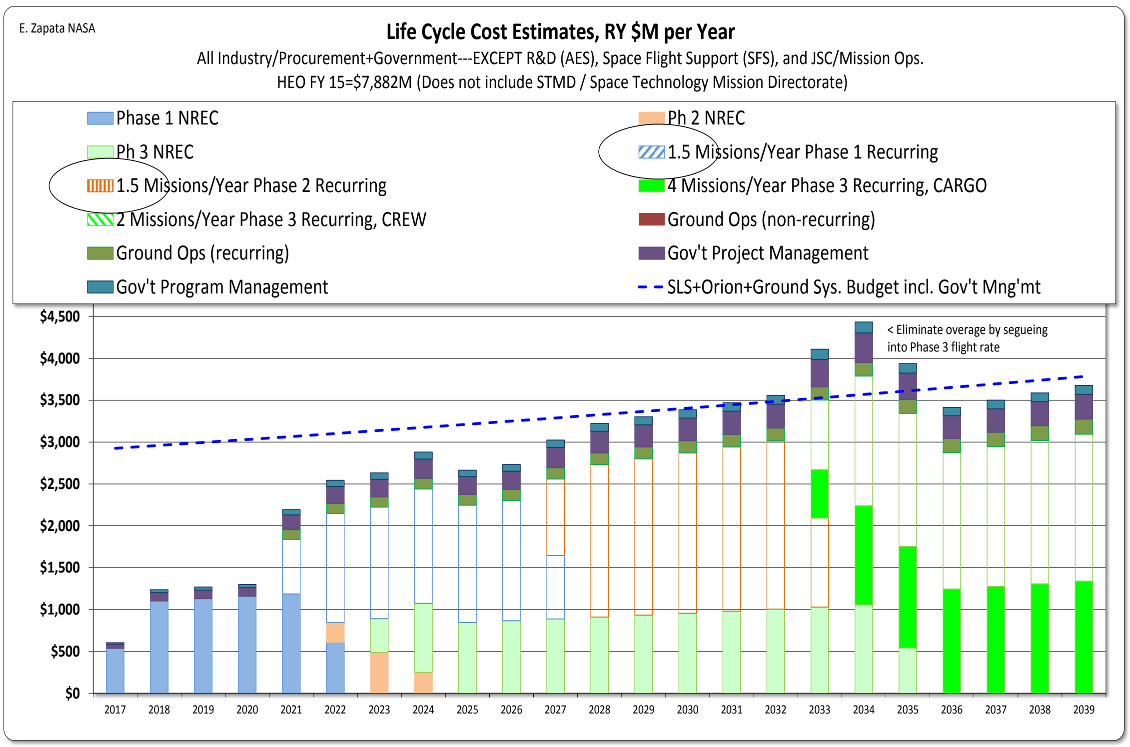


Figure LCC-9. Controlling Total Costs by Mission Rate. ***The baseline life cycle cost of the ELA within a context where no pre or post-ISS funding is available and the architecture must fit within its target yearly budget.***

The baseline ELA is all about partnerships. NASA's recent experience in development and operations (as services) have involved more than one partner when applying the partnership model. When comparing traditional development costs to that of recent partnerships (launch vehicles or spacecraft) any one data point can be compared to another. To make a fuller contextual comparison, it is necessary to account for how recent partnerships have the unique characteristic of investing in two providers. If a NASA investment in two providers is intrinsic to aligning incentives (by creating competition) in an analog to the COTS/CRS acquisition model, applying individual cost data from such efforts should reflect retaining two providers. Figure LCC-10 is the baseline ELA with the condition of two providers for launch services and spacecraft (including "fillable" in-space stages as apply). Understanding the degree to which dual partners, requiring two up-front development efforts (NASA investments), is separable or not from the acquisition model is important in forward work.

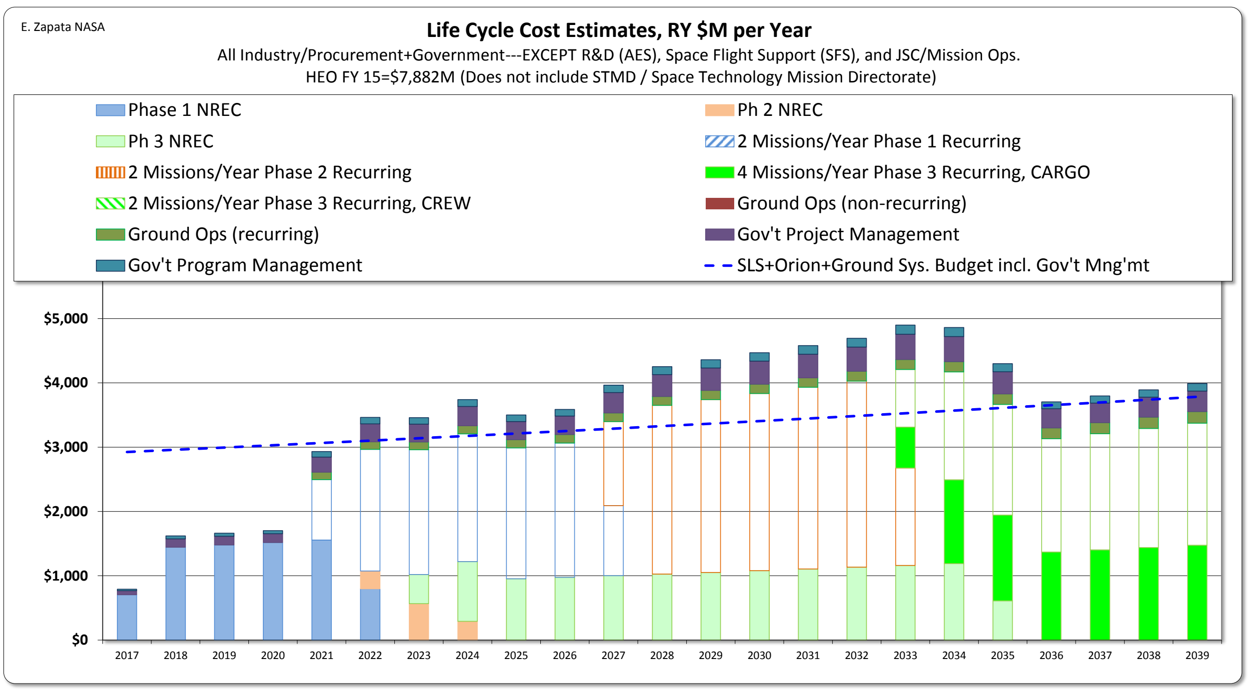


Figure LCC-10. Dual Service Providers: ***Baseline life cycle cost of the ELA with the added feature of dual launch service providers (including in-space stages and operations).***

Although the slight overage appears to violate the yearly budget guidance, Figure LCC-11 in the broader context of the entire HEO budget (same as LCC-10) is manageable with further optimization of the schedule.

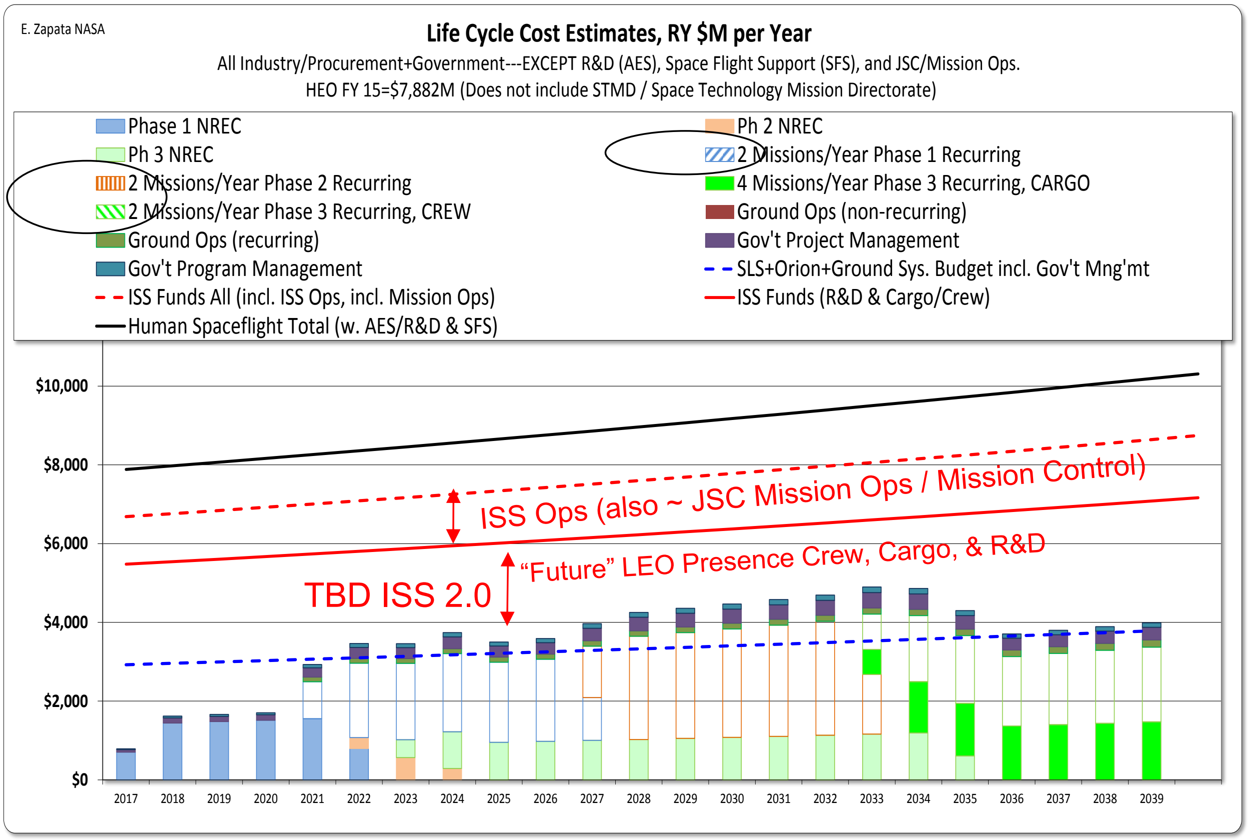


Figure LCC-11. Dual Service Providers; ***Baseline LCC of the ELA with the added feature of dual launch service providers (including in-space stages and operations), shown in a broad HEO budget context.***

Lastly, a useful variation on the baseline ELA scenario would consider the very lowest cost path, using the single lowest cost partners. There would be no redundant providers of any product or service (launch, spacecraft, landers, etc.) In addition, the variation seen in going from the NASA COTS-CRS acquisition model to the Commercial Crew acquisition model could conceivably be reduced further, assuming that the difference is being driven more by non-technical factors rather than technical factors of kind (cargo to crew). Figure X shows the existing variation in development and manufacturing costs as the paradigm shifts from commercial cargo, to commercial crew, to cost-plus.

This option would be consistent with a "what-if" case of a private investor, if looking to understand what would be involved in providing an end-to-end service with a singular purpose, the provision of propellant to a buyer, which could be NASA, at a node in lunar orbit. The "buyer", NASA or others, would be acquiring propellant for purposes other than the Moon, such as for Mars exploration (stages, spacecraft, etc.)

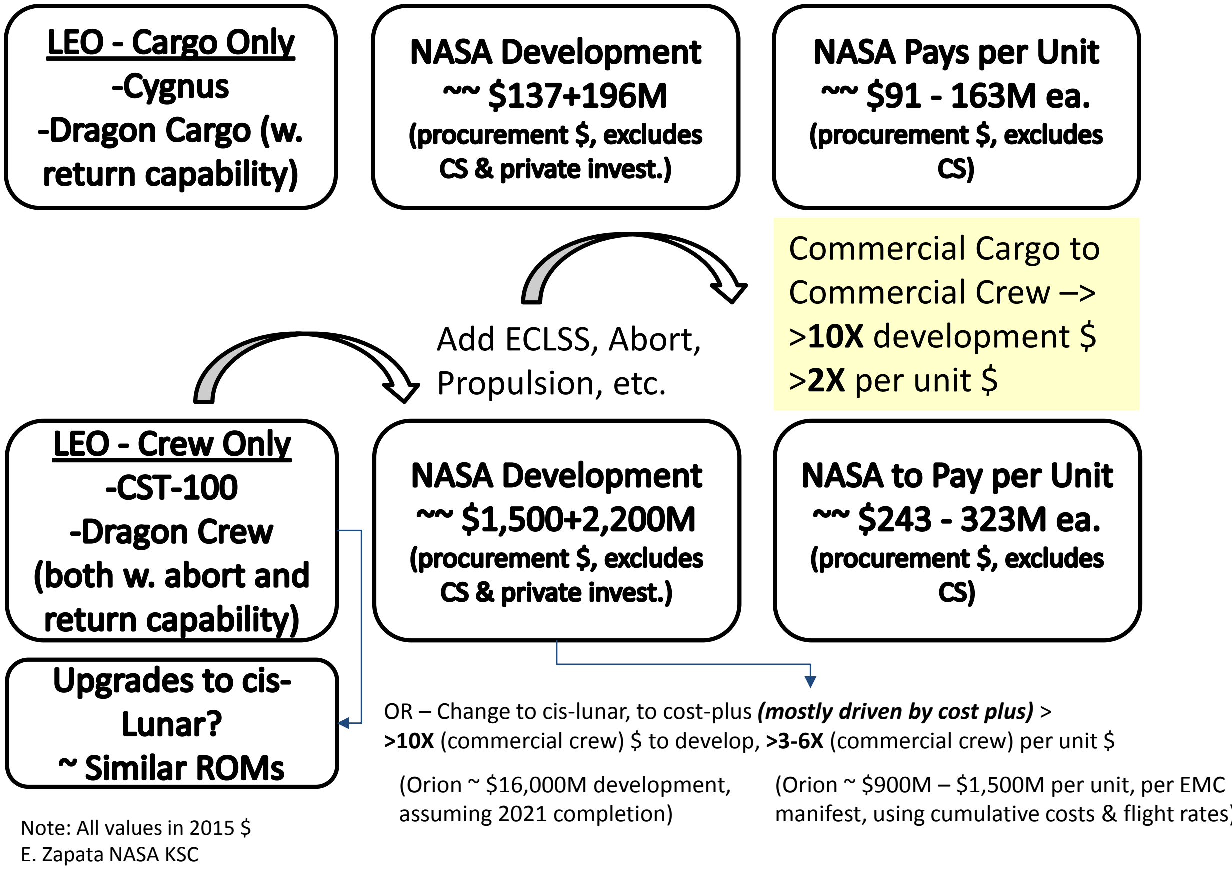


Figure LCC-12. Variation in LCC by Acquisition Strategy. ***Variation in development and manufacturing costs as an acquisition goes from a commercial cargo / service to a commercial crew / service to a cost-plus crew / owned paradigm.***

At a first order, in the private investor case, launch services are less, going with the lowest cost partner (but lacking redundancy in the supply chain). Similarly, relatively expensive dual developments, as for cis-lunar spacecraft or lunar landers are roughly halved, also from having just one partner. Being a private investor, the cost estimates of crewed spacecraft development and manufacturing are also further reduced from the Commercial Crew paradigm, assuming further non-technical drivers and efficiencies from the private investor paradigm. Lastly, government and some related costs have been removed from this view (program/project management, etc.) Figure LCC-13 shows the results for this case.

Forward work would be required to mature this case, especially to understand the technical vs. non-technical drivers in costs diverging as much as shown in Figure LCC-12 in going from the cargo to the crew acquisition. Also, the private investor paradigm has not been applied to the ISRU related costs (here the same as prior cases). Including the private investor advantages in the ISRU related developments would further improve this life cycle profile.

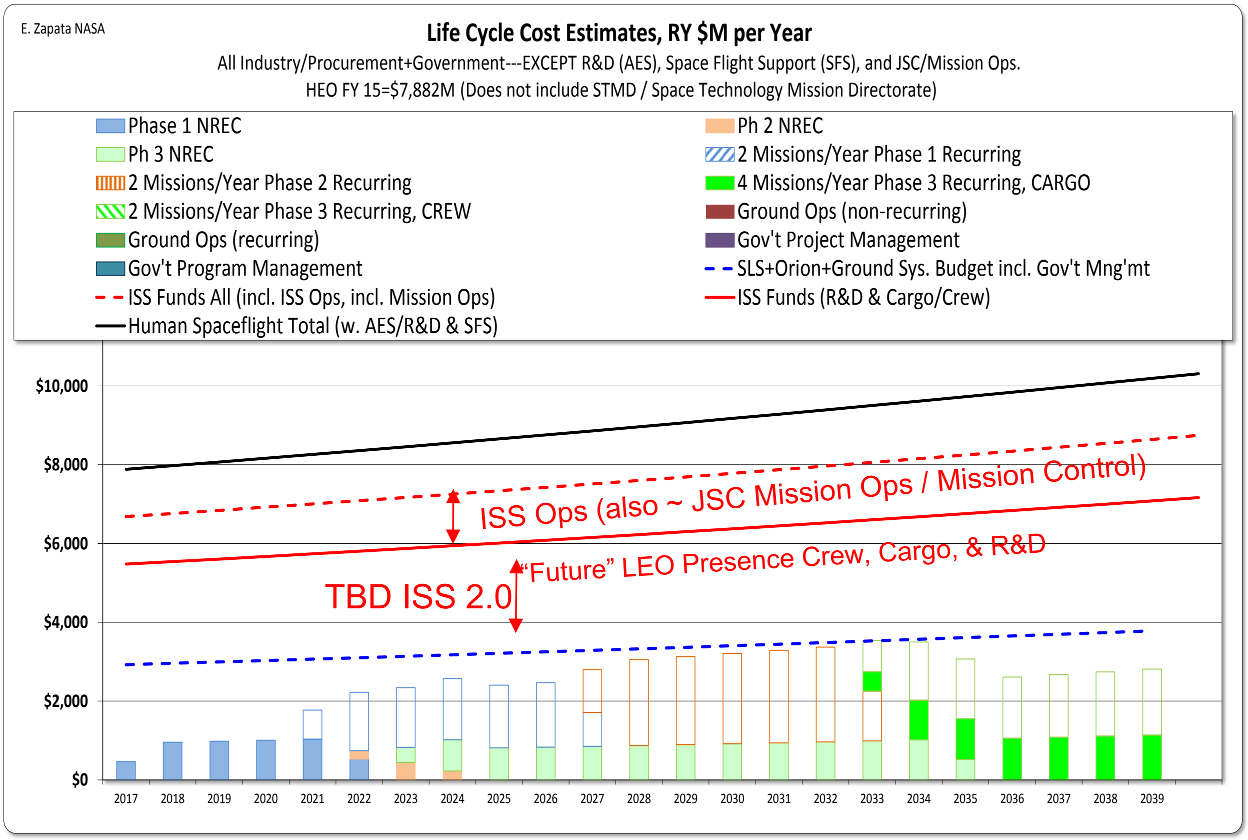


Figure LCC-13. LCC Private Investor Scenario. ***Baseline life cycle cost of the ELA, as a "lowest cost", no redundant partners, "private investor" scenario. Since further reductions in costs are possible under the private investor paradigm, these costs are a likely maximum.***

Frequently Asked Questions

1. Cost of First Footsteps on the Moon

   ~$4.6B (FY15$)

   In order, drivers of this value are (1) the development of two crewed lunar landers (dual partners), (2) the development/upgrade of commercial crew spacecraft for extended cis-lunar operation (dual partners) and (3) the cumulative effects of other necessary items (launches, stages, etc.) in Phase 1. This cost excludes ISRU and related developments and is consistent with costs capped at $3B a year, with a first lunar mission in 2022.

