FINAL REPORT

FOR

SELF-FINANCED, SELF-DEVELOPED AND SELF-SUPPORTING PROFITABLE LUNAR COLONY

A Phase I Steckler Project

NASA Contract No. NNX10AC64A

30 September 2010

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FOREWORD

The late Ralph Steckler, a successful assistant film director and photographer from southern California, maintained a lifelong interest in space colonization. Mr. Steckler left the significant remainder of his estate to NASA "for the colonization of space because [he believed] this is for the betterment of mankind." NASA accepted the gift under the National Space Grant College and Fellowship Act and as a result, this study was conducted. We dedicate this final report to Ralph Steckler's memory.

Dr. R. Aileen Yingst (UWGB), PI and Dr. Eric Rice (ORBITEC), Co-I, would also like to acknowledge the following people who contributed to this Phase 1 effort: ORBITEC – Dr. Martin Chiaverini, Mr. William Knuth, Dr. John Brandenburg, Mr. Brant White, Mr. Mike Fidler, Mr. Scott Munson, Mr. Mark Smith, Mr. Ron Teeter, Mr. Pete Priest; UW-Madison – Ms. Kandis Elliot (Computer Art); Space Settlement Institute – Mr. Alan Wasser; Space Settlement Design Competition – Ms. Anita Gale; AIAA/SCTC – Dr. Narayanan Ramachandran; Mr. Ken Cox – Consultant; Members of the AIAA SCTC, SRUTC, STTC; and various student and faculty members of the Wisconsin Space Grant Consortium.

1.0 INTRODUCTION AND BACKGROUND

This is intended to be a comprehensive report of the results of the work conducted under our Phase I Steckler grant. While we intend to publish some, if not all of this work, it will likely be published piecemeal under several different avenues, as the nature of the work is highly varied. Thus, we have included ALL results here. We direct the reader to Section 2.0 for a summary of results, and to Section 4.0 for a list of accomplishments organized by project goal/objective.

The emphasis of this Phase 1 effort was to develop: (1) a process for an assured economic-based development approach, (2) an innovative, cost-effective, Earth-Moon space transportation system concept, and (3) an innovative Lunar colony resource utilization development approach needed for a low-cost colony at the south pole of the Moon. The first task was to further improve the Lunar colony development approach (legal Lunar land ownership) and to perform education and outreach activities related to the approach. As a key part of our colonization approach and the development of capital, we evaluated an evolutionary "space transportation or space line" concept. The overall capacity, transport nodes, and transportation technologies along with safety and economy were the focus for Task 2. An in-space water [H/O] propellant strategy was baseline. Task 3 involved the development of a plan for using space resources from the Moon for: propellants, volatiles for life support, materials for habitat and other construction, materials for other support systems inside and outside of structures, and resources for equipment and devices needed for Lunar commercial enterprise. A self-sufficient Lunar colony concept previously developed by ORBITEC was used as a baseline guide. Task 4 outlined what we might do in future Steckler efforts to support further space colonization progress.

A colonization team was assembled and integrated to perform the Phase 1 effort. This team is led by the Wisconsin Space Grant Consortium (WSGC) and comprised of UW-Green Bay (UWGB), Orbital Technologies Corporation (ORBITEC), The Space Settlement Institute (SSI), The AIAA Space Colonization Technical Committee (SCTC), The Space Settlement Design Competition (SSDC) Group, and other participants.

Survival of the human race depends on moving out into the cosmos while the window of opportunity for doing so still exists. Besides helping to ensure the survival of humankind, the settling of space—including the establishment of permanent human settlements on the Moon and Mars—will bring significant economic and social benefits to all nations. It would open a new frontier, provide resources for growth of the human race, and energize our society. Space colonization has many benefits for mankind, including:

- Colonization allows survival backup for Earth-based life forms, since we are in jeopardy due to asteroid collision, nuclear war/winter, other environmental catastrophes, or uncontrollable disease epidemics.
- Creation of a second home in the universe for Earth-based life forms.
- Satisfy the need for more living space for an expanding human population at some time in the future.

- A Moon or Mars colony would extend the reach of humans to the outer planets of the Solar System and Universe.
- Promote world-wide teamwork for a world-wide goal and Earth unification.
- Colonization, through terraforming, could return Mars to its presumed earlier status with a more hospitable climate.
- Would be a major economic venture for the Earth's people.
- Colonization efforts would excite the spirit of human population.

The US Government has shown it can't provide and keep the vision nor provide the financial resources to pursue these goals in the near term, and may never will.

There appears to be one incentive, however, that could spark massive private investment leading to the establishment of permanent space settlements on the Moon and beyond with an immediate payback to investors. The concept of "land claims recognition" (developed by Alan Wasser and others [see Appendix A] over the last twenty years) seems to be the most powerful economic incentive, much more so than all the other incentives, such as government-funded prizes, corporate tax holidays (Jobes and Wasser, 2004), and other commercial opportunities. To create incentive in this model, governments would need to commit to recognizing private ownership in advance, rather than long after the fact. Land claims recognition legislation would commit the Earth's nations, in advance, to allowing a true private Lunar settlement to claim and sell (to people back on Earth) a reasonable amount of Lunar real estate in the area around a base, thus giving the founders of the Moon settlement a way to earn back the investment they made to establish the settlement. This model would be similar to that executed by Walt Disney, who, with the creation of Disneyworld, turned swampland in central Florida into some of the most valuable real estate on the planet. Appropriate conditions could be set in the law, such as the establishment of an Earth-Moon space line or space transport system open to all paying passengers regardless of nationality. For context, we include in Appendix B the bill "An Act to Promote Privately Funded Space Exploration and Human Settlement" (or for short -- "The Space Homestead Act") which was derived from The Space Settlement Prize Act (Wasser 2008).

The 1967 Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, generally called the Outer Space Treaty, is the primary basis for most international space law. The treaty was negotiated by the United States and the Soviet Union to end the costly space race between them. The Outer Space Treaty does appear to permit private property ownership in space and permit nations on Earth to recognize land ownership claims made by private space settlements. Wasser and Jobes (2008) provide seven examples that suggest that the Outer Space Treaty does not ban private property.

Our work is based on the assumption that such a model of private land ownership as outlined above is possible.

2.0 EXECUTIVE SUMMARY

This section provides an executive summary of the work conducted during this Phase 1 Steckler effort.

The approach of private land ownership on the Moon, offered by Alan Wasser and supported by Klaus Heiss, provided the framework for this study, as noted above. We began by reviewing and refining this overall approach. We refer to our refined model as the "Space Homestead Act". All of the arguments were discussed in many open and closed forums, and at this time, we believe it remains a valid proposition.

In this review process and formulation of a low-cost and safe Space Transportation System Architecture and development of a cost-beneficial Lunar Space Resource Utilization Plan, we conducted various outreach activities. They included team member interactions with: (1) the AIAA Space Colonization (SCTC), AIAA Space Resource Utilization (SRMTC), and AIAA Space Transportation (STTC) Technical Committees (usually made up of 30 to 40 professional members from around the country and world); (2) the WSGC; (3) attendees at AIAA conferences, including ASM-2010, JPC-2010, and Space 2010; (4) the University of Wisconsin at Platteville, and (5) the Space Settlement Design Competition Group. We also developed several presentations to use as outreach tools.

We developed a Space Transportation System Architecture that is described in the report based on certain key requirements:

- Exclusive use of ORBITEC's reusable low-cost USLV booster and its low-cost propane/LOX propellants for Earth launch
- H_2O in-space propellant economy based on water availability on Earth and Moon and its high performance, safety, and simple storability as water.
- Space depots at LEO (28.5 degree inclination), LLO (polar orbit inclination for easy access to the south pole), and LS (at the south pole base).
- Space base colony at the south pole to take advantage of the environment and access to water and other gases.
- A reusable Crew Return Vehicle (CRV) with a capacity of 5 passengers and cargo for Earth horizontal landing.
- A reusable Lunar Transfer Vehicle (LTV) with a capacity for 5 passengers and cargo to travel back and forth between the LEO depot and the LLO depot.
- A single-stage reusable lander.
- A Solar electric cargo system powered by water microwave electric thrusters.
- Initial hardware – all Earth supplied, with growth depending on SRU supplied materials.

We developed an approach for SRU that is based on cost-effectiveness of use. Initial key SRU materials are water, oxygen, hydrogen, iron, aluminum, silicon, silica, concrete, basalt, and lunar regolith itself.

We developed an outline for commercialization based on land ownership to proceed. We also developed a list of possible secondary commercial activities that one day could lead to profitability and significant growth of a colony.

Finally, we have proposed possible Steckler Phase 2 tasks that include:

- USLV Plug Nozzle Development
- Space Transportation Architecture and Cost Model
- Space Depot Concept
- Design of an Earth-based SRU Laboratory
- Processing of SRU Metals (Al, Fe, Si)
- SRU Cost Benefit Models
- Outreach and Education
- Commercial Program Planning.

3.0 PHASE 1 RESULTS

This project included 5 basic tasks that flowed from the goals and objectives of the Phase 1 proposal. The tasks conducted for this Phase 1 Steckler effort are outlined below and the results discussed in the sections that follow.

- Task 1. Develop the process for an assured economic development approach and to conduct public education and outreach activities
- Task 2. Develop an innovative, evolutionary, cost-effective, Earth-Moon space transportation system/space line concept to allow private Lunar land ownership
- Task 3. Develop an Innovative Lunar colony resource development plan based upon the basic needs and commercial activities of the Lunar colony
- Task 4. Provide preliminary plans for Phase 2 and 3
- Task 5. Prepare and deliver a final report and outreach presentation.

3.1 Develop the Process for an Assured Economic Development Approach and to Conduct Public Education and Outreach Activities (Task 1)

For this task, we further developed the process for a confident economic development approach and conducted public education and outreach activities for colonization of the Moon. Starting with Alan Wasser's approach developed by SSI, Dr. Klaus Heiss's approach and work of the Jamestown Group, and the direction and scope of the AIAA SCTC, we reviewed and assessed the strengths of the arguments. We reviewed the draft "Space Settlement Prize Act" by Wasser (2008) and modified it (see Appendix B). We engaged AIAA Technical Committees, including Space Colonization (SCTC), Space Transportation (STTC), and Space Resource Utilization (SRUTC). Dr. Rice, as a member of each committee, led the interactions. Alan Wasser participated as a member of the SCTC and provided his expertise to the TCs on the subject. Unfortunately, Dr. Klaus Heiss, former chair of the SCTC, passed away during the conduct of the project. We discussed the colonization approach and tasks with each committee several times during the duration of the project. We had extended discussions with the SCTC, chaired by Dr. Ramachandran. Dr. Rice presented the concepts to a large group at an Advanced Propulsion Session at the Join Propulsion Conference in July. Dr. Rice also presented the approach and study results to students and faculty at UW-Platteville and convinced the faculty to join the WSGC.

In terms of outreach, we created a AIAA/SCTC-funded Space Exploration College Scholarship and supported the Space Settlement Design Competition efforts of Anita Gale. An example of an RFP generated by this group is provided in Appendix C.

We have recently proposed a new AIAA Position Statement on the Colonization of the Moon (see Appendix D) within the SCTC and initiated a Space Colonization Award to the most active and productive AIAA participant in the field on a bi-annual basis.

We have recently begun a dialogue with members of the film industry considering the making of film about private space homesteading of the Moon. There is a request that members of the film industry review the Phase 1 report as the next step.

We developed or improved Space Colonization websites, namely of SSI, AIAA/SCTC, SSDC, and ORBITEC. One of the outputs from this task was an outreach presentation on this Phase 1 Steckler effort – the human colonization of the Moon.

We have developed an initial overall colonization approach to commercializing a transport system and colony using the Space Homestead Act model. Our approach is outlined below:

Overall First-Cut Approach to Private Human Colonization of the Moon and Other Celestial Bodies

[Approach to Develop Private Lunar Transportation & Lunar Settlement (PLTLS)]

1. Develop a Consortium of Interested Private Sector Individuals, Organizations, and Corporations (Commercial Support Group)
2. Further Draft, Promote and Pass into Law the "Space Homestead Act"
3. Conduct a Lunar Land Value Analysis
4. Develop the Baseline Requirements for the PLTLS
5. Develop the Baseline PLTLS System Architecture based on the Current Draft of the Space Homestead Act and this Phase 1 Steckler Study Results
6. Develop a Living Business Approach/Plan and Competition Assessment for PLTLS
7. Develop the Technical, Financial, Legal, Political and Other Critical Information that Is Needed to Close the Business Case.
8. Execute the Private Placement for PLTLS.

Next Steps: Development of Additional Critical Information Through Phase 2 and 3 Steckler Support and other Private Contributions

1. Evolutionary System Requirements Definition
2. Continuing Transportation and Settlement Architecture Development
3. Continuing Transportation System Hardware Definition
4. Continuing Lunar Settlement and Earth-Supplied System Hardware Definition
5. Develop Enabling and Enhancing Technologies and Models to Support the PLTLS
6. Develop Possible Growth Scenarios
7. Define Main (Lunar Land Ownership) and Contributing Commercial Activities and How Each Can Contribute to Overall Success
8. Define SRU Development Plan to Support Future Growth and Profitability

If this project team continues to be successful in the Steckler program by winning a Phase 2 proposal, we expect to continue with the plans outlined above.

3.2 Space Transportation System Architecture (Task 2)

As discussed in the Task 1 write-up, the space transportation system architecture is the key to carrying out homesteading and settlement on the Moon. This architecture was developed by ORBITEC engineers, Dr. Eric Rice, Dr. Martin Chiaverini, and William Knuth with the basic assumption that water would be the main source of propellant for in space propulsion and that we would need to initiate the system with a five passenger transportation requirement. The sections below provide a discussion of the other requirements and solution.

3.2.1 Mindjet Map of Space Transportation Architecture

When we began the effort, we began developing an architecture that had three time periods, initial, intermediate, and far term. We chose to focus on the initial phase. We used MINDJET software to develop the definition maps of the architectures, Figure 3.2-1 provides the summary of our baseline initial space transportation architecture that we have defined for the Phase 1 effort. The map provides all the key aspects that needed to be identified.

3.2.2 Architecture Element Discussion

In this section we discuss the various aspects of what we believes is the best low-cost and safe starting approach for the implementation of commercial space line and base on the Moon. Each of the architecture elements are discussed in the sections below:

3.2.2.1 Propellants

The selection of LOX/propane for Earth launch to LEO and beyond was made based upon the success ORBITEC has had in testing its vortex rocket engines with this combination. Propane has been a great propellant in terms of safety, operations, cost and performance, and it out performs methane in the USLV.

As far as in-space propellant, we selected hydrogen, oxygen and water as the propellants of choice for a clean, safe, non-toxic, and low-cost solution. Water is abundantly available on Earth and the Moon (as discussed below). The plan is to supply water to the LEO depot from the Moon and Earth. After the Moon base is established, we will supply Earth orbit, Lunar orbit, and surface depots from the Lunar water resources found at the south pole base on the Moon. Water will be stored and processed into hydrogen and oxygen as high-pressure gases and low pressure liquids. These propellants will then be stored at the Lunar surface and orbital depots. Water itself will be used as the propellant for the Solar Electric Propulsion (SEP) system that will carry cargo to and from the orbiting Lunar and Earth-based propellant depots. The significant availability of water on the Moon is discussed below.

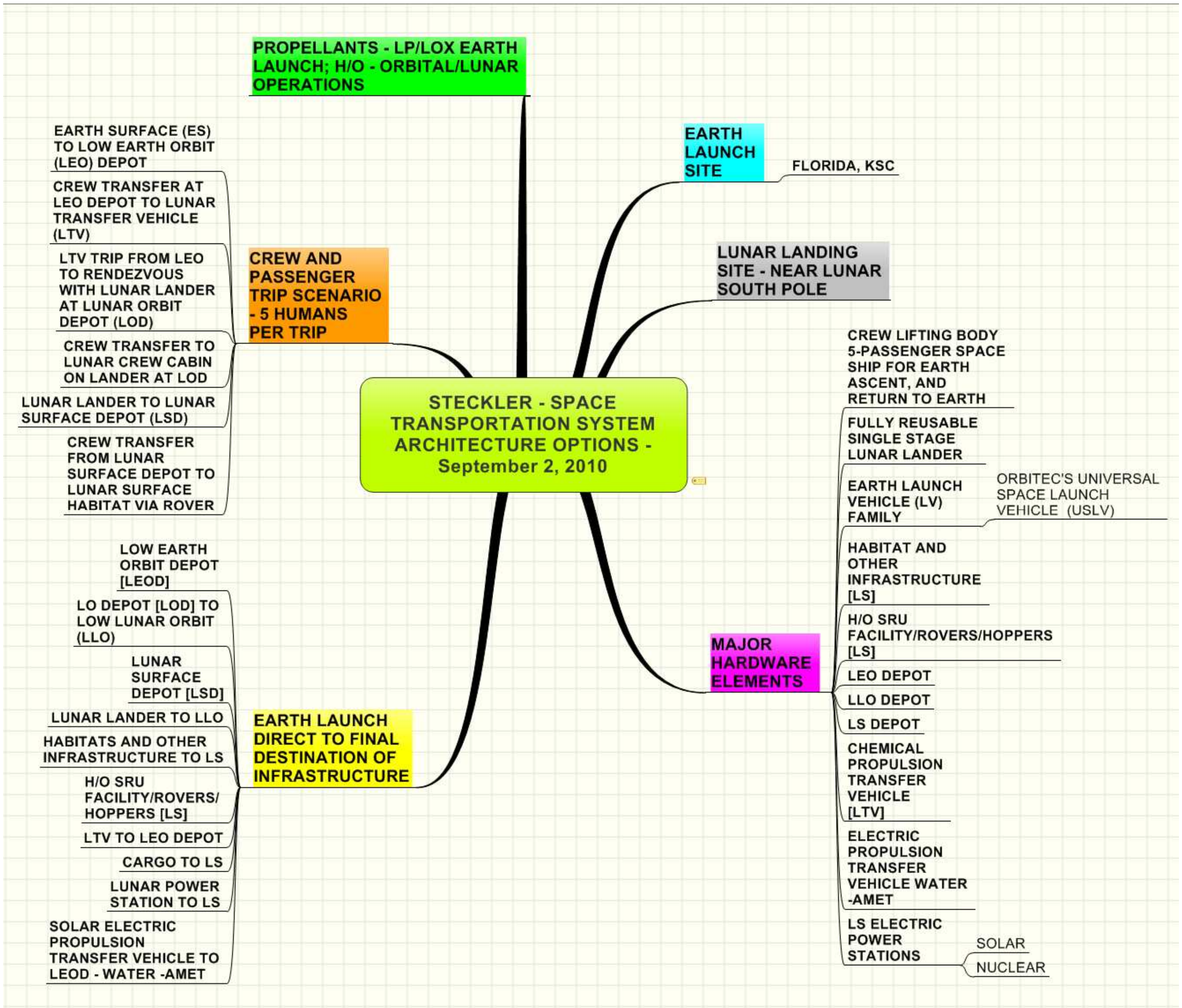

Figure 1. Mindjet Map of Steckler – Space Transportation System Architecture Options

The Moon likely has a large inventory of water, mostly at the poles in perpetually shadowed craters, but also distributed on/in surface rocks in decreasing concentrations as one nears the Lunar equator. The Lunar polar deposits have been found to have approximately 2% water by weight of water mixed with other volatiles normally found in comets (e.g., Feldman, et. al, 1998; Hand, 2009; Elphic, et. al., 2010). The water found in Lunar surface rocks away from the poles is roughly 1 part per thousand by weight with slightly more nearer the poles and slightly less near the equator. Water is now believed to be a part of all Lunar rocks in concentrations of approaching a part per thousand with total recoverable amounts on the Moon of billions of tons. The discovery of water on the Moon in these large amounts is of great importance for colonization and travel in the Solar system.

3.2.2.2 Earth Launch Site

For the moment we have selected Kennedy Space Center (KSC), Fl as the main launch site for Earth launch operations. We plan to place the Earth-orbiting depot at 28.5 degrees and therefore this launch site is compatible. If a lower cost launch site becomes available as the effort moves forward, then we will consider other sites.

3.2.2.3 Lunar Landing Site/Base, Near Lunar South Pole

The base would be located at the southern pole of the Moon. There are several reasons to choose this location. First, data from the Lunar probes has indicated significant amounts of frozen water ice at both Lunar poles in cold traps where the sunlight is severely limited or non-existent (bottoms of craters and depressions). This resource will provide a valuable feedstock for water, oxygen, and hydrogen to support Lunar surface activities, provide life support consumables, and allow low-cost transportation back to the Earth. Second, there are several areas at the south pole that receive near-constant Sunlight. Two locations near Shackleton crater at the Lunar south pole have been identified that collectively receive sunlight for ~98% of the time, making them excellent sites for the base and the associated Solar power systems [Bussey et al., 1999; Lafleur, et. al., 2010]. The availability of near continuous power eliminates the need for long-term energy storage. Third, the temperature environment is much more consistent than other non-polar Lunar sites, with few dramatic temperature shifts. The small changes in temperature will simplify the thermal control system requirements of the Lunar base and reduce cyclical thermal stresses. Lafleur, et.al. (2010) has reported the development of a new software model to predict sunlight as a function of position and height above the surface. Also, these authors report the development of a model that defines the position of the Earth as a function of position and height to support the locations of Moon-Earth communication systems on the Lunar surface.

3.2.2.4 Major Hardware Elements

The major hardware elements that we believe are minimal and necessary at the start of the commercial transportation and base system are listed and discussed below.

- Crew Lifting Body 5-Passenger Space Ship for Earth Ascent and Return to Earth
- Fully-Reusable Single-Stage Lunar Lander
- Earth Launch Vehicle (LV) Family – ORBITEC's Universal Space Launch Vehicle (USLV)
- Lunar Surface Habitat and Other Infrastructure [LS]
- Lunar Surface H/O SRU Facility/Rovers/Hoppers [LS]
- LEO, LLO, LS Depots
- Chemical Propulsion Lunar Transfer Vehicle [LTV]
- Solar Electric Propulsion Cargo Transfer Vehicle–Water – AMET
- Lunar Surface Electric Power Stations.

3.2.2.4.1 Crew Lifting Body 5-Passenger Space Ship for Earth Ascent, and Return to Earth

The vehicle for crew transport from the Earth's surface to LEO is initially projected to be a winged fly-back orbital vehicle that can carry 5 crew/homesteading passengers and some cargo. It is launched on the USLV-L. The spaceship would be captured by the large robotic arm on the LEO Depot and be placed in a protected and pressurized vehicle bay for crew transfer and servicing (It is also possible to use a docking port with no servicing container). The crew ship would remain docked at the depot until a crew is ready to return to Earth. The notional design concept is based upon a "larger" X-37-type vehicle. Currently, we do not intend to employ capsules like Orion that return to the water.

3.2.2.4.2 Fully-Reusable Single-Stage Lunar Lander

We plan on developing and using a fully-reusable, single-stage Lunar lander with its own integrated crew cabin and cargo storage volumes to carry crews and homesteaders (up to 5) to the Lunar base via the surface depot. Unlike the Apollo LEM and Altair, with their two descent and ascent stages, our lander will use hydrogen and oxygen liquid propellants provided at the Lunar orbit and Lunar surface depots. It will also have the capability to carry cargo both ways, transport water (generated on the Lunar surface), and carry extra LH_2 and LOX and water up to the Lunar orbit depot. National Lunar lander concepts are provided in Figure 2.

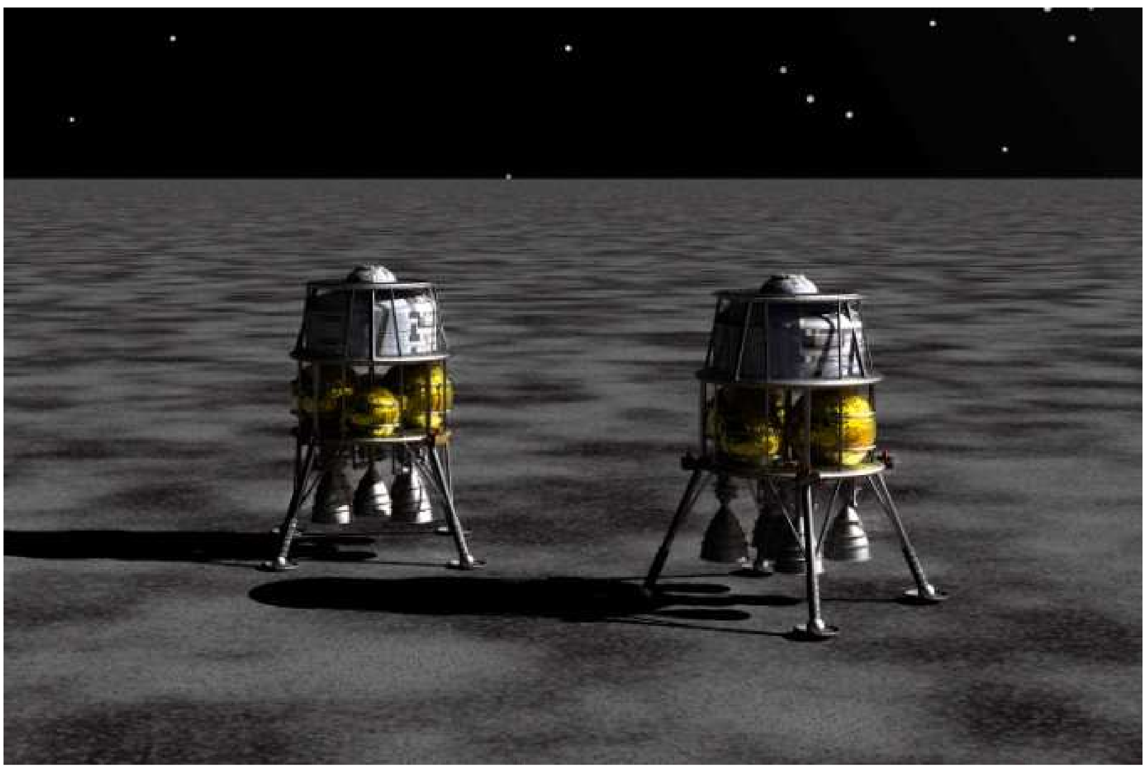

Figure 2. Notional Lunar Lander Concepts

3.2.2.4.3 Earth Launch Vehicle (LV) Family - Universal Space Launch Vehicle (USLV)

ORBITEC has been developing innovative, low-cost rocket propulsion since its founding in 1988. For this Steckler Study, we have selected the ORBITEC USLV Family to provide the Earth launch capability for the Space Transportation Architecture. We have been striving for systems that provide low-cost access to space through innovative new approaches to space launch/boost. We have been working on low-cost propulsion and launch technologies, including: new low-cost, vortex cold-wall rocket engines that use LOX/Hydrocarbon propellants; vortex-fed advanced hybrid engines; USLV-the Universal Space Launch Vehicle Family; and the HSLV-the

Hybrid Space Launch Vehicle as well as Solar and nuclear powered water-based microwave electromagnetic propulsion systems. The USLV Family is briefly discussed below.

ORBITEC's vehicle concept is a family of different sized Universal Space Launch Vehicles (USLVs) intended to provide responsive, low-cost launch services to the military, civil and commercial space communities for different sized payloads. Detailed conceptual layouts of the baseline vehicle configurations have been completed and initial mass breakdowns have been calculated and detailed cost analyses have been achieved. Figure 3 shows the baseline four conceptual vehicle configurations. The baseline vehicle configurations include conceptual designs of all of the major structural components. These component designs were used to prepare overall vehicle mass allocations and cost estimates. The primary structural component of each stage is the propellant tank system which is connected to adjacent stages by a skin and stringer-type interstage structure. A conservative structural design approach was taken, applying a safety factor of 1.5 and assuming all structural components were fabricated from an appropriate aluminum alloy.

Figure 3. USLV Family (S, M, L, and XL)

Key features of the vertical takeoff-vertical landing (via parachute) USLV family include: (a) integration of the propulsion in a plug cluster propulsion system; (b) use of propane fuel sub-cooled to atmospheric boiling LOX temperature to take advantage of the availability and low cost of the propellants, and the approximately 30% increase in density; (c) use of Vortex Combustion Cold-Wall (VCCW) thrust chambers to minimize chamber cooling issues and to take advantage of the rugged, highly-reliable, low-cost, simple chambers; (d) mixing and matching thrust chambers among the vehicles and use of different numbers of chambers for a given total thrust among stages to minimize the total number of chamber sizes required; (e) use of plug cluster nozzles for altitude compensation and their improved performance; (f) use of small enough chambers on each stage to provide high tolerance of chamber-out operation; (g) potential for air augmentation of the first stage to enhance mission performance; and (h) other unique proprietary innovations. Stored helium can also be used for pneumatic actuation of the two main propellant valves as well as the bi-propellant valves on each thrust chamber. Simplicity, commonality, low parts count, fast responsive turnaround and low maintenance result from the features shown above.

Reasoning for choices of major subsystems include:

Three Stage Vehicle System: Chosen for high-payload fraction, low Gross Lift-Off Weight (GLOW) minimizes liftoff thrust to save propulsion subsystem cost and minimize overall vehicle size, USLV propulsion system simplicity allows third stage staging without undue added risk or cost to the mission, and energetic third stage offers added mission flexibility.

Plug Cluster Nozzle: Chosen for ability to use small easily-developed chambers to obtain high total thrust, steering by chamber thrust modulation, capability to sustain chamber-out conditions without loss of mission, performance improvement by altitude compensation, potential for added performance via air augmentation of the plume.

Pressure-Fed Propellant Delivery System: Chosen for simplicity of design and operation, assured propellant delivery transients on startup, tolerant of thrust modulation flow rate changes, provides important secondary use for on-board power and pneumatic actuation of valves, aids in stage touchdown during recovery, avoids complexity of turbopumps and their drive gas supply system, and offers ease of refurbishment and reuse with minimal maintenance.

Vortex Combustion, Cold-Wall Thrust Chambers: Cold-wall operation provides indefinite service life, with inexpensive hardware, simple, repeatable start sequence to assure uniform light-off of the plug cluster, and ease of development in various sizes because of fundamental simplicity.

LOX/Sub-Cooled Propane Main Propellants: High density impulse performance, good cooling capacity, low-cost readily available fuel, sub-cooling process allows cold-trapping/removal of trace quantities of butane etc., residue-free cryogenic fuel avoids contaminant hazards in multiple reuse operations, is non-toxic in the event of spills, etc.

Sea Recovery of the First and Second Stages: The vehicles are designed with reusable first and second stages that are parachute-recovered at sea. The reasoning behind the preference for a VTOVL system with sea recovery stems from early SEALAR studies. Flyback first stages are significantly more complex to develop, operate and maintain because of their requisite aircraft features. They are heavier than their equivalent wingless stage counterparts, requiring higher liftoff thrust if vertical takeoff, and incurring higher drag losses in the atmosphere. They are more sensitive to weather conditions and wind shear aloft than vertical landing designs. Their size envelope adds to the features needed in the stacking sequence and on the launch platform. The wings are fragile and prone to damage in routine vehicle assembly and handling, which will require care and training. The vehicle will unavoidably require additional fluids in its servicing and operation. The aircraft will also be dependent on a landing strip, which further constrains its use. The Space Shuttle is an example of a flyback booster, albeit one that exaggerates the faults of such vehicles. However, it unavoidably combines all of the features needed for rocket flight with all the features (other than engines) needed for aircraft flight, all of which must work on every flight. All-in-all, flyback boosters add to vehicle and mission complexity, and risk rather than simplifying them. Achieving the goals of responsiveness and cost savings are difficult to foresee with such booster systems. Parachute stage recovery at sea has been assessed in SEALAR studies as well as other investigators to be less expensive than a winged horizontal landing vehicle. The first stage separates at approximately MACH 4-5 at about 100,000 ft altitude and 80 miles downrange. Drogue chutes deploy to slow the initial descent, and at the appropriate conditions, the main chutes unfurl. The main chutes provide approximately 15-20 nmi cross-range, to shorten the return to port. As the stage approaches the sea surface, the residual main pressurant is vented through selected thrust chambers, slowing the descent velocity further to on the order of 20 feet per second and producing a cushion of aerated water at the point of entry. Less risk of damage is expected from water than cushioned terrestrial landings. The stage is retrieved by a well-deck type ship and returned to port. The first stage is readily returned to port where it is given a fresh water wash, refurbished and returned to the vehicle assembly/stacking line for the next use. The low first cost of these stages allows several stages to be in the assembly queue to avoid delay of next flights. We also plan to recover the second stage in the water and will study and evaluate novel deceleration techniques in the future, as USLV becomes a reality.

