FINAL REPORT

on

SYSTEM ARCHITECTURE DEVELOPMENT FOR A SELF-SUSTAINING LUNAR COLONY

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FOREWORD

This document represents the Final Report on the Phase I study entitled "System Architecture Development for a Self-Sustaining Lunar Colony." This was a NIAC-Phase I study (Research Grant #07600-052) performed by Orbital Technologies Corporation (ORBITEC™), in Madison, Wisconsin, for NASA and the NASA Institute for Advanced Concepts (NIAC), managed by the Universities Space Research Association (USRA). The NIAC Program Director is Dr. Robert Cassanova.

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1.0 BACKGROUND

ORBITEC proposed and has conducted a Phase I 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. We defined self-sustaining as a colony that would be able to survive without any supplies or resources from Earth for an extended period of time. We will show that a design of a self-sustaining architecture is feasible and does represent an attractive alternative to what would be a regular Earth-supported lunar colony. The establishment of SSLC is necessary to drive new innovative approaches/developments 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 production of needed structures and commodities from lunar materials.

Today, there are no formal NASA coordinated efforts for lunar development or colonization. Much of the recent emphasis has been focused on Mars exploration because of the findings of possible life on the meteorite AH84001. However, interest and activity with respect to the Moon has been steadily increasing in NASA, Europe, Japan, China and India, and in the US commercial sector, primarily in the entertainment sector. Another space race to the Moon could very well develop. Examples of current programs include: European projects (ESA approved project SMART I mission), US Lunar Prospector, and the Japanese Lunar A penetrator probes and the Selene project. Any large-scale lunar development will likely be multinational and will require the efforts of a large number of people and organizations. Many attempts at structured requirement descriptions exist in literature [Duke et al., 1985]*, [Matsumoto et al., 1995], [Koelle, 1988], etc. However, one specific utilitarian purpose overshadows the requirements for bare survival in each study, making the study vulnerable to criticism of the assumptions underlying the use envisioned. There is also much published on the different reasons for establishing a lunar base [Smith et al., 1991]. By addressing the survival requirements separately, the architecture study is designed be much less sensitive to variations in requirements and ideas about the purpose of the colony. The primary purpose of the SSLC is to permit the survival of a group of humans on the Moon for an extended period of time without sustained supplies from Earth. In the process of developing this capability, we note that the technologies required to permit successful future space exploration and colonization of Mars are very similar and synergetic.

1.1 Levels of Autonomy for a Lunar Base

Four distinct levels of autonomy for a lunar base were identified to define the concept of self-sustaining. These four levels are briefly described below.

1) Complete Dependence

This base would utilize an open-loop life support system. All of the life support consumables (air, water, food) would be provided by Earth-supplied reserves. While there is an effort to minimize losses, there is no effort to recycle any materials. Everything required for survival

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* NOTE: References are provided in Appendix A Bibliography

must be supplied by shipments from Earth. This base can survive in isolation as long as its reserves allow, perhaps days or weeks. An example of this level of autonomy is the Space Shuttle.

Examples of Import Needs – oxygen, nitrogen, water, food, carbon, tools, machines & spare parts, propellants, electronics, drugs (including vitamins and minerals)

2) Limited Dependence

This base would utilize a partially-closed life support system. Air and water would be fully recycled. Some food would be produced locally and partially recycled. Make-up for losses in the system would be provided by Earth-supplied reserves. All other materials required would be supplied by shipments from Earth. This base can survive in isolation on its reserves for longer periods of time due to the recycling efforts, perhaps for months at a time. An example of this level of autonomy will be the completed International Space Station.

Examples of Import Needs – some oxygen, nitrogen, some food, water, carbon, tools, machines & spare parts, propellants, electronics, drugs (including vitamins and minerals)

3) Self-Sustaining

This base would utilize a fully-closed life support system. All life support consumables are completely recycled. Make-up for losses in the system would be provided by the base. The base has the ability to maintain tools, machines, and habitats for extended periods of time. For example, this would include production of wear parts in mining equipment. Items that are very difficult to produce locally would be provided by Earth. This base can survive in isolation for long periods of time, perhaps years. An example of this level of autonomy is the SSLC we studied in the Phase I effort.

Examples of Import Needs – complex tools, machines, electronics, drugs (including vitamins and minerals)

4) Self-Sufficient

This base provides for all of its needs, therefore it can survive in isolation for an indefinite period of time. An example of this level of autonomy would be a large permanent population of humans living on a fully terraformed Mars.

Examples of Import Needs – none

1.2 Functional Requirements of SSLC

Expertise in many areas is needed, and multinational collaboration across conventional industrial branches will eventually be necessary. A preliminary first level functional requirement breakdown was developed prior to the Phase I study. A representative list of the different areas of expertise (many are represented by our study team members) that was incorporated in the Phase I study is given in Figure 1.

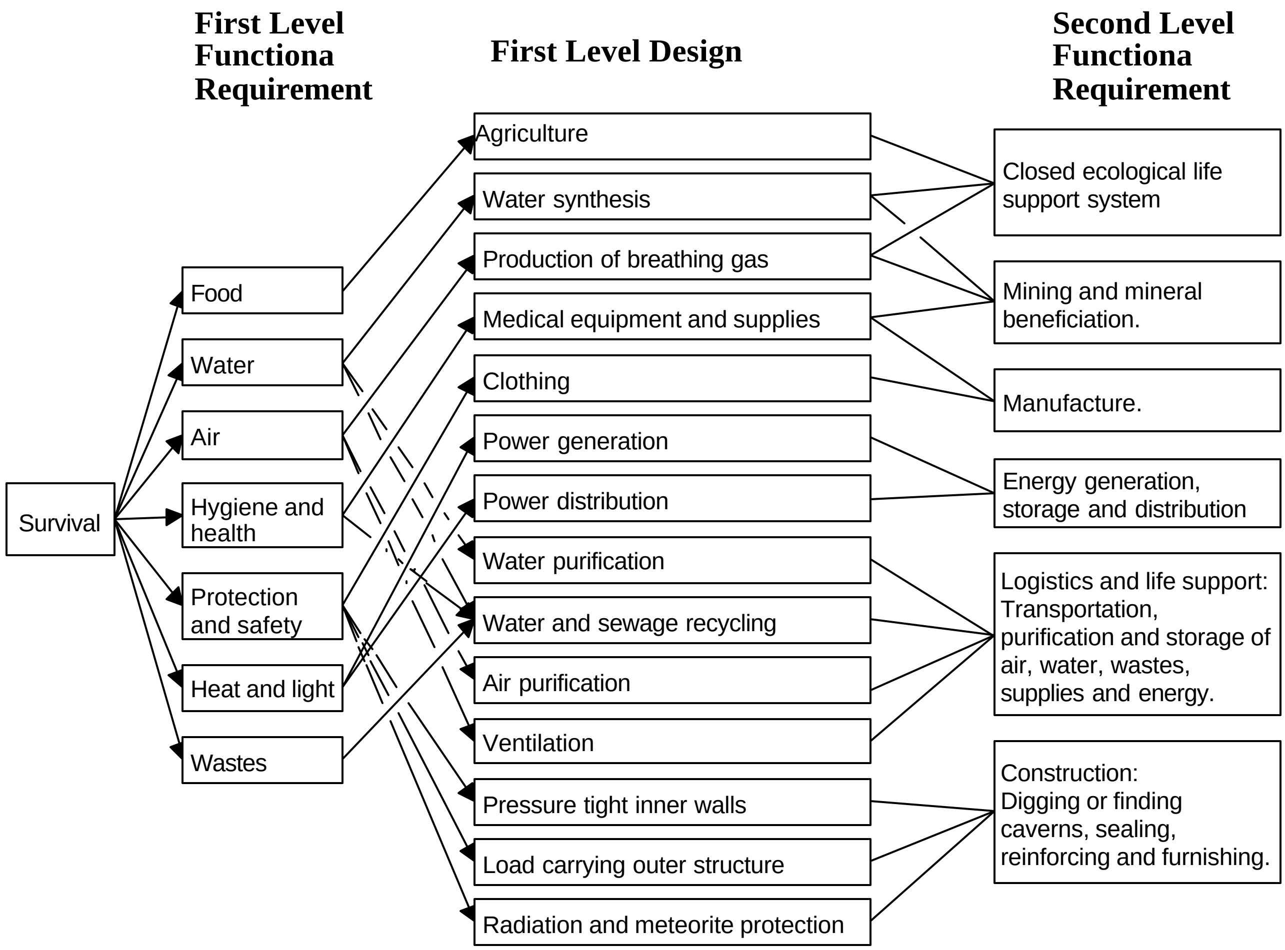


Figure 1. Requirement Breakdown for Human Survival

Biology: Effects of 1/6th gravity and radiation on humans, plants and animals, as well as closed system ecology, food production and processing, plant and animal transport, etc.

Human Behavioral Sciences: including psychology and sociology, especially with respect to isolated groups and confined spaces, family structure, social activities, etc.

Ground Transportation/Propulsion: personal rocket back packs and rocket-based platforms, small and large rovers, maglev transport systems, heavy haulers, power plants, rocket systems, etc.