2. Cost of Private Passenger Round Trip to the Moon (Phase 1)

   ~$780M (FY15$)

   This value is a total round-trip cost. This value would amortize over the total number of passengers (e.g., if three passengers, ~$250M ea.) In order, this is driven by (1) the lunar lander (which is expended), (2) a spacecraft (which is only partially reusable, the crew module) and (3) the number of launchers supporting the prior. It is a procurement cost, excluding certain government management and related costs.

3. Cost of Repeating Apollo (6 sortie missions to the Moon)

   ~$12B (FY15$)

   This value excludes ISRU and other related forward developments during this timeframe. It is consistent with costs capped at $3B a year, with the sixth lunar mission by 2026. It is a procurement cost, excluding certain government management and related costs.

4. Cost up to Permanent Operational Lunar Base producing 200 MT/year of Propellant

   ~$38B (FY15$)

   This is a cumulative cost of all the items (no exclusions) by the start of Phase 3 operations in 2034. It includes all costs, procurement and government management, DDT&E as well as all the lunar sortie operational mission costs of the previous decade. It is consistent with costs capped at ~$3B a year.

5. Cost of Private Passenger Round Trip to the Moon (Phase 3)

   ~$475M (FY15$)

As with Question 2, this value is a total round-trip cost. This value would amortize over the total number of passengers (e.g., if three passengers, ~$160M for each.)

Life Cycle Cost Assessment – Results Summary

The LCC results for the ELA, consistent with improved NASA partnerships and approaches, credibly:

- Met the ground rule budget target (<$3B a year)
- Met the ground rule mission rate (2 crew launches per year & related cargo etc.)
- Supported the programmatic / NASA budgetary feasibility of tangible evolutionary progress in exploring / pioneering / milestones in near, relevant timeframes
- Creates numerous commercial acquisition opportunities for private enterprise
    - Transportation services to orbit
    - Spacecraft services in cis-lunar space
    - Propellant markets at < $7,500/kg in LEO (delivered to an interface)
    - Propellant markets in lunar orbit
    - Spacecraft – smaller prospectors, rovers and landers
    - Spacecraft services, lunar surface landers (LCC has two lander providers, consistent w. COTS/CRS acquisition)
    - Cis-lunar commercial communications networks
    - Cis-lunar commercial in-space mission control & operations (un-crewed)
    - Surface elements; rovers, habitats, equipment, ISRU, etc.

Life Cycle Cost Assessment – Forward Work

Given the promising architecture, approach and results from this LCC assessment, forward work is well justified. Broadly, the team and analysis capabilities are especially well suited to address forward work, including:

- **Quantify economic, mass and other measures of efficiency in Mars via the Moon architectures**

- **Subject matter experts & tools are uniquely qualified to integrate an exploration architecture assessment**: Compare performance, reliability and life cycle costs of comparable staging, evolvable or other Mars architectures vs. Mars via the Moon approaches.

- **Assess economic efficiency**: Requiring less NASA budget, less optimistic NASA budget assumptions, arriving at Mars/Phobos sooner within a given budget, or overall less life cycle costs.

- **Assess economic advantage**: Increasing stakeholders, redundancy in providers, and indirect economic or commercial advantages.

- **Assess mass efficiency**: Requiring less IMLEO (Initial Mass in Low Earth Orbit) via integrating the Moon on the path to Mars (with ISRU and in-space refueling) vs. not.

- **Additional detail, optimization**: Refine and address elements to reduce uncertainty and risks, understanding and providing additional margin specific to elements and life cycle phases.

Managing Integrated Risks

ELA risk strategies were developed in parallel with initial architecture concept development considering net integrated "end-to-end" risks that could result in program failure. We defined and incorporated risk strategies very early during this foundational phase to drive a successful outcome for the ELA concept. We recognize that decisions made during the early phases of advanced planning and conceptual design have significant impacts on supportability[xxiii], that the majority of life cycle costs are locked in by early design, development, and manufacturing trade-off decisions[xxiv], and that cost commitment vs. cost expended data[xxv] suggests the Pareto Principle applies such that approximately 80% of a system's supportability is established by the time 20% of the design is complete. We believe addressing risk early on when selecting architectural concepts is every bit as important as building quality in rather than attempting to add it later.[xxvi] Imposing risk requirements and processes after key decisions have been made would likely preclude implementing the most cost-effective options. Likewise, we must avoid focusing on one specific aspect of risk to the exclusion of other aspects, otherwise solutions will be sub-optimal for integrated risk.

The ELA considered several different types of risks, broadly, those related to safety, reliability, and maintainability; technical implementation; as well as business, investment, cost, schedule, and programmatic risks. For brevity, we will refer to these simply as "safety and reliability", "technical", and "business" risks in this paper, but these terms include multiple considerations within each category. Safety risk is a key element and is the combination of (1) the probability that the system will experience an undesired event (or sequences of events) such as internal system or component failure or an external event and (2) the magnitude of the consequences given that the undesired event(s) occur(s). Technical risk includes inability to meet performance or technology objectives. Business risks includes events which could cause the company or program to fail. Examples include inability to obtain financing, running out of funds before sufficient revenues are available, inability to satisfy regulatory requirements, failure of a critical customer or supplier, and lack of sufficient market demand or political support.

The term "integrated risk" is used to include the net effect of all three risk types taken together. Although often steps taken to manage one type of risk negatively impact one or both other risks, this is not necessarily the case and two or more of these risks can be addressed synergistically. For example, launching a set of five robotic scouts per each of two early version FH vehicles not only addresses the technical and business risks of locating suitable resources, it also reduces safety and reliability risk by increasing FH flight experience. Note that while we have a separate discussion of business risks related to governance models because of the special importance of this consideration, other business risks were considered together with safety and technical risks throughout the study.

Risks must also be considered for multiple mission phases and through the life of a program. For example, a crew launch program that is focused on reducing ascent phase risk by limiting the number of engines as possible failure sources may reduce its mass allocation so much that robustness, which is designing with margins able to accommodate large uncertainties, is no longer possible, while cost and technical risks are increased. This may result in low launch phase risk, but risks due to in-space effects such as micro-meteoroid or orbital debris may be extraordinarily (and unnecessarily) high, resulting in a sub-optimized net mission end-to-end risk than if a balanced, integrated approach had been taken.

Safety and Reliability Risks

ELA success depends on effective management of a number of risks relating to safety of crew, delivery of cargo, and operational availability of many different types of equipment. A variety of failures and anomalies are inevitable and must be expected to occur while conducting any program of this magnitude, especially given the harsh environments and long durations these systems must operate. Identification of possible problems, consideration for their likelihood and consequence, and planning how they can be dealt with at the very inception of the program are all elements of what we call risk strategy. We have identified means to mitigate risks such as Loss of Mission, Loss of Crew, and even Loss of Program that can be incorporated early in the architecture concept development, where a very high level of leverage can be expected.

Defining effective risk strategies at this stage of formulation will greatly increase the chance that future work involving detailed reliability and risk analyses will yield favorable results. Although the level of detail and definition to perform such analyses is not available at this time, the strategies developed in this study are based on decades of experience with similarly challenging programs. However, implementation of the risk strategies identified in this study are not sufficient in themselves to ensure future success. As the program goes forward, more detailed reliability, safety, maintainability, probabilistic risk, and similar analyses and processes should be implemented, although the level of effort should be tailored to the levels of risk remaining given the risk strategies and the extent to which they are adopted.

The ELA approach to vehicle system safety and reliability risks was conceived with several concepts in mind that are concurrently and coincidentally being developed in studies of Resilient Architectures[xxvii] as applied to urban design. In this context, "resilience" is the ability of complex systems to operate with stability, not only within their normal design parameters, but also to be safely sustained through unexpected events or changing needs. While we know that we cannot design for every possible and unpredictable failure or other disruptive event (including external events such as those related to space or lunar environments), we can develop and apply various strategies to ensure that our systems can operate through disruptions and bounce back afterwards.

The above referenced article on resilient architectures notes that we can learn much from biological systems, which are incredibly complex in terms of number of components and interactions, yet have proven to be stable over many thousands of years in spite of countless disruptions and "shocks to the system." Some of these lessons and how we can apply them to the ELA to reduce risk include:

(1) These systems are distributed (non-centralized) and have an inter-connected network structure. This lesson can be applied to our architecture through application of common interfaces and standards which can interconnect our components, elements, systems, and sub-systems in multiple ways rather than by segregating them into neat categories of use, type, or pathway, which would make them more vulnerable to failure.

(2) They feature diversity and redundancy. This lesson can be applied to the ELA by having a variety of different kinds of components, elements, and subsystems, provided by different organizations, nationalities, cultures, and individuals, doing things in different ways, any one of which might provide the key to surviving a shock to the system (precisely which can never be known in advance).

(3) They display a wide distribution of structures across scales. This lesson can be applied to the ELA in developing the means by which we start with small scale tests and demonstrations, from which we can develop modular capabilities for functions such as resource location, characterization, extraction, ISRU processing, power, life support, and propellant delivery. These modular functions can then be replicated to increase capacity. Combining with (1) and (2) above, these structures are diverse, inter-connected, and can be changed relatively easily and locally (in response to changing needs).

(4) They have the capacity to self-adapt and "self-organize." Following from (3), ELA capabilities (and their parts) could be adapted and reorganized in response to failures, as well as evolutionary learning and discovery of new knowledge about what works (or not), or other changing needs.

Risk Strategies to Mitigate Loss of Launch Vehicle

The fundamental strategy to address the risk of launch vehicle failures is that no single launch failure should ever be catastrophic to Program success. This strategy is enabled by commercial acquisition and operation costs being nearly an order of magnitude lower than traditional approaches and is flowed through the entire architecture. The ELA features a large number of relatively low cost launches for each mission, potentially on some relatively immature new launch vehicles. This has raised concerns about what happens if one or more of these launches (or subsequent on-orbit operations) fail. This has been the subject of much investigation, both as part of this study and in prior studies by the author.[xxviii, xxix] A very effective strategy to manage this risk is to provide for contingency launches.

Using what is called "M of N" reliability techniques, any desired level of reliability (sometimes referred to as the number of 9's) for any given number of required launches (M) can be provided by planning for some greater number of launch vehicles (N), assuming any reasonable level of inherent reliability of the base vehicle being used. The difference between N and M is the number of contingencies provided. Selection of the number of contingency launches should be based on the expected Probability of Success per launch, the required overall success probability for the mission set, and consideration for tolerance to payload loss and schedule risk. These parameters should be traded to identify the most cost-effective solution. This strategy, shown in Figure RS-1, is effective when the consequence of losses, up to at least the planned number of contingency flights, is acceptable. An analysis of Falcon 9 reliability was performed (Appendix 1) and showed that the experience to the date of the analysis (March 2015) is bounded by the bars for low and high launch vehicle reliability, as shown in Figure RS-1.

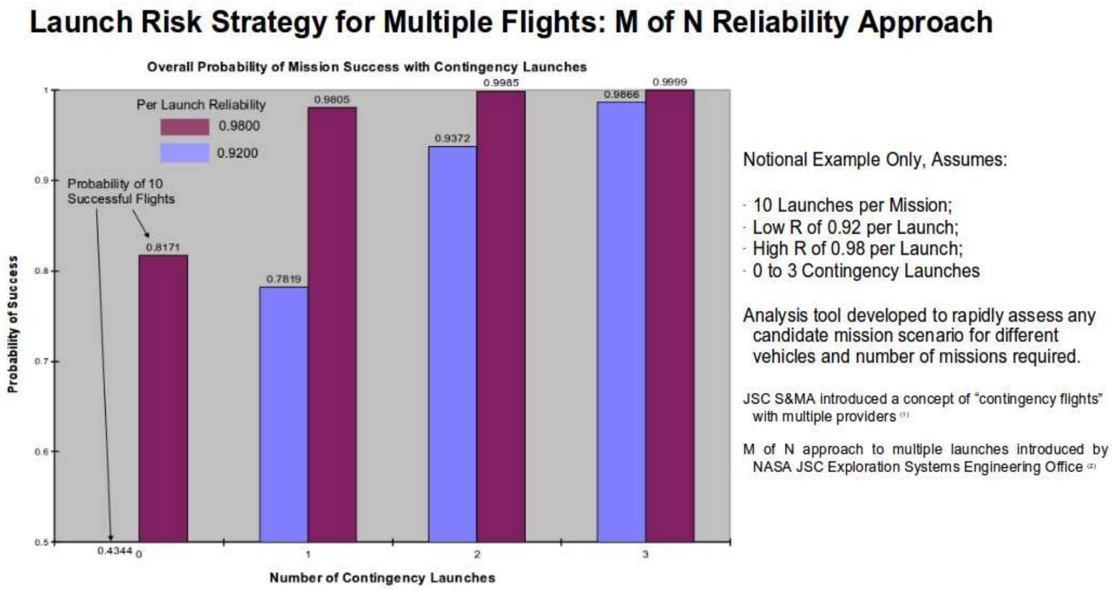


***Figure RS-1: Use Contingency Flights for Multiple-Launches.**[xxx] The Overall Mission Probability of Success (Ps), when many launches (M) are required, depends upon the Per Launch Reliability (R) and total number of launches planned (N), including contingency launches. Multiple providers protect against delays during failure investigation and has proven to be of great importance for ISS commercial cargo.[xxxi] Extremely high Mission Ps can be achieved with just a few contingency launches. This strategy allows vehicles with relatively low reliability or as yet undemonstrated reliability to provide a high probability of overall mission success if even a small number of contingency launches are planned. Even highly reliable launch vehicles can have a relatively low Mission Ps there are no contingencies planned. This is an especially effective strategy for rapidly maturing new vehicles through propellant delivery roles. It is also effective for in-space or lunar elements where multiple like-units are utilized and launched as a series.*

While the "M of N" strategy could be applied with just a single launch vehicle provider, the ELA risk strategy includes having at least two independent dissimilar launch vehicle providers operating from separate launch facilities, with payloads designed to a common standard to enable integration with either vehicle. Multiple independent providers are particularly important to address any down time resulting from needs to investigate failure cause and implement a corrective action to prevent a recurrence. Multiple launch facilities are important to mitigate delays caused by potential damage to the launch pads.

The strategy of having redundant providers is possible because of sufficient launch demand to support more than one provider and the public-private-partnership approach, which properly aligns incentives, thereby creating affordable systems. Since the systems are each affordable, two can now be afforded (especially critical in development) where before only one might have been possible. Furthermore, redundant providers reduces business risk by creating competition at the vehicle design level, while fostering cooperation at operational and supply chain levels by implementing design standards, which in turn can reduce technical risk. An objective of this integrated risk strategy is to create a business environment similar to that which existed among early airlines where competing companies would still cooperate in various ways for the overall good of the industry and which directly resulted in the rapid maturation and improved safety record while reducing costs.

This strategy is particularly well suited to the ELA launch demand because of the requirement for many frequent launches of identical or similar payloads. Unused contingency launches from one mission set may be subsequently assigned as a primary launch for the next mission set. This eliminates long ground storage times and resulting physical degradation that could otherwise occur if dedicated contingency launch vehicles spares were kept in long-term inventory. This strategy also minimizes business risk and inventory holding costs because only a minimum number of spares are required. Spares demand can be effectively addressed by having just a few launch vehicles and payloads processed in advance through the production pipeline throughout most of the program. An exception that may require special consideration may be certain unique payloads, though even these could have some common payload structure and components with only limited unique outfitting could mitigate even some of these cases.

