Cislunar-1000: Transportation supporting a self-sustaining Space Economy

Bernard F. Kutter[1]
United Launch Alliance, Centennial, CO 80111

Thirty years from now, 1,000 people could be living and working in the space around Earth and the Moon – waking up in commercial habitats, prospecting on the Moon and even harnessing power from solar power satellites for consumption on Earth. NASA's interplanetary probes and human exploration are opening the frontiers of space similar to how the Lewis and Clark Expedition opened the frontiers of America in 1804. This early exploration of America was followed by development of the first transcontinental railroad in 1869 opening America to pioneers and industry. Space is at a similar crossroads where a modern day space transportation system can open cislunar space to commercial development.

Elements of this transportation system are in development at United Launch Alliance. This system will be fueled by hydrogen and oxygen initially carried to space from Earth, but transitioning to space derived resources as lunar and near Earth asteroid water mining develops. The workhorses of this transportation system will be ACES and XEUS plying the trade routes of cislunar space, connecting Low Earth and Geostationary Orbits with Earth Moon L1 and the lunar surface.

This paper will describe the elements of the space transportation system, the benefits of lunar extracted water and how such a transportation system can enable a prosperous, self-sustaining Space Economy.

Nomenclature

ACES	=	Advanced Cryogenic Evolved Stage
CRYOTE	=	Cryogenic Orbital Test
DLRO	=	Distant Lunar Retrograde Orbit
EML1	=	Earth Moon Lagrange Point 1
EML2	=	Earth Moon Lagrange Point 2
GEO	=	Geosynchronous Earth Orbit
GPS	=	Global Positioning System
ISS	=	International Space Station
IVF	=	Integrated Vehicle Fluids
LEO	=	Low Earth Orbit
LH2	=	Liquid Hydrogen
LO2	=	Liquid Oxygen
NRO	=	Near Rectilinear Orbit
ULA	=	United Launch Alliance
XEUS	=	ACES derived Lunar Lander

I. Introduction

THE key to the success of the human venture in space is the establishment of a self sustaining space economy. In this economy, space activities generate wealth, not consume wealth. In the self sustaining space economy, the free market drives innovation, spurring growth and competition which drives more innovation. However, to date,

[1] Manager, Advanced Programs, 9501 E. Panorama Cir., Mail Stop C4200, AIAA sr. member.

there have been only two business models in space that work. The first is sell goods and services to a government. A government, in turn, has a number of potential purposes for space activity including national security, science and national prestige. However, this business has great difficulty harnessing the power of the free market. The second is providing commercial communications services to terrestrial customers. This involves building, deploying and operating communications relay satellites in Earth orbit. According to the Space Foundation's Space Report[1], the total value of all space goods and services in 2014 was approximately $300B. However, only about 10% of this is attributed to building and launching satellites. The single greatest contributor was terrestrial applications of the Global Positioning System (GPS).

To create a self sustaining space economy, commercial economic activities in space must be developed. Non-governmental wealth creating economic activities require consumers, and it happens that all consumers currently reside on Earth. Hence the challenge is to develop space activities that deliver benefits worth paying for to people on Earth. The enormous distances between objects in space suggests that the first place to look for activities that benefit Earth is in the vicinity of Earth and our nearest neighbor, the moon. In other words, any near term self sustaining economic activity will likely take place within cislunar space. One might also include near earth asteroids in the mix. John Marburger, the Science Advisor for President Bush, in a 2006 address at the Goddard Symposium[2], summarized it quite nicely: "It is likely that these near-Earth applications will always dominate the use of space because Earth is where the people are, as well as the environment that sustains them."

II. The Cislunar Econosphere

The first step in building a self sustaining economy in cislunar space is understanding what activities are possible and where they might occur. Figure 1 shows the basic geography of cislunar space and a list of possible economic activities. There are four main regions of cislunar space that are suitable for economic activities of various kinds: low earth orbit (LEO), geosynchronous orbit (GEO), high earth orbits, and the lunar surface. For simplicity, this paper omits a class of useful orbit between LEO and GEO. These mid-earth orbits (MEO) are primarily useful for navigation satellites like GPS.