Space Transportation/Propulsion: Hoppers, orbital vehicles, emergency transport vehicles, rocket systems, etc.

Automation and Robotics: Robots, automatic processing and manufacturing technology, self-replicating systems, control systems for safety and comfort, etc.

Mining and Processing of Resources: Mining of raw materials and mechanical and chemical processing of the lunar regolith to extract gases, liquids and solids needed for support and extension of the lunar colony, concrete and basalt processing, etc.

Facility Construction: Buildings, underground facilities (tunneled), inflatables, roads, launch pads, maglev tracks, etc.

Communications: Satellite communications, direct broadcast (lunar orbit, from Earth), local communications, cable, etc.

Manufacture of Tools, Equipment, Commodities: Manufacture of tools, parts and repair of existing equipment, production of needed products for survival and living, etc.

Solar and Nuclear Power Generation and Energy Storage: Solar power system manufacture, solar cell production, nuclear power systems construction, nuclear fuel production, electrical, chemical, and thermal energy storage for night and emergencies/breakdowns/eclipses, etc.

Recreation and Entertainment: Colonists require recreation and entertainment, which would include modifications to Earth-based activities; Entertainment could be from Earth-based activities (movies, news, shows, sports, etc.), etc.

Political Science/Government: Colonists will require a governmental/lawful system to guide, manage and control the events and processes, etc.

Commercial Activities: Both internal and external commercial activities include production of required products for the colony and the export of valuable recovered resources that Earth-based or other space-based systems require for exploration and space commerce, etc.

1.3 Role of ISRU in the SSLC

The key to survival of a self-sustaining lunar colony will be its smart use of in situ resources that are available. Chemical analyses performed on lunar samples from the Apollo missions indicate oxygen, silicon, aluminum, iron, calcium, magnesium, and titanium are the major components of lunar soil (see Figure 2). Oxygen comprises approximately 42 percent of the lunar soil by mass, while titanium accounts for only 3 percent (mare soils). All of these elements are chemically bound in various minerals, so the lunar regolith will require processing to extract the useful components. Oxygen could be "mined" by directly heating lunar regolith to moderately high temperatures and adding hydrogen and/or carbon to reduce the oxides to form water or carbon monoxide. These gases can be further processed to form oxygen, leaving recyclable hydrogen and/or carbon, metallic, and ceramic co-products in the processed regolith. Perhaps up to ~20% of the lunar regolith mass can be converted into oxygen using a carbon-based reduction process. It is likely that metals derived from this process can be used as fuels, construction materials, and other products.

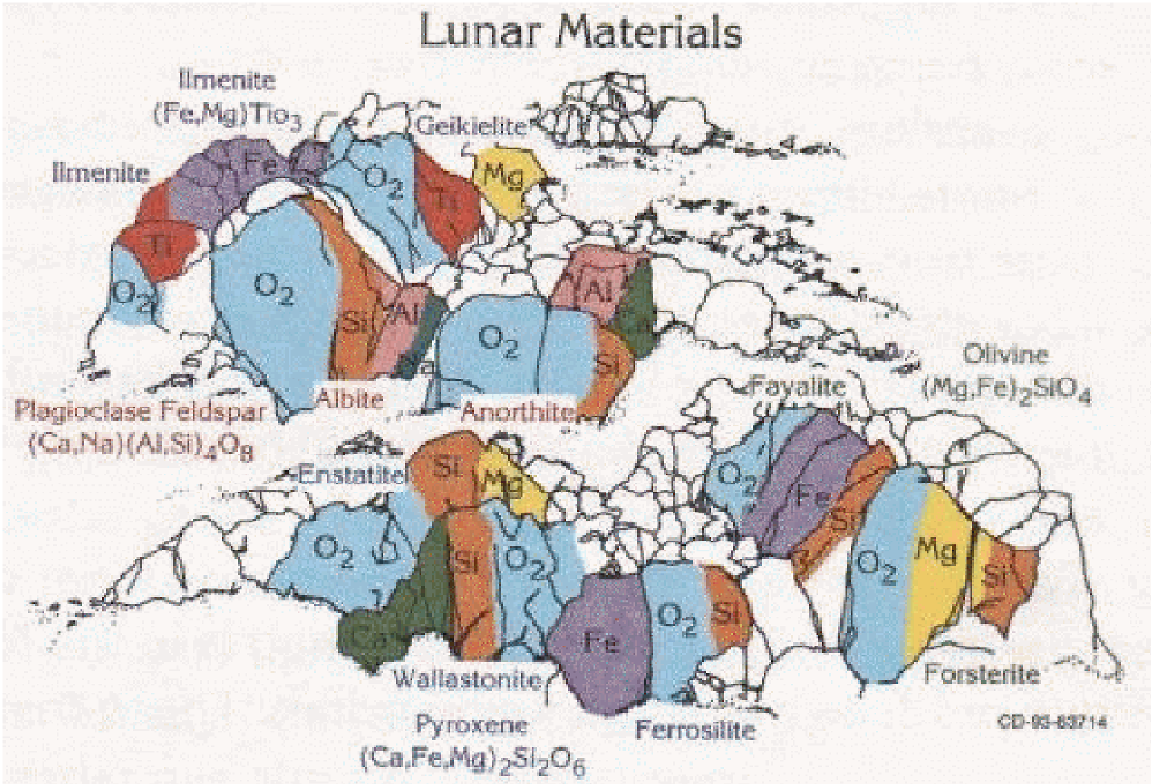


Figure 2. Illustration of the Resources Available in the Lunar Regolith

The lunar soil also contains small amounts of helium, hydrogen, nitrogen, and carbon deposited by the solar wind. These gases can be extracted directly by modest heating, but concentrations in the soil range from a few parts per million to a few hundred parts per million. Recent data from Lunar Prospector indicate that the north and south poles of the Moon may contain up to 300 million metric tons of water ice (or equivalent in hydrogen). There are likely other useful frozen gases present. Significant cost-benefits for a future lunar base are possible if a significant portion of this water ice (or hydrogen) can be extracted.

Lunar night and the energy storage are significant problems for lunar bases located near the equator. The SEI study [NASA, 1989] concluded the total energy requirements could only be answered with some sort of nuclear power station. After consideration, we concluded that the best location for the SSLC was at one of the sunlit crater rims near the south pole of the Moon. It appears feasible to locate solar photovoltaic cells at multiple locations to provide a nearly continuous source of electrical power.

A self-sustaining, renewable power source is also key to success of the colony. The SSLC will initially rely on a combination of nuclear power and solar energy. New solar photovoltaic arrays would be phased in over time to provide more redundancy and additional future energy capability. Collecting solar energy on the lunar surface and converting into power to support the base will require the manufacture of large arrays of solar photovoltaic cells. The major components, including solar cells, wires, microwave reflectors, and metal, glass, or ceramic support structures, must be manufactured using lunar resources. Laboratory experiments have shown the ability to make pure silicon for solar cell manufacture, iron for structures and wire, fiberglass and iron for reflectors, and several other products from simulated lunar regolith. The vacuum and low gravity of the Moon may actually aid in the manufacturing process of certain products. The mineral ilmenite, which is abundant in the lunar soil, can also convert sunlight to electricity; this needs further investigation. A recent workshop provides a significant discussion of these concepts both for utilization on the Moon and also on Earth [Beckey et al., 2000]. Other potential alternatives are nuclear fission heat sources or reactors, nuclear $D/^3He$ fusion systems and Low Energy Nuclear Reaction (LENR) - based power systems being explored by the Kulcinski (Wisconsin) and Miley (Illinois), respectively. Per Kulcinski, there is ten times more energy in the helium-3 on the Moon than ever existed in all the fossil fuels on Earth. A commercial fusion reactor based on helium-3 would generate a very slight amount of radioactivity, equivalent to the amount produced by hospitals in their nuclear medicine areas. Since the helium-3 may be worth as much as $2,000,000 per kg, this would be a very important energy source and commercial export for the lunar base colony.

By-products of the ^3He mining process include: H_2, H_2O, ^4He, N_2, CO, CO_2, and CH_4. Over 18,000 tons of volatiles would evolve from every ton of helium-3 extracted on the Moon. These volatiles represent a huge resource that can be utilized in a variety of ways. Hydrogen can be combined with oxygen in fuel cells to produce electricity and water. The nitrogen, oxygen, carbon dioxide, and water are all vital to life support operations. The nitrogen derived from the lunar volatiles can be converted, by the appropriate bacteria, to ammonia and then incorporated into proteins and other food materials. It can also serve as a gas to maintain atmospheric pressures in the living and working areas of the lunar base and for the plant growing facilities (just as on Earth). It is estimated that 20 m^2 area of plants would provide the daily caloric requirement of one person. A plant area of this size would emit approximately 1,500 g of oxygen and produce 2,100 g of CO_2 per day. A 10% loss of gases in food production, processing, and waste recycling operations is anticipated. Each person needs approximately 3,900 g of potable water per day. The number of lunar inhabitants that can be supported from the by-products of ^3He mining in the first few years ranges from over 1,000 colonists (N_2 needs) to over 20,000 (water and CO_2 needs) to more than 300,000 (O_2 requirements). As the mining production increased, it would become possible to support many more. Therefore, a helium-3 economy would not only benefit society on Earth, but might also be the key to establishing and maintaining a permanent self-sustained lunar colony.

