Making it on the Moon:
Bootstrapping Lunar Industry

by Dave Dietzler

Abstract: The cost of rocketing cargo into space is very high. Great savings can result if local resources like oxygen and materials from lunar regolith are used to build and expand Moon bases and create industrial settlements to supply materials for solar power satellites and space settlements, tourism, planetary defense, asteroid mining and research stations. This paper attempts to illustrate the components of a lunar "industrial seed" consisting of equipment needed to produce materials on the Moon and establish a growing industrial presence there that leads to space settlement. The first section discusses some of the issues surrounding transportation to the Moon and the second section quickly examines materials production, manufacturing and construction. Space settlers and industrialists must get an idea of how much propellant and cargo must be launched from Earth and plan out the actual cargoes to determine the size of capital outlay for a Moon mining project.

Section 1. Getting to the Moon

1. Introduction

At a 1975 Princeton conference for manufacturing facilities in space, three estimates were made for the mass of cargo that must be lifted to the lunar surface to establish a lunar mining base that could support a space settlement effort. A low estimate of 3,000 tons, an intermediate estimate of 10,500 tons and a high estimate of 20,000 tons were given [1]. The Princeton conference looked at the use of the Space Shuttle, a Shuttle derived HLV, and a chemically propelled tug for transfer of payloads from low Earth orbit to lunar orbit. In 1977, David R. Criswell described an initial lunar supply base amassing 800 tons, with 250 tons devoted to a lunar mass driver. The base would expand by using products made from mass driver launched regolith at a space manufacturing facility that also built large habitat and solar power satellites [2]. In 1981, NASA's Advanced Automation for Space Missions study focused on a 100 ton mass of self replicating robotic equipment [3]. The robotic manufacturing facility would replicate itself using lunar resources and eventually construct a lunar base and more.

There is quite a disparity in these numbers. These studies relied on use of the Space Shuttle. At the present time, it would seem that a Moon mining and space manufacturing effort aimed at the creation of solar power satellites and eventually space settlements could be achieved with Falcon Heavy rockets that are projected to put 54.4 metric tons of payload in low Earth orbit (LEO) for $90 million [4]. To minimize costs, lunar resources would be used to provide propellant for landing the bulk of the cargo, and lunar resources would be used to build up the surface base and facilities in outer space. It would seem safe to *speculate* that the mass of equipment needed to initiate a lunar base staffed by humans and robots would be around one thousand metric tons. This facility would use lunar resources to "bootstrap" up a larger base with several distant outposts that includes one or more mass drivers, solar power plants, digging machines, habitat with closed ecological life support systems, exploration vehicles and more to supply hundreds of thousands of tons of material every year to a solar power satellite construction facility at L5 or L4. The space construction facility would be built up largely with parts made on the Moon and it would use teleoperated robots rather than humans for the most part.

2. Transportation to the Moon

Affordable access to low Earth orbit (LEO) and beyond is needed. This will require reusable or partially reusable rockets (perhaps Falcon Heavy rockets), a space station/ propellant depot in LEO, and a station/depot at Earth-Moon Lagrange point one (EML1). Cargo tugs with low thrust electric drives that take months to reach the Moon but use very little propellant must be developed. Manned vessels with high thrust chemical rockets to dart through the Van Allen Belts and chemical rockets for landers that descend from L1 or LLO (low lunar orbit) to the lunar surface must also be built. There must be tracking stations on Earth and possibly navigation satellites in orbit around the Moon. Development of this inter-lunar transportation infrastructure alone will cost billions of dollars. Optimistically, this expenditure will lead to the development of space industry and trillion dollar markets. The cost of transportation to the Moon in the future might be a small fraction of what it is today, yet it will still be expensive. This demands the use of lunar resources for development on the Moon and in outer space.

Reusable solar electric tugs for transport of cargoes from LEO to low lunar orbit (LLO) will be essential. A high thrust rocket needs a velocity change (ΔV) of about 4 km/sec to go from LEO to LLO. For low thrust solar electric spacecraft a ΔV of about 8 km/sec is required [5]. Propellant requirements for electric propulsion with a specific impulse of 3000 to 3500 seconds are only about a fifth as much compared to LH2/LOX propulsion at 450 seconds as determined by using the ideal rocket equation. This seems like a tremendous advantage that can reduce both required payloads to LEO and launch costs. The trade-off is that electric propulsion takes a lot of time and solar panels will be degraded by passage through the Van Allen Belts.

Propellant depots in LEO and at L1 will store water that will be converted to LH2 and LOX when needed by manned spacecraft. Water is much denser than cryogens and doesn't necessitate heavy insulated tanks and boil-off reliquefication machines, so it is “easy” to store and transport in outer space. Converting water to LH2 and LOX will require plenty of power from solar panels to break the water down into hydrogen and oxygen by electrolysis. Cooling the gases to liquids might be accomplished with space radiators exposed only to the super-cold of outer space. Even so, the depots will consist of complex systems of pumps, compressors, piping, radiators, solar shields, electrolysis cells, solar panels, tanks and fuel cells. If rockets run a hydrogen-rich fuel to oxidizer ratio of 1:6 as did the Space Shuttle, more hydrogen than is present in water will be required. Tanks of hydrazine (N2H4) or liquid ammonia (NH3) could be shipped to the LEO and L1 depots where they are decomposed with solar heat and catalysts to get more hydrogen for the rockets and nitrogen that will be used later for life support systems on the Moon and in orbital stations. Hydrazine is liquid at “room temperature” and so is ammonia if it is stored under pressure; therefore, these make excellent hydrogen carriers. Water could also be cracked to hydrogen and oxygen and a 1:6 propellant mixture could be made with excess oxygen that is stored for other purposes.

Cargoes propelled by solar electric tugs would bypass L1 and go to LLO with enough liquid hydrogen for landing. They would pick up loads of lunar LOX also called LUNOX. Reusable landers would ferry cargoes down to the lunar surface. This will greatly reduce the amount of payload that has to be rocketed to LEO and beyond. Significant savings can be had if landers are not disposed of after one landing. Reusing landers and refueling them on the lunar surface with liquid oxygen is a more economical option.

3. Producing LUNOX

Liquid hydrogen for landers would come from Earth. Producing large amounts of hydrogen on the lunar surface will probably not be possible at early stages of lunar base development. Harvesting solar wind implanted hydrogen would involve mining and processing millions of tons of regolith. Mining for polar ices would require exotic mining machines that can work in super-cold craters powered with microwave beams from stations on crater rims. Polar highland terrain is rugged and sunlight is nearly horizontal making it difficult to capture solar energy. An initial lunar base could be sited in a polar location but it seems that ice mining will not occur immediately.

Oxygen could be produced more easily at any location by magma electrolysis of unbeneficiated regolith or by pyrolysis of regolith in solar furnaces or induction furnaces. Once an industrial settlement is built, mining vehicles can travel to other locations where basalt, pyroclastic glass, ilmenite, KREEP and other resources are available. Lunar regolith is about 40% oxygen by mass. In 1993, NASA and the JSC proposed a lunar oxygen plant and manned outpost on the Moon [6].

LIGHT	**ITEM**	**MASS (KG)**
1	LUNOX PLANT	7269
1	NUCLEAR REACTOR (40-60KWe)	5110
2	TANKER #1	1471
2	TANKER #2	1471
2	LOADER #1	1728
2	LOADER #2	1728
2	HAULER #1	962
2	HAULER #2	962
3	PRESSURIZED ROVER #1	5150
4	PRESSURIZED ROVER #2	5150
3	MOBILE POWER UNIT #1	1544
4	MOBILE POWER UNIT #2	1544
3, 4	SCIENCE PAYLOAD	2000
5	AIRLOCK/NODE SUPPORT VEHICLE	11010
6	LOGISTICS & SPARES	12454
	TOTAL:	**59553**

TABLE 2 — Lunar Outpost Elements

Without logistics and spares, airlock/node support vehicle, science payload and two pressurized rovers, the mass of the LUNOX plant, nuclear reactor, tankers, loaders, and haulers is 23,789 kg. One Falcon Heavy launch could put a combination lunar oxygen plant/lander amassing 37.86 tons with 16.54 tons of LH2 and LOX for landing the plant on the Moon in LEO. Given the mass of the LUNOX plant and attending machinery in the 1993 NASA/JSC study it seems this would be feasible. The plant would be propelled to LLO with a solar electric tug. It would be constructed of lightweight high strength carbon composites, plastics and alloys of aluminum and titanium. Fuel and oxidizer tanks for descent propellant could be used to store LOX once the plant was in place. A fuel cell power storage system could be included that uses the same cryogen storage tanks, pumps and refrigeration devices used for lander propellants. Water from fuel cells will be subjected to electrolysis and the resultant hydrogen and oxygen will be liquefied. Small teleoperated rovers amassing one to two metric tons each could mine up regolith and feed it to the oxygen generating plant. High efficiency gallium based multi-junction concentrator solar panels instead of a nuclear powerplant could power it.

4. Baseline: Expendable Landers

Before examining reusable landers that derive part of their propellant from the Moon it is necessary to look at the simple straightforward use of one-way expendable landers for comparison. The added cost and complications of lunar LOX production for reusable landers must be weighed against the direct strategy of using one-way landing rockets fully fueled in Earth orbit then sent to LLO.