The high launch rate is an important architectural design characteristic of the ELA, not an oversight, in other word, "it is a feature, not a bug". It is intended to support rapid reliability growth, and enable efficient use of facilities and personnel to reduce cost and therefore, business risk. A review of the NASA Johnson Space Center Safety & Mission Assurance study of historical progression of Shuttle launch risks provided valuable insights[xxxii] concerning reliability growth trends. Reliability growth is the result of operating a system, discovering its weaknesses, and correcting them to prevent recurrence of actual failures or close-call conditions. Reliability growth requires operating the system and improves slowly if the system is not operated frequently. It also requires actually correcting problems that are discovered in previous flights. Correction of known problems has historically not always been done promptly due to issues of retro-fitted on an existing vehicle such as the Shuttle, cost, and the impact of vehicle re-certification which drives up cost and affects schedule. The high ELA flight rate, enabled by the more risk-tolerant framework of the "M of N" approach, allows more rapid reliability growth as compared to traditional methods which "put all the eggs in one basket", so to speak. Figure RS-2 uses the actual flight-by-flight change in Loss of Crew Risk from the Space Shuttle Program, as reported in the Shuttle Risk Progression study and detailed technical analysis of launch rates using the Falcon 9 family of vehicles to meet ELA objectives to assess rate of reliability growth to maturation. Incorporation of a redundant provider would

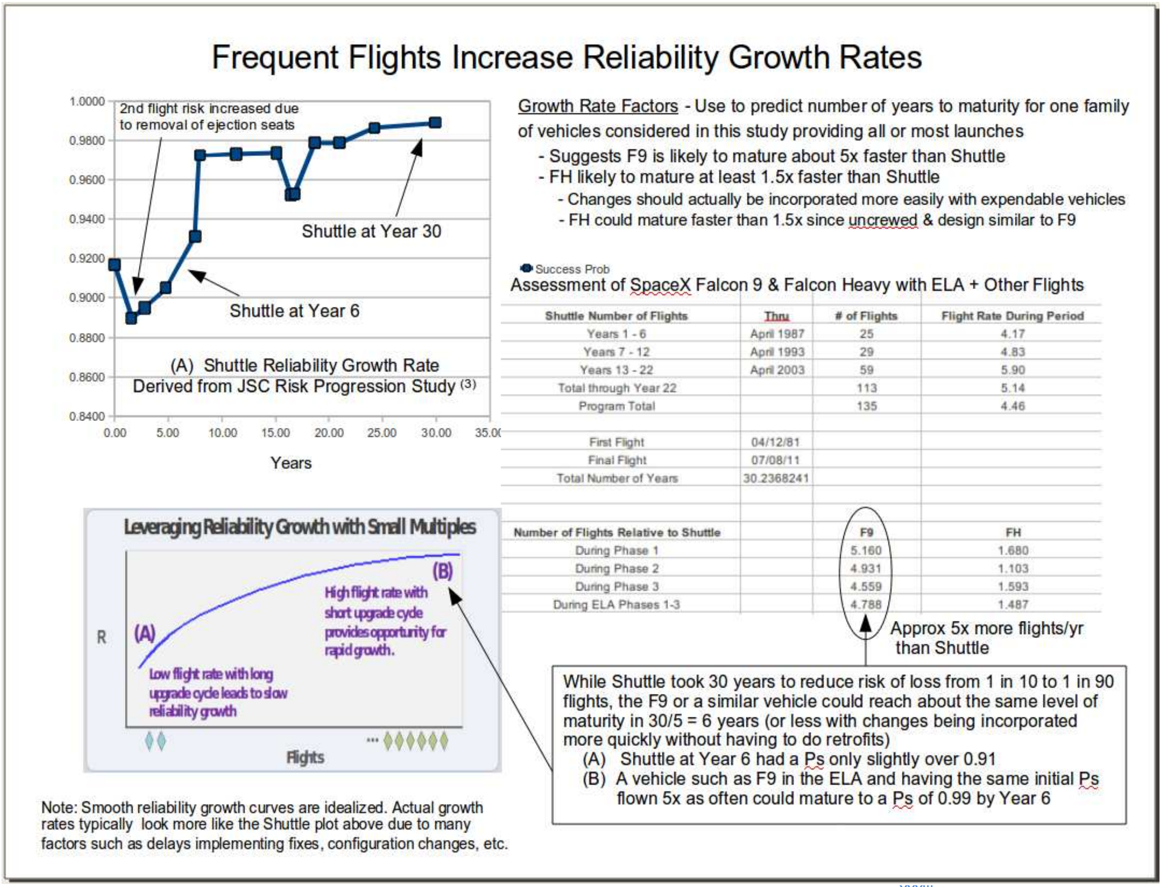


Figure RS-2: Frequent Use Constantly Reduces Risk & Increases Safety[xxxiii]. ***An affordable approach allows more units to be built, tested, and operated more routinely than an unaffordable system. This provides more opportunities to discover and fix problems.***

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decrease the maturation factors determined in this portion of the study in proportion to the percentage of launches assigned to each provider (which would not necessarily be equal, particularly if one provider's launch cost was significantly more than another). The maturation rates also assume that the commercial vehicles assessed would also have a nominal number of flights for other customers, which could increase or decrease the maturation rate. The relative ease with which commercial providers could implement changes as subsequent flight articles are delivered as compared to the Shuttle Program would likely increase the rate of maturation.

Another positive effect of the high flight rates needed for the ELA is that "demonstrated reliability" also increases rapidly. Although the curves follow a similar shape, *demonstrated reliability* is fundamentally different from *reliability growth*. While reliability growth involves correction of problems discovered from flight experience, demonstrated reliability is concerned strictly with increasing the number of trials to increase the level of certainty of the actual reliability of an unchanging design (Figure RS-3). High demonstrated reliability is often required for unique or exceptionally high value payloads. In such instances, launch on vehicles having the highest demonstrated reliability but significantly higher cost may be justified as a degree of "insurance" against loss. One risk strategy is to launch high value payloads on well-proven LV's until high reliability is demonstrated to reach similar confidence for new, lower cost options.

A study[xxxiv] by United Launch Alliance of Atlas and Delta Launch Vehicles shows number of flights required to demonstrate reliability to 50% vs. 95% confidence, and concluded that a common family of launch vehicles demonstrates reliability sooner than a unique vehicle.

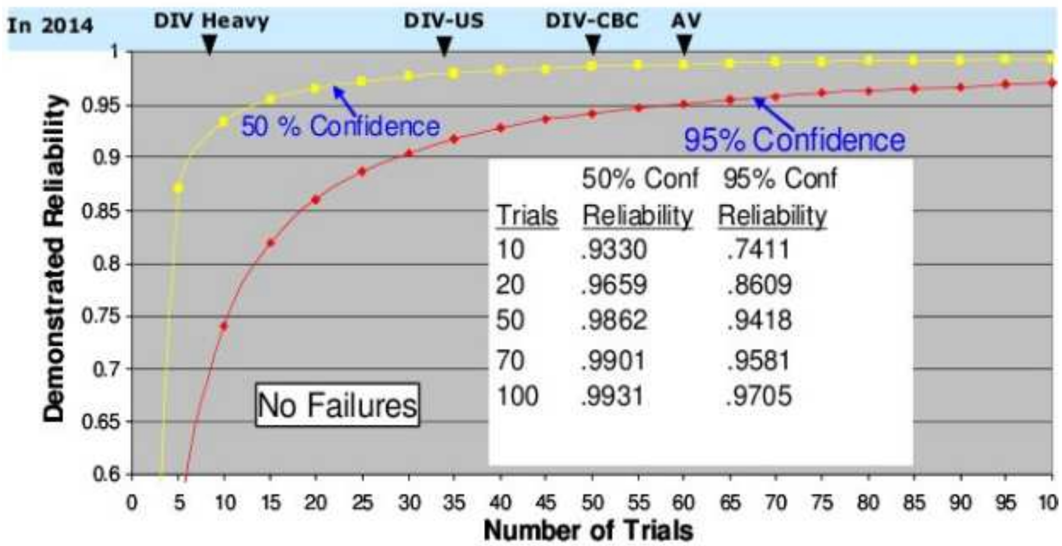

Figure RS-3: High flight rates accelerate reliability demonstration and growth. *High flight rates decrease the time required for reliability demonstration[xxxv] and reliability growth, two separate maturation effects. Use of a common design for similar applications or several smaller engines rather than one large engine increases the rate at which operating time or cycles are accumulated, leading to rapid maturation.*

A number of new design practices are also emerging as a result of lower launch costs that can also reduce launch risks. For example, rather than designing strictly for minimum mass and maximum performance, new trends enabled by lower launch cost are designing for greater robustness by increasing design and construction margins, consumables margins, incorporating additional redundancy, providing greater engine-out capabilities, and operating at lower power levels.

Risk Strategies to Mitigate Loss of In-Space Elements

In-space elements are items intended to operate mainly in various orbits, rather than through the Earth's atmosphere for launch or entry and landing, or for lunar descent, surface operations, and lunar ascent. These include items such as Earth departure and return stages, reusable tugs for transfer between LEO and lunar orbits for cargo and crew, propellant depots, crew habitation modules, logistics modules for spares storage, etc. Risk strategies for in-space elements build directly on the concepts of resilient architectures and contingency launches described above, including that no single element failure should be catastrophic for Program Success, and that there should be redundant providers for in-space elements to reduce the probability of common cause failures. A derived risk strategy then is to design and operate in-space elements such that they have sufficient consumable reserves to accommodate any reasonable delay due to calling up a contingency launch for the next element in the sequence. These elements should also utilize well-tested open standard interfaces for interoperability to accommodate rendezvous and docking, regardless of whether the element was provided by another commercial partner or an invited international participant.

In-space elements share many common requirements so components, subsystems, and structures developed for one in-space element should be used across multiple different elements to the maximum extent possible, although developed by at least two different providers for dissimilar redundancy. Leveraging common designs maximizes the rate of operating time accumulation for rapid reliability growth and demonstration of reliability. Establishing overall architectural requirements such that new in-space capabilities are introduced by phase allows early version designs to be used in applications that have relatively low consequences of failure before being used applications that have a higher consequence of failure. For example, designs used initially to support robotic scouting, followed by scaling up for cargo delivery to lunar orbit, could finally "graduate" to crew transfer or habitation applications. By implementing architectural requirements for phasing-in selected capabilities in a logical progression, test functions that would normally require a significant amount of dedicated test time for reliability demonstration, could instead be accomplished with a more limited test program followed by actual flight experience in roles where there are numerous low-consequence opportunities to "practice", while still accomplishing useful objectives. This strategy also reduces business risk/schedule risk by producing hardware in relatively large quantities so there are always spares in the pipeline that could at least be reconfigured if necessary, so in case one item does fail, replacements are always available (this can also reduce safety and reliability risk once a number of such items are on-orbit). It also reduces business/cost risk by reducing the cost of the number of unique developments required and by taking advantage of a greater production quantities to lower recurring costs. Finally, technical risk is reduced by having many units available to test. The current ELA plan is that crew vehicles for transfer from LEO to lunar orbit to be flight-tested incrementally. Initial crewed flights include initially building up time and operating experience in LEO where a quick abort and return to the surface of the Earth is possible. Once these vehicles are proven in LEO for crewed use, the plan is to flight-test them for a relatively short duration trip to lunar orbit and back to Earth, prior to reliance on the vehicle for long duration lunar stays.

We note that while incorporating the strategies described in this study into an architecture at inception can be very effective in establishing a much lower risk posture than by simply picking a convenient or lowest mass approach, these strategies are not by themselves sufficient to eliminate all failure modes and hazards. For example, traditional best practices will be needed particularly to address risks that may not be mitigated sufficiently by strategies such as contingency launch, spares, or safe haven (for example, a catastrophic collision). Some other considerations that become evident when performing traditional analyses include minimizing transport time, since reliability is a function of time and unnecessarily running equipment and exposing it to the space environment for long periods of time increases the probability of failure. So for example, such analysis would show that using conventional chemical propellants would reduce the probability of failure as compared to the much longer transit times for solar electric propulsion.

Risk Strategies to Mitigate Loss of Lunar Lander or Ascent Vehicles

Like the in-space elements, the ELA strategy is to introduce the lunar landers and ascent vehicles to the architecture in phases. Initial landing requirements will be for robotic scouting and prospecting for resources, which is necessary to reduce technical risk. This is followed by small non-reusable crewed landers, and finally larger reusable landers for bringing large elements to the lunar surface and launch of lunar-derived propellant and perhaps other resources. The approach is similar to in-space elements by planning early demonstrations in uncrewed modes (unless determined that net program risk is lower with a crew, as was done on STS-1), building up flight operational experience with less critical payloads prior to progressing to applications to deliver higher value elements or crew.

One lander risk strategy that the ELA team considered extensively for Phase 1 was to reduce the high technical risk of confirming the existence of useful deposits of ice, locating the best locations to extract it, characterizing the conditions under which it would need to be extracted, while simultaneously reducing safety and reliability and business risks. This would initially use two small, but mature launch vehicles (such as the F9 and upper stage) to test two small robotic landers, which would each deliver two rovers, each designed and produced by different providers. Once the landers and rovers are initially proven, the next step is to fly a sequence of two large but likely less mature launch vehicles (the FH and upper stage was analyzed in considerable depth for this step) to launch a mixed fleet of these landers/rovers (in the case of the FH, a total of five landers could be delivered to a lunar deployment orbit), each of which would be landed in different locations. This strategy provides an opportunity to gain experience with the relatively new launch vehicle and refueling its upper stage (though previously proven) and significant flight operation experience for both landers, while carrying relatively low cost robotic payloads. If the first heavy lift rocket fails, a second from another provider should be unaffected (or if only one provider were available, there would be time to investigate the failure cause and implement corrective action). Multiple opportunities to test the landers are provided, as missions succeed through deploying the landers. If the landers successfully land, multiple opportunities to operate the rovers are provided. If sufficient resource data has not been obtained after the two missions, a third could be added. The approach extends the concept of producing multiple copies to landers and rovers to encourage production efficiency and gain development and flight experience which transfer to the next generation of larger cargo landers.

For Phase 2, we continue to gain lander experience and maturity by prepositioning surface elements for testing ISRU production, transitioning to crew transport after reliability has been demonstrated on earlier missions. Additionally, some robotic ascent operations for sample return should be considered prior to relying on these vehicles for crew return to lunar orbit. Once a reusable lander is available, it may also be refueled on the lunar surface in an uncrewed demonstration mode. Consideration is needed as to whether human presence reduces ISRU processing or propellant transfer risks for initial demonstrations of the reusable lander for ascent. Early on, the crew should have a proven non-reusable version of the lander as their primary vehicle. Once the reusable lander enters normal crew service, a non-reusable lander should be stationed on the lunar surface in case of problems with the ISRU production, storage, or transfer and for rapid emergency evacuation for medical emergencies and mission abort.

Risk Strategies to Mitigate Loss of Surface Elements

Surface elements refer in general to all items intended to operate mainly on the lunar surface, including rovers, habitats, laboratories, ISRU material handling and processing equipment, surface-based power production, storage, and distribution equipment, etc. Surface elements should be largely driven by ISRU production requirements, which may need to be distributed across multiple locations. Building on the concept that architectural principles, plans, and high-level requirements ultimately establishes the achievable level of reliability and risk for a system, we examined how those requirements could be established so as to drive early design decisions that are inherently likely to improve safety and reliability, as well as reduce technical and business risks as well.

A question studied was what could a Master Planner/System Integrator do up front to maximize the chance of success without imposing detailed design requirements on the production systems of the commercial suppliers? Having the ability to do some small-scale production early followed by scaling up provides several benefits (for example, ISRU production technology demonstration, early source of propellant to demonstrate storage & transfer, reduce demand for resources from the Earth for the base itself, early vehicle reusability demonstrations, possible early revenue streams, and incremental capacity increases, future growth, etc.). So the Master Planner might set up architectural requirements for phased production capability. In this case, rather than specifying a production requirement of (for example) 780,000 kg of propellant as the target, the Master Planner could specify for example, an initial 78,000 kg capability and the ability to incremental increase it in say 5 or 10 steps over some defined period of time to the 780,000 kg target (which could be further increased for growth). The Master Planner could also specify or permit this 780,000 kg of propellant to be sourced from multiple sites by multiple providers using different technologies.

This high-level approach should encourage potential suppliers to develop a modular-like approach, though they may come up with a better way and should be free to propose it. If a reduced production rate is acceptable in the event of a failure (e.g., if there is sufficient schedule margin in the mission being supported or if there is sufficient storage capacity to make up for a reduced propellant production rate), each equipment item may not necessarily need to be able to provide full capacity independently. Use of a number of small items of each equipment type operating in parallel to the extent practical has several advantages over a large, monolithic approach, including:

(1) Enables starting at a small scale to reduce initial costs and allows taking advantage of multiple unit hardware production cost efficiency.

(2) Enables scaling up production to practically any level desired by adding more units (similar to a modular growth approach), permitting ISRU system design, test, and initial operations to proceed with uncertainty in requirements for customer mission(s) and enables growth beyond the maximum level if/or when it becomes necessary.

(3) Enables rapid reliability growth by multiplying the rate at which operating experience is accrued (unit-hours or cycles) as number of units increases and provides more opportunities for "test-analyze-fix" as problems become apparent.

(4) Enables another application of the "M of N reliability" concept to reach any number of "9's reliability" desired and still have 100% propellant production capacity.

(5) The smaller ISRU processing module can serve as a spare in the event one is lost in a transport failure or the module itself fails completely and cannot be repaired. This also reduces inventory of spares needed for each similar component.

(6) Facilitates relocating a complete minimum set of equipment to a different surface location to begin expanding operations.

The risk strategy of applying a phased incremental approach to ISRU requirements would likely have similar beneficial effects on other surface elements such as the supporting habitats, rovers, power production, storage, and distribution equipment, so at least partial redundancy comes online as ISRU capabilities increase. While mass-efficiency of an incremental approach may not be as high as for a single, large facility, it should be noted that under the new paradigm of lower cost launch, mass should no longer be the primary focus of new space system developments. "With the advent of lower cost launchers, satellite designers should rethink some of their traditional assumptions about how to control costs."[xxxvi]

Risk Strategies for Mitigating Loss of Crew or Loss of Mission

In Human Space Flight, safety is defined as the absence from those conditions that can cause death, injury, occupational illness, damage to or loss of equipment or property, or damage to the environment[xxxvii]. Loss of Crew (LOC) is death or permanently debilitating injury to one or more crewmembers. Loss of Mission (LOM) is the inability to complete defined primary mission objectives and can apply to robotic missions as well. Although not considered in traditional safety analyses, loss of funding and other business risks can also result in a Loss of Mission, or at the extreme a "Loss of Program", i.e., cancellation.

LOC and LOM are often the result of vehicle failures. Achieving high reliability at appropriate levels in the architecture is necessary, but not sufficient to achieve low risk for both LOC and LOM. Reliability is the probability that a system of hardware, software, and human elements will function as intended over a specified period of time under specified environmental conditions. LOC and LOM can also be the result of other causes (solely or in combination), such as micrometeorites, orbital debris, fire, toxic releases, human error, collision, etc. It is also possible to lose a mission but not lose the crew with a good emergency detection systems, escape, abort, rescue, repair, and/or survival capabilities. Such capabilities may also prevent LOM, allowing the mission to continue.