A closed-loop life support system is vital to survival of the colony. Carbon dioxide can be extracted from the lunar regolith to support plant growth for food. ORBITEC is developing automated plant growth chambers for the ISS that can be expanded for large-scale production in lunar greenhouses. It will be possible to fabricate bricks and panels from local materials (lunar concrete – T. D. Lin) and use them for constructing habitats, greenhouses, workshops, storage buildings, and ground transportation infrastructure. Metals can be extracted from local rocks and soil to make beams, wires, and solar power cells. The gases contained in the regolith can also be used in inflatable structures and clothing made from fabric woven from lunar basalt material.

1.4 Previous Lunar Architectures

Some architecture layouts are presented in the next few figures, which show some of the previous thinking on lunar base architectures.

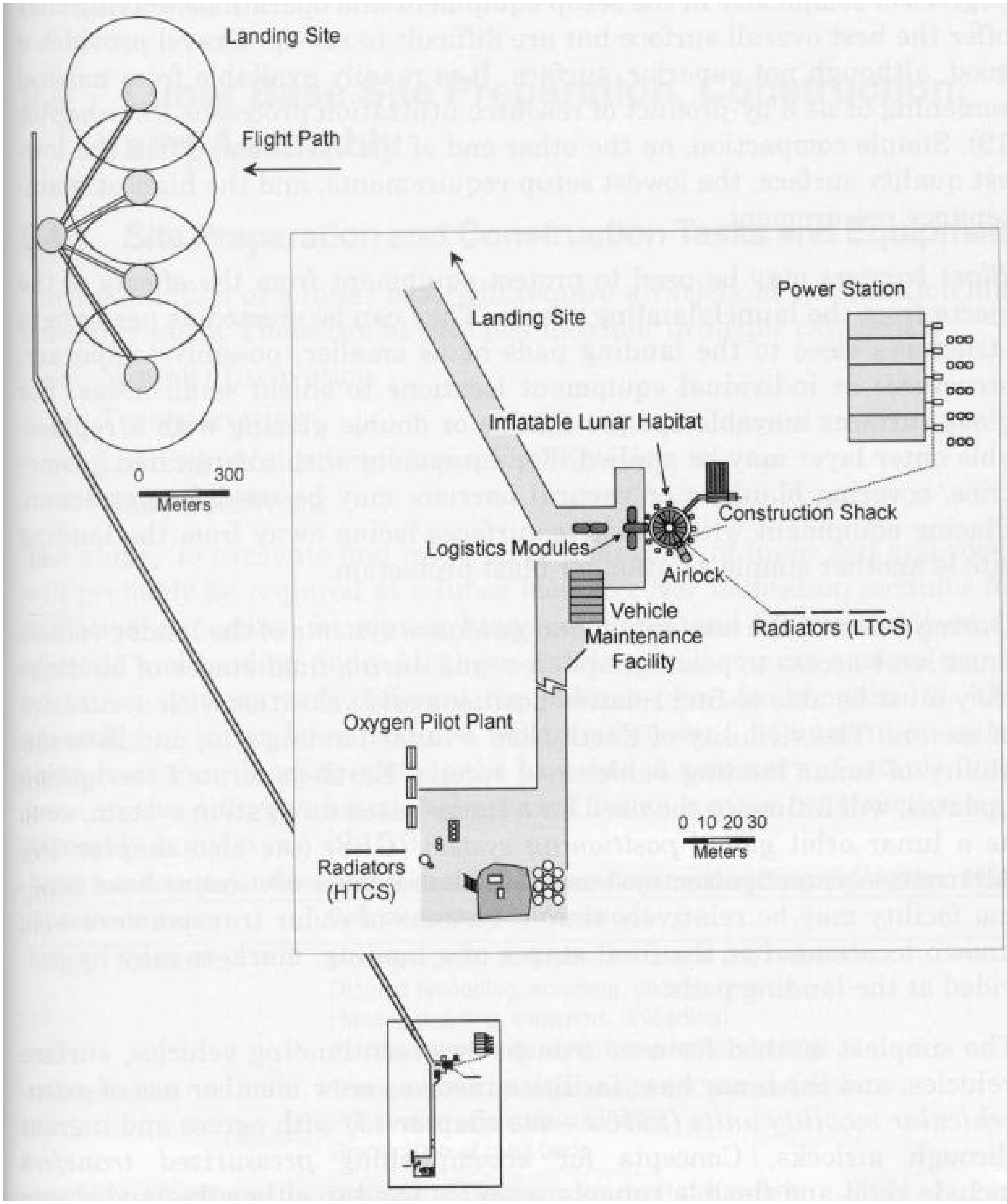


Figure 3. A Lunar Base Layout Developed During the Space Exploration Initiative in 1989-1990 [Alred, et al., 1989]

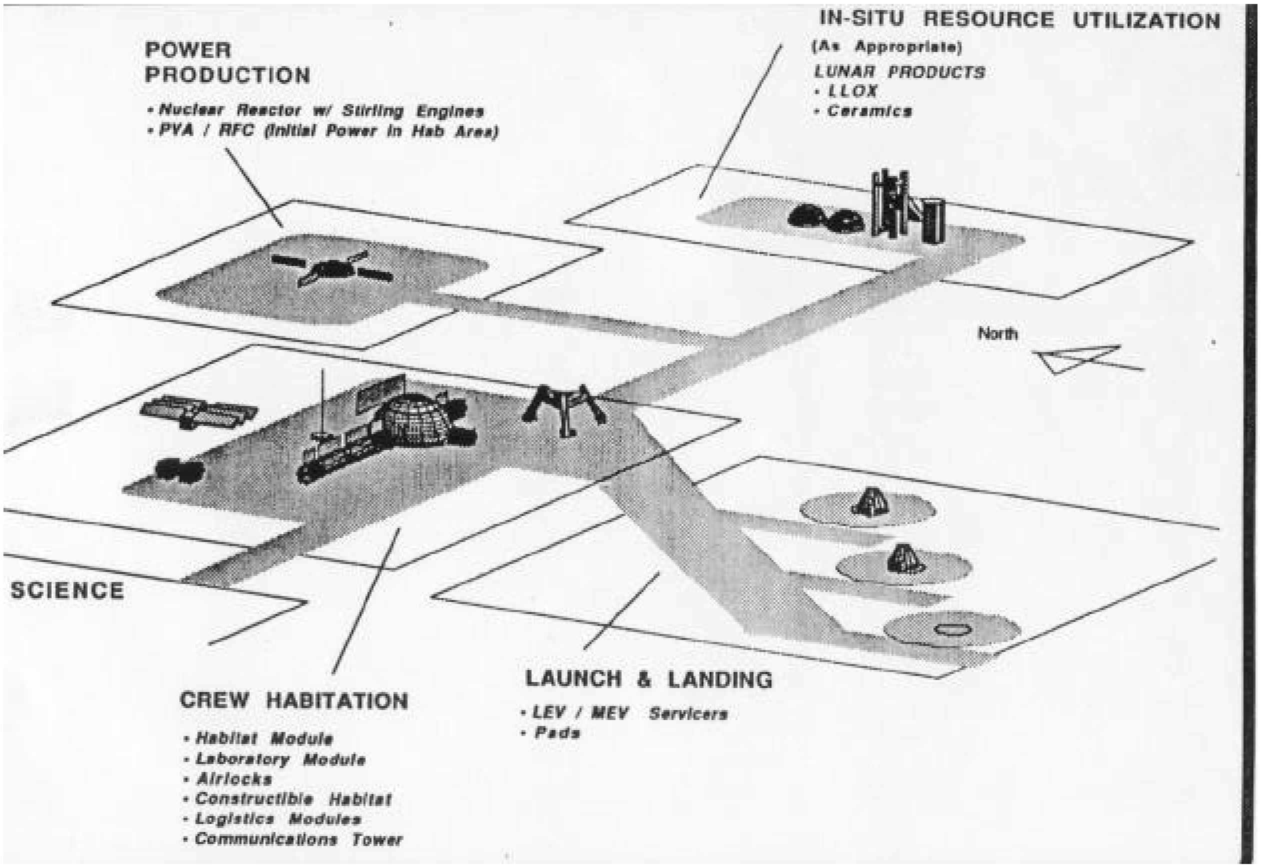


Figure 4. Architecture from the Space Exploration Initiative 90 Day Report [90 Day Report, NASA 1989]

Figures 3 and 4 depict plans that are spread over the lunar landscape with appropriate distances provided between launch pads and habitat. The effects of lunar lander engine exhaust blasting the lunar soil and chemical contamination from rocket plumes in 1/6 gravity are a significant design parameter. Solar power facilities must be positioned at sufficient distances from all dust generating activities (such as the launch and landing facilities and mining sites). Nuclear power facilities must be located a safe distance from the habitat. The ISRU facility is also located away from the main area.

An architecture [Eichold, 2000] was which we believe may be an appropriate conceptual design for a permanent lunar colony. It takes into consideration the integration of the individual into a community and community with the individual in an environment. These together with other considerations become important in a permanent base.