The ORBITEC vehicle family consists of four vehicle sizes having payloads of 2,000, 20,000, 50,000 and 300,000 lb (to LEO), respectively--see Figure 3. The commercial marketplaces are expected to have on-going and emerging requirements to launch various cargo sizes. Volumetric efficiency of larger vehicles saves relative inert mass, which results in higher payload fractions and lower cost per pound of payload. The vehicle characteristic are presented in Figure 4. However, it is inconvenient to schedule and more costly in labor hours to seek to manifest for a wide range of small payloads on a single large launcher on a regular basis. This gives rise to the need for smaller vehicles as well. The four vehicles of the USLV family (twelve individual stages in all) share a common design basis, use the same propellants throughout, use only eight different propellant tank systems, four sizes of thrust chambers, and valves, and retain commonality of electrical, electronics, Guidance Navigation and Control (GNC), pressurization and other hardware throughout. Therefore, learning curve benefits can be credibly applied. Likewise, spares, service and maintenance, technician training and flight operations and support equipment are common among the vehicles.

It is of interest to note that the individual stages are virtually self-sufficient other than for the vehicle Guidance, Navigation and Control (GNC) package. This allows the first stages to serve as the boost stage for nearly any upper stage package that has a compatible weight, and size envelope, and is able to accept the acceleration profile capability of the stage for its mission. This versatility adds to the mission flexibility possible. The operations scenario is based upon a waterborne approach where water canals are used for vehicle transport at the site. Launches are from overwater launch pads (see Figure 5–Cargo Launch of USLV-XL). Vehicle final assembly and stage stacking is performed in the horizontal assembly facility (HAF) on floating transporter/erector platform barges that are readily moved along the assembly line. Automatic ballast systems keep the barges level and maintain the deck elevations respective to each other.

Vehicle	USLV-S	USLV-M	USLV-L	USLV-XL
Payload (lb)	2,000	20000	50,000	300,000
GLOW (lb)	72,300	622,600	1,806,500	12,065,000
Dry Mass Fraction (%)	17	15	14	15
Total Propellant (lb)	60,000	523,000	1,536,000	10,255,000
Length (ft)	38	68	86	240
Stage 1				
Tank System OD (ft)	11.5	22.5	30	60
# Chambers	36	28	28	30
Engine Thrust (klb)	3	30	75	500
Stage 2				
Tank System OD (ft)	7.5	15.5	22.5	39
# Chambers	26	26	26	28
Engine Thrust (klb)	3	30	75	500
Stage 3				
Tank System OD (ft)	4.8	11.5	15.5	30
# Chambers	4	20	6	16
Engine Thrust (klb)	1.5	3	30	75

Figure 4. USLV Vehicle Characteristics

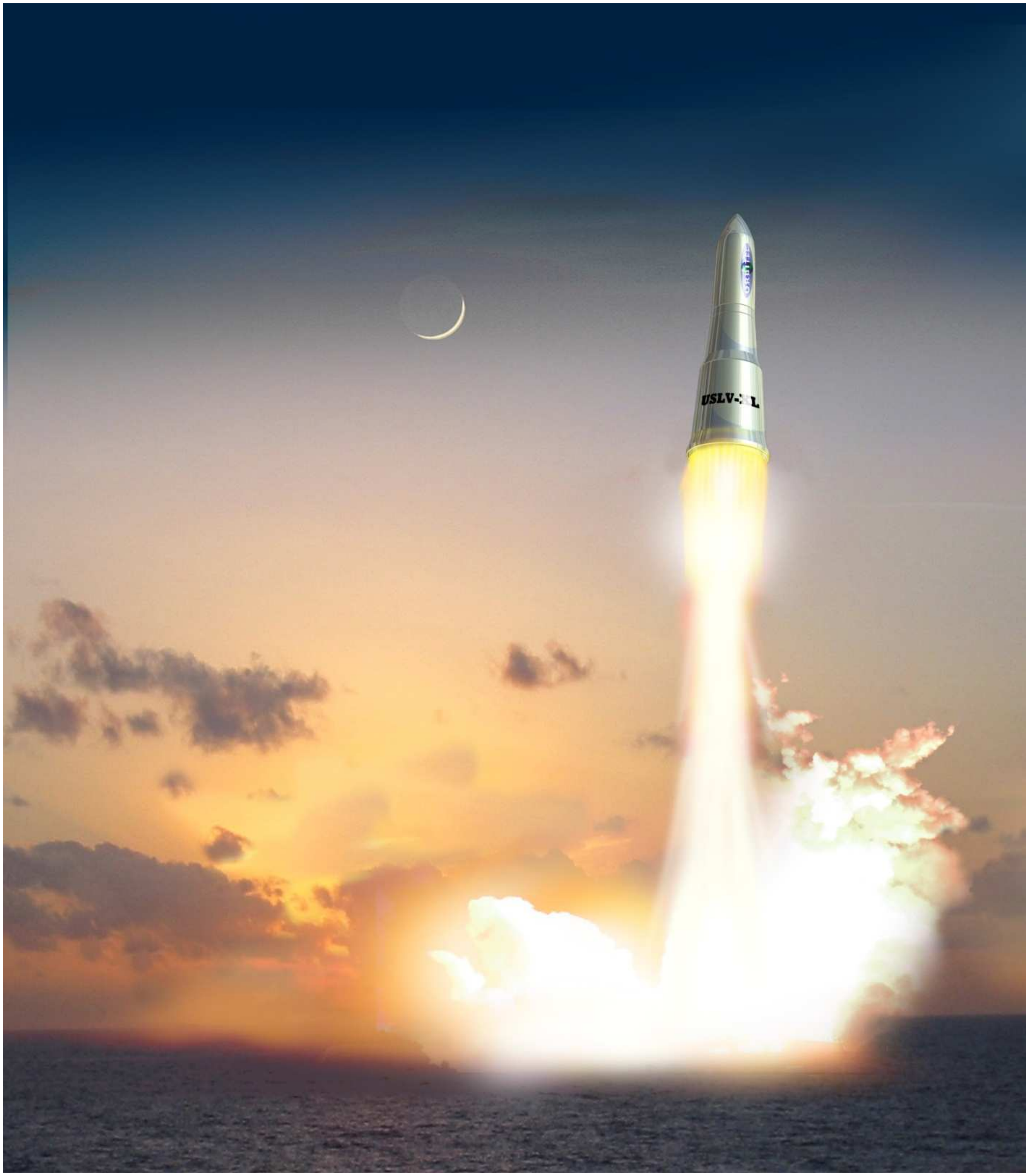

Figure 5. Cargo Launch of USLV-XL

Parallel water channels and their barges, served by common overhead cranes and support facilities allow the simultaneous assembly of several vehicles to proceed efficiently. The assembled empty vehicles are then readily moved on their erector barges via water channels out to the launch pads and erected into position on the pads by the combined use of the erector barge strongback and the hoisting gear on the launch tower. The vehicle tanks are filled with LOX and subcooled propane propellants, pressurant spheres are charged with helium, final payload checks are performed, the crews (for USLV-L) boarded, and the vehicle is cleared for launch. Launch platforms are configured to direct the exhaust plume into a deep water basin that engulfs and quenches the plume during liftoff to minimize acoustic pressure levels and plume afterburning. Shaping of the underwater and overwater structure directs the later steam plume flow out and away from the launch envelope. See Figure 6 that shows USLV-L launching a 5-person crew vehicle to the LEO Depot.

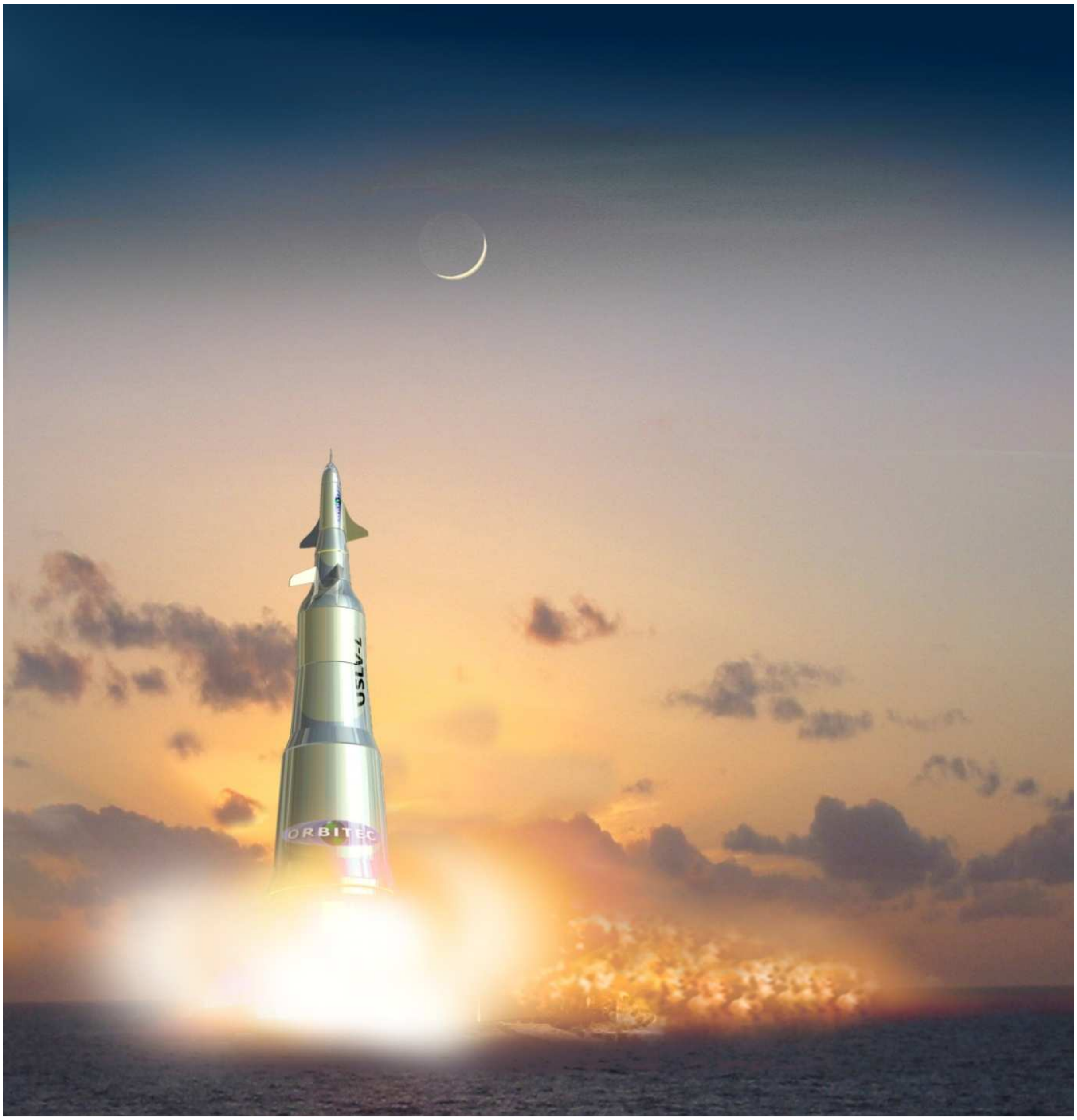

Figure 6. Crew Launch of USLV-L to LEO Depot

Performance of the USLV is based on the use of propane as the fuel. The density I_{sp} of LOX/sub-cooled propane, as shown below in Figure 7, is better than methane, and approaches that of kerosene. This is a major benefit in both pressure-fed and pump-fed systems. For a pressure-fed system the reduction in tank size (and wall thickness for a given pressure), offers a significant weight savings both in tank weight as well as in the pressurant system and residual pressurant.

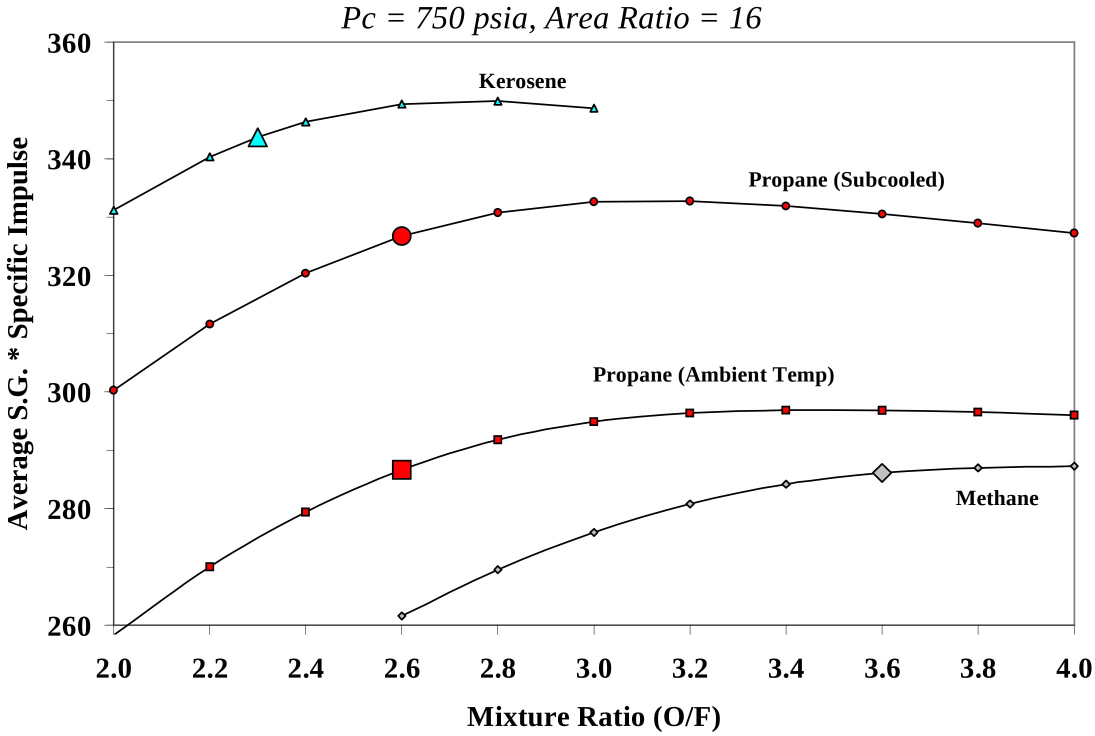

Figure 7. Density I_{sp} vs. Mixture Ratio for Various Hydrocarbon Fuels

Preliminary "cost per mission" estimates have been developed for the four USLV vehicle sizes. The estimates include the first costs of the vehicles, and launch labor, as well as support function labor for facility operations as well administrative support labor. Capital costs for DDT&E, manufacturing shops and launch facilities are not yet included for amortization. Figure 8 shows cost analysis results for the case of 1st and 2nd stage reusability.

Vehicle	Facility Ops Lbr	Refurb/Lnch Labor	Expend 3rd stg	Propellants	Total	Lb Cargo	$/Lb to LEO
SLV-S	$ 960,000	$ 1,463,500	$ 333,200	$ 12,500	$ 2,769,200	2,000	**$ 1,385**
SLV-M	$ 1,440,000	$ 2,324,200	$ 756,900	$ 108,300	$ 4,629,400	20,000	**$ 231**
SLV-L	$ 1,920,000	$ 3,698,900	$ 3,248,800	$ 319,500	$ 9,187,200	50,000	**$ 184**
SLV-XL	$ 2,880,000	$ 5,798,400	$ 4,490,400	$ 2,133,000	$ 15,301,800	300,000	**$ 51**

Figure 8. Cost Summary (in $) for Four USLV Sizes, with USLV Reusability

The primary cost driver for USLV launch costs is the refurbishment, assembly and launch labor, plus the administrative costs of operations. The simplicity of the USLV design offers both low first cost and simplified operations to achieve major cost savings. Figure 9 provides a cost comparison between the USLV family of vehicles and other current LVs.

Launch System	Cost ($M)	Payload (lb)	$ per lb to LEO
Falcon 1	8.5	1,500	5,700
USLV-S	**2.77**	**2,000**	**1,385**
Falcon 9	40	20,000	2,000
Ariane-5	140	35,000	4,000
USLV-M	**4.63**	**20,000**	**231**
Delta IV	170	50,000	3,400
Atlas V	400	50,000	8,000
USLV-M	**9.19**	**50,000**	**184**
Shuttle	800	54,000	14,800
ARES-V	1000	275,000	3,600
USLV-XL	**15.30**	**300,000**	**51**

Figure 9. **Comparative Costs to Other Vehicles by Class**

USLV Main Engines. As has been discussed extensively in foregoing sections, the main engine is actually integral with the stage propellant tank systems and depends on the tank system for mounting structure, propellant feed system and exhaust plume expansion surface. It is comprised of up to as many as thirty six individual relatively small identical thrust chambers, operating in unison to provide the desired total thrust. The chambers can be throttled to provide thrust vectoring and overall thrust control. Design and development on deep-throttling concepts has been initiated at ORBITEC, investigating variable area injector elements. It is anticipated that 10:1 throttling will be possible with the cold-wall chamber, by film cooling the chamber throat. Deeper throttling can be achieved if needed for the mission by the simple expedient of shutting down selected chambers. The chambers themselves are vortex combustion cold-wall chambers that operate without heat reaching the chamber wall (see Figure 10). They are arrayed around a central plug that provides the expansion surface. The arrangement allows the exhaust plume to expand to atmospheric pressure at all times and so is inherently altitude compensating for expansion ratio. This feature raises the mission-averaged I_{sp} for the stage, and provides an I_{sp} gain over that provided by the thrust chamber only. Steering with a plug cluster is achieved by thrust modulation. It is expected that it will be possible to throttle a bank of chambers up 5%, while throttling down an opposed bank of chambers by 10% without undue loss of total thrust during the steering action. This total 15% thrust misalignment imposed at the tank periphery is estimated to be the equivalent of approximately a 6 degree gimbal angle on a centrally mounted conventional thrust chamber.

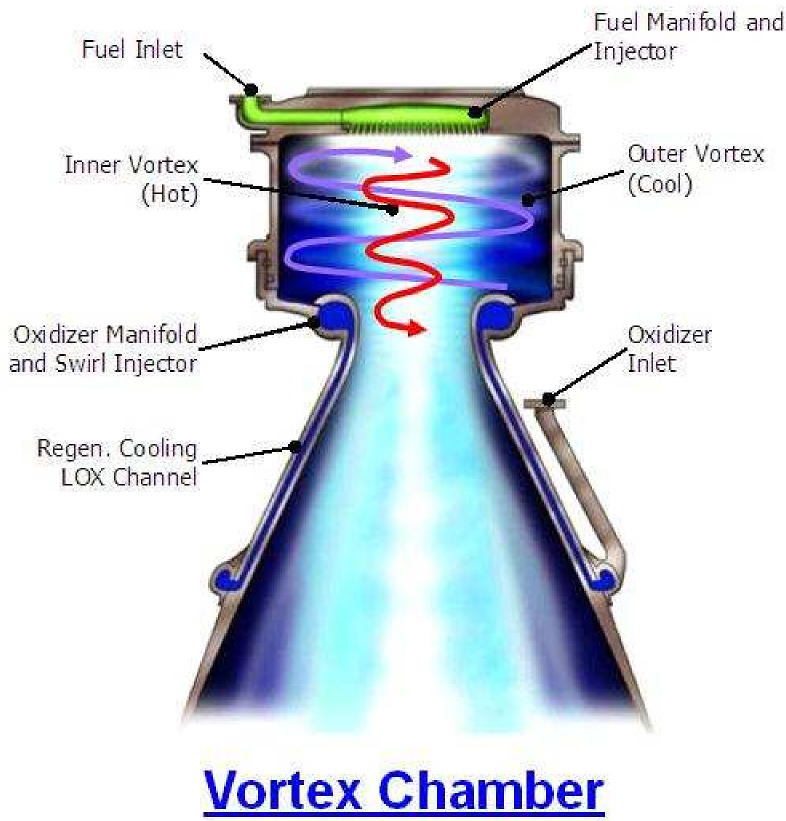

Figure 10. **ORBITEC's Vortex Cold-Wall Rocket Engine Concept**

Performance testing of the VCCW chambers with LOX/propane has demonstrated C* efficiencies of above 97% of theoretical. The vortex combustion process provides an extended flow path for the propellants in the combustion region to promote more complete combustion. With gaseous propellants such as with a pump-fed system, C* efficiencies above 99% were achieved. For the USLV family, the chamber sizes are 1.5, 3, 30, 75, and 500 Klb thrust. A given stage uses chambers of all one size.

The primary development efforts during the DDT&E phase will be to fully develop the plug cluster nozzle and the thrust chamber assemblies that make up the combustion devices. Investigation of plug cluster altitude compensation, and air augmentation may require use of a vacuum test facility. Other key aspects include system integration, development of steering by individual chamber(s) thrust modulation, and validating manufacturing methods. Testing of thrust chambers for the three smaller vehicles is not foreseen to be difficult. Indeed testing of the 1.5, 3 and 7.5 Klb thrust VCCW chamber assemblies is already under way at ORBITEC, as illustrated below in Figure 11.

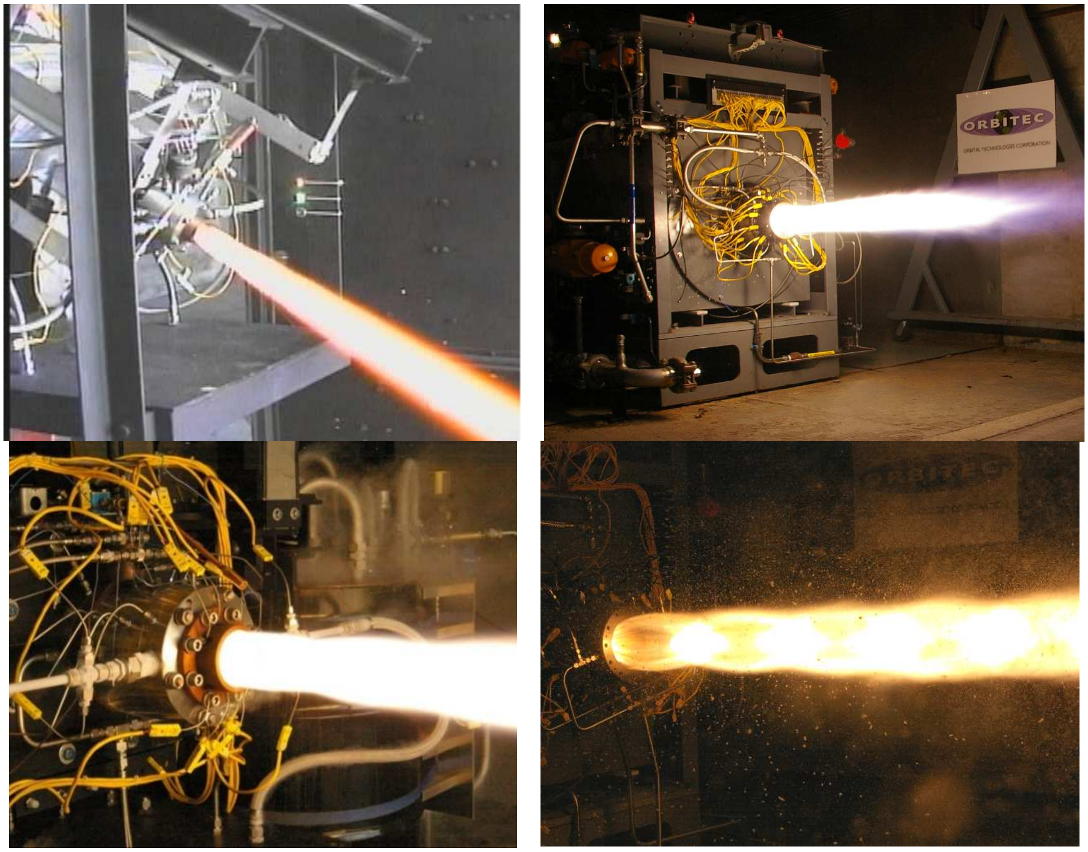

Figure 11. **USLV VCCW Engine Testing at ORBITEC's Test Facility**

However, the primary chambers on the XL vehicle are 500 Klb sea-level thrust and so require relatively large test stands. It is of interest to note that an individual stage can serve as a test facility since it will have the propellant feed system, thrust chambers and instrumentation needed for its operation. This feature will simplify the construction of test facilities. It may be possible to use USLV launch pads as test facilities during the DDT&E phase, to further reduce facilities cost.

3.2.2.4.4 Habitat and Other Base Infrastructure [LS]

In the beginning of the base development, we expect that base colony hardware will be made on Earth and be transported to the Moon. However, we project that over time the colony will reach about 100 people in the period of initial growth and be using significant Lunar resources to build colony facilities and other needed items. In our Phase 1 Steckler proposal, we proposed to use the Self-Sustaining Lunar Colony (SSLC) approach that we developed for a NIAC Phase 1 study effort (O'Handley, et.al., 2000) as the beginning baseline. See discussion below that describes an ultimate SSLC and new Lunar base/concept artwork that we have recently developed. This base and approach would likely be the choice of a first commercial Lunar colony (see Figure 12).

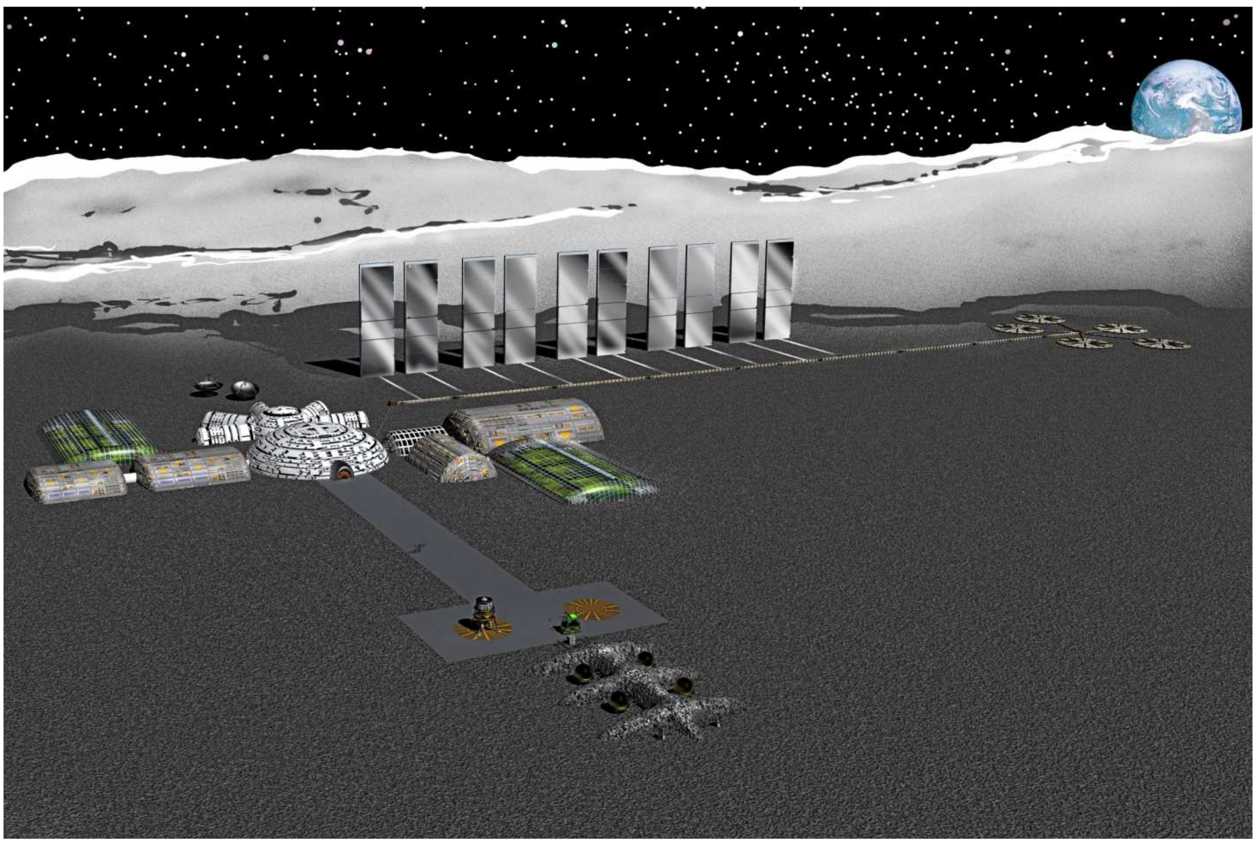

Figure 12. A Potential SSLC Layout

In 2000, ORBITEC conducted a NIAC-sponsored a Phase 1 study of an overall system architecture with the goal of designing a truly self-sustaining Lunar colony (SSLC), attempting to make it independent of sustained Earth resources and supplies. A self-sustaining colony would be able to survive without supplies or resources from Earth for an extended period of time. The design of a self-sustaining architecture appears to be feasible and represents an attractive alternative to what would be a regular Earth-supported Lunar colony. The establishment of SSLC is necessary to drive new innovative approaches and developments and commercialization that would ultimately support a much lower-cost and highly-survivable human colonization of the Moon, Mars, and other bodies in the Solar System. Once established, the SSLC will implement many innovative applications for the commercial production of needed structures and commodities from Lunar materials.

The SSLC was designed to minimize the dependence on Earth supplies. This has several benefits, such as reducing the operating costs of the colony and reducing the risks of operating the colony remotely. The original concept for the NIAC study was a self-sufficient Lunar colony that could survive in complete isolation from the Earth. After holding a requirements workshop with various experts in 2000, there was a consensus that total isolation from communications and possible involvement from Earth is both unlikely and unwise. As a result, the goal of the ORBITEC NIAC study was redefined from a self-sufficient Lunar colony to a self-sustaining Lunar colony. The purpose of the SSLC was two-fold. The first purpose is to establish a permanent human presence on the Moon with a minimum need for supplies from Earth (which is a goal of this Steckler Study as well). The second purpose is to serve as test-bed for technologies that would be in common between the SSLC and an eventual Mars colony (which is also a goal of Steckler).

The colony would be considered "self-sustaining" when it can survive without supplies from Earth for a period of 52 months. This represents the period of time a Mars colony would need to survive between supply missions from Earth, assuming one missed re-supply mission opportunity and the use of Hohmann transfer missions exclusively for supply. The SSLC would need to produce and recycle all of the consumables required over that time. It must also maintain all of the modules, facilities, and equipment.

In the NIAC study, we assumed that the SSLC would have a steady-state population of 100. However, the results of the study could be scaled to other colony sizes. The colony could become self-sustaining without becoming completely isolated from the Earth. For example, scientific and technical equipment needed for further science, exploration, and extension of commercial operations could be supplied. Communications and electronic data transfer with Earth would be extensive and will require a high band-width capability. Exposure to radiation during surface operations outside the Lunar habitat may limit the amount of time that humans could remain on the surface of the Moon or in the shielded SSLC habitats. Human survival is obviously a key factor in the SSLC. Figure 13 provides a summary of requirement for human survival.

Electrical and thermal energy for the colony is proposed to be initially supplied by a combination of nuclear power plants (two $\geq$ 1 MW plants) and Solar energy. This combination of energy sources would provide redundancy. New Solar cells manufactured on the Moon could be added to provide increased power capability and to replace failing Solar cells in already in operation. Concentrated Solar thermal energy would be used extensively in the ISRU processing and product manufacturing plants. Sunlight would be collected and used with artificial lights for plant growth within the SSLC.