Solar electric tugs orbited beforehand could move payloads from LEO to temporary low lunar orbit (LLO). Landing the loads would require a delta velocity of 1600 meters per second. With hydrogen/oxygen propulsion and a specific impulse of 450 seconds, it is found by using the rocket equation that a mass ratio of 1.437 is required.

Rocket	Stage	Fuel Type	Fuel Kg	Dry Kg	Dry/Fuel
Delta-IV	1	LOX/LH2	200000	18030	9.02%
Delta-IV	2 - 4mf	LOX/LH2	20412	2718	13.32%
Titan-IVB	Centaur	LOX/LH2	20950	2930	13.99%
Ariane 5	1	LOX/LH2	155000	15000	9.68%

Based on hydrogen/oxygen rocket stages that have actually flown, it seems tanks and rocket motors can be estimated to amass about 10% to 15% of propellant mass [7]. Since landers need frames and legs that can support a sizable cargo module it would seem safe to estimate that a lander itself would amass about 20% of propellant mass.

Mass of propellant and mass of lander for a 54.4 ton cargo can be found by:

$$(54.4 + P + 0.2P)/(54.4 + 0.2P) = 1.437$$

$$P = 26 \qquad 0.2P = 5.2$$

A propellant mass of 26 tons and a lander mass of 5.2 tons are required. The lander seems very light but it will work only in the low gravity of the Moon and it can consist of carbon composites and high strength lightweight aluminum and titanium alloys. About nineteen Falcon Heavy launches would be needed to place a little more than 1000 metric tons of cargo in LEO. Nineteen landers will amass 98.8 tons and require two more launches. Propellant mass will be 494 tons and this will demand nine more Falcon Heavy launches not considering the mass of the well-insulated solar-shielded LH2 and LOX tanks. In reality about eleven more launches for a total of 32 at a cost of $2.88 billion will be required. All 19 landers would be dismantled and their component materials used for manufacturing and construction on the Moon. Solar electric tugs would have to move a total of about 1,700 tons of payload, depending on the mass of the propellant tanks, consisting of "bootstrapping" equipment, landers and tanks of propellant from LEO to LLO.

5. Reusable Landers and Lunar Liquid Oxygen

The mathematics for determining the parameters for landers that use lunar liquid oxygen are not complicated but they are tedious, potentially confusing and require numerous iterations. It can be seen that at higher delta velocities the lander mass and residual LH2 mass for ascent become so large that using LOX derived from another celestial body with imported LH2 is not very helpful and it even becomes impossible. This technique would probably not be effective on Mercury or a Galilean moon. Fortunately, Mars and Titan have atmospheres that allow aerobraking, parachuting and the use of small amounts of retro-rocket propellant. The computational procedure follows:

1) "package" mass = payload + residual LH2 for return ascent + lander mass

2) lander mass L initially acquired by iteration = 20% of maximum propellant load

3) (package mass X MR) minus package mass = propellant mass for descent

4) 6/7 of propellant mass = LOX mass for descent.....LOXd

5) 1/7 of propellant mass = LH2 mass for descent.....LH2d

6) {(L + LOXd) x MR} minus (L + LOXd) = propellant mass for ascent

7) 6/7 of ascent propellant = LOX for ascent.....LOXa

8) 1/7 of ascent propellant = LH2 for ascent.....LH2a

9) LH2d + LH2a = total LH2 taken on in LLO

10) Package mass minus LH2a minus L = actual payload mass

11) LOXd + LOXa + LH2a = Pmax Propellant load maximum

12) 0.2(Pmax) = L

Reusable landers that shuttle payloads from LLO to the lunar surface fueled by hydrogen from Earth and LOX produced on the Moon would demand more tankage to contain larger amounts of propellant than needed with expendable landers. They would land on the Moon with enough hydrogen remaining for ascent to LLO and take on enough LOX for ascent and subsequent descent. With a ten ton "package" consisting of cargo, residual LH2 for return to LLO and lander, descent would demand 4.37 tons of propellant given a mass ratio of 1.437 for a 1600 m/s maneuver. Of this, 3746 kg would be LOX and 624 kg would be LH2 when using a 6:1 oxidizer to fuel ratio. This much liquid oxygen must be shuttled to LLO and the lander must be large enough to hold the LOX needed for ascent as well. Estimating a lander mass of 1.2 tons determined by repeated iteration requires that the initial mass of the package on the lunar surface, when loaded with propellant but without cargo except for return descent LOX, is 7.107 tons. This is found simply by multiplying the combined mass of lander and return descent LOX by a mass ratio of 1.437 for the 1600 m/s flight to LLO with 450 second LH2/LOX rocket engines. (1.2+3.746) X 1.437 = 7.107. Only 2.16 tons of this must be hydrogen and oxygen propellant for ascent. {(1.2+3.746) x 1.437}--(1.2+3.746) = 2.16. Using a 6:1oxidizer to fuel ratio, about 309 kg must be LH2 and 1,853 kg must be LOX. In LLO the lander would rendezvous with the tug and take on 933 kg of hydrogen—624 kg for descent and 309 kg for return ascent. Actual payload would be 8,491 kg since return ascent hydrogen cuts into payload mass. 10 – 1.2 – 0.309 = 8.491.

The maximum propellant load the lander must store is 5.9 tons when lifting off from the lunar surface. 3.746+ 2.16 = 5.9. Twenty percent of that is 1.18 tons so the 1.2 ton estimate for lander mass is acceptable.

By using ten tons for the "package" mass it becomes easy to work out the percentages:

Mass Estimates for Landers with 450 second isp

dV	**Mass ratio**	**Lander fraction of "package" mass**	**Ascent LH2 fraction of "package" mass**
1600	1.44	~12%	~3%
1800	1.5	~14%	~4%
2000	1.57	~17%	~5.3%
2200	1.65	~21%	~7.1%
2400	1.72	~25%	~8.9%
2600	1.8	~29%	~11.2%
3000	1.97	~40%	~17%
3500	2.21	~60%	~28%
4000	2.48	~90%	~46%

Landing a bit more than 1000 tons of cargo on the Moon would involve nineteen Falcon Heavy payloads at 54.4 tons each. Since the lander for a 1600 m/s descent from LLO with 450-second engines would amass about 12% of "package" mass, it can be determined:

$$L/(54.4 + L) = 0.12$$
$$L = 7.42$$

Package mass will be 61.82 tons and residual LH2 for return ascent to LLO will be about 1.9 tons. The actual cargo mass will be 52.5 tons as this LH2 mass cuts into cargo mass. Nineteen Falcon Heavy rockets are still needed to land 1000 tons of cargo. Two landers with one serving as a back-up would amass just under 15 tons. Liquid hydrogen for descent and ascent would be 9.33% of package mass. Roughly 110 tons of hydrogen would be transported from Earth. With tankage, that might become about 125 tons. Solar electric tugs would have to move a total of about 1,140 tons of equipment, landers and tanks of hydrogen from LEO to LLO. Twenty one Falcon Heavy launches would be needed to place this in low Earth orbit. One more launch would be needed to get the lunar LOX plant in place. Each 54.4-ton cargo module would contain equipment for “bootstrapping” on the Moon. Several small LH2 tankers propelled by solar electric drives will move lander fuel through space. These tankers would mate with landers in LLO and transfer fuel automatically. Since LLO is unstable due to mass concentrations the tankers will arrive to fuel one lander and cargo module at a time and then return to LEO or a space station at EML1.

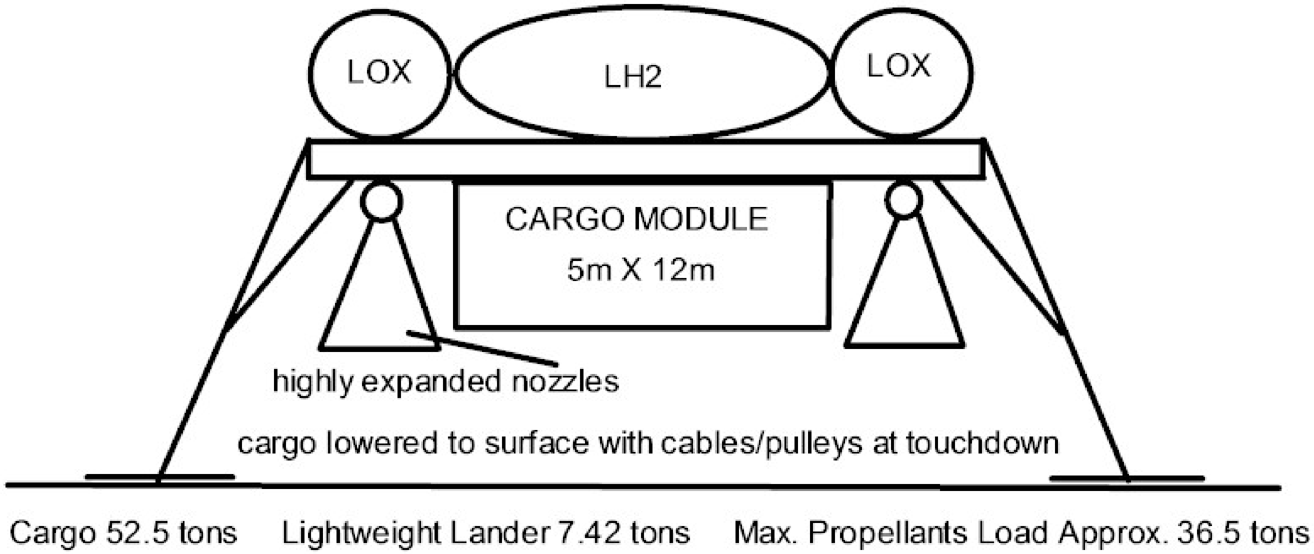

Fig. 1: Lander.

