SPACE COLONIZATION, A STUDY OF SUPPLY AND DEMAND

Dr. Dana Andrews
Seattle, WA, Seattle, WA United States, dandrews@andrews-space.com
Mr. Gordon R. Woodcock, Huntsville, AL, United States, grw@mindspring.com
Mr. Brian Bloudek, Newport Beach, CA, United States, bbloudek@steadyflux.com

Abstract

This paper steps back and looks at the fundamental economics of people working (and playing) in space, and shows scenarios that should result in successful colonies on the moon. The basic premise is the ever increasing cost of industrial metals necessary to generate renewable energy for a growing world population, and the relative abundance of those same metals on the near side of the moon. There is a crossover point, relatively soon, where it is cheaper and more environmentally friendly to mine the moon instead of the increasingly poor ores remaining on earth. At that point government and industry can form a partnership much like The Railroad Act of 1862 to incentivize construction of the transportation infrastructure and lunar mining equipment. The economics say the initial mining equipment will be tele-operated from earth, but over time the requirement for human maintenance and repair seems inescapable. We foresee a government presence on the moon almost from the start of the prospector phase to enhance safety and insure law and order, and those initial bases will eventually grow into towns and colonies.

Introduction

The definition of colony is a group of people who leave their native country to form in a new land, a settlement subject to, or connected with, the parent nation. To be successful a colony needs to be self-supporting and return the original investment to the native country or investors. Colonization got a bad reputation due to the excesses in the sixteenth and seventeenth centuries, but colonies may make a comeback in the twenty-first century for a variety of reasons. The first reason will be the pressing need for and the spiraling cost of acquiring nonrenewable resources. The world is using up the most accessible ores and petroleum, and eventually humankind will be forced to occupy and mine currently uninhabited territories like the Arctic Circle and Antarctica, as well as the deep ocean basins. As the cost of nonrenewable resources climb and the population grows, the mining equipment and drilling rigs will eventually move into these very remote areas, and since these areas are vast and very remote it makes sense that families will eventually follow. Robots will undoubtedly perform the most dangerous and least desirable jobs, but an all robot work force is still science fiction for the forseeable future. We see the colonization of Antarctica as the most likely precursor and analogy to colonization of the moon as the need for resources intensifies. We will examine the economics of this process to predict when and how lunar colonization might occur in sections 6 - 9.

A primary reason for the future tremendous pressure on metals is the need to replace petroleum and coal as a primary energy sources worldwide. We are at or very near peak petroleum production worldwide (Hubbert's Peak)[1], and moving into the second phase of petroleum production where oil sands and oil shale become significant contributors to the oil market. Efforts to replace expensive oil for transportation focus on increased efficiency and use of plug-in hybrid electric cars. Current technology for plug-ins is based on the lithium-ion battery and a high efficiency electric motor, and the demand for lithium, heavy metals and other rare elements (such as neodymium, boron and cobalt) required for the batteries and power-train is expected to grow significantly in the mid and long term. The increasing need for energy versus the dwindling supply of metals creates the opportunity to mine the moon. How metals prices will rise in the future is discussed in Section 1.

The key to resources from space is getting the cost per kilogram to orbit under $500 and that requires a Fully Reusable Earth to Orbit System (FRETOS), a topic we will cover in section 2.

1. Role of Metals in Meeting the Energy Crisis

The earth is vast enough that we will never run out of nonrenewable resources, but we will use up all the readily available resources to where it is uneconomical to mine or extract the fraction that remains. Figure 1 shows that the average grade of copper ore (in % copper) mined worldwide over time. The current average is well below 0.6% and right now it is uneconomical to process copper ore below 0.45%. Permanent scarcity due to mining economics is rapidly approaching for a number of commonly used metals (see figure 2 for predicted supply in years). Shortages of key industrial metals like tin, zinc, and lead in less than twenty years shows the magnitude of the problem.

