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Space Paradigm Shift

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Editors' Note: This article was received before the coronavirus emerged in China.

Abstract

There has been a significant change in our perspective of the Moon, how to get there, how much it will cost, and what to do when we get there. This paper examines some of those changes, and it looks at how the changes in rocket technology provide a paradigm shift for space exploration (mainly the Falcon 9, and proposed SpaceX StarShip and Super Heavy Booster). The paper explores the opportunity to use a consortium of government, commercial, and private entities to open up access to the Moon, and to provide a new commercial capability both on the lunar surface and in cis-lunar space, to manufacture useful resources to support human expansion into space. The paper uses several NASA reports as a base example, and it modifies them to show how a consortium approach could open up and expand our current efforts in space. This paper is meant to be an exploratory introduction to how we can shift our thinking to accomplish much more in space than we have to date. More work is required to refine the ideas in this paper, but the next ten (or twenty?) years hold much promise for a surge in space activities, I believe.

Introduction

Over the last sixty-seven years we have watched the US-NASA space program evolve from Mercury, Gemini, Apollo, and the Space Shuttle to the International Space Station, but we have been stuck in low Earth orbit (LEO) for the last fifty years. There were many successes we took pride in, both manned and robotic, and some failures, with loss of life that saddened and disappointed us. In the last twenty years there have been several satellite probes, by various nations, that have been sent to study the Moon, that have revealed surprises, and that have showed that we had a lot more to learn about the Moon. The quote, "been there, done that," was hollow and uninformed: we had not seen very much, and we had not done what we needed to do.

Change is happening, and there are at least six countries working on plans to return to the Moon, to stay and make use of it. There are many more companies actively involved in these plans to return to the Moon, making hardware and providing services to support various activities. This paper discusses some of these changes and makes some recommendations on what to do when we get to the Moon.

Overview – Paradigm Shift

There is a rocket launch paradigm shift that is revolutionary to the aerospace industry and space access in particular. The traditional aerospace companies that make hardware for NASA, the military, and commercial space activities have been surprised by a new set of start-up companies (new space) over the last decade. These orbital launch companies include SpaceX, Blue Origin, Bigelow Aerospace, and others, as well as the existing aerospace companies, which are having to change to compete.

Some of these new companies have been funded and are run by new age billionaires, who are using patient capital to finance their company activities. Each of these companies faces its own individual problems in getting started and running as an ongoing business. First and foremost is the business case for a new business with a high cost of entry, technical problems that cause failures of hardware, and losses that cause near failures of the business. Then, developing the final products and services to provide an ongoing business plan and securing paying customers. The historical record for these start-up rocket launch companies shows many failures and few successes.

An interesting success story for SpaceX in developing the Falcon family of rockets is a good case example. There are books written about the historic rise of SpaceX and its CEO and Technical Officer, Elon Musk, so we will not dwell on these details here. In short, SpaceX would have gone bankrupt if its third launch of the Falcon 1 had not been successful. However, SpaceX is not only running a successful launch business today with the Falcon 9 (F9) series of rockets, but also developing a new, larger rocket called the StarShip and Super Heavy Booster—(SS/SHB). All the F9 and the Falcon 9 Heavy (F9H) rockets have reusable first-stage boosters that land vertically back at the launch facility for easy refurbishment and relaunch, without any other significant transportation requirement. The SS/SHB is another revolutionary advance over, and on top of, the success story of the F9 and F9H. It will offer not only heavier launch capability than any other rocket planned today, but also both the first-stage booster and the second stage to orbit will be totally reusable, and the second stage will be refueled in orbit. This two-stage-to-orbit system will make the F9 and F9H obsolete in the long run, although these two Falcon rocket designs have reusable first stages and are therefore superior in both launch cost and performance to the other expendable launch vehicles. Table 1 gives the launch systems costs.

If the SpaceX SS/SHB is successful, and there are many who hope it will be, it will blow open the doors to accessing Earth orbit, cis-lunar space, the Moon, and Mars. The ability to launch heavier cargo into orbit at lower cost and to land heavier cargo on the Moon and Mars will make it possible to do many things we have only been able to dream about before: launch larger and more space stations, use space solar power, and set up and operate multiple lunar bases to continue and accelerate the exploration started half a century ago and to start learning how to use the lunar resources. As the lunar bases become operational and successful, the amount of traffic between Earth and the Moon will increase and the need for services and activity in Earth orbits and cis-lunar space will increase, particularly near the Lagrange points and other strategic orbits. As lunar resources become available, the lower cost of getting those resources from the Moon into cis-lunar space will further accelerate space activities.

Table 1. Launch Cost Estimates[1]

Launch System	Cost of Launch	Mass to LEO Expended (lbs.)	Mass to LEO Recovered (lbs.)	Mass to GEO Expended (lbs.)	Mass to GEO Recovered (lbs.)	Mass to Moon (lbs.)	Mass to Mars	Cost/lb. to LEO	Comments
Shuttle–STS	$1,600,000,000		60,600					$26,403	Max cost
Shuttle–STS	$606,000,000	N/A	60,600	N/A	N/A	N/A	N/A	$10,000	Empty orbiter (165,000 lbs.)
Space Launch System (SLS)	$2,000,000,000		150,000					$13,333	Max cost
SLS–Block 1	$1,000,000,000	120,000				81,571		$8,333	Manned: 37 tons (81,571 lbs.) to deep space including Orion and its crew
SLS–Block 2	$1,000,000,000	150,000				99,000		$6,667	Cargo: 45 tons (99,000 lbs.) to deep space
Ariane 5	$165,000,000	44,000	N/A					$3,750	
Proton M (UR-500)	$65,000,000	23,000	N/A					$2,826	
Atlas V–United Launch Alliance	$110,000,000	42,000	N/A		N/A	N/A	N/A	$2,619	Could have as many as five solid boosters
Vulcan	$99,000,000		39,160					$2,528	
Falcon 9–SpaceX	$62,000,000	23,100	23,100	9,914	N/A	N/A	N/A	$2,684	Launch costs can be as low as $50M
Falcon 9 Heavy–SpaceX (Max)	$150,000,000	141,000		N/A	N/A			$1,064	

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[1] Source: en.wikipedia.org/wiki/Comparison_of_orbital_launcher_families.

Launch System	Cost of Launch	Mass to LEO Expended (lbs.)	Mass to LEO Recovered (lbs.)	Mass to GEO Expended (lbs.)	Mass to GEO Recovered (lbs.)	Mass to Moon (lbs.)	Mass to Mars	Cost/lb. to LEO	Comments
Falcon 9 Heavy–SpaceX	$90,000,000	141,000	141,000	57,278	17,624	37,010		$638	$150M total, $1,063/lb. based on two launches
Big Falcon Rocket–SpaceX (Max)	$300,000,000	N/A	330,000	N/A	N/A	220,000		$909	"But even if the BFR launch costs were half of the shuttle launch costs, the cost per lb. would still be less than $1,000 with greatly increased capacity and capability"
Big Falcon Rocket	$200,000,000	N/A	N/A	N/A	N/A	220,000		$909	
Big Falcon Rocket–SpaceX	$165,000,000	N/A	330,000	N/A	N/A	220,000		$500	"$500/lb. to orbit would be ideal target. On orbit, refueling required–Depots?"
Blue Origin–New Glenn	$100,000,000		99,000		29,000			$1,010	Costs $2.5 billion and will fly 25-100 times

The lunar and cis-lunar space experiences will be an important test of hardware, people, services, and failures that will flow into and enhance the Mars research bases when they are started. The result will be a cascade of events over the following decades, as business opportunities unfold to support the demand for space exploration and the utilization of materials and services to support Earth's needs. Along with this expansion will come space settlement.

As the development of the SS/SHB (now called StarShip) continues, there will be significant risks, both technical and business. The initial new engine for the SS/SHB (the Raptor) has been designed and build and it has had its first flight test in a test vehicle called the Starhopper, on August 27, 2019, validating its initial performance parameters.[2] If prototype tests go as planned, operational StarShip flights with payloads could begin as early as 2021. A StarShip has been booked for a flight to the moon and back for 2023.[3]

One of the most important risks to the StarShip development effort is the general economic condition of the aerospace industry. If the economy suffers a serious recession and there are other distractions like wars, the currently available critical resources may be redirected, and thus stall the development work. Once the StarShip is developed, there will be another risk: to develop the customers and markets for its use. There will need to be a very big business base and high demand to justify the design and operating expenses of the StarShip. The StarShip is not required for a lot of the current launch business activities. The F9 and F9H are taking on that business very well. The StarShip *is* required to get to the Moon and Mars, and to support cis-lunar space and lunar base activities.

The StarShip is an *enabler* for accelerating human activity in space. The new heavy lift capability will accelerate exploration and science projects, and it will make it possible to have basic and heavy industry as well. The heavy-lift capability will make it possible to bring first-generation capital equipment from Earth to the Moon (more about this later).