There are some high-priority items that may be needed from Earth because they are difficult or impossible to produce on the Moon. The space transportation system would be provided in the form of Lunar transfer and landing vehicles, which could be operated between the surface and an orbiting depot located in Lunar orbit or from a LEO depot.

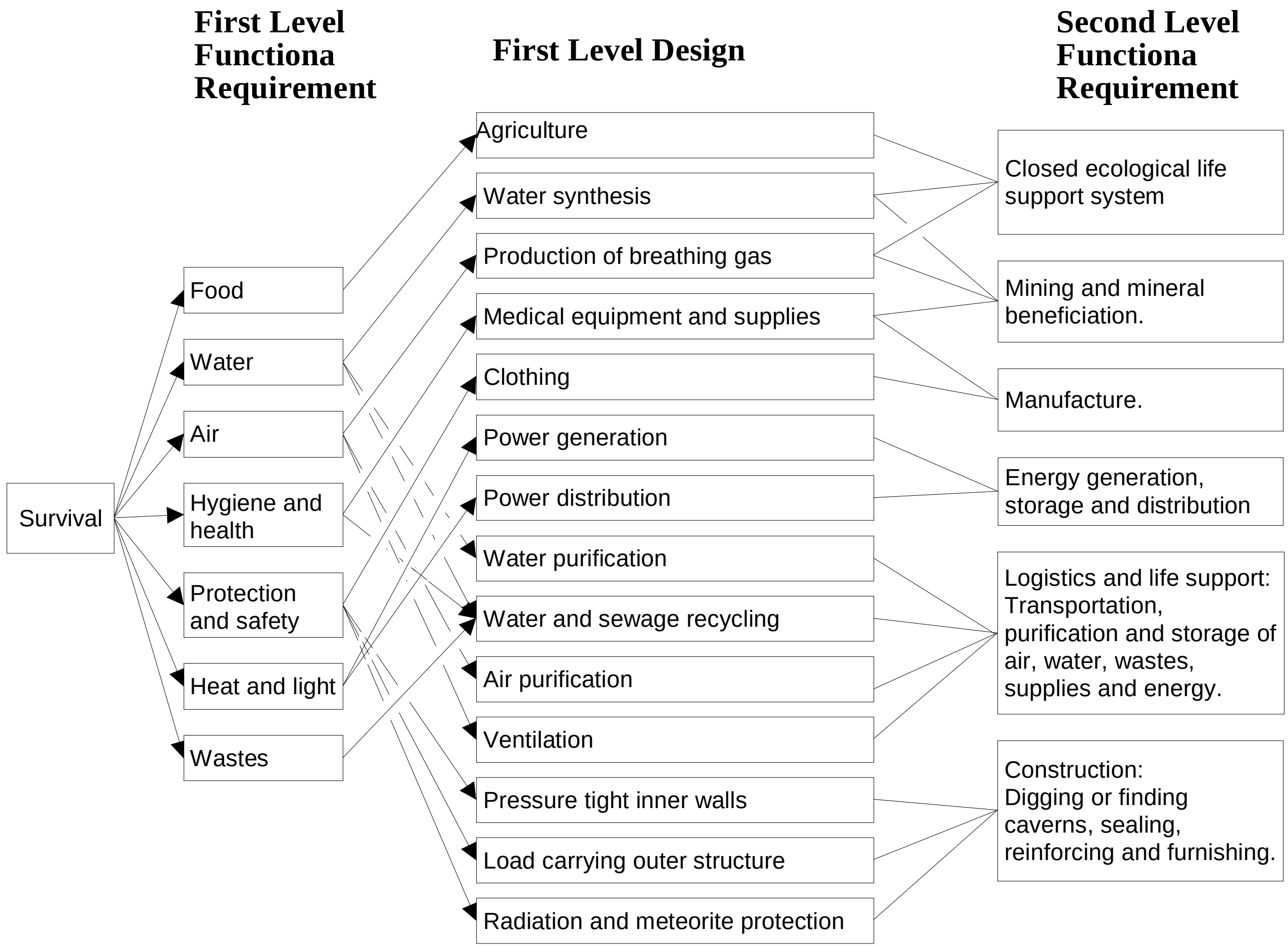

Figure 13. Requirement Breakdown for Human Survival

A prerequisite for even for short periods of self-sustaining operation of the SSLC is a completely Closed Ecological Life Support System (CELSS). As a baseline, we are assuming the atmospheric pressure inside the pressurized modules would be maintained at 10 psi (Earth equivalent pressure at 10,000 ft. elevation). A 0.5% volumetric loss rate per day [Duke, 1989] is assumed from the pressurized modules of the colony. One of the main needs for SRU processing is to replace these lost gases. The total ingress and egress losses of the atmospheric gases needs to be determined for each airlock operation.

The CELSS would provide all the atmospheric requirements for living on the Moon. The food acreage would be sized to support 100 people and include growing, harvesting, and producing foodstuffs with sufficient redundancy to support the SSLC in the case of a large-scale crop failure or accident. Because of the unfiltered Solar and galactic radiation on the Moon this "green house" must be totally self-contained in an underground area with Solar light provided through a light collection and distribution system (see Figure 14). An artificial source of light is also necessary and will be provided for by the SSLC power system. By proper design, it would be possible to integrate the agriculture and animal areas into attractive park areas that could be used for leisure and recreation (see Figure 15).

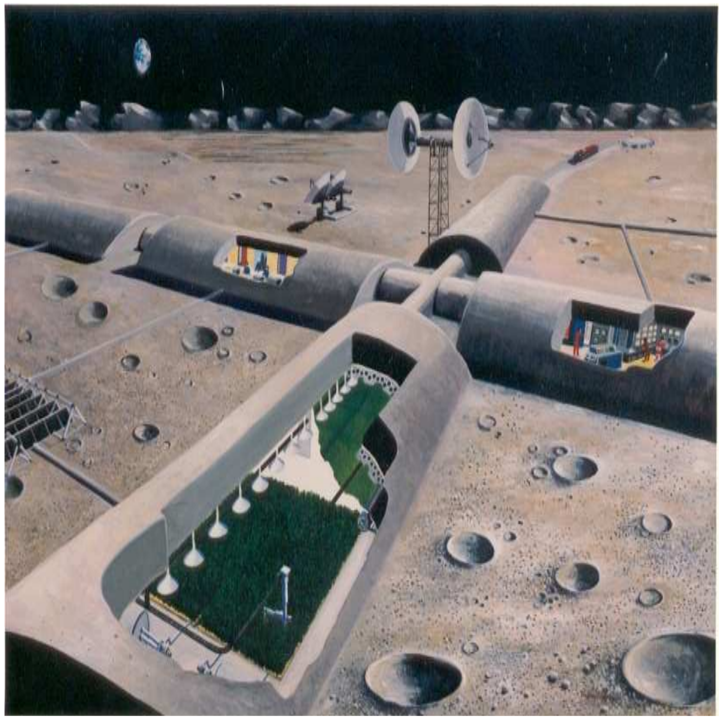

Figure 14. A Functional Concept of a Lunar Colony

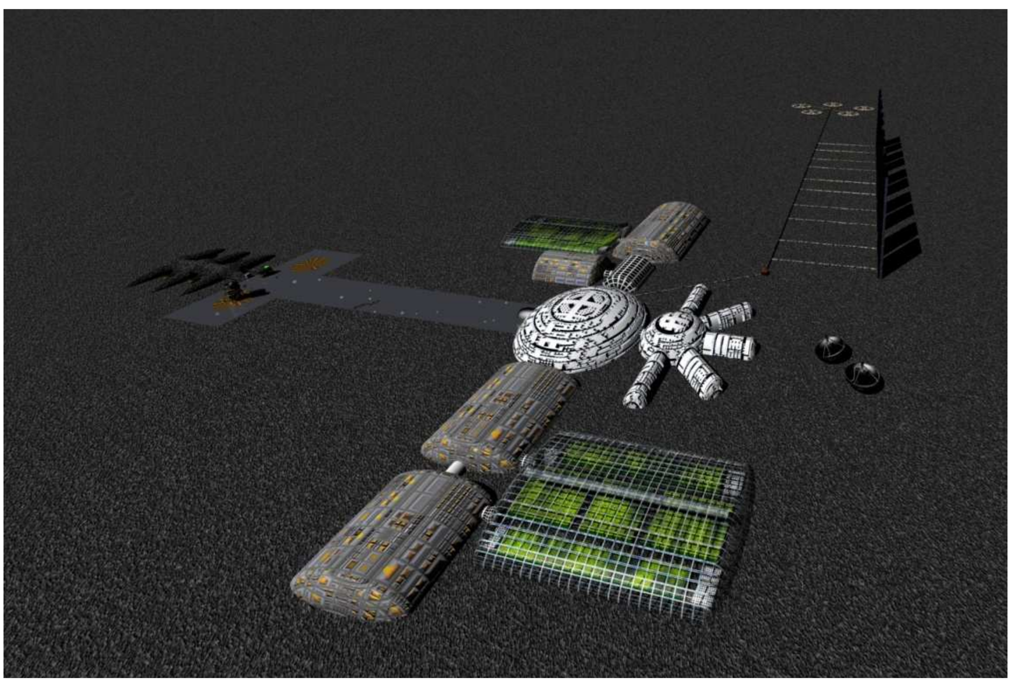

Figure 15. An ORBITEC Notional Lunar Base/Colony Concept

Sufficient emergency reserves of all life support consumables (such as oxygen, food, water, etc.) would be kept within the SSLC. The reserves would only be used in the event of a large-scale CELSS equipment failure, SRU production facility failure, crop failure, or other catastrophic event. In addition, there is a requirement to provide a healthy environment at all times in the SSLC. This includes preventing dust and any pathogens from entry and growth within any structures of the SSLC. Dust was identified as a significant problem during the Apollo missions. All attempts should be made to prevent the entry of dust into the habitat volume.

Space suits would be required for all human operations on the Moon surface. These suits must provide temperature, atmospheric pressure, micrometeorite and radiation protection. The impact of dust on the wear and operation of the suits must be considered. The use of a dust cleaning stage for any items entering the colony should be evaluated.

Robotics and automated processes would be extensively used for surface construction and maintenance of the SSLC facilities. This would help to minimize the radiation dose to the Lunar colonists. The amount of regolith shielding must be sufficient to prevent radiation from adversely impacting the health of the colonists inside the habitat.

A surface transportation system would be required to prepare and maintain the site for habitation. This surface transportation would be used to move colonists and cargo within the SSLC and the surrounding areas. This may be a fully robotic operation. A launch and landing complex (Lunar Surface Depot) would be provided near the SSLC to accommodate the space transportation system operation.

Telecommunications, navigation and information management are other important requirements. A constellation of communication satellites in Lunar orbit would provide continuous communications capability with the Earth from all locations on the Moon. This same communications system could provide warnings of impending Solar events, which would require the immediate attention of all the colonists. Surface navigation poses a serious challenge and a GPS type system should be established. Early robotic exploration and maneuvering on the surface would require GPS-like navigation. The information system would provide the contact with the Earth at all times and at all locations on the Moon. The medical information system would be maintained on Earth, but a complete medical resource library would always be available at the SSLC. A self-test and repair computer system is required, with sufficient redundancy.

A physical fitness area and low gravity countermeasures must be considered, since bone demineralization is considered to be a serious problem for Lunar inhabitants returning to the Earth after an extended stay. This area could be combined with a sports entertainment facility to encourage increased physical activity of the colonists. This would promote improved physical and metal health. Figure 16 provides a possible layout of a complete Lunar base/colony.

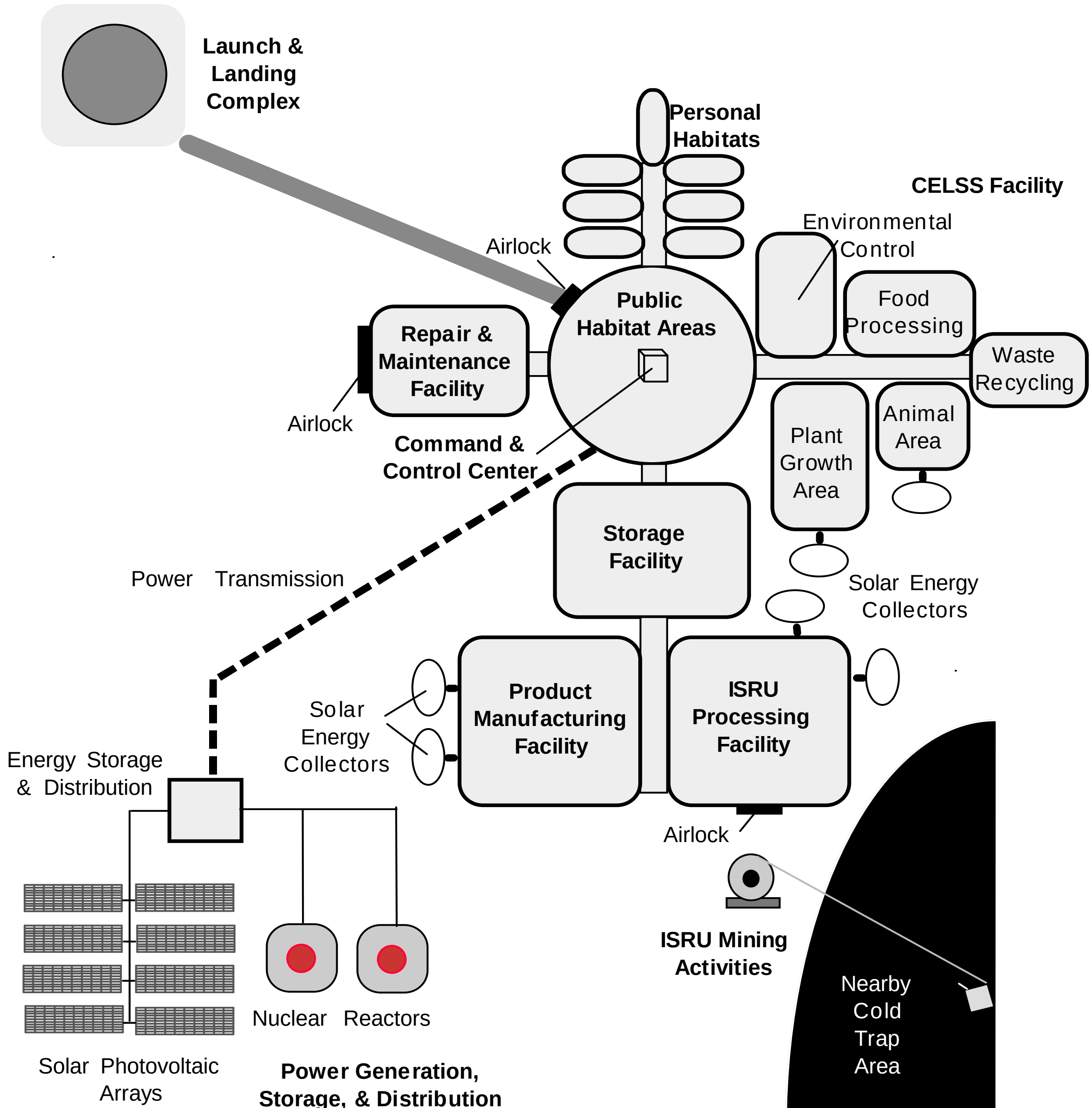

Figure 16. A Potential SSLC Layout

3.2.2.4.5 H/O SRU Facility/Rovers/Hoppers [LS]

The H/O SRU Surface Facility is the key place where water is processed to form hydrogen and oxygen gas and liquid when required. Rovers and Lunar Hoppers are required and shall be both crew operated from on board or operated from inside control rooms. The rovers and hoppers would be fueled with liquid or gaseous H/O. More detailed definition of these vehicles would come in Phase 2.

3.2.2.4.6 LEO Depot

The Low Earth Orbit Depot (LEOD) located in a 28.5° circular orbit (alt-TBD) is defined by the following list of features and an artist concept as shown in Figure 17:

- LOX/LH_2/GO_2/GH_2/H_2O/GHe/LN_2 Tanks
- CELSS
- Food Production
- Habitats for >10 crew
- Science Observation/Research Labs for Earth and Space Observations and Microgravity R&D
- Solar Power Arrays
- Water Electrolysis System
- LTV and Crew Return Vehicle (CRV) Docking / Refurbishment Pressurized Vehicle Bays
- Robotic Logistics Arms.

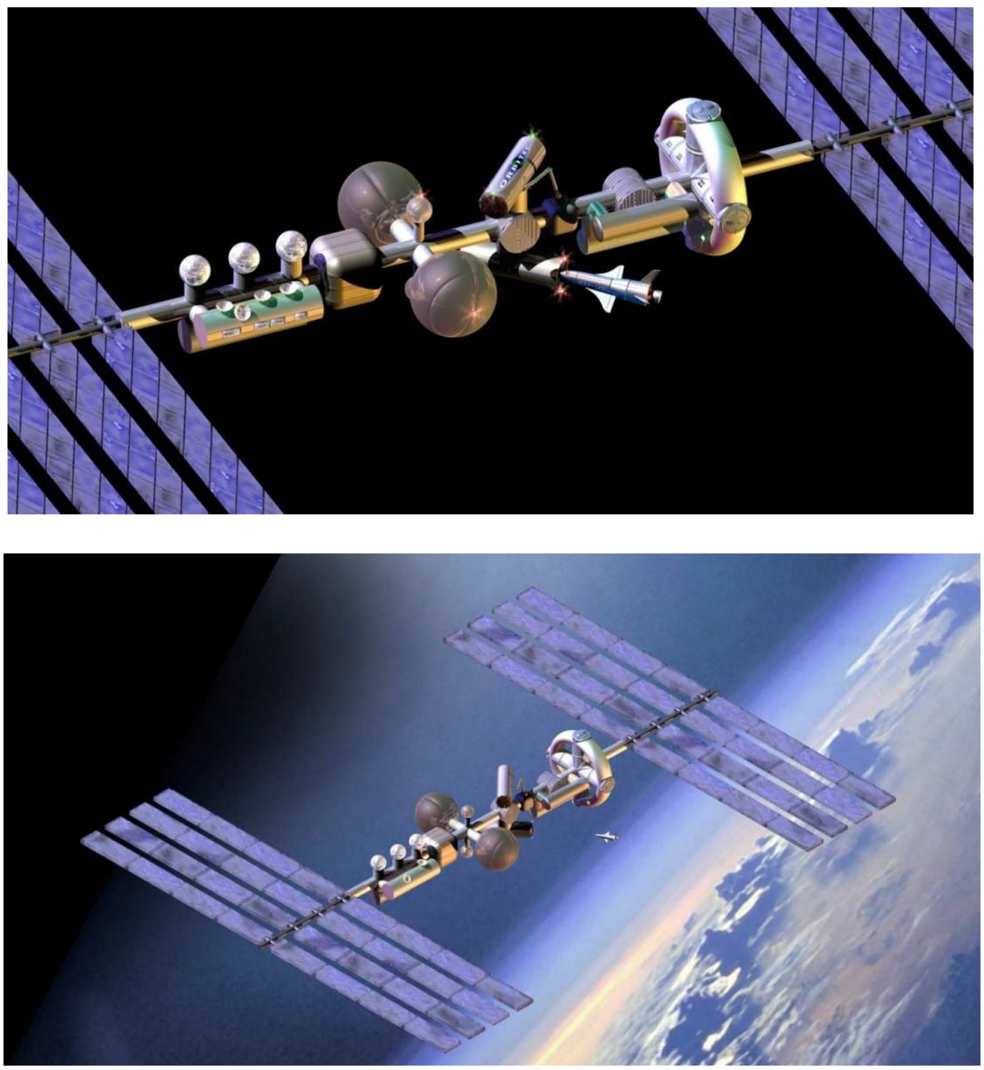

Figure 17. LEO Depot

3.2.2.4.7 LLO Depot

The Low Lunar Orbit Depot is to be placed in a Lunar polar orbit (altitude -TBD) and is defined by the following features:

- $LOX/LH_2/GO_2/GH_2/H_2O/GHe/LN_2$ Tanks
- Habitats for >10 crew
- Solar Power Arrays
- Water Electrolysis System
- LTV and Lunar Lander Docking / Refurbishment Pressurized Vehicle Bays
- Robotic Logistics Arms.

An artist concept of the LLOD is shown in Figure 18.

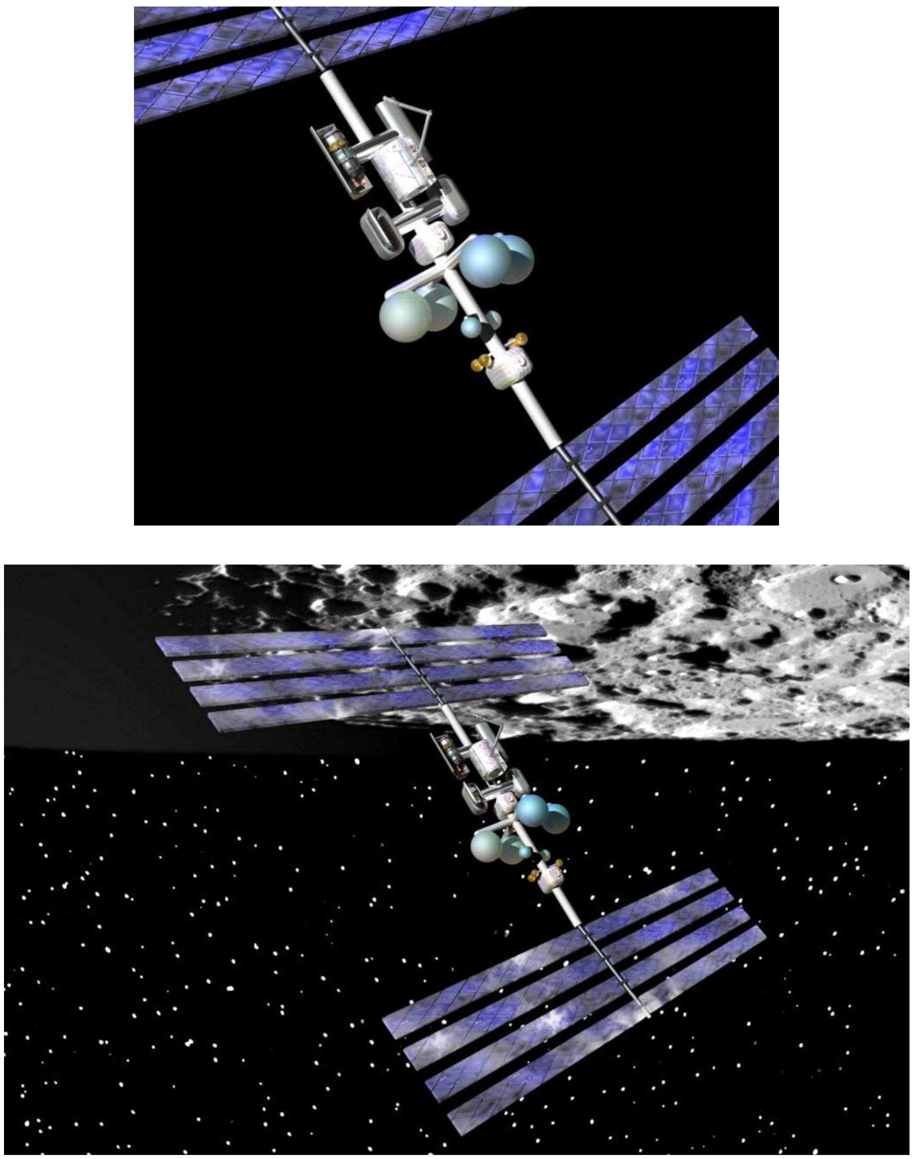

Figure 18. Notional LLO Depot

3.2.2.4.8 LS Depot

The Lunar Surface Depot (located near the South Pole) is defined by the identified features listed below:

- $LOX/LH_2/GO_2/GH_2/H_2O/GHe/LN_2$ Tanks
- Rovers, Transporters, Hoppers, Landers and Facilities
- Water Electrolysis System
- Propellant/Vehicle Servicing
- Life Support Systems.

3.2.2.4.9 Chemical Propulsion Lunar Transfer Vehicle [LTV]

The Lunar Transfer Vehicle (see Figure 19) would have accommodations for 5 crew/passengers and cargo in a crew cabin and cargo storage volume. The vehicle would use 2 vortex LH_2/LOX rocket engines and has appropriate LH_2, LOX, and water tanks to store the needed propellant for transport propulsion and propellant supply delivery to the depots. It would also transport LN_2 from Earth for the colony's atmosphere.

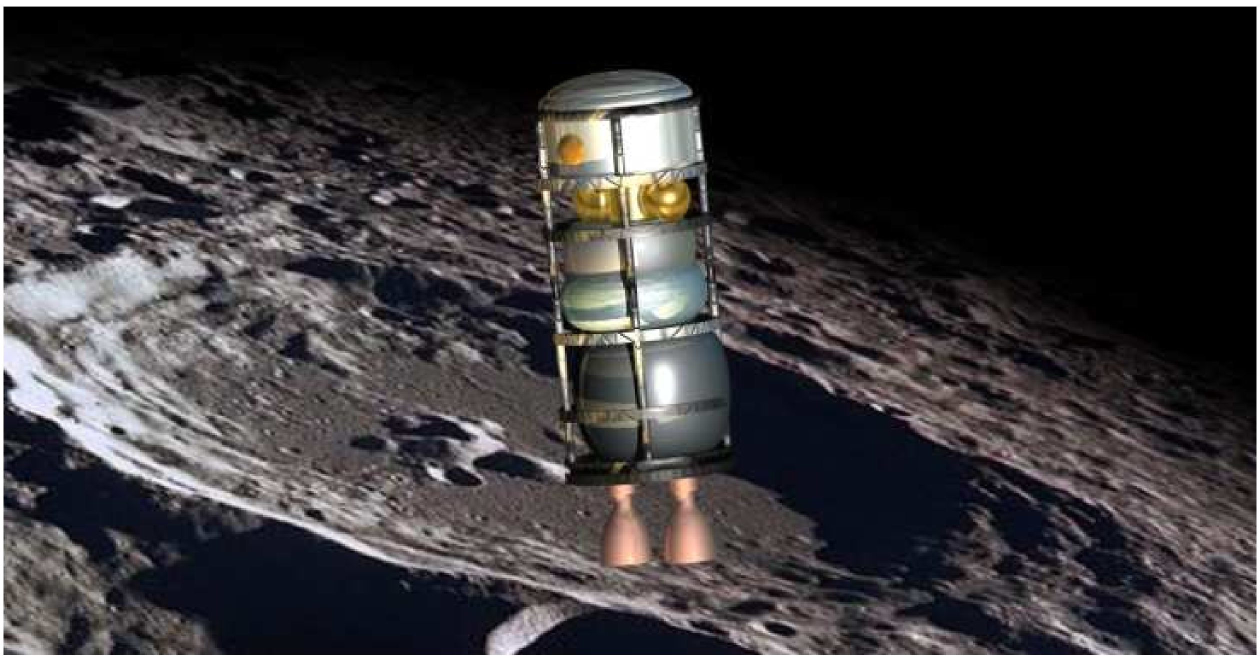

Figure 19. Lunar Transfer Vehicle [LTV]

3.2.2.4.10 Solar Electric Propulsion Transfer Vehicle - Water – Advanced Microwave Electric Thruster (AMET)

The Solar Electric Propulsion (SEP) Transfer Vehicle would use advanced 75 kw microwave electric thrusters to propel large unmanned cargo to the Lunar Orbit Depot or Lunar Orbit that would be subsequently be lowered to the Lunar surface via chemical propulsion. The I_{sp} is expected to be ~800 sec for this propulsion system.

3.2.2.4.11 LS Electric Power Stations

Initially, the Lunar Surface electric power station would be a single unit located on a crater wall summit near the south pole base. As the activity and scope increases, a nuclear power unit would be placed in a crater nearby. Eventually, as the colony grows, a second 1 Mw nuclear plant would be installed in a second crater.

3.2.2.5 Earth Launch Direct to Final Destination of Infrastructure

The purpose of this section is to define major hardware elements that will be direct launched to their final destination position from the Earth's surface or from the LEO Depot. Detailed mission analysis will be conducted for these infrastructure placements during the next phase of the effort. The items to be launched direct are:

- Low Earth Orbit Depot (LEOD)
- Low Lunar Orbit Depot (LLO)
- Lunar Surface Depot (LSD)
- Lunar Lander to LLO and the LLOD
- Habitats and other Infrastructure to LS
- H/O SRU Facility/Rovers/Hoppers to LS
- LTV To LEO Depot
- Cargo to LS
- Lunar Power Station to LS
- Solar Electric Propulsion Transfer Vehicle to LEOD - Water Advanced Microwave Electric Thruster (AMET).

3.2.2.6 Crew and Passenger Trip Scenario - 5 Humans Per Trip

The trip scenario for human crew and passenger travel is outlined by the action list given below:

- Earth Surface (ES) to Low Earth Orbit (LEO) Depot in a crew ship launched by USLV-L
- Crew Transfer at LEO Depot to Lunar Transfer Vehicle (LTV)
- LTV Trip from LEO to Rendezvous with Lunar Lander at Low Lunar Orbit Depot (LLOD)
- Crew Transfer to Lunar Crew Cabin on Lander at LLOD
- Lunar Lander to Lunar Surface Depot (LSD)
- Crew Transfer from Lunar Surface Depot to Lunar Surface Habitat/Base via a Rover.

3.3 Develop an Innovative Lunar Colony Resource Development Plan Based Upon the Basic Needs and Commercial Activities of the Lunar Colony (Task 3)

The goal of this task was to develop an innovative Lunar Colony resource development plan based upon the basic needs and commercial activities of the Lunar Colony. ORBITEC has been a leader in the space resource utilization for well over 20 years. ORBITEC staff were involved in a Lunar Propellant Benefit Study (Teeter, et. al., 1987). In the 1980's, we were involved in evaluating mining the Moon for He^3 and studied the synergism of a Lunar base and a He^3 mining operation. Rice and Gustafson developed the AIAA Position Paper on ISRU in 1997 (AIAA, 1997). Rice has most recently been developing position statements for the AIAA from the AIAA/Space Resources Utilization Technical Committee (2008) and AIAA/Space Colonization TC (2008). ORBITEC over the years has been developing the most efficient oxygen production approach (carbothermal process) on the Moon (PILOT Program). ORBITEC has also been developing a unique and low-energy planetary excavator for Lunar mining activities (Gustafson, 2008). We have participated in studies for the NASA Institute for Advanced Concepts (NAIC) on: a Self-Sustaining Lunar Colony (O'Handley, et.al., 2000); a Phase 1 and 2 NIAC study of a Mars colony transportation needs (Rice, 2002, 2000); and a NIAC study to develop a Lunar water recovery plan (Rice, 2000). We have identified and/or developed chemical processes that can produce many of the materials needed to build and construct the habitats, buildings, underground facilities, and surface infrastructures needed for a growing Lunar colony.

The ultimate key to success will be smart use of space resources that are available on the Moon. Chemical analyses performed on Lunar samples from Apollo missions indicate O_2, Si, Al, Fe, Ca, Mg, and Ti are the major components of Lunar soil. O_2 comprises approximately 42% of the Lunar soil by mass, while Ti accounts for only 3% (mare soils). All of these elements are chemically bound in various minerals, so the Lunar regolith will require processing to extract the useful components. O_2 could be "mined" by directly heating Lunar regolith to moderately high temperatures and adding methane to reduce the oxides to form water or CO (Carbothermal Process). These gases can be further processed to form O_2, leaving recycled methane gas and Si, Fe, and other metallic and ceramic by-products in the processed regolith which can be processed into useful products. Also now with the proven supply of water at the poles and other locations, there is great motivation to use water for our needs. In the sections below, we identified and listed key materials, laid out a plan of attack on an SRU development approach for a commercial Lunar colony venture to be carried out as we move forward on this project.