6. Concluding Remarks for Section I

In addition to the launches for the solar electric tugs which will be required if either lander strategy is used, twenty two Falcon Heavy launches are required. Reusing landers and using lunar LOX requires ten fewer Falcon Heavy launches. This allows a saving of $900 million. Approximately 661 metric tons of liquid oxygen must be produced over a period of several years by the robotic oxygen plant. At 100% recovery that would necessitate the mining of roughly 1650 tons of regolith. At a more realistic 50% recovery of oxygen from regolith about 3300 tons must be excavated and processed. That would be obtained from a pit about forty meters square to a depth of about one and a half meters dug out by teleoperated robots.

Section II. Building it on the Moon

1. Location

The first thing that must be done before the construction of a lunar industrial facility is determining the best place to locate it. Polar locations offer craters containing ice and prolonged sunshine. Preferably, the location for the first industrial settlement will have plenty of flat ground with very few boulders. A mare/highlands "coast" might be ideal. Ilmenite, basaltic mare regolith, KREEP, pyroclastic glass deposits, highland regolith and lava tubes should be reasonably nearby. Polar ices should also be accessible. A location in Mare Frigoris might be best [8]. According to Peter Kokh,

> “In the north, Mare Frigoris offers coastal areas less than half the distance from the north pole than southern coastal regions (Mare Australe, Mare Nubium, or Mare Humorum) are from the south pole. Further, Mare Frigoris is in the ‘Imbrium Fringe’ area that Lunar Prospector has shown to be thorium-enriched. Previously, this author had been partial to a settlement in Mare Crisium...but Mare Frigoris comes in a close second in this regard. Here, just north of the crater Plato and the Alpine Valley (providing access to Mare Imbrium and the whole ‘chain’ of nearside maria) might be an especially propitious place to set up an initial settlement.”

Highland regolith is richer in calcium and aluminum and mare regolith is richer in iron, titanium and magnesium. Locating at the edge of the mare will allow access to both kinds of regolith while polar locations are all in highland areas. The downside of a mare location is that darkness will last for two weeks at a time and power storage systems will be needed to maintain life support and protect equipment from the cold. The first payload to be landed would be a LUNOX production plant as discussed above to load reusable landers.

2. Site Preparation

Once a site is selected it needs to be prepared. The site must be leveled and small craters must be filled in. Boulders must be dynamited and the rocks pushed aside. Markers must be placed to indicate the locations of solar panel farms, landing pads, roads, walkways, a warehouse, a pad for production machinery and inflatable habitat modules. Robotic bulldozers and graders will be called for. There must also be a solar panel farm and wiring systems to recharge the batteries in the bulldozers and graders. These machines might be powered by tethers or microwave beams from the solar panel farm. Receiving antennas on the machines will just be low mass wire meshes with some Zener diodes and this will not burden the 'dozers and graders. This would free the machines from the burden of heavy battery or fuel cell packs and the need to shut down and recharge for several hours at a time. Robots that can drill holes in boulders and place explosives will also be needed. Logically, all the robots will retreat to extreme range when boulders are blasted.

Clearly, the first payloads to the Moon, after the LUNOX production plant, must be solar panels and associated hardware along with several bulldozers and graders. Robots to deploy the solar panels and wiring systems will also be needed. To protect the machines during nightspan it might be desirable to have infrared lamps to keep parked machines warm and power storage systems to energize the lamps. Batteries, flywheels or fuel cells come to mind.

Fuel cell systems will require insulated tanks to store liquid hydrogen and liquid oxygen, plumbing systems, water electrolysis systems, and refrigeration devices to liquefy hydrogen and oxygen. That sounds like a complicated mess when compared to batteries or flywheels; however, there is an important advantage to the use of fuel cells for nightspan power storage. Fuel cell systems can augment rocket fuel storage facilities with their cryogenic reactant storage tanks and liquification systems.

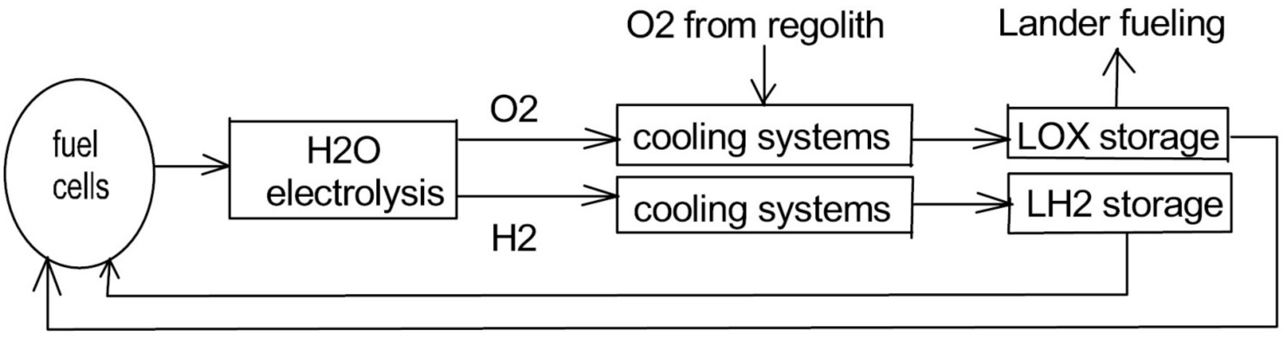

Fig. 2: Fuel cell and rocket propellant systems overlap.

The LUNOX plant will have its own small robot regolith loaders. More mining capacity may be desired. It should be possible to equip bulldozers with mining shovels so that these can do two jobs instead of just one. Attempting to define the components of a lunar "industrial seed," we can imagine the first payloads to the Moon will include but not be limited to:

- LUNOX production plant
- general purpose teleoperated robots
- solar panels, supports, motors, reflectors, wiring, switches, invertors, etc.
- power storage systems, probably fuel cell systems complete with insulated tanks for cryogens, piping, pumps, valves, electrolysis and refrigeration systems that can double as a rocket propellant depot
- microwave transmitters and/or tethers
- bulldozers and graders that can also excavate
- IR lamp systems
- oxygen generators (e.g. vapor pyrolysis or magma electrolysis)
- pumps etc. for "gassing up" lander rockets

3. Early Development

Once the site is leveled out and large rocks removed, it will be developed. Landing rockets will cause dust to spray all over and dust could damage machinery especially if it gets into bearings. Dust sprays could disaffect solar panels also. Several landing pads will be made. Wheeled robots with microwave generators could sinter or melt the basaltic ground to a depth of several inches (5 to 10 cm) at least. Bulldozers could berm up regolith around the pads. With three pads one rocket could be lifting off while another lands and a third one is waiting for service. Landers or "Moon Shuttles" might have wheels on their landing legs so they can be towed off the pad. The landing pads should be fairly big. A diameter of one hundred meters will allow a large margin of safety if a rocket is a bit off course. The pads would be located about a kilometer away from the habitat so that the chance of a Moon Shuttle rocket going off course and crashing into the habitat and killing everyone is very low. Roads from the landing/launch pads to the habitat and work area will be paved using microwaves to sinter the regolith.

Lunar workers and their machines and robots will need a nice hard floor to work on. A solid surface to mount production machines on can be made by microwave roasting of the regolith as would be done to make landing pads and roads. Plain old ground, i.e. loose regolith that has not been compacted and sintered with microwaves to make a solid surface, is not good. Spacesuited human workers and robots would kick up dust and some machines, such as power forging hammers, would pound or vibrate into the dusty surface. The floor might be thicker than the pads and roads. A large foil or aluminized Mylar parasol to shield machines and workers from the hot sun by day and prevent heat from radiating away into space by night could be erected, and teleoperated robots could work the production machines. Now and then humans will have to go outside in turtleback spacesuits to do some work. There will be microwaved walkways from the habitat modules to the production machine area. There will also be a warehouse consisting of a microwaved pad with a parasol to store cargo containers as they arrive by Moon Shuttle.

In addition to solar panel farms there must be power storage for nightspan not only to keep machines warm with IR lamps but to power lights, radios, computers and mechanical life support systems in habitat modules. A small nuclear generator would help. The microwaved basalt pads will serve as "thermal wadis" and cool slowly after sunset. That will be easier on the machines. Sudden thermal shock can crack metals. Even in polar locations there will be periods of darkness but these will last only a couple of days while in lower latitudes, where the mare are, darkness will prevail for two weeks out of every month. In the distant future there could be a solar power satellite at EML1 and a circumlunar power grid with solar panel farms around the Moon to supply full power at all times.

