

Lunar In –Situ Resource Advantages

There appears to be an initial equity investment in lunar settlement research and infrastructure development that must be done telerobotically - using automatic and semi-autonomous processes. It also appears difficult to write a successful lunar business case without some initial subsidy or “seed development.” LunaCorp is one such company still working on this business case.

What minimum investment might be required to get a lunar settlement operational; producing some commercially useful or valuable products or services? Several lunar business models are evaluating this challenge. E.g. Space Solar Power may be one key driver for lunar in-situ resource development - providing photovoltaic “fabric” made on the Moon to SSP Sats at GSO. Twenty to one energy economics make this an attractive proposition to consider. Some valuable insight can therefore be gained from SSP studies into the approximate monetary (and otherwise) advantages and cost/benefit ration: To start a lunar campsite designers point to telerobotics and semi-autonomous robots. Such systems are in growing use today on the earth.

- On September 19, 2001 surgeons performed the first Trans-Atlantic telesurgery¹ - robot-assisted operation on a human. Surgeons in New York operated a robotic control console linked to a ‘patient-side’ robotic system in Strasbourg, France over 14,000 km away. The ‘surgeon-side’ was connected to the ‘patient-side’ through dedicated 10 megabits per second ATM connections.
- Inco operates the world's first totally robotic mine is now in Sudbury, Canada. This was the work of the Mining Automation Program, a 5 year R&D effort to create tele-operated and autonomous mining machines.

<http://www.telemineing.net/>

<http://www.telemineing.net/whatistelemineing/>

Leif Bloomquist, who worked in the project, has a great website also:

<http://www.accesslevelblack.com/>

“We had to bring together space+robotics technology, wireless LANs, and even virtual reality and video game interfaces. ... The whole point is to enhance safety by having no humans underground, and to boost productivity by saving the time to travel underground and have one driver controlling a whole fleet.”

- Skyworker is a robot designed for working in orbit on SSP assembly. Skyworker is an assembly, inspection and maintenance robot that will softly and autonomously transport and manipulate payloads of kilograms to tons over kilometer distances.² Free flying robots expend too much fuel for large scale construction. Fixed manipulators lack sufficient reach for huge facilities, and they require strong attachment points. Skyworker overcomes these problems by walking and working on the structure it is building. Skyworker can move a payload at a constant velocity while walking, a huge advantage for power efficiency.

¹ Nature 2001;413:379-380 <http://www.nature.com/nature/prepub/413379.pdf>

²<http://www.frc.ri.cmu.edu/projects/skyworker/>

These widely varying types of telerobotics and mining technologies can show us the way to develop the Moon entirely telerobotically and reduce costs hugely by removing humans from the early and dangerous infrastructure setup. Telesurgery, Inco's Sudbury, Skyworker and many other programs show it can be done. E.g. with only freight in the first five years or so of development, the 18% lower fuel costs of the Belbruno transfer orbit. Belbruno takes advantage of metastable orbits by using lunar and solar gravitational tidal advantages to reduce fuel requirements. Belbruno takes longer, (a month or two) but freight does not require air, water, and food during shipment as people do, and so can take advantage of the great fuel savings.

The minimal lunar settlement of people would occur after much low cost telerobotic or automatic and semi-autonomous work processes and infrastructure were completed. A small closed loop lunar farm could be in full operation before people arrived. In situ resource development would provide most of the necessary materials. SSP Photovoltaic fabrication and shipping to GSO is one of the largest cash market tourism and video tourism is another. So we assume there is a cooperating lunar settlement providing such services at a "reasonable" fee.

IF there is to be a settlement on the Moon, it will surely have to be some sort of partnership-exchanging services to meet the general budget, which give and take from each operational area. (see below) For example, one subsidized operation may develop agriculture by starting with locating a carbonaceous chondrite impact for its carbon and hydrocarbon availability to the lunar settlement.

1. The Moon is a far superior place for many different types of astronomy.
 - A.
 - i. Large telescopes with extraordinary light-gathering power for very deep universe studies, with very long exposures
 - ii. Stable platform for optical interferometry
 - iii. Shielded from Earth (far side) for SETI and long wavelength IR
 - iv. Potential location for very large X-ray and neutrino observatories
 - v. Very low temperatures in cold traps for IR telescopes
 - B. Full Earth, including magnetosphere, can be viewed continuously from the Moon
 - C. The far side of the Moon is useful for radio astronomy installations, and deep space communications facilities.
All would be shielded from Earth's radio noise.
 - D. No atmosphere, no ionosphere, no wind, little corrosion, little or no secondary cosmic rays
 - E. High stability, and very low levels of seismicity
 - F. No electromagnetic radiation from the Earth on the far side of the Moon
 - G. Very low, stable temperatures and no light in polar craters
 - H. An attitude in space known in terms of both position and libration
 - I. Very low rotation rate, allowing long-duration observations
 - J. Studies of the Sun and the Solar System:
 - Solar chromosphere and corona (flux, energy)
 - Solar burst noise
 - UV solar astronomy (spectral studies)