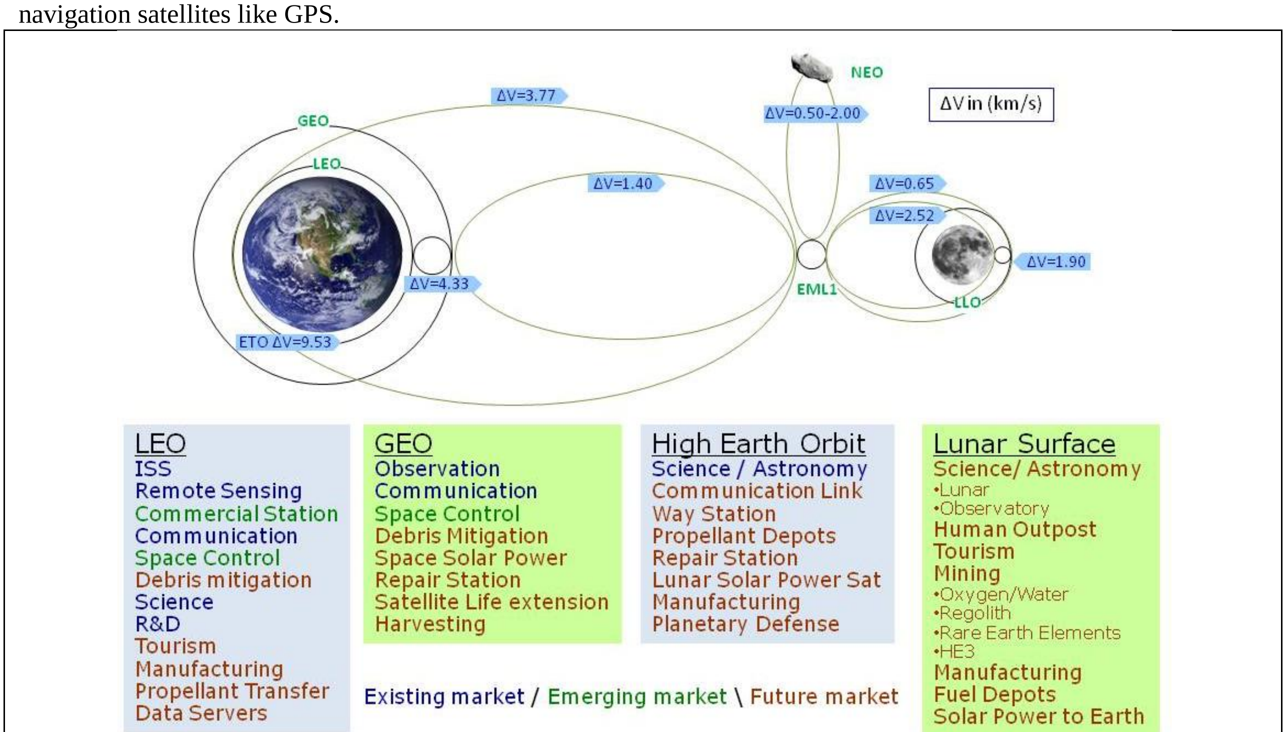

Figure 1. The geography of cislunar space and potential economic activities.

LEO consists of a region of space up to about 1000 km above the Earth's surface. Useful orbits in LEO are nearly circular and have orbital periods of around 90 minutes. A wide range of inclinations are employed. Highly inclined orbits are useful for earth observation and sensing. Low inclined orbits are easily accessed and are suitable for way points to locations beyond LEO and space stations like the International Space Station (ISS).

GEO orbits are useful for communication and earth observation. These orbits have a period of 24 hours. Hence, satellites in geosynchronous orbit appear fixed (or nearly fixed) with respect to the surface of the Earth. True geosynchronous orbits have zero inclination, but in practice, some small inclinations are employed. GEO is also expected to be the preferred orbit for space based solar power satellites.

High earth orbit is a collection of orbits that are useful as waypoints or staging points to the lunar surface or locations beyond cislunar space. They consist of halo orbits circling one of either Earth-moon Lagrange point 1 or 2 (EML1 or EML2), or a class of orbits called distant lunar retrograde orbits (DLROs) or near rectilinear orbits (NROs). All of these orbits are similar in the energy needed to reach them from Earth and have different features that make them useful for different purposes. For the remainder of the paper, I will use EML1 as a proxy for this class of orbits.

The lunar surface is the key location for resource extraction. As Marburger said a decade ago, one of the goals of the space program is to bring the resources of space within the economic sphere of humankind. The moon is the obvious place to start. The lunar poles are likely to be an early location for this kind of activity for two reasons. First, due to the fact that the moon's rotation axis is very nearly perpendicular to the ecliptic, there are region near the poles that are sunlit for nearly 100% of the time. For the same reason, there are regions near the poles that are in permanent shadow. Nearly permanent sunlight provides nearly unlimited solar power for resource extraction activities and avoids the 14-day night of equatorial regions. Second, the permanently shadowed regions contain, we now know, large quantities of water ice, as much as 10 billion tons per pole by some estimates.

Water extracted from ice is a critical resource for the cislunar economy. It is obviously required to support any human activity and is easily separated into its constituent oxygen and hydrogen through electrolysis. Oxygen is essential for breathable air. And when liquefied, hydrogen and oxygen form the most powerful chemical rocket propellants known. Mining lunar ice for rocket propellant is likely to be the first economic use of lunar resources.

III. Transportation within Cislunar Space

Current activities in space are limited in large part by transportation costs. It costs \$4,000 to \$10,000 per kilogram to get from Earth to low earth orbit. It costs four times as much to get to GEO and nine times as much to get to the lunar surface. The key to enabling a self sustaining cislunar economy is to dramatically reduce the cost of transportation. And the key to lowering transportation cost is to make use of space resources.

The geography of cislunar space is dominated by the gravity well of Earth, Figure 2. An enormous amount of energy is required to get from the surface of the Earth to LEO. This is the primary reason for the high cost. Once in LEO, much less energy is required to go anywhere else in cislunar space. This disparity nicely divides the transportation system into two segments: 1) Earth to orbit and 2) within cislunar space. There are many operational systems currently servicing the Earth to orbit market segment. All of them utilize some variation of a multi-stage chemical rocket. All are currently expendable although several companies are experimenting with various forms of partial reusability.

Once in orbit, the transportation problem becomes simpler in many respects, but new challenges are introduced. On the simpler side, the energy levels to be managed are much reduced and there are no aerodynamic forces to contend with. Some of the challenges include getting the system elements into cislunar space, reusability, finding fuel, the thermal environment and mission durations.

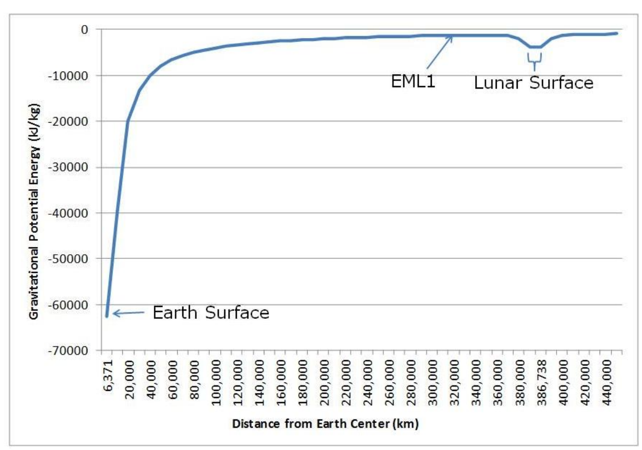

Figure 2. Energy levels in cislunar space.

One of the most importatnt findings of space science in the last decade is the wide presence of water throughout the solar system. There are significant amounts of water on Mars, contained within many asteroids and even at the lunar poles. Water can be easily electrolyzed into hydrogen and oxygen using solar power which can then be used for rocket propellant. Hence, it makes sense to base the cislunar transportation system on liquid hydrogen (LH2) and liquid oxygen (LO2), the constituents of water and the highest energy chemical propellant known..

United Launch Alliance (ULA) has most of the world's experience operating LO2/LH2 propulsion systems in space. The second stage of both ULA's Atlas V and Delta IV launch systems utilize LO2/LH2 as propellant. Furthermore, the functionality of these stages is largely what is needed for the cislunar transportation system.