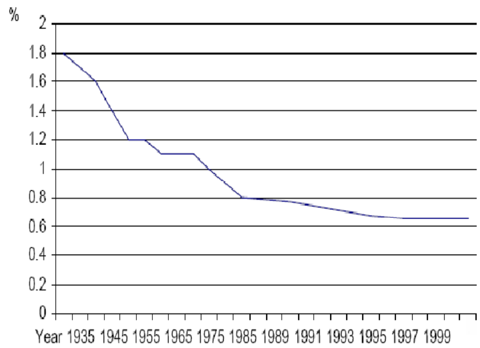

Figure 1 – Copper Ore Grade over Time

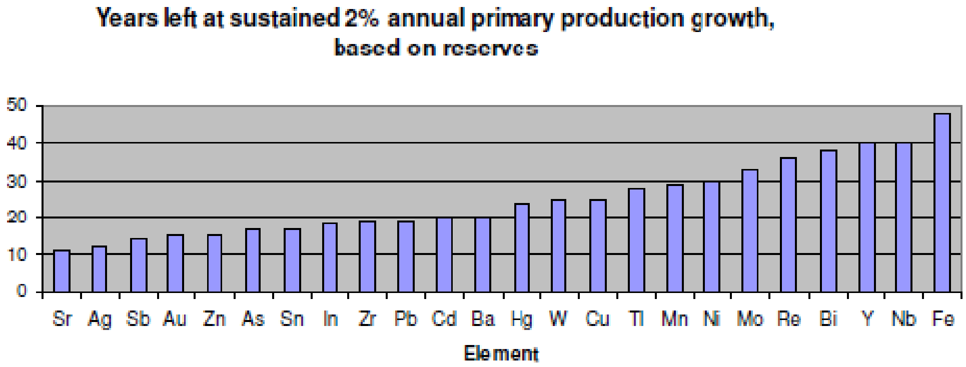

Figure 2 – Years Remaining until Depletion of Reserves of Basic Elements at 2% Annual Growth

The problem is as the grade of the ore decreases, it requires more energy to process each ton of ore and more volume to dispose of the tailings. Therefore, the planet is approaching a catch 22 situation, where we are running out of both readily available nonrenewable metals and readily available non-energy resources. This means the critical metals we need to efficiently convert to renewable energy sources are increasing expensive because of scarcity; and eventually this will become worse until we will lack the energy to mine the remaining low-grade supplies. An example is platinum, shown in figure 3. Platinum is a key industrial metal needed to support increased world GDP. The price of platinum was increasing slowly for many years and then increased by a linearly by a factor of five in the last ten years. Obviously, demand is outstripping supply, despite the increases in productivity brought on through automation. Unless new supplies are found we expect the price of most "energy metals" like platinum to continue to increase at current rates.

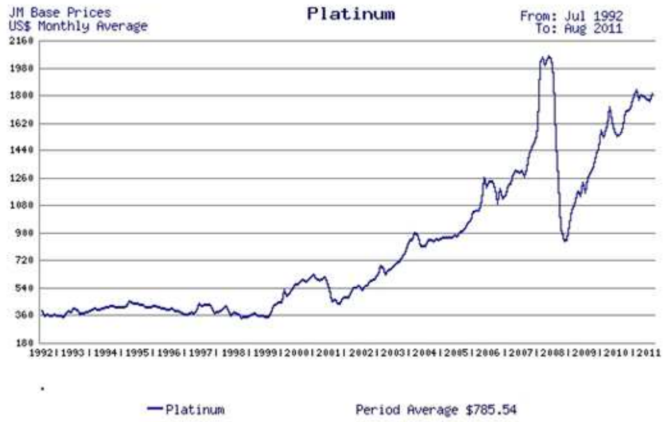

Figure 3 – Platinum Metal Spot Prices over 20 years

At current rates of price growth, platinum should cost $252,300/kg by 2035 when lunar mining matures.