Secondary payloads to the Moon will include but not be limited to:

- more solar panels, wiring systems, power storage, possibly a small nuclear generator
- at least two rovers (preferably more in case one breaks down) with microwave generators to make pads and roads
- inflatable habitat with mechanical life support systems, and some tanks of oxygen to inflate the habitat
- parasols with support poles to protect workers and equipment from solar heat and to prevent radiation of heat from equipment by night
- running lights, flood lamps and radio antennas
- supplies of dehydrated and freeze dried foods, drinking water and medicines, clothing, bedding, towels and wash cloths, light weight furniture, recreational supplies (dart board, chess set, playing cards, board games, dice, etc.), toiletries and sundry items (toilet paper, toothpaste, brushes, razors, blades, soap, lotion, shaving cream, etc.)—deodorant, cologne, and perfume will have to wait until lots of air cleaning vegetation is cultivated within the habitat [9]

At least this much should be in place before human crews move in and start working. The bulldozers and graders with shovel attachments must cover the inflatable habitat with six meters of regolith for radiation, thermal and micrometeoroid protection. Protection from galactic cosmic rays in free space would require about 11 tons of regolith per square meter of hull to reduce radiation dosage to 20 mSv/yr and 6.6 mGy/yr. On the lunar surface, the Moon blocks out half of this so 9 tons per square meter would be needed [10]. Since bulk regolith is about 1.5 times as dense as water, 6 meters of regolith would suffice [11]. Without shielding humans could make only brief sorties on the Moon. It is foreseeable that robots might experience glitches that halt the project and humans become necessary to get things going again. Space workers could land and stay inside their spacecraft for a few days until they get the machines back up and running.

4. Excavating

The bulldozers and their shovels are just the beginning. Massive amounts of regolith must be moved to support a serious Moon mining operation with the goal of building mass drivers, solar power satellites and other constructions in space. A slusher system seems best [12]. This consists of a bucket attached to some steel cables. A winch pulls the bucket through the dust and it picks up a load. The load is lifted and dumped into a truck or an ore car on rails. A second set of cables wrapped around some pylons with pulleys at the edge of the excavation is pulled on by the motorized winch and the empty bucket is dragged out and readied to scoop up another load of regolith. This will be more efficient than making excavators scoop up a load, carry the load and their own weight to the refinery, dump the load and drive back to the hole, and repeat the process. The slusher can work continuously. At first trucks will perhaps haul lunar regolith to the refinery on microwaved basalt roads. Later on, a railway system will be constructed. Cars riding on steel rails will endure much less rolling friction and that will save energy. They won't kick up dust either. When the slusher has dug up a pit and can dig no more, it can be relocated. Rail systems can be extended to the new dig site. Slushers will be set up in different locations to dig mare regolith and highland regolith. Mare regolith is richer in iron, magnesium and titanium and can be melted down and cast as is. Highland regolith is richer in calcium and aluminum. These “soils” would be processed differently depending on what substances are desired.

The Moon Shuttles will land a few more payloads at this time:

- slusher systems consisting of cables, buckets, motorized winches, pylons
- hauling trucks

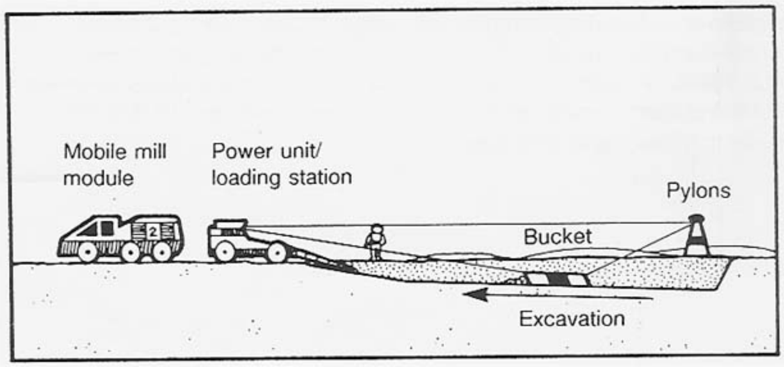

Fig. 3: Side view of slusher mining system. Image credit: NASA.

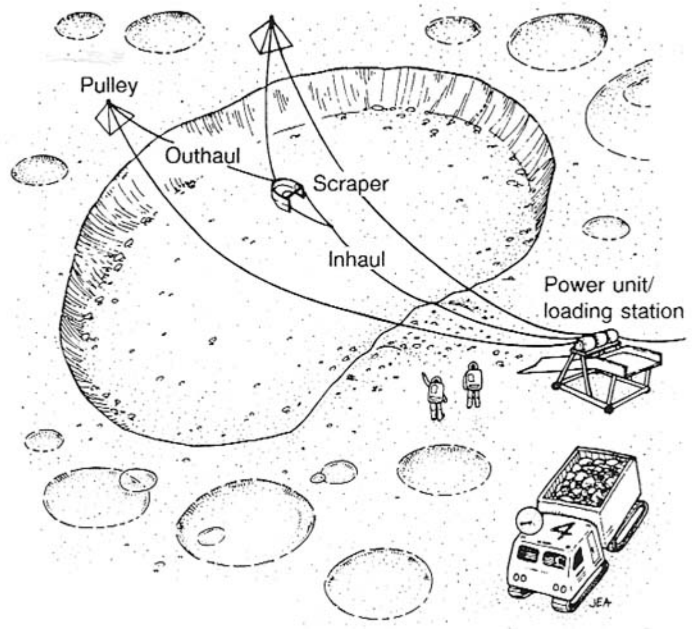

Fig. 4: Open pit mine with slusher system. Image credit: NASA.

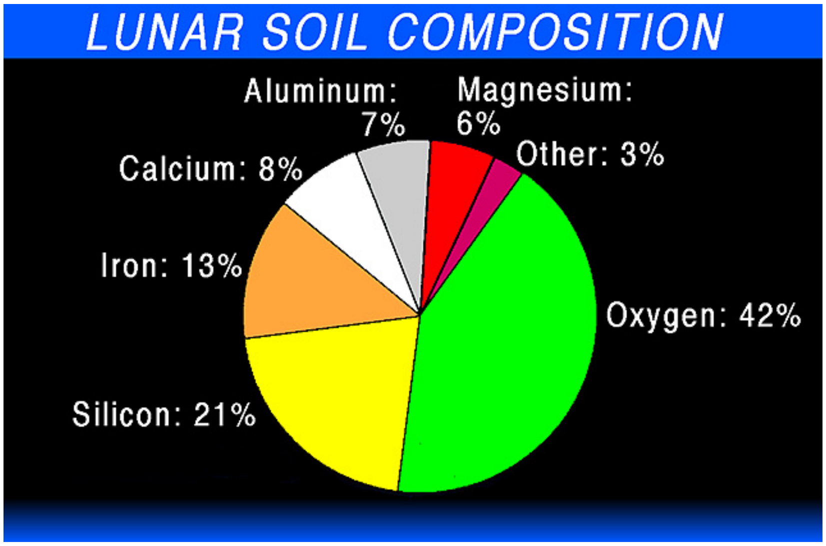

Fig. 5: Regolith composition (used with permission from Space Studies Institute).

5. Materials Production

There are many proposals for the extraction of materials from lunar regolith. The regolith is rich with oxygen, silicon, iron, calcium, aluminum, magnesium, titanium and has significant traces of manganese, chromium, sodium, potassium and phosphorus. Even without complex electrochemical systems for extracting these metals there are resources of great value. Mare regolith is basaltic. It can be dug up, melted in a solar or electric furnace, and crude castings can be made in molds dug into the ground and finer castings can be made in iron molds. It can also be sintered instead of cast. Sintering means that the material is compacted into molds and heated only enough for the edges of its particles to fuse together. This can make worthy items like bricks, blocks, tiles, slabs and rods without as much energy as full melting and casting requires. Basalt can also be melted and drawn through platinum-rhodium bushings to make fibers. A wide variety of things, perhaps even habitat modules and solar power satellite frames, could be made from basalt and glass. Metals will still be needed for vehicles, digging machines, railways, spacecraft, electrical systems, electric motors, etc.

Iron molds sound like heavy cargoes to import to the Moon. Perhaps they could be made on the Moon in large numbers. Magma electrolysis yields ferrosilicon and silicate ceramic as well as oxygen [13]. Ceramic blocks could be cast in molds dug in the ground. It might be possible to perform serial magma electrolysis in which case iron could be derived separately from silicon. This iron could be powdered and fed into 3D printers that use electron beams or lasers to fuse metal layer by layer to make all sorts of shapes. If serial magma electrolysis is not possible there is another resource of great value on hand**—**meteoric iron-nickel fines that are present in regolith all over the Moon at concentrations of a few tenths of a percent by mass. These could be harvested by rovers that have low intensity magnetic separators. This could be the first metal produced on the Moon. The particles are fused with silicates and can be purified by running them through centrifugal grinders to shatter the brittle silicates followed by another magnetic separation. In 1981, Dr. William Agosto projected that this system could produce 552 tons of a 99% pure iron/nickel feedstock annually [14]. After sieving and sizing, the powder could be placed in 3D printers to make iron molds of various sizes and shapes for casting and sintering basalt. A third way to obtain iron involves the roasting of regolith at 1200°C in the vacuum to drive off FeO, condensing the iron oxide and reducing it with hot hydrogen or using electrolysis to free up the iron and obtain oxygen [15].

Additive manufacturing ("3D printing") with metals is commonplace today. Stainless steel, low alloy steel, maraging steel, cobalt and nickel alloys are all used presently [16]. Direct metal laser sintering can produce solid parts without using a binder and it can make parts with complex geometries that CNC milling cannot [17]. Planetary Resources and 3D Systems actually printed up a model spacecraft with powdered meteoric iron-nickel material [18]. Certainly, lunar meteoric iron-nickel particles can also be used for additive manufacturing with electron beams or lasers.