3.3.1 Mindjet Map of SRU and Non-SRU Resources Needed for the Lunar Colony

During various working sessions over the course of the study effort, we developed the first cut at a resource map consisting of the basic non-transportation elements that would be the focus of a future "take" or "make" (Lunar SRU) decisions after the initial placement of a small base or colony on the Moon. Since this is a pure commercial venture, the lowest-cost approach is the key goal. The identification of those items that contribute to the best utilization of financial resources is key to the long-term best value of the commercial investments. The initial list of Lunar SRU materials, processes, products, and services that support evolving space colonization are provided in Figure 20 along with those items that should be, may be, should not probably be produced on the Moon. We give the following categories in the Map: Sunlight Resource Use, Lunar-Supplied Regolith Raw Materials, Earth-Supplied Items, and Other Possible Near-term Lunar Products and Services. These are briefly discussed below in the subsections that follow.

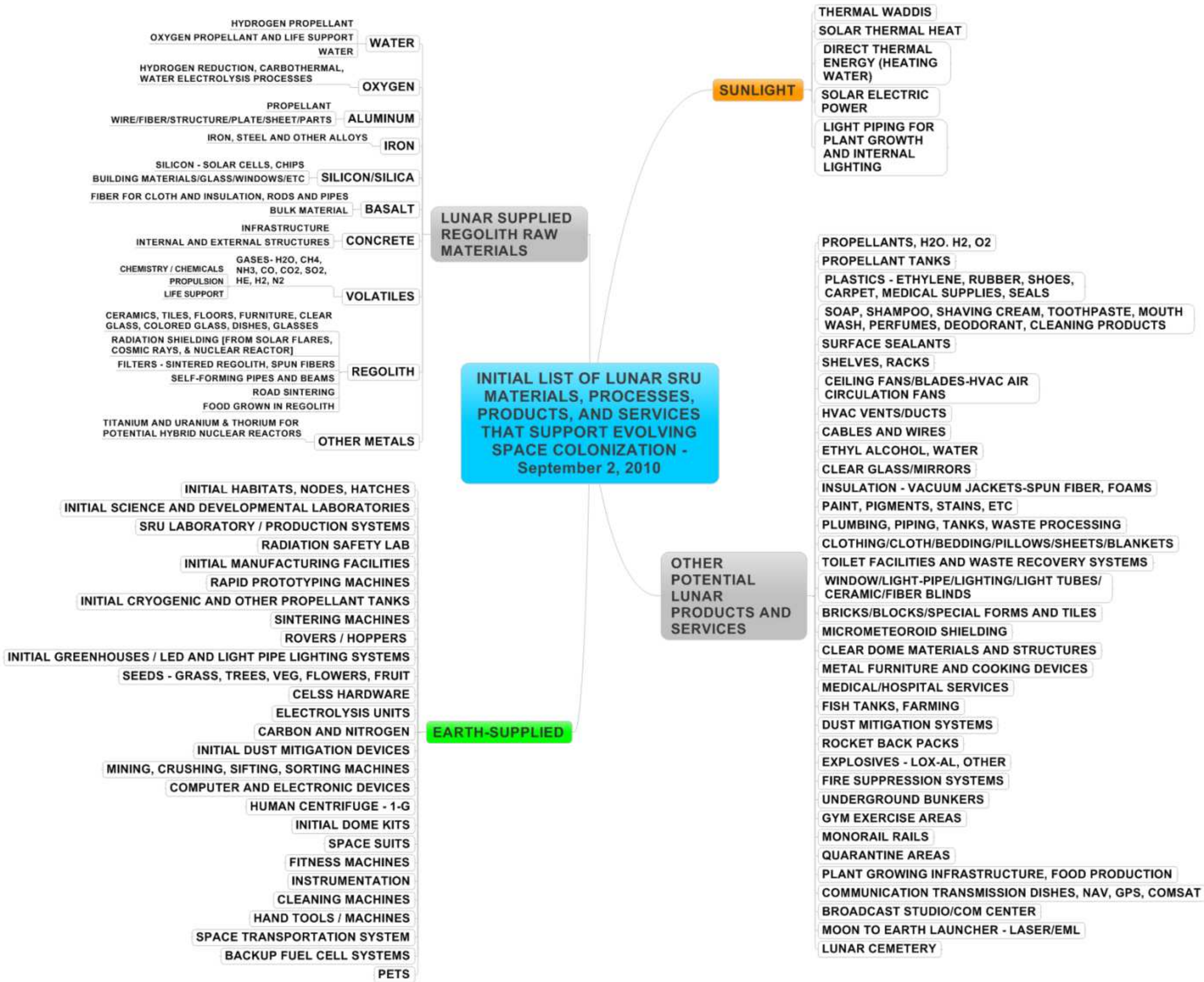

Figure 20. Lunar SRU Mindjet Map

3.3.2 SRU Element Discussion

In this section we discuss the various SRU elements and non-SRU elements of a Lunar colony as we envision the possibilities for a commercial enterprise.

3.3.2.1 Sunlight

One reason for choosing a south polar site for the colony is the availability of nearly constant Sunlight availability (see additional discussion in Section 3.2.2.3). Having near 24-hour Sunlight is a great advantage for the colony. Having the ability for near-constant thermal Solar energy for heating and powering the colony provides lower risk and lower cost. Lighting via light piping provides higher production/yields of plant-based food and consistent lighting of facilities. Applications include the following: thermal waddis (thermal storage in Lunar material), other Solar thermal heating, direct thermal energy (heating water), Solar electric power, light piping for plant growth and lighting of facilities.

3.3.2.2 Other Potential Lunar Products and Services

In the process of defining a profitable space colony on the Moon, we need to design, select materials, and choose approaches that make sense to an evolving complex. We need to make the cost-effective plans that optimize resource use – that is from the Earth and from the Moon. A well integrated design/cost analysis needs to be developed that can be integrated/processed time and time again as the development grows to come out with the optimum solution. Figure 21 below identifies the first Lunar products and services that may make sense to provide on the Moon at some point in the development and growth of the colony that is of interest here.

Propellants H_2O, H_2, O_2	**Underground bunkers**	**Rocket back packs**
Propellant tanks	**Paint, pigments, stains, etc**	**Explosives - LOX-Al, other**
Plastics – ethylene	**processing**	**Fire suppression systems**
Rubber, shoes, carpet, medical supplies, seals (see Appendix E)	**Clothing/cloth/bedding/pillows/sheets /blankets**	**Insulation - vacuum jackets-spun fiber, foams**
Soap, shampoo, shaving cream, toothpaste		**Plant growing infrastructure, food production**
Mouth wash, perfumes, deodorant, cleaning products	**Window/light-pipe/lighting/light tubes/ ceramic/fiber blinds**	**Communication transmission dishes, NAV, GPS, comsat**
Surface sealants	**Bricks/blocks/special forms and tiles- ceramic/concrete**	**Ceiling fans/blades-HVAC air circulation fans**
Shelves, racks	**Micrometeoroid shielding**	**Gym exercise areas**
Quarantine areas	**Clear dome materials, and structures**	**Monorail rails**
HVAC vents/ducts	**Metal furniture and cooking devices**	**Broadcast studio/com center**
Cables and wires	**Medical/hospital services**	**Moon to Earth launcher - laser/EML**
Ethyl alcohol, water	**Fish tanks, farming**	**Lunar cemetery**
Clear glass/mirrors	**Dust mitigation systems**	

Figure 21. Products and Services that May Make Sense to Provide on the Moon

3.3.2.3 Earth-Supplied Hardware (non-SRU)

In the beginning of the development of a Lunar base or colony, there are certain support systems that have to be supplied from Earth to provide the minimum risk to the crews and passengers. As of the time of this assessment, SRU needs much more technology development to provide confidence that the investment will be successful and all will be safe. Once SRU technology has been perfected and proven, then that is the time to consider taking on the critical hardware items as SRU-produced. Figure 22 provides our current state of thinking on what will be Earth-supplied.

Initial habitats, nodes, hatches	Initial Dust mitigation devices
Initial science and developmental laboratories	Mining, crushing, sifting, sorting machines
SRU laboratory/production systems	Computer and electronic devices
Radiation safety lab	Human centrifuge - 1-g
Initial manufacturing facilities	Initial dome kits
Rapid prototyping machines	Space suits
Initial Cryogenic and other propellant tanks	Fitness machines
Sintering machines	Instrumentation
Rovers/hoppers	Cleaning machines
Initial greenhouses/LED and light pipe lighting	Hand tools / machines
Seeds - grass, trees, veg, flowers, fruit	Space transportation system
CELSS hardware	Backup fuel cell systems
Electrolysis units	Pets
Carbon and nitrogen	

Figure 22. Earth-Supplied Hardware/Other Items

3.3.3.4 Lunar-Supplied Regolith - Raw Materials

After a review of available resources on the Moon and a review of the developing Lunar colony from a Earth-supplied initial hardware plan, coupled with the near-term planned use of Lunar volatiles, and a growth scenario as the architecture is implemented and used, we prioritized a list of initial raw materials to focus on. Those raw materials are discussed below and also in Appendix E.

3.3.3.4.1 Water

There are three basic approaches to extracting water (H_2O) that have been identified. The first involves the in-situ heating of H_2O/regolith without excavation. The H_2O/regolith is heated and water vapor is collected at the surface by freezing, so that it can be transported mechanically out of the shadowed area, or liquid or gaseous water is transported by heated pipeline from the cold trap. The second approach is to excavate the H_2O/regolith mixture, but process it in a furnace situated in the cold trap and transporting liquid or gaseous water from the cold trap to a collection site outside of the shadowed area. A third option is to excavate the H_2/O-rich regolith and transport it from the cold trap to a Sunlit area for processing. Interesting complications may arise in the processing if other volatiles are significantly present (e.g., Hg, CH_4, Na, etc.).

Each of the H_2/O recovery approaches considered is composed of several elements:

- **Regolith Preparation or Collection** - This includes any conditioning of the H_2O/regolith that is required before it can be processed. It also includes the collection of the H_2O-rich regolith and placement in the reaction chamber, if required.

- **Energy Source** - This is the source of all the energy required in the extraction process. Energy requirements include the excavation equipment, reaction chamber, and transportation before and/or after processing.
- **Energy Delivery to Shadowed Area** - This is the method that energy is delivered to the excavation and extraction sites. This could include power cables, microwaves, reflectors, fuel cells, batteries, chemical reactors, pipes, etc.
- **Extraction Process** - This is the method that the H_2O is being separated from the regolith. Some possible methods include distillation, mechanical separation, filtration, etc.
- **Regolith or Resource Transportation** - This is the method of transport of the processed resource or regolith out of the shadowed area.

Figure 23 provides a preliminary set of processes for mining and extracting H_2O in each of these areas.

The most important environmental parameters for designing the extraction processes and systems are listed below:

➢ **Form of H_2O/Regolith (implies physical properties of cohesion, strength)** - This variable is most important in defining the excavation mechanisms that can be utilized. The following are the most likely configurations:

  - Finely granular - formed by gardening of Lunar soil with introduction of ice grains
  - Ice chunks mixed in the regolith - formed by gardening of comet ice layers
  - Solid ice/regolith layer - formed by continuous accumulation of ice and diffusion of water
  - Trapped H_2 gas from the Solar wind.

H_2O/Regolith Preparation or Collection	Energy Source	Energy Delivery to Shadowed Area	H_2O Extraction Process	H_2O/Regolith Transport
H_2O/Regolith Preparation - Hammer & scoop - Air hammer - Auger - Block cutting - Explosive	Electrical - Nuclear reactor - GPHS-RTG - Chemical reactor - Fuel cell - Photovoltaics	Electrical energy - Wires, cables - Fuel cells - Batteries - Beamed power	Vaporization - Microwaves - Electrical furnace - Beamed heating - Chemical	Pipe out of shadow - Liquid water - Steam/vapor - H_2 gas Tanks on rovers
H_2O/Regolith Collection - Scoop - Auger - Drag line bucket - Bulldozer	Direct Heating - Nuclear reactor - GPHS-RTG - Solar - Chemical - Laser	Thermal energy - Solar reflector - Insulated pipes - In-situ reactor - Beamed light - Chemical	Melting - Chemical - Solar - Nuclear - GPHS-RTG	Mechanical - Drag lines - Buckets - Gondolas - Conveyor belt - Dumbwaiter
		Mechanical energy - Cables - Belts	Condensation on cold plate	Ballistic - Rocket - Catapult

Figure 23. Preliminary Set of Processes for Mining and Extracting Water

- **Concentration of H_2O** - The concentration of H_2O is important in determining whether processing should be done totally within or partially outside of the cold trap. If the concentration of H_2O is low, it would be necessary to process a lot of regolith mixture to extract a small amount of water. Thus, processes that require less material movement would be favored. At the extreme, in-situ processing may be required for economic extraction at low resource concentrations. The concentrations currently reported by the Lunar Prospector mission are on the order of 1.6%. In this range, there would be significant tradeoffs between local extraction within the cold trap and excavation and transportation of regolith mixture to a processor outside of the cold trap. It is currently believed by the Lunar Prospector team that both H_2 and H_2O exist at the poles, with H_2O being predominant in the cold traps and H_2 being predominate in the polar non-permanently shadowed areas. It still may be possible that deposits of near-pure ice buried beneath a layer of dry regolith could be excavated. The final processing of the water ice could occur outside the cold trap where Solar energy was readily available. An assessment of water contamination by other volatiles also needs to be made. The use of other volatile material also needs assessment.
- **Scale of Deposits** - The scale of the deposit determines the distance between the cold trap and adjacent areas that have access to Solar energy. This is important in designing transportation systems for energy and materials in and out of the cold trap. It also determines the time scale in which systems must operate in the cold trap before returning to a sunlit area. Finally, the scale of the deposit determines how much H_2O can be extracted and, therefore, the degree that extraction apparatus needs to be relocated.
- **Terrain Accessibility** - Small craters should not present any serious accessibility problems, but there may be boulders in the subsurface on the rims. Larger craters may pose severe access problems due to rugged crater walls, substantial relief, and the abundance of boulders. Access challenges in low relief terrain in permanent shadow should be minimal. Terrain accessibility would determine the style of access for surface mobility systems.
- **Availability of Solar Energy** - The highest availability of solar energy would be for the small craters located outside the Aiken Basin. There may be areas of permanent Sunlight on the rim of the larger south pole crater. Availability of Solar energy close to the H_2O deposits would influence the selection of energy provision and transmission approaches.
- **Temperature** - Temperature in the cold trap is determined by the amount of scattered light that can be received and by the heat conduction through the surface. Any extraction system to be utilized within the cold trap must be capable of operating in temperatures ~70 K. It should be assumed that machinery would have to radiate heat to deep space.

Three extraction approaches were developed: (1) In-situ Ice Extraction via Microwave Heating; (2) Local Extraction of the Ice/Regolith Mixture with GPHS-RTG (General Purpose Heat Source - Radioisotope-fueled, Thermoelectric Generator) Thermal Processing and Steam Pipe Transport; and (3) Local Drag Line Extraction of the Ice/Regolith Mixture with Solar Thermal Processing Outside the Permanent Shadow. These approaches were developed to represent a number of different subsystems. They represent three combinations of the many possible subsystems that could compromise a complete extraction system. A brief discussion for each of these extraction options follows; a detailed system study is needed to evaluate each concept and others

Approach #1. In-situ Ice Extraction via Microwave Heating - (1) A photovoltaic array (see Figure 24) converts Sunlight into electricity. The electricity is carried into the permanently shadowed area through a power cable. (2) The electricity powers a mobile microwave generator that is aimed at ice-containing regolith. No excavation is utilized. A dome covering is placed over the area that is being processed to contain water vapor. The microwave energy selectively heats and vaporizes the ice. The water vapor migrates from the regolith and is collected on cold plates located just above the surface. (3) The solid ice is removed from the cold plates and transported out of the shadow in a storage tank mounted on a H/O fuel cell-powered rover.

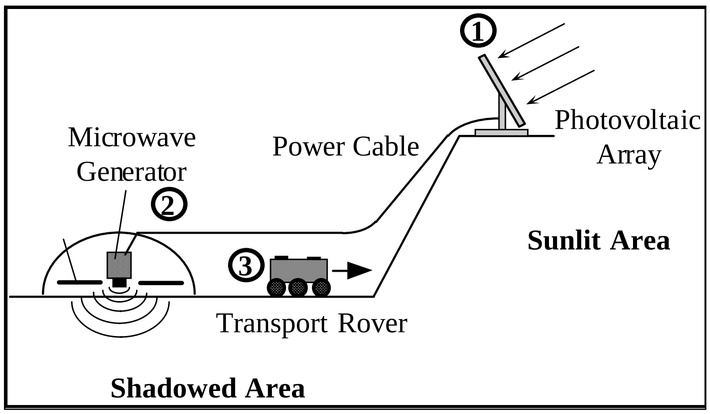

Figure 24. Schematic Diagram of Extraction Approach #1

Approach #2. Local Extraction of the Ice/Regolith Mixture with GPHS-RTG Thermal Processing and Steam Pipe Transport. (1) The ice/regolith mixture is excavated mechanically from the surface within the permanently shadowed area and carried by rover to a water extraction furnace (see Figure 25). The furnace is heated via nuclear GPHS modules, which stacked within the furnace wall. These GPHS modules are similar to the RTG modules used in the Cassini mission. The ice and regolith mixture is loaded into the processing chamber and sealed. The heat melts and vaporizes the ice. (2) The steam from this process is collected, heated further if necessary, and transported out of the permanent shadow in a sealed, highly insulated, steam pipe. A turbine-based electrical generator driven by the steam would provide electrical power for support equipment and heating the steam pipe, if required. The dry, processed regolith is removed from the processing chamber and new ice and regolith are added. (3) The steam passes through the pipe out of the shadowed area. A secondary generator turbine helps to recover some of the energy of the steam. The steam is condensed and collected for storage in a tank.

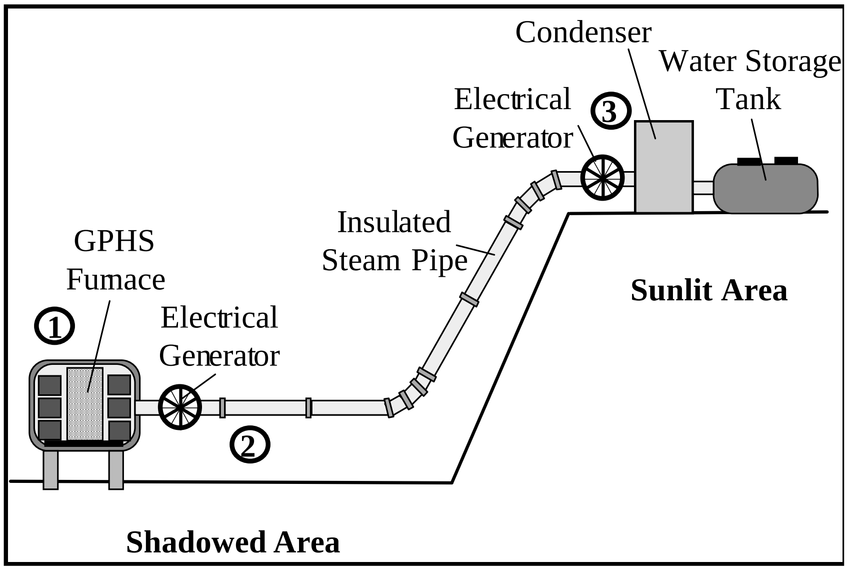

Figure 25. Schematic Diagram of Extraction Approach #2

Approach #3. Drag Line Removal of Ice/Regolith and Solar Thermal Processing Outside the Permanent Shadow. (1) Ice/regolith mixture is excavated and transported out of the shadow with a drag-line bucket (see Figure 26). If the ice/regolith mixture is hard, small explosions will be used to break the ice into smaller pieces that can be transported outside the permanent shadow for processing. If the ice/regolith mixture has a granular form, the surface preparation step is not required. (2) In a sunlit area, the ice/regolith mixture is placed into a Solar furnace, a sealed, passive Solar energy collector, which will melt the ice. The liquid water will be collected and filtered to remove particulate contaminants. The water may need distillation before use. (3) The water is stored as a liquid in storage tanks.

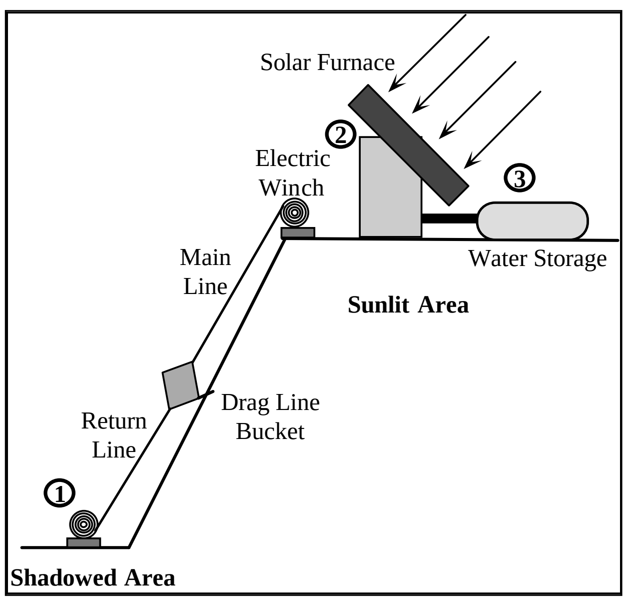

Figure 26. Schematic Diagram of Approach #3

3.3.3.4.2 Oxygen

There are several ways to provide oxygen on the Moon: they are discussed below and in Appendix E.

Oxygen Production via Carbothermal Reduction of Regolith. Oxygen can be produced via carbothermal reduction of ilmenite and various silicates found in the Lunar regolith. The carbothermal reduction process has three steps. These steps are: (1) reduction of metallic oxides (e.g., ferrous, silicon, titanium) with methane (at >1625 C) to form carbon monoxide and hydrogen; (2) reduction of carbon monoxide with hydrogen to form methane and water; and (3) electrolysis of the water to form oxygen and hydrogen. The process can be operated in a nearly closed-loop manner by minimizing or eliminating the loss of carbon in the processed regolith. The advantages of this process are: (1) yields much more oxygen per kg of Lunar regolith than hydrogen reduction, (2) can use Lunar regolith with little or no beneficiation, (3) oxygen production creates useful by-products, such as iron and silicon, and (4) can be operated in a nearly closed-loop manner. A disadvantage is that it requires high processing temperatures (>1625 C).

Oxygen Production via Hydrogen Reduction of Ilmenite. Oxygen can be produced via hydrogen reduction of ilmenite found in the Lunar regolith. The hydrogen reduction process has two steps. These steps are: (1) reduction of the ilmenite with hydrogen (at >800 C) to form water, and (2) electrolysis of the water to form oxygen and hydrogen. The process can be operated in a nearly closed-loop manner by recycling the hydrogen formed in Step 2. The processed regolith can then be further refined to extract iron (e.g., magnetic separation, acid leach) that is formed during the reduction process. The advantages of this process are: (1) moderate processing temperatures (typically 900-1100 C) that are below the bulk melting point of the regolith; (2) creates iron as a by-product; and (3) can be operated in a nearly closed-loop manner. Disadvantages are: (1) low yield of oxygen per kg of regolith processed than carbothermal process; and (2) beneficiation of the regolith is required to increase the ilmenite content.

Oxygen Production via Lunar Water Ice Extraction. Water ice at the Lunar poles can be collected and used to produce oxygen. This process would have three steps: (1) collection of the ice-regolith mixture, (2) thermal extraction of the water from the regolith, and (3) electrolysis of the water to create hydrogen and oxygen. Advantages are: (1) low processing temperatures are required (<100 C): and (2) creates hydrogen as a by-product. The disadvantage is the collection of the water ice requires mining/excavation equipment to operate in a harsh operating environment (dusty, vacuum, 40-60 K – see Section 3.3.3.4.1).

Oxygen Production via Regolith Heating in the Presence of Insitu Hydrogen. Oxygen can be produced via heating the regolith using the insitu hydrogen found in the lunar regolith. The hydrogen reduction process has two steps. These steps are: (1) reduction of the ilmenite with hydrogen (at >800 C) to form water, and (2) electrolysis of the water to form oxygen and hydrogen. The process can be operated in a nearly closed-loop manner by recycling the hydrogen formed in Step 2. The processed regolith can then be further refined to extract iron (e.g., magnetic separation, acid leach) that is formed during the reduction process. Advantages are: (1) moderate processing temperatures (typically 900-1100 C) that are below the bulk melting point of the regolith; (2) uses less hardware; (3) creates iron as a by-product; and (4) can be operated in a nearly closed-loop manner. Disadvantages are: (1) low yield of oxygen per kg of regolith processed than carbothermal process; (2) beneficiation of the regolith is required to increase the ilmenite content; (3) low yield and production rates expected; and (4) poor energy efficiency without added hydrogen.

3.3.3.4.3 Aluminum

Carbochlorination is a complicated process that can be used to produce oxygen and aluminum. Lunar mare regolith is magnetically separated to remove ilmenite, then electrostatically separated to isolate anorthite. The anorthite is then transferred to the Carbochlorination unit where it is heated to process temperature in the range of 675-770 C. If process temperature exceeds 772 C, $CaCl_2$ melts and alters the thermodynamics of the Carbochlorination reactions. The total reaction can be represented by:

$$CaO{\cdot}A1_2O_3{\cdot}2SiO_2(s) + 8C(s) + 8Cl_2(s) > 2AlCl_3(g) + CaCl_2(g) + 2SiCl_4(g) + 8CO(g)$$

After the Carbochlorination reactions are completed, the gaseous products, metal chlorides, salts and CO, are passed through a series of condensers. The first condenser removes enough heat to bring the temperature to 90 C, and $AlCl_3$ is removed as a liquid. The second condenser is cryogenic and brings the remaining gas temperature of -30 C. This second condenser removes all CO gas and the remaining liquid salt, $SiCl_4$, is cycled back into the Carbochlorination unit. As the concentration of $SiCl_4$ builds up in the Carbochlorination unit, it reacts with CO and reverses the Carbochlorination of SiO_2 reaction. This frees up chlorine atoms to form $SiCl_4$ and C atoms form CO. The CO gas can then be converted to the C and O by the Bosch reactor. It is estimated that approximately 50% of all chlorine from $SiCl_4$ could be recovered. To reclaim additional chlorine from $SiCl_4$ and $CaCl_2$ precipitate, the residue in the Carbochlorination unit must be further processed. Advantages are: (1) low temperature requirement; (2) process is well understood for terrestrial applications; (3) the Alcoa process can be used and is the most efficient way to extract Al; (4) hardware for the Bosch Reactor may be used for many Lunar base applications; and (5) there is potential to obtain Al in powder form for use as propellant and metal composite processing. Disadvantages are: (1) recycling of C and Cl_2 may require as much or more hardware than the hardware needed for extraction of desired resources; (2) for extraction of 1 kg Al, 10-20 kg of Cl_2 are required; (3) many C-Cl-O combinations may be thermodynamically favored which necessitates monitoring the O_2 and Cl_2 fugacities during the reactions in the Carbochlorination unit; (4) hot chlorine gas is extremely corrosive and creates a maintenance problem and highly corrosion resistant materials must be used for the Carbochlorination unit; and (5) this process has little potential to run independent of Earth support for Lunar base applications.

3.3.3.4.4 Iron

Iron can be produced via carbothermal reduction of ilmenite found in the Lunar regolith. The carbothermal reduction process has three steps. These steps are: (1) reduction of ilmenite with methane (at >1300 C) to form carbon monoxide and hydrogen; (2) reduction of carbon monoxide with hydrogen to form methane and water; and (3) electrolysis of the water to form oxygen and hydrogen. The process can be operated in a nearly closed-loop manner by minimizing or eliminating the loss of carbon in the processed regolith. The processed regolith can then be further refined to extract iron (e.g., magnetic separation, acid leach). The advantages are: (1) creates useful by-products, including oxygen and silicon; and (2) can be operated in a nearly closed-loop manner. A disadvantage is it requires high-processing temperatures (>1300 C) near the bulk melting point of the regolith.

3.3.3.4.5 Silicon via Carbothermal Reduction of Regolith

Silicon can be produced via carbothermal reduction of various silicates found in the Lunar regolith. The carbothermal reduction process has three steps. These steps are: (1) reduction of the silicates with methane (at >1625 C) to form carbon monoxide and hydrogen; (2) reduction of carbon monoxide with hydrogen to form methane and water; and (3) electrolysis of the water to form oxygen and hydrogen. The process can be operated in a nearly closed-loop manner by minimizing or eliminating the loss of carbon in the processed regolith. The processed regolith can then be further refined to extract the silicon. The advantages are: (1) creates useful by-products, including oxygen, iron and slag; and (2) can be operated in a nearly closed-loop manner. Disadvantages are: requires high processing temperatures (>1625 C), and Si separation at high purity is a challenge.

3.3.3.4.6 Basalt Fiber for Many Applications

The basalt fiber production equipment is quite simple and the process is simple to maintain. Basalt continuous fibers are made from basalt rocks using a single component raw material in a single-stage process. Crushed basalt (or basalt from the mare on the Lunar surface) is transported to the melting furnace. The molten basalt is prepared to forming fibers in the section of the furnace called a “feeder.” The melt flows through a bushing with specially designed orifices. The bushing is heated and controlled very precisely. The fibers are drawn down from the melt and cooled rapidly as they exit the bushing. A sizing is then applied to the surface of the fibers by the device called a “sizing applicator.” The components of the sizing impart strand integrity, lubricity, and resin compatibility. After the sizing is applied, the filaments are gathered into a bundle called a “strand” by means of a gathering shoe before approaching the take-up device. The attenuation rate, and therefore the final diameter, is controlled by the take-up device. The strand passes from the gathering shoe to a winder where it is wound onto a forming tube. The dried tubes are ready for further processing. A typical plant on Earth may have a capacity of 260 tons per year and might run on diesel or natural gas. The furnace is typically run at about 1500 C. Various supplies of air and water are used for cooling. The lunar designs will include a new bushing material to extend the bushing life beyond the current 150 days, new heat sources, and thermal cooling that minimizes consumable resources.

The composition of extraterrestrial basalts is close to that of Earth basalts. The Wisconsin and Minnesota basalts have been used as the chemical basis for development of lunar simulants. Production of fibers and fiber products from these basalts and basalts from many other parts of the world have been demonstrated. The technology development and maturation approach has significant technology transfer value as it imports current capability from over 30 years of commercial operations outside of US; augments the processes with new technologies for robust, remote, and automated operations; applies the capability directly to key exploration objectives; and inserts the capability back into the US commercial market. The basic fiber production processes and the final product fabrication processes are well-known industrial processes that can be adapted for remote, automated operation. The current basalt fiber production is showing major growth in commercial markets as it demonstrates the highest economic value on Earth with high structural properties (on the order of Kevlar) at a very low cost and a large resource of inexpensive raw materials.

The advantages are: (1) Basalt fibers are excellent for a variety of woven fabrics, high tensile strength cables or ropes, and three-dimensionally reinforced solids/composites; (2) tensile strength three times that of steel rebar and weight only one third that of steel; (3) high stability at cryogenic (-200 C) and high temperature (+700 C) applications; (4) high freeze-thaw and ultraviolet exposure stability; (5) high corrosion resistance in oxygen, salt water, alkaline media's; (6) flexible, not "sticky", thermodynamically stabile and considered as non-carcinogenic material; (7) thermal coefficient expansion is close to concrete; (8) superfine basalt fibers possess an excellent thermal isolation, sound and vibration suppression/damping material; (9) multi-filament continuous fibers in amorphous state are exhibit property to consolidation into the complex fiber-strand (ROVING) with extendible applications; (10) basalt fibers have excellent commercial potential in future human space mission applications due to the high mechanical performance/price ratio. Basalt fiber has the highest mechanical performance/price ratio as compared with other fibers currently available in composites reinforcement. This advantage arises due to excellent mechanical performance, and simplicity and ease of mining, processing and fiber production. This advantage will carry over to and be even more important to space exploration/colonization applications. There do not appear to be any disadvantages.