“The premise of utilizing a lunar crater, since they are common and of varying sizes, suggests a number of advantages. The crater walls form a base of support for a dome over the center. A tensile structure of fiberglass cable slung low over agricultural crops support a central oculus to amplify daylight inside the dome. The crater provides a circular configuration, which generates an spherically efficient geometry, provides gracious appearance and implies a circular transportation/robotic perspective, the crater allows occupants an outlook towards a central agricultural zone which receives sunlight and towards which other highly visible human activity is oriented."

The consideration of utilizing an existing crater is shown in Figure 5.

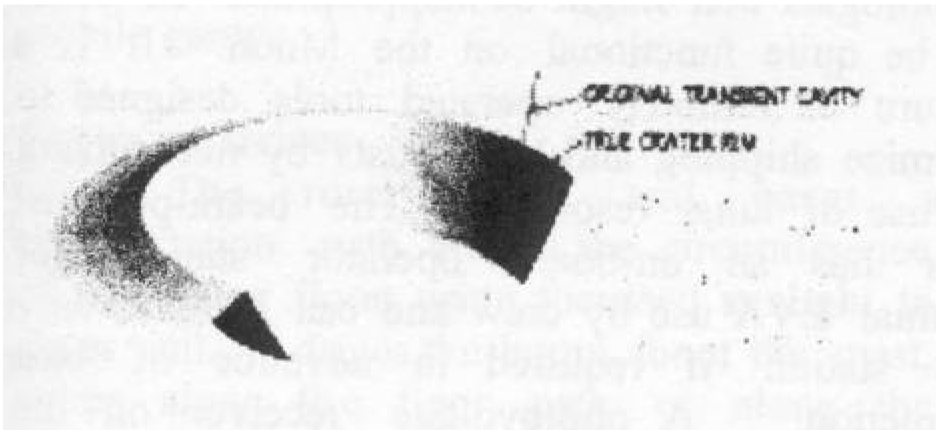


Figure 5. Conceptual Design of a Crater Lunar Base

To house the habitat in a large crater capable of being rimmed with cliff dwelling like structures is proposed to be a more efficient way to establish a permanent base. This minimizes the excavation necessary and the cliff dwellings provide additional shielding from radiation. A challenge to this type of structure is that the permeable nature of the lunar regolith must be accommodated to seal the pressurized environment. A dome placed over this crater could then be covered with regolith from 1 meter to 10 meters in depth depending on the future research into radiation and the allowed annual dose for an individual. Some consideration will need to be studied for how to introduce sun into the environment both for use in agriculture, which would occupy the base of the crater and provide the green spaces mentioned above. Devices that would admit sunlight and not radiation will be fundamental to the lunar base architecture.

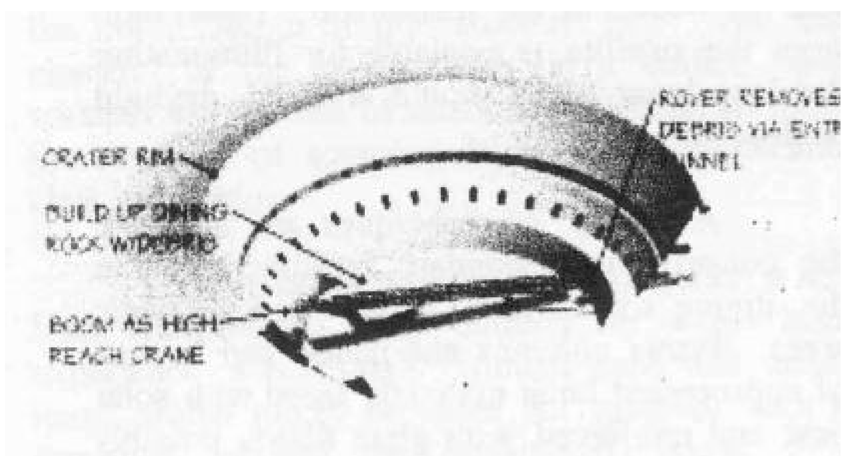


Figure 6. Initial construction of the "Cliff Dwelling-Like" Structures

Admission of sunlight in some form and visual access to green growing plants are deigned to be of significant human factor importance. "Mission duration affects habitability requirements, for example: planned for long duration missions, reduced gravity impacts spatial configurations in that ceilings must be higher and spaces larger because objects travel further, leisure and recreational facilities have increased importance, a sense of community must be sustained and reinforced over time." [Eichold, 2000]

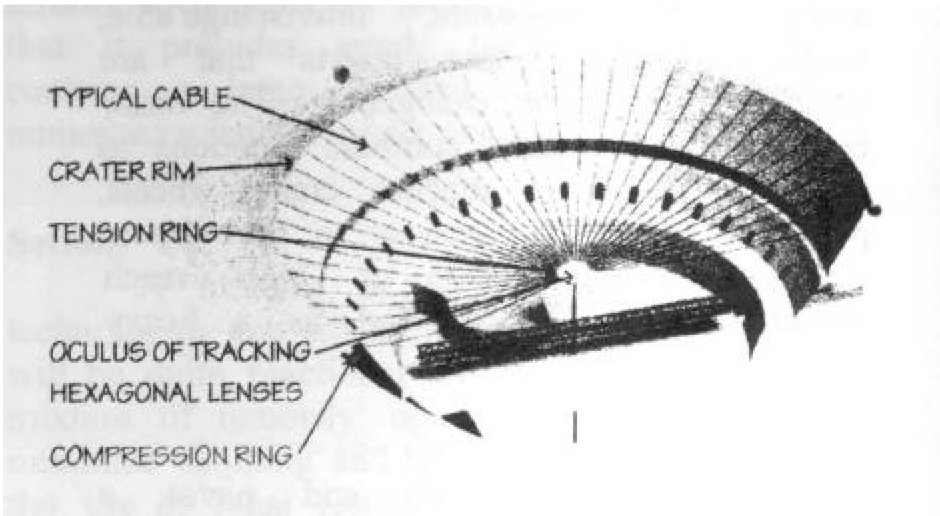


Figure 7. Final Stage with Dome Structure in Place

1.5 Other Previous Related Work

Although travels to the Moon have been discussed in the literature throughout the history of mankind, the first reasonably realistic plans for building a lunar base were probably conceived during the cold war. The US army made a study of a lunar base in 1959. President Kennedy accepted the challenge of the USSR in 1961 and started the race to the Moon, which was won by the USA in July 1969 with the first human landing on the Moon. The first human landing on the Moon was a giant enterprise, involving directly more than 400,000 people in 20,000 companies. Even though much of the technology then used is now more or less routine, the establishment of a lunar colony will require considerable technical development, and will naturally force cooperation of organizations that would not otherwise have any contact.

The International Astronautical Federation (IAF) has had annual meetings since 1950 and many papers on the subject of lunar development have been presented during these international congresses. The International Academy of Astronautics created a "Return-to-the-Moon" committee in 1985. This committee has compiled and published a study entitled "The Case for an International Lunar Base" [Koelle, 1988]. This activity is continued at present by an "IAA Subcommittee on Lunar Development" with the participation by the author and some 30 people from ten different countries.

An international lunar workshop with more than one hundred participants was held at Beatenberg in Switzerland (3 June, 1994). At this workshop, a "Declaration on Future Lunar Development" was prepared. Following the Beatenberg declaration, space agencies from all over the world met in Hamburg, at the "EGS Moon Workshop" (3-7 April 1995) and in full agreement decided to create an International Lunar Exploration Working Group (ILEWG). The charter of ILEWG is to: (1) develop an international strategy for the exploration of the Moon, (2) establish a forum and mechanism for the communication and coordination of activities, and (3) implement international coordination and cooperation.

To facilitate communication among all interested parties, ILEWG agrees to establish an electronic communication network for exchange of science, technology and programmatic information related to lunar activities. All interested space agencies will appoint two or three members. A chairperson is selected among the ILEWG members every two years. ILEWG will meet regularly, at least once a year, and will lead the organization of an International Conference every two years to discuss the state of lunar exploration. Formal reports will be given at COSPAR meetings.

There are many non-profit organizations dealing explicitly with lunar exploration, such as the Space Studies Institute (SSI), American Institute of Aeronautics and Astronautics (AIAA), National Space Institute (NSI), American Astronautical Society (AAS), Artemis Society International (ASI), and the Lunar Institute of Technology. There are also several commercial enterprises with activities explicitly aiming at exploiting lunar resources. Examples are Shimizu Construction Company, InterLune InterMars Corporation, Lockheed Martin, Permanent, Boeing, LunaCorp, ORBITEC, Pioneer Astronautics, Literati, Carbotek, and The Lunar Resources Company.

2.0 ADVANCED CONCEPT DESCRIPTION

The advanced concept of this Phase I effort has been the design of an architecture for a self-sustaining lunar colony (SSLC). The SSLC is being 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 SSLC involved a colony that could survive in complete isolation from the Earth. After holding a requirements workshop with various experts, 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 this Phase I study was redefined from a self-sufficient lunar colony to a self-sustaining colony. Refer to Section 1.1 for a discussion of the differences between self-sustaining and self-sufficient. The idea was raised that the SSLC could become a "self-sustaining Mars test bed located on the Moon." This idea was accepted by the workshop participants and the purpose of the SSLC became two-fold. The first purpose is to establish a permanent human presence on the Moon with a minimum need for supplies from Earth. The second purpose is to serve as test-bed for technologies that would be in common between the SSLC and an eventual Mars base.