Strategies to inherently reduce risk of LOC and LOM have been considered extensively in developing the ELA. Previous sections have addressed how the architecture has been structured to achieve high levels of reliability. For crew, the reliability growth strategy constantly reduces risk and increases safety. Reliability growth occurs because affordable systems can be flown at a higher tempo for any given yearly budget. Learning at the higher tempo and volume of manufacturing and operations, and affordable (efficient) methods to turn learning into improvements in hardware, software and processes will create ever safer systems from launch through surface operations and return. Unaffordable systems end up with a reduced tempo, for any yearly budget, making learning and its reliability growth a slow process (too slow to avoid critical failures, sooner rather than later).

LOC/LOM risk is also largely established by how crew and mission objectives are phased in to the program. The sequence of tests, demonstrations, and capability/infrastructure build-up, particularly considering what is done in uncrewed modes for crew-capable elements or robotically, and when they are done will likely have a significant impact on LOC/LOM. Providers may graduate from cargo to crew, also addressing risk. In practice, this has happened with US ISS cargo then US ISS crew.

Strategies for optimal use of robotics, humans, or both received particular attention. For the ELA, early scouting and prospecting as well as initial ISRU tests and infrastructure set up was based on robotics. If the crew is going to depend on ISRU, then clearly the system must be verified before the crew must depend on it. But verification does not necessarily have to be all robotic. Setting up a complex ISRU system may be easier and less costly if we can take advantage of astronauts' capabilities. Advanced remotely operated robotics have significant advantages for some types of activities and may increase safety, reduce costs, and improve the likelihood of success of human missions.[xxxviii] However, studies also have found that the time to perform some types of tasks can be much longer using robots alone.[xxxix] Robotic systems will likely fail at some time and while robotic servicing of robotic systems is possible, direct human intervention will likely reduce net risk in many cases. Human perception is also often necessary to solve problems. Some of this may be done remotely, but there are times that this will likely not be effective. For a commercial operation, time is money and high costs and long schedules are also risky to investors. Approaches that are not cost effective or take too long may result in a Loss of Program if funding is discontinued. Decisions should consider minimizing net integrated risk.

During the course of this study, this issue was discussed with oil and gas robotics experts at the Deep Space Deep Ocean Conference in The Woodlands, Texas in April 2015. It was reported that as much as they would like to use robotics for everything, their experience was that initial applications would generally need humans to get new processes working, but that the robotics were best used once the processes were set up and repeatable. Their experience was that humans were still also necessary to tend to the robotic systems.

Other strategies to reduce LOC/LOM risk at the architectural level is the use of common design standards, interoperability, and production of multiple units to reduce number of spares needed. This architectural approach also facilitates connection of utilities (e.g., back-up power feed, transfer consumables, etc.) for cross-strapping as a contingency and can serve to providing alternatives such as safe haven capabilities, emergency lunar ascent return and to the Earth. Of course, there are many design details that are beyond the scope of this study which will have a direct effect on LOC/LOM and appropriate safety and risk analyses and trade studies will need to be worked in due time.

Risk Strategies for Mitigating Crew Health and Medical Conditions

The potential for crew to be affected by health or medical conditions during transit to or from the moon, at depot facilities, or while working on the surface must be considered, including those that may be long-term and not directly result in LOC, e.g., radiation illness. The strategy of incrementally increasing crew stay times on the lunar surface provides an opportunity for gaining the necessary knowledge and experience for mitigating potential long term Lunar health effects. This would include developing techniques to provide protection from effects such as dust and radiation.

Prior risk analyses have found a relatively high probability of loss of mission due to crew health or medical (including dental) effects[xl]. A key driver of high contribution to crew medical risk for LOM in one such study was due to limited availability of medical supplies and equipment, which was based on the ISS medical kit. The ELA strategy of using multiple low cost launches for cargo creates an opportunity to provide significantly more extensive kits to study and address a greater variety of medical and dental equipment and, if necessary, exercise equipment to counter the low gravity conditions (current experience is only in near zero-gravity rather than 1/6 Earth gravity).

Risk strategies to address both types of crew medical risks should be incorporated in early lunar architecture planning. Like for other risk areas addressed above, detailed efforts on crew health and medical risks will be needed to address all the known effects and best practices that have evolved on the ISS, Shuttle, and prior programs as the ELA systems are developed.

Conclusions for Integrated Risk Management

The Evolvable Lunar Architecture (ELA) study incorporated many strategies to manage risks beginning upon initial conception of the architecture when these strategies can be most effective. We considered that increasing costs in an attempt to reduce other risks beyond some point would actually increase net risk in the sense that if the program is canceled due to excessive costs, its still a failure. While we cannot know the exact sweet spot where cost of risks realized and cost to mitigate risks is at a minimum or exactly what risk tolerance may ultimately be accepted by commercial providers, we do believe this study can help guide implementation of an architecture where net benefits is likely to exceed net risks. For example, early scouting and prospecting retires the risk that water is not available, so subsequent efforts could focus on alternatives such as regolith for O2 and radiation shielding, and still provide most of the exploration mass required.

The ELA also provides a net integrated (combined "safety and reliability", "technical", and "business") risk reduction for deep space human exploration by reducing the total number of very large, high cost/high performance, 100+ MT heavy lift exploration flights to a rate that is operationally supportable with existing integration and launch infrastructure. This is possible by enabling maturation and utilization of low cost commercial launch capabilities and development of lunar resources to provide approximately 80% of the total mass required for such exploration. It inherently has the flexibility that such deep space missions could still be conducted by launching all or some portion of the propellant from Earth if necessary to mitigate the risk of lunar propellant not being available or of sufficient quantity when needed. Availability of lunar propellant could also reduce risk for development of the heavy lift vehicle because mass of propellant can be offloaded, permitting lower cost solutions to mass growth problems and increased structural margins.

The ELA approach incorporates knowledge gained from decades of experience in flight vehicle experience, including lessons learned about early mission risk and progression of risk as a vehicle gains insights through flight history to understand reliability growth and first flight risk.

(1) The ELA uses these insights to establish a framework in which new launch vehicles can be rapidly matured while consequences of the risks are kept low.

(2) High flight rate, reusable landers and in-space elements, and ability to launch propellant separately from crew or core systems provide an opportunity to change design optimization from performance to cost, safety, and reliability.

(3) The ELA risk assessment findings are consistent with previous NASA Propellant Depot Alternate DRM 34 study, Figure RS-4.

(4) The new lunar destination for this study effectively eliminates launch site availability as a major contributor to unreliability because short launch windows needed for asteroid rendezvous (as assumed in the previous study) are not necessary.

(5) Use of stage refueling, in lieu of a dedicated propellant depot for the early phase of the ELA further improves on previous results.

(6) In one technical alternative assessed for the ELA, propellant storage and transfer of RP and LOX in Phase 1, rather than LH2 and LOX, reduces some technical risk while effective LH2 storage/transfer is developed and demonstrated in parallel.

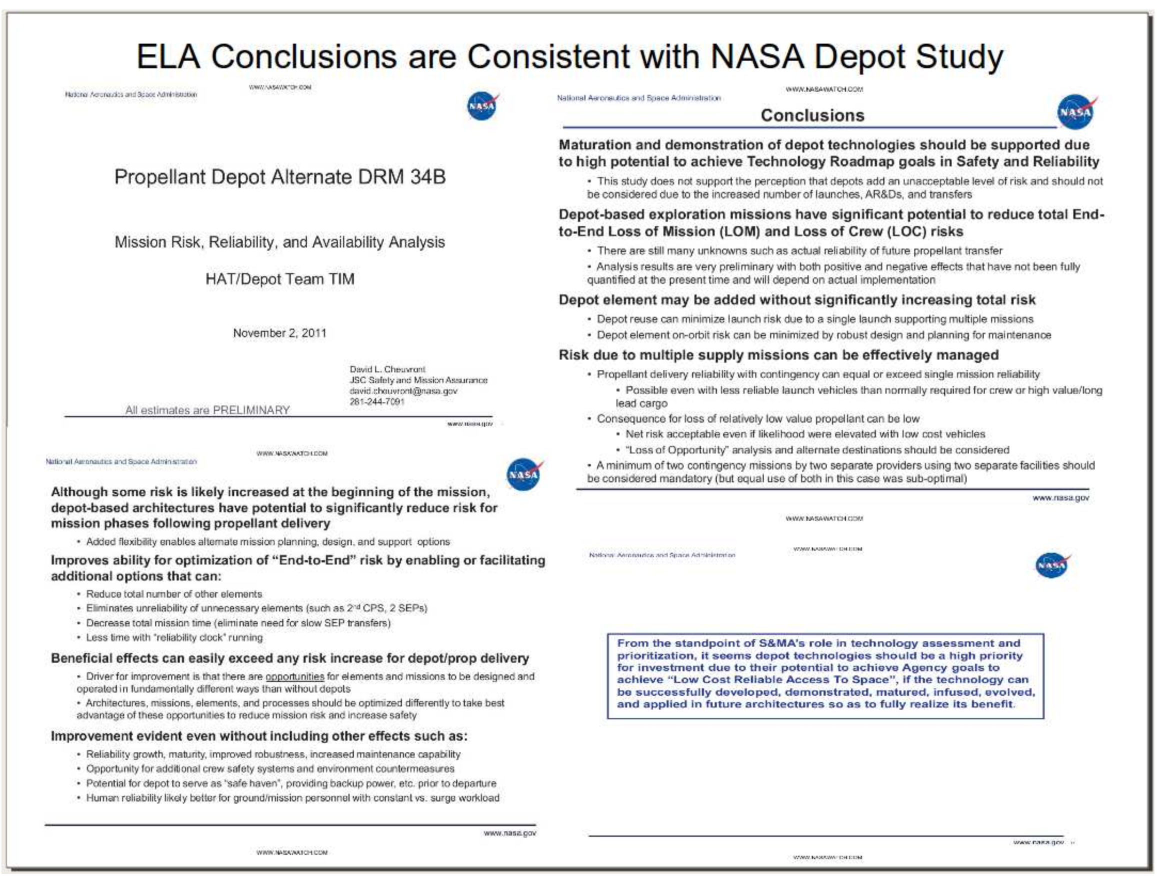

Figure RS-4: ELA Conclusions Consistent with NASA Depot Study. *The 2011 NASA Human Architecture Team Depot Risk Analysis[xli] showed that a net end-to-end reduction in risk compared to non-depot architectures was expected. Drivers for improvement included opportunities for innovation in mission and element design including rapid reliability growth, improved robustness, greater mission flexibility, improved human reliability for sustained continuous rather than surge launch operations, use of a depot facility for orbital checkout of deep-space elements prior to departure, and as a safe-haven in case problems were found during check-out.*

Mitigating Business Risks

Do public-private-partnership methods provide an alternative for developing, financing, and operating human spaceflight infrastructure in deep space? Might recent progress with COTS, ISS Commercial Resupply Services, and Commercial Crew be modeled by America to develop new human spaceflight infrastructure in a manner that is more sustainable and affordable? Can deepspace infrastructure operate with significant private activity at a cost low enough that allowed NASA to at the same time focus most of its resources on sending humans to Mars?

Although complete answers to these critical questions cannot yet be provided, we know there are significant limitations and weaknesses of the PPP approaches. These limitations must be acknowledged and addressed when considering expanded use of these approaches.

Weaknesses of PPP Model

In practice there are many practical challenges to using PPP methods that need to be examined, understood and managed. In principle, there are trillions of dollars of cash in private capital markets that can be tapped for good business cases that effectively manage the following issues.

The key to accessing this capital is to provide an adequate risk-adjusted return on investment. The problem is that the space industry is exposed to much higher degrees of risk and uncertainty compared to alternative investment opportunities, including:

1. **Instability of USG long-term commitments (cancellation risk)**: The uncertainty of the long-term commitment of the U.S. Government to any deep space mission is a critical factor. The U.S. government space policy has a history of changing its space policy with every change in President and every change in key leadership in the U.S. Congress. Investors generally demand a very good reason for large investments in business plans predicated on long-term commitments from the U.S. Government. For example, in the case of investments in cargo delivery to the International Space Station, investors were convinced that NASA would honor its contractual commitments, because the ISS already was in orbit, and without cargo delivery it would be abandoned and then destroyed. However, in this situation there is no existing lunar base at this time to anchor a contractual commitment.

2. **High degrees of technical and development risk**: Even the best managed space companies have failures.

3. **Burdensome, non-commercial, contract processes & terms**: The application of FAR-based cost-plus contracting in most cases limits the incentive to invest significant private capital in a deal. When the U.S. Government applies FAR-contracting processes, excepting "commercial term" FAR part 12, it is generally a non-partnership relationship.

4. **NASA oversight "certification" regulatory risks**: While NASA certification sounds good on the surface, there are hidden costs. NASA "certification" standards means that NASA is serving as the defacto "regulator", which standard economic

practice understands can significantly drive up costs and risks to the suppliers. To the extent that NASA's "certification requirements" are uncertain, this increases the perceived risk of investment by industry even more.

5. **Large, sustained capital requirements**: The investments required for returning humans to the surface of the Moon cost billions of dollars, and the investment to enable a permanent operational human base on the Moon will cost tens-of-billions. If 100% privately financed, the required amount of capital is beyond the ability of all but the most rock solid business cases.

6. **Long and uncertain product development periods**: We estimate that a human return to the surface of the Moon using existing technology will take 5-7 years of development. The short term focus on most traditional investors require a return on their investment in less than five years.

7. **Lack of clear and transparent resource utilization and property rights**: At the present time, there is a lack of clear, certain and transparent ability by private industry to utilize the benefits of any investments it might make in lunar infrastructure.

Mitigating Business Risk with an International Lunar Authority

During this study, evaluated and compared many different approaches to mitigating these business risks. NexGen identified evidence that an "International Lunar Authority" could significantly mitigate many of the most significant weaknesses of the PPP acquisition strategy.

In general, authorities have proven to be very successful at developing resources, for building infrastructure, and then managing complex infrastructure operations after development is complete. Authorities blend the powers of government with the economic efficiency of private industry, while managing hugely complex high-tech industries where the safety of the public is involved.

CERN, or the European Center for Nuclear Research, is a specific example of an international authority that was created by international treaty. Originally developed to mitigate the relative economic weakness of smaller European countries in comparison to United States in science and technology, CERN is now the world's leader in fundamental physics research. While America's traditional "go it alone" strategy has collapsed — most visibly with the cancellation of the Superconducting Super Collider and the closing of Fermilab's Tevatron — the CERN "international authority" approach has proved to be much more sustainable.

The Port Authority of New York and New Jersey (PA-NYNJ) provides another example of the efficacy and effectiveness of the authority model. PA-NYNJ now manages a $7 billion annual budget with $3 billion per year going to new infrastructure development, without any dependence on government funding. The PA-NYNJ manages some of the most complex infrastructure and construction projects in the world, and it enjoys broad and consistent political support. It has proven to be a very effective and sustainable model. This report looks at the PA-NYNJ history in detail, and documents many lessons learned.

One general example we are all intimately familiar with is the modern airport. A large airport authority can have a billion-dollar budget managed by one central organization in a complex constantly changing high-tech industry. Airports are subject to tens-of-thousands of pages of regulations that are enforced by a multitude of local, state and federal government agencies. They govern thousands of private companies that are engaged in intense economic competition. An airport can have hundreds of flights per day, be responsible for millions of people flying per year, and do so with an amazing track record of safely protecting the public.

Some authorities have powers to levy taxes and fees, and the power to float public debt. Authorities also manage property rights. One of the most valuable assets in an airport is the right to an airport terminal or a gate, and the right to develop the property right next to the terminal.

The "authority" model works in many circumstances and has spread around the world. Authorities are also used for seaports, for toll roads, for managing water systems, for power plants, and for protecting sensitive environmental regions, such as the Great Barrier Reef in Australia.

This report also identifies and assesses other potential models for development and operation. Some of these provide case studies with valuable lessons learned for NASA including:

- McMurdo Station (Antarctica)
- Tennessee Valley Authority
- COMSAT/INTELSAT
- National Parks
- Creation and breakup of Boeing-United Airlines monopoly
- Closed vs. open architectures

NexGen's analysis represents a preliminary assessment, and is not conclusive. The implications of making such a major change in "governance" are large and complex. NexGen believes that such an authority, perhaps composed of our original partners in the International Space Station (Europe, Canada, and Japan), could be created. However, before proceeding, the United States would need to assess the "International Authority" model in more detail.

A Combination of Authority Models is Required

NexGen's conclusion is that a combination of the powers of the Port Authority of NY and NJ (PA-NYNJ) and those of CERN are required to achieve the goals of an International Lunar Authority. If the International Lunar Authority acquires the powers of one, but not the other, it is likely to fail in achieving all its objectives.

It is "usage fees" that funds the work of pure port authorities, like PA-NYNJ. Without an initial economic base, the pure authority model can't work. At the moment, the Moon has no economic activity and no customers of products and services produced on the Moon. Since we have zero economic base to begin with on the Moon, we need to have an interim phase that transitions to the pure port authority model. The CERN authority model, which is 100% funded by governments under an international treaty, would work well for this interim phase. However, it should be understood by all parties, and be part of the design that the lunar authority needs to wean itself off of government subsidies.

Merging the traditional port authority model to the CERN model appears to manage this transition. The International Lunar Authority (ILA) would more like the CERN at first, but be designed with all the powers of the PA-NYNJ model to start using as the economic activity on the Moon grows. These economic-based "authorities" need to be designed in from the beginning, as they will be extremely difficult to add later.

As the commercially-operated lunar base develops "customers" for propellant delivery and other products/services — the Authority will charge a "fee" or "toll" on those products/services as a percentage of price. This new revenue stream can be used to off-set the funding received from the government members. At which point the amount of funding from the government's can be reduced and eventually eliminated.

While this transition has some obvious challenges, it is achievable if it is planned from the beginning. The partnership analogy in this case is the how Tennessee Valley Authority's dependence of federal government funding was reduced over time and finally eliminated.