Lower capacity rockets with a limited payload and higher cost, have forced us to execute expeditionary programs, with minimal if any infrastructure to support continuing and expanding activity. Even with the NASA SLS launch system, there is little infrastructure planned in space or on the Moon. To use lunar in-situ resources (ISRU) in a significant way, we will need to place resource processing facilities on the Moon, and to be able to refine and transport them back into cis-lunar space to appropriate depots.

I am reminded of the development efforts for very large aircraft, the resulting teething pains technically, and the business and market demand shortfalls. The aircraft of interest are the Boeing 747, Lockheed C-5A, and Airbus A380. I was actively involved in

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[2] See Guy Norris, "SpaceX's Starhopper Verifies Raptor Performance for StarShip," *AWST*, September 2-15, 2019.

[3] On November 30, 2019, StarShip Mk1, which was being built in Texas, suffered a fatal failure when being tested with cryogenic fluids. It was an explosive failure, with the ship destroyed. StarShip Mk2, being built in Florida with the same design, was terminated. A new StarShip Mk3 started construction in Texas. Videos are available online.

manufacturing, quality, and mass properties for two of these aircraft, and I read a lot about the third. The C-5A is no longer in production. The Boeing 747 is still in production (after fifty years), and it has gone through several redesigns to stay relevant, but it seems to be the right size: not as big as the Airbus A380. Currently, the A380 is still in production, but probably not for long. The market demand for these large aircraft is changing again, and airlines are looking for smaller aircraft to serve shorter routes more cost effectively. Production termination will occur before Airbus has fully amortized its development and production costs. This could be a warning example for the SS/SHB. Competition will heat up, and there will be a next, follow-on generation of even larger rockets.

A review of current (large) rocket launch systems reveals a significant difference between each of them and their market potentials. In general, some of the older rocket designs are more expensive than the newer designs, since the industry has been trying to reduce costs on a continuous basis. It is clear from Table 1 that the new rocket competitive launch costs to LEO will be in the $500/lb. to $1,000/lb. range, and this will only be possible with reusable rocket boosters with easy turnaround (i.e., vertical landing at launch facilities). Expendable rockets will not be cost competitive in the future, perhaps even sooner than expected. It is questionable how cost effective and productive the SLS, being developed by NASA, will be, given the new age rocket company systems and their competitive advantage. Also, the launch cost has come down with smaller rocket systems like the Electron as well, and other new systems are coming online.

Some observations about SpaceX F9, F9H, and United Launch Alliance (ULA) Atlas V.

1. There is a paradigm shift in the way SpaceX has developed and is operating the Falcon 9 *reusable* rocket systems (Both F9 and F9H).

2. The costs are well below the traditional learning curve because the rockets are not thrown away.

3 They can choose to price competitively with ULA Atlas V system, making a lower bid, thus maximizing their profit and satisfying customers at the same time.

4 For larger launch customers, the F9H can launch below ULA Atlas V systems costs for a bigger market share, thus denying their competition that part of the business or initially securing a higher profit.

5. If the SS/SHB can reduce costs below F9H, as predicted, then we could see $500/lb. to $1,000/lb. launch costs (potential short-term monopoly?). SS/SHB launch capacity would also more than double.

6. SS/SHB easily has the range to reach the Moon and Mars if there are refueling depots in cis-lunar space.

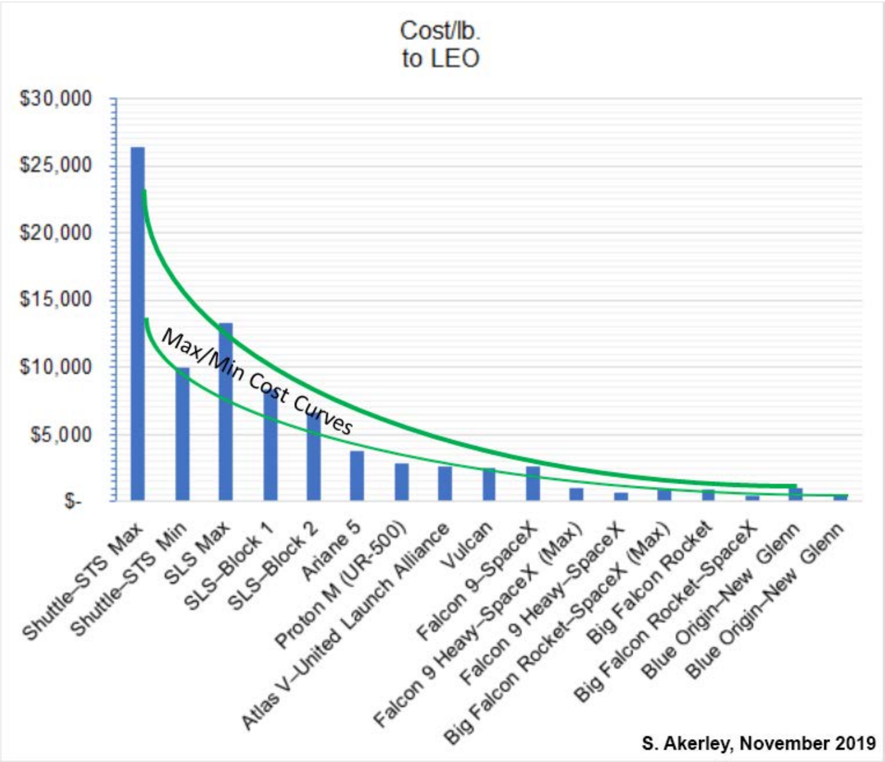
7. Blue Origin and New Glenn will need to compete cost-wise with the F9H initially, and then with the SS/SHB.

8. Perhaps Blue Origin's plans for New Armstrong will be competitive in cost and lift capacity with the SS/SHB.

Table 1 shows the costs/lb. to LEO in relation to the older rocket systems, but also the effect of reusability. There is some variation in these numbers, so a minimum and maximum cost trend is shown, clearly leading to a $500 to $1,000 cost per pound to orbit mentioned earlier. Over the next twenty years, this should reduce even more.

Lower Launch Costs

Figure 1 shows the maximum/minimum cost curves to LEO for the various launch systems.



S. Akerley, November 2019

Figure 1. Maximum/minimum cost curves for several launch systems.

As the rate of launch frequency increases, high reusability of launch hardware and competition improvement will occur over time, and the cost of the hardware will experience a learning curve cost reduction. So, with experience and higher usage of reusable systems, we should expect these costs to decrease further. This phenomenon is well known, and Figure 2 expresses it well.

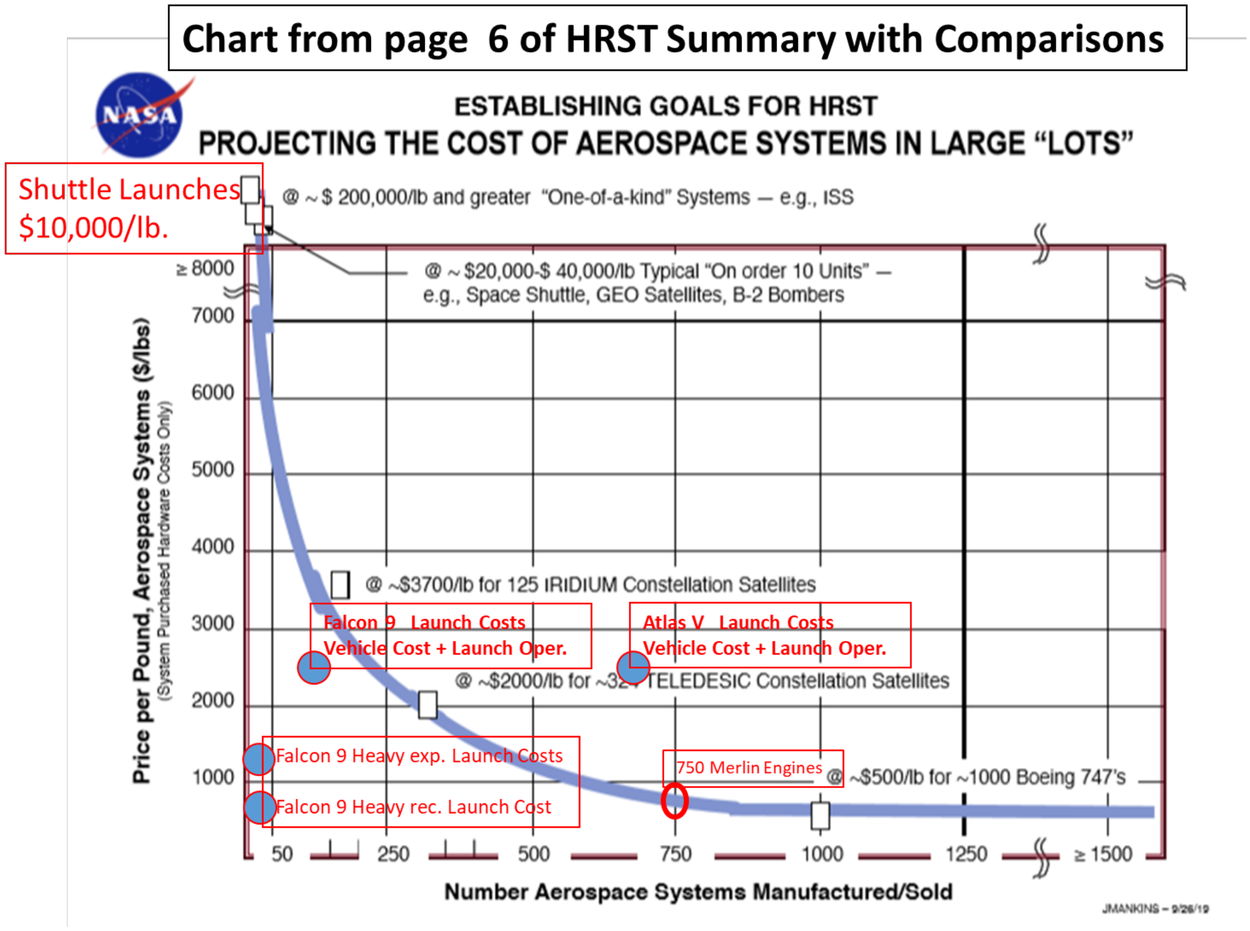


Figure 2. Cost curves for several launch systems.