The SSLC is intended to fully utilize lunar in-situ resources and minimize or eliminate the use of Earth-supplied materials and products. The SSLC would not only provide a permanent human presence on the surface of the Moon, but it will serve as a test bed of important technologies required for future excursions into our solar system and in particular, Mars. The Phase I effort concentrated on a steady-state condition, after the SSLC is fully established and functioning. Once this preliminary architecture is completely developed, the build-up phase and the expanding colony phase would be examined in Phase II.

The colony would be considered "self-sustaining" when it can achieve the goal of surviving without any 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 Holman 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 this study, we have assumed that the SSLC would have a steady-state population of 100. However, all of the results could be scaled to other colony sizes. The lunar colonists are considered to be permanent residents for a minimum period of 52 months (to meet the definition of self-sustaining). 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 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.

The SSLC would be located at the southern pole of the Moon. Robert Goddard stated "the best location on the Moon would be at the north or south pole with a liquefier in a crater (for propellant production)." There are several reasons to choose this location. First, data from the

Lunar Prospector has indicated significant amounts of frozen water ice, or at least bound hydrogen at both of the 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 fuel to support lunar surface activities, provide life support consumables, and allow transportation back to the Earth. Second, there are several areas at the south pole that receive near-constant sunlight. Two locations near the 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 SSLC and the associated solar power systems [Bussey et al., 1999]. 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. Surface temperatures at the south pole remain close to –53 +/- 10 C [Heiken et al., 1991]. Other places on the Moon, outside of the poles, can see temperature swings over 400 C during lunar day to night cycle. The small changes in temperature will simplify the thermal control system requirements of the SSLC and reduce cyclical thermal stresses.

Electrical and thermal energy for the colony is proposed to be initially supplied by a combination of nuclear power plants (two ≥ 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.

Even though the colony is designed to be self-sustaining, it would still require an on-going transportation system to and from the Earth. There are some high-priority items that may be needed from Earth because they are difficult or impossible to produce on the Moon. Space transportation would be provided in the form of a lunar transfer vehicle, which could be operated between the surface and an orbiting station located in orbit at a libration point or as a cis-lunar cycler that is staged from the ISS. The roll of the ISS in the future exploration of the Moon and Mars needs to be examined.

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). However, the mixture of oxygen and nitrogen would be changed to maintain the partial pressure of oxygen that exists at sea level on Earth. This would provide a compromise between the ISS 14.7 psi and the requirements for nearly immediate EVA capability and exposure to the lunar surface environment for emergencies. Note that this should be verified through experiments to determine any effects on human inhabitants, plant growth, and animal health. 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 ISRU 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 sized to support 100 people and will 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. 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.

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, ISRU 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 are cargo within the SSLC and the surrounding areas. This may be a fully robotic operation. A launch and landing complex 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 that the mean time to failure of much greater than 52 months.

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 8 shows one potential layout of the SSLC. The primary elements are labeled on the map. Note that the map is not drawn to scale.

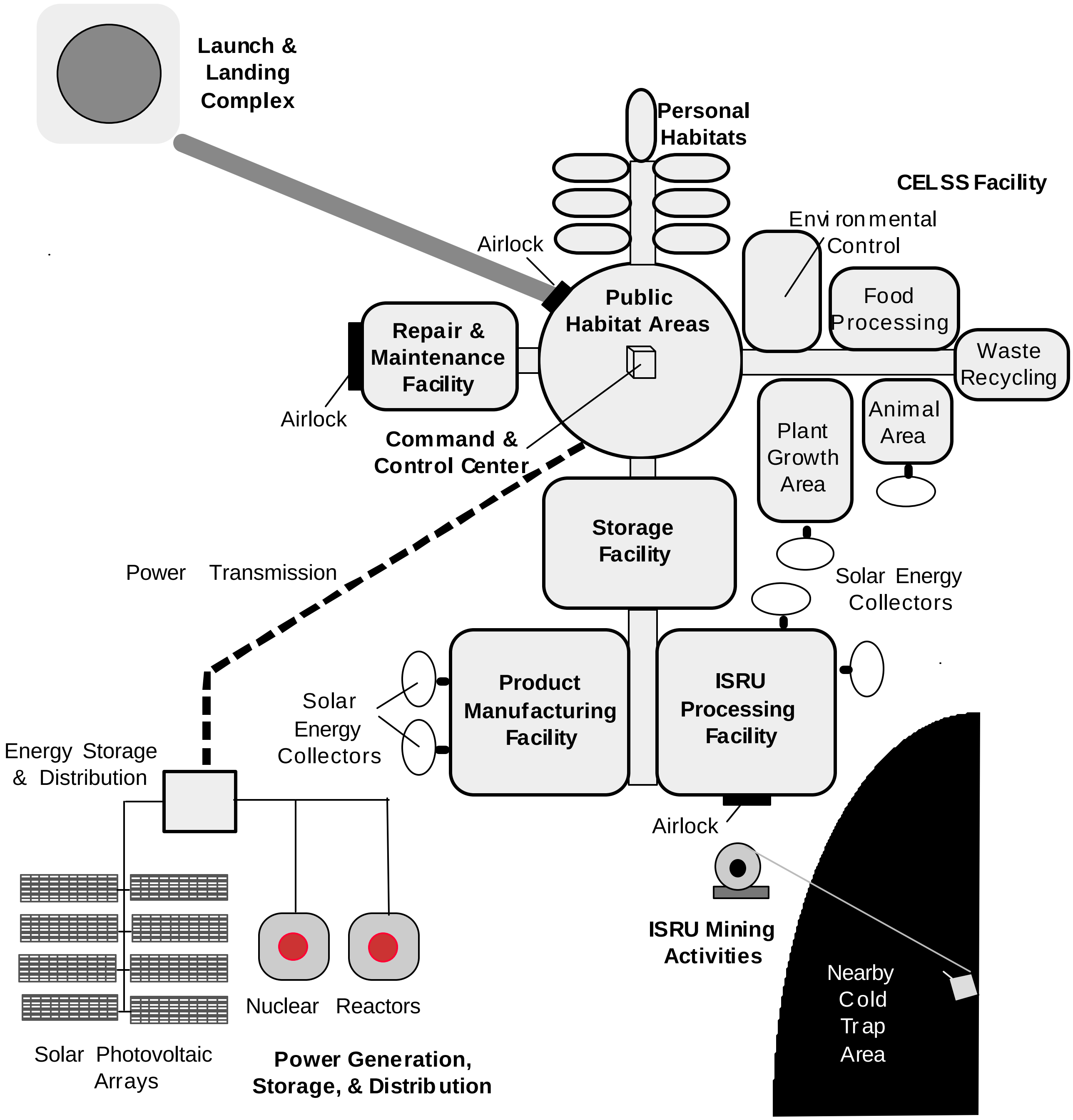


Figure 8. A Potential SSLC Layout

3.0 STUDY RESULTS AND FINDINGS

The following sections summarize the results and findings of the Phase I study. The sections are organized by the Phase I work tasks. The work tasks are listed below:

- Develop Basic Requirements for the Self-Sustaining Lunar Colony
- Define Minimum Earth-Supply Requirements
- Develop Examples of Lunar ISRU Production Activities and Products
- Define the Preliminary System Architecture
- Create Multidisciplinary Consortium of Contributors for the Lunar Colony.

3.1 Develop Basic Requirements for Self-Sustaining Lunar Colony

A requirements workshop was held on June 22-23, 2000 at the ORBITEC headquarters in Madison, Wisconsin. A broad range of experts were invited to help define the basic requirements of the self-sufficient lunar colony. A summary of the workshop results, including the agenda for this meeting and the list of participants, is found in Appendix B. A significant effort was put into a definition of self-sufficiency. The definition agreed upon is the same as that given in the Phase I proposal, namely "survival of an isolated group of humans on the lunar surface over an indefinite period of time that fully utilize lunar in-situ resources and minimize the use of Earth-supplied materials/products." However, there was a consensus that total isolation from the Earth (including communication) is both unlikely and unwise. As a result, the goal of this Phase I study was redefined from a self-sufficient lunar colony to a self-sustaining lunar colony (SSLC). Please refer to Section 1.1 for a discussion of the differences between self-sustaining and self-sufficient. The idea was raised that the SSLC could become a "self-sustaining Mars test bed located on the Moon." This idea was accepted by the workshop participants and the purpose of the SSLC became two-fold. The first purpose is to establish a permanent human presence on the Moon with a minimum need for supplies from Earth. The second purpose is to serve as test-bed for technologies that would be in common between the SSLC and an eventual Mars base. The following basic requirements were developed based on the results of the workshop.

The colony would be considered "self-sustaining" when it can achieve the goal of surviving without any 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 Holman 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 this study, we have assumed that the SSLC would have a steady-state population of 100. However, all of the results could be scaled to other colony sizes. The lunar colonists are considered to be permanent residents for a minimum period of 52 months (to meet the definition of self-sustaining). 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 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.