- X-ray solar astronomy (spectral studies)
- g-ray solar astronomy (spectral studies)
- Solar charge particles (flux, energy)
- Solar magnetic field
- Outer planets
- Planetary atmospheres
- Thermal studies of the planets
- K. Studies of Distant Space:
 - Faint and bright objects
 - Wide-band photographic photometry
 - Stellar high-energy phenomena (flare detection)
 - Outer envelopes of stars (gross structure)
 - Periodic irregularities study (detection of planets)
 - High resolution photography
 - High dispersion spectroscopy
 - Low-frequency radio astronomy
 - Radio astronomy (lunar far side only)
 - Galactic nucleon and electron studies
 - Galactic particle scattering
 - UV astronomy
 - X-ray astronomy
 - g-ray astronomy
 - Optical astronomy
 - Neutrino astronomy

2. In situ lunar manufacturing.

- A. Prospective market at GSO for Photovoltaics is many billions. The Moon's industrial base could manufacture solar cells from lunar regolith materials and thus could produce many megawatts of (commercial) power on the Moon within a few years after the first base has been established.
- B. Building materials, especially those based on different types of glass have a rich research base to "build" upon.
- C. You can operate electronics based on thermionic emission (electron flows from heated cathodes) in the natural high vacuum of the Moon. This Natural Vacuum Electronics (NVE) is highly resistant to radiation. Large three-dimensional complex structures for electron flows could be built allowing the invention of new electronic devices based on the free flow of electrons between and through many controlling grids. This applies to communications, computation, and power distribution devices. Many applications of (vacuum tube) technology are still state-of-the-art.
- D. There are no dust storms on the Moon to damage equipment or

structures.

E. Local lunar resources to be exploited include:

Gravity, which could be extremely useful for operating gravity-sensitive hardware, such as phase separators or dust/particle collectors. It also allows heat transfer by natural convection and it helps the growth of plants in that they can sense the "up" direction. Sunlight may be useful for habitat and greenhouse illumination. Glazing or light piping through fiber optics may be used, with adequate radiation protection.

Soil may be used as a source of useful minerals, as construction material, plant-growth substrate (as glass- or rock-wool), as heat sink, or adsorbing material in water filtration.

F. Possible product groups:

Liquid propellants

Technical gases

Food

Raw materials (e.g., water, cement, glass, metals, etc.)

Feedstock (e.g., ilmenite, volcanic glasses, etc.)

Power

Nuclear fuels (e.g., helium-3)

Electric materials (e.g., conductors, semi-conductors, resistance alloys, electrodes)

Pharmaceuticals

G. Possible Services:

Location for an Archive of Humankind

Launch services for space transportation systems

Maintenance and repair of space transportation systems

Space observation and protection of Earth in emergencies

Training services for other space projects

Health care to special ailments

Waste storage services

Tele-Entertainment

Tele-Education

Tourism

3. Safety - "Houston we have a problem" See attached powerpoint slide.

If an accident should occur and the settlers send a "May Day" for an emergency assist, say just for a small 1 metric ton pallet of rescue materials. How long will it take to get it to them???

for Moon three days. For Mars 26 months (orbital launch window period).

4. Solar power at Mars is much weaker than at Moon. At earth orbit

Solar Radiation is 1.367 kWatts/m² At Mars solar radiation is a factor of 2.36 weaker - 0.58 kWatts/m²

The proposed Mars' missions are based on nuclear power that will

likely meet significant political opposition.

5. Belbruno Transfer - a low delta V earth to moon transfer used only once to date by the Japanese satellite Muses A, later renamed Hiten. 18% gain in efficiency over the standard Hohmann transfer. It further improves energy cost of Moon travel. A nice summary of ELLE and this important transfer is at "Easy Low-Cost Lunar Explorer (ELLE)" Produced by the 1998 GSFC NASA Academy August 5, 1998

http://academy.gsfc.nasa.gov/1998/html/project.html#_Toc427469120

6. How do you make money on tourism to Mars?? Maybe to the Moon, but Mars???
7. Water appears to be available on both Moon and Mars.
8. Life studies on Mars/Moon - Even if a few spores were found on Mars, there is no chance that we could differentiate it from life that might have splattered from earth in one of our old meteor impacts.