3.3.3.4.7 Advanced Lunar Concrete Steam Process (ALCSP or DMSI) [The Low Water Process]

Advanced Lunar Concrete Steam Process (ALCSP) or DMSI process will produce rapid-setting, high-strength concrete from Lunar soils with greatly reduced consumption of water (< 5% of the pre-cast concrete) than conventional methods and with a substantial reduction in the cement fraction required. It involves: (1) mixing cement and aggregate in a dry state and (2) exposing the mixture to a pressurized steam to cause the hydration reaction. The prospect of these results is based on initial tests with actual Lunar materials and Lunar material simulants. Concrete produced from Lunar soils provides a practical means for construction of rugged structures for personnel living quarters, plant/animal habitats, roadways, laboratories, equipment and machine foundations, solar/meteorite shields, bunkers, containers, and the many other structures and articles that will be found necessary or desirable for life support on the Moon and Mars. With the establishment of Lunar and Mars water available in the soils at the poles and elsewhere, this prospect and ultimate use is enhanced.

The ALCSP (DMSI) method was developed by Dr. T. D. Lin and it involves: (1) mixing cement and aggregate in a dry state and (2) exposing the mixture to a pressurized steam to cause the hydration reaction. Lunar concrete has been studied since 1981. In 1986, NASA provided 40 grams of Lunar soil collected during the Apollo 16 mission for a concrete experiment. The regolith sample was used as aggregate to make one 25 mm (1-inch) cube for a compression test. The measured strength exceeded 700 kg/cm^2 (10,000 psi) twice as strong as the minimum strength required by ACI Building Codes for concrete column design. In 1987, NASA supported a research project for structural analyses and preliminary designs of a 3 story cylindrical pre-stressed concrete structure (36 m diameter and 22 m high) subjected to atmospheric pressure on the inside and zero pressure on the outside. The results verified the suitability of a concrete structure subjected to one atmosphere internal pressure and vacuum outside, with live/dead loads of 1/6 g. In 1988, NASA supported a program to study the effects of Lunar temperature extremes (-157 C at night and 120 C at high noon) on concrete panels that approximated parts of concrete structures standing on the Lunar surface and subjected to Solar radiation. The analytical results showed that maximum tensile stress developed due to the thermal gradient caused by Lunar sunshine was 2.8 kg/cm^2 (40 psi), less than the tensile strength (7 kg/cm^2 100 psi) of the concrete of the study. The low thermal stresses are attributed to the slow rate (0.5 C/hr) temperature changes during the 28-day Lunar cycle. Again, the existence of Lunar boulders is a good example to demonstrate the likely durability of concrete in the lunar environment. In 1989, a NASA SBIR project was awarded to study the feasibility of lunar cement production using Lunar anorthosite and basalt simulants. Cements made by pulverizing and sintering anorthosite and basalt were separately used to cast 25 mm (1-inch) cubes. A conventional moist room was used to cure the anorthosite paste cubes, while a steam chamber was used to cure the basalt paste cubes. The anorthosite cubes developed an average strength of 385 kg/cm^2 (5,500 psi), and the basalt cubes developed an average strength of 500 kg/cm^2 (7,100 psi). This project demonstrated that simulated lunar anorthosite and basalt can be used to make quality cements.

3.3.3.4.8 Waterless Sulfur/Regolith Mix – Based Concrete (WSRM)

Experiments carried out on Lunar soil samples returned by Apollo missions revealed that sulfur could be extracted from Lunar soil by heating it at moderate temperature (~1000-1200 C), which can be achieved with standard solar concentrators on the Moon. Sulfur is sufficiently abundant on the Moon that it may be available as a by-product from Lunar oxygen production or gas recovery. Analysis of the Lunar samples returned by the Apollo missions indicate that sulfur, 11th in weight abundance, is available in the mare soils and rocks. Sulfur may offer an alternative to “Portland cement” as a binder in making concrete for use in Lunar construction. Advantages to this process are: (1) zero water consumption: (2) compressive, tensile, and flexural strength as well as fatigue life that may be greater than those obtained with conventional Portland cement concrete in certain environmental conditions: (3) rapid setting, achieving a minimum of 70-80% of ultimate compressive strength within 24 hours of casting; higher chemical resistance against acids and salts; and (4) low water permeability. Disadvantages are: (1) temperature variation is critical factor affecting strength of sulfur concrete, it should not exceed 119 C (M.P. of S); (2) temperature should be kept < 96 C to prevent surface melting and volume change of S; (3) problems with effects of low pressure/vacuum and very low temperature on S sublimation; (4) relatively poor durability of sulfur concrete in response to repeated thermal cycles. Key technology gap is the performance of sulfur in extreme conditions such as very low temperature and very low pressure is not known and must be investigated if sulfur concrete to be used as a construction material in space.

3.3.3.4.9 Volatiles

Volatile gases are available all over the Lunar surface. In the warmer zones, the Solar wind has deposited gases from the Sun's wind in the Lunar soil since the beginning (see Duke, et.al., 1998). At the poles there is a wide variety of gases deposited via gas migration, cometary and meteorite impacts all over the surface followed by migration over the ages. At the poles (shadowed areas) we can harvest water, methane, ammonia, carbon dioxide, carbon monoxide, sulfur dioxide, helium, hydrogen, nitrogen and perhaps mercury. These are all important for all kinds of applications: propulsion, life support, chemical product production, etc.
Concepts for recovery of Lunar volatiles and their use for a Lunar colony have received increased credibility because of the confirmation of the Clementine discovery of ice in permanently shadowed deep polar crater floors on the Moon.

The LCROSS impact data, though still partially embargoed, are consistent with approximately 30 parts per thousand weight in the permanently shadowed regolith on the crater floor (Elphic, et. al., 2010). The water is mixed with a familiar "dirty ice cocktail" of oxides of carbon, and sulfur, methane and ammonia commonly seen in comets.

We can estimate the composition of the Lunar volatiles found at the Lunar poles by assuming they are primarily due to cometary impacts and reflect Solar abundances of volatile elements. Hydrogen is the most abundant volatile, but will occur in ices only as a chemical combination with heavier elements. For every 100 atoms of oxygen, there are 50 atoms of carbon, and, 16 atoms of nitrogen, and 2 atoms of sulfur. (Arnett, 1996).

Depending on chemical conditions, and based on studies of comet spectra (DiSanti, et al.,1999) we will get ices in the Lunar craters that will be approximately the following chemical composition: 59% H_2O, 10% CO, 10% CO_2, 10% CH_4, 10% NH_3, and 1% SO_2 . Access to these ices means abundant chemicals to supply a Lunar colony.

Trapped gases from the Solar wind are present generally in the Lunar regolith. Hydrogen is most common and is present in the weight fraction of 10 parts per million (Fegley and Swindle, 1993) or at a mole fraction of approximately 1 part per thousand. Carbon as carbon dioxide and nitrogen as gas are also present in the 100 parts per million level as a weight percentage.

Therefore, the Lunar poles offer access to 100 times the concentration of water and other volatiles as does the equatorial regolith and argues strongly for location of an initial Lunar base in the Polar regions. The discovery of abundant Lunar volatiles is transformative to planning for Lunar colonies and allows the use of the Moon as a springboard in a generational effort to expand human presence across the Solar System.

Plastic can be easily made from the Lunar volatiles. The simplest plastic to make on the Moon is also generally useful. The plastic polyethylene is widely used on Earth for packaging, carpet, utensils, furniture, and structures. Polyethylene can be made starting with CO_2 and H_2 gases. Both hydrogen and carbon dioxide can be derived from newly discovered Lunar volatiles, which contain carbon monoxide, methane, and water. In general, carbon dioxide and hydrogen can be converted into methane by the Sabatier process, proposed for making rocket fuel from the Mars atmosphere (Zubrin and Weaver, 1993):

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The methane can then converted into ethylene by first making ethane:

$$2CH_4 + 2CH_4 \rightarrow 2C_2H_5 + H_2$$

which is then partially oxidized to form ethylene:

$$4C_2H_5 + O_2 \rightarrow 4C_2H_4 + 2H_2O$$

Alternatively it is suggested by Rosenberg (1998) that ethylene can be made in one step with the proper catalyst.

$$2CO_2 + 6H_2 \rightarrow C_2H_4 + 4H_2O$$

Ethylene can then be polymerized into polyethylene plastic and then used as it is used on Earth (Rosenberg, 1998). This plastic can also be used as binder for a composite structural material consisting of regolith and polyethylene (Sen, et al. 2010). This is an important material supporting a Lunar colony.

3.3.3.4.10 Regolith

The Lunar regolith is a resource by itself as is or with a little bit of processing. Products that we can derive easily from the regolith include ceramics, tiles, floors, furniture, clear glass, colored glass, dishes, glasses, Radiation shielding [from Solar flares, cosmic rays, & nuclear reactor], filters - sintered regolith, spun fibers, self-forming pipes and beams, soil to grow plants in, and road material. Slag-bricks are discussed below.

The Slag–brick production equipment is quite simple and the process is simple to maintain. Slag-bricks of various forms can be made from slag from carbothermal or hydrogen reduction processing ot virgin Lunar regolith in a single-stage process. These materials are transported to the melting furnace. The molten material is prepared to forming/cast bricks in a similar way bricks are made on Earth. The furnace is typically run at about 1400 to 1600 C. Various supplies of gas and water are used for cooling. Advantages are: (1) relatively easy way to use Lunar regolith for construction on the Moon; (2) can be easily cast into forms that can be assembled into useful items; (3) use of byproducts; (4) if byproduct, can use heat of previous process; (5) bricks are strong and will last forever; and (6) can be used in conjunction with inflatibles. A disadvantage could be can be energy intensive if not derived from a by-product.

3.3.4 Lunar Commercial Activities to Support Profitability of the Private Lunar Transportation & Lunar Settlement (PLTLS)

As an activity to develop an attractive approach for humans to settle the Moon, it may not be enough to rely on land value alone, therefore, we wanted to identify additional commercial activities that could be supported by colonists and their organizations. A list of possible activities (see Figure 27) has been identified and require further study as this effort moves on.

Lunar Sports and Facilities, Amusement Park	Radiation Shields
Energy – Solar Power, Energy Storage, Solar Cell Production	Telemedicine Medical Services, Burn Treatment Services
Propellant Servicing, LOX Production, Water and Hydrogen Production, Volatiles Production	Rail Gun, EML, or Laser Beamed Propulsion Back to Earth, Probe Launching
Communications Services	High-Vacuum Manufacturing
Navigation Services, Flight and Ground	Archival of Data Assets
Entertainment with Rovers	Storage of Nuclear Materials
Movie Production	He3 Production
Advertising	Satellite Refueling and Servicing at the Depots
Transport Services	Water Extraction
Lunar Casino	Life-Support Services/Supplies
Lunar Tourism	Taxi Flight Service - Hoppers
Facilities - Habitats	EVA Systems
Raw Materials	Rovers
Lunar-Produced Products	Logistics Resupply
Space Resource Utilization (SRU)	Road Building and Excavating
Agricultural Services/Food Production	Mono-Rail Construction
Repair/Manufacture/Fab/Assembly	Mining
Microwave Power Transmission	Provision of Building Materials / Forms / Bricks
Large Mirror Manufacture	Self-Forming Pipes and Other Structural Shapes
Launch Lunar Materials Back to Earth	Centrifuge Facilities for Health and Fitness Services
Manufacturing of Solar Cells	Lunar Jewelry and Rocks for Sale
Detectors, Sun Observations, Solar Wind Measurements, Dust Measurements	Earth Power Beaming
Export Special Beverages to Earth	

Figure 27. A List of Possible Lunar Commercial Activities

3.3.5 Approach to Developing a Lunar SRU Development Plan for PLTLS

After a review of all possible Lunar space resource raw materials and products and their potential applications that have been identified here, we came up with a logical plan of how a SRU Development Plan for the PLTLS. This multi-step process is listed below. We expect to expand the details of this approach in Phase 2.

1. Develop SRU cost-benefit models to make “take” or “make” (on the Moon) cost assessments
2. Identify all Earth-based products/systems/components required for the Initial Operating Capability (IOC) of the entire colony and transport system

3. Identify SRU-derived products/systems/components and their required materials from the Moon that could be implemented at a future date, if Moon-production is shown to be economically beneficial (take or make assessment)
4. Develop a Cost-Benefit Model for Private Lunar Transportation & Lunar Settlement (PLTLS) system for the most promising candidate SRU processes
5. Identify the most feasible, cost-effective materials and products that could be produced in the future and which ones are highly developed at this time and can be demonstrated easily
6. Begin Earth-based private R&D on the most cost-beneficial products and materials for the future that require technology development
7. Develop an Earth-based private laboratory to conduct the SRU process development or demonstrations for most cost-effective SRU products and processes
8. Develop a detailed mission model as a function of colony growth rate scenarios based on the most cost-effective approaches.

3.4 Provide a Preliminary Plan for Phase 2 (Task 4)

Obviously there is a lot of work to be done to plan for a PLTLS. After an assessment of what we think would be most beneficial to the Steckler goals, the commercial entities that are expected to be leading the main PLTLS activity, NASA, the USAF, and the Earth's population, we have come up with some recommended areas of work to be defined within a funded budget of $250K with some in kind efforts. The work tasks suggested for Phase 2 at this time are:

USLV Plug Nozzle Development – The achievement of very low cost access to space is an absolute requirement for space colonization. The USLV that we have proposed to use as the Earth to LEO booster will likely achieve that goal; however, we need to demonstrate and verify the aerodynamic plug nozzle integrated with the distributed vortex engines to gain support for the USLV development from investors and other sponsors. Therefore, we propose a task in Phase 2 to design a USLV stage for eventual fabrication and full-duration static firing at ORBITEC's test facility.

Space Transportation Architecture and Cost Model - We propose to continue to work on the details of the Space Transportation System Architecture and all of its elements (see Figure 3.3-1). We will develop a traffic model for the installation through IOC and a growth model that makes sense with a land ownership/homestead scenario by one corporate organization. We will conduct detailed mission analysis and develop physical sizes and weights for all the elements. We will also develop a Space Transportation System cost model that we can use to determine the projected costs of each component in the system and the overall cost that will be eventually needed for an assessment of the business case. We will also re-assess the assumptions that we have made in Phase 1. During this task, we will also assess the TRL levels of the technologies that we plan to incorporate into the system and evaluate the R&D effort it will take to bring the specific technology to flight-readiness.

Space Depot Concept Design – We have proposed three propellant and servicing depots as key parts of the system. We plan to conduct a detailed concept design of the LEO, LLO, and LS Depots. As we progress with work in the above task, we will use that data to perform detailed design and size the depots. We will also assess what servicing the depots could provide to the potential other space users (e.g. other Earth Orbit, Lunar, Mars, or asteroid missions).

Design of an Earth-based SRU Laboratory – During Phase 2, we propose to outline an SRU laboratory that can be built and developed to conduct a wide range of space resource utilization research. The effort would involve the making of raw materials from simulated Lunar regolith and Lunar volatiles and the production of products made from the raw materials. We would use the results of the SRU cost models to influence what would be chosen for the design. This would then become an analog for the Moon base.

Processing of SRU Metals (Al, Fe, Si) – We believe that water, hydrogen, and oxygen recovery will be well developed through NASA sponsorship over the next few years. The next elements in line as beneficial players in the SRU game are aluminum, iron and silicon. We plan on working on processes that produce these metals during the Phase 2 effort (see Sections 3.3.3.4.3, 3.3.3.4.4 and 3.3.3.4.5)

SRU Cost Benefit Models – To make intelligent "take" or "make" (on the Moon) we need to know the cost benefit factor of using a given Lunar material to use or make other products. A cost benefit model will be developed that can determine whether Lunar raw material or its use in a product made on the Moon is worthwhile against the option of taking it from Earth to the Moon. The total transport cost is obviously a key, and that will be determined in the Space Transportation task above.

Outreach and Education – We plan to expand our education and outreach activities by involving Midwest Aerospace Engineering Colleges in our vehicle design and SRU efforts. We will look to the WSGC Members first and then reach out to schools like: Northwestern, Ohio State, Illinois, Minnesota, Purdue, Michigan, Georgia Tech, Texas, and USC. We will make additional information available on our website and we plan to provide lectures and coordination workshops to students and faculty. We will also engage several local high schools in the Wisconsin area.

Commercial Program Planning – We plan to provide guidance to companies and individuals who wish to gain involvement in this approach to colonizing the Moon. Through this task, we would prepare a draft plan of implementation and hold workshops to gain inputs from potential shareholders.

4.0 ACHIEVEMENT OF GOALS AND OBJECTIVES IN PHASE 1

The objectives for this Phase 1 effort were:

1. Enhance/enable the Vision for Space Exploration, including the wishes of Ralph Steckler
2. Develop the process for an assured economic development approach and to conduct public education and outreach activities
3. Develop an innovative, evolutionary, cost-effective, Earth-Moon space transportation system/space line concept to allow private Lunar land ownership
4. Develop an Innovative Lunar colony resource development plan based upon the basic needs and commercial activities of the Lunar colony
5. Provide preliminary plans for Phase 2 and 3
6. Prepare and deliver a final report and outreach presentation.

Accomplishments organized by objective:

1. Enhance/enable the Vision for Space Exploration, including the wishes of Ralph Steckler

   We completed this goal/objective - we developed space transport approaches that can provide low-cost safe transport to the Moon and back for Lunar homesteaders. We began the investigation of how to make our approach the lowest cost by investigating SRU cost benefit. We have provided one of the most creative approaches to Lunar colonization that has been conceived.

2. Develop the process for an assured economic development approach and to conduct public education and outreach activities

   We completed this goal/objective – we have proposed a viable process for colonization and we have begun educating the space community, Congress, and the public through outreach. We have come up with a logical progression to complete the final goal.

3. Develop an innovative, evolutionary, cost-effective, Earth-Moon space transportation system/space line concept to allow private Lunar land ownership

   We completed this goal/objective – we have developed an excellent space transportation architecture for the low-cost and safe transport of passengers/homesteaders to and from the Moon.

4. Develop an Innovative Lunar colony resource development plan based upon the basic needs and commercial activities of the Lunar colony

   We completed this goal/objective – we have developed an Innovative Resource Development Plan that is expected to provide the most profitable approach to a Lunar colony.

5. Provide preliminary plans for Phase 2 and 3

We completed this goal/objective – we have provided preliminary plans for Phase 2. Phase 3 plans need to wait until Phase 2 is complete.

6. Prepare and deliver a final report and outreach presentation.

   We completed this goal/objective – we have prepared and delivered the final report and outreach presentation.

We met these goals and objectives and that provides the ground work to make absolutely meaningful first-step advances in space colonization. We look forward to working on a Phase 2 contract.

5.0 SUMMARY AND CONCLUSIONS

A list of key conclusions and recommendations based on the conduct of the Phase 1 Steckler Study was developed and are provided below:

- We believe that it makes logical sense to start building a Commercial Support Group made up of large and small businesses and other organizations. ORBITEC is ready to move ahead and lead it if a Phase 2 effort is granted.
- The work conducted in the Phase 1 study and proposed Phase 2 effort, while supporting the goals of Steckler, should provide significant benefit to NASA, in the transportation architecture, SRU, and commercial market development areas for buy-in to occur.
- The initial recommended tasks for Phase 2 have been chosen to support Steckler goals and the needs of NASA; we recommend their support.
- The space transport architecture should be considered by NASA as its choice. We recommend that it be presented to the NASA program offices: ORBITEC offers to do this.
- We recommend continued dialog with film makers and that we provide the Phase 1 report to them for review for future film possibilities.
- We recommend NASA put out a detailed press release on the results of the Steckler Study efforts.
- This Wasser approach is worthy of continued pursuit; it is well thought out and developed – this team believes this approach is ready to move ahead. This effort could have the biggest impact on human colonization that has ever been imagined.

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APPENDIX A. The Space Settlement Initiative
September 2010

Appendix A
The Space Settlement Initiative

Will people ever live and work on the Moon and Mars?

Will the settlement of space take place in *your* lifetime?

The settlement of space would benefit all of humanity by opening a new frontier, energizing our society, providing room and resources for the growth of the human race without despoiling the Earth, and creating a lifeboat for humanity that could survive even a planet-wide catastrophe.

Unfortunately, it seems clear that, as things stand now, space settlement will not happen soon enough for any of us to see it. But that could be changed! The legislation proposed on this web site would:

- save NASA and the taxpayers the cost of developing affordable space transport by allowing private enterprise to assume the burden of settling space
- make it possible for ordinary people to purchase tickets and visit the Moon as tourists, scientists, or entrepreneurs
- create vast wealth from what is now utterly worthless

Space development has almost stopped, primarily because no one has a sufficient reason to spend the billions of dollars needed to develop safe, reliable, affordable transport between the Earth and the Moon. Neither Congress nor the taxpayers wants the government stuck with that expense. Private venture capital will support such expensive and risky research and development ONLY if success could mean a multi-billion dollar profit. Today, there is no profit potential in developing space transport, but we have the power to change that.

We have the power to create a "pot of gold" waiting on the Moon, to attract and reward whatever companies can be the first to assemble and risk enough capital and talent to establish a "space line" and lunar settlement. How? By making it possible for a settlement to claim and own -- and re-sell to those back home on Earth -- the product that has always rewarded those who paid for human expansion: *land ownership*

Lunar and Martian real estate is currently worthless. But that real estate will acquire enormous value after there is a settlement, regular commercial access, and a system of space property rights. ***Lunar or Martian property ownership could then be bought and sold back on earth, raising billions of dollars.*** This is a plan to be sure that money is used as an incentive and reward for those who invest in a way to get there and stay there.

In the mid 1960's, President Johnson saw he was going to be forced to take money from the space race to fund the Vietnam War. He feared that, if that let the Russians win the race to the Moon, they might claim ownership of the Moon. So he proposed, negotiated, and the U.S.

Senate ratified, what became known as the 1967 "Outer Space Treaty." Among other things, this treaty prohibits any claims of *national* sovereignty on the Moon or Mars, etc. Therefore no nation can claim or "grant" land in outer space.

But, quite deliberately, the treaty says nothing against private property. Therefore, without claiming sovereignty, the U.S. could recognize land claims made by private companies, regardless of nationality, that establish human settlements on the Moon or Mars. The U.S. wouldn't be "granting" or giving the land to anyone. It isn't the U.S.'s to give. The settlement itself says "because we are the first to actually occupy this unowned land, WE claim ownership of it" - and the U.S. just "recognizes" - accepts, acquiesces to, decides not to contest - the settlement's claim of private ownership.

The proposed legislation would commit the U.S. to granting that recognition if those who have established settlements meet specified conditions, such as offering to sell passage on their ships to anyone willing to pay a fair price. Entrepreneurs could use that promise of U.S. recognition to help raise the venture capital to develop the ships needed to make the claim.

The dollar value of a Lunar land claim will only become big enough to be profitable when people can actually get to the land. So Lunar land deeds, recognized by the U.S. under this plan, can be offered for sale only after there is a transport system going back and forth often enough to support a settlement and the land is actually accessible. It will finally be understood to be land in the sky, not pie in the sky.

It would take a really large land claim to be worth that huge investment, of course, but there is an amazingly large amount of land out there waiting to be claimed. For example, a claim of 600,000 square miles, about the size of Alaska (just under 1,600,000 square km.) would be only around 4% of the Moon's surface, but would be worth almost 100 billion dollars at only $260 an acre (4047 square meters). At $500 an acre it would be worth $192 billion. Of course the price of the land, especially the best land, might be much more by then.

It will be offered for sale after months of worldwide press coverage produced by the race to be the first to settle the Moon. There will be land buyers with business purposes for buying and using land, but there will be a much bigger speculative and investment market. Many people who will never leave Earth will buy Lunar land. Some in hopes of making a profit, others just to be part of the excitement or to leave an acre to their grandchildren, or put their name on a crater.

The profits on land sales which take place in the U.S. will, of course, be subject to U.S. taxes, so the Budget Office will score this legislation as a revenue producer, not a cost to the U.S. It sounds strange because we haven't done it yet, but there is growing sentiment for extending private property and the benefits of free enterprise to space. Former House Science Committee chair Bob Walker has suggested that the Bush administration would like to develop such a legal structure.

Before copyright and patent laws, no one could own songs, stories or ideas. The passage of those laws, creating intellectual property, made whole industries possible and added greatly to the world's wealth from things that had previously been valueless. Creating lunar property could be the incentive to open the space frontier to everyone, thus benefiting all of humanity.

Would you support such innovative legislation? If so, please tell others about **www.SpaceSettlement.org**. Better yet, tell your Congressman and Senator about this idea. If you live in another country, why not suggest such legislation to your own government?

I want to thank the *Moon Society/Artemis Society* for their recent endorsement of the Space Settlement Initiative. Such endorsements are very helpful. Finally, I want to thank Dave Brett very much for creating and maintaining this web site.

Alan Wasser
September 2010

Please send your comments to me at: SpaceSettlement @ att.net (remove the spaces on either side of the @ and please mention "Space Settlement" in the subject line so your message doesn't get accidentally deleted with spam.)

The following questions and answers explain the details of this proposal:

1. What is the real purpose of enacting a land claims recognition law?
2. Will promising property rights be enough to produce the necessary investment in developing affordable space transport?
3. What does international law say about private property ownership in space?
4. Can there be property ownership without national sovereignty?
5. What if other nations refuse to recognize land claims in space?
6. Why not give smaller, limited land grants for easier steps than settlement?
7. Could lunar land really be worth enough money to make a difference?
8. What conditions should the U.S. set for recognition of a claim?
9. How much land should a settlement be able to claim...and why?
10. Why must the space line and settlement be open to all paying passengers regardless of nationality?
11. Wouldn't it help if a major company announced that, if a land claims recognition law were passed, it would try to develop affordable space transport?
12. Are the weaknesses and compromises in this plan likely to be permanent?
13. Didn't the earliest version of this plan talk about "Lunar land grants"? Why aren't you using that phrase any more?

14. Did land grants work?
15. You can't farm Lunar land, and Earth doesn't need its minerals. So how could Lunar land be put to profitable use?
16. If you can't give figures, now, proving the profitability of the end uses of Lunar land, how could anyone raise big money for Lunar land?
17. Could other sources of revenue be enough, without land claim recognition?
18. What if the settlement does not produce enough operating revenue to pay off its debts and make a profit?
19. Could this law produce a new "space race"?
20. Why is U.S. legislation, in particular, so important?
21. Could the U.S. withdraw from the Outer Space Treaty, claim national sovereignty on the Moon, then award property rights to whomever it pleased?
22. What about defense? Does recognizing a land claim obligate the U.S. military to defend the settlement?
23. What effect would this have on NASA and the aerospace companies?
24. What do the experts say about this idea?
25. Who came up with this idea?

1. What is the real purpose of enacting a land claims recognition law?

The creation of a legal system of property rights for space is *not* the long-term objective.

The establishment of a property rights regime for space is only a means to an end, not an end in itself. The real purpose is to enable the expansion of the habitat of the human species beyond the Earth by offering a huge financial reward for privately funded settlement.

It is the only way to create an economic incentive sufficient to encourage private investment to develop affordable human transport to the Moon and Mars.

There are alternative space property rights schemes being proposed by some lawyers that would, instead, make settlement even harder than it would be now. They would require that, if you do pay to develop space transport, you would then have to pay the UN or some other body even more for the land you want to settle.

Property rights legislation should be judged by how well it encourages space settlement, not on how elegant the resulting property rights system is. Property laws could be left to evolve after settlement, except that settlement just isn't happening without them, so we need something like this legislation to jumpstart it.

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2. Will promising property rights be enough to produce the necessary investment in developing affordable space transport?

Hopefully, promising property rights will turn out to be enough to produce the necessary investment. But it is impossible to know, this early, whether it will be. After all, it is impossible to know now how much it will cost to develop safe, reliable, affordable space transport, or how long it will take.

But we can be certain that promising property rights would help generate the investment we need.

There is also no way to be sure just how much Lunar land will be worth when recognized deeds are being sold by people who can actually take you (or your customers) to that land. But a piece of Lunar land the size of Alaska would certainly be worth a very large amount of money.

Right now there is a sizable demand for phony deeds to Lunar property, so it is safe to assume there will be a much bigger demand for real deeds to Lunar property. We'll talk about how to estimate the dollar value of lunar land in the answer to question 7, below.

Those who say property rights are not needed until after settlement has actually taken place are counting on near -term incentives (such as space tourism, servicing the space station, etc.) to produce all the necessary investment in affordable space transport, the establishment of on-orbit infrastructure and then settlement itself. It is very much open to question whether such near-term incentives could be sufficient, but it is certain that adding a very big long- term incentive, on top of whatever near-term incentives there are, would have to help.

Imagine that you are an entrepreneur trying to get a venture capitalist to fund your research on a radical new idea that you think might reduce launch costs by an order of magnitude or more. He asks, *If you succeed in this risky venture, how are you going to use it to make enough profit to make it worth my while?* You tell him your projections of space tourism profits, etc., and he is impressed, but not enough. Then you add: in addition to all that, if we do reduce launch costs enough, it could later be used to establish a settlement on the Moon and immediately gain U.S. recognized ownership of 600,000 square miles that could be sold, and/or mortgaged, starting the very next day. If that were valued at only $260 an acre, it would be an instant gain of an almost $100 billion dollar asset on your books. At $500 an acre it would be worth $192 billion ($192,000,000,000.00). Is there any chance that would not help your case? Even at only $100 an acre it would be almost $40 billion.

In order to spur the development of affordable space transport, this law doesn't need to bring in all the needed investment by itself. There are existing incentives, but not enough. We need only bring in sufficient additional financing to tip the balance. The promise of property rights for space settlement is a very low cost, low risk, "do-able" way to attract that supplementary venture capital.

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3. What does international law say about private property ownership in space?

Early in the negotiations for the 1967 "Treaty On Principles Governing The Activities Of States In the Exploration And Use Of Outer Space, Including The Moon And Other Celestial Bodies", generally called the *Outer Space Treaty*, the USSR suggested that the treaty ban private activities in space but, at the insistence of the Americans, all such provisions were dropped from the final treaty. According to the New York Times report of the U.S. Senate ratification hearings for the Treaty, (March 7, 1967) Senator Albert Gore (Senior) worried that the "benefit of all" provisions of Article 1 of the treaty might inhibit space activities. The Times says Arthur Goldberg, who negotiated the treaty for the U.S., reassured Gore by describing "the article as a 'broad general declaration of purposes' that would have no specific impact until its intent was detailed in subsequent, detailed agreements."

The one serious attempt to establish such a follow-up agreement was a disaster that the U.S. Senate refused to ratify, specifically because it attempted to ban private property. It was the 1979 "Agreement On The Activities Of States On The Moon And Other Celestial Bodies" generally referred to as "The Moon Treaty". It would have replaced the "benefit of all mankind" language with the drastically different "common heritage of mankind" doctrine. Some third world countries have claimed that the "common heritage" doctrine would mean that anyone wanting to establish a lunar settlement might have to pay off the leaders of every nation on Earth.

Fortunately, since it wasn't ratified by the U.S. or any other nation that was then spacefaring, the Moon Treaty is generally regarded as a dead letter, and is not binding on the U.S. or its citizens. Thus, The Space Settlement Institute is firmly convinced that, as things stand now, private entities can claim ownership of land on the Moon "on the basis of use and occupation" although nations cannot.

For a fully detailed, footnoted discussion of the many legal questions, opinions and precedents involved, as published in SMU Law School's Journal of Air Law & Commerce, the oldest and most respected law journal in its field, see: "Space Settlements, Property Rights, and International Law: Could a Lunar Settlement Claim the Real Estate It Needs to Survive?"

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4. Can there be property ownership without national sovereignty?

In countries like France, which follow what is called "civil law" (as opposed to "common law" which the U.S. inherited from the U.K.) property rights have never been based on territorial sovereignty. Instead they are based on the "Natural Law" theory that individuals mix their labor with the soil and create property rights independent of government. Government merely recognizes those rights.