Basalt could be a very important base material. It is harder than steel and abrasion resistant. It is strong in compression but not so strong in tension and it is rather brittle. Uses for basalt include [from reference 19]:

- **Cast basalt:** Machine base supports (lathes, milling machines), furnace lining for resource extraction operations, large tool beds, crusher jaws, pipes and conduits, conveyor material (pneumatic, hydraulic, sliding), linings for ball, tube or pug mills, flue ducts, ventilators, cyclers, drains, mixers, tanks, electrolyzers, and mineral dressing equipment, tiles and bricks, sidings, expendable ablative hull material (possibly composited with spun basalt), track rails, "railroad" ties, pylons, heavy duty containers for "agricultural" use, radar dish or mirror frames, thermal rods or heat pipes housings, supports and backing for solar collectors.
- **Sintered basalt: N**ozzles, tubing, wire-drawing dies, ball bearings, wheels, low torque fasteners, studs, furniture and utensils, low load axles, scientific equipment, frames and yokes, light tools, light duty containers and flasks for laboratory use, pump housings, filters/partial plugs.
- **Spun basalt (fibers):** Cloth and bedding, resilient shock absorbing pads, acoustic insulation,

thermal insulation, insulator for prevention of cold welding of metals, filler in sintered "soil" cement, fine springs, packing material, strainers or filters for industrial or agricultural use, electrical insulation, ropes for cables (with coatings).

Meteoric iron/nickel fines can be used for more than making molds for casting or sintering basalt. They contain 5 to 10% nickel, 0.2% cobalt and traces of germanium, gallium and platinum group metals (PGMs). Iron, nickel and cobalt can be separated by treating the fines with carbon monoxide gas. High temperature vaporization, ionization and electrostatic separation might also be applied. Nickel and PGMs have catalytic properties. Nickel can make steel harder and stronger without making it more brittle. Cobalt can be used for high speed drill bits and cutting tools. It can also stain glass a deep blue. Germanium and gallium can be used in electronics and photocells.

There are also traces of solar wind implanted volatiles (SWIVs) in regolith. Significant quantities of hydrogen, helium, nitrogen, water, carbon monoxide, carbon dioxide and methane can be obtained by heating regolith up to about 700°C [20]. At higher temperatures sulfur, potassium and sodium will also be liberated [21]. Teleoperated machines that plow through the relatively smooth mare with bucket wheel loaders could roast out these elements in an onboard furnace and store the substances in tanks [22]. The machines would only return to base when their tanks were full and heavy stationary refrigeration equipment could separate the gases and liquids. Hydrogen could be combined with oxygen to make water for life support systems and gardens. Nitrogen would be very important for fertilizer. Carbon could be used to make steel and add CO2 to atmospheres that support plant life.

Steel seems to be an unlikely material on the Moon where only small amounts of carbon exist. In reality, a tiny amount of carbon makes a large quantity of steel. Mild steel is 0.05% to 0.35% carbon. Alloyed with some nickel, very high quality steels can be made. There will be no roaring coke-filled blast furnaces or basic oxygen furnaces sending out showers of sparks on the Moon. Steel could be produced by the ancient crucible steel process. Iron powders, rods or plates would be packed with carbon powder and brought up to red heat in a furnace made of basalt or of a ceramic made on the Moon, such as the spinel-rich ceramic produced by magma electrolysis for about a week. The carbon will dissolve into the iron and form steel. The steel and carbon could be magnetically separated and the steel could be homogenized by melting to disperse the carbon evenly throughout the metal. During this melting the steel could be mixed with calcium aluminate flux to remove impurities. The CaAl2O4 flux could be produced by roasting highland anorthite at 2000°C [23].

Highland regolith contains less iron and magnesium than mare regolith but it is richer in calcium and aluminum. It can make a ceramic that does not melt until 1500°C, unlike basalt that melts at about 1250°C. Roasting highland regolith at up to 2000°C can drive off silicon dioxide and enrich the calcium and aluminum oxide components to make hydraulic cement. If anorthite is extracted by electrostatic separation and roasted at 2000°C and hotter, calcium aluminate can be obtained [23]. A furnace that can handle temperatures this high might consist of a slip cast aluminum oxide or silicon carbide crucible. Concentrated solar energy or an electron beam would heat the material in the crucible. Only part of the charge would be heated while the rest of the material, in this case anorthite, serves as insulation. Robots will dig out roasted material that has released SiO2 and formed calcium aluminate (CaAl2O4). Electrochemical processing of CaAl2O4 can yield aluminum and calcium metals [24]. Calcium is an excellent electrical conductor. It might be possible to condense the SiO2 released and use it for glass making. If the furnace crucible can have active cooling achieved by drilling passages in its walls through which an inert gas is pumped that dumps its heat into the cold of outer space from shielded radiators, it might be possible to construct more effective high temperature furnaces on the Moon.

We can see that additional payloads to the Moon should include but not be limited to:

- solar or electrical furnaces for melting and pouring basalt
- small digging tool attachments for making crude sand molds in the ground
- some iron starter molds for basalt
- platinum-rhodium bushings for basalt fiber drawing
- heaters to sinter basalt packed into iron molds, packing tools for robots
- heaters, perhaps induction heaters, to melt steel
- magma electrolysis cells
- metal powdering equipment (centrifugal electric arc perhaps)
- rovers with low intensity magnetic separators for harvesting meteoric iron fines
- centrifugal grinders
- 3D printers that can make heavy iron molds
- carbon monoxide processing equipment
- rovers for harvesting solar wind implanted volatiles
- cryonic refrigeration/distillation equipment
- electrostatic separation devices
- furnaces for roasting anorthite at 2000°C +
- electrochemical equipment for aluminum and calcium extraction
- lithium fluoride and calcium fluoride electrolyte
- inconsumable cermet electrodes

With this equipment it should be possible to produce iron molds for basalt and furnaces with basalt, anorthite or spinel-rich ceramic linings for steel. Nickel, cobalt, small amounts of germanium, gallium and PGMs, hydrogen, helium, nitrogen, carbon, sulfur, iron, aluminum and calcium also become available. Two more metals can also be had—magnesium and titanium. Ferrosilicon from magma electrolysis can be mixed with magnesium oxide obtained by roasting mare regolith at 1500°C+. The mixture can be heated to 1200°C under vacuum conditions so magnesium metal will boil out and can be condensed. Titanium can be obtained by mining in ilmenite rich mare regolith. The ilmenite can be concentrated with electrostatic separators [25]. A fluidized bed can be made of welded steel plates and pipes and possibly some basalt parts in which the ilmenite is treated with hydrogen gas at 1100°C. Water and fused particles of titanium dioxide and iron will form. The water will be electrolyzed to recover hydrogen and gain oxygen [26]. The TiO2 and iron particles must be separated, possibly by treatment with CO gas to form iron carbonyls [27]. The titanium dioxide could then be electrolyzed in FFC cells with inconsumable electrodes to obtain sponge titanium metal. This would be melted in a high temperature furnace at over 1800°C or powdered for 3D printing.

Besides fluidized beds for ilmenite processing, metal plates both flat and curved and metal pipes will be needed to build pressurized cabins for ground vehicles, railroad cars and spacecraft, habitat modules, rocket propellant tanks, liquid and gas storage tanks, and numerous other products. This would call for payloads of:

- rolling mills for making metal plates
- centrifugal casting machine to make basalt pipes
- extruder to make metal pipes
- accessory devices for making magnesium and titanium extraction devices
- FFC cells with calcium chloride electrolyte

However, rolling mills and extruders can be very massive pieces of equipment. A rolling mill could amass 40,000 kilograms or more and an extruder up to 10,000 kilograms or more, although there are smaller lighter versions, even bench top scale rolling mills and extruders. A Falcon Heavy rocket could put 54,400 kilograms in LEO, so the problem is not getting it up there. If 1000 metric tons of cargo was lifted to the Moon, a 40 metric ton rolling mill would only be about four percent of the total. Several pieces of heavy equipment besides a rolling mill, like extruders, a large engine lathe and forging presses, could be sent to the Moon and there would still be plenty of space left over for other things if 1000 tons is the mark. The question is, might it not be better to send the machinery for making heavy equipment on the Moon? Then make several copies of the heavy equipment on the Moon? How would this be done? What are these machines for?

6. Metal Massive, Unitary, Simple Things

It is not always necessary to melt and cast metals. That requires lots of energy, time and labor by men and machines. Cold metals can be shaped by rolling, extrusion and spinning. This work hardens the metal. When this is not wanted, metals can be hot worked. It takes energy to heat the metal but not as much as melting does and less horsepower is needed to roll or extrude the softer hot metal.

- **Foils:** food wrapping, parasols, solar shields, reflectors to increase solar panel output.
- **Sheets:** buckets, bins, tool holders, shelves, drawers, computer and electronics casings, tableware.
- **Flat Plates:** slusher buckets or scrapers, excavator buckets, bulldozer and road scraper blades, ground vehicle parts, spacecraft frames, metal floors, fluidized beds (with some tubes and other parts), appliance parts and casings, even pots and pans by stamping small circular thin metal plates.
- **Curved Plates and Spun Domes:** rocket propellant tanks, fuel cell reactant tanks, water tanks, tanks for oxygen and other gases, pressurized ground and space vehicle cabins, parabolic solar trough reflectors, spun domes for radio and solar concentrator dishes.
- **Rails, Bars, Beams:** ground vehicle and earth moving equipment frames as well as other parts, building support structures, railroad tracks.
- **Rods:** axels, “tent” or canopy poles, radio antennas, rebar, “telephone” poles for power lines and phone lines.
- **Wires:** power lines, phone lines, electrical wiring, motor coils, steel cables for earth moving equipment.