2. How to Gain Cheap Access to Space

Cheap access to space requires airline-like operations of the Earth-to-Orbit launch system (Airport-to-Orbit essentially). A fully reusable launch system can reduce mission costs to the cost of propellants, refurbishment, flight operations, insurance, and amortization of the recurring and non-recurring development costs. A horizontal-takeoff TSTO with two 24 hour turnaround orbiters and one airbreather first stage can support roughly 360 missions per year (five days off for major servicing and severe weather), and this corresponds to a cost/mission of roughly $2.5 M or $250/kg (2010$). The transportation cost details are covered in a companion paper, IAC-11.D3.2.7, titled "Use of Space Resources on Earth, Fact or Fiction?" The key to achieving these low launch costs is a very low refurbishment cost between flights[2], and we expect to achieve 2.5% of first unit costs for refurbishment costs based on a novel approach.

To enable a FRETOS with existing technologies we propose using a hanging momentum-exchange tether to relax the mass fraction and the reentry heating requirements. See figure 4. The benefit comes from allowing the launcher to transfer the payload to the tether payload capture device while the launcher is suborbital (300 km by -1800 km orbit). The total ideal velocity for a rocket-powered suborbiter launched from subsonic aircraft to the tether is 7,141 m/sec. (The same system launching to a 300 km by 300 km orbit requires 8,733 m/sec). By the Rocket Equation, the mass inserted into the rendezvous orbit (226.8 mT mass is dropped from aircraft) is

45.4 mT for the suborbiter and 31.7 mT for the orbiter to a 300 km circular orbit. This 43.25% increase in inserted mass means more payload and reusable features on the suborbiter. The other advantage is reentry speeds. An orbiter returning from a 300 km orbit starts reentry at 7.604 km/sec, while our suborbiter starts reentry at 6.064 km/sec relative to rotating atmosphere. Peak heating is relative $(\rho/\sigma)^{\wedge 0.5} * V^{\wedge 3}$, after Eggers[3], where ρ is air density, σ is the nose radius of the sub/orbiter, and V is the relative velocity. When we simulated the two different reentries, we got a few surprises. The suborbital reentry dives deep into the atmosphere, resulting in short bounces at high normal gees (~ 8 gravities, but vehicle is unmanned) with short bursts of high peak heating (the high densities during each bounce is overwhelming the reduced velocities). As a result, the relative peak heating for the suborbiter is actually 174% of the orbiter, but the total integrated heating for the suborbiter is only 11% of that for the orbiter. This allows the suborbiter to be built using Hastaloy foil over titanium structure, which is a very low maintenance approach. This technology was rejected for the space shuttle, and the very high maintenance of the shuttle tiles is probably the main reason it never became operational.

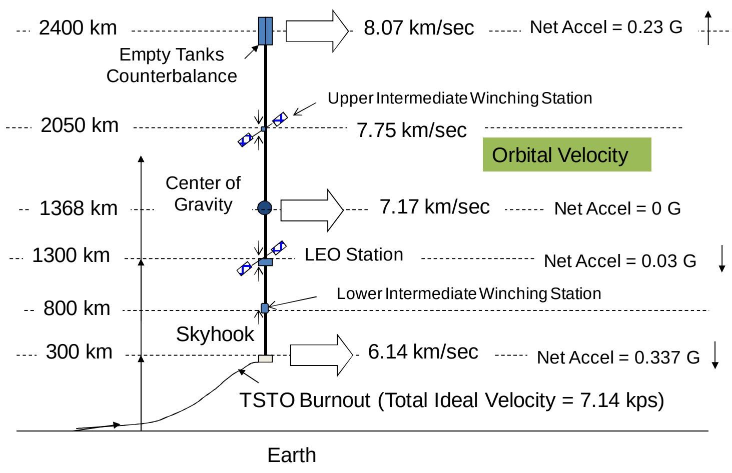

Figure 4. Tether Upper Stage w/ Space Operations Center

3. Tether Upper Stage (TUS) and Space Operations Center (SOC)

The TUS and SOC are keys to reducing the costs of mining the moon and eventual colonization. The TUS captures payloads suborbital and transfers them up to a stable orbit between 1300 and 1400 km altitude. It does this by adding energy and momentum through solar panels and advanced electric thrusters. The SOC combined with the LEO Station maintains crew quarters, tourists, and permanent residents in relative comfort and handles the large volume of cargo outbound. Freight and human cargo is captured at the bottom of the tether and moved rapidly up to the SOC by winching up the tether with the cargo. The initial TUS system masses 220 mT of which 105 mT is the actual tether made from Dyneema SK-75, an existing fiber.