Throughout history, actual settlement, "occupation and use" has been the traditional basis for claims of ownership of land that had no sovereign. Columbus claimed the land he discovered by leaving a garrison on it, not by planting a flag. We want the U.S. to treat the settlement, itself, as having one of the attributes of a sovereign: the right to claim private ownership of unowned land by right of use and occupation.

For property rights on the Moon, the U.S. will have to recognize Natural Law's "use and occupation" standard, rather than the common law standard of "gift of the sovereign", because the common law standard cannot be applied on a Moon where sovereignty itself is barred by international treaty. The U.S. will have to say that, because there can be no government on the Moon, a true settlement can give itself title, just as though it were a government, and its property deeds, for land under its control, will be recognized by U.S. courts of law, (subject to specified limitations) just as titles issued by France, China and even Iraq, are recognized by U.S. courts.

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5. What if other nations refuse to recognize land claims in space?

Because the US market represents such a large fraction of the world's economy, and because it often leads the way on economic matters, US recognition is by far the most important - and the place to start. But it certainly would be very desirable if other nations then joined in, especially those with significant space industries, such as the members of the European Union, Russia, Japan and China. Therefore, it is important that those nations see more benefit to themselves in joining than resisting.

The legislation in this proposal strongly encourages reciprocal arrangements with other nations. It instructs the State Department to actively seek those agreements. If needed, it allows State to negotiate treaties that require that settlements be multi-national consortia, to assure other nations that this isn't going to be just an American land grab. If necessary to get the UN on board, it even allows State to negotiate treaties requiring the inclusion of citizens of at least one developing country as investors or providers of an equatorial launch site.

Will this be enough to guarantee all nations sign on? Probably not at first, but it won't really make a significant difference to land buyers if Libya and Cuba, etc., refuse to recognize their land deed, as long as they know the US and the major spacefaring nations will.

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6. Why not give smaller, limited land grants for easier steps than settlement?

It would be nice if we could offer a series of graduated rewards for each little advance in space development, but it can't be done legally,... and the grants wouldn't be worth anything much if it could be done. Where the U.S. has sovereignty, and is the source of ownership, the government can give ownership of land, or limited rights to its use, for whatever reasons it chooses. But, since no nation can claim sovereignty on the Moon and Mars, the U.S. has nothing to give. The only thing governments can do is to recognize, or not recognize, a claim made by a private entity which has a good case for making the claim.

This law would not prohibit anyone from making a claim to any space real estate based on anything, or nothing at all, including "I want it, so it is mine". Nor would it require anyone else to pay any attention to such a claim. It would only require that the U.S. government must recognize a claim based on actual settlement and "use and occupation".

It will take hard work to get Congress and the courts to accept even settlement and "use and occupation" as a basis for space land claim recognition, even though that has always been the basis for claims of ownership of new land. Space claims based on anything less than settlement would be virtually impossible to justify to the courts and the world.

More important, human settlement of space is our real goal! We are a lot more likely to actually see it happen if it is the required condition to win anything. Giving limited ownership for less could reduce the incentive, for both the winners and losers of the first round, to keep going full out toward settlement. Only when there is a live human being waiting on the Moon for the return flight can we be really sure that there will be a return flight, even if the accountants say, "put it off for a few years, or more."

But the most important reason to reserve grants for actual settlement is the following:

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7. Could lunar land really be worth enough money to make a difference?

It isn't how much land you get that matters. It is how many dollars it is worth!

The surface of a sphere is four times pi times the square of its radius. The Moon's mean radius is 1080 miles so its surface area is 14,657,415 square miles. One acre = .001562 square miles, so the lunar surface has approximately 9,383,748,198 acres. (Mars, by the way, has almost 35 and a half billion acres.)

So how much could those 9.38 billion Lunar acres be worth in dollars? First, let's figure the absolute minimum, worst case dollar value. It seems a more than reasonable floor to assume that REAL Lunar deeds would - at the very least - be worth no less than the proven market price of phony ones.

Since 1980 a man by the name of Dennis Hope has made a small fortune selling Lunar "deeds". He simply announced that he had claimed the Moon, set up his own "Lunar Embassy", and has sold unrecognized Lunar land "deeds" for $15.99 an acre ($18.49 if you want your name printed on the deed). Many people buy these "deeds" even though there is no way to get there, and nothing can be done with them. Dennis Hope has sold over 1.1 million of these "properties" to people in 165 countries, according to Greg Nemitz, Hope's former "National Marketing Director" (and, not surprisingly, the most determined opponent of requiring "use and occupancy" before claiming Lunar land.)

So Hope has proven beyond doubt - by selling so very many of these "deeds" all over the world at $15.99 per acre, - that real deeds, recognized by the US and actually accessible by a then-existing commercial space line - would certainly be worth no less than $15.99/acre.

15.99 times 9,383,748,198 acres = $150,046,133,679. That is over $150 billion dollars - absolute minimum worst -case value.

Of course, US government recognized land would be worth many times more per acre. For example, at $260 per acre it would be $2.4 trillion. At $500 per acre it would be $4.7 trillion. Even at only $100 it would be $938,374,819,756.00, almost a trillion dollars.

I assume that would be much more than the necessary incentive, so I've been proposing recognizing claims of no more than 4% of that - 600,000 square miles - but if need be, the size of the recognition could be increased up to whatever it took - up to that limit of $938 Billion dollars. Do you think a chance to win a "prize" worth almost a Trillion Dollars would be enough to interest Boeing or Lockheed? Further, much can be done to increase the value of that land over time.

First, the dollar value of an acre of lunar land goes up exponentially the day buyers can actually buy a ticket and go there, or send a representative or a customer. That means the value of the land goes up exponentially if we hold it back until there is a space line going back and forth.

The value of the land claim can be similarly increased if we capitalize on the media coverage of a space ship taking off to try to win the race to establish the first human settlement on the Moon. The day people land on the Moon, set up permanent habitation, and stay there while the ship goes back for more people, they will be the whole world's heroes -- on every TV screen and front page on Earth! Trips to and from the moon will be terribly expensive at first. But deeds to small parcels within the vast area around a settlement will be much more affordable. People around the globe will have a chance to buy those deeds as a way to support the project, or just feel part of the excitement.

Then, and only then, will a lunar land claim reach the multi-billion dollar value that would make a real difference, enough to justify even the billions it took to win it.

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8. What conditions should the U.S. set for recognition of a claim?

It should set an appropriate limit to the amount of land that can be claimed, (and it will be easier to increase the size of a grant, later, than to reduce it). It should require the settlement to behave by international norms. It should require that the settlement be open to all and prohibit anti-competitive behavior. Regulations could even include protection for sites of historical or other special importance.

It might also be required that only a certain percentage of land sale revenue can be used to repay the cost of establishing the settlement and taken as profit, the balance being retained to support the settlement itself until it can find ways to earn enough to become self sufficient.

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9. How much land should a settlement be able to claim...and why?

The first settlement on the Moon should be able to claim up to 600,000 square miles. Getting to Mars will cost much more and Mars itself is larger than the Moon. Therefore the first Martian settlement should be able to claim up to 3,600,000 square miles, roughly the size of the United States. That would be worth $600 billion at $260 an acre, or $1.15 trillion at $500 an acre. Even at only $100 per acre it would be 230 billion dollars.

Some critics object that would allow a settlement to claim more land than it can use, but the amount of land that can be used depends on what you are using it for. Nineteenth century land grant farmers used 40 acres and a mule. Modern mechanized farms use vastly more land than that. Cattle ranchers use much more land than farmers. But none of those are the size criteria that should be used for a Lunar settlement because, of course, the settlement will not make its living by either farming or ranching.

The plan is to let settlements recoup the cost of getting there in the first place by selling land. If you are in the real estate business, especially if you are selling totally raw Lunar land, you can use all the acreage you can get title to. So the "right" size for a claim is that size which is just large enough to justify the cost of developing reliable space transport and establishing a settlement. Small enough to force the development of cost effective, affordable, transport, and small enough to still leave room for future settlements.

That's how the proposed settlement sizes were derived. Real estate experts guessed at the minimum the land would bring when you could buy a ticket and get to it. Space experts guessed at what was the least that financially efficient private companies could hope to establish settlements for. The average settlement cost estimates, divided by the estimated average dollars per acre, gave the number of acres needed. Converted to square miles, that worked out to approximately 600,000 square miles on the Moon and 3,600,000 square miles on Mars.

Fortunately, that is quite small enough to still leave plenty of room for subsequent settlements, since it is only around 4% of the Moon, 6.5% of Mars. Since it is much easier to follow than to lead, and we want to encourage leadership, no settlement after the first gets even that much.

Each subsequent settlement gets 15% less land than the previous one. Finally, no entity can get recognition for more than one settlement on a body. Therefore there is no possibility of anyone monopolizing all the land.

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10. Why must the space line and settlement be open to all paying passengers regardless of nationality?

International law clearly requires that opening the space frontier must "benefit all mankind" and that there must be "access to all areas of celestial bodies".

The Outer Space Treaty in its very first article, says, "The exploration and use of outer space, including the moon and other celestial bodies, shall be carried out for the benefit and in the interests of all countries ... and shall be the province of all mankind. ...and there shall be free access to all areas of celestial bodies."

Article XII says: "All stations, installations, equipment and space vehicles on the moon and other celestial bodies shall be open to representatives of other States Parties to the Treaty on a basis of reciprocity. Such representatives shall give reasonable advance notice of a projected visit, in order that appropriate consultations may be held and that maximum precautions may be taken to assure safety and to avoid interference with normal operations in the facility to be visited." All settlements and property owners will have to accept that rule unless the Treaty is ever changed.

Establishing a space line and settlement open to all paying passengers, regardless of nationality, would certainly benefit all mankind, thus making it both necessary and sufficient to meet that very important condition of international law.

The question of compliance with the access requirement of the Outer Space Treaty upsets a lot of people, on both sides of the issue. Greg Nemitz (former "National Marketing Director" of Dennis Hope's "Lunar Embassy") calls me a Communist for acceding to the access requirement, because it means property owners can't have an absolute right to keep everyone else off their land. Wayne White, however, insists my plan fails because it does not go far enough to comply with that same "free access" rule. I, of course, think I've made the best compromise possible until and unless the treaty is revised.

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11. Wouldn't it help if a major company announced that, if a land claims recognition law were passed, it would try to develop affordable space transport?

Of course, it would help immensely!

It would make a huge difference if someone capable of operating at thatlevel, such as a really big investor or a Fortune 500 company, took the time to think carefully about the economics and realized how profitable owning land on the Moon could be.

Of course, Congress would give the idea much more credibility if they heard someone representing Boeing or Lockheed tell them that passing a land claims recognition law would lead to a serious privately funded space development effort. The problem, unfortunately, has been like the classic "which comes first: the chicken or the egg?"

Smart businessmen aren't interested in putting their efforts into business plans dependant on laws which, not only haven't been passed yet, but haven't even been introduced. Smart Congressmen aren't interested in putting their efforts into introducing legislation to create industries that businessmen aren't even talking about yet.

If you can be the one who gets some billionaire investor, or key CEO, (perhaps someone you happen to know or work for), to break that log jam by investigating and promoting the idea, the future colonists on the Moon will probably build a statue to both of you someday.

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12. Are the weaknesses and compromises in this plan likely to be permanent?

The most probable immediate outcome of U.S. passage of a land claims recognition law would be the prompt start of international negotiations -- negotiations which will never happen otherwise -- toward a new treaty (or new bilateral treaties) in which a number of the weaknesses and compromises necessary at this stage could be resolved.

Hopefully the resulting new space treaty will provide uniform international recognition of property rights in space in return for providing non-discriminatory access to all. Enforcement mechanisms, revision of the free access rules, permanence of claims, questions of sovereignty and legal jurisdiction, size of subsequent claims, etc., etc., might also be on the agenda.

At the moment, the diplomatic community, much of which would prefer space remain open only to governments anyway, sees much higher priorities than a new space treaty. If this legislation passes, and nothing further is done, the U.S. will have created the de facto property regime for the Moon, and settlement will seem imminent. That should give the diplomatic community a strong incentive to start negotiations toward a new treaty.

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13. Didn't the earliest version of this plan talk about "Lunar land grants"? Why aren't you using that phrase any more?

I stopped using that phrase because it conveyed the misimpression that the land is currently someone's to grant. The current phrase is therefore the less catchy but more accurate "land claims recognition" and the words "land grant" are used only to talk about what we cannot do, or (as in the next Q & A) historical analogies on Earth.

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14. Did land grants work?

Although classic land grants cannot be used in space because sovereignty is prohibited, the objective of land claims recognition in space is the same as the objective of land grants on Earth: the use of property rights as an incentive to get private individuals to do something of great value to the whole society.

Much of the United States was developed by the use of land grants, from large parts of the original 13 colonies through the settlement of the West. Congress, not wanting to use government funds, used land grants to encourage the building of the transcontinental railroads.

Fortunately, the application of land claims recognition to space has a big advantage over the use of land grants for building railroads. To get a railroad built, someone (usually whoever has the best political connections) must be selected and given a monopoly over the right of way before they have proven that they can and will deliver on their promises. Railroad companies' promises were often broken. In space the system can be structured to promote real competition, rewarding only those who have actually gotten the job done, by requiring actual "use and occupation" for all property claims.

BACK

15. You can't farm Lunar land, and Earth doesn't need its minerals. So how could Lunar land be put to profitable use?

Basic industries like farming and mining are the first things people think of when considering putting land to profitable use, but they are very far from being the only way to make a profit on land. In fact, if you'll think about the United States today, a surprisingly small percentage of the land is being put to profitable use for farming or mining ...and it's an even smaller percentage of the profits actually being made on land. Far more profits are being made on U.S. land by people who use it as something to speculate on or invest in.

Most Lunar land will first be put to profitable use that way: as something to speculate on or invest in. Karl Marx might have thought that shameful, but I don't. It is a perfectly good way to put land to profitable use. ...and if it results in opening up the final frontier for all mankind, it would be wonderful!

Later, if land speculation and investment can pay to develop the infrastructure, many, many other uses for the land will open up. A few we can foresee: tourism related businesses, facilities for astronomy and scientific research, facilities for producing TV broadcasts for Earth (Lunar gravity will produce fascinating entertainment and sports programs), a landing field for visiting ships, with repair and re-supply facilities for those ships. Solar power collectors will take a lot of land, and location will matter a lot.

Hydroponic farming for the inhabitants of the Lunar base will be profitable, and so will mining of things they need, especially water. Small factories will appear to produce things that originally had to be imported from Earth, starting with oxygen and construction supplies. The first export products will probably be small Lunar rock souvenirs or jewelry. Later, maybe Helium 3 could be exported.

But the most profitable uses will appear in the future and are certainly beyond our ability to predict now. Could Ponce De Leon have predicted that that "worthless" swamp in the middle of Florida would end up as Disneyland? Would you expect Lewis and Clark to predict that those "worthless" snow covered mountains would eventually find very profitable use for ski lodges?

BACK

16. If you can't give figures, now, proving the profitability of the end uses of Lunar land, how could anyone raise big money for Lunar land?

That's "cart before the horse" thinking, -- and this plan is not at all about raising money for Lunar land. There is no Lunar land to buy.

This is about raising money for the development of affordable space transport and the money doesn't have to be raised all at once, just enough to keep the experts working hard on solving the next piece of that puzzle. Only when safe, reliable transport has actually been developed, and launch costs have been brought low enough that even the accountants think a settlement could make a sufficient profit by selling land, will it be time for anyone to try to raise the big money to actually establish a settlement.

If they succeed in creating a functioning space line and settlement, they then get ownership of the land and can try selling it. Only then (perhaps a decade after the law was enacted?) do they have to make projections about the future end uses of the land. Only then, when the cost of transport is known, can they be expected to make meaningful financial estimates.

Some land, especially close to the base, will, by then, have identifiable uses and will sell for high prices to prospective entrepreneurs with serious business plans.

Outlying land that still does not have identifiable uses will have to be sold for much less, which is why the settlement is allowed to claim so much of it. But it will still sell to those who take the long view or hope to make a profit by re-selling when the market price rises, as it always does eventually with land. There have been many fortunes made buying and selling "worthless" land that did not yet have identifiable uses and so land buyers have always been very tolerant of that.

It is important to us that those who establish the settlement be able to sell enough of their land to make back many times their investment in developing or purchasing affordable space transport. But it does not matter at all, now, which of those who buy land from the settlement will get rich on it and which will end up holding the deeds for years for little or no profit.

By creating a space line the settlement will enable many others to start Lunar enterprises. Some will do badly, some will do well. Eventually sources of revenue other than land sales will grow to the point where they can pay the operating expenses, fund the growth of the Lunar base, and still return a profit. Land buyers will sense that potential. But there is certainly no requirement that those later revenue sources be precisely identified now, before the enabling legislation has even been passed.

BACK

17. Could other sources of revenue be enough, without land claim recognition?

All these years after humanity first landed on the Moon, no one is investing serious money in going back to stay. That fact alone is proof that the currently possible sources of revenues are not enough and must be augmented somehow.

This project will not only cost a lot, it will take a lot of time, pushing the limits of how long investors will wait for a return. The other ways to make money will all take additional time and investment to start paying off. Only land sales can produce returns as soon as the settlement is established, and therefore they will be the first dollars earned by the investors. That would make land sales particularly important in the business plan of any private settlement effort.

BACK

18. What if the settlement does not produce enough operating revenue to pay off its debts and make a profit?

If not, then sooner or later it ends up like the Iridium satellites or the U.S. land grant railroads. The railroad companies went bankrupt, but the new owners kept operating the trains. Bankruptcy wipes out the debt, but the system still functions and the world has its benefits.

This legislation must be structured to be sure that, if a settlement company goes bankrupt, its ships and settlement will be sold, if need be, for pennies on the dollar, to others who will keep them operating. Big land buyers may require the settlement to take out a performance bond or insurance to guarantee the ships will keep flying, even if the original settlement company were to default.

BACK

19. Could this law produce a new "space race"?

The first lunar settlement would have a big advantage over others that came later. Clementine and Lunar Prospector have demonstrated that the poles of the Moon have many potential advantages over other areas of the Moon. The lunar poles have water which is frozen and/or bound into the lunar soil. In addition, the polar mountain tops are not cursed with 14 days of darkness every month.

The team that is first to find a way to build affordable human transport to the Moon would get first choice of the Lunar poles. The second would have to settle for 15% less land, and the less desirable pole. Claims after that would be worth much less. That should provide a powerful incentive to race to be the first.

BACK

20. Why is U.S. legislation, in particular, so important?

The United States will probably be the first and most important market where land deeds will be sold to the public. In that case, it will be the U.S. courts that will rule on whether Lunar land sales are valid transactions or frauds. What this legislation does is tell the U.S. courts what standard to use in making that ruling. Further, it is not at all unusual for quite a few other nations to follow the U.S.'s lead on things like this.

However, this legislation is most definitely not just for the benefit of Americans!

Given today's global economy, it is almost certain that all entrants in the race to establish a settlement will be multi-national consortia. The investor/owners will be drawn from all around the world, as will the land buyers. Most particularly, the teams of aerospace companies cooperating to build the ships will be from many nations. It is just too big a job for one company, or even one nationality, to undertake alone.

BACK

21. Could the U.S. withdraw from the Outer Space Treaty, claim national sovereignty on the Moon, then award property rights to whomever it pleased?

The Outer Space Treaty says any nation can withdraw from the treaty on one year's notice. Some suggest this would be a simple route to establishing private property on the Moon, but it is a dead end. There is no chance at all we will withdraw from the treaty because, in some ways, it provides a sound framework for activities in space, and it includes provisions, such as banning weapons of mass destruction from space, that are considered much too important to tamper with.

That may actually be a blessing in disguise. If the U.S. did have sovereignty, land grants would undoubtedly be handed out on the basis of political connections, not on the basis of actually having opened the space frontier. Those who had received the land grants could then charge those who wanted to establish a settlement, rather than funding them. Thus, private property established that way might delay settlement, rather than hasten it.

BACK

22. What about defense? Does recognizing a land claim obligate the U.S. military to defend the settlement?

No! U.S. recognition of land ownership means its courts, not its military, must defend ownership. At the most, the U.S. might impose economic sanctions against any aggressor, if there ever were one, which there almost certainly won't be.

Settlements themselves will issue land deeds, settle internal disputes, handle their own internal security and, in later years, their own defenses as needed. But aggression is not going to be the problem it would be on Earth, because it really wouldn't pay economically. Hollywood movies notwithstanding, it really isn't going to be like the Old West because it's so much harder to get to and from the moon, or to hide once you're there.

The dollar value of the land, at least in the early years, is its market value on Earth - its salability to speculators and investors on Earth, - and no one would buy stolen land from someone who is not the recognized owner. So the very act of stealing Lunar land makes it instantly worthless.

It makes overwhelmingly better sense to buy land from the first settlement - which will be eager to sell land and/or provide transportation to and from the Moon at reasonable prices, - than to spend billions building one's own space line and then waste it mounting a war of aggression to steal already claimed land. Anyone who had such ships could use them to establish a whole new legitimate settlement, rather than fighting to steal some of the 4% of the Moon in the first settlement.

Similarly, on the individual level, early Lunar settlements, unlike old west gold rush mining camps, will not have a problem of stronger neighbors kicking weaker neighbors off their land. That's because the settlement and space line control everyone's access to and from the Moon, as well as everyone's oxygen and food supply and ability to ship anything back to Earth. The fact that it could, if it had to, stop refilling an unruly settler's oxygen tanks will make it very easy for a settlement's small police force to enforce discipline among individual settlers.

BACK

23. What effect would this have on NASA and the aerospace companies?

This legislation would create a huge demand for space ship design ideas and expertise, greatly benefiting the companies. NASA would continue to do basic research and design that would help everyone, and individual centers might well be allowed to contract to work on specific problems on a proprietary basis. NASA could also play a role in helping to determine whether ship designs are safe and reliable and whether a genuine permanent settlement has been established.

BACK

24. What do the experts say about this idea?

Esther Dyson, the world famous technology consultant, says "I like this idea. It would create a broad constituency to do something, sort of a cross-border would-be citizenry of the moon that I hope can spur governments and investors to action!"

Peter Diamandis, creator of the X Prize, says "I agree, ownership will be the only powerful driver to open our frontier."

Rosanna Sattler, the prominent space lawyer, (with Posternak Blankstein & Lund of Boston) says "Although commercial space law is still in its infancy, the authors' call to enact space legislation based on the principles of the Deep Seabed Mineral Resource Act would be a great leap forward in the quest for economic expansion in the high frontier."

Dr. Jeff Fisher, Director of the Center for Real Estate Studies and Professor of Finance and Real Estate at the Indiana University School of Business, points out "How many people are rich today because their great great grandparents happened to have some land that at the time was not considered useful for development?"

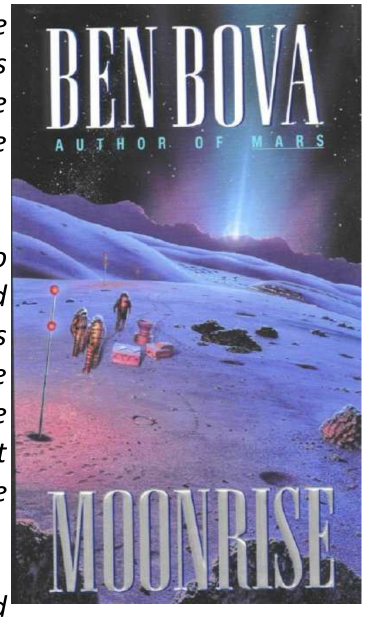
Space Entrepreneur Gregory Bennett, says “[Land claims recognition] clears the legal path for everything we want to do in the realm beyond the sky. This may be the most realistic and achievable way to accomplish our goal of establishing permanent human settlements on the moon. It is certainly a necessary step.”

The Space Settlement Initiative has been endorsed by Red Colony, The Moon Society, The Artemis Society, and *Stephen Ashworth's Space Age*

BACK

25. Who came up with this idea?

Alan Wasser is a former broadcast journalist at ABC News and CBS News, who then owned and operated a successful international business, which he sold. He was the Chairman of the Executive Committee (CEO) of the National Space Society. Alan was also a member of the Board of Directors of ProSpace, and is an Advocate of the Space Frontier Foundation.



He was the first to propose that the first human settlement on the Moon might use a permanently sun-lit mountain top at the moon's south pole, the existence of which was only later confirmed by the Clementine mission. Much of Ben Bova's novel Moonrise takes place on that lunar mountain, which Bova named "Mt. Wasser."

Alan is the originator of the idea of using land claim recognition to make privately funded space settlements potentially profitable, and therefore possible in our lifetime. He is the author of numerous articles on the subject of space property rights, most recently in The Explorers Journal, the official magazine of the Explorers Club, Space News, Ad Astra, Space Governance, Space Times and Space Front among others. Space Governance published a rough draft of the proposed legislation.

SMU Law School's Journal of Air Law & Commerce, the oldest and most respected law journal in its field, recently published an article Alan co-wrote with Douglas Jobes, entitled Space Settlements, Property Rights, and International Law: Could a Lunar Settlement Claim the Lunar Real Estate It Needs to Survive?. For more about him, personally, see Alan's bio at the Space Settlement Institute web site.

But this project is much more than the work of just one person. Many others have contributed a great deal to it, deserving thanks and credit for supplying key ideas, explaining the fine points of international law, promoting the idea, helping with writing and editing or in other ways, and even by attacking the plan and exposing weak points that needed fixing. Among the many who contributed are Douglas Jobes, David Wasser, Colin Doughan, Eric Rice, Scott Pace, Marianne Dyson, Glenn Reynolds, Gordon Woodcock, Declan O'Donnell, Ray Collins, Arjen Van Ballegoyen, Bryce Walden, Leonard David, Lawrence Roberts, Ben Bova, Rick Tumlinson, Arthur Smith, Carol Kochman, Toni Sonet, Art Dula, Robert Zubrin, Jim Bennett, Bob Werb, Charles Wood, Fred Ordway, Jim Benson, Pat Bahn, Peter Kokh, Grant Davis, Ed Wright, Alford Lessner and Charles Miller. Sincere apologies to the many others who should have been mentioned but have been accidentally overlooked.

Alan, standing next to a tiny bit of transplanted Martian "land", a piece of a Martian meteorite that fell to Earth in 1962 in Zagami, Nigeria. Alan welcomes your comments on the Space Settlement Initiative. His email address is Space Settlement @ att.net (remove the spaces on either side of the @ and please mention "Space Settlement" in the subject line so your message doesn't get accidentally deleted with the flood of spam.)

A personal note from Alan Wasser on the subject of credit: Although I originated this concept, the greatest credit should go to whoever gets it enacted into law, which I have not been able to *do. Someday, someone will come along with the charisma, wisdom, perseverance, position and/or connections to convert this from an idea to reality. If you are the person who can do that, you deserve to have your name attached to the plan, way ahead of mine. If you can do that, there will be settlers living on the Moon and perhaps Mars, in your lifetime, and you will richly deserve the statue they will build to you in the center of the settlement. Would you like to make the history books? Here's your chance! - Alan Wasser*

Read the first draft of "An Act to Promote Privately Funded Space Settlement"

To learn more about this proposal, visit The Space Settlement Institute

Return to the top of the Questions and Answers section

Web Site Updated: September 2010

APPENDIX B. STECKLER PROJECT WEBSITE

1. **Space Homestead Act**
2. **Steckler Study Input Request**

AIAA / SPACE COLONIZATION TECHNICAL COMMITTEE
REQUEST FOR COMMENTS

BILL SPONSORING REQUEST
From: Dr. Eric E. Rice, AIAA / SCTC
1212 Fourier Drive
Madison, WI 53717
608-335-9495

for
An Act To Promote Privately Funded Space Exploration and Human Settlement

To Promote Privately Funded Space Exploration and Human Settlement by promoting incentives for entrepreneurial investment in space and by assuring appropriate property rights for those who seek to develop space resources and infrastructure.

Be it enacted by the Senate and House of Representatives of the United States of America in Congress assembled and approved by the President of the United States.,

SECTION 1. SHORT TITLE

This Act may be cited as "An Act to Promote Privately Financed Space Settlement".

SECTION 2. FINDINGS

The Congress finds that—

(1) The expansion of the human habitat through the establishment of space settlements is a normal continuation of the age-old human drive to explore and settle unknown territory and will be of inestimable value for America and all mankind;

(2) Privately financed space exploration and settlement is preferable to taxpayer financing, because the government needs to limit its own expenditure

(3) Space exploration and settlement with private financing will produce new tax revenues for the United States;

(4) A new, additional, incentive is needed because the potential short-term profit sources are currently much too small to attract the billions of dollars of private capital necessary;

(5) The potential value of land on the Moon, Mars, or an asteroid can provide an additional economic incentive for privately funded space settlement at no cost to the government;

(6) There is currently no international law on private land ownership in space, because most major nations have deliberately refused to ratify "The Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, 1979, (hereafter called the "Moon Treaty"). The U.S. Senate's refusal to ratify means that the Moon Treaty's provisions are not "the law of the land" in U.S. courts, and therefore do not inhibit the actions of U.S. citizens or legislators;

(7) More importantly, the framers of the Moon Treaty found it necessary to attempt to write a rule forbidding private ownership of land on the Moon, clearly confirming that such an objective had not already been accomplished by "The Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies", 1967, (hereafter known as the "Outer Space Treaty"), nor by U.N. resolution GA/res/1962;

(8) The ratification failure of the Moon Treaty means there is no legal prohibition in force against private ownership of land on the Moon, Mars, etc., as long as the ownership is not derived from a claim of national appropriation or sovereignty (which is prohibited by the Outer Space Treaty);

(9) Presumably it is only a matter of time until new treaties are negotiated, establishing a functional private property regime and granting suitable land ownership incentives for privately funded space settlements. The U.S. will, of course, abide by such new international law when it has ratified such a new treaty. But, given the urgent need for privately funded human expansion into space, as soon as possible, something must be done immediately, on a provisional basis, to correct the present inefficiencies in the international standard on property rights in space and to promote privately funded space exploration and settlement;

(10) For property rights on the Moon, Mars, etc., the U.S. will have to recognize natural law's "use and occupation" standard, rather than the common law standard of "gift of the sovereign", because sovereignty itself is barred by existing international treaty;

(11) U.S. courts already recognize, certify, and defend private ownership and sale of land which is not subject to U.S. national appropriation or sovereignty, such as a U.S. citizen's ownership (and right to sell to another U.S. citizen, both of whom are within the U.S.) a deed to land which is actually located in another nation. U.S. issuance of a document of recognition of a settlement's claim to land on the Moon, Mars, etc., can be done on a basis analogous to that situation;

(12) This legislation concerns only the issuance of such a U.S. recognition and acceptance of a settlement's claim of private land ownership based on use and occupation, regardless of the nationality of the owner, and nothing in it is to be considered a claim of national appropriation of, nor sovereignty over, any outer space body, or any part thereof;

(13) The U.S. does not claim the right to "confer" private land ownership, and the U.S. states it is most definitely not making any claim of "national appropriation by claim of sovereignty, by means of use or occupation, or any other means" as prohibited by the Outer Space Treaty.

SECTION 3. DEFINITION

Private entity: An individual, corporation, or consortium of companies and individuals or a consortium of individuals that is not controlled by any sovereign state or government.

SECTION 4. RECOGNIZING EXTRATERRESTRIAL PRIVATE PROPERTY

(1) All U.S. courts and agencies shall immediately give recognition, certification, and full legal support to land ownership claims based on use and occupation, of up to the size specified in Sections 6.1, 6.2, and 6.3 below, for any private entity which has, in fact, established a permanently inhabited settlement on the Moon, Mars, or an asteroid, with regular transportation between the settlement and the Earth open to any paying passenger.

(2) For a land claim to receive such recognition and certification, the settlement must be permanently and continuously inhabited. The location and the population of the settlement may change, as long as there continues to be an inhabited settlement within the original claim.