It can be plainly seen that the simple objects made by rolling, extrusion, spinning and drawing have many uses. The heavy equipment needed for this can mass produce these items from lunar metals. Aluminum, pure iron, meteoric iron-nickel and steel will be most useful. Magnesium is soft but not very ductile unless it’s hot. Titanium is hard to cold work but can be hot worked. Many titanium parts could be made from powder by electron beam fusing or sintering, a kind of 3D printing, outside in the vacuum.

7. Casting on the Moon

There can be no doubt that materials production devices from meteoric iron harvesting rovers to solar and electrical furnaces and other things including solar panels for power must be sent to the Moon ready to work (and supply materials) or nothing can happen at all. Some production devices like 3D printers must be sent up ready to work also.

Working with metals will require furnaces for melting and heat treating and heavy machines like rolling mills to work the metals into useful things. Meteoric iron containing 5% to 10% nickel and pure iron from other sources could be converted to steel by roasting it with carbon. This is the ancient crucible steel process. The Moon doesn't have a lot of carbon but a tiny amount of carbon can make a large quantity of steel. Casting that steel into large rollers a meter or more (40 inches) in diameter and two meters (80 inches) long that are later ground and polished with CNC (computerized numerical control) machines to within two ten thousandths of an inch presents a problem. Fairly pure silica or olivine sand will be needed for expendable molds along with clay and water to bind the mold. While sand might come from regolith, clay is non-existent on the Moon and water is precious. In the vacuum the water will sublime and the wet mold will dry up. Unless this job is done inside a pressurized structure so that the water can be recovered from the air within, that water will be lost.

What about using binders other than clay? Sand molds can be made with resin but the Moon lacks the light elements needed to make resin so it would be imported and recycled. The resin bonded sand mold would have to be contained in a sealed metal box so that when hot metal was poured in and the resin volatilized it could be recaptured. Sodium silicate is another potential binder. This compound can be made on the Moon but it must be dissolved in water and then mixed with sand. In the vacuum the water would evaporate so the job must be done inside a pressurized structure, and the sodium silicate must be allowed to dry out before moving the mold outside and pouring metal. Making molds or cores from plaster or cement will also require a pressurized structure where water vapor is condensed from the air. Not only that, there is no way to mix plaster or cement with water out in the vacuum. The water will evaporate in a flash. At least the actual metal casting can be done outside. Casting large parts inside some kind of habitat module would release a lot of heat and that would demand a powerful air conditioning system. It might get so hot inside that only robots can work within.

It seems doubtful that metal objects amassing several tons could be cast inside large inflatable structures even with a concrete floor. Such a structure will still be needed for making sand molds bound with sodium silicate solution and for making molds and cores out of plaster or cement. Airlocks and wheeled carts or pallet jacks will be needed to get large molds outside and to get solidified castings inside.

Rolling mills will require heavy frames to support the rollers. Very crude castings could be made in cavities dug in the ground. Basaltic mare regolith (m.p. 1150 to 1350°C) in contact with molten steel at 1500°C will melt and form a crust on the parts. This crust could be chipped off, ground and wire brushed off by robots. CNC machines could grind the crude frame casting into a finished product. Casting in anorthositic highland regolith which melts at about 1500°C might be more effective [28].

8. Grinding Metals

Rough castings will have to be finished by grinding and polishing with CNC milling machines. It is not likely that large heavy parts like steel rollers and extruder barrels would be made entirely by CNC machining of big blocks of steel. This would wear out expensive imported tungsten carbide cutting tools. If it is possible to cast and grind out massive, unitary and simple parts on the Moon and import the complex, lightweight and electronic parts it should be possible to achieve substantial savings. There are CNC milling machines that can machine 60,000 kilogram (132,000 pound) workpieces, but they are as big as a two car garage [29]. On the Moon, workpieces to be shaped into rollers would only amass about 9,000 to 14,000 kg (20,000 to 30,000 pounds). In low gravity they would weigh one sixth as much and be easier to move around. There are CNC machines that could work pieces this large and they amass about 16,400 kg (36,000 pounds). It would seem to make more sense for Moon miners to send up a 16 ton CNC machine that can be used to make numerous machines from rough castings rather than send up complete 40,000 kg rolling mills and other heavy machines that cannot replicate themselves.

Fig. 6. Hurco VMX84i-50t. Weight 16,700 kg (36,806 lbs). Travel 213 cm X 86 cm X 76 cm (84x34x30 inches). Table size 218 cm X 86 cm (86x34 inches). This machine comes close to what is needed on the Moon to make parts for heavy equipment [30]. Image used with permission from Hurco Inc.

Machining requires lubricant. Sometimes water is used. This won't work in the vacuum. It seems CNC machining will have to be done inside the same pressurized structures where molds and cores are made. Tools will get hot but there will not be nearly as much heat released by machining as there would by melting and casting parts weighing several tons. Lubricant/coolant will be recaptured, filtered, cooled and reused over and over again. Working inside a pressurized structure will also protect CNC machines from extremes of lunar temperature.

9. MUS/cle

This is a situation where Peter Kokh's MUS/cle strategy can be applied [31]. “MUS” stands for massive, unitary and simple while “cle” stands for complex, lightweight and electronic. If we can just make the large heavy parts of machines on the Moon and import the electronic controls and perhaps the electric motors, the cost of sending cargo to the Moon will be reduced and the industrialization of the Moon becomes more practical.

If CNC machines can make large heavy or massive, unitary and simple parts on the Moon from rough metal castings it will reduce the requirement for transporting heavy objects by rocket and amount to huge savings. Since steel casting presents the problem of the Moon’s lack of sand, water and clay (unlike Mars where clay exists), and the need for a pressurized foundry even if the sand, water and clay were available, it might be that CNC machining will be the best way to shape steel parts from crude molds of all sizes that would ordinarily be made by sand casting. The 3D printers could make small intricate steel parts needed in limited numbers including gears, molds and dies, and the rolling mills and extruders would mass produce large steel and aluminum plates and sheets, beams, rails, pipes, etc.

A combination of pressurized structures where molds and cores can be made along with CNC milling machines, 3D printers, machine shops with drill presses, lathes and other machine tools, solar and electric furnaces and accessory equipment in addition to some other imports should make it possible to produce heavy rolling mills, extruders, large engine lathes and forging presses on the Moon. When all this equipment is working it should be possible to make anything out of metal that has to be made of metal.

10. Manufacturing

The best of terrestrial conventional manufacturing techniques will be applied on the Moon even in the age of 3D printing. Casting is important. There could be times when casting is faster and cheaper than 3D printing; however, casting will require a pressurized foundry or a sealed metal container so that liquid metals don’t evaporate into the vacuum. Liquids evaporate in a vacuum. This makes thin film physical vapor deposition (PVD) with molten metals in a vacuum possible. Free vacuum will make PVD easy on the Moon but it can complicate casting. Atoms of molten metal will not reach lunar escape velocity but there could be loss of material due to boil off from molds unless they are sealed or the casting job is done indoors.

Small parts made of aluminum and magnesium could be cast in plaster molds inside the foundry. Plaster, calcium sulfate, would be obtained by leaching anorthite with sulfuric acid. While basalt, steel and iron might be cast outside in the vacuum without too much loss of material by evaporation, wetted sand molds would ordinarily be required to cast these metals and that necessitates a pressurized foundry to recover water vapor from the sand molds that steams off into the air. Sand molds require a binder, usually clay; however, clay is formed by hydrological processes and it will not be found on the Moon, but there might be clay on Mars. It might be possible to use a little chemical magic to make synthetic clay. Polymers and sodium silicate should also be considered. Polymers that burn off in the form of CO2 can still be recycled. The CO2 can be extracted from the air in the casting module and be reacted with hydrogen to form polymer precursors like ethylene.

Molten metals will emit lots of heat and a powerful cooling system will be required in the foundry in addition to concrete floors and barriers that can stand up to spilled liquid metal. Concrete is a mixture of gravel, sand and cement. Cement can be produced by roasting highland regolith at over 1500°C to drive off SiO_2 and MgO and enrich CaO and Al_2O_3 components. If a setting time retarder is needed, some $CaSO_4$ can be made by leaching regolith with sulfuric acid.

As discussed previously, a pressurized structure where molds and cores can be made with sand, binders, cement and/or plaster and machining can be done with lubricants/coolants that can be recycled is necessary. This structure or foundry could be made of inflatable Kevlar modules that have concrete floors poured within and are covered with regolith for radiation shielding. Cement will demand a lot of water and it can only be mixed and poured inside pressurized modules. As it dries and sets it will release most of its water into the air and condensors could recover water from the air. Water can come from polar ices. It can also be obtained by combining LUNOX with imported hydrogen or hydrogen from solar wind implanted volatiles mining. Since water is 8/9s oxygen this could be worthwhile.