GOVERNANCE CASE STUDIES

Port Authority of NY-NJ

The Port Authority of New York & New Jersey (PANY-NJ) is the largest, and by some accounts most successful, port authority in the world. It was formed in 1921 to solve a political problem, and has organically grown to manage 4 major international airports, bridges, tunnels, the largest bus terminal in the world, the World Trade Center, and the Trans-Hudson Corporation. PANY-NJ never received a direct government appropriation[xlii], excepting $200,000 in initial startup funding from the two founding states. Today, it's annual budget is $7 Billion per year, all of it from infrastructure use fees, and includes a $3.6 Billion capital program for development projects. A 2008 study[xliii] estimated that just the local seaport economy alone has generated over 250,000 jobs, nearly $50 Billion in income, and over $5 Billion in federal, state and local tax revenue, per year.

This analysis benefitted substantially from information provided by Hugh Welsh[xliv]*, who served for 33 years at PANY-NJ, and retired as First Deputy General Counsel.*

For centuries, New York and New Jersey — which sit on opposite sides of the New York harbor — have been locked in an intense competition for jobs, commercial industry, and tax revenue. The stakes of this competition increased significantly with the development of the Erie Canal, and then the railroads leading into the area.

Hugh Welsh reports "*The early part of the 18th century was marked by bitter competition between New York and New Jersey that included fishermen shooting at each other and many legal battles, including the famous case of Gibbons v. Ogden. Eventually boundary disputes were resolved but economic competition continued. The growing railroad traffic into the region provided tension which eventually ended up with several municipalities in NJ suing before the ICC claiming that the railroads should charge less for service to NJ then NY.*"

While competition among adjacent communities is natural, it can also be destructive as many of the region's problems, such as bridges and tunnels, and water utilization require an integrated solution. The region had a very powerful economy as a foundation, which would benefit by the development of bridges and tunnels between the two states. While the economic benefits of integrated solution were apparent, this benefit alone was not sufficient for effective action by the political process.

It is only when the latest skirmish in this long battle came before the Interstate Commerce Commission (ICC), and the ICC delivered a not so veiled threat to resolve this dispute in a more lasting fashion, that effective action was taken. Using the Port of London as a legal precedent, Julius Henry Cohen drafted a treaty (called a "compact" in the U.S. Constitution) between the two states and presented the draft to the ICC to prove the two states were serious. The compact creating the PANY-NJ took hold and was approved by the U.S. Congress in 1921. Each state put in $100,000 of seed money. The authority was financed by the ability to float bonds to pay for new infrastructure.

The PANY-NJ rapidly developed a series of tunnels and bridges based on bonds, which were covered by the usage fees. After it proved its effectiveness, the local governments started asking the PANY-NJ to take on additional development projects. In the 1940s, the PANY-NJ was asked to begin developing airports, which led to Newark, La Guardia and JFK International.

In the 1950s, in the post World War II boom, the port authority was able to scale significantly, taking on an increasing number of development projects. One of the authority's more innovative projects would transform transportation and economies around the world.

The PANY-NJ cut a deal with SeaLand Corporation, and agreed to develop the world's first standardized container port in New Jersey. Standardized containers would transform cargo transportation around the world over the next couple decades. (See separate case study on standardized containers.)

According to Hugh Welsh, former PANY-NJ First Deputy General Counsel, key features of the PANY-NJ approach that contributed to its great success include:

- Partner w/ Industry (Avoid Competing): PANY-NJ management avoids, as much as possible, getting into situations that has the authority compete against private industry. Authority has focused on projects that private industry does not go near. The authority pulls in the private sector as a partner. Over time industry has become a champion and ally of the PANY-NJ.

- Narrow Landlord Integrator/Coordinator Role: PANY-NJ was chartered to be a "landlord" not an "operator" when developing maritime terminals and airports. From the beginning, its role was focused on coordination and cooperation. The authority was not authorized to build or manage the daily operations of the airports and maritime terminals it was responsible for creating. The authority contracted with the private sector to construct and operate the necessary infrastructure. To this day the authority leases land, or other rights, to private companies who then develop the airport and maritime facilities.

  As a result of clearly aligning its functional role and responsibilities with industry, the PANY-NJ enjoyed stable and positive political relations with both state governents that has been sustained over a period of 90 years.

> **LESSON**: *Contrast the PANY-NJ's experience with the Tennessee Valley Authority and COMSAT/INTELSAT, as described later in this section, which were in constant political fights with industry interests who believed those organizations were inappropriately encroaching on, and limiting, private industry opportunities.*

Hugh Welsh noted that the lesson of "avoid competing with industry" has been further validated by the instances when the PANY-NJ made an exception to this rule.

- o With bridges and tunnels, the PANY-NJ served in the role of owner-operator without controversy. Operating bridges and tunnels is generally accepted as a natural government function.

- o However, after the PANY-NJ accepted the request by New York and New Jersey political powers to develop the World Trade Center (WTC), with the justification that it was a project beyond the ability of commercial developers, it became controversial. Upon examination, it can be seen that the WTC competed with commercial real estate projects for customers (e.g., tenants).

- Political Neutrality: The PANY-NJ was politically neutral, and stayed out of politics. This policy is critical as there is, has been, and will be constant tension between the two states; between the two political parties; and between local politicians. Over the authority's 90-year history, there has been constant attempts to introduce politics into the decision-making process. The authority achieved its success, in part, by protecting its ability to make decisions based on the merits.

- Long-Term Planning Stability: The authority has been able to plan and develop infrastructure in a 25-year plan because of its political independence. While elected leaders are constantly changing, as are the political winds, this long-term planning ability enabled the development of infrastructure on a very effective and efficient basis.

  The authority's structure helps establish a level of independence to decide to invest and develop infrastructure, consistent with its charter. Politicians are constantly attempting to influence what projects the authority develops. While each of the 6 members of the board from each state are appointed by that state's governor, those members have a very independent attitutude. First, the members are unpaid so they tend to be very successful and financially independent board members, who bring a great deal of insight to the authority. Second, because they are successful and financial independent, they are willing to tell their state's governor "No". Third, they serve six-year terms, in off-set periods, which means that they will survive beyond the term of the governor who appoints them, and the governor can not stack the authority's board. This promotes stability.

  As a result of all these factors, politicians change, and state government's change, but the authority's leadership direction, management and planning tends to be quite stable.

- Local Regulations: Authority is not subject to the local city or county's building codes and zoning laws. This allows the authority to operate much more efficiently and effectively.

LESSONS LEARNED:

A) Authorities have the proven ability to efficiently manage some of the most complex development and infrastructure projects in the world. They can manage advanced technology projects, where human lives are at risk, where environmental protection is important, while also optimizing for economic efficiency and minimizing overhead costs.

B) Authorities are understood and trusted by commercial firms and private investors. An authority model, properly designed, will encourage and promote private investment and partners. They provide an effective interface between government and private industry.

C) Authority-like organizations are effective at integrating projects at the boundaries of different governments. They can provide long-term stability and the ability to plan.

D) Limiting the authority's functional responsibilities to the landlord "system integrator" role, to focus on financing, coordination, and cooperation, functions — i.e., avoid competing with private industry for development and operations — further promotes partnership and long-term political stability.

E) Structuring the board, and the decision-making process of the authority, to be independent from the politicans is critical to effective long-term operations and economic efficiency of the authority.

NOTE: *For this case study, the lessons learned from the PANY-NJ are primarily based on its ability to effectively develop and manage infrastructure in its first 50 years of existence, starting as a minor entity struggling just to survive and then rapidly growing to deliver innovative services to a large geographic region. During this period PANY-NJ had significant competition so it needed to be lean, effective and committed excellence to succeed. In recent years, the PANY-NJ has demonstrated many of the characteristics of a monopoly … and a level of service much different than earlier in its history. Current citizens it is supposed to serve report it has become a bloated, slow moving entity that delivers less than stellar quality services, while repeatedly raising fees and tolls.*

The lesson is that competition and choice is critical at all levels, and makes everybody better at their job.

CERN

CERN, the European Organization for Nuclear Research, is now the premier high-energy physics research laboratory in the world. It manages what are probably the most advanced, complex and expensive scientific instruments in the world. It is controlled by 21 member European nation-states, but it allows participation from non-European countries such as the United States.

CERN was the first major international scientific laboratory ever; and the first in a series of major European multi-national collaborations after World War 2[xlv]. It was officially ratified by convention (a form of treaty) in 1954 by 12 nations, as a response to the need for European countries to finance high-energy physics research, and the inability of any single country to invest the amounts required for state-of-the-art high-energy physics research systems.

Today CERN operates the largest and most powerful particle colliders in the world. The Large Hadron Collider now operates at 8 trillion electron volts (TeV). Meanwhile, in 2011 the United States shut down[xlvi] its most powerful collider Fermilab Tevatron, which was only capable of producing 1 TeV. This cancellation follows the cancellation of the Superconducting Super Collider (SSC) by the U.S. Congress in 1993 at the beginning of an earlier era of deficit reduction. The SSC had a planned energy of 20 TeV. The crisis has been well documented by others.[xlvii]

While American high-energy physics has stalled, CERN has been able to make steady sustainable progress because it was 1) International in nature, and 2) Shared the costs among the members, making it more affordable. Fifty years ago America was the clear world leader in high-energy physics, with CERN playing catch up. Today CERN is the clear world leader in high energy physics. America appears to have conceded that the international partnership approach is the only model that works for big high-energy science. The partnership model appears to be the primary difference. There are potential lessons learned here for NASA and “big engineering” space projects.

The primary startup problem for CERN was political. A group of leading European scientists generated increasing levels of buy-in from European countries, ultimately leading to its formation. They began the process in 1946, and completed the ratification of the organization in 1954.

Strikingly, CERN's founders succeeded at keeping the politicians out of how the organization would be managed, and what systems would be developed. These questions would be left to the scientists and engineers and to the CERN organization. As an international organization set up by treaty, the organization was able to set up its own streamlined procurement and management processess.

CERN has a bifurcated structure. A board level organization (a "Council") is composed of representatives of the participating governments. That Council hires a Director-General (CEO) who has specifically enumerated powers in the Articles of the organization. The Director-General is responsible for daily management and operations, and a council of scientific experts is in charge of prioritizing which research projects will be developed. This structure removes both the development of strategic priorities, and the day-to-day operations, from the short-term instabilities of political appointees.

CERN's strategy was to specifically focus on fundamental research, and intentionally avoided investing in any significant industrial applications, as this would have created political/policy problems for its members. This reduced the need for the member states to get involved in the administration of the laboratory to protect their industrial and commercial interests.

LESSONS LEARNED: Aspects of CERN that may be applicable to a lunar governance model:

A) EFFICIENT: CERN's structure appears to be more efficient than the ISS partnership structure. As an international treaty organization, it appears that it is not subject to the national acquisition regulations of its constituent members.

B) LEAN & EFFECTIVE: CERN's structure, by allowing a Director-General to manage daily activities, appears to enable best management practices, enabling lean development by a world-class team. It can hire and fire, like a business, and pay salaries that are competitive with private firms, and therefore it is able to recruit and retain some of the best people in the world.

C) FLEXIBILITY: Because no single nation's commitment (or lack thereof) will collapse the activites of CERN, this provides individual nation's with the flexibility to increase or reduce their financial commitments over time. If NASA decided to shift its focus and resources to going to Mars, this flexible organizational structure will enable other nations to manage the infrastructure without NASA's large financial contribution.

D) POLITICAL NEUTRALITY CREATES POLITICAL INDEPENDENCE: The CERN decision-making process on which facilties should be built — as well as the design, development and operation of those facilities — was independent of the politicians who appointed the CERN board members. Political independence has contributed significantly to CERN's ability to conduct effective long-term planning and development; which is quite similar to a characteristic identified in the case study of the Port Authority of New York and New Jersey.

Tennessee Valley Authority

Some commentators suggest the Tennessee Valley Authority (TVA) as a governance model for space development and operations. The TVA[xlviii] is a federally-owned corporation created by congressional charter in 1933. TVA's charter was written by the same lawyer, Julius Henry Cohen, who wrote the charter for the Port Authority of New York and New Jersey (PANY-NJ) a decade earlier.

The TVA was successful in its early years — achieving the objective of creating jobs in the Tennessee Valley in the midst of the Depression while controlling the flooding to help farming, and providing low-cost electricity to the South. Today, TVA is the nation's largest public utility, selling power to distributors that serve 9 million people and 650,000 businesses and industries in most of Tennessee and portions of Alabama, Georgia, Kentucky, Mississippi, North Carolina and Virginia. It runs three nuclear plants and scores of gas-turbine, coal-fired and hydroelectric power plants. Its revenues in 2011 were $11.8 billion.

Some historians[xlix] describe the TVA's unique contribution as providing a holistic integrative solution of a complex multi-faceted flood control and electricity problem for an entire river valley. However, that problem is not unique. For example, California has managed similar problems in its large river valleys, with many dams to generate electricity, and flood control projects, and did not need to use a government corporation.

The TVA has similarities to the PANY-NJ, and some differences from the PANY-NJ, which are worth noting.

TVA Model Similarities:

(1) Efficient Technical Management: The TVA has demonstrated the same capability to manage large-scale complex technical projects as was also demonstrated by the PANY-NJ, CERN, and COMSAT/INTELSAT.

(2) Geographic/Political Integration: The TVA demonstrated (again) the value of a single managing organization to integrate a large-scale project for multiple (seven state) governments whose interests do not always align — thereby solving critical political problems. This ability to integrate multiple governments has also been demonstrated by PANY-NJ, CERN, and INTELSAT.

(3) Private Financing: TVA also had the ability to sell bonds to the financial markets in the same manner as PANY-NJ-NJ and COMSAT-INTELSAT. This debt financing ability allowed TVA to leverage the direct federal appropriations that it also received.

TVA Model Differences:

a) Appropriations in Early Years: The TVA provides an important precedence for a notional lunar base authority as it received large federal appropriations during its first several decades of operations to develop the initial infrastructure.

As the TVA developed a larger and more affluent customer base, which it was able to charge use fees to, over time the TVA weaned itself off of federal appropriations. This weaning process started in 1959 when power program appropriations were ended, and concluded in 1999 when economic development and environmental protection appropriations stopped.

One reason the PANY-NJ did not need appropriations is the NY Harbor region had an extremely strong economy, and there was no doubt among the investment community that the use fees for bridges and tunnels would cover the cost of building the infrastructure. However, the Tennessee Valley was much poorer, and the people had much less ability to pay, reducing the ability to raise the large amounts of bonds to build the infrastructure. The TVA experience has more in common — than that of the PANY-NJ — with future space markets and applications, as space markets are considered speculative and risky by commercial bond investors.

b) TVA was a "Government Corporation" with Operating Authority. When President Franklin Roosevelt asked Congress to set up the TVA, he stated he wanted "*a corporation clothed with the power of government but possessed of the flexibility and initiative of a private enterprise.*" So, while the PANY-NJ was limited to acting as a "landlord authority", the TVA had much broader powers and authority for the entire system. While the PANY-NJ could only achieve its goals by acting as a landlord, and finding private industry partners to operate the facilities, the TVA would take on the role of operator.

These two differences are politically critical, as they have been the source of 50 years of heated political rhetoric centered on the TVA. The TVA became the subject of a conservative backlash in Congress, which has lasted decades. Proposals to expand the TVA models to other areas were quickly killed, being labeled "socialist". Conservative politicians from Ronald Reagan to Barry Goldwater have attacked the TVA model. Reagan famously criticized the TVA on a GE-sponsored radio show as being "big government" in 1962[l]. He was fired by GE for doing so, and changed his party affiliation to Republican. Barry Goldwater then criticized the TVA as being "socialist" in 1963, and proposed selling the TVA[li]. Today there are still conservatives and libertarians who want to privatize or sell off the TVA, and who criticize it for a wide range of reasons (exemption from federal laws, exemption from state, federal, local taxes, etc.)[lii]

Further, both FANNIE MAE and FREDDIE MAC, which contributed the national housing collapse and the great recession of 2008-09, are government corporations. So too was COMSAT, which was heavily criticized as a government-sponsored monopoly that slowed down innovation in the commercial satellite industry.

Why has the TVA encountered so much criticism, while the PANY-NJ did not? In NexGen's assessment there are two fundamental reasons:

(1) The PANY-NJ aggressively partnered with private industry, in both development and the operations of infrastructure. Further, the PANY-NJ avoided infrastructure projects that private developers could handle. This converted potential competitors into strong partners, and created powerful and sustained relationships with private industry in the geographic region.

In direct contrast, the TVA owned and operated all of its infrastructure. There are hundreds of privately-owned electrical utilities and related commercial firms across the country. Many of them see the TVA as intruding in functions better left to private industry. They see TVA primarily as a competitor, not as a partner.

(2) The PANY-NJ focused on serving governmental, or quasi-governmental functions. There is broad public agreement that financing the development of bridges, tunnels, and airports is generally a government or quasi-government function. Thus, the PANY-NJ was not serving an industry role, and thereby competing with industry.

In contrast, the TVA is perceived, correctly, as taking on some roles generally reserved to private industry in America — the job of an electrical utility — and converting it into a government operation. While the TVA also had some government functions thrown in (i.e., flood control, clean water, environmental protection), these were politically overshadowed.

LESSONS LEARNED:

- A governing entity of a lunar base will need direct government support for decades until it can wean itself from those appropriations through effective economic development. The TVA demonstrates this is feasible and provides a political precedent.
- Limit the roles and functions of the Lunar Authority to those functions that are perceived to be governmental or quasi-governmental in nature.

COMSAT-INTELSAT

Some members of the space community advocate the government corporation model, used by COMSAT-INTELSAT, for space infrastructure development. While potentially attractive on the surface, an examination of the approach illustrates significant problems.

In summary, COMSAT and INTELSAT were established for policy reasons, not for technical, business, or financial reasons[liii]. U.S. commercial industry was ready and willing to finance and develop commercial comsats from the very beginning. COMSAT-INTELSAT became the dominant space communications satellite entities for nearly 25 years. Once established, they created high barriers to entry, which slowed down innovation in international satellite communications. When Panamsat broke their international monopoly in the 1980s, industry innovation and growth accelerated.

