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A cislunar transportation system fueled by lunar resources

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ABSTRACT

A transportation system for a self sustaining economy in cislunar space is discussed. The system is based on liquid oxygen (LO2), liquid hydrogen (LH2) propulsion whose fuels are derived from ice mined at the polar regions of the Moon. The elements of the transportation system consist of the Advanced Cryogenic Evolved Stage (ACES) and the XEUS lander, both being developed by United Launch Alliance (ULA). The main propulsion elements and structures are common between ACES and XEUS. Both stages are fully reusable with refueling of their LO2/LH2 propellants. Utilization of lunar sourced propellants has the potential to dramatically lower the cost of transportation within the cislunar environs. These lower costs dramatically lower the barriers to entry of a number of promising cislunar based activities including space solar power. One early application of the architecture is providing lunar sourced propellant to refuel ACES for traditional spacecraft deployment missions. The business case for this application provides an economic framework for a potential lunar water mining operation.

1. 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, 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 a small fraction was 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.” (I was in the audience for Marburger's speech and it has shaped my thinking ever since.)

2. 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. Fig. 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, I have omitted a class of useful orbit between LEO and GEO. These mid-Earth orbits (MEO) are primarily useful for navigation satellites like GPS.

LEO consists of a region of space up to about 1000 km above the

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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	eXperimental Enhanced Upper Stage

Earth's surface. Useful orbits in LEO are nearly circular and have orbital periods of around 90 min. 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 approximately 24 h. Hence, satellites in geosynchronous orbit appear fixed (or nearly fixed) with respect to the surface of the Earth. True geostationary 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 [3].

High Earth orbit is a collection of orbits that are useful as way-points 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 [4,5]. 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 [6].

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. 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.

3. Transportation within cislunar space

Current activities in space are limited in large part by transportation costs. It costs $5000 to $10,000 per kilogram to get from Earth to low Earth orbit. It costs four times as much to get to GEO and seven 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

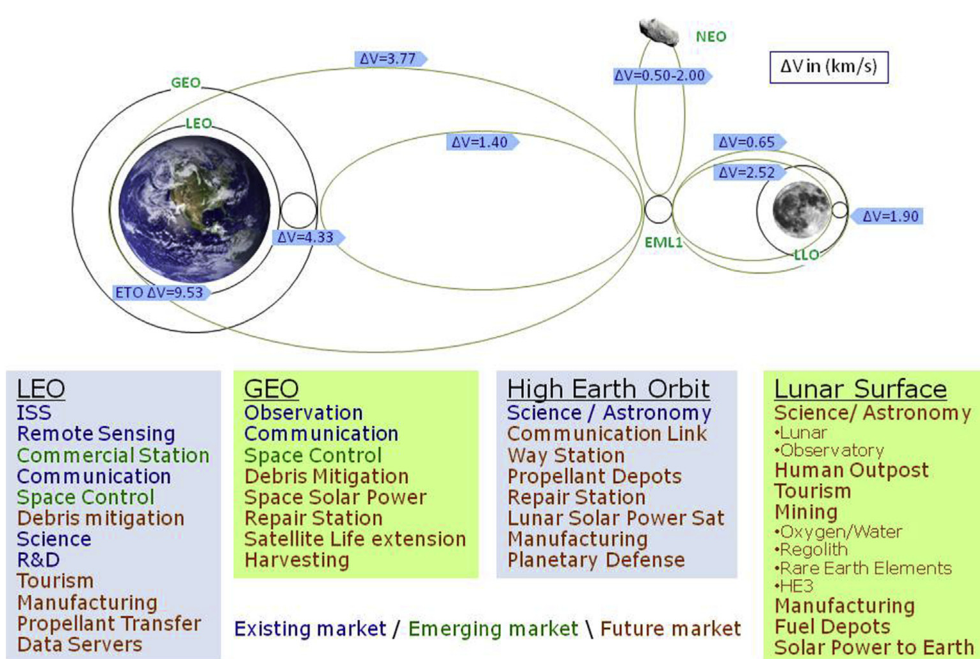

Fig. 1. The geography of cislunar space and potential economic activities that might take place in each location. Activities representing existing markets are in blue font, emerging markets are in green while potential future markets are in orange. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

transportation cost is to make use of space resources.

The geography of cislunar space is dominated by the gravity well of Earth. See Fig. 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 and the thermal environment.

Given the apparent availability of water from either asteroids or the Moon, it makes sense to base the cislunar transportation system on liquid hydrogen (LH2) and liquid oxygen (LO2). 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.