IV. Transportation System Elements & Technologies

The next generation upper stage for ULA's Vulcan fleet of launch vehicles is perfectly suited to anchor the transportation for cislunar space. This stage is called ACES[3], an acronym for Advanced Cryogenic Evolved Stage, and is expected to be available by 2023, Figure 3. ACES is 5.4 meters in diameter and about 15 meters long. It utilizes 68 tons of LO2/LH2 propellants and has a propellant to dry mass fraction of 0.92, exceeding the best in the world mass fraction of Centaur, the upper stage for Atlas and the initial variants of Vulcan.

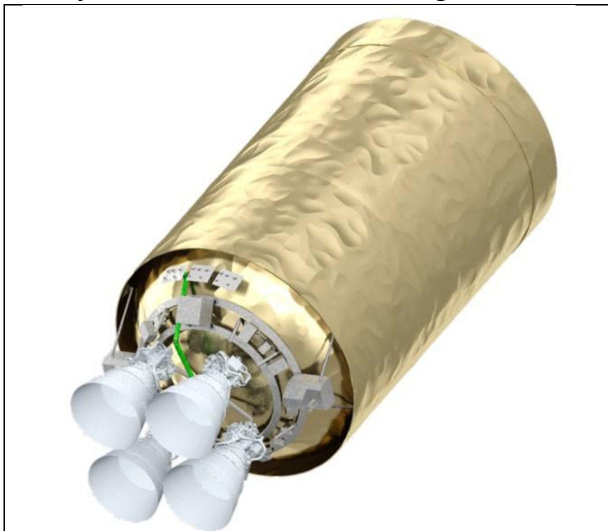

Figure 3. Advanced Cryogenic Evolved Stage (ACES). The backbone of the cislunar transportation system.

There are several advanced technologies that enable the utility of ACES as the cornerstone of a cislunar transportation system. First is Integrated Vehicle Fluids (IVF). IVF enables all the functions of the stage to be accomplished using just LO2 and LH2. This allows the stage to be fully reusable with refueling from propellants extracted from lunar ice deposits. Second are technologies for long duration storage of the cryogenic propellants. The basic ACES will reduce boiloff of the cryogenic propellants extending mission duration to a week or more, an order of magnitude improvement over Centaur. Storage in dedicated vessels, like tankers or depots, can be extended to years. Third is on orbit transfer of cryogenic propellants essential for refueling. Finally, ACES can be equipped with a kit that transforms it into a lunar lander called XEUS[4].

A. Integrated Vehicle Fluids

Integrated Vehicle Fluids (IVF)[5] is a technology that enables acryogenic upper stage to become a long duration in-space stage. A traditional upper stage utilizes at least four different fluids to perform its function. For example, the Centaur uses LO2 and LH2 as main propellants, helium to pressurize the tanks and hydrazine for attitude control. It also uses large non-rechargable batteries for power. Helium capacity, hydrazine capacity and battery capacity all limit the life of the stage in terms of pure time and the number of time the main engines can be ignited. IVF removes all of these limitations. With IVF the only limitation to the life of the stage is LO2/LH2 propellants.

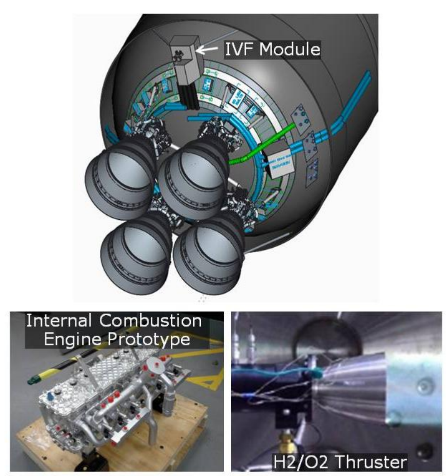

Figure 4. Integrated Vehicle Fluids enables ACES operability to support cislunar transportation.

The core of the IVF system is a small internal combustion engine, Figure 4. This engine runs off of hydrogen and oxygen gas from the ullage of the main propellant tanks. The engine is used to power a compresser which puts warm hydrogen and oxygen gasses back into the tank for pressurization. The engine also feeds gas through GO2/GH2 thrusters for attitude control and runs a generator for electrical power.

All of these components reside in a module located on the aft end of the stage. The ACES stage includes two IVF modules for redundancy.

B. Cryogenic Storage

Current cryogenic upper stages like the Delta IV cryogenic Second Stage (DCSS) or the Centaur are capable of missions of up to twelve hours in duration. One of the critical limiters is the loss of propellants via boiloff. At atmospheric pressure, LH2 boils at -253^0 C. LO2 boils at -183^0 C. In space, the heating environment is primarily due to radiation, the sun being the main source. In LEO, radiation from the Earth becomes a significant source of heat as well.

Figure 5. CRYOTE 3. A long duration cryogenic test bed.

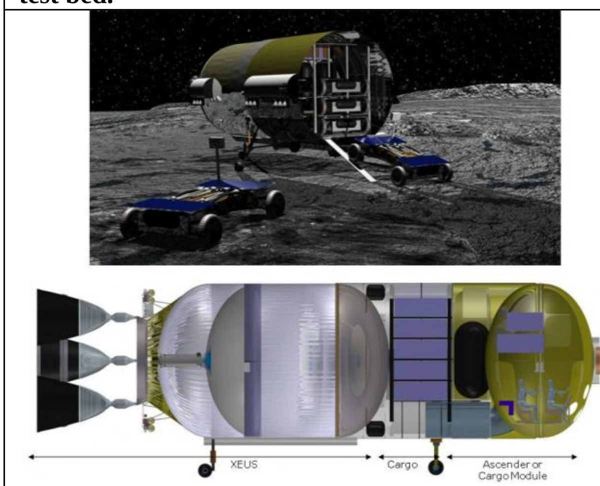

Figure 6. XEUS, ACES derived lunar lander.

ULA has leveraged its experience in cryogenic upper stages to develop a suite of technologies to eliminate LO2 boiloff and reduce LH2 boiloff by two orders of magnitude. These technologies have been developed over many years and verified in a series of tests at NASA's Marshall Spaceflight Center (MSFC) called CRYOTE. Figure 5 shows the CRYOTE 3 test tank.