Arthur C. Clarke invented the geostationary orbit satellite concept in 1945. In 1955, two years before Sputnik, AT&T Bell Labs became one of the first commercial firms to start exploring the concept and utility of GEO comsats.[liv] AT&T approached NASA in 1960, to propose a partnership entirely financed and led by AT&T, with reimbursable services from NASA. AT&T had also started discussions with various European countries, including Germany, France and the United Kingdom about international service[lv]. Separately, Hughes Aircraft started developing ideas for comsats in 1959[lvi] and also approached NASA in 1960.

Instead of enabling a commercial-led system development by AT&T, the U.S. government committed its own funding when NASA issued a Request for Proposals on January 4, 1961. Both AT&T and Hughes responded, but NASA did not pick either of them, instead choosing a 3rd company Radio Communications of America (RCA) on May 18, 1961. AT&T decided to continue with its plans to privately finance 100% of its own commercial comsat, which included a $6 million reimbursable payment to NASA for launch services. NASA then issued a sole-source contract to Hughes on August 11, 1961 to create Syncom 1, which would become the first geosynchronous communications satellite.

AT&T's Telstar 1 would beat the competition to orbit, and become the first commercial communications satellite on July 10, 1962. AT&T's demonstration of its commitment to commercial comsat development failed to produce the result they desired in satellite operations. Not only did national policy subsidize competition in satellite manufacturing, it also prevented AT&T from becoming an international satellite communications operator. The very next month, on August 31, 1962, President Kennedy signed the Communications Satellite Act, which created a monopoly on international satellite communications to a new government corporation called COMSAT, which then set up INTELSAT.

LESSONS LEARNED: COMSAT was set up to solve a political problem, not a business problem. AT&T proved it had the technical, business and financial capability as well as the corporate commitment to develop a commercial comsat business, excepting its need for launch services. It was defacto U.S. national policy to prevent an extension of the AT&T monopoly into satellite construction, development, and operations. First, NASA intentionally created a full 3-way industry competition through flight demonstration when AT&T was only requesting launch services on a reimbursable basis. Second, the U.S. Congress created COMSAT, which then set up INTELSAT, instead of allowing AT&T to become an international satellite operator.

This political history has specific relevance to this PPP Analysis of Alternatives. Would the international partners accept the choice of a U.S. company as lead system integrator to manage a lunar base? Would ESA, JAXA, Russian and Canada write large annual checks to a Boeing, Lockheed Martin, or other U.S. company?

From an innovation perspective, having three (3) well-funded competitors develop satellite technology all the way through flight demonstration produced major dividends. Analysis demonstrated that GEO comsats had significant economic advantages, but neither U.S. government (i.e., ARPA), or U.S. industry, could figure out how to make a satellite light enough to get to GEO on existing launch vehicles. U.S. government programs for geosynchronous satellites failed. Both AT&T and RCA developed medium Earth orbit satellites, and planned large satellite constellations to provide continuous service. It was Hughes Aircraft's innovative concept for a light spinning spacecraft that enabled the very first GEO comsat.

Hughes innovation became the basis for rapid commercial satellite industry development. Hughes would soon find itself defending its valuable patents in court for many years. This innovation was the justification for NASA's sole-source contract with Hughes for Syncom, and was the reason that COMSAT's first purchase was from Hughes.

Creation of INTELSAT & A Monopoly

In 1964, the International Telecommunications Satellite Organization, or Intelsat, was established in 1964 by COMSAT as the international telecommunications provider to the western world. It grew to be owned by over 100 national governments, with a 25% share owned by the United States, and headquarters in Washington, DC.

By the early 1980s, Intelsat had a clear and legally established international monopoly for satellite telecommunications. There were some small competitors who had authority to operate within a country such as Americom in the U.S. and Telesat in Canada. A rare exception to the rule had to be made on a case by case basis such as Eutelsat in Europe.

For the most part Intelsat had the international telecommunication business to itself. Intelsat procured, owned, and operated the satellites, and the local telecomm representative marketed those services in country. All cards were stacked in Intelsat's favor. They had the world's telecomm firms lined up as shareholders and partners, while the regulatory authorities created preferential rules, and the capital markets would not risk funding a competitor. While the manufacturers serving Intelsat had continued to promote rapid innovation in the technology of GEO comsats, Intelsat proved to be slower at innovating in the services it was willing to provide to its customers.

An Entrepreneur Breaks the Monopoly

If you were a successful American television entrepreneur like Rene Anselmo, and you saw a big opportunity to offer Spanish language television and video to international customers in South America, you had to go through Intelsat. If you had a deal with CNN to offer Spanish language cable news services across all of South America, and were convinced this was the future, you still had to go through Intelsat. When Intelsat turned Anselmo's request to transmit "entertainment TV" down, Anselmo refused to take "No" for an answer. He formed his own satellite company (Panamsat), and in 1984 he applied to the FCC to launch a satellite into orbit.[lvii]

While Intelsat was armed with top lobbyists, Anselmo battled with his own wits, sending members of Congress and others antic letters featuring his dog Spot. Then a 1985 FCC ruling authorized private satellites, and Anselmo was on his way.

Anselmo could not raise any capital for his venture. Instead, he bet his entire personal fortune of almost $100 Million on Panamsat, and still he had to cut some corners and take some extraordinary risks. He got a great deal on a launch by agreeing to be a customer for the Ariane 4 on its maiden launch. This was a huge risk for the maiden voyage of a brand new launch vehicle from a company that had four launch failures since 1981. Anselmo then purchased an $80 million satellite for $45 million from RCA Astro Space Electronics (now Lockheed Martin Commercial Space) after another customer cancelled their order. He launched the satellite with only a fraction of the insurance needed to launch again. He launched the satellite without frequency (or "landing") rights to operate in many of his target countries. Fortunately, the launch was a success, the satellite worked, and hold out countries very quickly began providing him with necessary landing rights.

Almost immediately, the growth rate of the commercial communication accelerated. Major national satellite operators (Eutelsat, Americom) expanded into international markets, and the satellite manufacturers also invested in satellite operators (e.g., Hughes Communications created Hughes Electronics in direct competition with its good customers Panamsat and Intelsat). CNN International and many other entertainment services sprang into existence. Digital satellite radio and satellite television, satellite by internet, satellite phone, pagers, asset tracking and remote payment systems all became hot new growth markets in the 1990s. Many tens of billions of dollars of private capital were invested in new companies and new services that may not have existed under a market dominated by one international monopoly.

In 1997. only a decade after launching its first satellite, Panamsat merged with Hughes Electronics and became the largest and most profitable satellite operator in the world. By all definitions, Panamsat was a huge success, and changed the global satellite industry for the better.

CONCLUSION: Because the Intelsat/COMSAT monopoly was broken, today commercial comsat industry revenues now greatly exceeds all government space industry revenues. In 2014, global revenues for this industry were $203 Billion.[lviii] The rapid growth that was unleashed after the Intelsat/COMSAT monopoly was eliminated provides evidence that a "government corporation" will slow down innovation and growth beyond what is achievable by other approaches.

AT&T (Monopoly, Regulated Utility)

For most of the 20th Century AT&T had a complete (and regulated) monopoly on phone service. AT&T is a study in contrasts. The steady predictable large profits of the AT&T monopoly enabled the creation of Bell Labs, which is legendary in the amount of innovation it supported in the 20th Century. But AT&T also used its monopoly power and control over the closed architecture to prevent development and delivery of many innovative innovative services from 3rd parties.

Following the invention of the telephone in 1876, the phone spread rapidly throughout the nation. After Bell's patent expired in 1894 expired, the business was a totally open market. But the network effects of the phone service, combined with the capital intensity of laying wires across the nation to all homes, soon generated what is a natural monopoly. In 1913, the U.S. Attorney General allowed AT&T to control telephone service as a regulated monopoly.

In 1925, AT&T established Bell Laboratories, which is arguably the singlest biggest source of innovation in 20th Century American history. It is perhaps only rivaled by Thomas Edison's laboratories in the 19th Century. Bell Labs invented the transistor, the laser, the solar cell, the fax machine, radio astronomy, information theory, modern cryptography, the UNIX operating system, the C and C++ programming languages, TDMA and CDMA cell phone technology, and the first communications satellite (Telstar 1). Seven Nobel Prizes have been awarded for work completed at Bell Laboratories.

While the amount of innovation generated by the AT&T Bell lab system was amazing, there were downsides to the closed AT&T system and monopoly. In 1947, AT&T scientists conceived the idea of the cell phone, but did nothing with it. In 1959, Thomas Carter patented a "wireless phone", but AT&T threatened to discontinue service to any customer who used the phone. Carter filed an anti-trust suit against AT&T in 1965 (and won in 1968). The trend of AT&T resisting innovation and competition continued, and in 1982 the U.S. government broke up AT&T into its major components.

> *"Effective, aggressive competition, along with regulation and control are inconsistent with each other, and cannot be had at the same time."*
> - Theodore Vail, 1910, CEO of AT&T

As a result of these changes, which were forced on the dominant telecomm supplier, we have seen repeated waves of innovation in the telecommunication industry. Prior to the intervention by the U.S. government on behalf of the public, most homes had perhaps one phone line with a rotary phone. In the last few decades, the average American home has been introduced to wireless phones, speaker phones, cell phones, smart phones, answering machines, modems, DSL, ISDN, fiber optics in the home, fax machines, call waiting, caller ID, call forwarding, 3-way calls, WIFI, and free internet based phone calls. Although technology had a critical part in this process, the importance of an open top-level architecture with open standard interfaces to enable easier introduction of new and improved services cannot be understated.

> **LESSON LEARNED:** A system designed around competition, modular systems, and open interface standards will increase innovation and long-term economic growth in space.

Boeing-United Airlines Monopoly

In 1929, Bill Boeing executed a vertical integration[lix] strategy by consolidating a plane manufacturer, an airline, an engine manufacturer, and airports all in one holding company. This was an obvious strategy, which was similar to the strategy that Hughes Communications executed in the 1990s by creating Hughes Electronics to compete with Panamsat.

In 1933, Boeing Air Transport started offering service on the innovative Boeing 247. The 247's low single wing, smooth and streamlined all-metal construction, retractable landing gear, and fast speed placed it far ahead of the competition at that time. Boeing reserved the first production run of 60 planes for its own airline, United Airlinees, and refused to sell early 247's to United's competitor Transcontinental and Western Air (TWA).

The U.S. Government quickly decided this was a problem and passed anti-trust legislation to deal with it in 1934. A new requirement of U.S. airmail contracts prevented aircraft manufacturers from owning airlines. The consolidated Boeing company was split into 3 parts: Boeing, United Airlines, and a company that became known as United Technologies (which included Pratt & Whitney).

Irregardless of the U.S. Government anti-trust action, private sector activity also would almost certainly have solved this problem on its own — at least in the short term.

In 1932, TWA executives correctly anticipated, that Boeing would refuse to sell 247s and began soliciting competitive alternatives from five other manufacturers, including Douglas. The result was the DC-1, which quickly evolved to the DC-3 that eclipsed the 247 and came to dominate the world aircraft manufacturing business.

By refusing to sell 247s to TWA in the same manner it was to United Airlines, and not treating TWA like a highly-valued customer, Boeing created its most serious competitor (Douglas). This poor Boeing business decision would enable Douglas Aircraft to usurp Boeing's leadership position in the commercial aircraft manufacturing industry.

LESSONS LEARNED:

- Private industry, particularly market leaders, will naturally attempt to vertically and horizontally integrate multiple funtions in order to reduce competition and increase prices on customers.
- While monopolies are not always illegal, reducing and eliminating competition can create barriers that slows down innovation.
- Both smart government and industry foresight and action can work to prevent monopoly action, to promote long-term growth.

National Parks & Private Tourism

America's National Parks have been opened, to a great extent to tourism, by the National Park Service (NPS). The U.S. Government (USG) could have closed the parks as wilderness areas, but decided otherwise.

The NPS has explicitly encouraged railroad companies and other commercial interests to build hotels and other tourism-related facilities in the national parks. Commercial firms pay fees, which the National Park Service uses to build roads and trails.

Americans drive to the national parks, creating millions of visits by private tourists, and strong public support for the National Park system. The family vacation is now part of the American culture.

Some have suggested this as a model for space infrastructure:

- USG could encourage private firms to build infrastructure to promote and encourage tourism at deep space government-managed facilities.
- Commercial firms pay fees to facility manager that help with upkeep of those facilities.
- Government also acts to create a favorable regulatory climate for space tourism.
- Private citizens experience space through both remote access/direct participation.
- The NPS is a case study that suggests that tourism is a natural commercial opportunity, which can be leveraged by NASA in the following manner:
    - The governing authority for the International Lunar Authority signs contracts for habitation/storage/support services at the lunar base, as an anchor tenant

customer. Private operators develop, own, and operate Hab/storage/support facilities.

This is how the Port Authority of New York and New Jersey operates. It is similar to the firm-fixed-price ISS contract with Hamilton Sundstrand for water delivery services, and other commercial ideas that the ISS program is considering right now.

- Companies can then add private tourism capacity at the marginal cost of facility operations
- Firms then sign up commercial deals with their own suppliers, creating a private-sector space ecology.
- Creates efficiencies using private-sector management, which are likely to cut lunar base operational costs.
- NASA benefits as tourism brings economies of scale.

McMurdo Station (Antarctica)

Some space policy analysts suggest McMurdo Station in Antarctica as a potential governance model for future development of deep space. While interesting, upon examination significant shortcomings of this model, related to economic development, become apparent. Although there is much to learn from the historical context of the development McMurdo Station, the model itself has serious shortcomings in the area of economic development. McMurdo is a traditional government development and operation model that is effective at pure science and environmental protection but which has no demonstrated ability to encourage private investment and commercial activity.

McMurdo is the largest research base in Antarctica and the staging point for U.S. Antarctic research. Established in 1956, McMurdo was for many years operated by the US Navy, including flights to and from Christchurch, New Zealand. In 1972, primary responsibility for managing and funding the US Antarctic Program was transferred from the US Navy to the National Science Foundation (NSF). On February 5, 1982, President Reagan signed presidential memorandum 6646[lx], which clarifies that NSF has the lead U.S. mission responsibility for Antarctica and directs other U.S. federal agencies to support NSF.

Since the late 1960s the U.S. government has increasingly relied on a prime contractor to provide science support, operations and maintenance, logistics support and construction in the Antarctic. These large support services contracts run in roughly 10-year cycles. Since 1999, the Raytheon Polar Services Company has performed this role. In December 2011, Lockheed Martin Corporation was announced as the winner of the most recent competition[lxi]. The potential value of this 13-year contract is approximately $2B.

Others suggest Antarctica as a model as there is now a great deal of tourism to Antarctica. Approximately 50,000 people per year travel to Antarctica.

Finally, some suggest Antarctica as a model as it has a legal status similar to that of the Moon. It is a remote and extreme environment that is utilized primarily for scientific research. No nation can claim its land as specified under an international treaty[lxii].

That is where analogy ends. Upon examination, the specific problems with McMurdo/Antarctica as a governing model are:

1) No Policy Requirement to support Commercial: According to Brian Stone[lxiii], Division Director of the NSF Office of Polar Programs, NSF has no legal or policy requirement to support, enhance, enable, or stimulate commercial activity at the South Pole. Their sole mission is focused on science. As a result, the model has precluded the encouragement of private economic activity by the U.S. government.

2) Traditional Cost-Plus Operations Contract: According to Dr. Ken Ford[lxiv], formerly of the National Science Board that governs NSF and former Chair of the NASA Advisory Council, the key decisions at McMurdo are made by the NSF. The contractor operates the station under a FAR-based cost-plus contract and has little economic incentive to reduce costs or expand the scope of economic activity at McMurdo. It is a traditional government contract, not a partnership that incentives commercial development.

3) Economic Resource Utilization Prohibited: Mining in Antarctica is explicitly prohibited by treaty. Since the original Antarctic treaty was unclear on mining in Antarctica, the 1980s there was an effort to establish an Antarctic mining treaty to enable mining for resource production. In response, Australia and France led an effort to prohibit the same. As a result, the 1991 Madrid Protocol[lxv] to the Antarctic Treaty now explicitly bans mining in Antarctica.

4) Fractionated Systems Integration: According to Dr. Brian Stone, NSF Director of the Office of Polar Programs, both the logistics and supply as well as telecommunications services are provided by a mix of both commercial suppliers and other U.S. government agencies. While in theory it makes sense to consolidate all these operational functions under a single non-governmental organization, in practice it is not feasible under current policy and law. For this reason, NSF is the only organization that can integrate the full system.

According to Dr. Stone, various parties have proposed that all these operational functions be consolidated and that NSF delegate full system-level responsibility for Antarctic operations to another entity. While NSF leadership might be interested in doing so, there is a major barrier that is outside of NSF's control that prohibits this model. First, a non-governmental entity will not have the authority to direct the DOD to provide services, as NSF can today under presidential memo 6646. DOD provides many unique logistical services on a marginal cost reimbursable basis, which would be extremely costly to duplicate by another entity. Second, while there is no technical reason a commercial firm could not duplicate the cold weather capabilities of a C-17, a Navy fuel transport ship escorted by icebreakers, or a south pole medivac capability, the economics of doing so are prohibitive. The marginal cost to the Navy of providing these services is very low given that this capability and its support infrastructure is already paid for by the Navy's primary mission.

5) Drive-by Tourism: While there is a large and growing demand for trips to Antarctica— with more than 50,000 private visitors by ship every year — the vast majority of the tourists are limited to drive-by viewing from a cruise ship. This business

has very little impact on the Antarctic, and also adds very little to the Antarctic economy, and eliminates any economic incentives for private investors to put their money into Antarctic infrastructure.

Those few tourists allowed to step on to Antarctica only make a temporary landfall by small boat. There are no permanent tourism facilities or infrastructure located on the continent of Antarctica. Such commercial facilities are prohibited. Any private industry proposals to develop permanent commercially-focused infrastructure must acquire approval through an Environmental Impact Assessment process as specified in the 1991 Madrid Protocol for Environmental Protection. None have been approved.