This particular learning curve example was taken from a NASA study for a highly reusable space transportation system, and it was created in 1998. It has taken two decades to get to the point where reusability is a reality and can reduce launch costs. The next hurdle will be to increase reusability and safety, thus reducing system and operations costs further.

Note that the learning curve has some notional entries in red that show some examples and thought exercises about system costs. The cost of launching an Atlas rocket has improved over its life, but it is at the end of its useful design life, which is why the ULA is developing its new rocket the Vulcan (included in the chart). Although the listed launch cost of the F9 is just a little lower than the cost of an Atlas launch, there is probably a larger profit margin for the F9, as it is a much newer system, and it can easily compete with the older Atlas system. It has been observed that all of the F9 rockets have a cost and operations advantage, in that there have been more than 750 Merlin engines produced, with associated learning in manufacturing and operations improvements, which gives an additional reason for the lower cost of the F9 rocket, and its reliability. Additionally, the F9 rocket has improved engine sensors on its nine engines, and a high degree of flight automation that improves both safety and operations costs.

Figure 3 comes from a NASA report from 2003, titled *Cost Considerations to Ambitious Human/Robotic Exploration*.[4] The chart is based on the 100-day class missions, for example, a human lunar return ETO transport. Figure 3 shows that some of the base assumptions have changed, as we no longer have the Shuttle or Titan IV in the lower chart line. However, the cost model is still a good historical example of the reality of the last decades, which we then use to consider some of the changes.

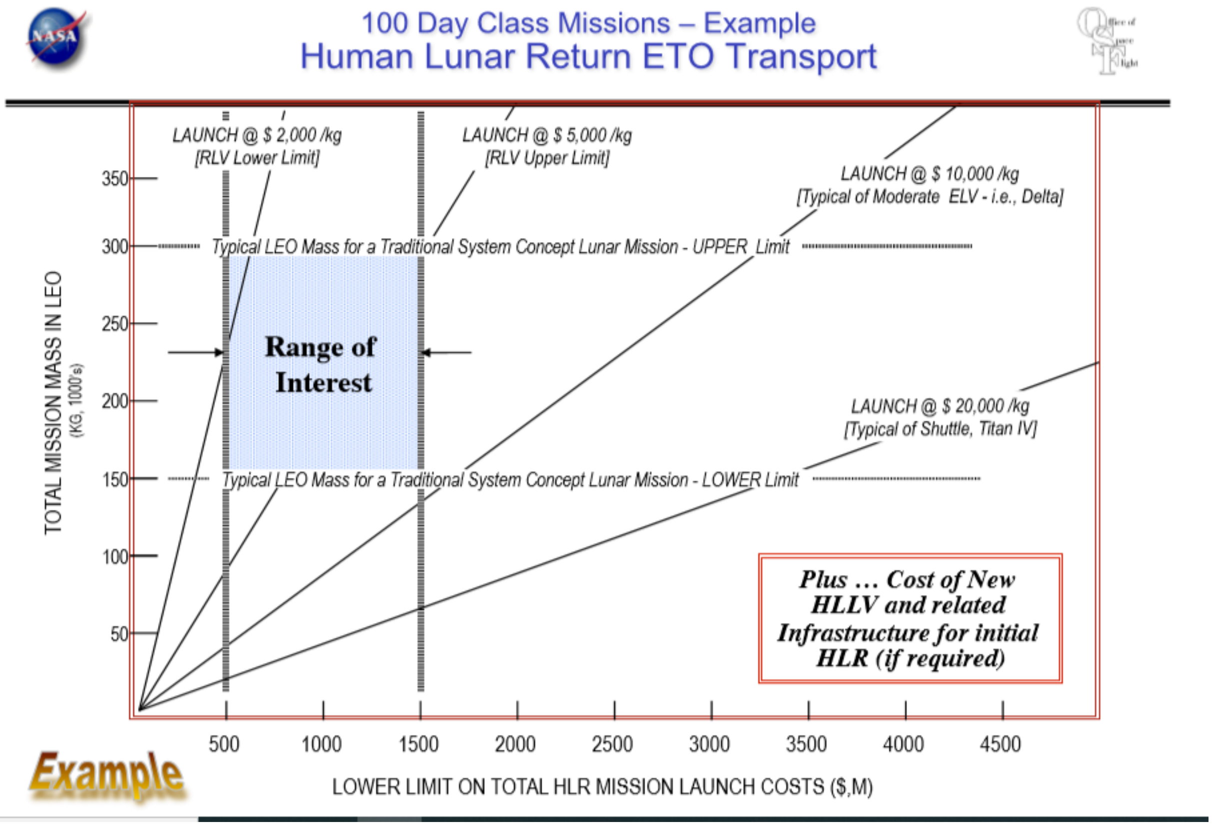


Figure 3. Costs of various options for a human lunar return mission.

In Figure 4, there is added data that is relevant to the new SpaceX vehicle (SS/SHB) in red. As is consistent with previous information in this article, there is a new lower cost to orbit than was possible in 2003.

It is notable that the payload lifted to orbit by SS/SHB is much more than was possible previously. The cost of lifting that payload has decreased. The resulting missions are less expensive, and they can do more. Even some of the newer rocket systems (F9, F9H) will become less and less competitive as the SS/SHB goes into regular use. This will change what can be done and how it will be done, and it will potentially accelerate when it is done.

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[4] John C. Mankins, *Cost Considerations for Ambitious Human/Robotic Exploration—The Need for Transformational Space Infrastructures* (Washington, DC: NASA, 2003).

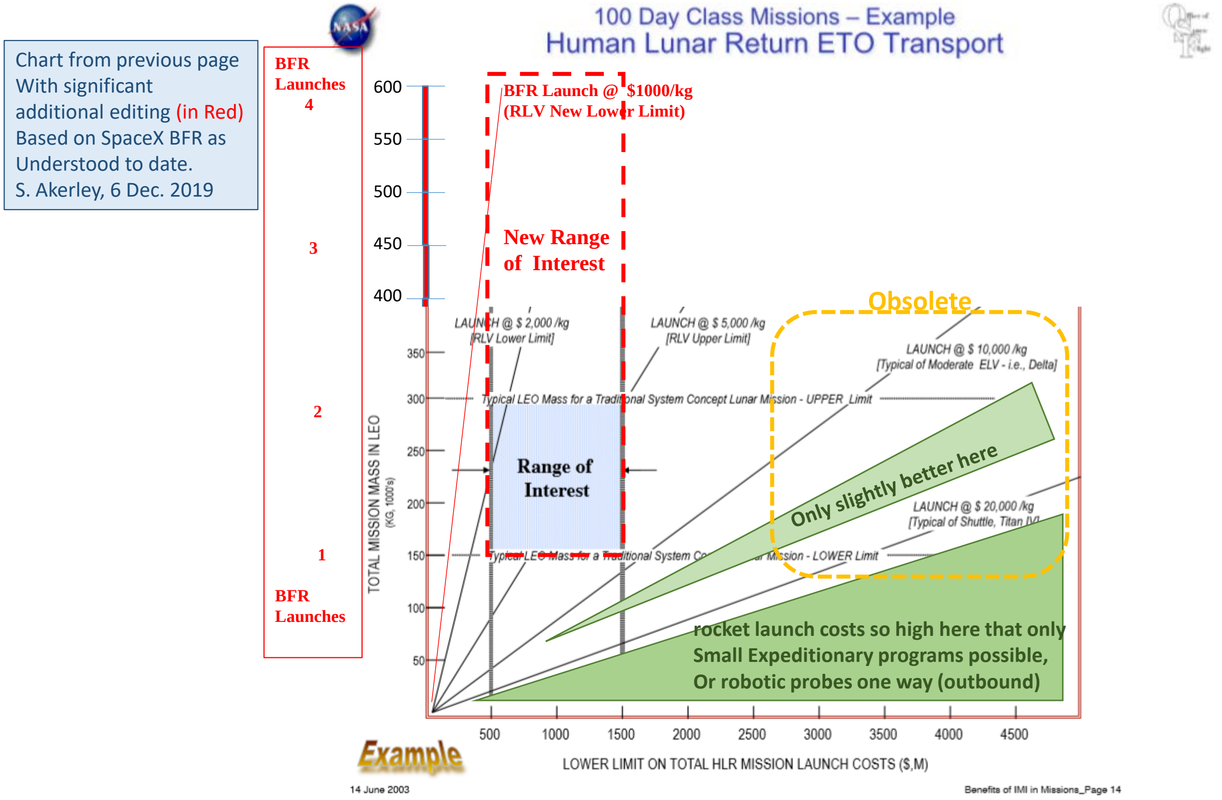


Chart from previous page With significant additional editing (in Red) Based on SpaceX BFR as Understood to date. S. Akerley, 6 Dec. 2019

Figure 4. Target costs of various options for a human lunar return mission.