(3) Deliberate abandonment of the settlement shall be grounds for invalidating land ownership recognition derived from that settlement, but there shall be no penalty for brief unintentional absences caused by accident, emergency, or aggression.

(4) Recognized ownership of land under this law shall include all rights normally associated with land ownership, including but not limited to the exclusive right to subdivide the property and sell portions to others, to mine any minerals or utilize any resources on or under the land, as long as it is done in a responsible manner which does not cause unreasonable harm to the environment or other people;

(5) If the requirements of this law continue to be met, all rights, privileges, and responsibilities shall be immediately transferable by sale, lease, or other appropriate means to any other private entity.

(6) As long as the required conditions continue to be met, U.S. recognition documents shall remain valid for 100 years or until the U.S. ratifies a treaty that establishes an international property rights regime which gives comparable reward to privately funded settlement, whichever comes sooner;

(7) The U.S. pledges to defend recognized extraterrestrial properties by imposing appropriate sanctions against aggressors, whether public or private. It pledges never to allow the sale to U.S. citizens of any extra terrestrial land which was seized by aggression. But it makes no pledge of military defense of recognized extraterrestrial properties.

(8) If, after ten years, these limits prove to have been insufficient to get privately funded settlement efforts started, Congress, or some national or international authority it delegates, shall consider whether the maximum size of claims should be enlarged.

SECTION 5. CLAIMANTS' OBLIGATIONS

(1) The claimant must commit to consistently make good faith efforts to promptly offer, or arrange for, safe and reliable transportation to and from the settlement to all, regardless of nationality, who are willing to pay a fare sufficient to cover expenses and a reasonable profit.

(2) The claimant may not unreasonably deny landing rights, and the right to transport passengers and cargo, to any other safe and peaceful vehicle willing to pay a reasonable fee for such landing rights.

(3) The claimant may set appropriate standards of behavior and safety, etc., for passengers and cargo and the use of its facilities, but it may not act in an anti-competitive manner.

(4) If demand for transport exceeds supply, and the claimant is making a good faith effort to increase the availability of transport, it may give preference to passengers and cargo offering the largest financial inducement.

SECTION 6. RECOGNIZED CLAIM SIZE

On Earth's Moon

(1) The private entity that establishes the first such settlement on the Moon and meets the other conditions of this law shall be entitled to receive full and immediate U.S. recognition and certification of its claim of ownership of up to 600,000 square miles in a contiguous, reasonably compact shape which includes its base.

On Mars

(2) Given the greater distance, higher costs and larger amount of available land on Mars, the private entity that establishes the first such settlement on Mars shall be entitled to receive full and immediate U.S. recognition and certification of its claim of ownership of up to 3,600,000

square miles in a contiguous, reasonably compact shape which includes its base.

On Asteroids

(3) The private entity that establishes a permanently inhabited base on an asteroid shall be entitled to receive full and immediate U.S. recognition and certification of its claim of ownership of up to 600,000 square miles in a contiguous, reasonably compact shape that includes its base, or the entire asteroid if its surface area is smaller than 1,000,000 square miles.

SECTION 7. SUCCESSIVE CLAIMS

(1) No entity (nor two entities which are effectively under the same control) shall receive recognition for a controlling interest in two land claims on the same body;

(2) Each successive settlement on a body may receive recognition for a claim of up to fifteen percent less than the preceding one was entitled to;

(3) An entity in control of one settlement may sell services, such as transport, to a genuinely independent entity which establishes a different settlement and makes a second claim on that body.

SECTION 8. CONCURRENT CLAIMS

(1) In the event it cannot be established which of two settlements on the same body was established first, each may claim seven and one half percent less territory than it would have been entitled to if it were clearly the first of the two.

(2) If, in such a case, the land claims of the two settlements overlap, and the claimants are unable to divide the land between them through negotiation, a U.S. court shall allocate the land between the two settlements as seems fitting, before recognizing the claims.

SECTION 9. INTERNATIONAL RELATIONS

(1) The U.S. urges other countries to adopt similar laws, and the State Department is hereby instructed to try to negotiate a new multi-lateral treaty, or bi-lateral treaties with individual like-minded nations, making the same land claims recognition rules into international law.

(2) All rights and privileges conferred by this law shall be available equally to the citizens (individual and/or corporate) of any nation which passes laws or ratifies a treaty offering similar rights to U.S. citizens.

(3) If need be to secure international agreement, the State Department is authorized to agree to treaties which require that all claimants must be consortia which include companies or citizens from several different countries. It can even be required that at least one of the partners in each consortium be from a developing country.

UWGB / ORBITEC STECKLER SPACE COLONIZATION STUDY

LUNAR COMMERCIAL ACTIVITIES DATA INPUT FORM

We are seeking ideas for Lunar commercial activities (LCAs) that can be developed on the Moon and support Lunar Human Colonization. LCAs would involve a near-term and far-term approach that support the land ownership approach. [view text of draft act]

We seek input on basic commercial activities and services that could be provided by a Lunar Colony to others on or off the Moon's surface. Please complete the form below and then click the "submit" button to send us your input. Thank you for your input.

LCA Element Name:

LCA Service / Products:

Potential Buyers:

Cost / Benefit Estimate:

General Comments:

Your Name:

Organization:

Address:

Office Phone:

Cell Phone:

Email:

Submit

UWGB / ORBITEC STECKLER SPACE COLONIZATION STUDY

LUNAR SPACE TRANSPORT (ST) DATA INPUT FORM

We are in the process of developing an approach for a low-cost Space Transport System or Space Line between the Earth's surface and the Moon's surface to support Lunar Human Colonization. The Transport Plan would involve a near-term and far-term scenario that supports the land ownership approach. [view text of draft act]

We seek input on basic propulsion systems, vehicles, modes and depots of various types. Please complete the form below and then click the "submit" button to send us your input. Thank you for your input.

ST System Element / Vehicle Name:

ST System Element / Vehicle Description type:

- Chemical
- Electric
- Nuclear
- Other

Propellants:

Propellant Sources:

Cost / Manpower:

Earth-Required Materials:

Surface / Orbital Support Facilities:

References / Bibliography:

General Comments:

Your Name:

Organization:

Address:

Office Phone:

Cell Phone:

Email:

Submit

UWGB / ORBITEC STECKLER SPACE COLONIZATION STUDY

LUNAR SPACE RESOURCE UTILIZATION (SRU) DATA INPUT FORM

We are in the process of developing a Space Resource Utilization (SRU) Development Plan for near-term and far-term Lunar Human Colonization that supports the land ownership approach. [view text of draft act]

We seek input on basic materials, products and processes for Lunar structures, laboratories, habitats, basic infrastructure and basic human needs. Please complete the form below and then click the "submit" button to send us your input. Thank you for your input.

Material and Product:

Space Resource Acquisition:

SRU Process Description:

Energy / Power Use Estimate:

A&R / Manufacturing Description:

Key Raw Materials:

Expected Annual Production Rate:

Cost / Manpower:

Earth-Required Materials:

References / Bibliography:

General Comments:

Your Name:

Organization:

Address:

Office Phone:

Cell Phone:

Email:

Submit

APPENDIX C. RFP "ALASKOL" SPACE SETTLMENT CONTRACT

By

Space Settlement Design Competition Group

Anita Gale

REQUEST FOR PROPOSAL
26 July 2033

"Alaskol" Space Settlement Contract

INTRODUCTION

This is a request by the Foundation Society for contractors to propose the design, development, construction, and operations planning of the first space settlement on the surface of the Earth's Moon Luna.

STATEMENT OF WORK

1. Basic Requirements - The contractor will describe the design, development, and construction of the Alaskol space settlement community, and develop plans for operations required to maintain the community.

2. Structural Design - Alaskol must provide a safe and pleasant living and working environment for 15,000 full-time residents, plus an additional transient population, not to exceed 2000 at any time, of business and official visitors, guests of residents, and vacationers; some of the visitors will be scientists studying the Moon. Provide natural light and views of surrounding terrain.
2.1 Exterior design drawings must identify all volumes and their uses, must illustrate the local terrain and compatibility with it, and must clearly show dimensions of major structural components. Identify construction materials used for major structural components. The design and materials must be capable of retaining their functionality and appearance in the lunar environment, without requiring significant expenditures of settlement resources for maintenance and repair. Show how to meet the customer's target to acquire 80% of construction materials from the Moon. The proposal will specify means for providing protection from radiation and debris penetration.
Minimum requirement: overall exterior view of settlement, showing locations and sizes for launch / landing site(s), vehicle maintenance facilities and parking areas, cargo and resources storage and/or warehousing, public utilities, heavy industry, residential/commercial areas, and agriculture.
2.2 The Alaskol design must specify uses of interior space, with areas designated and drawings clearly labeled and dimensioned to show residential, industrial, commercial, agricultural, port facilities, and other uses. The proposal must provide justifications for facility sizes and locations.
Minimum requirement: overall map of interior land areas, showing usage and sizes of those areas.
2.3 Describe the process required to construct the settlement, by showing the sequence in which major structural components will be assembled, and capabilities available at intermediate phases.
Minimum requirement: drawing(s) showing several intermediate steps of settlement assembly.
2.4 As mitigation of risk that lunar dust may cause failures of primary airlock seals, show how each building inside Alaskol can be sealed to preserve atmosphere for up to three days. Describe notification system(s) and procedures to be implemented in the event of major pressure loss.
Minimum requirement: show interior building design details enabling preservation of atmosphere inside, in the event of a failure in the settlement's primary atmosphere containment system.

3. Operations and Infrastructure - Describe facilities and infrastructure necessary for building and operating the community, including conduct of businesses and accommodating incoming and outgoing spacecraft and surface vehicles--which may maintain different air pressures than Alaskol.
3.1 The proposal will identify a recommended location on the lunar surface, within 5° of latitude of the equator in order to reduce orbital plane change required for incoming vehicles, and the reasons for its selection. Identify sources of materials and equipment that will be used in construction and operations, and means for transporting those materials to the Alaskol location.
Minimum requirement: chart or table identifying materials and equipment required for the settlement construction process, and from where and how those materials and equipment are shipped.

3.2 The proposed Alaskol design will show elements of basic infrastructure required for the activities of the settlement's residents, including (but not limited to):

- food production (including growing, harvesting, storing, packaging, delivering, selling),
- electrical power generation and distribution,
- internal and external communication systems,
- internal and Luna surface transportation systems,
- atmosphere/climate/weather control, with internal pressure maintained at 0.8 Earth atmosphere
- household and industrial solid waste management,
- water management (including fresh water distribution and sewer routing), and
- day/night cycle provisions.

Define separate means of access throughout and between facilities, for pedestrians, bicycles, emergency and service vehicles, and robots. Include designs of transportation vehicles (showing dimensions) for use in and around the settlement.
Minimum requirement: drawing(s) showing locations of systems which provide required infra-structure, and, as appropriate, their configurations (e.g., show routings of water and waste services).
3.3 Identify existing or new on-orbit infrastructure required for settlement operations (e.g., vehicles, satellites, and power plants). Vehicle requirements will specify desired payload weights and sizes, mission durations, flights per year, fleet sizes, and turnaround time between missions.
Minimum requirement: chart or table describing space-based infrastructure and vehicles required for settlement operations.
3.4 Assays have identified a wide variety of useful materials on Luna, although at widely scattered locations. Show designs for road-building equipment that can pave 250 miles (400 km) of one-lane roads and/or lay 250 miles of rails annually in most types of lunar terrain. Show designs for long-haul bulk carrier vehicles that will travel the roads and/or rail system(s).
Minimum requirement: drawing(s) of road-building equipment showing how it/they will operate; identify quantities of each type of equipment to meet 250 mile annual paving goal.

4. Human Factors - Quality of life is important to Foundation Society members, who plan to maintain traditional comforts without the sacrifices normally associated with a frontier environment. Assure that natural sunlight and views of the lunar surface are readily available to residents.
4.1 Alaskol communities will provide facilities for services that residents could expect in a comfortable modern community environment (e.g., medical, parks and recreation, access to fine food and entertainment), variety and quantity of consumables and other supplies, and public areas designed with open space and consideration of psychological factors.
Minimum requirement: map(s) and/or illustrations depicting community design and locations of amenities/services, with a distance scale.
4.2 Include designs of typical residential homes, clearly showing room sizes; include residential options for single family homes, townhouses, apartments, dormitories, and co-housing communities. Full-time inhabitants will be Foundation Society members who manage settlement maintenance and operations, provide services as needed by the community and for trade, and operate businesses on Luna. Anticipated demographics of the original population are:

Married adults	46%	(average age 38, median age 35)
Single Men	30%	(average age 33, median age 36)
Single Women	23%	(average age 36, median age 32)
Children	1%	(average age 6, median age 5)

Minimum requirement: external drawing and interior floor plan for each specified type of home design, and the area (preferably in square feet) for all residences.
4.3 Designs of systems, devices, and vehicles intended for human use will consider enhancement of productivity in the lunar environment, both inside and outside the settlement. Spacesuit designs will be required for work and recreation on the surface; show features to mitigate degrading effects of lunar dust and prevent entry of dust into pressurized areas of the settlement.
Minimum requirement: illustrate spacesuit donning/doffiing processes, including differences (if any) between suits designed for work and recreation.

4.4 Tourists enjoying recreational activities outside of pressurized volumes are unlikely to fully appreciate the high priority required for preventing lunar dust from entering interior areas of the settlement. Describe plans for training all new arrivals at Alaskol in dust mitigation processes.
Minimum requirement: show examples of training materials for prevention of dust contamination.

5. Automation Design and Services - Specify numbers and types of computers, software, servers, network planning, and robotic operations required for Alaskol's facility, community, and business operations. Computer system descriptions will include types and capacities of data storage media, data collection, data distribution, and access of users to computer networks. Show robot designs, clearly indicating their dimensions. Identify locations and sizes of repair, maintenance, and storage facilities, and special transportation routes for robots.
5.1 Describe use of automation for construction. Consider automation for transportation and delivery of materials and equipment, assembly of the settlement, and finishing the interior.
Minimum requirement: chart or table describing automated construction and assembly devices.
5.2 Specify automation systems for settlement business and production processes, maintenance, repair, and safety functions, including backup systems and contingency plans for failures. Define physical locations of computers and robots for critical functions. Show schematic(s) of networking system(s) enabling real-time data acquisition from remote and widely scattered lunar materials harvesting operations. Robots that operate outdoors must retain their functionality and appearance in the lunar environment. Describe means for authorized personnel to access critical data and command computer and robot systems; include descriptions of security measures to assure that only authorized personnel have access, and only for authorized purposes.
Minimum requirement: chart or table listing automation applications for operation of the settlement and its business areas, and showing particular computers and robots to meet each automation need; identify sources of computers and robots, and shipping criteria if not manufactured on Luna.
5.3 Specify automation systems to enhance livability in the community, productivity in work environments, and convenience in residences. Emphasize use of automation to reduce needs for manual labor. Provide for privacy of personal data and control of systems in private spaces. Describe access to community computing assets and robot resources from individuals' homes and workplaces. Specify how many of each computer and robot type will operate at Alaskol.
Minimum requirement: drawings of typical computers and robots that people will encounter during their everyday lives in Alaskol, and diagram(s) of network(s) to enable computer connectivity.
5.4 Employ automation systems to both enhance recreational experiences for visitors, and prevent them from engaging in risky behaviors. Describe location(s) and situation(s) in which these systems will operate. Incorporate monitoring and alert system(s); define conditions that will trigger alerts and the process(es) implemented in the event of an alert. Specify full-time and standby personnel required for operation of specified system(s).
Minimum requirement: show automation system(s) that enhance both entertainment and safety. Specify user interface(s) with these systems.

6. Schedule and Cost - The proposal will include a schedule for development and occupation of Alaskol, and costs for design through construction phases of the schedule.
6.1 The schedule must describe contractor tasks from contract award (28 July 2033) until the customer assumes responsibility for operations of the completed settlement. Show in the schedule the interim dates required to meet the Foundation Society's target completion date of 2045.
Minimum requirement: durations and completion dates of major design, construction, and occupation tasks, depicted in a list, chart, or drawing.
6.2 Specify the costs associated with Alaskol design through construction in U.S. dollars, without consideration for economic inflation. Include estimates of numbers of employees associated with each phase of design and construction in the justification for contract costs to design and build Alaskol. Show cost breakdown for tasks, within the Foundation Society's target budget of $250B.
Minimum requirement: chart(s) or table(s) listing separate costs associated with different phases of construction, and clearly showing total costs that will be billed to the Foundation Society.

7. Business Development - Alaskol will host a variety of commercial and industrial ventures, which may change with time. The basic design must include sufficient flexibility to accommodate development of additional compatible business types with little configuration change. The original configuration must, however, accommodate three major business pursuits:

- Hub for development of lunar infrastructure
  - Summarize anticipated lunar infrastructure requirements for the next 30 years, presuming average annual increase in lunar surface population of 500 people in all locations. (development of anticipated infrastructure items not included in Alaskol contract cost).
  - Summarize predicted supporting assets to implement anticipated lunar infrastructure requirements (development of supporting assets not part of Alaskol contract cost, with the exception of items previously noted in this RFP).
- Supply depot for lunar and space operations
  - Plan expansion of agricultural and consumables production facilities to enable supplying anticipated lunar population increase.
  - Plan transportation and distribution system expansion to supply growing lunar population not resident at Alaskol.
- Major tourist destination
  - Anticipate average tourist stays of two weeks.
  - Provide amenities for tourist activities during a two-week stay.
  - Show two possible two-week tourist itineraries, appealing to different interests.
  - Show examples of indoor and outdoor facilities that offer sports and competitive opportunities uniquely suited to the lunar environment.

8. Special Studies - Include plans for emergency procedures to react to two disaster scenarios:

- Damage to an inhabited part of the facility due to meteorite or debris penetration, or collision by a vessel, including a 1.5 meter diameter hole that allows contained atmosphere to escape
  - Describe plan to isolate affected volume from other parts of the settlement
  - Provide a schedule of repair activities and resumption of full services in affected volume
- Contamination of atmosphere in connected areas due to explosion with hazardous chemicals
  - Describe provisions for relocation of affected personnel and activities during clean-up
  - Schedule activities to return the settlement to full operation

EVALUATION STANDARDS

Evaluation of each design presentation considers four general categories of factors:

A. Thoroughness - Design meets depth and diversity of requirements in the entire Statement of Work (SOW). Graphs, tables, drawings, and compliance matrices aid evaluation of this factor.

B. Credibility - Design addresses requirements, safety, physical laws, and cost/schedule in a believable manner. Errors, impossibilities, omissions, and illogic are penalized.

C. Balance - Proposal places equal emphasis on four technical areas: structural design, operations, livability, and automation. Proposal is organized in a logical, easy-to-follow manner.

D. Innovation - Design demonstrates original thinking to address SOW requirements. Technologies are applied and combined in unique and creative ways.

ADDENDA

An alternate name may be suggested for this community, within the Foundation Society's established naming convention that requires the name to end with the suffix "ol" (settlement is "on Luna") and begin with the letter "A" (first settlement at an "ol" location).

If a proposal is submitted that has more than the allowed 50 pages, only the first 50 pages will be evaluated by the customer.

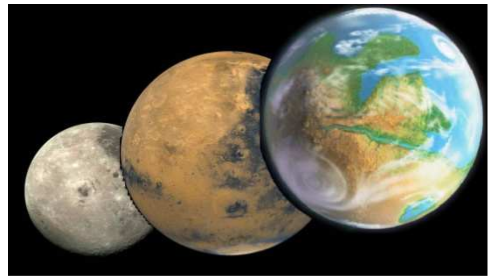
Drawings and/or maps included in the proposal must show dimensions consistently in English (feet/miles) or metric (meters/kilometers) notation.

APPENDIX D. MOON BASE 2020: ROBUST IMPLEMENTATION OF LUNAR EXPLORATION AS A STEPPING STONE TO MARS AND BEYOND

by

AIAA Space Colonization Technical Committee

September 2010



The AIAA Space Colonization Technical Committee (SCTC)
Moon Base 2020: Robust Implementation of Lunar Exploration as a Stepping Stone to Mars and Beyond

RECOMMENDATIONS (No order of priority is implied)
The SCTC position is for NASA to embark on the Moon first path while keeping open the later opportunity to visit other near Earth bodies. Moon-Base 2020 should be an engineering test bed for technologies applicable to long-term exploration missions. Without these technologies, long-term exploration goals will be elusive. The AIAA/SCTC recommends that the following actions be implemented by the Administration, U.S. Congress, and supporting Government agencies as appropriate:

- Implement a suite of orbital and Lander precursor missions to the Moon to collect high-resolution data on: the lunar environment; water, hydrogen and other resources to establish ground truth on resource distribution; and surface property characterization. The lander missions should demonstrate technologies and methods for continued lunar human presence - as a laboratory to begin with the ultimate aim of settlements if conditions permit.

- Establish and implement a strategic plan for use of space resources with substantial funding for SRU payloads, launch vehicles, robotic vehicles, Landers for dedicated Lunar SRU missions, and Lunar surface test beds.

- Develop an “in-situ’, self-sustaining infrastructure of solar energy production and storage derived mostly from Lunar materials, and wireless power distribution (power beaming) for both nuclear and solar energy transmission on the Moon.

- Deploy communications and navigation satellite system capability for cis- and transLunar space to support lunar development.

- Establish cost-effective crew and cargo space transportation systems with the capability to utilize lunar-supplied propellants.

- Implement test beds on the Earth, ISS and the Moon for human health issues related to long-term space flight, including tele-medicine, low-g environments, radiation and psychological issues.

- Implement test beds for closed life support systems for sustaining a lunar base.

- Implement test beds for in-situ manufacturing systems for sustaining a lunar base.

- Develop a human lunar south pole base where valuable water/hydrogen, material, mineral resources can be explored/used and continuous sunlight can be utilized in a less extreme thermal environment.

- Develop technologies for lunar surface and subsurface mining and excavation.

- Develop needed lunar-specific resource production equipment to foster expansion of lunar/terrestrial commerce.

- Extend current advanced technology programs including electromagnetic, momentum transfer and other fuel-less launch technologies to establish capabilities that can be applied on the Moon.
- Develop solar, nuclear and other advanced energy systems to support lunar base and orbital power needs.

Government agencies need to enable business development in the following areas to ensure sustainable viability of the exploration vision:

- Base and life support
- Resource processing and manufacturing
- Lunar communication systems
- Lunar navigation systems
- Lunar transportation systems
- Space rescue capability similar to the Coast Guard
- Methods for indemnifying business ventures from lawsuits based on fatalities or injuries
- Government sponsored anchor-tenant production contracts
- Government loan guarantees.

It is also recommended that the United States work with international partners to set precedent(s) through a constructive interpretation and evolution of applicable space law(s), including provisions for:

- Free-market rules and approaches to the exploration and development of space
- Extension of international conventions on property and mineral rights to include assets in space based on US and other historical precedents in the history of exploration
- Extension of land management conventions and régimes to include provisions for homesteading.

Dr. Narayanan (Ram) Ramachandran
Chair, AIAA Space Colonization technical Committee (SCTC)
Dated June 30, 2010

APPENDIX E. LUNAR SRU SUMMARY

APPENDIX E. LUNAR SRU SUMMARY

E.1 Introduction

The key to making a Moon colony a profitable, growing entity is to make maximum use of location and optimized SRU processes. Energy will be as precious a commodity on the Moon as it is on Earth so its use must be carefully managed and used. Initially, high-energy refining was to be favored on the Moon for Lunar resource recovery because water was scarce; however, lower-temperature aqueous processes for metal recovery used on Earth are now much more practical for Lunar resource processing with the increased availability of volatiles. The carbo-chlorination process is a useful process for recovering materials from the Lunar regolith and will also be discussed and compared with other processes.

A collected family of baseline processes for Lunar resource recovery, in some cases using high energies and temperatures, are discussed. The processes have been characterized since the 70s and represent the best attainable methods for obtaining materials from the Lunar regolith before large amounts of Lunar volatiles were found.

The OLPF (ORBITEC Lunar Process Flow), which is a synergistic family of processes making use of abundant volatiles is presented. It will be seen from the OLPF that abundant volatiles allow a family of processes that requires, in most cases, lower energies, temperatures, and least toxic species than those considered before. Because of this, the OLPF may allow a Lunar colony to be established more economically and quickly than before.

The best place to locate a Lunar colony is near the poles where volatiles are known now to be abundant. This has been a baseline concept in our Lunar colony concept overall (O'Handley, 2000). However, though oxygen is recoverable from volatiles at the poles, the volatiles must be viewed primarily as source of hydrogen, carbon, and nitrogen, and a separate source of oxygen may be necessary to free Lunar recoverable oxygen for life support.

The availability of Lunar resources is also determined by the distribution of rock types on the Lunar surface. Rocks from the Lunar highlands are rich in aluminum and poor in iron because they are composed mainly of feldspar. Rocks from the maria contain some feldspar, but consist mostly of pyroxene, olivine, and ilmenite, which are minerals that are rich in iron and poor in aluminum.

Hydrogen is perhaps the most valuable volatile for use in Lunar resource recovery because it can reduce many elements from their oxides and produce a pure metal and water. The hydrogen in the water can then be separated from the oxygen by electrolysis to recover hydrogen for recycling and oxygen for life support. The electrical power needed for water electrolysis is:

$$249 \text{ kJ/mole } H_2O \text{ (18g)} \rightarrow 1 \text{ mole } H_2 \text{ (2g) } ½ \text{ mole } O_2 \text{ (16g)}$$

Chlorine is a very valuable element for Lunar resource recovery using various processes. Chlorine may be recovered from Lunar regolith by simply passing water through it at low temperatures and collecting soluble chlorides such as salt (NaCl). This washing process to recover soluble salts can be fairly efficient since all water can be recycled. The wash can be concentrated by heating under reduced pressure and chlorine then recovered from a concentrated solution by electrolysis. Therefore, chlorine can be considered an easily recovered Lunar resource.

Carbon is very useful in recovering metals from Lunar sources, as it is on Earth. Carbon can be used as an electrode material to recover metals from molten salts or oxides; however, electrolysis of oxides will consume the positive electrodes and form CO and CO_2. Carbon can also be used in carbo-thermal reduction processes as methane which is then converted to carbon monoxide and water while capturing oxygen. The resulting mixture of CO and H_2O can be purified to CO by condensation of the water, electrolysis of the water to recover oxygen and hydrogen. The CO or CO_2 is then reconverted to methane by the hydrogen in the reverse water-shift process:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

The methane can also be decomposed on hot carbon to make new electrodes

$$CH_4 + heat \rightarrow 2H_2 + C$$

or be used to reduce more regolith. The best place for oxygen and iron recovery from the Lunar regolith is in the maria which are ilmenite rich. The nearby highlands can supply anorthite which yields aluminum.

As on Earth, the most useful metals for Lunar use are those which are easy to free from oxygen and that are abundant. To build a Moon colony one needs iron, aluminum and silicon in the form of glass, to build structures. Copper, which is rare on the Moon can be replaced for electrical wiring by aluminum. Magnesium and titanium are valuable for some applications and can be derived from iron and aluminum recovery process. Silicon will also be used for Solar cell production.

In summary, to begin our more detailed discussion of Lunar resource recovery, we will discuss recovery of volatiles from the polar regions and from the global regolith, we will then discuss baseline processes already studied for Lunar resource recovery for various important materials. We will then also discuss the OLPF system for recovering Lunar resources that makes use of the recently discovered rich deposits of volatiles. In the OLPF the new paradigm of minimum-energy, aqueous-rich synergistic processes will be used as a guiding principle, to make maximum use of the newly discovered large quantities of volatiles. The discovery of the volatile-rich polar deposits can produce a “sea change” in thinking about Lunar resources and the whole process designed to recover them. In particular, it will be seen that by using the

OLPF, the new volatile discoveries make a growing, self-supporting Lunar colony, much easier and faster to establish.

E.2 Lunar Volatiles

Concepts for recovery of Lunar volatiles and their use for a Lunar colony have received increased credibility because of the confirmation of the Clementine discovery of ice in permanently shadowed deep polar crater floors on the Moon.

The LCROSS impact data, though still partially embargoed, are consistent with approximately 30 parts per thousand weight in the permanently shadowed regolith on the crater floor (Elphic, et. al., 2010). The water is mixed with a familiar “dirty ice cocktail” of oxides of carbon, and sulfur, methane and ammonia commonly seen in comets.

We can estimate the composition of the Lunar volatiles found at the Lunar poles by assuming they are primarily due to cometary impacts and reflect Solar abundances of volatile elements. Hydrogen is the most abundant volatile, but will occur in ices only as a chemical combination with heavier elements. For every 100 atoms of oxygen, there are 50 atoms of carbon, and, 16 atoms of nitrogen, and 2 atoms of sulfur (Arnett, 1996).

Depending on chemical conditions, and based on studies of comet spectra (DiSanti, et. al.,1999) we will get ices in the Lunar craters that will be approximately the following chemical composition: 59% H_2O, 10% CO, 10% CO_2, 10% CH_4, 10% NH_3, and 1% SO_2. Access to these ices means abundant chemicals to supply a Lunar colony.

Trapped gases from the Solar wind are present generally in the Lunar regolith. Hydrogen is most common and is present in the weight fraction of 10 parts per million (Fegley and Swindle, 1993) or at a mole fraction of approximately 1 part per thousand. Carbon as carbon dioxide and nitrogen as gas are also present in the 100 parts per million level as a weight percentage (see Figure E-1).

Therefore, the Lunar poles offer access to 100 times the concentration of water and other volatiles as does the equatorial regolith and argues strongly for location of an initial Lunar base in the Polar regions. The discovery of abundant Lunar volatiles is transformative to planning for Lunar colonies and allows the use of the Moon as a springboard in a generational effort to expand human presence across the Solar system.

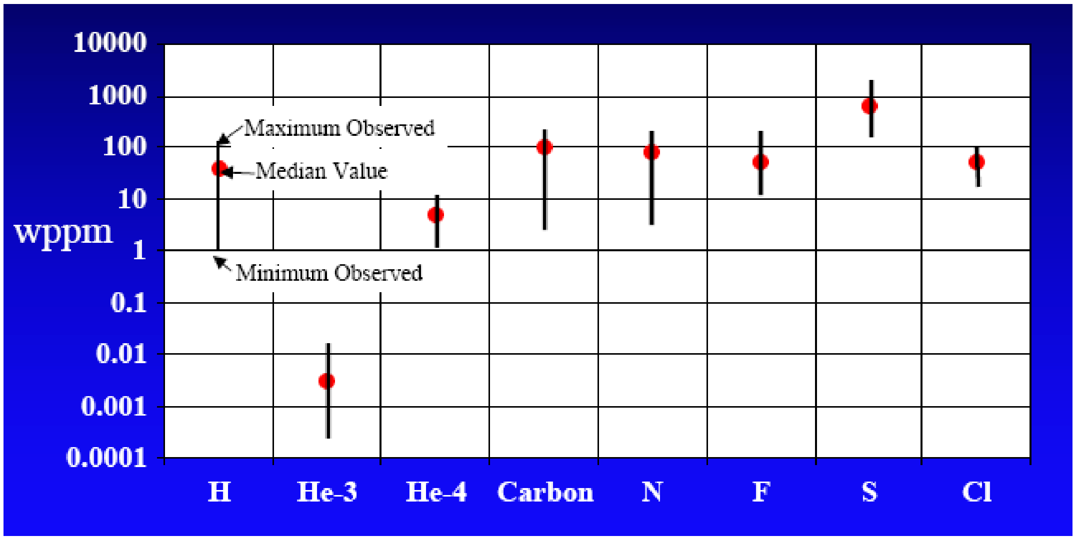


Figure E-1. Weight Abundance of Volatile Elements (from Kulcinski, 1996)

E.3 Baseline Lunar Resource Recovery Processes Iron Recovery

The energetically most favorable way to recover iron from the Lunar regolith is to reduce ilmenite ($FeTiO_3$) with hydrogen and also to recover oxygen (Ekhart, 1999). Ilmenite is found abundantly in high Ti basalts on the Lunar Maria (see Figure E-2). Ilmenite is also a rich source for titanium on the Moon as can be seen by the correlation of iron and titanium concentrations (see Figures E-2 and E-3).