Casting on Earth seems like a fairly straightforward manufacturing process. On the Moon it becomes rather highly involved. Fortunately, the need to cast anything really huge does not exist. Large metal things like plates and I-beams can all be made outside with rolling mills and extruders. Lunar workers could teleoperate robots that load billets of metals into machines that extrude beams for vehicle frames and weld them up outside with arc welders. Friction stir welding could be used with aluminum. A rapidly rotating ceramic tool is guided along the joint where two metal pieces meet. Friction with the spinning tool generates heat that fuses the aluminum. Much can be made with flat and curved metal plates produced by feeding ingots or slabs of metal into rolling mills. Those plates can be square or workers can laser cut them into various shapes including disks. Beams and rails can be rolled. Beams of various dimensions, rods, bars, rails, pipes, and metal fibers can also be produced by extrusion.

This is the “Lego set” lunar makers have to work with. Rods can make axles. Beams can make vehicle frames. Pipes or tubes can also make vehicle frames. Flat plates can make buckets and ore bins. Disks can be used for wheels and maybe presses can even stamp out wheels. Rails by extrusion are rails. It shouldn’t be too hard to make ore cars, rails and buckets and cables for slushers with rolling mills, extruders, presses and a small foundry with machine shop along with 3D printers.

A big engine lathe instead of a giant press could spin metal domes from circular metal plates (disks) outside. Beams and rods can make power cable towers and supports for reflector systems. If one is imaginative enough, it might be possible to extrude basalt. Take a billet of basalt, get it red hot and soft, and squeeze out beams for making things like towers and supports. Drill holes in the beams with lasers and bolt them together with steel bolts and one can come up with all sorts of structures. Solar furnaces will require lots of frame members to support reflectors and crucibles. Parabolic solar trough reflectors can be made by rolling and curving sheet metal and dish reflectors can be made by spinning. Hemispheres made by spinning could be welded together to make spherical storage tanks for water, LOX, LH_2 and other liquified gases. This work can all be done outside with machines mounted on solid basalt pads with parasols to shield everything from the blistering hot lunar Sun and trap warmth by night.

Forging metals will also be important when this can make parts faster and in larger quantity than 3D printing. Drop forges would have to be very tall and have massive weights in low lunar gravity.

Compressed oxygen could drive forging hammers too. Electromagnetic systems are also possible. Since the Moon lacks oil and leakage into the vacuum is likely, forging presses would probably not be hydraulic. All sorts of parts can be made from hot metal blanks. All varieties of steel dies might be made by 3D printing; however, printed parts are sometimes more porous and weaker than cast parts. Casting steel dies in the lunar foundry might be called for. The steel dies would be heated and water quenched to harden and temper them. Steam from the quenching of hot metals would be condensed from the air in the pressurized foundry module. Forgings will be in demand. A jet liner contains thousands of forged parts. Rockets, ground vehicles, robots, rovers, refrigeration devices, machine tools and many other things will contain forged parts.

It is true that 3D printing can make some large parts like an airplane wing, but it is slow. It wouldn’t make sense to print an I-beam, which would probably be the biggest single part made of metal on the Moon besides parts for heavy equipment. An I-beam would be rolled or extruded outside. There might not be any demand for large I-beams anyway until lava tubes are sealed and pressurized and buildings are constructed within using conventional techniques. Curved plates and domes for “sausage” shaped habitat modules can be cranked out by rolling and spinning. An airlock hatch seems like something that would be cast. It could be possible to stamp or forge hatches outside if there is a big enough press and some disk shaped billets.

Lunar makers must strive to make vehicles and machines on the Moon using 3D printing, rolling, extruding, stamping, forging and only rarely casting. They will have pressurized machine shops where parts are drilled and milled with great precision. There will be assembly shops or garage modules where vehicles and machines are put together. Operating machine tools and assembling things will not generate the extensive heat that melting and casting metals will.

Fasteners will be necessary. Bolts and screws are made in a bolt rolling machine that rolls rods (made by extrusion) between two dies. Nuts and rivets are also going to be required.

To continue with the payload list for setting up a bootstrapping lunar industrial base:

- inflatable module for foundry with powerful cooling system
- cement mixer to make concrete for foundry floor and barriers
- electric arc and friction stir welders
- 3D printers as needed
- more solar panels and associated hardware, wiring, etc. to power machines
- very large engine lathe
- cutting lasers, perhaps a cutting table
- forging hammers
- sulfuric acid leaching systems (these might be made of acid resistant basalt on the Moon)
- machine tools (drill presses, lathes, grinders, boring and milling machines, etc.)
- CNC milling machines
- bolt rolling machines
- spare parts for machines—could be printed up on the Moon as needed

11. Construction

There will be basalt poles to support power lines and telecommunications cables. There will be basalt supports for solar panels. Solar farms will cover thousands of square meters of land. There will be melted or sintered regolith roads and railways consisting of steel rails and steel ties on beds of gravel. Shelter is of utmost importance. It seems that it will be desirable to construct shelter on the Moon instead of continually importing inflatable Kevlar modules from Earth. Aluminum cylinders with domed ends could be used. It might even be possible to make box shaped habitats by welding up flat metal plates and welding in internal supports like webs.

Contour crafting is interesting. This is basically 3D printing on a large scale using cement. However, hydraulic cement won't work outside in the vacuum. The water will evaporate before the concrete can set. This kind of cement could be used with bricks, cement board and slabs to make steps, walls, even furnishings inside of pressurized modules. In sealed and pressurized lava tubes entire buildings could be constructed using conventional techniques. Water would be needed to make all this cement and that would come from polar ices, solar wind implanted volatiles, mining for hydrogen and/or imported hydrogen combined with LUNOX as mentioned above. Sulfur cement might be used inside pressurized spaces.

Outside on the Moon it might also be possible to use sulfur cement. There are substantial traces of sulfur in the regolith that can be extracted by roasting regolith at up to 1200°C. The sulfur would simply be mixed with sand (sieved regolith) and gravel, heated to 140°C to melt the sulfur and then poured. A contour crafting gantry could be used to "print up" all sorts of structures. The only drawback is that the extreme heat of lunar day (127°C at the equator) could melt the sulfur (m.p. 115°C) and the construction would collapse. Bulk regolith is an excellent thermal insulator. The temperature at a depth of one meter at the equator is a constant -20°C [32]. If the work is done behind or beneath foil shields and the structure is covered with several meters of insulating loose regolith then it should be safe.

Another possibility is the construction of fused rock structures. The contour crafting gantry would need a bucket consisting of a high temperature resistant metal like molybdenum or tungsten in which regolith was melted and oozed out to form domes of rock, layer by layer, with layers a few centimeters thick. It might also be possible to use a nickel-steel bucket with an active cooling system. Fused rock structures should be very strong and the material needed to make them is just sitting on the Moon waiting to be excavated. A contour crafting gantry seems like a heavy cargo to the Moon. It seems likely that Moon miners will have the steel beams and other parts needed to build contour crafting gantries for doing all kinds of work on the Moon. Two more additions to the lunar industrial seed would be:

- Contour crafting gantries, or just the components that cannot be made on the Moon
- Crucibles made of molybdenum or tungsten with heating elements

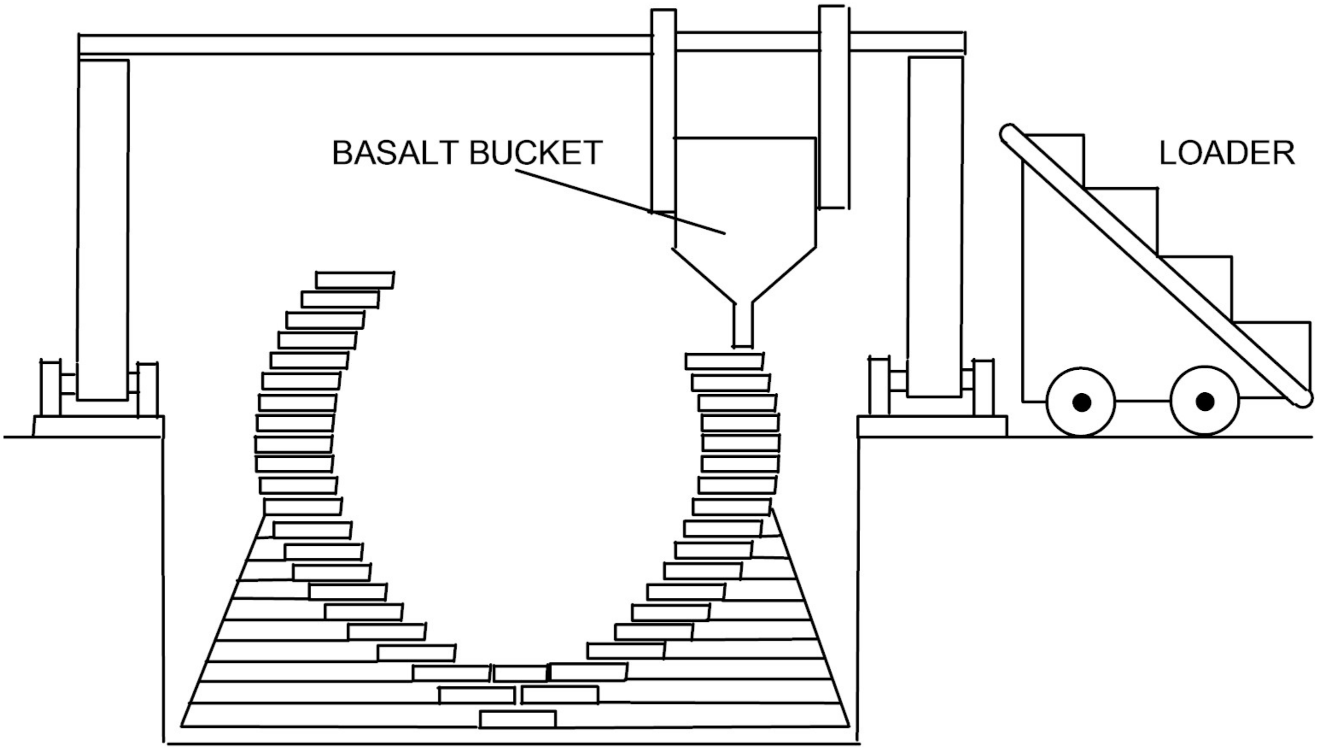

Fig. 7: Cross sectional diagram of machine printing cylindrical habitat with extruded molten basalt.