New Opportunities and ΔV

The lower launch costs and increased launch rate will open opportunities for access to space. These new opportunities will expand gradually from LEO outward, to include all cis-lunar space, all the way to the Moon, as outlined below (Figure 5):

Low Earth Orbit (150-1,200 miles altitude [2,000 km])

Medium Earth Orbit (1,200-22,000 miles altitude)

Geosynchronous Earth Orbit (22,236 miles altitude)

High Earth Orbit (above 22,236 miles altitude)

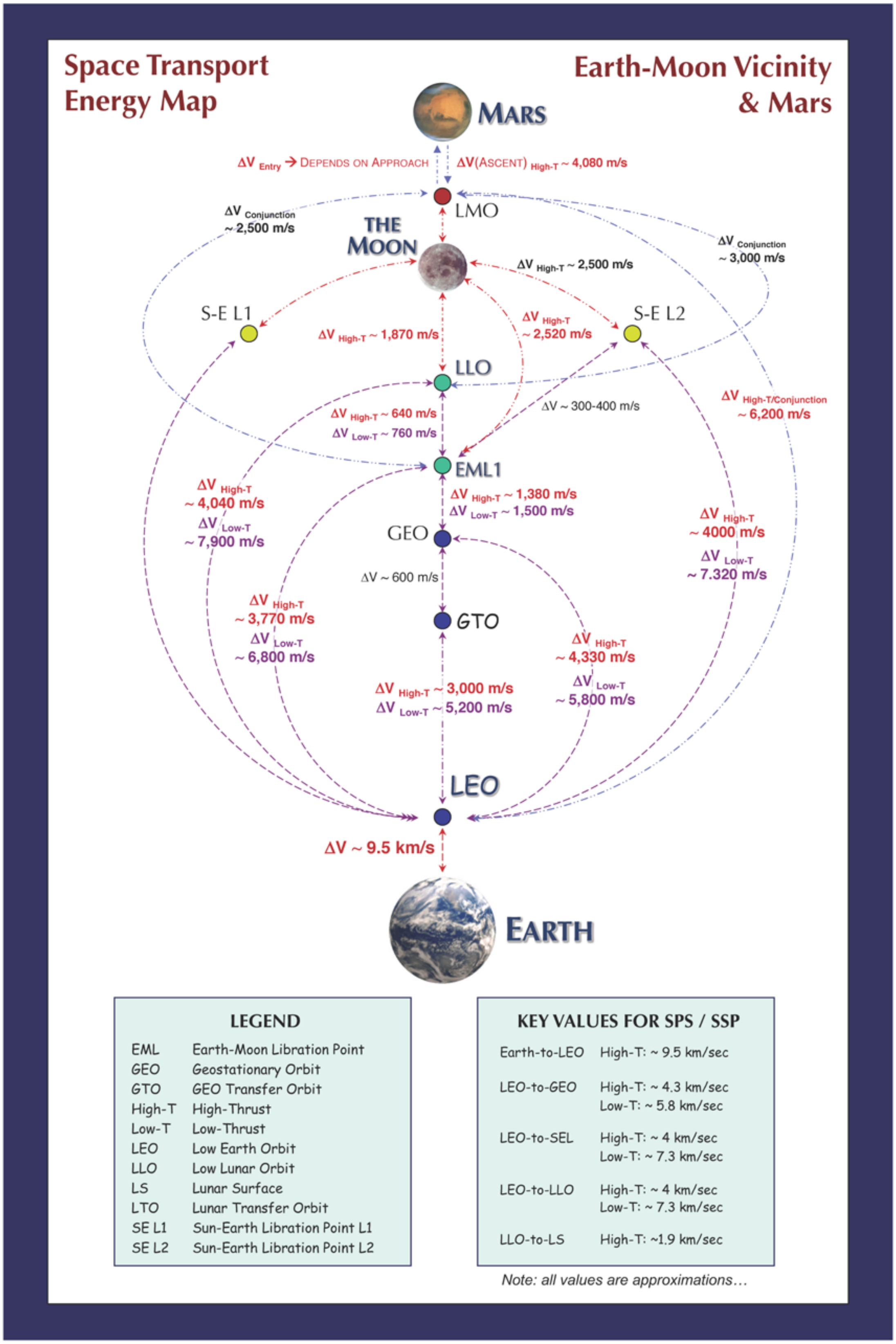
Stations at Lagrange Points and Depots

Lunar Orbit/Gateway

Lunar Surface

And beyond

When we return to the Moon, there are resources that we will want to use for construction projects, and fuel both on the Moon and at depots in cis-lunar space. We will want to do this because it will be less expensive than bringing the same resources up from Earth.



LEGEND

EML	Earth-Moon Libration Point
GEO	Geostationary Orbit
GTO	GEO Transfer Orbit
High-T	High-Thrust
Low-T	Low-Thrust
LEO	Low Earth Orbit
LLO	Low Lunar Orbit
LS	Lunar Surface
LTO	Lunar Transfer Orbit
SE L1	Sun-Earth Libration Point L1
SE L2	Sun-Earth Libration Point L2

KEY VALUES FOR SPS / SSP

Earth-to-LEO	High-T: ~ 9.5 km/sec
LEO-to-GEO	High-T: ~ 4.3 km/sec Low-T: ~ 5.8 km/sec
LEO-to-SEL	High-T: ~ 4 km/sec Low-T: ~ 7.3 km/sec
LEO-to-LLO	High-T: ~ 4 km/sec Low-T: ~ 7.3 km/sec
LLO-to-LS	High-T: ~1.9 km/sec

Note: all values are approximations…

Figure 5. Space energy transport map.

There is a famous quote, by Robert Heinlein; “Once you get to Earth orbit, you are halfway to anywhere in the solar system.” This is a general reference to the amount of energy required to get into Earth orbit vs. travel to any of the planets. An easy and graphical way to see this is by looking at a ΔV chart (change in velocity). An example of such a chart of the Earth Moon System, is the 2019 “Space Transport Energy Map,” provided by John Mankins (Figure 5). Although this is a generalization, it is a good foundation for considering ΔV (velocity roughly correlates to cost) of getting materials from the Moon vs. Earth into space.

Using this ΔV data and assuming a high thrust propulsion system, the energy to reach LEO is the major share of the energy for getting to the moon. Or, conversely, it is easier (energy wise) to get a pound from the lunar surface to the Earth-Moon Lagrange Point 1 (EML1) (2.5 km/s) than from the Earth’s surface to EML1 (9.5 + 3.7= 13.2 km/s), roughly 1/5 the ΔV cost (see Table 2).

Earth to LEO = 9.5 km/s

LEO to EML1 = 3.7 km/s

EML1 to Lunar Orbit = 2.5 km/s

LMO to Surface (Descent) = 1.8 km/s

Table 2. Space Transportation Cost Worksheet (Based on ΔV – Cost per kg)

Transport Leg	ΔV (m/s)
Earth to LEO	9,500
LEO to EML1	3,770
EML1 to Moon	2,520
LMO to Surface (Descent)	1,870
Moon to LMO (Ascent	1,870
LMO to EML1	2,520

	Total ΔV	$/kg	$/lb.
ΔV Earth to Moon Surface	17,660	$2,045	$929.47
ΔV Moon to EML1	4,390	$508	$231.05
Difference	4	4	4

All other cost drivers being equal, the transportation cost of a pound of anything from the Moon to the EML1 location would be one quarter of the cost to get it from Earth. Or, conversely, if you can make it and use it on the Moon, you avoid the excessive transportation cost from Earth. However, the situation is a bit more complicated than that (the cost of ΔV above is based on $500/lb. to LEO; a range of costs is considered later).

Resources (Lunar ISRU)

Table 3 shows the most abundant surface resources on the Moon. Notice that there are many interesting and possibly useful elements, and that the top four are the primary ingredients for concrete cement, but that there is an energy cost to harvest them, refine them, and make them useful.