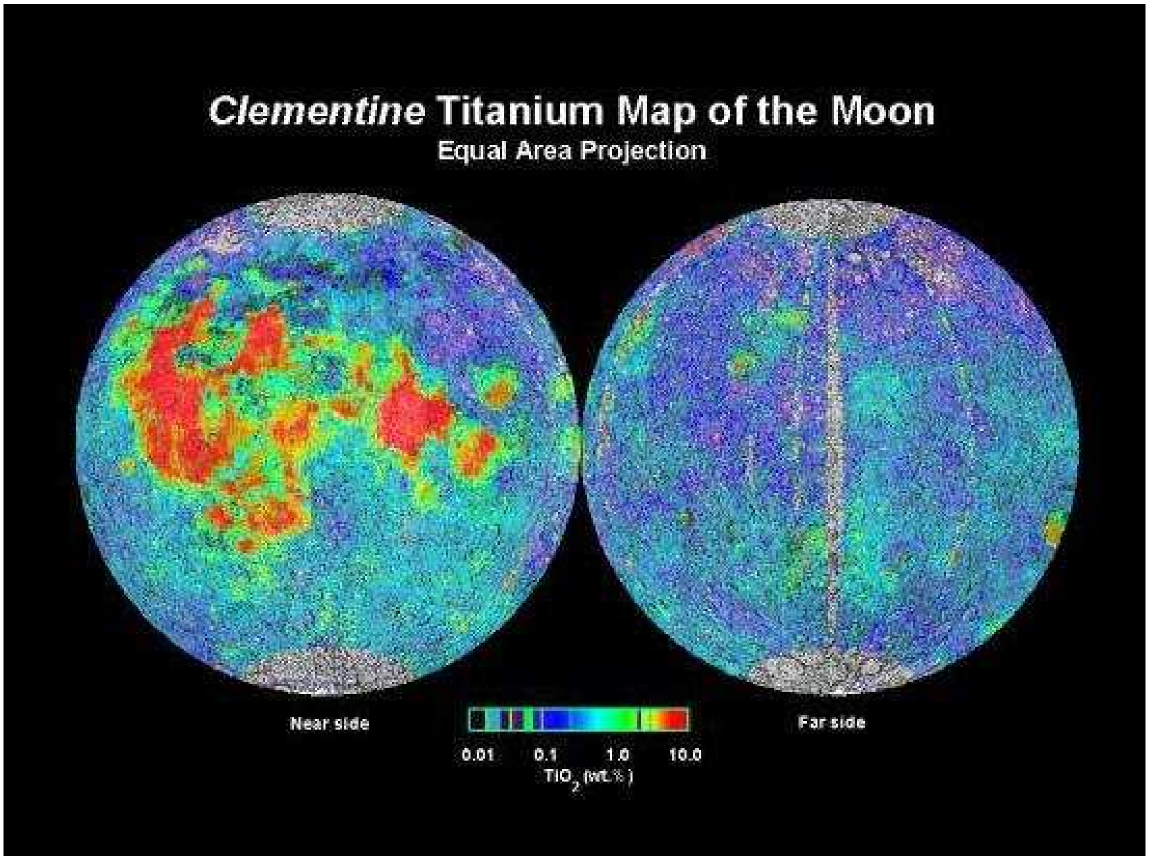


Figure E-2. Ti Distribution on the Moon. Source: Lunar and Planetary Institute (www.lpi.usra.edu/lunar/missions/clementine/images)

Ilmenite is best processed by either straight hydrogen (Williams and Erstfeld, 1979) or by the carbo-thermal process (Gustafson, White, and Fidler, 2009). The hydrogen reduction process is very straightforward:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$

where H_2O is recovered and put through electrolysis to produce hydrogen and oxygen. The hydrogen is then recycled and oxygen is stored and used. TiO_2 recovered from the process can be used for titanium (and silicon) and paint production.

A very efficient high-yield source of oxygen, silicon and iron is the carbo-thermal process which can take unsorted Lunar regolith and reduce it at high temperature. This produces mixed carbon monoxide and dioxide, and water, which can be processed to reform oxides of magnesium and titanium, along with iron, silicon,and ferri-silicon.

Separation of iron and silicon from ferri-silicon can be accomplished, with abundant Solar and electric energy, by turning the solid into a plasma and doing separation by electromagnetic mass spectroscopy (Schubert, 2005). ORBITEC has recently developed a new proprietary way to process iron and silicon separately in a modified carbo-thermal process. Alternatively, ferri-silicon can be reacted with chlorine to form ferric chloride, $FeCl_2$ and, silicon tetra-chloride $SiCl_4$, a gas at 100 C, and the iron and silicon can be separated for further processing:

$$FeSi + Cl_2 \rightarrow FeCl_2\,(solid) + SiCl_4\,(gas)$$

The iron can be obtained from the ferric chloride, with abundant electric power, by electrolysis with carbon electrodes and the silicon tetra chloride can be decomposed into chlorine and silicon by high-temperature electrically heated plates, where the silicon deposits as crystals.

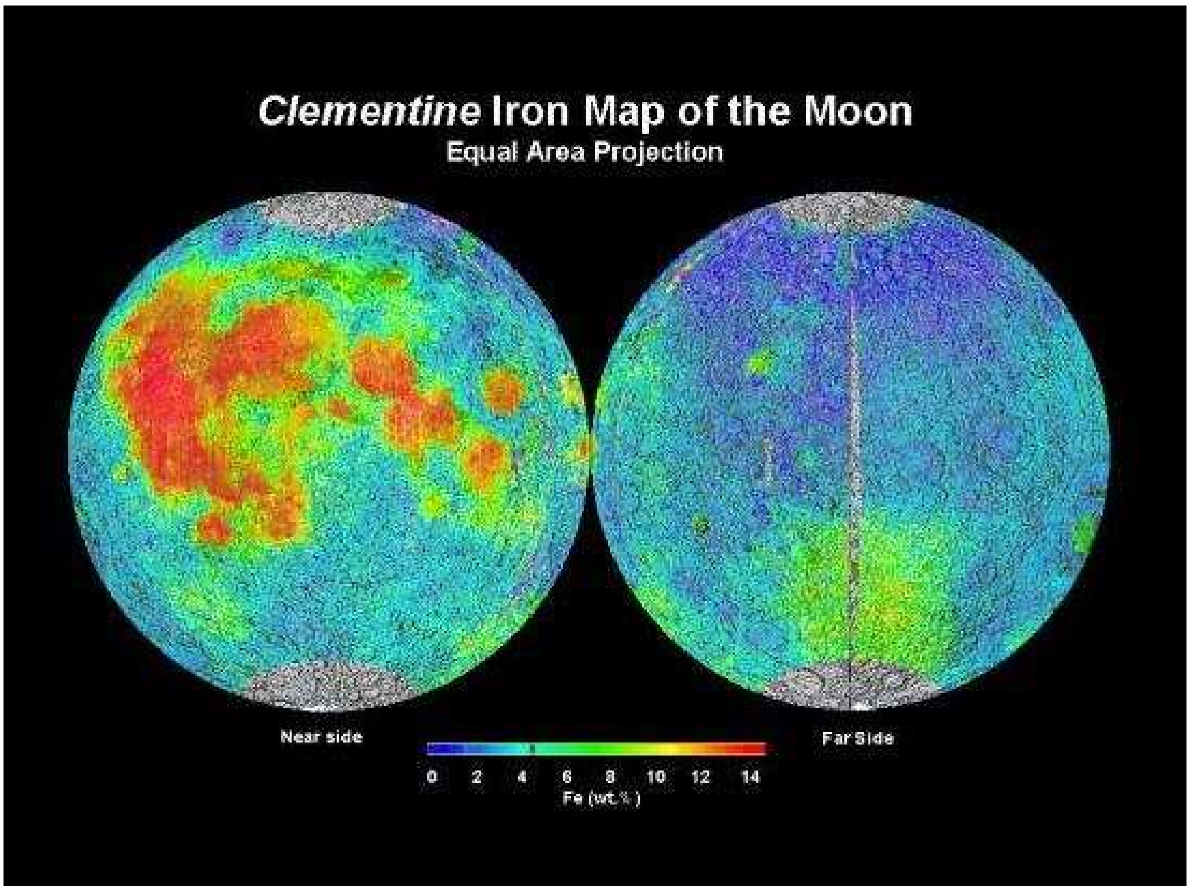


Figure E-3. Fe Distribution on the Moon. Source: Lunar and Planetary Institute (www.lpi.usra.edu/lunar/missions/clementine/images)

Aluminum Recovery. Aluminum can be refined from anorthite, which is a plagioclase feldspar found in the highlands of the Moon (see Figure E-4), whose aluminum content has been assayed by Apollo and Luna return samples as well as by Lunar meteorites (see Figure E-5).

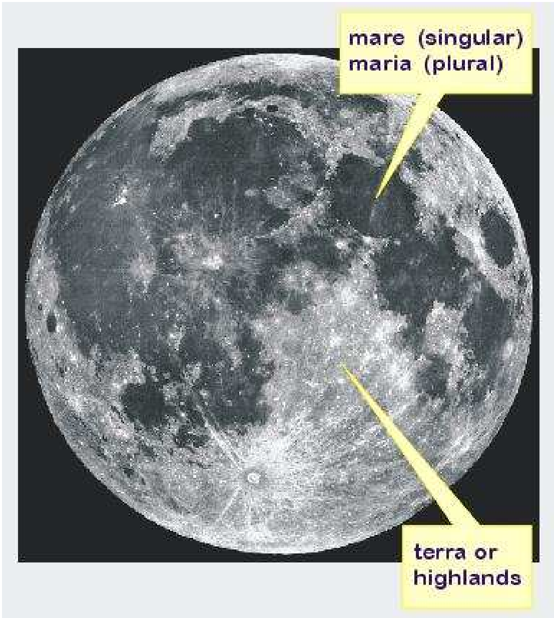


Figure E-4. The Aluminum Rich Lunar Highlands (light) and the Iron Rich Lunar Maria (dark)
Source: Lunar and Planetary Institute (www.lpi.usra.edu/lunar/missions/clementine/images)

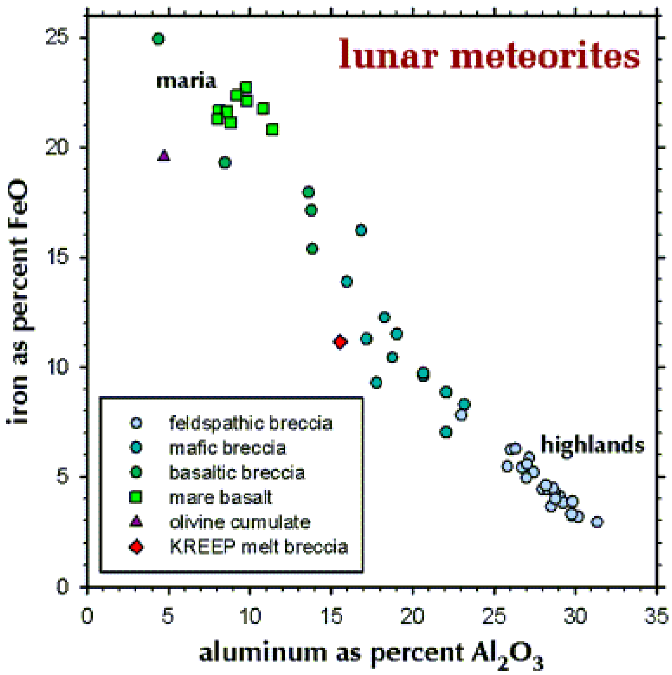


Figure E-5. A Graph of Iron and Aluminum Content Based on Lunar Samples and Meteorites
Source: University of Washington Seattle
(www.meteorites.wustl.edu/lunar/moon_meteorites.htm)

On Earth, aluminum is recovered from bauxite, Al_2O_3, which is weathering product of feldspar, usually in weakly acid soils. Carbo-thermal recovery of aluminum from anorthite has not been shown practical due to the presence of calcium. Instead, due to the discovery of rich volatiles on the Moon we can use the primarily aqueous, lime sintering process to break down the anorthite and free aluminum as its oxide. This process is described by Dietzler (2007).

Anorthositic highland regolith is 75% to 90+% plagioclase ($CaAl_2Si_2O_8$ and a little $Na_2Al_2Si_2O_8$) with some pyroxenes and olivines. Magnetic separation will clean the iron bearing minerals including titanium bearing ilmenite out of this leaving fairly pure anorthite-$CaAlSi_2O_8$. Intense Solar heat at 1500 C to 2000 C could boil the remaining iron oxide, silica and magnesia out of the anorthite as well as sodium and potassium, leaving calcium aluminate-$CaAlO_4$. This could be leached in sulfuric acid.

$$CaAl_2O_4 + 4H_2SO_4 ==> CaSO_4 + Al_2(SO_4)_3 + 4H_2O$$

Calcium will form $CaSO_4$, calcium sulphate (plaster of Paris), and water. $Al_2(SO_4)_3$ will be dissolved in water that will be drained out of the leaching tank, dried to recover water, and roasted to Al_2O_3. Al_2O_3 is not attacked readily by sulfuric acid. The $CaSO_4$ (anhydrite, gypsum) can be filtered out with a glass cloth filter, dried, and the water recycled and used to reconstitute H_2SO_4. During the roasting of $Al_2(SO_4)_3$ to Al_2O_3 sulfur dioxide and sulfur trioxide will form and these will react with water to reform sulfuric acid, basically. The Na, K, FeO, SiO_2 and MgO roasted out of the anorthostic material with Solar heat will be condensed in a ceramic retort since these have many valuable uses of their own.

The Al_2O_3 is then carbo-chlorinated to yield $AlCl_3$ which is electrolyzed. Electrolysis of $AlCl_3$ does not consume the precious Lunar carbon electrodes as does conventional Hall-Heroult electrolysis of Al_2O_3. The carbo-chlorination step yields CO_2 that must be shifted to methane that can be decomposed to carbon and hydrogen on red hot refractories like Solar heated black cast basalt.

Carbo-chlorination can also be used on mixtures of metal oxides such as found in the Lunar regolith or anorthite. Chlorine and carbon, free or in the form of methane, are introduced to react with metal oxides under pressure. However, this requires high pressure and high temperatures, requires thick-walled chambers.

Because the chlorine reacts with the oxides, producing solid chlorides, releasing oxygen which immediately reacts with the carbon to form carbon dioxide, the reaction can proceed despite the fact that chlorine is less oxidizing than oxygen. Silicon dioxide reacts with the chlorine and methane to create H_2O, CO, and $SiCl_4$. This will also produce a mixture of metal chlorides which can be made into metal by electrolysis.

There is some advantage to converting oxides to chlorides in that the electrolysis process does not consume its carbon electrodes as carbon dioxide, but releases chlorine. However, this must be balanced against the hazards of high-pressure chlorine processes, and the knowledge that the carbon can be recovered and recycled.

The recovery of aluminum and oxygen from anorthite can be done via the carbo-chlorination process (Teeter et al.,1987).

Acid leach process using hydrofluoric acid, HF, can recover oxygen from silicon and metal oxides (MO) making up the regolith:

$$2HF + MO + SiO_2 \rightarrow H_2O + MF_2 + SiF_4.$$

The recovery of oxygen and aluminum via the acid leach process is discussed by Teeter et al. (1987). However, hydrofluoric acid is very toxic and corrosive and will create hazards in a Lunar base. However, like chlorine, fluorine can be recovered from Lunar regolith where it exists in 10 ppm concentrations.

Silicon and Glass. Silica will be a byproduct of aluminum production from anorthite and may come out a useful glass for structures. Pure silicon will also be valuable on the Moon for Solar panels and can be derived from silica by carbo-thermal processes, as on Earth:

$$SiO_2 + C \rightarrow CO_2 + Si$$

This means basically the problem of silicon is just the problem of getting high-purity silica.

Silica can be best recovered as part of the recovery of aluminum for anorthite, where it is recovered as a gas from the initial high heat treatment. When combined as silicates of magnesium or iron it can be easily freed by leaching out the iron and magnesium using acids, leaving pure silica.

Melt-mixing of silica with sodium oxide, another byproduct of anorthite processing for aluminum, will yield soda glass for windows and fiberglass insulation and cloth.

Magnesium. Magnesium is a very useful metal for making strong, lightweight alloys with aluminum. Its best source is olivine rock which is $(MgFe)SiO_3$. Magnesium can be refined by acid leaching of olivines (Teeter, et al., 1990):

$$(MgFe)SiO_3 + HF = H_2O + MgSiF_6 + FeF_2$$

The $MgSiF_6$ must be decomposed in the presence of oxygen again to form MgO and SiF_4 which is a gas.

The recovery of magnesium via the acid leach process uses the very powerful and toxic hydrofluoric acid process, and its hazards should be weighed against other processes.

Titanium Recovery. Titanium is useful for high-strength-to-weight applications, such as turbines, flywheels of inertial energy storage, spacecraft parts and Earth gravity carousels, and water handing, since it is corrosion resistant.

Titanium is freed from its oxide, TiO_2, which is a byproduct of aluminum production, by the Kroll process, which is a carbo-chlorine process exposing the TiO_2 to hot chorine and carbon:

$$Cl_2 + C + TiO_2 \rightarrow TiCl_4 + CO$$

The titanium tetrachloride is heated with magnesium to form salts and titanium sponge:

$$TiCl_4 + 2Mg \rightarrow Ti + MgCl_2$$

E.4 The OLPF (ORBITEC Lunar Process Flow) for Lunar Metal Processes Utilizing Abundant Lunar Volatiles

Strategies and processes for Lunar resource recovery need to be revised in light of the discovery of significant Lunar volatiles in the polar regions. These volatiles, which resemble in composition "dirty snowball" cometary ices, are dominated by water, but include ammonia, methane, and sulfur dioxide. The Lunar "hierarchy of needs" of recovered resources for a growing colony can be summarized, in order of importance, as oxygen, iron, silica for glass, aluminum, silicon for Solar cells, magnesium and titanium. Previous strategies for Lunar resource recovery tended to emphasize energy and highly reactive chemicals rather than water to separate out Lunar metals and oxygen. However, high temperature–highly corrosive processes may not be attractive in an early Lunar colony. Ideally, for instance, all oxygen production for life support should be derived from electrolysis of distilled water to preclude contamination. With the discovery of abundant Lunar volatiles; however, it is now possible to design a OLPF to recover Lunar resources that involves efficient recycling, low toxicity, and low pressures and temperatures. The key fact enabling the OLPF is the chemical instability of most Lunar minerals to terrestrial conditions of water and weak acids.

The chief Lunar surface minerals of interest for any Lunar resource strategy are ilmenite, anorthite and olivines. These minerals are abundant in the regolith and are also found concentrated in specific areas. Ilmenite is found abundantly on the maria and anorthite is abundant on the Lunar highlands. Olivines are found mixed with both but can be easily separated from both because olivine is more strongly magnetic.

These three minerals are abundant on the Lunar surface, but are rare on the Earth's surface because they all degrade rapidly in the presence of water and carbon dioxide or other acid gases. The very unearthly nature of the Lunar surface, anhydrous and subject to high-temperature extremes, makes the minerals there extremely unstable in the presence of water and weak acids, such as carbonic acid. Therefore, the OLPF makes use of this fact to create a process flow that makes use of the terrestrial conditions that will exist inside the Lunar colony and allow the most crew access to processing areas. In other words, by emphasizing low toxicity, semi-terrestrial, aqueous based processes, familiar to Earth, the recovery of Lunar resources can occur in areas that are adjacent to and share conditions with crew quarters. This will greatly increase the ease of construction and startup of the growing Lunar base.

The basic processes used are magnetic separation, carbo-thermal reduction, and hydrogen-based processes with recycling of reactants by water shift and electrolysis, plus some familiar terrestrial processes for refining of aluminum using high-temperature electrolysis: the Hall–Héroult process, and the Kroll process for recovery of titanium, where the $MgCl_2$ must subjected to electrolysis in the terrestrial process. The advantage here is that both chlorine and carbon dioxide are less strongly bound to metals than oxygen, and chlorine is the least toxic of the halogens and widely used on Earth.

The OLPF is designed for ease of startup and efficient process flow, so that processes and waste materials from one process are then used to create other materials farther down the process chain. In general, the process end points for each material end up with CO_2 or H_2O as byproducts for recycling in the process. Hydrogen and oxygen are recovered by electrolysis. The CO_2 produced can be turned into methane and water by the water-shift process:

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$

Thus, the discovery of abundant Lunar volatiles allows closed cycles at lower energy per unit of material produced. An overall diagram of the process is seen in Figure E-6.

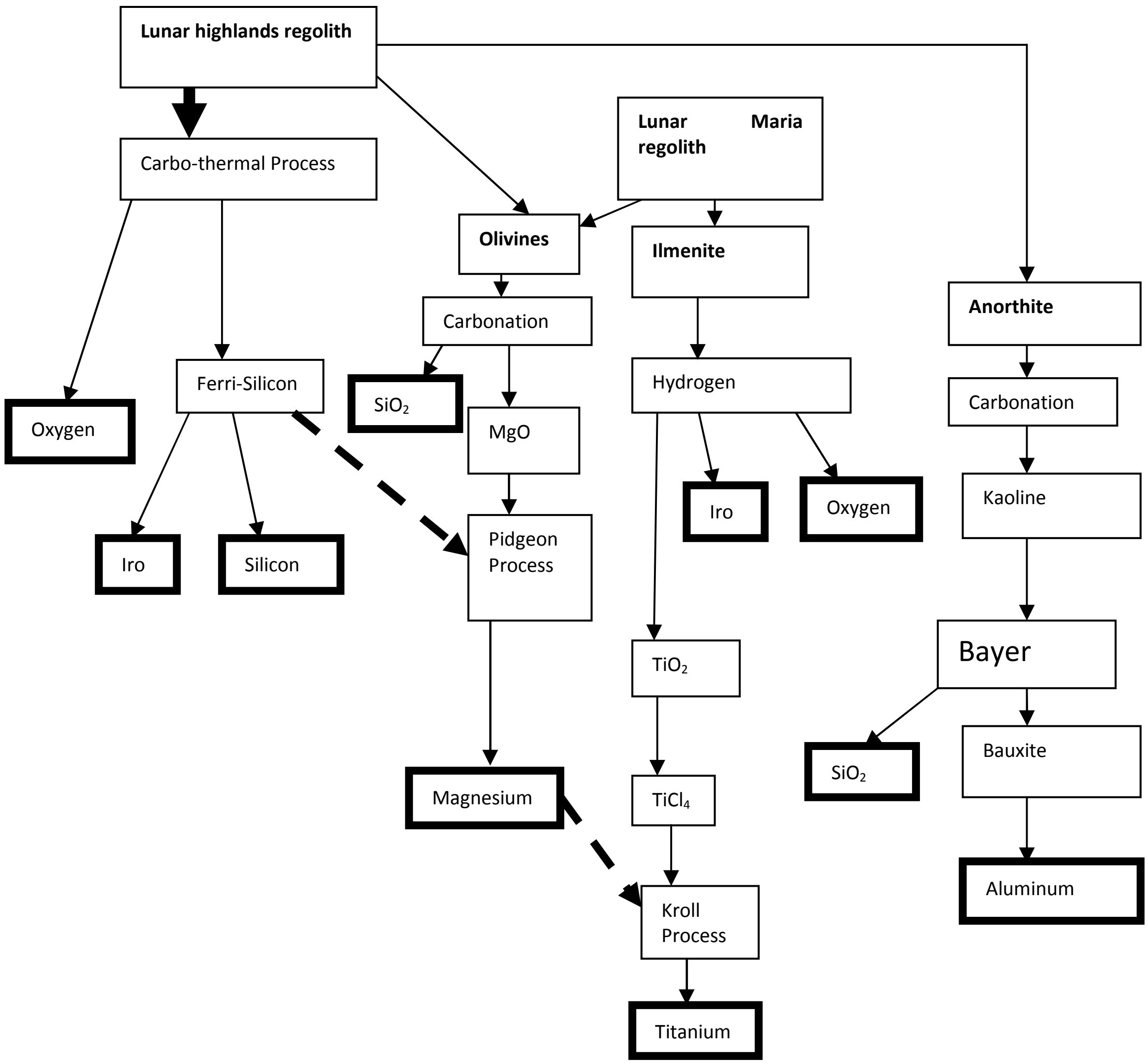


Figure E-6. An Overall Diagram of the OLPF

The OLPF System. The initial plant would consist of carbo-thermal processing of highlands regolith near the Lunar pole base. This will involve methane being put through heated regolith to produce ferri-silicon, water, carbon monoxide and mixed refractory oxides (Gustafson et al. 2003). It is possible iron can be separated from the melt magnetically (Rice, 2005).

The water is separated from the carbon dioxide by condensation. The carbon dioxide is then mixed with hydrogen and heated in the presence of a catalyst to make methane to return to the process (and water). The water is subjected to electrolysis to recover oxygen and return the hydrogen to the process. Therefore, this initial system does not need sorted feedstock, makes oxygen, and requires a water shift process plant and electrolysis plant to be activated. Its wastes are refractory oxides and ferri-silicon.

The ferri-silicon can be reacted with sodium hydroxide solution to create hydrogen, which is a standard method for creating hydrogen for military balloons on Earth. Ferric oxide and sodium silicate are the standard byproducts which can be separated. The ferrous oxide can be reduced with hydrogen to form iron (Sha and Qiu, 2007) and the sodium silicate can be mixed with hydrochloric acid to make salt and silica.

Thus, iron, silica and oxygen can be produced from this initial plant.

Iron. A secondary plant can be established on the north Maria to mine and process ilmenite. The hydrogen reduction of Ilmenite is the lowest energy method of harvesting oxygen from the Lunar soil (Williams and Erstfeld,1979)

First we sort ilmenite from olivines magnetically and then heat the ilmenite to make it more magnetic and then separate it from the non-magnetic component. The purified ilmenite is then heated in the presence of hydrogen to recover oxygen in the form of water. The residue is TiO_2 and iron. The water is recovered and electrolysis yields oxygen and the hydrogen is recycled.

The hydrogen process is very straightforward:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$

This process can be expected to eventually provide all the oxygen and iron necessary for the growing Lunar colony.

Silicon and Glass. Silica will be a byproduct of initial carbo-thermal and aluminum production from anorthite and may come out as useful glass for structures. Pure silicon will also be valuable on the Moon for Solar panels and can be derived from silica by carbo-thermal processes, as on Earth:

$$SiO_2 + C \rightarrow CO_2 + Si$$

The carbon dioxide is recycled or converted to methane and water by water shift to recover hydrogen and oxygen.

Aluminum. Aluminum is a valuable lightweight metal for electrical wiring, spacecraft parts, and Lunar habitats. An anorthite mine will be established on Lunar highlands material, probably near the initial base. Anorthite can be attacked by carbonic acid in a process called "carbonation" with perhaps some hydrochloric or sulfuric acid to speed the reaction, to form calcium bicarbonate which is very soluble

$$CaAlSiO_3 + H_2CO_3 \rightarrow Ca(HCO_3)_2 \text{ (dissolved)} + Al_2(SiO_2)_3$$

$CaCO_3$ is precipitated by adding CaO (lime) or by degassing the solution, $CaCO_3$ is then heated to become CaO $+CO_2$. The aluminum silicate is broken down by NaOH solution, in the terrestrial Bayer Process, to leave silica and dissolve-out aluminum as its hydroxide. The aluminum oxide is then subjected to electrolysis in the Hall–Héroult process with molten Cyrolite with carbon electrodes as on Earth.

Aluminum oxide electrolysis is very energy intensive requiring 838 kJ of electrical energy per mole (27 g) of aluminum produced. Carbon dioxide is also produced by the oxygen electrode and must be recycled by water-shift into methane and decomposed to carbon for recycling into new electrodes.

Magnesium is a much less energy intensive metal than aluminum. MgO forms at 601.8 kJ per mole (25 g) and can be decomposed using straight thermal energy rather than electrolysis, and a very useful for alloying with aluminum, or used as a structural metal with some aluminum as an alloying agent.

Magnesium. Magnesium is a very useful metal that is easily recovered, and, when alloyed with a small fraction of aluminum, can be used as in place of aluminum for many structural roles on the Moon. To obtain magnesium, we utilize the olivine from the refining of the ilmenite and anorthite and react it with carbonic acid, to yield magnesium carbonate and iron carbonate in solution and leaving silica. We also use the ferri-silicon from our initial carbo-thermal process.

$$FeMgSiO_3 + H_2CO_3 \rightarrow (FeCO_3 + MgCO_3) \text{ solution} + SiO_2$$

We oxygenate the solution to precipitate the iron as ferric Fe(III) iron hydroxide and leave the magnesium carbonate in solution.

$$(FeCO_3 + MgCO_3) \text{ solution} + O_2 \rightarrow Fe(OH)_3 + MgCO_3$$

We evaporate the $MgCO_3$ solution and heat further to yield magnesium oxide and recover the CO_2.

$$MgCO_3 + \text{heat} \rightarrow MgO + CO_2$$

The CO_2 is then recycled in the process. We then use the Pidgeon process using ferri-silcon from our earlier carbo-thermal process to reduce the magnesium.

$$MgO + FeSi \rightarrow Mg + FeO + SiO_2$$

Therefore, the recovery of magnesium is much less energy intensive than that for aluminum and therefore magnesium-aluminum alloy should be used instead of pure aluminum for structures and spacecraft parts.

Titanium. Finally, using our TiO_2 from the ilmenite, we use the terrestrial Kroll process to convert this into titanium tetra-chloride.

$$TiO_2 + Cl_2 \rightarrow O_2 + TiCl_4$$

add magnesium to get titanium sponge and magnesia

$$TiCl_4 + 2Mg \rightarrow 2MgCl_2 + Ti$$

The magnesium chloride is then subjected to electrolysis, as on Earth, to produce magnesium metal and chlorine, which are recycled in the process:

$$MgCl_2 + \text{electric power} \rightarrow Mg + Cl_2$$

The electrolysis of magnesium chloride requires 641 kJ per mole of magnesium produced, and is thus much less energy and material intensive than that of $TiCl_4$ at 763.2 KJ/mole and thus lowers the energy cost of titanium.

Titanium could be used for corrosion resistant life support components, spacecraft parts, and rotational energy storage.

Summary. Basically, a mining center on the north edge of the south maria such as Mare Imbirum will lead to access to both highland anorthite and maria ilmenite. The ilmenite will yield oxygen, iron, and titanium. The anorthite will yield aluminum and glass. Magnesium is much easier to use on the Moon than on Earth, because of the lack of oxygen and lower gravity, so magnesium-aluminum alloy may be much better to use than aluminum for many structural uses.

Many previous studies of Lunar resources have assumed from the outset that water and other volatiles will be scarce, whereas energy from the Sun will be abundant. This situation favored dry-high temperature processes and those involving highly toxic acids or corrosive gases. However, the problems of confined living spaces in early Lunar colonies and the problems of handling toxic materials in those same close quarters cannot be underestimated. For instance, producing oxygen for breathing in the same area as high toxic hydrofluoric acid is used to break down regolith is a safety risk. For this reason, the discovery of Lunar volatiles is not only welcome, but means that the whole family of processes for recovering oxygen and metals from the Lunar regolith can be reexamined and less toxic and dangerous alternatives can be considered.

With volatiles now available from the poles, lower temperature aqueous based processes, similar to those found on Earth, can now be used rather than energy-intense Solar-powered processes formerly favored. This means a Lunar colony can be established at less initial cost, become self-supporting sooner, and begin expanding using Lunar materials more rapidly than previously estimated. The increased availability of volatiles, and hence Lunar resources, means that a generational approach now makes sense, whereby the Moon is colonized as a forward base, and then used to stage expeditions and colonization efforts further into space, such as to Mars.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