The SSLC would be located at the southern pole of the Moon. There are several reasons to choose this location. First, data from the Lunar Prospector has indicated significant amounts of frozen water ice, or at least bound hydrogen at both of the 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 fuel to support lunar surface activities, provide life support consumables, and allow transportation back to the Earth. Second, there are several areas at the south pole that receive near-constant sunlight. Two locations near the 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 SSLC and the associated solar power systems [Bussey et al., 1999]. 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 SSLC and reduce cyclical thermal stresses.

Electrical and thermal energy for the colony is proposed to be initially supplied by a combination of nuclear power plants (two ≥ 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.

Even though the colony is designed to be self-sustaining, it would still require an on-going transportation system to and from the Earth. There are some high-priority items that may be needed from Earth because they are difficult or impossible to produce on the Moon. Space transportation would be provided in the form of a lunar transfer vehicle, which could be operated between the surface and an orbiting station located in orbit at a libration point or as a cis-lunar cycler that is staged from the ISS. The roll of the ISS in the future exploration of the Moon and Mars needs to be examined.

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 ISRU 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 sized to support 100 people and will 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. 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.

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, ISRU 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 are cargo within the SSLC and the surrounding areas. This may be a fully robotic operation. A launch and landing complex 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 that the mean time to failure of much greater than 52 months.

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.

It is required that the following technologies, at a minimum, be in place at the time of the establishment of the SSLC:

- Totally closed ecological life support system (CELSS)
- In-situ resources utilization (ISRU) to meet the major needs of the SSLC (oxygen, nitrogen, water, hydrogen, iron, silicon, concrete, etc.)
- Surface nuclear and solar power systems
- Earth/Moon transportation infrastructure with transportation nodes
- In-space operations
- Communication and navigation satellites in lunar orbit
- Solar flare warning system
- Lunar dust control system
- Radiation protection
- Aerobraking to minimize the propellants needed for transportation to Earth.

3.2 Define Minimum Earth-Supply Requirements

The first step under this work task was to quantify the needs of the SSLC. During the Phase I effort, the basic life support needs were investigated in detail. After this was complete, other needs for the SSLC were identified. These needs were compared with the potential ISRU products defined (see Section 3.3). The needs that are not expected to be met by the ISRU products became the minimum Earth-supply requirements. The following sections outline the basic needs of the SSLC for life support (make-up for lost gases) and a discussion or other needs of the SSLC and the resulting minimum Earth-supply requirements.

3.2.1 Basic Life Support Needs of the SSLC

A model of the basic life support needs of the SSLC was developed in a Microsoft Excel file (see Figure 9). This model is designed to calculate the daily losses of water, oxygen, nitrogen, and carbon due to diffusion losses from the pressurized modules and operation of the airlocks. The major components of the model are briefly described below.

Human Requirements Per Day **–** This table in Figure 9 lists the needs for an average inhabitant of the SSLC. The requirements are based on the ISS design loads for consumables. This includes the total amount of water, oxygen, and food solids required per person per day.

Production via Higher Plants **–** This table in Figure 9 lists the plant areas required to support each lunar colonist. A total plant area of 20 m^2 is needed per person to meet the water (through transpiration), oxygen (through photosynthesis), and food requirements.

Atmosphere Composition **–** This table in Figure 9 lists the partial pressures of oxygen, nitrogen, water, and carbon dioxide with the pressurized volumes of the SSLC. The total atmospheric pressure is assumed to be 10 psi, which is equivalent to the pressure at ~10,000 feet above sea level on Earth. However, the partial pressure of oxygen within the SSLC would be maintained at the same level as at sea level on Earth. This reduced total pressure reduces the loss of gases from the pressurized volumes of the colony while the higher partial pressure of oxygen prevents the effects of fatigue associated with high altitudes on Earth. It is not known what long-term effects, if any, that this atmosphere would have on the lunar colonists, but it is considered a viable choice for the SSLC.

Habitat Volume **–** This table in Figure 9 lists a range of values for the pressurized volumes required per person, based upon a review of the literature on the subject. A total of 1,215 m^3 was assumed for this model. This value is broken down into the various components in Table 3. The analysis performed in the NASA Space Settlements: A Design Study [Johnson, 1977] was modified and applied to the SSLC.

Inputs – This table in Figure 9 lists the input parameters to the model. The number of inhabitants has been set to a baseline value of 100. The initial water supply represents how much water is present in the water recycling loop at any given time. It does not include the emergency reserves of water that would be required. The appropriate amount of reserves for the SSLC will be determined in Phase II. The diffusion losses represent the atmospheric gases that leak through

Human Requirements Per Day [1]
(kg/person-day)

Water Requirements	
Drinking Water	1.6
Food Preparation	0.75
Clothes Wash	12.5
Hand Wash	4.1
Shower Water	2.7
Food Water	1.15
Urinel Flush	0.5
Dish Wash	5.45
Total Water	**28.75**
Oxygen	**0.85**
Food Solids	**0.62**

Production via Higher Plants [1]

Consumable	**Plant Area Required per Person (m^2)**	
	Min.	**Max.**
Water	3	5
Oxygen	6	10
Food	15	20

Atmosphere Composition [2]			
Oxygen	22.7	kPa	(3.3 psi)
Nitrogen	44.8	kPa	(6.5 psi)
Water	1	kPa	(0.15 psi)
CO_2	0.4	kPa	(0.06 psi)

Habitat Volume (m^3 per person)		
***Min.* [3]**	***Max.* [2]**	***Assume***
1000	1738	1215

INPUTS

Number of Inhabitants	100	
Initial Water Supply	8	days
Diffusion Losses*	0.5	% per day
Airlock Losses**	0.05	% per day
Recycling Efficiency***	97	%

OUTPUTS

Ongoing Requirements for SSLC		
Water	91	kg/day
Oxygen	204	kg/day
Nitrogen[+]	342	kg/day
Carbon	3	kg/day

[+] = This amount of nitrogen requires 4,382 metric tons of regolith to be processed each day or 43 metric tons of ice-rich regolith.

* = 0.57% per day rate used by Duke[4] for inflatable at 50.7 kPa,
0.21% used by Eckart (Lunar Base Handbook) for rigid modules at 101.4 kPa,
0.33% used by ORBITEC (Inflatable Module for Lunar/Mars Surface Facility) at 69 kPa

** = 0.11% per day rate used by Duke[3]

*** = Highest rate found in literature is 97% efficient[4]

Habitat Characteristics		
Water	1121.7	kg
Oxygen	35984.9	kg
Nitrogen	62141.3	kg
Total Volume	121500.0	m^3
Plant Area	2000.0	m^2

[1]= Eckart (1994)

[2]= Space Settlements: A Design Study (1975)

[3]= Duke (1989)

[4]= MacElroy and Klein (1985)

Figure 9. Model of the Basic Life Needs for the SSLC

the pressurized volumes and seals (in terms of the % of the total SSLC volume). The airlock losses represent the amount of atmospheric gases that are lost during each operation (in terms of the % of the total SSLC volume). The ISS airlock design has a high gas loss rate; nearly 10% of the airlock volume of gas is lost during each operation [Sridhar et al., 2000]. The SSLC will require airlocks with much lower losses. The recycling efficiency represents how much of the resources can be completely reused in the SSLC. The highest estimate of recycling efficiency found in the literature was 97% [MacElroy et al., 1985]. Any unrecycled elements would accumulate in the SSLC over long periods of operations. It is important for the SSLC to attain close to 100% efficiency, at least for the primary life support components (oxygen, water, food, etc.).

Outputs **–** This table in Figure 9 lists the calculated losses of various resources per day. These resources represent gases lost through leakage and airlock operations. It also includes losses in the recycling systems. These are the primary products of the model. The total amount of regolith needed to produce the amount of nitrogen required per day is also calculated. See Section 3.3.3 for further discussion.

Habitat Characteristics **–** This table in Figure 9 lists some of the calculated characteristics of the SSLC. The amount of water includes water present in the recycling loop, but it does not include the emergency reserves of water that would be required for the SSLC. The appropriate amount of reserves for the SSLC will be determined in Phase II. The amount oxygen and nitrogen are calculated from the respective partial pressures and the total pressurized volume of the SSLC. The total volume of the SSLC is the product of the volume requirements per person (1215 m^3) and the number of inhabitants. The total plant area is the product of the plant area required per person (20 m^3) and the number of inhabitants.

The life support model indicates that replenishing nitrogen will be a major need for the SSLC. Unfortunately, nitrogen exists in relatively low concentrations on the Moon. Oxygen is the next largest need, but oxygen is relatively abundant on the Moon. The presence of water or hydrogen in the cold traps near the SSLC will allow the water need to be met with local resources. See Section 3.3.1 for a further discussion of the local lunar resources available. An important technical issue is minimizing the loss of gases from the SSLC. This will include the use of materials with loss gas permeability, developing seals with very low leakage rates, and developing airlocks that minimize the amount of gas lost during each operation.