All of these technologies are passive, that is, they do not require any power to operate. Examples include design of the tank to reduce or eliminate penetrations or attachments, design of the tank to minimize the surface area of the hydrogen tank walls, enhanced multi-layer insulation, use of hydrogen boiloff to vapor cool warm spots and a common bulkhead between the LO2 tank and the LH2 tank with enhanced insulation. The later technology allows the hydrogen to cool the oxygen and avoid Oxygen boiloff. Boiling hydrogen is almost 10 times more efficient in removing heat than boiling oxygen.

These technologies combined enable ACES missions of up to a week without refueling, more than enough time to transit from EML1 to LEO and return. When these technologies are implemented into a dedicated long duration storage vessel (not a stage) and equipped with a sun shield, storage times of years can be achieved.

C. Refueling

Having eliminated all fluids but LO2 and LH2, ACES is fully reusable if it can be refueled. The key technology for refueling is the capability to transfer propellants from a storage vessel to ACES in space. This technology has been demonstrated and perfected in the CRYOTE test program.

The basic approach makes use of ULA's experience in transferring cryogenics under settled conditions, that is, under a small acceleration. This insures the propellants are in a known position in the tank. The donor tank is pressurized above the recipient tank and flow begins. A small amount of propellant is lost to chill the transfer line to liquid temperatures. The recipient tank includes a "shower head" to create droplets. These droplets cool the gas in the empty recipient tank, reducing the pressure and creating a suction effect that results in a nearly 100% full recipient tank with almost no loss of propellants.

D. Horizontal Landing

The ACES stage provides the backbone of the in-space portion of the cislunar transportation system. But to exploit lunar resources, we need a way to get large masses to and from the lunar surface. Fortunately, much of what you need for a lander is already inherent in ACES. The main engines can bring the stage close to the lunar surface. What remains is the terminal descent and landing.

XEUS solves this problem by adding four banks of thrusters to the side of ACES to enable a horizontal landing. See Figure 6. In keeping with the overall architecture, these thrusters run off LO2/LH2 propellants from the main propellant tanks. The thrusters will require the addition of modest electric LO2 and LH2 pumps which are powered by IVF). The addition of landing avionics and landing legs complete the XEUS mission kit. Like ACES, XEUS is fully reusable with refueling.

V. An Initial Business Case

Having established that the technology for a cislunar transportation system will exist early in the next decade, we now turn to consider the business case of resourcing propellant from the moon. Once the transportation infrastructure is in place, the cost of any activity in cislunar space will become drastically reduced. This is primarily due to the (presumed) availability of low cost propellant that does not have to to be shipped out of the Earth's gravity well.

One great benefit of using ACES as the back bone is the possibility that the ACES stages could be operated in space after fulfilling a normal mission deploying a satellite. ULA's nominal flight rate is ten missions per year to a variety of different orbits. Normally the spent upper stage is disposed of either by re-entering the atmosphere or by putting the stage into a disposal orbit. In the cislunar economy, each of these stages can be reused over and over again. In the business case analysis, it is assumed that the hardware cost of the ACES is paid for by the initial satellite launch customer. The transportation cost using ACES in space is then the cost of ground based operators plus the cost of propellant. For this analysis, it is assumed the cost of ground based operations to be $2 million per flight segment. A flight segment is defined as a round trip between two cislunar locations, e.g. EML1 to LEO and back.

Based on these assumptions an initial business case can be made to provide lunar sourced propellant in LEO for ACES refueling. A fully fueled ACES in LEO can then be used to transport satellites from LEO to GEO. If the cost of propellant obtained from the moon in LEO is less than the cost to ship propellant to LEO from earth, the business case can be closed. Based on these considerations, a preliminary price point for propellant can be established. Figure 7 shows a comparison of the cost of lunar propellant at various locations in cislunar space compared to the cost of propellant shipped from Earth. Note that the cost of LO2/LH2 propellant on the surface of the Earth is a negligible $1/kg.