Today, the entire Antarctic region has become a "natural preserve" that focuses primarily on science and environmental protection to the nearly complete elimination of on-site tourism and prohibition against privately-financed tourist infrastructure. It provides a start contrast to the case study of the National Park System.

6) Cultural/Value Barriers to Economic Utilization: The Antarctic community's antipathy to economic utilization extends to even those forms of commercial activity that do not damage the Antarctic environment. For example, elements of the United Nations are criticizing those who adapt science to prospect for extremophiles to use in the biotechnology industry. Some parties[lxvi] are attempting to prevent private firms from developing intellectual property from biological samples coming from Antarctica.

The entire culture and value system of the international Antarctic community is aligned to discourage and prevent private investment in developing facilities, infrastructure and resources in Antarctica. If a similar culture and value system is allowed to develop around planetary and orbital destinations, NASA's strategic objective of extending and sustaining human presence across the solar system will become more difficult.

7) Lack of Clarity on Criminal Jurisdiction: As a remote and relatively unpopulated jurisdiction that is covered by international treaty, there are areas of Antarctic-related law that are unclear and could facilitate criminal activity. For example, some legal commentators[lxvii] suggest that an American could get away with murder as it would not be technically illegal.

LESSONS LEARNED:

The Antarctica case provides a clear contrast to several other case studies examined herein. Antarctic operations are a case study on how to minimize and prevent private investment in space. Antarctica illustrates what NASA should not allow to happen. If NASA wants to encourage and promote private investment in deep space utilization and infrastructure, NASA should:

- Take steps to support limited private property utilization rights, consistent with international law, such as the Deep Seabed Mining act, and oppose treaties similar to the 1991 Madrid Protocol on Environmental Protection of Antarctica.
- Encourage and promote private investment in privately-owned infrastructure, as illustrated by the National Park System and Port Authority of New York and New Jersey.

- Enable private space passenger travel to the destination for purposes other than science, and not allow science and environmental protection to become the dominant strategic purpose.
- Address potential legal jurisdictional issues related to confusion over which international law applies for a wide variety of laws, including criminal law, and laws protecting intellectual property.

Open Architectures — Increasing Private Investment & Accelerating Innovation

One of the purposes of this study is to provide suggestions on how to increase the likelihood that private industry will invest significant resources into a lunar base. Analysis supports the position that an "open" architecture with open standard interfaces, as contrasted to a "closed" architecture, are likely to increase benefits to NASA and the American people. More specifically, allowing one company to control or dominate multiple key segments of the industry reduces competition, slows innovation, and drives up prices over time.

The Conflict between Open Architectures and Closed Architectures:

It is common knowledge among business professionals that private corporations strongly prefer, seek out, and invest in businesses with high barriers to entry that eliminate or reduce the competitive pressures. High barriers to entry allow providers to defend higher profit margins, which justify risky investments.

For this reason, when given a choice, suppliers will usually attempt to steer customers towards architectures that are "closed" or "vertically integrated". One common method to steer customers is to only invest corporate resources in closed or vertically integrated architectures, and not offer the customer the choice of an open architecture as an alternative.

Historically, businesses only offer "open" architectures when forced to do so by their customers, by government action in support of customers (e.g., anti-trust), or by the competitive situation. Earlier this report provided examples of open architectures that were established only after overcoming long-term active resistance by the beneficiaries of the pre-existing closed or vertically integrated systems.

Collectively, and individually, these case studies illustrate the major benefits of open architectures with common interface standards among the major elements. Open architectures accelerate free market innovation in the process that economist Joseph Schumpeter described as "creative destruction".

IMPLICATION: *It is in NASA's (and the nation's) interest to disaggregate the supply chain & create an open architecture.*

Given forethought and purpose, NASA has the ability to disaggregate[1] the supply chain into its major individual elements and create an "open architecture."[2] The result

[1] "Disaggregate" is defined as "to dismantle or segregate into smaller elements".

[2] "Open Architecture" is defined as "a system of elements for which the specifications for integrating the elements into the system are made publicly accessible." Individual elements of the system or architecture may be privately owned and proprietary.

will be lower barriers to entry for new suppliers, increased competition, and accelerated innovation.

This recommended approach will not be desired by some firms. Private industry is naturally incentivized to limit and inhibit competition — to increase prices, reduce business risk and increase leverage over the customer — by offering their customers vertically integrated or closed architectures.

If NASA allows the competitors to offer either open or closed architectures, many competitors will choose to offer closed architecture solutions, even when they could have offered open systems of greater value to the customer. This will limit NASA's choices and is likely to create a "non-optimum" outcome for NASA.

This same economic logic suggests that NASA should explicitly design an "open architecture" by taking the following steps:

1) Disaggregate the supply chain to/from the lunar base, and its other major functional parts.

    a. Major functional segments of a fully operational lunar transportation system include, at minimum: i) Earth-to-orbit launch, ii) Reusable crew spaceships for crew, iv) propellant depots, v) reusable lunar landers, and eventually vi) reusable orbital transfer vehicles.

    b. Crew and cargo should, in general, be delivered separately for both safety and performance reasons. The large bulk of the cargo needed at the Moon can be delivered at lower cost with the elimination of unique systems needed by humans (e.g., ECLSS, food, water), and with reduced risk to human life.

2) Establish open standard interfaces between these major functional parts. If a company owns and controls the interfaces, then it controls the functional parts on each side of the interface.

3) Require that crew and cargo systems be designed to be launched on at least 2 existing launch vehicles that are substantially different. Disimilar redundancy is standard commercial comsat industry practice. It increases competition, prevents lock-in by a commercial firm, and reduces overall system risk.

4) Prevent vertical integration and integration across the interfaces. No one company should have control over the entire system. If NASA, or an International Lunar Authority, chooses to buy an integrated end-to-end service from a commercial provider, NASA (and the Authority) needs to make sure there is sufficient competition to prevent any single supplier from having too much leverage. While it may be attractive as a cost-savings in the short term, it will slow down innovation, increase risks, and drive up costs in the long-term.

Open Architecture Implications & Suggestions

1) Design and manage the Internation Lunar Authority in a manner that breaks it down into its key functional segments.

a. System Integrator/Station Manager
b. Habitation;
c. Communication;
d. Propellant Storage;
e. Robotic Servicing/Repair/Maintenance
f. Transportation

2) Don't allow any one company or organization to establish control over multiple key segments of the service supply chain. Such a result would inhibit competition.

3) Nothing in suggestions 1&2 prohibits NASA from purchasing an integrated service from one company[3], as long as the underlying architecture is open, and the service provider does not have the ability to establish exclusive control over key elements via vertical integration.

[3] The alternative is for NASA to choose to be the integrator.

Case Study Figures of Merit (FOMs) & Summary AoA

<u>FOM Definitions</u>:

- **International Partners:** Ability to develop international government partnerships, and stimulate financial support from governmental partners
- **Private Investment**: Ability to promote and encourage private investment.
- **Quick Debt Capital:** Ability to rapidly obtain financing from debt markets.
- **Economic Benefit**: Track record at creating/promoting economic growth.
- **Innovation**: Ability to enable, promote and stimulate innovation, including opportunities for new entrants to innovate and compete.
- **Management Efficiency**: Ability to use best (world class) practices to effectively and efficiently manage cost, schedule, technical and risk in both the development and operational phases; and ability to optimize for lower long-term life cycle costs.
- **Regulatory and Economic Utilization Rights**: Ability to create and enforce regulations and rules necessary to effectively develop geographic region, including property rights, spectrum allocation, other economic rights, technology standards, environmental protection, etc.
- **Political Sustainability**: Demonstrated ability to sustain changes in government leadership over the long-term, as well as changes in partner governments.
- **Strategic Flexibility**: Ability to enable individual governments to seamlessly join/leave the partnership, and to shift their resources elsewhere (e.g., to Mars) at a later date as/when they choose. Ability for the partnership to internally expand to other regions (e.g., lunar surface) as desired by sponsoring governments.

Governance Models / **Figures of Merit**	**Baseline** (ISS, Shuttle, Constellation)	**NASA Partnerships** (COTS, LSP, Comm'l Crew)	**Lead U.S. Corporation** (AT&T/Bell)	**International Authority** (PA-NYNJ, TVA, CERN)	**International Corporation** INTELSAT/Fannie Mae/Freddie Mac
International Partners	Green	Green	Red	Green	Green
Private Investment	Red	Yellow	Yellow	Green	Green
Quick Debt Capital	Red	Green	Green	Green	Green
Economic Benefit	Red	Yellow	Yellow	Green	Yellow
Innovation	Yellow	Green	Green	Green	Yellow
Non-govt Customers	Red	Green	Green	Green	Green
Management Efficiency	Red	Yellow	Green	Yellow	Yellow
Econ Valuable Use Rights	Yellow	Yellow	Yellow	Green	Yellow
Political Sustainability	Yellow	Yellow	Yellow	Green	Green
Strategic Flexibility	Yellow	Green	Green	Green	Green

Pros of International Lunar Authority	
PROS	**Description**
Increased Political Independence Enables Improved Decision-making by Managers	In many cases, NASA managers and executives find that their options are eliminated or severely constrained by politics. An authority can be structured to be politically independent, which reduces the political constraints on decision-making. While no government funded organization will have complete independence, as the budget is always a method of control, an Authority can be more independent of short-term political considerations than NASA. The "CEO" or "Managing Director" would not be a political appointee. Board can be structured to have long-term appointees, with offsetting terms, chosen for their subject matter expertise who don't feel beholden to short-term political interests.
Long-term Planning is More Effective (with reduction in political interference)	The increased stability of the authority, combined with political independence, increases the value of long-term planning. Both CERN and the PANY-NJ both regularly execute on decade and multi-decade plans. However, NASA finds it increasingly difficult to execute on 5-year plans for developing new systems, let alone multi-decade plans. This is a fundamental aspect of 4-year presidential cycles, and other politicians deciding to mandate how a system will be designed (which holds until they lose power.)
Can Borrow Funds	An authority can borrow funds to enable optimal infrastructure development. Both CERN and PANY-NJ have easy access to low cost capital as needed for infrastructure projects. If there is a surprise, they can quickly get access to capital. However, NASA is not allowed to borrow capital to help manage the natural development curve of projects. Instead NASA is forced to take other measures, including cancelling important projects, or stretching out projects, which creates delays and cost increases.
Politically acceptable to assign Utilization Rights	Even if legal, the mere suggestion that the United States government may allocate "property rights" to a U.S. corporation in outer space is highly politically charged in international diplomatic forums. The creation of an International Authority that would allocate "utilization rights" would at least partially solve this political problem, in much the same way that the International Telecommunications Union plays a politically useful role for developing international agreement about spectrum utilization in GEO.
More Trusted by Industry as a Good Partner = Increased Private Investment	Authorities are well understood and trusted by commercial firms and private investors. An authority model, properly designed, will encourage and promote private investment and partners. From the perspective of industry, the U.S. Government is difficult (at best) to develop a long-term partnership with. It costs industry a lot, in both time, money and lost opportunities, to get to a signed contract. Even then the commercial partner cannot be sure the government will not terminate for convenience. Further, every change in the White House, in the Congress, and in NASA's leadership is a source of risk for a commercial partner.
Increases NASA's Long-term Strategic Flexibility **(e.g., Eliminates need for "Abandon in Place")**	No single nation's support will collapse the activities of the International Authority; which allows each nation to shift and adjust its support levels over time. This enables strategic refocusing over time. As an example, the authority structure would make it easier for NASA, to decide to shift resources from activities at a lunar base to focusing on humans on Mars. An authority would be planning from day 1 for this day. The independent organizational structure will enable other nations to assume more responsibility without requiring a wholesale restructuring or considering the idea of "abandon in place", as was proposed under Constellation program.

Increased Political Sustainability over the Long Term	As exemplified by the ascendancy of CERN and the collapse of the U.S. Super-conducting Super Collider, a deepspace waystation or a lunar base, will have improved long-term political sustainability as compared to the traditional approach. The improved sustainability will be for multiple reasons: 1) Lower cost development (using commercial practices) and increased efficiency of operations will reduce political pressures driven by budget, 2) Ability to persuade private industry to directly invest further reduces costs born by government, and 3) With a clear definition of roles & responsibilities, commercial industry will be an active political supporter.
Improved Employee and Expertise Retention	Allows use of "best practices" from employee retention, and training. An international authority will not be subject to government human resource laws and regulations, meaning it can pay salaries that are competitive with major firms.
More Efficient Procurement	An authority will be more efficient than any US government agency can be, which is subject to many U.S. laws and the Federal Acquisition Regulations (FARs). Allows use of "best practices" for procurement.
Improved Management Tools and Practices	Authorities can be managed more like a large private business firm, with adoption of best management practices across all manager areas, including budget, design, development and operations.
Increased Innovation	An authority model enables the elimination and reduction of many of the addressable barriers to innovation created by the environment surrounding a large government agency. An acceleration of innovation will be a natural outcome of 1) increased private investment by commercially-motivated firms, 2) a reduction in political interference, 3) long-term planning stability, 4) improved management tools, and 5) improved retention of the best employees.

Cons of International Lunar Authority	
CONS	**Description & Mitigation**
Reduced USG Control	By setting up an independent "authority", the United States government will be giving up some control over the operations and activities that will be managed by that International Authority. **MITIGATION**: The authority's true independence will be constrained by its ability to generate other sources of funding. The Authority's need for funding will become the US Government's primary source of control.
Requires advice & consent of 2/3rds of U.S. Senate	While the International Space Station program required negotiation of an international agreement, as well as the support of Congress, an International Authority will require a treaty between the countries, which has a higher hurdle to cross. Article 2, Section 2 of the U.S. Constitution provides that "*The President...shall have Power, by and with the Advice and Consent of the Senate, to make Treaties, provided two thirds of the Senators present concur...*"

Public Benefits

NASA tasked the NexGen team assess the public benefits of the Evolvable Lunar Architecture (ELA), and how those benefits could be sustained and maximized.

Economic Growth

A commercial-partnership based return to the Moon is more likely to generate a larger than expected return on investment for U.S. economic growth compared to traditional cost-plus space investments. In the commercial-partnership model, U.S. industry invests private capital, which creates additional incentive to generate new applications and uses. The improved alignment of incentives between NASA and the private sector increases the likelihood of accelerated growth of a globally competitive US space sector, especially new and entrepreneurial non-government applications. Markets in general, and the profit-motive in particular, are useful filters to steer investments towards higher-value returns on economic investments. In parallel, NASA's missions can benefit from leveraging these economic improvements, opening possibilities that would have been too expensive otherwise.

A recent example of this has already been produced by the COTS/CRS partnership. America lost world leadership in space launch nearly two decades ago as measured by our share of commercial launches. In 2014, America passed Russia and tied Europe for the world lead in the number of commercial launches[lxviii] as a result of the ascendance of SpaceX's Falcon 9 launch vehicle in commercial markets. NASA can take an appropriate share of the credit for this success as NASA served as SpaceX's strategic partner in stimulating the development of the Falcon 9 launch vehicle.

National Security

A commercial lunar architecture will accelerate the development of technologies and innovations of direct benefit to U.S. national security. In particular, higher launch rates of launch vehicles used the Department of Defense (DoD), and use of on-orbit propellant transfer, will significantly lower the cost of DoD launch services. Low-cost and reliable access to space is critical to U.S. national security.

It is possible that a lunar architecture could close the business case for a commercial reusable launch vehicle (RLV) that could substantially eliminate the United States vulnerability to Pearl Harbor style attacks in space. Since commercial RLVs could provide a surge capability to rapidly replenish our space assets, just the existence of RLVs will reduce the incentive to attack American assets in space in the first place. This mean we are less likely to need to use them in a war. RLVs are a stabilizing deterrent to war.[lxix] ELA may also stimulate advances in robotics and telepresence that may have important DoD impacts.

Diplomatic Soft Power

A permanent settlement on the Moon, based on free enterprise and democracy, will be the ultimate "shining city on the hill". The establishment of a sustainable, affordable, and permanent human base on the Moon, led by America and in partnership with free-market, democratic nations from around the world, will send an unequivocal positive message to the rest of the planet about American leadership, and the long-term future of democracy and freedom.

America could use this initiative to establish an international lunar partnership as the most exclusive club of free democratic nations. By leading an international lunar development partnership, the US will be able to promote western-based international norms of behavior on another celestial body.[lxx]

Technology and Innovation

A) **Cheap Access to Space —** One of the innovative aspects of the ELA is the disaggregation of propellant during its delivery from Earth to low Earth orbit. Propellant is a completely fungible payload, is about 80% of the mass that needs to be launched from Earth for missions to the Moon and Mars, and is inherently low cost to manufacture. Therefore it is a nearly ideal payload to launch on new launch vehicles, which may be higher risk at the beginning, but that have the potential for much lower costs. Launching propellant is the kind of demand-based opportunity that may drive new investments in much lower cost launch systems, such as reusable launch vehicles (RLV). By launching lots of propellant missions, a commercial RLV may close its business case, further driving down launch costs accelerating the growth many ancillary economic and national security benefits to the United States discussed in this section.

B) **Robotics** – Lunar development requires increased robustness of robots in harsh and remote environments, with less need for human intervention, the ability to self-repair, and greater autonomy. Advances in robotics will be needed in areas that are not currently prioritized outside NASA. Robotic innovations created for lunar development will have direct Earth applications across many fields including security, resources, utility/services, and personal bionics/assistance. Many of these advances will drive U.S. economic growth.

C) **Environmental Systems** – Development of a permanent lunar base demands more reliable closed loop/sustainable life support systems than habitation on the ISS due to the increased cost and time of getting mass to the Moon, and the longer replacement period for any systems that break down. Investments in the development of closer to closed loop water, food, waste and energy systems will have direct Earth applications, providing greater resilience against natural and man-made disasters, and improved environmental stewardship. There will be economic and competitive benefits resulting from more efficient systems. Such systems will be essential for long duration solar system exploration/settlement.