Table 3. Lunar Surface Chemical Composition[5]

Compound	Formula	Composition	
		Maria	Highlands
Silica	SiO_2	45.4%	45.5%
Alumina	Al_2O_3	14.9%	24.0%
Lime	CaO	11.8%	15.9%
Iron (II) Oxide	FeO	14.1%	5.9%
Magnesia	MgO	9.2%	7.5%
Titanium Dioxide	TiO_2	3.9%	0.6%
Sodium Oxide	Na_2O	0.6%	0.6%
		99.9%	100.0%

The energy cost to process these raw materials into commercially useable resources is in Table 4. Significant amounts of energy are required to process these materials, and a relatively large scale ISRU facility will be necessary to process these materials economically to make meaningful products to support a lunar base, or for activities in cis-lunar space.

One initial idea was to use lunar iron to make and roll steel plate to make tanks to hold volatiles collected and processed at the lunar poles. Another approach would be to use alumina to make aluminum for tankage. However, making aluminum costs considerably more energy than making steel.

Various types and sizes of tanks would be required, but in all cases, it would be cheaper and easier to use lunar materials than to transport the heavy tankage from earth. However, upon researching the required processing steps, a need to bring in a significant amount of equipment to do this becomes apparent. In addition, the equipment has multiple functionality for a wide range of products, so it is obvious that it is possible to provide the lunar base(s) with more than just tankage. So, the business opportunity grows much larger if there is adequate power. The power requirements and transport requirements on the Moon are still significant, even if they are less than those for transporting materials from Earth.

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[5] Source: en.wikipedia.org/wiki/Geology_of_the_Moon.

Table 4. Energy Required to Produce 1 kg of Material (Reordered by Energy Required, Grouped by Material)[6]

Material	Source	Energy kWh	Comment	% on Surface
Volatiles	Lunar Poles	TBD	Water and other volatiles (distillation and separation)	In cold trap deposits
Water	Electrolysis	3.66	Separation of oxygen and hydrogen	In cold trap deposits
Oxygen	Bound in Compounds	TBD	Byproduct of baking or refining processes	40
Glass	Sand/Silica	9.70		
Iron	Iron Ore	6.95	Uses lots of carbon—2 kg CO_2	14
Iron	Iron Ore	9.73	Electric anode process[7]	14
Steel	Recycled	4.17		
Steel[8]	Iron	13.90		
Copper	Copper Sulfide Ore	34.70	For aluminum alloy and electrical wiring	
Aluminum[9]	Recycled	4.75		
Aluminum	80/20 Mix	60.80		
Aluminum	Bauxite	95.00	Uses lots of carbon[10]—4 kg CO_2	
Aluminum	Bauxite	171.00	Non-carbon anodes (from 1.2 Volts to 2.2 Volts + 80%)	
Nickel	Ore	75.00		
Titanium	Ore	261.00		
Silicon	Silica	65.30		
Silicon	Electronics Grade Silicon[11]	2,154.90		
Magnesium			Similar to aluminum, but much more energy required	

Upon studying these charts, looking at availability of resources, and looking at energy cost to process, several conclusions can be drawn:

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[6] Source: www.lowtechmagazine.com/what-is-the-embodied-energy-of-materials.html.

[7] Alternative processes for aluminum smelting using inert anode cells (oxygen evolution) include (a) lanthanated tungsten (La_2O_3); (b) MIT chromium iron alloy.

[8] Many companies are using electric arc furnaces to make steel, particularly specialty steel like stainless steel and high-temperature alloys. However, they usually use 40 ton, 80 ton, or larger capacity furnaces. A smaller furnace would be a good candidate for casting iron and steel on the Moon initially. Clearly a higher capacity is possible if the power is available. See en.wikipedia.org/wiki/Electric_arc_furnace.

[9] For the aluminum smelter process, see anscon.com.

[10] See Columbia Climate Center, *Mitigating Emissions from Aluminum* (New York: Columbia University Press, 2012), climate.columbia.edu/files/2012/04/GNCS-Aluminum-Factsheet.pdf.

[11] Martin J. Pitt, “On the Enthalpy of Formation of Silicon,” unpublished paper.

- There is a lot of oxygen bound in the compounds on the Moon.
- Silica and alumina are very abundant.
- Iron is #4 in abundance, at 14% in Maria locations (mostly high-quality ore).
- If silica can be found and processed in a relatively pure form, it can be used to make glass. Or, if not so pure, it will be possible to make bricks for construction purposes.
- Iron oxide can be electromagnetically separated from the regolith and it can be processed easily into iron and steel, with appropriate capital equipment for foundry and rolling mills.
- Volatiles at the lunar poles look like the easiest resources to harvest on the Moon. This will be important for obtaining propellant, assuming the processing can be done efficiently.
- Then, the next easiest resources to harvest will be silica and iron (lowest energy to process).
- An electric anode process can be used to smelt aluminum instead of carbon, but 80% more energy would be required.
- An electric anode process can be used to smelt iron instead of carbon, but 40% more energy would be required.
- If water can be obtained (in lava tubes?), then it may be possible to make concrete, since the primary ingredients of cement are available: lime—CaO, alumina—Al_2O_3, and silica—SiO_2.[12]

Initial harvesting of volatiles at the poles, at the top of the resources table, will be relatively inexpensive, but it will initially require bringing down large empty tanks for storage. When the Moon has an established ISRU industry to utilize large quantities of lunar resources, it will be possible to manufacture a wide range of structural product and tankage to support the growth of the lunar bases and outposts. The lunar product range will expand from volatiles to glass and iron/steel casting, which are the next resources, going down the resources/energy list. The first large-scale steel products will be steel long stock (angle iron, I-beams, tubes, bars, rods, wire, etc.), because this will be the easiest energy wise, and it will expand to hot rolled plate for tankage and welded structures and/or cold rolled sheet steel. But these products require a significant capital equipment base and a large amount of energy to run.

If iron is available in the regolith near the lunar polar regions, then it may be possible to collect it electromagnetically and to use it to make small precision hardware if the required power is available, using 3D printing techniques, to produce iron and steel tools and fittings. More than likely, just as on Earth, larger manufacturing facilities will be strategically located near resources and markets. The important decisions for site locations are driven by many factors, starting with points of interest. Some will be based on science, while others will be based on transportation, location near resources, available power, and delivering product to the market, which are all major selection criteria, as well as cost drivers.

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[12] See todaylibertyordeath.blogspot.com.

The power requirements for any lunar outpost will initially require surface-mounted solar panels for base power, but they will have to evolve to much higher power levels over time to support heavier activity. This may eventually require either a nuclear power plant, or if available, space solar power (SSP) systems orbiting the Moon.[13] Depending upon the necessary amount of industrial processing, the power levels will need to be adequate to the task, or they will limit the activity. Thus, there will be limited industrial activity at first, but the growth of outposts and bases will require parallel growth of power, resource utilization, and larger industrial applications to support growth. Figure 6 shows the relative energy requirements for processing various important ISRU materials.

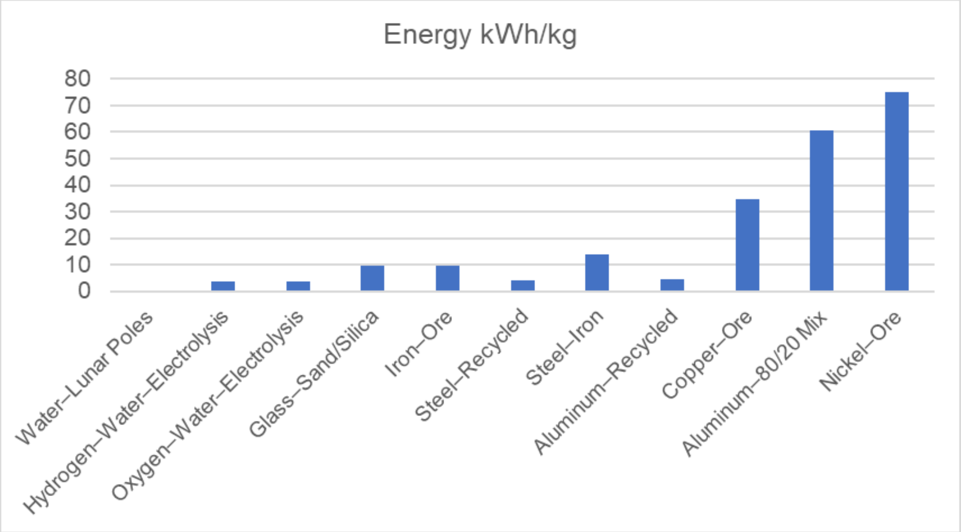

Figure 6. Energy requirements for processing ISRU materials.

Some ISRU materials will require a significant increase in available power before they can be economically produced on the Moon. Figure 7 shows this next group of higher energy materials.

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[13] Source: https://en.wikipedia.org/wiki/Nuclear_power_in_space.