We are proposing that there are four TUS and SOC combinations in LEO to support the lunar mining effort. They are roughly 90 degrees apart and operate semi-autonomously, serviced by myriad different airports around the world (any major airport with cryogenic storage capability could qualify). Each suborbiter lands approximately 90 degrees east of where it took off, so orbiters are constantly moving east, and the 24 hour-turnaround means they return to their starting point roughly every four days.

4. Reusable Solar Electric Tugs (ReSETs)

Human reentry modules are stored at the SOC and cargo modules are assembled for transfer to the Reusable Solar Electric Tugs (ReSETs) that ply spiral orbits from the SOC to the Transfer Station (TS) circling the near Earth-Moon Lagrange Point (L1) and back. The 400 kWe ReSETs are designed to use a wide range of propellants from Xenon and Argon launched from earth, to process gas generated by partial oxidation of waste from the SOC.

Two ReSETs can transfer a Heavy Lunar Lander with propellants and the full 60 mT mining base to L1 in just over 300 days, and be back at the SOC in less than 50 days. Each of the ReSETs carries a cryogenic refrigerator to prevent boiloff of lander LOX-hydrogen propellants during the long trip. The ReSET uses state-of-the-art solar cell technologies, existing structural materials, and advanced electric thrusters now in test.

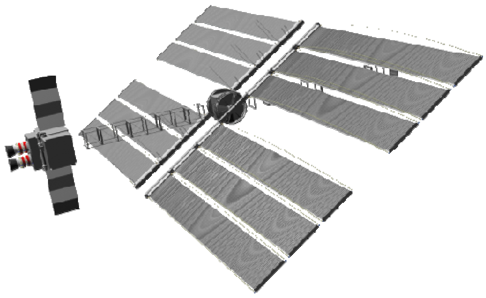

Figure 5 ReSET Configuration

5. Lunar Lander

Our lunar Lander was designed to meet two criteria. First, the least reliable event for any lunar landing mission is the actual touchdown (it makes up 25% of the total risk)[4]. Hence, the most reliable approach is to land only once for each mission and to use a lander with engine-out capability (loss of engine is the second biggest risk). Hence, the Lander has five RL-10 derivative engines, masses 140 mT when it leaves the L1 Transfer Station (L1TS), and lands just over 60 mT of payload anywhere on the lunar surface. The heavy lunar configuration is shown in figure 6. The lunar Lander and all payloads are 5 m or less in diameter to fit inside the FRETOS shroud. The Lander uses existing technologies throughout.