12. Motors

At first, equipment from Earth will be complete with motors. There will be electric motors galore on the Moon in a range of sizes. They will be used for vehicles, digging machines, contour crafting gantries, slushers, railways, rolling mills, extruders, forging hammers, compressors, refrigeration equipment, ventilation fans, water pumps, sewage pumps, 3D printers, small electronics, spacesuit backpack mechanisms, solar panel and antenna tracking systems, coolant pumps, appliances, sewing machines and looms, power tools, machine tools, farm equipment, even electric razors and toothbrushes, etc. A substantial part of lunar industry will involve electric motor production.

Aluminum wire will probably be used since copper is so rare on the Moon. Sparse carbon and hydrogen will be combined with plentiful silicon and oxygen to make silicone insulation for the motor windings. Iron and steel will be available. Motors might run on DC, or direct current from solar panels might be inverted to 3 phase AC to run 3 phase motors. Such motors can be lighter and more powerful. Entrepreneurs who set up a factory on the Moon that makes a wide variety of electric motors and replacement parts from lunar sourced materials will have a reliable market with a real future. Another payload for the lunar “seed:”

- Electric motor winding machines and any specialized tools needed to get electric motor production going on the Moon

13. Solar Panels

Lunar industry will have a voracious appetite for electrical energy. It would seem reasonable then that solar panels and related gear should be made on the Moon. Dr. Peter Schubert has designed a device that works in a manner similar to a mass spectrometer. The device can produce oxygen, silicon, silicon doped with phosphorus, aluminum, iron, and possibly other elements too [33]. This device does not require imported chemical reagents like chlorine and fluorine. It consists of some exotic materials that would have to be imported like thorium oxide and platinum-rhodium. Much of the machine, like the piping systems, waste heat radiators and cryochillers could be made on the Moon from steel and ceramic materials. Boron for p-type silicon is rare on the Moon. Aluminum could be used instead. Phosphorus for n-type material is available. Aluminum could also be used for backing and wiring. Glass could be produced for anti-reflection coatings. More lunar industrial seed cargoes could include:

- Complete and partial Lunar Dust Roasters and All Isotope Separaters

If for some reason this device fails to deliver, then silicon might be produced by serial magma electrolysis. This could be zone refined to a high degree of purity. If this fails, then silicon extraction will require the use of corrosive fluorine imported from Earth. Fluorine could be shipped easily in salt form and electrolyzed to free up the halogen [34]. This will increase costs, but the cost of imported fluorine will not be as great as the cost of imported solar panels given the huge need for them.

14. Replication

It will not be cost effective to keep importing heavy production machines, robots, bulldozers, habitats, etc. These things must be made on the Moon in greater and greater numbers as lunar industry and populations grow. The Moon cannot “cut the cord” with Mother Earth completely. Computer chips will come from Earth. Factories with clean rooms where integrated circuit chips are made cost billions of dollars. In the more distant future such factories might emerge on the Moon. Until then the mechanical parts for robots, vehicles and other machines will be made on the Moon while the electronic brains are imported.

The various manufacturing methods like 3D printing, rolling, extruding, forging, machining by hand and with CNC (computerized numerical controlled) machines and casting will be used. To replicate some machines, large part casting might be required. An inflatable, made of Kevlar (which has more tensile strength than steel) with a concrete floor, could do small casting jobs, but large parts will have to be cast outside in polymer or sodium silicate bound sand molds. Some carbon and water would not be sacrificed if the mold is sealed. Loss of water or organic chemicals can be avoided if lava tubes of reasonable size can be found, sealed and pressurized with oxygen. Within a lava tube it would be safe to pour hundreds of pounds of molten metals and recover water vapor from the sand molds with dehumidifiers. Living quarters, offices and workshops could be bricked up inside of lava tubes to house hundreds, perhaps thousands, of humans someday.

15. Hypothetical Materials

Ferrosilicon from magma electrolysis might serve as a low performance rocket fuel after powdering. Iron and silicon burn furiously in pure oxygen. Monopropellant might be made from a mixture of ferrosilicon and liquid oxygen. Bipropellant rockets using LOX and FeSi mixed with a carrier liquid, perhaps silane, might be more reliable and safer. Ferrosilicon might not be as powerful a fuel as aluminum but it will be much easier to produce. It can be acquired by magma electrolysis while aluminum production requires imported chemicals and numerous steps. Monopropellants consisting of aluminum powder and LOX have been studied [35]. Ferrosilicon deserves more investigation.

Basalt fibers bound with polymer resins are now being used to reinforce concrete. Resins will not be plentiful on the Moon. There will be some carbon for steel and some for agriculture and some for organic chemicals, but those organics will be pricy. Glass fiber reinforced glass matrix composites have been suggested. Unfortunately very little work has been done with this material. The pure silica fibers would add tensile strength and fracture resistance to a matrix of glass that has been doped with sodium and calcium to lower its melting point [36]. Why not a basalt fiber reinforced basalt matrix composite? The matrix could have its melting point reduced so as not to melt the fibers by doping with sodium, potassium, calcium and/or magnesium. It seems that this material would be “easier” to produce than glass fiber reinforced glass composites. Basalt is readily mined and melted. Moon miners have to look at lunar basalt compositions too. Lunar basalt has more iron in it than terrestrial basalt. It might be desirable to alter iron contents with magnetic separations. Casting basalt and fiber drawing in the vacuum and low gravity must be studied. On Earth, makers of basalt products cool the fibers with a water spray. In space, a sealed chamber and a spray of cooled helium gas that is recycled might be called for to cool the fibers.

If basalt fiber reinforced basalt matrix composites are feasible and cheap, then this could be a material for space frames for power satellites, space stations, space shipyards, large telecommunications platforms and space telescopes. No imported reagents would be needed. Manufacturing this stuff, which would have a density of about 2.95 vs 2.7 for aluminum, in quantities needed for solar power satellite construction, should be cheaper than producing aluminum.

The primary structure of a powersat is about ten percent of its total mass or about 5,000 tons for a 50,000 ton 5GWe SPS and 10,000 tons for a 100,000 ton 10 GWe satellite [37]. If 20 powersats a year are built and each is rated at 10 GWe then in 50 years there would be 1000 of them and 10 TW of power. That’s a vast amount of energy. At present the world uses about 15 TW and it is predicted that civilization will demand about 30 TW by 2050 A.D [38]. However, two-thirds of this is waste heat, so 10 TW of electrical power could energize the world if everyone switches to electric heat and electric cars. About 200,000 tons of aluminum would be needed annually just for SPS frames. This would require quite a bit of infrastructure on the Moon. It would require the costly importation of halogens to make electrolyte using various proposed methods for electrowinning aluminum from lunar regolith. Fiberglass or basalt might be cheaper. If basalt fiber reinforced basalt composites are possible and cheap, this would drastically increase the value of lunar basalt and make the case for a mare/highland coast installation much stronger. Basalt composites reinforced with silica fibers or fibers made from melted and drawn anorthositic highland regolith should also be investigated.

Insignificant traces of copper exist in regolith. Calcium conductors might serve as an alternative to aluminum. According to Geoffrey A. Landiss, “An alternative material for electrical conduction is metallic calcium. This is not used on the Earth because of the extremely high reactivity of calcium in an oxygen atmosphere, but this may not be a problem on the Moon. Calcium has the property of having one of the highest conductivity to density ratios of any easily-available metal, that is, metallic calcium makes the lightest wires. However, aluminum is adequate for wire use, and aluminum technology is well developed...” [39].

Solar power satellites could benefit from lighter conductors. Mass driver coils might be made of calcium too. That could be of value for mass driver propelled spaceships. Calcium might be extracted from slag produced during extraction of other metals. This warrants more investigation.

16. The Bottom Line

It could be true that history is governed by economic factors. If so, then lunar development will be governed by costs and profit margins, especially if the Moon is developed by private entrepreneurs who have to keep an eye on the bottom line. It seems reasonable that products that can be produced on the Moon with lunar available resources alone will be cheaper than products that rely on imports, but reality and the marketplace can defy common sense. For instance, it would seem that it would be cheaper to pump up oil from deep wells in the U.S. rather than ship oil in supertankers across thousands of miles of ocean, but it’s not. Presently, there is no way to predict any of the costs of doing business in outer space. Rocket launches cost tens of millions of dollars just to reach low Earth orbit and they may explode. Reliability must be improved. Prices for rocket launches to LEO will probably come down in the future. That seems to be the trend for so many products be they aluminum, computers or automobiles and microwave ovens. Even if the price for a rocket launch comes down by a factor of ten to one hundred, it will still be expensive to travel in space, and the use of onsite materials and energy will still be preferred.

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