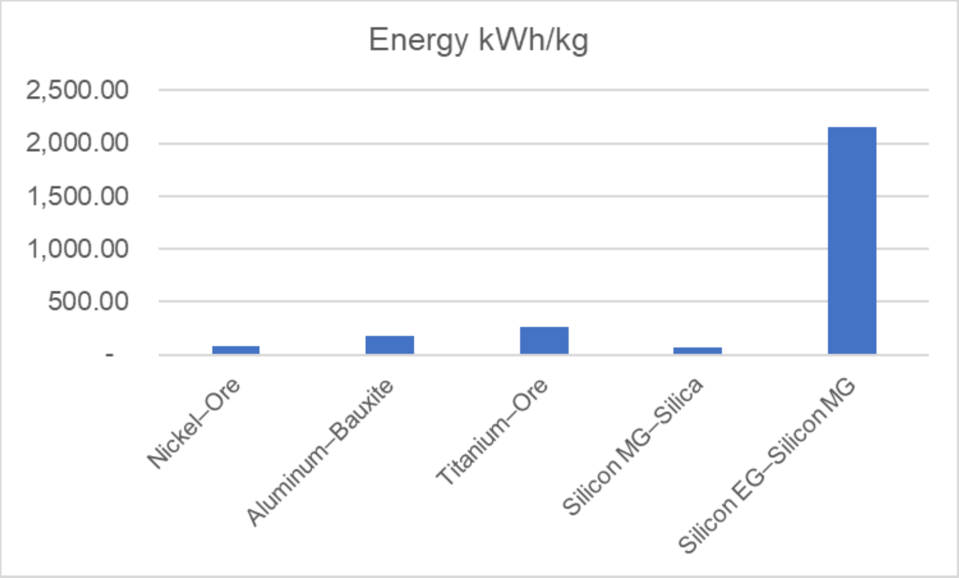

Figure 7. Energy requirements for processing higher energy ISRU materials.

The Moon is an ideal location for agricultural/farming research to learn how to grow food and support outposts off and away from Earth. This can be done most easily in sealed lava tube segments below the surface of the Moon. We know they exist, but they have never been explored. This is a separate topic, but it is a primary consideration for outpost site selection, because these tubes will need to be explored so we can utilize them for bio-regeneration, closed loop life support, and self-sufficiency.

Next let us consider the site selection process for outposts and bases. If scientific research is the only site selection activity, then lunar activity and growth will be slow and expensive. If, however, the rationale is expanded to include large-scale ISRU utilization and increased human presence, then industrial-size ISRU production along with bio-regeneration, growth of food, and other living necessities will be factors in site selection. Then this expanded scope of criteria will help to drive and fund the lunar growth activity. This in turn will energize the entire cis-lunar space economy with increased transport and trade activity, based on the availability of less expensive lunar resources.

A Basing Plan

John Mankins developed a reference plan called the Human and Robotic Modular Infrastructure/System (HARMONY).[14] Its objectives are to use robots and humans in a complementary fashion to achieve space exploration objectives. Robotic systems are used for the initial basing activity to set up human habitats and other lunar support systems, such as the communications and solar panels. This minimizes the risk to the humans, while maximizing the potential progress and reducing the cost.

This approach of paired efforts from robots and humans aligns with what we want to do. The first outposts will be at the poles, because that is where the water is. Water is the

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[14] John C. Mankins, "Human and Robotic Modular Infrastructure/System (HARMONY)," Paper presented at the 51st International Astronautical Congress, October 26, 2000, Washington DC.

highest priority resource for making propellant and for life support. Oxygen from regolith with be the next most important ISRU for development. The basing plan suggests a four-phased approach:

Polar Outposts:

Phase 0	Precursor robotic missions (check out locations, prepare for outpost emplacement).
Phase 1	Lunar outpost emplacement (initially only one or two sites at or around poles).
Phase 2	Human lunar return preparations (in space infrastructure emplacement).
Phase 3	Human and robotic exploration with ISRU experiments (first human return for a hundred days).
Phase 4	ISRU emplacements and start production (start making and using ISRU – water, oxygen, hydrogen, iron, silica, other?).

In addition, there is a new teaming approach, in which NASA is asking for commercial partners to provide lower cost access to LEO. The new HARMONY plan recommends expanding this commercial approach even further to include industrial and science/exploration partners. In this new approach, commercial and industrial partners would help to accelerate and pay for the expansion into space, plus providing accelerated ISRU.

After establishing the first outpost(s) at the lunar poles, it will be of interest to reiterate the same phased approach to setting up outposts in other locations on the Moon, but with added phases as appropriate at each location to complete the exploration and characterization of the site. For example, if the site is near a large reservoir of regolith with a good concentration of iron, the site would be considered for a mine and/or quarry and an iron smelter and steel processing facility. Or, if the site is located near a skylight, it would be sensible to examine the interior of the lunar lava tube exposed by the skylight, and to evaluate its potential for a large human base. So, in that case, the phased approach to setting up the outpost might look like the one shown below.

Equatorial and Mid Latitude Outposts (Alternate Advanced Mission Option):

Phase 0	Precursor robotic missions.
Phase 1	Lunar outpost emplacement.
Phase 2	Human lunar return.
Phase 3	Human and robotic exploration with ISRU experiments.
Phase 4	ISRU emplacements and start of production.
Phase 5	Lunar lava tube robotic exploration.
Phase 6	Lunar lava tube human and robotic exploration and development.
Phase 7	Initial lava tube base.
Phase 8	Advanced human subsurface outpost and advanced bio research.

There needs to be a strong focus on how to use the lunar ISRU resources, and a start to preparations for industrial-level production. If we do not start using the resources, our efforts to go deeper into space will not materialize very quickly. The optimal situation for humanity is to learn to develop and use the lunar resources to maximize our potential for expansion into space. The basic and heavy industries will help to pay the way.

Heavy Industry–Capital Equipment

As we are doing basic ISRU experiments (Phase 3), we will need to start considering how to use the lunar resources and what will be required for ISRU (capital equipment) emplacements, to start production in Phase 4. In Phase 3, small laboratory-sized equipment will be necessary to make sure we understand the details of what is available and possible, and what the requirements will be for larger scale production. The capital equipment for Phase 4 will be custom designed for lunar operations: it will be designed, set up, and tested on Earth first, then disassembled in modular fashion and packaged for shipment to the Moon. Commercial partners will provide the design, set up, and test on Earth, and then they will make arrangements for lunar support for setup on the Moon with automated (tele-robotic) installations with Earth-based operators. A first estimate of the necessary capital equipment is as follows:

Capital Equipment, Iron and Steel Foundry

- Solar panels mounted on heliostat tracking systems to follow the sun during sun light operations (sunlight operations = fourteen days).[15]
- Solar reflectors mounted on heliostat tracking systems to follow the sun during sunlight operations.
- Electric arc furnace (1 ton capacity). Will weigh about 10-20 tons and require about 1-2 MWhe.

To produce about 1 ton of iron for casting:

- Preheat oven for iron ingots entering rolling mills, will use Heliostat Solar Reflectors, 2 MWh.
- Sintered regolith for oven enclosure. Not much electricity required, but a lot of heat.
- Rolling mill for long stock. Estimated to weigh about 20-40 tons, requires about 2-5 MWhe.
- Long stock includes angle iron, I-beams, bars, rods, and wire.
- Rolling mill for plate stock. Estimated to weigh about 20-40 tons, requires about 2-5 MWhe.
    - Plate stock is hot-rolled steel plate of various thicknesses.
- Rolling mill for sheet stock. Estimated to weigh about 20-40 tons, requires about 2-5 MWhe.
    - Sheet stock is cold-rolled steel plate of various thicknesses.
- Some of the weight may be reduced by using lunar resources, but there is no reduction in the electrical power requirement.

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[15] See www.heliogen.com; www.lightmanufacturingsystems.com.

Capital Equipment, Glass Foundry:

- Solar panels mounted on heliostat tracking systems to follow the sun during sunlight operations.
- Solar reflectors mounted on heliostat tracking systems to follow the sun during sunlight operations.
- Furnace (1 ton capacity), with extrusion pour/casting capability, and preheat oven for glass melting and forming/blowing will use Heliostat Solar Reflectors, 1-2 MWh.
- Sintered regolith for oven enclosure. Not much electricity required, but a lot of heat.

Basic Support Industry and Services:

- Strip mining and refining of ores; iron, silica, alumina, etc.
- Machine shop for precision machining requirements.
- Welding shop for steel assemblies.
- 3D print shop:
  - Large to medium sized regolith sintered structures.
  - Small to medium sized metal precision parts.
  - Small sized plastics and other materials.

Aluminum smelting will come later, since it requires 6-10 times more electrical power than iron or steel, but it could use some of the same rolling mill systems as steel.

Electronics grade silicon will require even more energy to process, since growing silicon crystal is very heat intensive (20x more than aluminum).