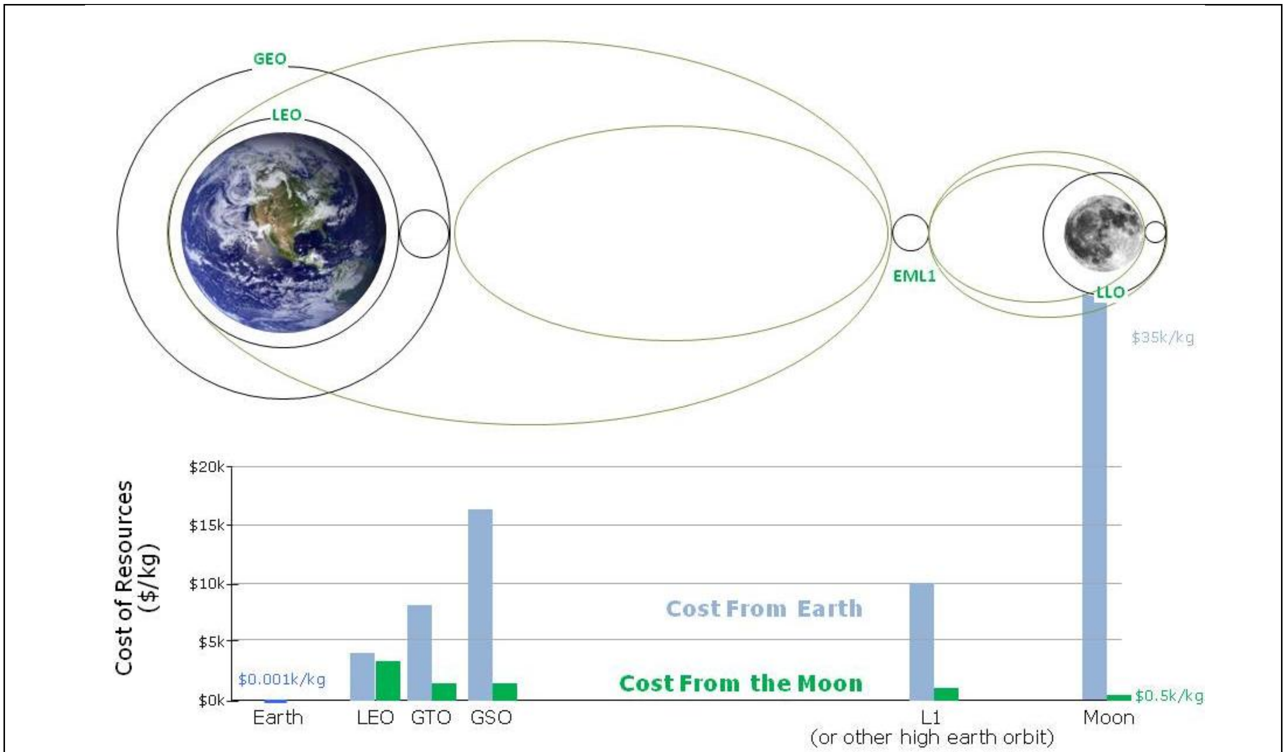

Figure 7. Propellant costs at various cislunar locations. Costs for lunar sourced propellant are based on propellant in LEO at $3 million per ton, to close the business case.

A price for lunar derived LO2 and LH2 propellant of $3M/ton in LEO will enable a launch company like ULA to reduce the overall price per kg to GEO by lifting a payload to LEO, then using ACES fueled with lunar propellant to take it from LEO to GEO. Since ACES and XEUS are used to transport the propellant from the moon to LEO, price points can be established for propellant in other locations. For example, the business case is the same whether propellant is purchased in LEO for $3M/ton, or GEO for $1M/ton or at the moon for $0.5M/ton.

To size the propellant mining operation on the moon, it is assumed that one will need sufficient propellant to support a conservative three ACES trips from LEO to GEO. Each ACES requires 70 tons of propellant. Using ACES and XEUS, it takes about 4 tons of propellant to transport 1 ton to to LEO. That means we need to produce 5 tons of propellant on the moon for every ton needed in LEO. Finally, due to the fact that rocket engines burn LO2/LH2 propellants in a mass ratio of approximately 5.5 to 1 and that water comes in the ratio of 8 to 1, we need to mine about 1.5 tons of water for each ton of propellant. Putting this all together, to support 3 ACES flights per year, the plant needs to extract almost 1,600 tons of water. Table 1 summarizes some of the key business parameters.

Table 1. Lunar resource LH2 & LO2 propellant revenue stream.

Tons of propellant delivered to LEO	210
Price in LEO	$3M/ton
Tons of propellant produced on the moon	1050
Price at the moon	$0.5M/ton
Tons of water mined	1575
Total revenue at moon	$525M
Total revenue in LEO	$630M

VI. Lunar Source Propellant Cost Benefit to Cislunar Transportation

Having affordable propellant resourced from the Moon can reduce the cost or Cislunar transportation by a factor of 3 or more. This reduced transportation cost will help commercial companies close their business cases creating more demand for Cislunar transportation. Such a virtuous cycle is what is required to move the space economy beyond government funded initiatives and commercial telecom where the space economy has been stuck since the 1970’s.

Table 1. Examples of Cislunar transportation cost goals as one transitions from purely Earth based propellant to lunar derived propellant.

Launch	Performance	Cost Metric	Description
V564A	3.8 mT	$37,000/kg	Single launch (fully Earth resourced)
2 * V564A	12 mT	$25,000/kg	Distributed launch[6] (fully Earth resourced)
V564A	12 mT	$20,000/kg	Refueled in LEO with 35 mT lunar propellant
V564A	16.5 mT	$11,000/kg	Refueled in elliptical Earth orbit with 35 mT lunar propellant
2* V546A	26 mT	$11,000/kg	Distributed launch & refueled in elliptical Earth orbit with 70 mT lunar propellant
4 * V564A	4 crew	$200m/crew	Traditional crew mission, ACES delivers crew capsule and lander to low lunar orbit (fully Earth resourced)
V504A + XEUS + Crew Module	6 crew	$80m/crew	XEUS shuttles people back and forth between LEO and the Lunar Surface using 70 mT of lunar propellant in LEO and 70 mT of lunar propellant on the lunar surface

VII. Cislunar 1000 Vision Progression

The following describes how the ACES and XEUS cislunar transportation might help enable a robust, self sustaining space economy.

Low Earth orbit

The ISS has been an incredible facility for learning how to build complex objects in space, how to live in space and the numerous and sometimes surprising benefits space offers. It is likely that the ISS will continue to add to humanities knowledge for years to come. Developments of commercial industries in space are quickly demanding more than the ISS can provide. This includes frequent (months or better) access, return of goods, production facilities and the ability to work with dirty and risky processes. New facilities designed to support commercial activities in space are needed.

ULA and Bigelow Aerospace are planning to launch the first B330 commercial space habitat in 2020 to start addressing the demands of commercial industry. Commercial activities fall into two broad categories: Development and production of goods and services to support terrestrial consumption; Goods and services to support in space consumption. The former includes manufacture of ultra pure optical fibers, healing of computer chips, and pharmaceuticals[7]. The latter includes manufacturing goods that will be consumed in space, e.g. in the space stations and to build space stations, giant communication platforms and eventually solar power satellites. Made in Space is already demonstrating 0-G additive manufacturing at the ISS. The ability to build hardware that doesn't have to survive the rigors and confines of launch will open an entire new generation of space products.

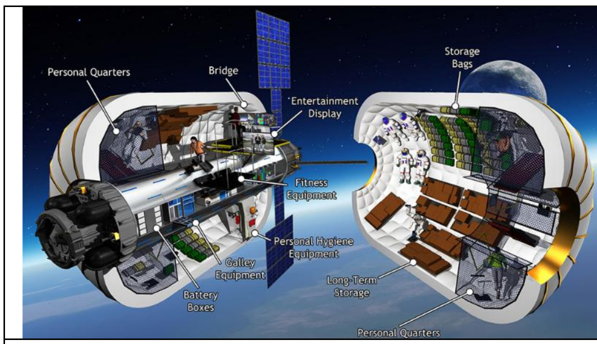

Figure 8. ULA and Bigelow Aerospace plan to launch the B330 in 2020 to support commercial LEO activities. Credit Bigelow Aerospace.