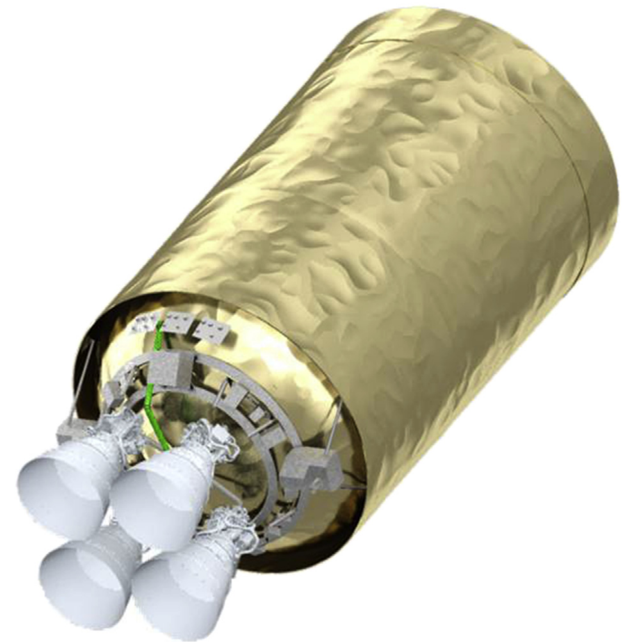

Fig. 3. Advanced Cryogenic Evolved Stage (ACES). ACES is the backbone of the cislunar transportation system. The stage utilizes LH2/LO2 propellants and up to four engines.

4. Transportation system elements and 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 (see Fig. 3) [7], an acronym for Advanced Cryogenic Evolved Stage, and is expected to be available by 2023. ACES is 5.4 m in diameter and about 15 m 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 0.90 mass fraction of Centaur, the upper stage for Atlas.

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 (Experimental Enhanced Upper Stage).

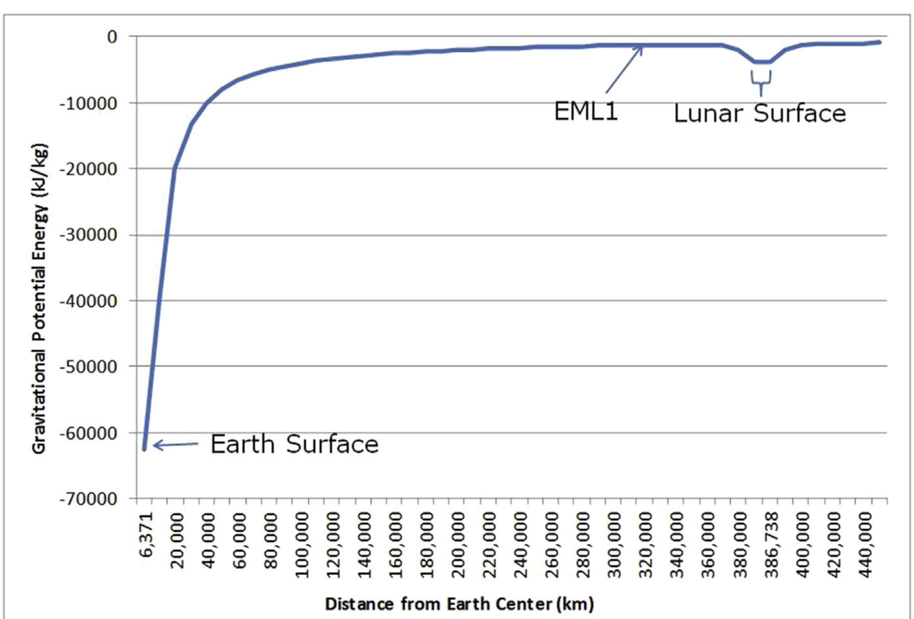

Fig. 2. Energy levels in cislunar space as a function of distance from the Earth's center.

4.1. Integrated Vehicle Fluids

Integrated Vehicle Fluids (IVF) is a technology that enables an 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-rechargeable batteries for power. Helium capacity, hydrazine capacity and battery capacity all limit the life of the stage in terms of time and the number of times 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.

The core of the IVF system is a small internal combustion engine. See Fig. 4. This engine runs on hydrogen and oxygen gas from the ullage of the main propellant tanks. The engine is used to power a compressor which puts warm hydrogen and oxygen gasses back into the tank for pressurization. The engine also feeds gas through LO2/LH2 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.

4.2. 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 Celsius. LO2 boils at −183 Celsius. 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.