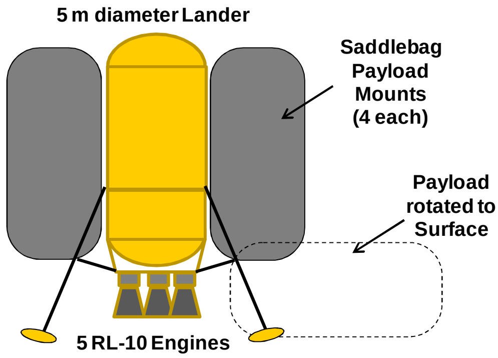

Figure 6. Heavy Lunar Lander Configuration

6. Lunar Mining

The lunar surface has been sampled at sparse locations, but we really don't know what lies under most of the regolith. Lunar surface prospector rovers are absolutely required before any organization would seriously plan mining the moon. But, based on existing data, we can assume we will be going after Platinum Group Metals (PGMs) and Rare Earth Elements (REEs) both found in abundance on the near side of the moon. About two-thirds of all known meteorites contain iron-nickel (FeNi) metal. "Iron-nickel" means that the metal is mostly iron but it contains 5-30% nickel, as well as a few tenths of one percent cobalt, plus high concentrations (by terrestrial standards) of strategic metals such as the platinum group, gold, gallium, germanium**,** iridium, and others. Interestingly enough, the lower the Fe-Ni metal content in the meteorite, the *more* enriched the Fe-Ni metal is in these rare and precious metals and elements. These elements readily dissolve into the metal that exists, and the less metal that exists, the less diluted they are. Many asteroids are richer in most of these precious metals than the richest Earth ores which we mine. Further, these metals all occur in one ore when it comes to asteroids, not in separate ores. Many of the richest ore bodies on earth are meteorite impact craters from geological times. In particular, the impact crater at Sudbury, Ontario, is rich in iron, nickel, cobalt, copper and platinum group metals. Are similar metals present in impact craters on the Moon? Geologists at Sudbury say that the valuable metals at Sudbury did not come from the impactor, but welled up from deep within the Earth. If this is so, why don't more volcanic upwellings contain rich ores of nickel, cobalt, copper and PGMs? Until we go to the Moon and study more impact craters to determine whether or not they are rich in these metals we cannot be certain. Particles of Fe-Ni metal make about 0.5% of the regolith and can be magnetically separated, but copper is present only in traces in the regolith. There is a huge nickel-iron impact zone on the near-side of the moon (figure 7.)

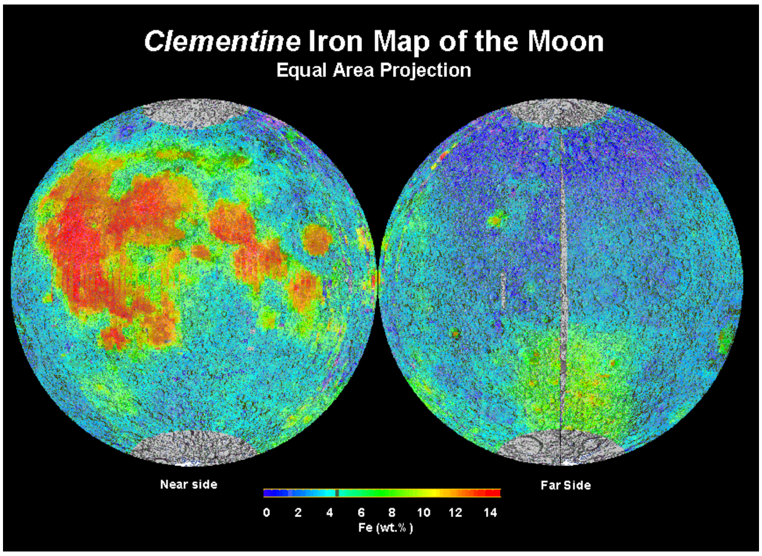

Figure 7. Percent Iron in the Lunar Regolith

The other product of interest is KREEP[5] (a combination of Potassium Rare Earth Elements, and Phosphorus) generated during the formation of the moon and concentrated where the last magma froze. Uranium and thorium are good indicators for KREEP (they kept the magma hot near the end) and figure 8 shows the concentration of Thorium in the regolith based on Lunar Prospector data.

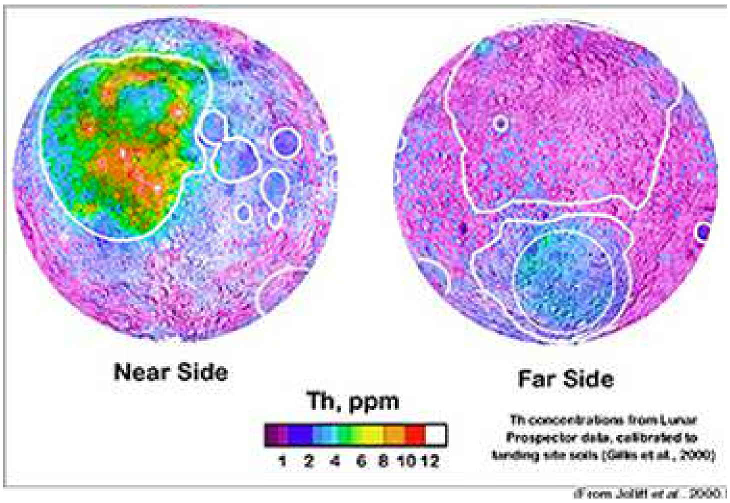

Figure 8 Thorium Concentration (indicator for KREEP)