Lunar Prospecting

Water extraction from the moon is likely to be humanities first application of resourcing material beyond earth. Over the past decade we have learned so much about the Moon from spacecraft such as LRO, LCROS and a fleet of other international spacecraft. Most importantly we have learned that there exists permanently shadowed craters on the north and south poles of the moon that have large quantities of water and volatiles including N2 and CO2. It will be necessary to determine the details of the water ice concentrations, distribution and mixing with the regolith to figure out how to extract these volatiles. On site prospecting is the necessary next step to determine this water/regolith makeup and its value as a resource.

NASA's resource prospector is specifically being developed to map the regolith/water makeup across miles of a crater floor. NASA's public private program CATALYST, including Astrobotics, Masten Aerospace and Moon Express, is developing three unique small lunar landers. Launched in the coming years as rideshare along with commercial and government primary payloads, these landers offer the ability to affordably deliver payloads to the lunar surface to prospect in numerous locations on the lunar surface. Early missions could include “dropping” dozens of neutron spectrometer balls from miles above the lunar surface[8]. Following survival of hard landing these balls would provide detailed local (10’s of meters) understanding of the water concentration around each neutron spectrometer ball. The use of dozens of these neutron balls will enable coarse mapping of an entire crater.

Subsequent missions could land small battery powered coring machines in the areas of most interest. Such coring drills could sample the first several meters of regolith. This would determine the regolith ice mixture, hardness, depth of useful ice, ability to work with the regolith and demonstrate actual water extraction, a necessary step to getting significant commercial investment.

Landing equipment in the cold environment of the permanently shadowed craters will also provide the opportunity to learn how the equipment survives this harsh environment. How does the steady, cold impact equipment operation. What the impact of the sharp lunar regolith is on the operational life of the equipment. All of this learning is necessary to support a successful commercial water extraction endeavor.

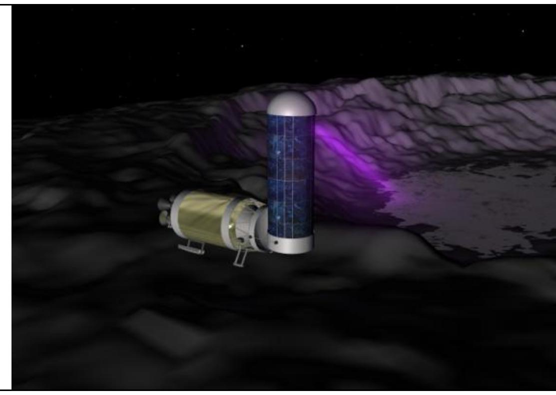

Figure 9. The Power Tower System delivered to the rim of Shackleton Crater by Vulcan XEUS. The Solar Array telescopes to 100m height to passively soak up the nearly continuous grazing sunlight. Lasers mounted to the top of the tower beam energy into the permanently shadowed crater to support the water extraction.

Figure 10. The Water Extraction Facility sublimates the ice under a large engineered tarp, collects and compresses the diffuse water vapor and condenses the vapor to liquid water for storage and eventual transfer to the Water Processing Facility.

<u>Lunar Propellant Production</u>

Following the prospecting is when the commercial extraction of lunar water can begin. This starts with XEUS landing on the crater rim with a Power Tower System, Figure 9, designed to beam energy into the permanently shadowed crater. The rims surrounding many of these permanently shadowed polar craters offer the unique attribute of near permanent grazing sunlight. From this sun light large quantities of cheap power can be produced nearly 24/7. One of the challenges is that these craters are huge, for example Shackleton is 21 km wide by 4.2 km deep. This scale makes power transmission lines from the crater rim to the crater floor impractical, necessitating wireless power transfer.

The power tower system consists of a large solar array, a fuel cell power storage system and numerous high efficiency finely pointable diode lasers mounted to the top of the tower. The solar array consists of multiple, nested 25m long cylinders. During launch the power tower cylinders are pointed in line with XEUS to fit in the payload fairing. For deployment the cylinders are rotated 90^0. Then using built in block and tackle the nested inner cylinders are extended vertically exposing their solar array surface. Each solar array is designed to produce ~200 kw electrical. The fuel cell power storage system provides energy during the up to 48 hour periods of shadow on the crater rim. High efficiency diode lasers are used to beam upwards of 100 kw into the crater. Despite the high efficiency of diode lasers, nearly half of the energy will be lost to waste heat. This waste heat is dissipated with a cooling loop in the top cylinder that moves waste energy from the diode lasers to the shadowed side of the cylinder where the energy is radiated to space.

The second XEUS mission lands the Water Extraction Facility in an area of the crater where prospecting demonstrated attractive water content that is also in view of the power tower on the crater rim, Figure 10. The water extraction could consist of a large, flexible surface, an engineered tarp, covering designed to collect low pressure, diffuse water vapor. Laser beams from the power tower on the crater rim directly warm the ice/regolith mixture under the tarp, sublimating the ice. The tarp is designed to be transparent for the laser frequency light while being opaque to infrared energy to minimize heat loss. The diffuse vapor would be collected, compressed, condensed and stored.

The third XEUS landing delivers the Water Processing Plant in close proximity to the Water Extraction Facility. Lasers from the Power Tower are beamed onto frequency unique solar arrays on the processing plant to provide electric energy. The water collected in the Water Extraction Facility is transferred via an insulated hose that is robotically coupled to the Water Processing Plant. In the Water Processing Plant, this water is purified of particulates and extraneous volatiles. The purified water is then electrolyzed into pure gaseous hydrogen and oxygen. The constant cold surface temperature of -223^0 C on the permanently shadowed crater floor benefits liquefaction of hydrogen and oxygen. With a liquefaction temperature of 183^0 C the gaseous oxygen is simply passed through a radiant heat exchanger to liquefy and then is stored in the propellant tanks of the XEUS that delivered the Water Extraction Facility. Liquefying hydrogen, with a temperature of -253^0 C, requires a little more work. The gaseous hydrogen is first compressed. The warm, high pressure hydrogen is then cooled in a radiant heat exchanger. Expansion cooling results in a portion of the hydrogen being liquefied. This liquid hydrogen is separated and stored in the propellant tanks of the XEUS lander that delivered the Water Processing Plant. The remaining cold hydrogen gas is recycled back through the cooling loop. This process is similar to terrestrial, commercial cryogenic liquefaction plants, Figure 11.