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. Fig. 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 area of the hydrogen tank walls, enhanced multi-layers 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

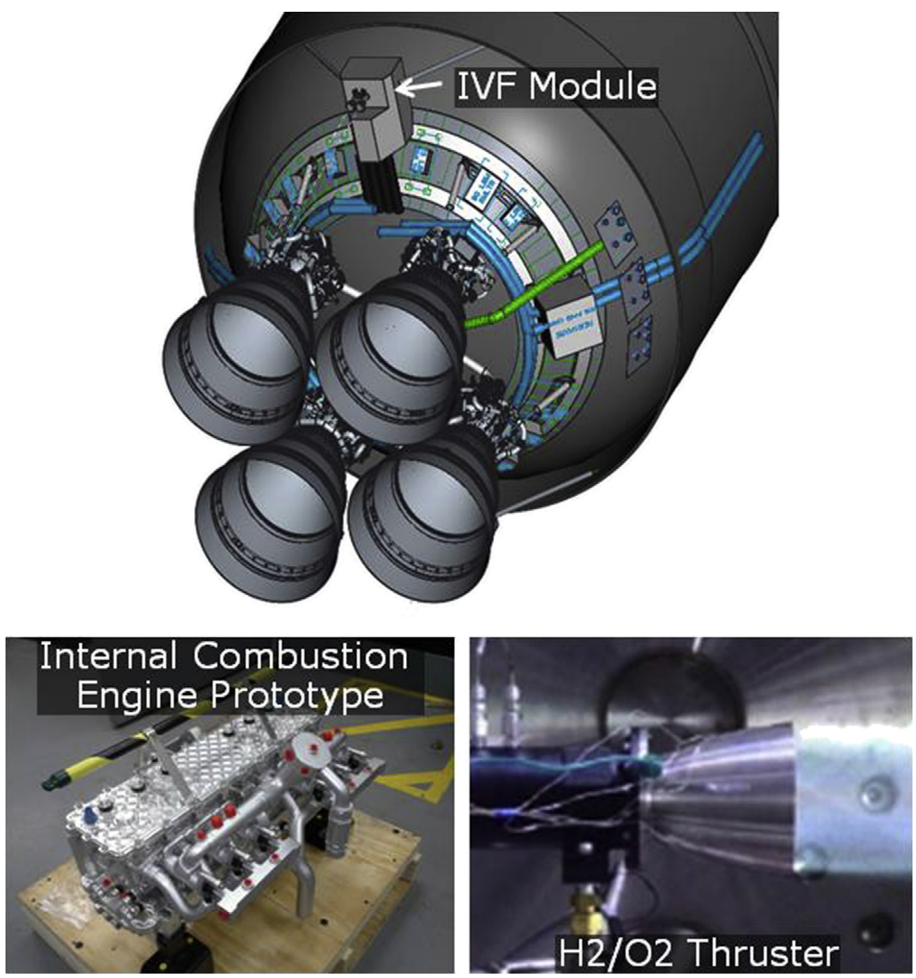

Fig. 4. Integrated Vehicle Fluids (IVF). The system consists of two modules located on the aft end of the ACES stage as shown in the top image. A prototype of the internal combustion is shown in the lower left image. A vacuum test of the hydrogen/oxygen thruster is shown in the lower left image.

Fig. 5. CRYOTE 3. A long duration cryogenic test bed. Shown is the three meter diameter, flight like propellant tank insulated for the initial phase of testing.

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.

4.3. 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 [8].

The basic approach makes use of ULA's experience in transferring cryogenics under settled conditions, that is, under a small acceleration. This ensures 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 losses.

4.4. 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 is needed for a lander is already inherent in ACES. The main engines can bring the stage close to the surface, but a separate system is required for the final descent.

XEUS solves this problem by adding several banks of thrusters to the side of ACES to enable the stage to land in a horizontal orientation. The landing maneuver is vertical with respect to the lunar surface. See Fig. 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 some electric pumps (powered by IVF). And landing legs will need to be added. Like ACES, XEUS is fully reusable with refueling.