Proposed Industrial Initiatives Plan

So, given what we know, it is proposed that along with a revised and current version of the HARMONY Basing Plan for setting up the first bases on the Moon, we will solicit industrial participation to create industries on the Moon, to help to support lunar development and growth. The first industries proposed are lunar volatiles from the lunar poles (water, oxygen, and hydrogen), and other undefined volatiles, to support fuel depots and life-support needs. Next would come the easier industries, glass and iron, as they require about the same relatively low energy levels to operate. More oxygen would be a byproduct of the iron foundry industry, and eventually the aluminum industry.

The following cost study for the initial iron and steel Industry on the lunar surface is a study model based on the HARMONY plan. It is not an alternate to the HARMONY plan, but it is an industrial initiative addendum to a HARMONY-like plan. It would require other industrial initiatives to be working parallel as well, such as the mining and refining industry, machine shop industry, welding industry, and glass industry. Each of these industries would be created and run by industrial partners as part of a larger scale initiative to develop the lunar resources and to support human expansion and settlement.

Table 5 is patterned after the HARMONY plan, running from Phase 0 through Phase 4. The robotic systems will be patterned after the NASA robonaut design,[16] and they will be tele-operated from Earth. The robonauts will be the onsite workers for the modular assembly of the iron and steel mill systems, and they will be mounted on R2 (electric) Jeep vehicles. The habitats shown here are Bigelow BE330-based designs, and they would need to be housed/protected in a regolith dome structure for radiation protection and thermal stability. It is anticipated that the outpost set up and foundry/steel mill set up will work in parallel and share some resources. A lot of the original HARMONY systems and their costs are not included, or are reduced, in this study because the industrial initiative would run parallel with or post HARMONY outpost set up. Some of the items excluded/reduced because they are not specific for this activity are:

SSP—Space Solar Power systems
EPS—Electronic Power Systems
Cryogenic Propellant Depot

The estimated costs for Phases 0, 1, 2, and 3 are as accurate and complete as can be determined today. However, they are estimates, and there are so many variables that when the actual program planning starts, these work sheets will need to be revised. One of the biggest variables is the market size and demand for steel. Steel is a primary structural material, and it will be required, just as it is here on Earth, in building larger structures. That variable will drive the production volume, furnace capacity, mass, and power requirements for the furnace and rolling mills. Although SSP and EPS units have been included, they may not be required in the phases identified initially, if at all. Phases 0, 1, 2, and 3 are precursor and preparation missions that set up for Phase 4, which is the start of industrial capacity emplacement. Phases 1-3 may be scaled back if there is less initial effort required. Phase 4 could be increased later as conditions require.

The most important result of this exercise is to provide an example and to start the dialogue about what would be required for industrial scale implanting on the lunar surface to start iron/steel ISRU processing. It will not take as long to amortize the costs when the industrial partners decide to get involved.

The post-Phase 4 exercise has even more uncertainty, but this too has some of the same unknowns as the other phases, and it is heavily dependent on how the market evolves. This part of the exercise is primarily a look into what is possible (Table 6).

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[16] Robonaut 2 From NASA: www.nasa.gov/mission_pages/station/main/robonaut.html; www.nasa.gov/pdf/464887main_Robonaut2_FactSheet.pdf.

Table 5. New HARMONY Revised Plan (2020), Part 1

PHASE 0 **Capital Equipment, Iron and Steel Foundry**	**Number Required**	**Mass lbs.**	**Additional Mass**	**Total Mass lbs.**	**Purchase Cost Each**	**Total Cost**	**Power Each kWh**	**Power Total kWh**	**Transport DV Cost $930 US**	**Comments**	
Solar panels (6) on each heliostat (150/6 lbs. = 25 lbs., on 833 assemblies + heliostat)	1,000	150	15,000	165,000	$2,000	$2,000,000	1	1,000	167,400,000	Electric	6 Panels per heliostat
Robonauts	4	330	2,000	3,320	$5,000,000	$20,000,000	-0.5	-2	4,947,600		
R2 (elect.) Jeep	4	4,000	15,000	31,000	$1,000,000	$4,000,000	-6.6	-26.4	42,780,000		
Robonaut garage, charge, repair, night retreat	1	16,000		16,000	$5,000,000	$5,000,000			14,880,000		
Remote control/communications system	1	2,000		2,000	$1,000,000	$1,000,000			1,860,000		
Mission operations	1				$10,000,000	$10,000,000			-		
				217,320		$42,000,000				**Total Cost Phase 0**	**$273,867,600**

PHASE 1 **Capital Equipment, Iron and Steel Foundry**	**Number Required**	**Mass lbs.**	**Additional Mass**	**Total Mass lbs.**	**Purchase Cost Each**	**Total Cost**	**Power Each kWh**	**Power Total kWh**	**Transport DV Cost $930 US**	**Comments**	
Solar panels (6) on each heliostat (150/6 lbs. = 25 lbs., on 833 assemblies + heliostat)	1,000	150	15,000	165,000	$2,000	$2,000,000	1	1,000	167,400,000	Electric	6 Panels per heliostat
Robonauts	6	330	2,000	3,980	$5,000,000	$30,000,000	-0.5	-3	5,561,400		
R2 (elect.) Jeep	4	4,000	15,000	31,000	$1,000,000	$4,000,000	-6.6	-26.4	42,780,000		
Robonaut garage, charge, repair, night retreat	1	16,000		16,000	$5,000,000	$5,000,000			14,880,000		
Remote control/communications system	1	2,000		2,000	$1,000,000	$1,000,000			1,860,000		
SSP units	3	6,600		19,800	$90,000,000	$270,000,000			18,414,000	To where?	
EPS units	3	4,400		13,200	$50,000,000	$150,000,000			12,276,000	To where?	
Mission operations	1.5				$20,000,00	$30,000,000			-		
				250,980		$492,000,000				**Total Cost Phase 1**	**$755,171,400**

PHASE 2 & 3 **Capital Equipment, Iron and Steel Foundry**	**Number Required**	**Mass lbs.**	**Additional Mass**	**Total Mass lbs.**	**Purchase Cost Each**	**Total Cost**	**Power Each kWh**	**Power Total kWh**	**Transport DV Cost $930 US**	**Comments**	
Solar panels (6) on each heliostat (150/6 lbs. = 25 lbs., on 833 assemblies + heliostat)	1,000	150	15,000	165,000	$2,000	$2,000,000	1	1,000	167,400,000	Electric	6 Panels per heliostat
Robonauts	6	330	2,000	3,980	$5,000,000	$30,000,000	-0.5	-3	5,561,400		
R2 (elect.) Jeep	4	4,000	15,000	31,000	$1,000,000	$4,000,000	-6.6	-26.4	42,780,000		
Robonaut garage, charge, repair, night retreat	1	16,000		16,000	$5,000,000	$5,000,000			14,880,000		
Remote control/communications system	1	2,000		2,000	$1,000,000	$1,000,000			1,860,000		
SSP units	3	6,600		19,800	$90,000,000	$270,000,000			9,900,000	LEO	
EPS units	3	4,400		13,200	$50,000,000	$150,000,000			6,600,000	LEO	
Cryogenic propellant depot	6	13,272		79,632		$-				Transport where?	
Bigelow habitat BE330 #1 + Regolith sintering robots	1	50,000	20,000	70,000	$50,000,000	$50,000,000			83,700,000		
Mission operations	1.5				$20,000,000	$30,000,000			-		
				400,612		$542,000,000				**Total Cost Phase 2 & 3**	**$874,681,400**

Table 5. New HARMONY Revised Plan (2020), Part 2

PHASE 4 **Capital Equipment, Iron and Steel Foundry**	**Number Required**	**Mass lbs.**	**Additional Mass**	**Total Mass lbs.**	**Purchase Cost Each**	**Total Cost**	**Power Each kWh**	**Power Total kWh**	**Transport DV Cost $930 US**	**Comments**	
Solar panels (6) on each heliostat (150/6 lbs. = 25 lbs., on 833 assemblies + heliostat)	5,000	150	25,000	750,000	$2,000	$10,000,000	1	5,000	720,750,000	Electric	6 Panels per heliostat
Solar reflectors on heliostats	2,000	67	210,000	134,000	$2,000	$4,000,000	1	2,000	319,920,000	Heat	
Electric arc furnace (1 ton capacity)	1	30,000	3,000	30,000	TBD		-2,000	-2,000	30,690,000		
To produce about 1 ton of iron for casting Ingots and/or SiO2–glass						$-					
Rolling mill ingot preheat oven (sintered regolith)	1	2,000		2,000	$10,000	$10,000	-2,000	-2,000	1,860,000	Heat	
Rolling mill for long stock (modular)	1	60,000		60,000	$1,000,000		-3,500	-3,500	55,800,000		
Long stock includes angle iron, I-beams, bars, rods, and wire.						$-					
Electrical interconnects system (harnesses)	TBD	25,000									
Remote control/communications system	1	2,000		2,000	$1,000,000	$1,000,000			1,860,000		
Robonauts	2	440		880	$5,000,000	$10,000,000			818,400		
R2 (elect.) Jeep	2	4,000		8,000	$1,000,000	$2,000,000	-6.6	-13.2	7,440,000		
Robonaut garage, charge, repair, night retreat	1	16,000		16,000	$5,000,000	$5,000,000			14,880,000		
Bigelow habitat BE330 #2 + Regolith sintering robots	1	50,000	20,000	70,000	$50,000,000	$50,000,000			83,700,000		
Additional facilities on Moon	TBD										
Additional equipment on Moon	TBD										
Mission operations	1.5				$20,000,000	$30,000,000			-		
Operations costs for 1 year on Earth											
Facilities on Earth											
Satellite costs											
Supplies for personnel on Moon											
Communications architecture											
Audio visual communications systems											
										Total Cost Phase 2 & 3	**$1,349,728,400**