The details of lunar mining were covered in previous papers[6-7], and will only be summarized here. The nickel-iron particles are separated from the bulk regolith magnetically, and then the iron, nickel, and cobalt are gasified using hot carbon-monoxide (the carbonyl process) leaving the elements not dissolved by carbon monoxide behind, Hopefully, this will be mostly PGMs and rare earths left behind as powders. The 99.8% pure cobalt, nickel, and iron are recovered separately as powders or ingots by selective absorption during regeneration of the carbon-monoxide.

7. Metals Delivery to Earth

The enriched rare metals will be sent to earth using high technology slings. Modern high strength fibers can sustain the loads to whirl a 180 kg nickel-iron balloon at 3050 m/sec using a 200 m radius sling. The balloon is weighted with rare metals foam for rigidity and to maintain a predetermined center of gravity for earth entry. The balloons contain a thick central disk the diameter of the balloon that contains cast pressure bottles and distributes the rotation loads. On each side of the disk, foil hemispheres of nickel are welded on. The hemispheres are made by spraying molten nickel into a hemispherical mold using plasma/powder metallurgy. The forward section of the disk is filled with foamed rare metals for structural support and placement of the center of gravity. The cast pressure bottles are welded together, and pressurized to high pressure with nitrogen gas propellant. The entire balloon is pressurized to approximately one atmosphere with nitrogen to maintain stiffness for Earth entry. The front half of the sphere is covered with sintered regolith ablator and back half of the central disk has redundant recoverable control packages embedded in it. Each control package has a deployable antenna, solar cells plus battery, small GN&C, and a steerable nozzle for cold gas rocket RCS and OMS. The mass of each control package is 3 kg and the propellant gas is 24 kg. The control packages can vent gas from the balloon during aerodynamic heating and refill the balloon from the bottles as the balloon cools off after entry.

A 200 m radius sling shown in figure 9 will generate 4750 gees at the payload just prior to release. A 750 kg counterweight of lunar-produced iron is carried on the counter arm and is captured in an impact pit (the counterweight is traveling at 740 m/sec and gets reshaped each launch. Spinning up the sling requires 3600 kW-hrs of power of which about 2400 kW-hrs is recoverable with 80% efficient combination motor generators and flywheels. Assuming quad-redundant 200 kWe motors, it will take 4.5 hours to load, spin up and release, and three hours to slow down and stop while recovering the energy. During the 4.5 hours spin up, a 300 kWe array could make up the energy shortfall. At a rate of one launch every 8 hours during daylight, a single sling delivers ninety tons of useful metal every year. Assuming 10 tons is the powder containing ~ 75% PGM and rare earth metals, and the 65 tons is mostly nickel with some cobalt (~ 500 kg), the current value per year per mine is about $250M for the PGM, $45,000 for REE, $1.4M for the nickel, and $25,000 for the cobalt. These numbers will mostly likely be factors higher in twenty years. The hub with motors, arms,

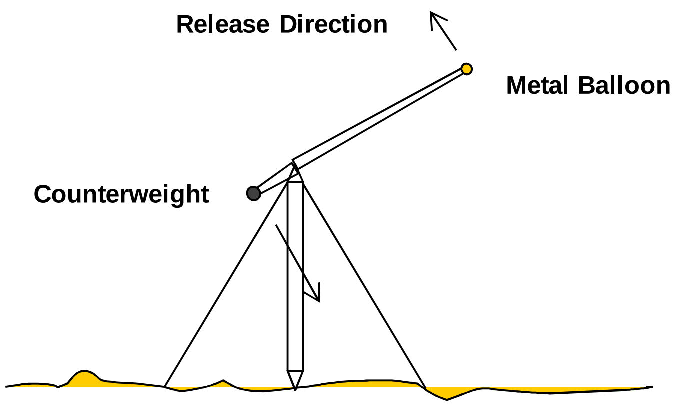

Figure 9. Lunar Sling launching from 35 deg latitude)

flywheels, and power control units masses about ten tons and would be delivered in one piece. The tower, the base, and the guy wires would be lunar manufacture.