5. An initial business case

Having established that the technology for a cislunar

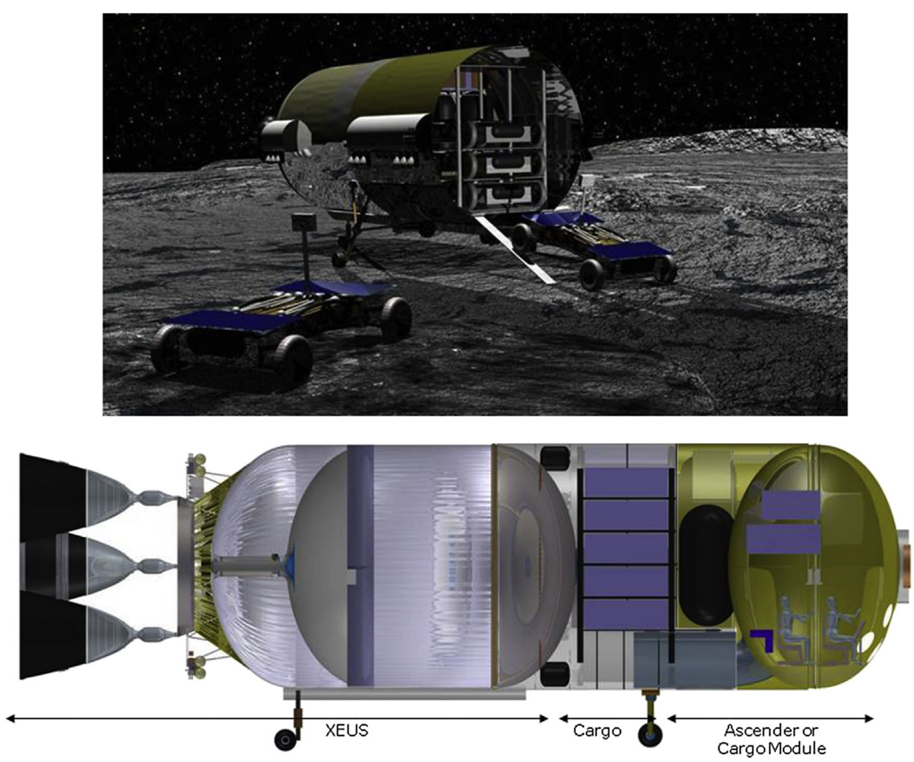

Fig. 6. XEUS, ACES derived lunar lander. The upper image is an artist rendition of XEUS deploying cargo on the lunar surface. The lower image shows a cross section of the stage with a crew module.

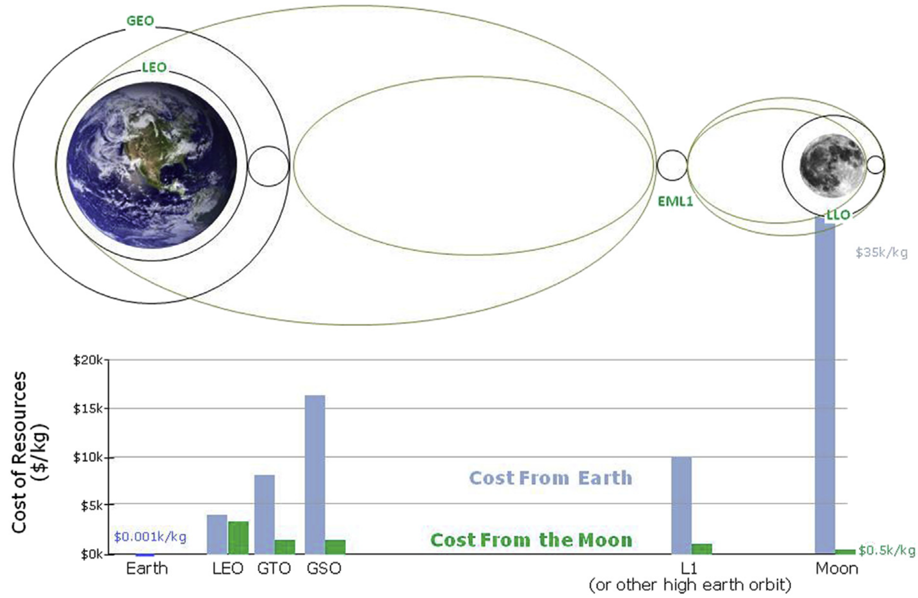

Fig. 7. Propellant costs at various cislunar locations. Costs for lunar sourced propellant are based on propellant in LEO at $3 million per ton, to close the business case.

transportation system will exist early in the next decade, I turn my attention to the business considerations. 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 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, I've assumed that the hardware cost of the ACES is paid for by the initial satellite customer. The transportation cost using ACES in space is then the cost of ground based operators plus the cost of propellant. For this analysis, I've 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. Fig. 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.

A price of $3 M/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 $3 M/ton, or GEO for $1 M/ton or at the Moon for $0.5 M/ton.

To size the propellant mining operation on the Moon, I assume three ACES trips from LEO to GEO per year. Each ACES requires 70 tons of propellant. Using ACES and XEUS, it takes about 4 tons of propellant to transport 1 ton 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 anout 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 1600 tons of water. The following table summarizes some of the key business parameters. (see Table 1).

6. 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, which 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 allowable price on the Moon by a factor of two, dramatically improving the business case.

Table 1
Summary of some of the key business parameters for lunar propellant mining.

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

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 [3]. 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 then be launched 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, purchasing propellant to fuel the transportation system.

Acknowledgements

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