Subsurface installations on the Moon can be used for genetic engineering experimentation and production that is highly isolated from the Earth's biosphere. (Moveable shielding can be used for radiation breeding experiments as well.) The lack of air or flowing water means that escaped viruses, bacteria, or spores will not migrate about the lunar environment.

9. Physiological damage during flight from Earth to Mars would be much worse than earth to Moon. They may require hospitalization upon arrival at Mars. Zubrin wants to try for artificial gravity using the spent booster as a rotating counterweight, but what does it do for control dynamics?
10. There will be a much lower probability of failure for flights to Mars that are based on the experiences of human space operations in cis-lunar space than those without. Apollo succeeded because of Gemini. Gemini succeeded because of Mercury. Mercury succeeded because of the X-15, etc, etc. Finally, spacecraft can be produced in quantity on the Moon and launched (by mass driver) to all areas of the solar system, including Mars, shortly after the industrial base has been established. Lunar development will thus be the quickest and most effective means for us to become a true space-faring civilization. The goals of the Mars' team will be achieved more reliably, on a far grander scale, and probably sooner by going to the Moon first: Major common designs, operations, methods, and procedures that can be learned in the lunar environment and must be mastered before attempting a Mars mission include:
Transfer vehicle construction and design

Landing vehicle construction and design
Planetary habitation module construction and design
Planetary resource utilization plant and equipment design and operations
Cryogenic propellant storage and transfer systems
Planetary surface vehicle construction and design
Surface science and construction equipment design
Life support systems operations and refinements
In-space planetary vehicle assembly and transplanetary injection
operations, including aerocapture
EVA-based planetary field operations
On-site planetary science and sample analysis methods and procedures
Planetary construction methods and procedures
Trust in automated and computer-controlled systems operations
Planetary outpost site management techniques and procedures
Human factors management (crew psychology and dynamics)

11. Telerobotic support of Lunar near side and polar missions can be operational 100% of the time. Mars telerobotics is not only painfully slow, but must shut down at Martian night (half the time) and when Mars is farthest from the earth due to the sun's blocking of transmission. With a Lunar comm sat, even the far side becomes accessible. A Mars comm sat is also of less help.

Short light time makes teleoperation from Earth feasible and practical. (The delay, about 2.5 seconds round trip, is enough to require training but it isn't impossible as for Mars where the delay is 10 to 40 or more minutes.) We can perform around-the-clock mining, manufacturing, and scientific experiments on the Moon with direct real-time control from Earth - not possible with Mars most of the time.

(The software/hardware slaving technique known as preview telerobotics can even improve the capabilities of lunar teleoperation.) The proximity of the Moon to the Earth will allow us to use very high band-width communications for numerous lunar activities - many orders of magnitude greater than communications support capabilities for Mars. This enables workable telerobotics processes from huge telescope systems to complex manufacturing and monitoring. High communications bandwidth is available to facing half of Earth and 95% of GEO at all times.

12. It's much easier to get off the Moon. Ascent to lunar orbit is about 2 km/s; to Mars orbit about 4 km/s. Return to Earth from surface: Moon, about 2.9 km/s, Mars about 6.3 km/s. This is of great importance for any industrial product which might be returned to Earth (or GSO) for profit.
An accelerator launcher for the Moon is quite feasible – an electromagnetic catapult or a light gas gun (gas guns can be designed

such that very little propellant is lost). The point is that on the Moon you could build an industry and build a launch device to send the products (encased in a lunar-built protective heat shield) to Earth. The device would entirely use lunar resources for operation. Therefore you can transport your product to Earth without having to fly rockets.

13. Lunar polar regions may be at least as hospitable as Mars. No temperature extremes, reasonable availability of solar power (not assured on Mars because of dust storms), and sources of volatiles. The Mars guys used to say that the Moon had no volatiles and was therefore not a suitable target for settlement. Even then they were technically wrong, but with the Prospector discoveries it now seems they were very wrong.
13. The Lunar transportation window is always open instead of Mars window, which is open for about 2 months out of 2.2 years.
15. High vacuum at the lunar surface with near-infinite pumping speed. This is important to some industrial as well as scientific processes. The vacuum at the lunar surface is about as good as achievable with a "wake shield" in Earth orbit; about 10 to the minus 12 torr.
16. Continuous sunlight for ~350 hours. This may be highly beneficial to solar furnace processes needing long durations of continuous heat.
17. Geologically very stable. Remote areas of the Moon may be ideal sites for storage of long-half-life nuclear wastes. People have even argued for storage of plutonium. Hard for terrorists to get to, no risk of water transport or corrosion, no risk of dispersal in Earth's biosphere. Yet it could be retrieved if it was important enough.
18. The Moon beats Mars hands down as a site for developing space industries, assuming all or major part of the market is on Earth. Transport cost is less by about a factor of 10 (part of this is due to trip time difference so don't take credit again for trip time.) For plausible products, the manufacturing environment is better.