3.2.2 Minimum Earth-Supply Requirements

The previous section identified the major losses of life support consumables that would occur in the SSLC. It is conceivable that the SSLC would be able to produce all of these resources through ISRU activities. One possible exception may be nitrogen. If there is not a significant source of nitrogen (i.e. from ammonia present in the polar cold traps), the SSLC may require nitrogen to be supplied from Earth, perhaps in solid form. The SSLC would be designed with the ability to maintain tools, machines, and habitats for extended periods of time. For example, this would include production of wear parts in mining equipment. However, items that are very difficult or impossible to produce locally would be provided by Earth. The key to making the SSLC self-sustaining is to ensure that the colony has the ability to repair and maintain tools, machines, and structures, even it they do not have the full capability to produce them with local resources. It may be possible that a rapid prototyping machine could be used to produce a wide variety of items using electronic instructions sent from Earth. The amount of Earth supplies required can be minimized through intelligent use of ISRU resources and by designing the SSLC components with a long life. For example, the pressurized modules could be designed for an indefinite life (with proper maintenance). Furniture and fixtures in the SSLC could be designed for a 30+ year life. Clothing could be designed to last for an entire crew rotation (6 years), thus requiring only periodic repair and cleaning. Table 1 is a list of potential Earth-supply items that may be needed by the SSLC after it is established and functioning. An economic analysis is needed to compare the costs of making various products on the Moon with local resources with importing them from Earth. The ultimate purpose of ISRU is to lower the cost and risk of human exploration and colonization. Therefore, any items that could be imported from Earth at a lower cost than produced from local lunar resources would become part of the Earth-supply requirements.

Table 1. Potential Earth-Supply Needs for SSLC

Medical Supplies
• Vitamin and Mineral Supplements
• Drugs and Medication
• Antibiotics
• Birth Control Devices
• Complex Medical Tool and Machines
Agricultural Supplies
• Trace Minerals for Plant and Animal Growth
• Eggs, Embryos, Young Animals & Insects, Seeds
• Microorganisms for Food Production (i.e. yeast, bacteria)
• Carbon
• Nitrogen
Complex Tools and Machines
• Electronics
• Construction and Mining Equipment
• Motors and Engines
• Rovers
• Spare Parts
Miscellaneous Supplies
• Certain Personal Hygiene Products
• Space Suits
• New Clothing

3.3 Develop Examples of Lunar ISRU Production Activities and Products

The main focus of this work task was to assess the local lunar resources that may be available at the SSLC and determine viable ISRU products. The following sections outline the potential lunar resources available near the south pole of the Moon followed by a conceptual design for an ISRU production plant. The work done in Phase I under this work task concentrated on products needed to support the life support needs for the SSLC. Some additional products that can be recovered, such as silicon and iron, are also identified.

3.3.1 Lunar Resources Available

Before specific ISRU processing concepts can be developed for the SSLC, the lunar resources available must be defined. Detailed chemical analysis of the Apollo lunar samples at several sites have been well documented. This includes the chemical composition and mineralogy. Figure 10 shows the average composition of the lunar rock and regolith samples from Apollo. The evolution of volatile gases from the lunar regolith during heating has also been carefully measured. Figure 11 shows the original gas release pattern for an Apollo-11 sample. Figure 12 illustrates the range of temperatures at which various lunar volatiles are released.

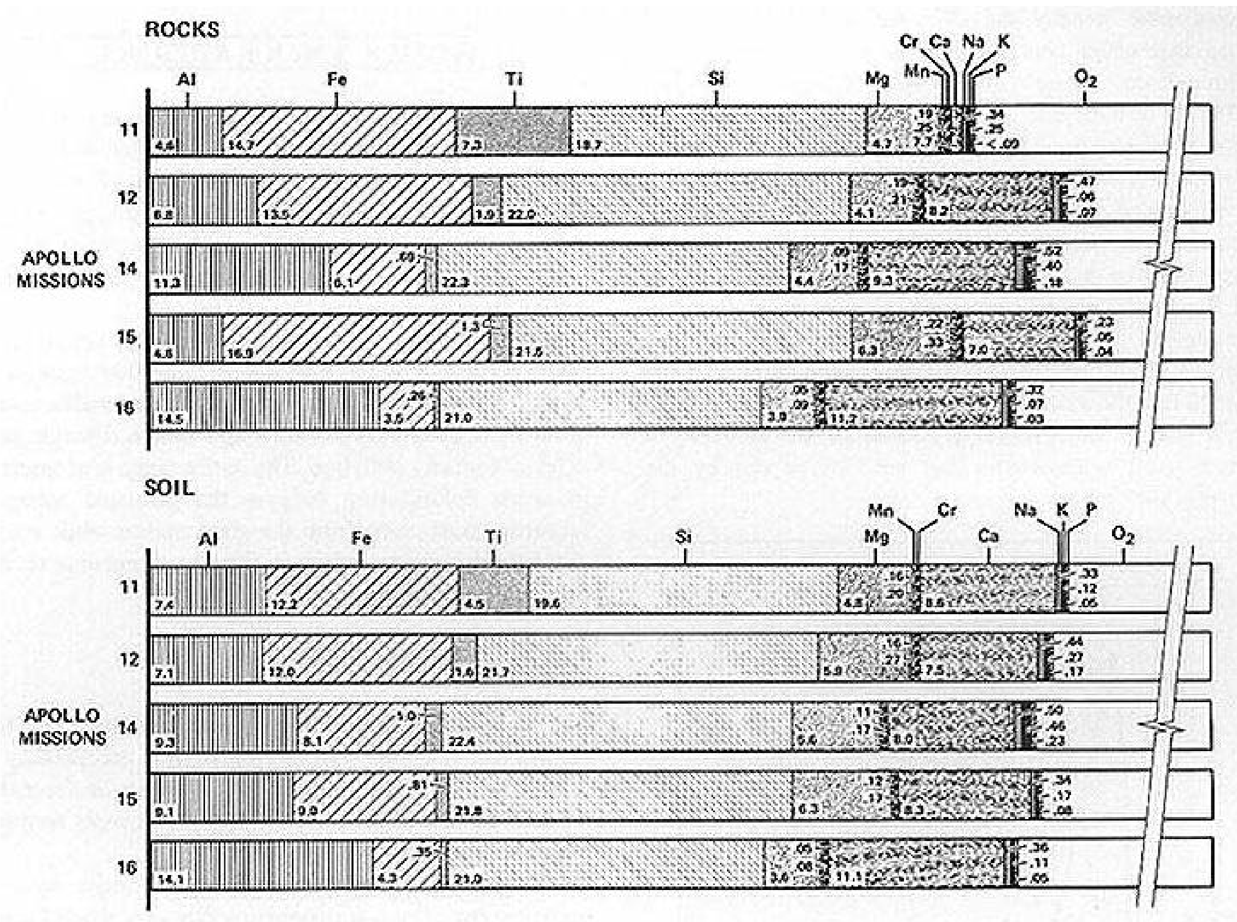


Figure 10. Average Composition of Apollo Samples (excluding oxygen and elements <1,000 ppm) [Johnson, 1977]