POST PHASE 4 Capital Equipment, Iron and Steel Foundry	**Number Required**	**Mass lbs.**	**Additional Mass lbs.**	**Total Mass lbs.**	**Purchase Cost Each**	**Total Cost**	**Power Each kWh**	**Power Total kWh**	**Transport DV Cost $930 US**	**Comments**	
Solar panels (6) on each heliostat (150/6 lbs. = 25 lbs., on 833 assemblies + heliostat)	5,000	150		750,000	$2,000	$10,000,000	1	5,000	697,500,000	Electric	6 Panels per heliostat
Solar reflectors on heliostats	2,000	67		134,000	$2,000	$4,000,000	1	2,000	124,620,000	Heat	
Electric arc furnace (1 ton capacity)	1	30,000		30,000	TBD		-2,000	-2,000	27,900,000		
Rolling mill for plate stock (modular)	1	80,000		80,000	TBD		-4,000	-4,000	74,400,000		
Plate stock is hot rolled steel plate of various thicknesses.						$-					
Rolling mill for sheet stock (modular)	1	100,000		100,000	TBD		-5,000	-5,000	93,000,000		
Sheet stock is cold rolled steel plate of various thicknesses.						$-					
Mission operations	1.5				$20,000,000	$30,000,000			-		
Electrical interconnects system (harnesses)	TBD										
Remote control/ communications system	1	2,000		2,000	$1,000,000	$1,000,000					
										Total Cost Phase 4	**$1,062,420,000**

Table 6 gives a summary of the various phases of the lunar industrial ISRU facility emplacement for iron and steel is shown below. Note that the cost for emplacement at $500/lb. to LEO is in yellow highlight. The cost at $1,000/lb. to LEO is the next line, and the last lines sets out the costs if the price drops to $300/lb. (not likely). The top line is the original HARMONY plan for comparison.

Table 6. Phases of the Lunar Industrial ISRU Facility Emplacement for Iron and Steel

HARMONY Comparison	Phase 0 $ Million	Phase 1 $ Million	Phase 2 & 3 $ Million	Phase 4 $ Million	POST Phase 4 $ Million ISRU Only	POST Phase 4+ $ Million
HARMONY Costs (2000)	$640	$3,600	$11,800	$1,650		$970,001
New Plan Costs (2024) Steel Mill @$500/lb. to LEO (1.00)	$274	$755	$1,350	$1,350	$1,062	$-
New Plan Costs (2024) Steel Mill @$1010/lb. to LEO (2.02)	$553	$1,525	$2,726	$2,726	$2,146	
New Plan Costs (2030) Steel Mill @$300/lb. to LEO (.61)	$167	$461	$823	$823	$648	

Mission operations costs are included in the cost for lunar capital equipment emplacement. However, mission operations are a part of the ongoing program and operations costs, which are estimated at approximately $20 million per year. The cost of human presence on the moon is not addressed in this exercise beyond the two Bigelow BE330 habitats. Human operations will be treated as a separate accounting and estimating process. The initial set up and operation of the facility is intended to be tele-robotic and automated to a large extent.

Using the information from the above iron/steel ISRU facility implanting, we can deduce the following:

If launch costs are $500 to LEO, then the iron/steel implantation project cost would be $3.7 billion, and the cost would be amortized in 20.0 months, after producing 1,663 tons of steel (long stock).

If launch costs are $,1000 to LEO, then the iron/steel implantation project cost would be $7.5 billion, and the cost would be amortized in 40.5 months, after producing 3,360 tons of steel (long stock).

These estimates do not include shared cost by other partners in Phases 0 and 1, which could reduce costs, or synergistic influences from other industries and activities, which could share some of the same transportation and power services

Concluding Remarks

There needs to be a strong focus on how to use the lunar ISRU resources, and a start to preparations for industrial-level production. If we do not start using these resources, our efforts to go deeper into space will not materialize very quickly, if at all. Certainly, if there is no heavy lift capability, humanity will forever be mired in the expeditionary science only mode of space operations. This is not good enough!

The optimal situation for humanity is to learn to develop and use lunar resources to maximize our potential for expansion into space. And then, other near-Earth object resources, and the asteroids. The basic and heavy (resources) industries will help to pay the way and make it possible.

Once the first industrial (ISRU) facility is operating on the Moon, others will follow. It remains to be seen which ones will be first, and how big the operations will be. There are various predictions for how the Moon will be used in the future. There are the small lunar village scenarios (for only science) like the Antarctic analogue of 150 to 1,000 people, not much ISRU, and certainly not on an industrial scale.

There is a more aggressive vision of industrial ISRU that sees thousands of humans living and working in space, with an ongoing and expanding ISRU industry that expands throughout the solar system.

And then there is the (Gerard O’Neill/Jeff Bezos) vision of millions of people working in space and no heavy industry on Earth. The NSS vision is more like the last one.

If we are to become an interplanetary species, then ISRU on a large scale is required. We will need the heavy industrial activity to support our off-Earth existence, and it in turn will help to pay the way. We must not be timid about what we are to do. We must think like Gerard O’Neill, Elon Musk, and Jeff Bezos—bigger is better.

Comments About Assumptions

In preparing this study, many assumptions were necessary, and undoubtedly further study will show change and revisions to the original worksheets and ideas. Some of these assumptions are discussed below, and they will evolve further as a balanced mix of commercial, industrial, science, and exploration partnerships is established.

IT IS PARAMOUNT that the SpaceX SS/SHB becomes a reality, and it really does reduce cost per lb. to LEO. Also, that other competitive systems are designed and implemented in an ongoing process of improvement.

ΔV to LEO was used as a basis for costing ΔV in the cis-lunar space area. This assumes the cost for ΔV is a constant in this area, which may not be true.

Refueling depots in cis-lunar space will be required. An estimate for using StarShip to go to the Moon, land, and return to Earth, will require five to six tankers, or four to five depot rendezvous.

The ability to obtain fuel from lunar pole locations (not from Earth) for depots is assumed.

For Phases 0 and 1, two StarShips to the lunar surface will be required, thus, one LEO tanker and as many as four depot visits for fuel will be necessary, one depot in lunar orbit, one at EML1, and one in LEO on return.

Multiple heavy industries will be required, in some cases, to support each other, but this paper only focuses on the effort to establish a steel industry as an example.

The technology readiness of electric arc furnaces to make steel on Earth is TRL 9, but in a vacuum environment on the lunar surface, it may not even be TRL 8, and maybe as low as TRL 6. There will be very little carbon available on the Moon to use in industrial processes.

The technology readiness of steel-making on the Moon may not be TRL 9, as it is on Earth, but it may be TRL 6 or 7 (aka the ability to meet alloy and mechanical properties similar to those obtained on Earth).

The technology readiness of tele-robotic systems to perform the required work on the Moon has not been demonstrated, although it has been demonstrated on the ISS; thus, it may be TRL 6.

The operation and support of Bigelow BE330 habitats will be auxiliary to tele-robotic operations for human visitation, it may be part of the science, exploration, commercial, and industrial consortium, and thus it may be covered under a separate budget and accounting system to be used primarily for human visitation support.

Support industries and iron/steel works will be part of a larger new HARMONY-type plan to start with initial outposts, and then to spread and grow industrial capability and to initiate larger scale settlement and life support in conjunction with lunar exploration and scientific investigations.

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Editors' Notes: This technical article by Stevan Akerley is an outstanding example of quality research and analysis for a critically important Space development study. It meets the requirements for a master's level thesis. It sets out a plausible scenario for developing the Moon and beginning to move into Space, including costings. It should provide a foundation for further development work into Space settlement. Stevan Akerley is one of KSI's first academic scholars after Florida State licensing in 2019, and he may be the first scholar to complete a KSI Certificate Program. ***Gordon Arthur and Bob Krone*.**

About the Author: Stevan Akerley is a retired aerospace engineer from Pratt & Whitney, UTC, with forty years of manufacturing and engineering experience with automated N/C equipment and measurement sensor systems in manufacturing applications. He also has experience in precision manufacturing, machine measurement, CAD/CAM software development, quality assurance, and tool and equipment design. Stevan was involved in project and program management on multiple engine programs.

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