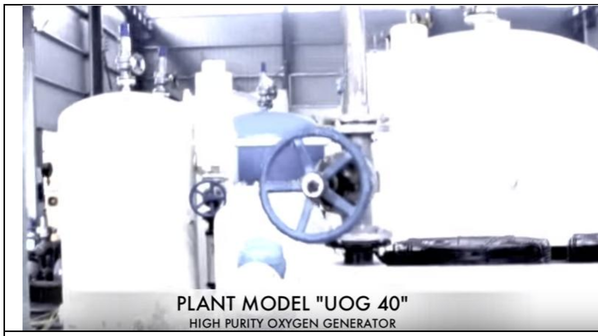

Figure 11. The Water Processing Facility operates similarly to terrestrial mobile cryogenic plants. Credit Universal Boschi

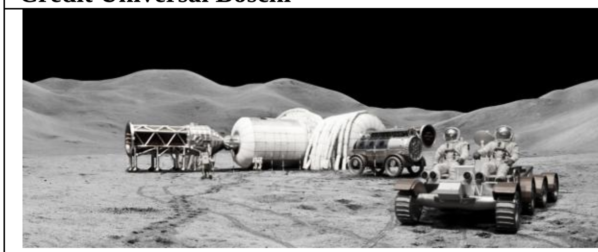

Figure 12. Notional lunar outpost. Credit Bigelow Aerospace

Figure 13. Notional entrance tunnel leads to the lunar colony's subsurface air lock could look like the tunnels in the salt mines of Wieliczka Poland.

Additional Power Towers, Water Extraction Facilities and Water Processing Plants are added as demand warrants. Once 140 tons of LO2 and LH2 have been collected a reusable XEUS with propellant transfer tank is landed. This XEUS delivers 70 tons of LO2 and LH2 to L1 for distribution to LEO and other cislunar destinations as demand warrants.

People

With power, water and LO2/LH2 propellants, the robotic water mining facility is likely to be an attractive oasis for an early crewed lunar base. The first people are likely to be government sponsored since supporting people in space is very expensive. These people will go to the Moon for exploration and science. These early people will stay for months in habitats brought from earth, potentially B330 derivatives covered in regolith to protect the people from radiation, Figure 12. The early people will use the base as a hub to explore the crater, set up astronomy telescopes shielded from solar radiation and earth radio transmissions. They will also benefit the water mining by performing maintenance and repairs on the equipment.

The lunar base will also benefit from the extracted water to supply potable water, oxygen and the LO2/LH2 propellants to power the crews return to Earth. As demand warrants, other volatiles, e.g. N2 and CO2, will be collected by the Water Processing Plant and sold to the lunar base. As the power available and surface capabilities grow materials beyond water, including metals and silicates will be extracted, processed, stored and consumed.

As the lunar base grows planers will look for lower cost, locally derived housing solutions that can support people indefinitely. One possibility will be manmade tunnels dug through the solid basalt of the crater floor. The surface regolith will be excavated to reveal the solid basalt. A descending tunnel, Figure 13, will be dug using teleoperated jackhammer tractors, Figure 14. Once the tunnel has been excavated to the desired depth of the lunar colony a horizontal tunnel will provide a level entry courtyard that serves to ready people and hardware to enter the colony through an air lock. Beyond the air lock begins the central corridor of the colony. Off of this central corridor are alcoves that provide room for shops to service the robotic mining equipment and assemble/manufacture hardware for the growing colony.

Off of the central corridor are two slightly descending tunnels that make up the heart of the subsurface colony. The shallow descent allows water from various uses to drain to the water treatment facility located at the colonies low point.

Along these two corridors are situated individual courters, shower/bathroom facilities, kitchen/dining facilities and recreation areas. The underground habitat can include large caverns to avoid claustrophobia, Figure 15. Further along are the gardens where plants both provide food as well as air regeneration. Initially the farms will only include vegetables grown in vertical trays using LED lighting, figure 16. Over time the farms will expand to include grains, fruit trees and berries. To satisfy demand for meet, the farms will include a limited supply of fish, chickens and goats that are relatively efficient at turning dining waste into protein.

At the bottom of the tunnel will be sanitation and recycling where all of the colonies waste is recycled to support the colonies needs. With $1/6^{th}$ Earth's gravity, the sanitation will be able to use modified terrestrial techniques including settling ponds, pebble bed filtration and oxygen injection, Figure 17. These simple, reliable sanitation techniques can be implemented primarily using lunar resources.

At the far end of the central corridor is a second airlock that provides redundant accesses to the colony. Beyond this second airlock the teleoperated jack hammers continue excavation providing future growth for the colony.

The first colony tunnel system is robotically excavated over the course of a few years. The jack hammer robots and automated hauling equipment are teleoperated 24/7 by operators on Earth. All of the equipment is battery powered, charged by the growing number of Power Tower Systems on the crater rim. Following completion of the basic tunnel excavation, key features will be cut out of the basalt. These key features include trenches for sewage/waste water transport and electrical lines and pools for fish and the sanitation ponds. Grinding robots will follow up, smoothing the floors for eventual human habitation.

Figure 14. Teleoperated jack hammer cuts the tunnels that are the foundation of the lunar colony.

Figure 15. A subsurface lunar colony can have large, vaulted rooms similar to this cathedral 200m below ground level at Wieliczka Poland.

Figure 16. Food for the colonists will be grown within the colony. Many of the vegetables and fruits can be vertically grown in confined spaces. Credit Freight Farms.

Major hardware, such as coils of pipe and wiring, pumps, electrical heaters, LED lights, etc, to support outfitting the new colony will be brought from Earth and pre stocked in the nascent colony tunnel system. Once the need for significant rock removal and hardware stocking is satisfied, the airlocks will be installed. The entire colony tunnel system is then pressurized for the first time. The required GN2, GO2, water vapor, and trace gasses are all provided by the Water Processing Plants.

Figure 17. Terrestrial waste water sanitation systems will be modified to support the lunar colony's $1/6^{th}$ G environment.