(The Moon does not necessarily beat near-Earth asteroids, but any particular one of these is only occasionally accessible.) I think of the Moon as the logical site to begin to develop space industries, and secondarily as a science site. I think of Mars as mainly a science site, especially if any credible evidence of past or present life crops up.

19. We can transport equipment from Earth's industrial base to the Moon in three days, and use lunar materials and solar-electric power to create a commercial lunar industrial base. After several iterations of growth and development, the industrial base will be able to manufacture all of the products necessary for the global human exploration and development of the Moon. The lunar industrial base can be established far sooner, and will be much larger, versatile, and less expensive (potentially self-supporting) than a comparable Mars industrial base.
20. Earth-like biospheres that are protected from micrometeorites and radiation can be created in underground shelters on the Moon. Experiments with regenerative life support systems, agriculture, etc., can then be performed to develop the technological self-sufficiency that is necessary for a space-faring civilization. We will need to do this BEFORE we can go to Mars, and the Moon is the best available site for R&D; the Moon is the ideal space station.
21. SCIENCE:
 - A. The Moon is a keystone in unraveling several important questions about planetary formation that include the formation and early history of BOTH the Earth and Mars.
 - i. Planetary differentiation into core, mantle and crust
 - ii. Ancient impacts, including a possible major influx of impactors in the inner solar system about 4 billion years ago (at the time life was emerging on Earth)
 - iii. Natural large impact crater laboratory
 - B. Moon records information about ancient sun
 - C. Laboratory for 1/6 g experimentation and high vacuum experiments
 - D. Studies of Earth and Cis-Lunar Space:
 - i. Earth atmosphere and Atmospheric heat balance
 - ii. Ocean circulation and Oceanographic heat balance
 - iii. Spectral reflectivity and albedo of the Earth
 - iv. Upper atmosphere UV scattering (upper atmosphere interactions)
 - v. IR Temperature sounding (temperature structure of atmosphere)
 - vi. Eclipse spectroscopy of the upper atmosphere (constituents of the upper atmosphere); Aurora-airglow (correlation with solar activity); Auroral electrons (geomagnetic storms)
 - vii. Magnetospheric tail and Cis-lunar medium
 - ix. Range measurements (libration points, orbits)
 - x. Surface phenomena (zodiacal light, Gegenschein)
 - xi. Terrestrial topography
22. RESOURCES
 - a. Moon is close enough to LEO to make resources useful in space development
 - b. Ice on Moon could greatly accelerate space development

- c. Completely reasonable to support large numbers of people there with local resources.

23. TRANSPORTATION

- a. Lack of atmosphere and low gravity field make transportation possible with very low energy and at much lower cost.
 - i. Direct launch to orbit or Earth, using same vehicle as was landed on Moon (on Mars you need two stages, so face the Shuttle problem, how to have a reusable launch vehicle).
 - ii. Oxygen, at least, and probably hydrogen, can be readily obtained from the regolith, if not from ice at poles
- b. With lunar resource development, transportation from Moon to LEO can become 1/20 the cost of Earth to LEO. This will ultimately lower the cost of Earth to LEO transportation.
- c. Moon to orbit transportation via electromagnetic mass driver can become exceedingly inexpensive.
- d. Large laser beam projectors from Moon can power solar sails far out into the solar system. Benefits from slow rotation and lack of atmosphere.

24. Economic development of LEO

- a. Low transportation costs open possibilities for tourism
- b. Materials production opens possibilities for solar power, helium-3 mining scenarios
- c. Easier to support humans for long duration on Moon than on Mars.
- d. Potential for high vacuum technology development

25. Within anorthositic highland terrains on the lunar far side may exist the lowest natural radiation environments that can be found (low natural radioactivity from K, U, Th; no solar wind or light at solar night; lower neutrino flux). Potential for low radiation experiments.

26. Moon may be required as a quarantine station and R&R location for people coming from Mars or further out in solar system, returning to Earth (or coming for the first time).