The concept of operations (CONOPS) is to launch the balloon spacecraft into an earth intercept trajectory and then fine tune the trajectory as it flies by the L1 transfer station, so that the balloon enters into restricted regions of the Pacific and Indian Oceans. With a ballistic coefficient of 20 kg/m^2 (4 m diameter) the balloons should survive earth entry and be salvageable after a splashdown at 22 m/sec (the foil hemisphere entry body halves will probably tear away on impact, but the built-in flotation foam will keep the core disk floating).

8. Lunar Mining Development Costs

The entire mining project costs were estimated using existing data[8-11] and cost estimating tools[12]. These costs are summarized in Table 1 below.

Table 1. Summary Cost Estimates for Twenty-Year Lunar Mining Scenario

Years After Go-Ahead	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	LCC, $M
Tether DDT&E, $M	20	50	80	80	30																260
Space Business Park DDT&E, $M	30	60	120	120	50																380
Tether & Space Business Park Recurring, $M				20	60	100	100	80	80	60	40	40	40	40	40	40	40	40	40	40	900
Tether & Business Park ELV Launch Costs, $M					125	250	125	125	125	125	125										1000
FRETOS DDT&E, $M	140	450	615	645	560	390															2800
Number of FRETOS Launches							30	100	250	500	750	1000	1000	1000	1000	1000	1000	1000	1000	1000	10630
FRETOS delivered/ year								1	1	2	3	4	4	4	4	4	4	4	4	4	43
FRETOS Recurring Costs, $M								150	135	256	360	468	452	448	440	428	420	416	408	400	4781
FRETOS Launch Costs, $M							128.4	283	612.5	1225	1838	2450	2450	2450	2450	2450	2450	2450	2450	2450	26136
ReSET DDT&E Costs, $M			50	100	300	300	100														850
ReSET Flights/year							2	8	20	40	60	80	80	80	80	80	80	80	80	80	850
ReSET delivered/year							2	6	12	20	20	20	4	4	4	4	4	4	4	4	112
ReSET Recurring Costs, $M							700	1344	1596	2100	1890	1680	322	319.2	317.8	316.4	315	313.6	312.2	310.8	11837
Lunar Lander DDT&E, $M			200	600	1200	1000	500	250													3750
Landers Delivered per Year							1	4	10	20	30	40	40	40	40	40	40	40	40	40	425
Lunar Lander Recurring Costs, $M							125	310	600	800	1050	1250	1050	950	875	850	825	800	775	750	11010
Mining Equipment DDT&E, $M		80	150	400	1100	600	200														2530
Mining Equipment Recurring Costs, $M							100	320	640	1024	1229	800	740	688	672	652	628	608	600	592	9292.8
Operations Cost, MY/yr	5	10	15	20	25	30	50	80	150	300	400	500	600	700	800	900	1000	1100	1200	1300	9185
Operations Cost, $M	1.3	2.5	3.75	5	6.25	7.5	12.5	20	37.5	75	100	125	150	175	200	225	250	275	300	325	2296.3
Lunar Built Fraction							0	0	0.1	0.15	0.2	0.2	0.25	0.3	0.33	0.35	0.38	0.4	0.45	0.5	3.61
Average Working Mines each year							1	5	16	38	71	113	155	197	238.2	279	320.2	361	403	445	2642.4
Product back to Earth, mT/year							10	51	156	371	706	1171	1676	2221	2806	3431	4096	4801	5546	6331	33373
Yearly Totals, 2010$M	191.3	643	1219	1970	3431	2648	2091	2882	3826	5665	6631	6813	5204	5070	4995	4961	4928	4903	4885	4868	77824

These numbers reflect the outputs from various models and no overhead or management factors have been applied (20% would be typical). After application of 20 % management factor, the total mining scenario costs about $100 B in 2010$. This is lot of money, but the return on investment could be lucrative.