It is anticipated that the colony atmosphere will slowly leak through cracks in the basalt, requiring continuous makeup gases. Since the surrounding rock is cold (50^0 k) the water vapor will freeze in the cracks providing a nearly hermetic volume for habitation. Early on heaters will be running full tilt, warming the inside of the colony to 20^0 C. Much of this energy will be absorbed by the surrounding rock as the rock lining the colony warms. Over time the colony will come to a thermal balance with the surrounding basalt where minimal heating energy beyond the energy required to maintain the colony activities is needed to maintain ambient temperature.

After people with the help of teleoperated robots have outfitted this first insitu colony, people will have time to turn to experimenting with more local manufacturing. Silicates and some metals extraction and processing are likely to be early materials of interest. Initially the silicates will be used for manufacturing glass and pottery for consumption within the colony. The metals will initial by used to satisfy local demands for simple metallic structures such as dividers, pipes and electrical conductors. The local capabilities will grow to support more complex hardware such as Solar Power Tower.

Solar Power Satellites

Combining the burgeoning manufacturing capabilities in LEO and the Moon along with resource extraction on the Moon will enable production of extremely large, complex space structures such as Solar Power Satellites[9], Figure 18. These Solar Power Satellites will beam power down to Earth providing clean, reliable energy. While early demonstration systems will be built on Earth and launched to GEO. Economics of transporting hardware up Earth's deep gravity well will encourage that most of the SPS hardware mass will come from the Moon and NEO's.

This transition from costly SPS technology demonstration systems to cost competitive operational systems will mark humanities growth from an Earth bound species with a space program to a space fairing civilization using space for the betterment of humanity.

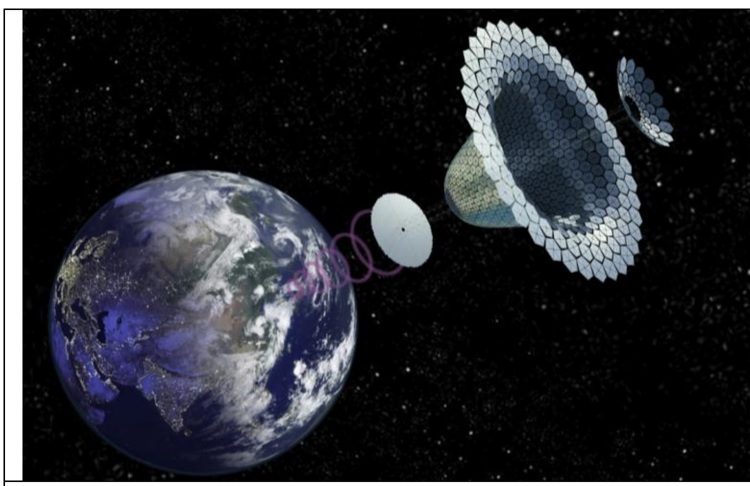

Figure 18. Solar Power Satellite construction will benefit from lunar derived resources, on-orbit manufacturing and a robust Cislunar transportation system. Courtesy John Mankins

VIII. Conclusion and Next Steps

The business case presented above makes no claim whether it is economically feasible to mine and process lunar propellants for $500,000 per ton. My opinion is that it is quite challenging, though not impossible. One would have to be very clever about the choice of mining techniques as well as find very rich ice deposits. And these prices likely force a completely robotic operation. All costs significantly increase once humans are involved. However if propellant is available at that price, a business case can be made based on simply moving mass from earth to GEO and GEO has been the staple of the launch market since inception.

There are a number of opportunities to improve the business case. For example, aerobraking in Earth's upper atmosphere can significantly reduce the propellant cost to transfer mass from the moon to LEO. This could increase the price on the moon by a factor of two, dramatically improving the business case. Furthermore, if uses for propellant beyond LEO are found, the business case improves.

What we have shown is that there is some economic incentive to spur the creation of the first elements of infrastructure needed for a self sustaining cislunar economy. Once the transportation system is established, transportation costs will decrease enabling other business cases to close and other economic activity to commence. For example, once lunar propellant is available, the cost to launch mass to the surface of the moon decreases by more than a factor of 2, improving the business case for a second propellant plant or any other lunar surface operation.

One application that has the potential to bring enormous economic benefit to people on Earth is space based solar power. It is estimated that a gigawatt space solar power station might require 12,000 tons of mass. If launched from earth, it would cost $190B just for transportation. The use of lunar propellant would reduce the cost by 40%. If all the material for the power station was sourced from the moon, the transportation cost drops to around $6B. This puts it into the realm of feasibility for the $6 trillion energy industry.

What are the steps to achieve this first piece of the cislunar infrastructure? ACES is currently under development by ULA as part of our product development strategy. Once ACES is operational, modifications for XEUS are very straightforward. There is much work to be done in terms of characterizing the nature and distribution of lunar ice deposits. Once the ice is characterized, mining strategies can be developed and tested. Demonstrator missions will be launch to the moon in preparation for full scale revenue bearing operations. Finally, investors and customers must be found to initiate that first step. ULA is willing and eager to be one of those customers.

References

[1]The Space Foundation, *The Space Report 2015*, http://www.spacefoundation.org/programs/research-and-analysis

[2]Marburger, John, Keynote address to the 2006 Goddard Symposium, Greenbelt, MD. http://www.nss.org/resources/library/spacepolicy/marburger1.html

[3]Barr, Jonathon, *ACES Stage Concept, new Capabilities, at a Lower Recurring Cost,* AIAA Space 2015, Pasadena, CA. http://www.ulalaunch.com/uploads/docs/Published_Papers/Upper_Stages/ACES-Stage_Concept-AIAASpace_2015.pdf

[4]Kutter, Bernard F., "Robust Lunar Exploration Using an Efficient Lunar Lander Derived from Existing Upper Stages", Space 2009.

[5]Zegler, Frank, "Development Status of an Integrated Propulsion and Power System for Long Duration Cryogenic Spaceflight", Space 2012

[6] Kutter, Bernard F., "Distributed Launch – Enabling Beyond LEO Missions", Space 2015

[7] Carroll, Carol, "Microgravity and Commercial Potential, A Report to Michael Suffredini" November 2014

[8] Spudis, Paul, "The Value of the Moon", April 2016

[9] Mankins, John, "the Case for Space Solar Power", January 2015