27. Excellent location for asteroid interdiction capabilities.

28. The Moon is extremely well suited for as a base for some military operations to police the users of near Earth space and its resources.

Such military capacity could include projectile weapons, particle beams, electromagnetic beams, and robotic vehicles of various types, using energy gathered and stored on the Moon, for example.

In this regard, the Moon is more relevant to the Earth than Mars is.

This important military capability was an implied threat during Apollo, but could become a commanding platform if a space-capable power chose

to exercise that military capability.

29. The Moon can provide radio relay services to the Earth and similarly the Earth can provide relay for lunar bases and vehicles. These services can be a profit-making business that is not dependent on the availability of synchronous satellite orbit slots.
30. The Moon can be an agricultural center for the solar system. The Moon has an advantage of being high up within the Earth's gravity well.
31. The Moon would be a great location for an amateur radio station that could talk to stations all over the Earth using very modest power output (20 to 50 watts to a directional antenna). This would be great for crew recreation as well as a method for publicizing the activities in space to school students etc. Similar amateur radio activities have been routinely conducted on the MIR space station and on the space shuttles.
32. In-situ Construction technologies are very poorly understood. One which has been described is evaporating metal onto an inflated or otherwise deployed very light form. It needs to be done in vacuum to work well. Similar processes are used experimentally on Earth. There has been very little development and we don't know how well it would work.

Another notion is to overwrap a light form with glass (or other) fiber. This would probably work either place. However, the lunar vacuum would greatly aid in producing strong glass fibers from regolith. Water adsorption on glass is one of the principal causes of fracture propagation. Again, not a well-understood technology.

There has been some discussion and experimentation with making things of cast basalt. It is occasionally used here on Earth. Moderately strong, all you have to do is melt it, but it's brittle, so a poor structural material. In a lunar vacuum solar furnace you might find a way to reinforce it with something like alumina fibers, making a ceramic composite. Don't think anyone has tried that as an experiment.

More conventional manufacture means depend on availability and formability of materials. Iron and low grades of steel should be pretty easy to produce on the Moon. Asteroidal nickel iron is pretty tough material, and it is present on the Moon in some quantity; approaches 1% in the regolith. There are probably rich ore bodies of this stuff but at present we do not know of any. There is plenty of iron on Mars but it is oxidized so would have to be smelted. The common means of doing that on Earth is reduction by carbon (coke), which probably isn't practical on Mars because there is probably no coal or other reduced

carbon. Hydrogen might work as a reducing agent (I am not sure it will reduce iron, at least all the way to metal), and if so, could be obtained from water by electrolysis. Or one could use some sort of electric arc furnace. But any smelting scheme is complicated compared to finding the stuff already reduced, as it is on the Moon.

Aerospace guys always want to make stuff out of aluminum or titanium (or, recently, graphite). All of these will be difficult on the Moon or Mars compared to iron and steel. Aluminum and titanium are plentiful on the Moon, but in oxidized form and the reduction processes are difficult. (That's why they are more expensive than steel here on Earth.) There is no reason to want to make habitats out of lightweight metals unless they are intended to fly.

33. The Moon would be a good location for a large high-powered broadcast station that could broadcast to half of the Earth at a time. The station would broadcast simultaneously on several channels in several languages directly to residential receivers. The languages used would change to accommodate the nations facing the Moon at any given time. This station would be powered by a large photovoltaic array and the electronics could be shielded from radiation in a subsurface location. Directional antennas transmit the signal to the Earth. The station would be operated by remote control from the Earth and would be periodically maintained by personnel from the Lunar base. This type of station would eventually replace many short wave broadcast stations.

34. Robotic / infrastructure / scientific payloads can be sent to and from the Moon at irregular intervals. They will be designed to fit together, regardless of when they arrive. If needed, some of them can be made to hibernate while waiting for companions. Budgets, politics, single mission failures, etc., will not necessarily impede the incremental, global exploration and development of the Moon, by design. Mars can develop the same philosophy, but not as easily, and on a much longer time-scale. Better to develop the Moon first, then go gang-busters on to Mars when we're better prepared.” - David Schruck

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(Author: The Moon: Resources, Future Development and Colonization
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“In *The Moon: Resources, Future Development and Colonization*, the authors consider the rationale and steps necessary for establishing permanent bases on the Moon. Their innovative and scientific-based analysis concludes that the Moon has sufficient resources for large-scale human development. Their case for development includes arguments for a solar-powered electric grid and railroad, creation of a utilities infrastructure, habitable facilities, scientific operations and the involvement of private enterprise with the public sector in the macroproject...

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