D) **In Situ Resource Utilization (ISRU)** – Humans cannot afford to ship everything we will need for deep space human bases or permanent settlements. As we have repeatedly learned on the frontier, humans must learn to live off the land to enable long-term affordable presence and eventually settlement. Investing in lunar ISRU will result in advances in engineering (chemical, processing etc.,), and materials in order to develop processes and machinery capable of extracting resources 'in situ' and generating useable products such as water/fuel, parts (3D Printing) and construction materials. While then allowing us to live and work more cost effectively in space, ISRU will likely result in economic and environmental benefits when applied to resource processing and reclamation situations on Earth, particularly those involving extreme environmental situations.

E) **Additive Manufacturing** — Lunar development will drive significant investment in unique kinds of additive manufacturing. Because of the cost and time of transporting tools, equipment, and building materials to the Moon and Mars, additive manufacturing (a.k.a. 3D printing) with local materials will be a particularly valuable capability. Lunar R&D will focus in particular on additive manufacturing applications, which will have many direct Earth applications from the home to the factory.

F) **Derivative Innovations in Space** — Once advances in low-cost access, robotics, ISRU, propellant transfer, and additive manufacturing have been stimulated and resources are being produced and used in space, other businesses that have been waiting for the availability of such resources will come into being, generating a boom in space based industry. Potential applications include in-space manufacturing and assembly of very large-scale structures, advanced robotic repair of satellites, space-based solar power, and mining of rare high-value materials for use on Earth. These new applications will further increase demand for space services, lowering costs for all, and create a virtuous cycle that will ultimately drive space-based resource costs down to the benefit of all on Earth.

G) **International Social Development (Derivative Benefit)**: The internet transforms lives and communities but more than 60% of humanity does not have it. Terrestrial based networks cover only 10% of the planet. While several firms (OneWeb, SpaceX) plan to build broadband satellite constellations in LEO their prices will still be too expensive for billions of people.

To the extent that a commercial lunar base will significantly drive up the commercial launch rate, and further drive down the cost of space access, a significant benefit will be reductions in the cost of developing large LEO satellite constellations. This will further reduce the cost of internet access service to the entire planet, making internet affordable and available to millions more, and deliver positive change to billions of people in their communities around the world.

H) **Environmental Monitoring (Derivative Benefit)**: Today's space-based Earth-monitoring systems have significant limitations. Satellites in GEO can monitor most of the globe, but significant limits on imaging/sensor resolution. Satellites in LEO can look at single narrow spots on Earth at any time with higher power/resolution, but a hundred or more are needed for continuous coverage. Some firms have plans to build large constellations of satellites in LEO, and some are building early prototypes, but those systems are severely limited by the lack of low-cost reliable access to space.

To the extent that a commercial lunar base will significantly drive up the commercial launch rate, and further drive down the cost of space access, a significant benefit will be reductions in the cost of developing large LEO satellite constellations. This will enable more affordable low Earth orbit constellations of satellites that can monitor the entire planet in high resolution and deliver 24-7, 365-day-per-year high-resolution measurements. Particular applications include

a) More accurate weather predictions (benefitting billions);

b) Much better major storm (hurricanes, tornados, tsunamis) tracking and warnings, savings lives;

c) The ability to constantly and accurately monitor the Earth's total energy radiation budget will significantly improve the scientific inputs used in our environmental models of the Earth.

Scientific Advances

Human and robotic presence on the lunar surface will also provide opportunities to advance science and human knowledge about ourselves and our Universe. Humans, and biological life generally, has only lived in one-gravity (G) and zero-G. A sustained presence on the Moon will allow scientists to research the effects of long-term living at $1/6^{th}$-G. Together with studies on various radiation effects, scientists will gain a better understanding of our biological life's ability to live off the Earth and how to mitigate health issues of a future spacefaring civilization. There are also unique astronomical observation possibilities such as a radio telescope on the far side of the Moon in the radio-quiet zone.

STEM Education and Inspiration

The drama of private space ventures transporting crew and cargo to the International Space Station is the most inspiring story happening today in aerospace education. Enrollment is up at aerospace engineering schools, while children are comparing Elon Musk to Steve Jobs and the fictional Tony Stark of Iron Man, inspiring many to go into engineering careers. However, the inspiration created by entrepreneurs transporting cargo and people to a space station in low Earth orbit is a small fraction of the potential inspiration of affordable human flights to another celestial body, and humans living on the Moon. In all the areas mentioned above, but particularly for the technology and innovation of humans living on the Moon, there is great STEM-related potential for capturing the next generation's attention.

While an affordable and sustainable human return to the Moon has everything needed to capture and inspire the public's imagination, and to provide hands-on experiences for the engineers and innovators of the future, it cannot be taken for granted that this will just happen. Children relate to Apollo as history … and not part of their future. Current activities in space do not deeply penetrate the publics' general awareness, or the school curricula. Assuming a national decision to implement the ELA, the responsibility to communicate, promote and engage the public and our children should be taken as seriously as the details of the architecture.

Sustaining and Maximizing the Public Benefits

There are several keys to sustaining and maximizing the public benefits of the ELA.

First, by leveraging existing commercial launch systems, and in-space technologies, the overall lunar base becomes more sustainable, and delivers additional synergistic benefits to the public via other users of the same systems and infrastructure. A space system for which NASA is the only user is almost by definition an unsustainable system. If NASA is only one of many customers, it is much more stable politically and economically, as it can share the cost burden with all those other customers. Further, all those customers become natural allies of NASA, as they benefit from sharing costs with NASA.

Second, it is critical to require and encourage significant private risk capital in the partnerships, and to remove any barriers that prohibit private industry using the technologies and systems developed in other commercial applications. This creates natural incentives for private industry to apply the new technologies, innovations and capabilities to solve problems here on Earth. To the extent that the U.S. government can align both the risks and rewards between itself and commercial partners, the greater the expected benefits to the public.

Third, a key part of the ELA strategy for sustainability is the development of an International Lunar Authority based on a combination of CERN and traditional public infrastructure authorities. CERN has proven to be a much more sustainable development model, in contrast to the traditional U.S. approaches like the U.S. Superconducting Super-collider.

For all of these reasons, the ELA is inherently more sustainable than traditional NASA program development methods.

Appendix A — Study Team Biographies

Charles Miller (Principal Investigator)

Mr. Miller is the President of NexGen Space LLC, which provides client-based services at the intersection of commercial space, civil space, national security space, and public policy. He is a former NASA Senior Advisor for Commercial Space where he advised senior NASA leaders on commercial space options and strategies. He was the leader of the NASA team that evaluated emerging commercial space opportunities, where he led assessments of commercial orbital debris mitigation and removal, satellite servicing, and funded Space Act Agreements. He also served as NASA program executive for the Commercial Reusable Suborbital Research (CRuSR) program, manager of NASA's Commercial RLV Technology Roadmap study, and the leader of NASA's propellant depot study team. Prior to NASA, he co-founded Nanoracks LLC, and served as President and CEO of Constellation Services International, Inc.

Dr. Alan Wilhite (Co-Principal Investigator)

Dr. Wilhite is the Langley Distinguished Professor in the School of Aerospace Engineering at Georgia Tech and also serves as the co-Director of the Georgia Tech Center for Aerospace Systems Engineering. He teaches graduate classes and supervises research in Systems Engineering and Aerospace Systems Design. He has more than 60 published articles and several book chapters on space systems engineering. He has served as a researcher, systems program manager, and senior executive involved in the design and development of NASA space and aeronautic systems. He was Director of the NASA's Independent Program Assessment Office responsible for evaluating all major programs and projects for the NASA Administrator. He is an AIAA Associate Fellow and has served on several AIAA Technical Committees such as Space Systems, Space Transportation and Computer Aided Design. He is also a member of the International Astronautical Federation on the Systems Engineering committee. He conducts research in systems of systems architecture design, robust design, aerodynamics, propulsion, MDO, operations, cost, systems engineering, and risk. He has served as NASA's external chair for systems engineering and conducts research supporting NASA's vision in space exploration.

Edgar Zapata, KSC (Life Cycle Cost Analysis)

NexGen will leverage an unfunded contribution from Edgar Zapata of NASA Kennedy Space Center (KSC). Mr. Zapata has worked with NASA at KSC since 1988. He has held responsibility for Space Shuttle systems including the Shuttle External Tank and the Shuttle cryogenic propellant loading systems, and related flight and ground propulsion systems. Since the mid 90's he began work to translate real-life operational experience and lessons learned into improvements in flight and ground systems design, technology, processes and practices. He has participated in most major agency-level human exploration studies, including the Exploration Systems Architecture Study, the Constellation Strategic Analysis Team, the Constellation Standing Review Board, the NASA Programmatic Risk Assessment Team and most recently (2011) leading the cost modeling of Propellant Depot scenarios for the Human spaceflight Architecture Team.

Mr. Zapata's current work is focused on (1) Reusable Booster Systems (RBS) and low cost access to space in collaboration with the US Air Force Research Laboratory (AFRL) and the Defense Advanced Research Projects Agency (DARPA), and (2) Nano-launcher studies for low cost access to space for emerging space and nano-satellites. Mr. Zapata's work over the years is documented at:
http://science.ksc.nasa.gov/shuttle/nexgen/rlvhp.htm

David Cheuvront (Risk, Safety & Mission Assurance)

David Cheuvront has 37 years of aerospace experience in numerous engineering and business disciplines, including 19 years at NASA JSC. At Rockwell International, Cheuvront solved key maintenance challenges in the preliminary design of the Space Station *Freedom*, and was hired by NASA JSC to help solve problems in reliability and maintainability in human spaceflight. Cheuvront served as a NASA Test & Verification Lead, with responsibility for all ISS subsystems & elements. Cheuvront then served as Technology Integration Manager for JSC Engineering's Advanced Development Office, where he supported special projects to improve performance, technical, cost, risk, and schedule for exploration architectures. He served as Assistant to Chief of Staff-Technical for Systems Engineering & Integration in the Constellation program, and as Safety Lead for the Orion Crew & Service Module within JSC's Safety & Mission Assurance Shuttle & Exploration Division.

In 2011, Cheuvront led a team of more than two-dozen JSC safety and technical specialists who completed a risk analysis for a NASA Headquarters study of propellant depot concepts. He retired from NASA in 2013, and currently consults and advises commercial start-up ventures.

Robert Kelso (Lunar Robotics & ISRU)

Rob Kelso retired in 2011 after spending 37 years at NASA-Johnson Space Center, including serving as a Shuttle Flight Director in JSC's Mission Control Center. Kelso led NASA's efforts to leverage commercial lunar robotics developments for several years. Kelso was the NASA Manager and architect of NASA's Innovative Lunar Demonstration Data (ILDD) program for buying data on commercial lunar landing systems under milestone payments, which contracted with six (6) Google Lunar X-Prize (GLXP) teams. Kelso also developed the NASA Lunar Orphan Flight Test (LOFT) project, which identified a series of existing NASA payloads that could use a commercial flight to the surface of the Moon. One of Kelso's last jobs was to lead NASA's efforts in the preservation and protection of the Apollo lunar landing sites on the Moon.

Currently, Mr. Kelso is the Executive Director of the Pacific International Space Center for Exploration Systems (PISCES), which is located in Hilo Hawaii, and funded by the State of Hawaii. PISCES objective is to provide a simulated lunar/planetary environment on Earth for space agencies and commercial space businesses around the world to develop and test technologies.

American University School of Public Affairs & Dr. Howard McCurdy

The American University School of Public Affairs has agreed to serve as a member of the NexGen Team to assess the findings and serve as an external reviewer of the assumptions and estimates within the team's study. The validation work will be conducted through the School's Innovation Research Group and organized by Dr. Howard E. McCurdy, Professor of Public Affairs and group founder. The Innovation Research Group is a collection of scholars who provide objective analysis of governmental policies that promote innovation, especially those that involve public-private partnerships and outer space. The School of Public Affairs was founded in 1934 to educate public servants, has more than seventy-five full time faculty members, and is one of the top-ranked schools of its kind. Dr. McCurdy is a professor in the School of Public Affairs and an expert on science policy. He has authored seven books on the American space program, including *Faster-Better-Cheaper: Low-Cost Innovation in the U.S. Space Program*, *Inside NASA: High Technology and Organizational Change*, and *Space and the American Imagination*.

Appendix B — Independent Review Team Bios

Joe Rothenberg (Chairman): Mr. Rothenberg served as NASA Associate Administrator for Space Flight from 1998 to 2001, and as Director of the Goddard Space Flight Center from 1995 to 1998. After NASA he served as President of Universal Space Network Inc., and as Technical Advisory Board Chairman of SkyBox Imaging, which was purchased by Google.

Jim Ball: Mr. Ball is the former Program Manager for Spaceport Development at NASA Kennedy Space Center, and is the current President of Spaceport Strategies, LLC where he manages launch site development activities by Space Florida.

Hoyt Davidson: Mr. Davidson is the Managing Partner of Near Earth LLC. Previously, he was a Managing Director in the Telecomm Group at Credit Suisse First Boston (CSFB). Mr. Davidson was one of two Managing Directors of the Donaldson, Lufkin & Jenrette Space Finance Group, which raised over $25 billion for satellite related projects.

Frank DiBello: Mr. DiBello is the President and CEO of Space Florida. He was vice chairman of SpaceVest venture capital firm, and the founder and managing partner of KPMG Peat Marwick's Commercial Space and Advanced Technologies Practice.

Jeff Greason: Mr. Greason has nearly 20 years experience managing innovative technical project teams at XCOR Aerospace, Rotary Rocket Company (RRC), and Intel Corporation. He serves as a member of COMSTAC, and served as a member of the President's Human Space Flight Review Committee (Augustine Committee) in 2010.

Gene Grush: Mr. Grush is the former Propulsion and Power division chief within NASA JSC's Engineering Directorate. He has several decades of technical experience in human spaceflight with the Space Shuttle, ISS and deep space human exploration.

Alexandra Hall: Ms. Hall is the Principal at Sodor Space, former CEO and Co-Founder, Airship Ventures, Inc. (2007-2011, Senior Director, Google Lunar X-Prize, XPrize Foundation (2011-2014), and former CEO/Executive Director of the Chabot Space and Science Center.

Jeffrey Hoffman: Dr. Hoffman is a former NASA astronaut and currently a professor of aeronautics and astronautics at MIT. While in the Astronaut Office he served as Payload Safety Representative, CAPCOM, and he led the Payload and Habitability Branch. At MIT he teaches courses on space operations and design.

Ed Horowitz: Mr. Horowitz is Chairman of EdsLink LLC, a New York City based venture capital firm. He currently serves the Chairman of ViviSat, Co-Founder and Board Member of U.S. Space LLC, and Chairman of Fairpoint Communications (NASDAQ: FRP). He is a former President and CEO of SES Americom.

Christopher Kraft: Mr. Kraft is the founder of NASA Mission Control, America's first space flight director, and former Director of NASA Johnson Spaceflight Center (1972-

1982). Mr. Kraft came to NASA from its predecessor organization, the National Advisory Committee for Aeronautics (NACA), serving as a member of the Space Task Group in 1958, which was entrusted with the responsibility for putting America's first man in space.

Steve Isakowitz: Mr. Isakowitz is President of Virgin Galactic. Prior to that he was NASA Deputy Associate Administrator for the Exploration Systems Mission Directorate, former CFO of the U.S. Department of Energy, and a former White House OMB manager with NASA oversight. He is the author of International Reference Guide to Space Launch Systems.

David Leestma: Mr. Leestma is a former NASA astronaut, who most recently managed NASA JSC's Technology Transfer and Commercialization Office. He also served as JSC's Project Manager for the Space Launch Initiative, Assistant Program Manager for Orbital Space Plane, and Manager of JSC's Exploration Programs Office.

Michael Lopez-Alegria: Mr. Lopez-Alegria is a former NASA astronaut and previously served as President of the Commercial Spaceflight Federation. At NASA he served as ISS commander, and assistant director of flight crew operations.

Thomas Moser: Mr. Moser served for over 40 years in various NASA positions in the development and operations of human space exploration, including Deputy Associate Administrator for Human Spaceflight and Space Station, first NASA Program Director for Space Station, and Director of Engineering at JSC. In the private sector he was V.P. of Space Systems at ANSER, and V.P. at Fairchild Space & Defense, and Executive Director of Texas Aerospace Commission.

James Muncy: Mr. Muncy is the founder of PoliSpace, a space policy consultancy focused on the nexus of business, public affairs, and space technology. He has worked in the White House Office of Science and Technology Policy, and on the Professional Staff of the House Science Committee's Space and Aeronautics Subcommittee.

Gary Payton: Mr. Payton is a former NASA astronaut who served as Deputy Under Secretary of the Air Force for Space Programs, and NASA Deputy Associate Administrator for Space Transportation Technology where he managed the X-33, X-34, X-37 and DC-XA projects. He is a Professor at the USAF Academy where he teaches Astronautical Engineering.

Eric Sterner: Mr. Sterner is former NASA Associate Deputy Administrator for Policy and Planning and Chief of Strategic Communications. He is a former Staff Director for the House Subcommittee on Space and Aeronautics.

Will Trafton: Mr. Trafton is a former NASA Deputy Associate Administrator and Associate Administrator for human spacefight, former President of Boeing Sea Launch, former President of Kistler Aerospace, and former President of International Launch Services. He served as Chair of COMSTAC from 2006 to 2012. He is currently CEO at

Boston Capital Leasing.

James Vedda: Mr. Vedda is senior policy analyst at Aerospace Corporation, and a former Associate Professor of Space Studies at the University of North Dakota. He is the author of Becoming Spacefarers: Rescuing America's Space Program and Choice, Not Fate: Shaping a Sustainable Future in the Space Age.

Robert Walker: Mr. Walker is the former Chairman of the House Committee on Science and Technology, Chief Deputy Whip, and Vice Chairman of the Budget Committee. In 2001, he served as chair the Commission on the Future of the U.S. Aerospace Industry. In 2004, he served on the President's Commission on Implementation of the U.S. Space Exploration Policy.

Gordon Woodcock: Mr. Woodcock has 60 years of experience in aerospace engineering, including over 100 technical papers and articles. He worked for Boeing, NASA, Space America, and Gray Research consulting on flight simulation development, image processing, propulsion, and space mission architectures.

End Notes

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