Based on our model, in the twentieth year there were 2642.4-445 ~ 2200 working mine-years during the program (no products delivered during first year of operation for each mine), and if the average iron-nickel contained 200 pm PGM, during this period roughly 22,000 mT of combined PGMs plus additional rare earth elements were delivered to earth. Current platinum production is roughly 500 mT worldwide so lunar mining increases the amount of platinum available to 1500 mT/year. Assuming demand remains high and the current prices hold ($50M/mT), this is roughly $1.1T return on investment. A 1100% return on investment is certainly of interest.

9. Project Development Plan

A successful lunar mining program requires the cost of the product delivered to the processors on Earth be cost competitive with the same product mined on Earth and delivered to the same processors. Since the cost of developing and delivering the transportation system and mining equipment must be part of the return on investment equation, several assumptions were mandatory.

First, a national or international organization must sponsor the project by passing the lunar equivalent of the U.S. 1862 Railway Act where the United States Congress awarded 6,200 acres of land and guaranteed loans of between $16,000 and $48,000 for every mile of track that was laid to the U. S. West Coast. This spurred the development of the western United States.

For a future lunar mining project, the guaranteed loans means low interest rates, and the award of lunar land means the investors own the property they are developing and provides additional collateral for development loans. Instead of loans for every mile, the loans could be for launching of the TUS and SOC, first flight of the FRETOS, delivery of the L1TS by ReSET, and first heavy lunar payload delivery. There could be an issue with the Outer Space Treaty, which states the moon belongs to all world inhabitants. If legal issues arise despite an international effort, then the nation participants could formally withdraw from the treaty (requires a year wait to withdraw). Space enthusiasts would like to forego government involvement, but for a project of this magnitude, investors will demand their investments be protected by government oversight. Besides the moon would be an absolutely lawless arena. The natural habitat for government is to provide law and order in such venues.

Second, the development needs to be privately led to have any chance of being profitable. Government bureaucrats have repeatedly demonstrated their inability to meet cost and schedule goals. The government's job here is set legal precedence, protect the interests of the investors, and guarantee loans when real progress is demonstrated.

10. Colonization

The proposed program doesn't specifically plan for colonization, but provisions for people living at the SOC were included in the masses, and the lunar mining project only booked 2/3 of the available launch slots, because a large tourist industry was assumed. An entire lunar base could easily be included as payload on one heavy Lander mission. There will come a time when enough tele-robotically operated hardware is on moon, that it makes sense to include a human trouble-shooter. It also makes sense to include a government lunar base even sooner, to make sure the tele-robots are not poaching ore or equipment (remember the Western Army Forts were needed to keep order). There are several actions that could be taken to reduce the cost of delivering humans to the moon. The heavy Lander can easily be modified to be a reusable Trans-Lunar Injection (TLI) stage for a lunar excursion module, for instance. Therefore, we are fairly confident that at the conclusion of the 20 year program proposed here, there will not only be a small colony on the moon, but probably a hotel or two.

11. Summary & Conclusions

The key to success for any economic scenario (plan) is correctly predicting supply and demand versus various pricing points. We based our supply and demand analyses on dozens of previous publications and surveys as well as extensive personal experience. The precursor to this paper, presented last year, examined bringing critical metals back to earth from the moon as the economic driver for developing low cost access to space. The economic scenarios evaluated include commercial development of lunar resources through platinum group metals, energy metals (uranium and thorium), and rare earth metals vital for future advanced technologies.
The basic scenario still holds, provided adequate resources exist on the moon. We will not know the extent of lunar resources until lunar rover prospectors are landed, but current data and current results are intriguing and a lunar colony is a definite possibility.
In the mean time, we should be developing the key technologies for lunar mining and doing everything we can to stretch current existing resources of "energy metals". That includes serious recycling programs (Current estimates are that 26% of extractable copper and 19% of extractable zinc is now lost in non-recycled waste), as well as strategic substitution programs to replace metals we know are going to be scarce in the near future. This is happening real time in the electric car industry.

Our future has seldom been so uncertain, and cooperation so important, as in the current era.

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