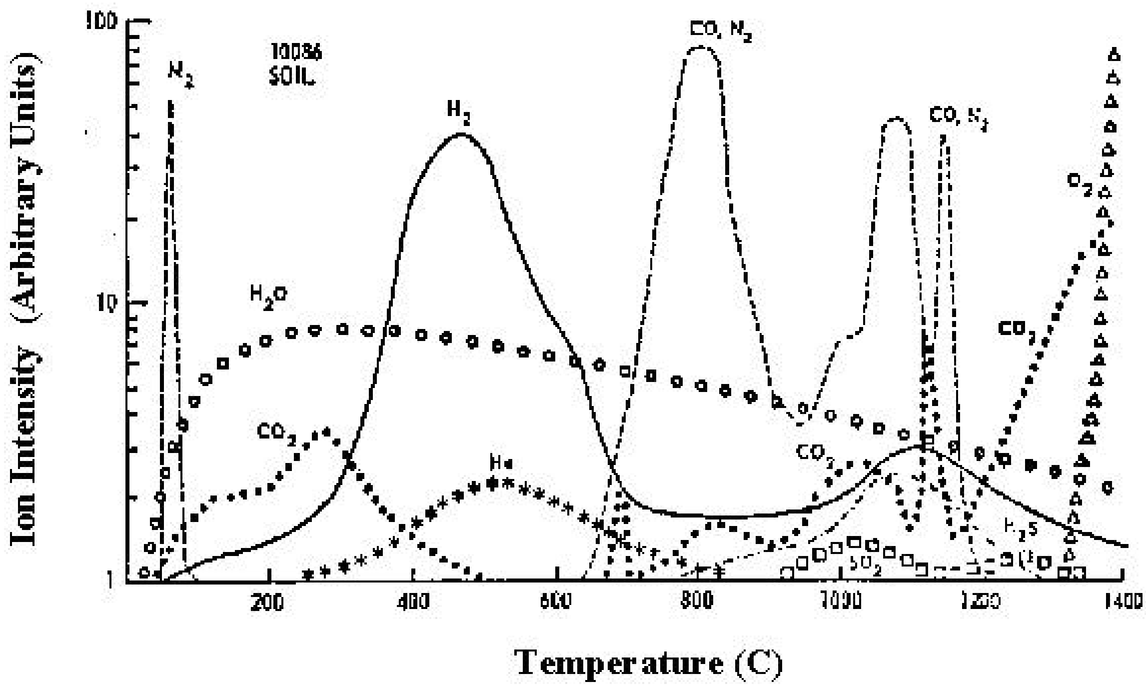


Figure 11. Original Gas Release Pattern for Apollo-11 Sample 10086

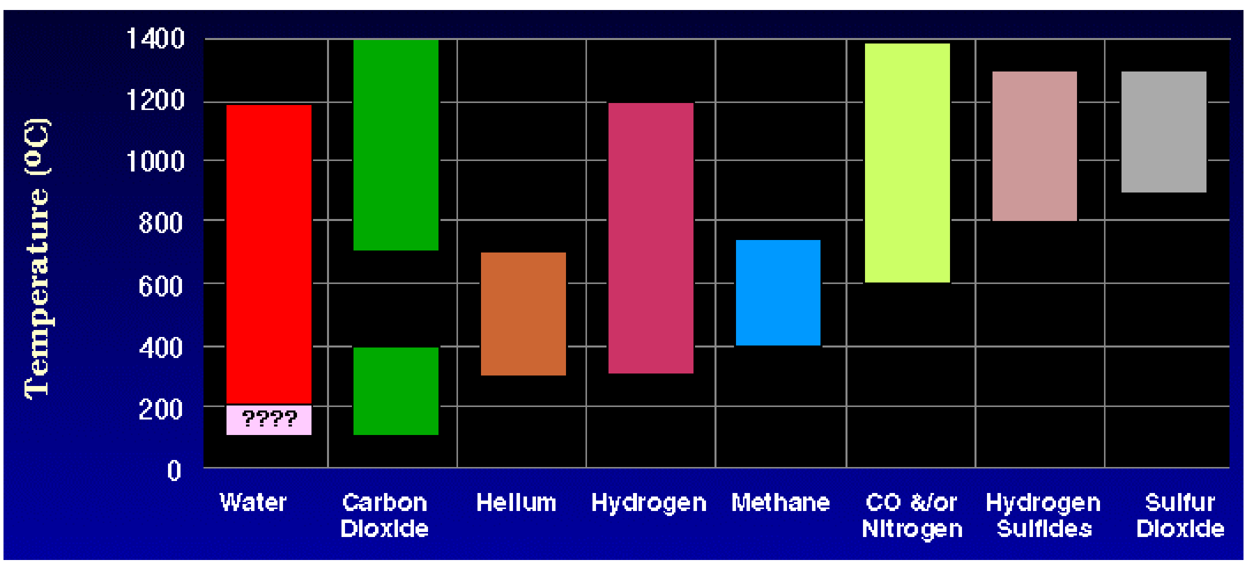


Figure 12. Range of Temperatures for Release of Lunar Volatiles

Lunar Prospector has measured elevated levels of hydrogen in certain areas near the lunar poles. The form of this hydrogen is unknown. Many researchers have inferred that the hydrogen is in the form of water. If the hydrogen is in the form of water, it is likely from comets that have impacted the Moon over the eons. The most common of the frozen gases in comets is water, but other ices include CO, NH_3, and H_2CO. If water ice is present in the cold trap areas, it is reasonable to assume that these other ices are also present (in smaller quantities). Figure 13 shows maps of the hydrogen measured by Lunar Prospector at the lunar poles. New higher resolution maps are currently being developed by Dr. Alan Binder and his team.

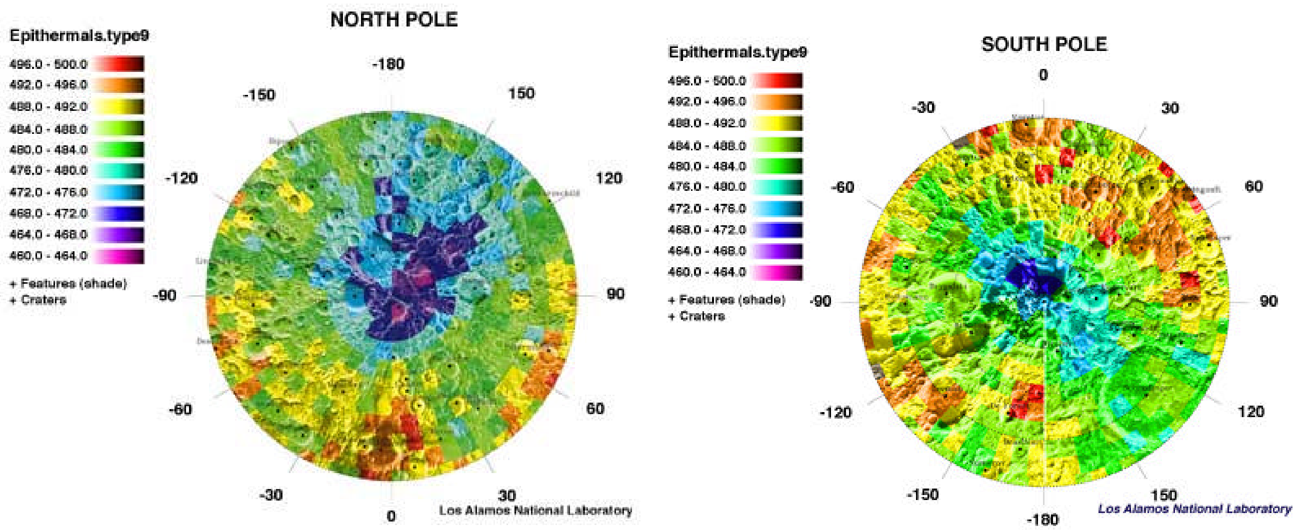


Figure 13. Comparison of the Neutron Data Map of the Moon's North and South Poles (Figure courtesy of DOE Los Alamos National Laboratory)

Two scenarios are presented below. The first scenario assumes that water and other ices are present in the cold trap areas of the south pole near the SSLC. The second scenario assumes that only hydrogen is present in the cold trap areas. In both scenarios, volatile gases are assumed to be present in the lunar regolith in quantities similar to those measured in the Apollo samples.

ISRU Resource Scenario #1

One major resource under this scenario is the ice-rich lunar regolith found in the cold trap areas near the south pole. The latest analysis of data from the Lunar Prospector indicates approximately 300 million metric tons of water ice (or the equivalent amount of hydrogen) is present at an average concentration of ~1% by mass (or ~1,500 ppm of hydrogen). However, this average concentration level assumes that the water (or hydrogen) is evenly distributed over the footprint of the Lunar Prospector neutron spectrometer. If we assume that the water ice is concentrated in the permanently shadowed cold traps near the poles, the concentration of water ice may be as high as 10% [Binder, 2000]. Comets are considered the primary source of lunar water in the lunar cold traps [Duke et al., 1998]. The frozen gases in comets are typically 75-80% water, with the remaining amount consisting of carbon monoxide, ammonia, and formaldehyde. For this study, we assume that average comet composition is 79% H_2O, 7% CO, 7% NH_3, and 7% H_2CO. The same ice composition is expected in the lunar cold traps. Table 2 lists the assumed composition of the ice-rich regolith found near the south pole. These gases can be released by heating the ice-rich regolith in a closed container.

Table 2. Assumed Composition of the Ice-Rich Lunar Polar Regolith

Volatile Gas	*Concentration (ppm)*
Water (H_2O)	100,000
Ammonia (NH_3)	8,700
Methane (CH_4)	8,700
Formaldehyde (H_2CO)	8,700

In addition to the potential frozen gases/ices in the polar regolith, other volatile gases, such as H_2O, H_2S, CO, CO_2, NH_3, HCN, and noble gases, can be recovered through additional heating. Some of these gases could also be oxidized to produce CO_2, N_2, SO_2, and additional H_2O. Table 3 lists the average volatile elements measured from heating Apollo 11 samples.

Table 3. Volatile Elements in Lunar Regolith

Element	***Concentration (ppm)***	***Nominal Value* (ppm)***
Hydrogen (H)	0.1-211	60
Carbon (C)	10-280	154
Nitrogen (N)	13-153	78
Helium	1-63	46
Sulfur	20-3300	1240

**=Nominal Value represents average level from Apollo 11 samples*

It was widely believed that the hydrogen, helium, carbon, and nitrogen were derived mainly or entirely from the solar wind. The concentration of solar wind gases in regolith are a function of maturity, which in turn is a function of length of exposure to the solar wind. The polar areas of the Moon receive less than 10% of the exposure to the solar wind as the equatorial regions on the far side of the Moon. This should reduce the levels of volatiles available in the regolith around the SSLC (which is located at the south pole). However, there is some new research that indicates that up to 90% of the nitrogen in the regolith is not from the solar wind. Nitrogen has a surface correlated component from the solar wind and a volume correlated component (possibly from some other source). The other source(s) of the nitrogen is not known, but it may be reasonable to assume that the level of nitrogen is relatively constant across the lunar surface [Wieler, 1999]. If the lunar regolith is further heated to ~1630 C in the presence of carbon or methane, the carbothermal reduction process can produce oxygen, silicon, and iron.

ISRU Resource Scenario #2

This scenario assumes that only hydrogen exists at elevated levels within the polar cold traps (no other volatile ices present). The hydrogen exists at levels of ~1,670 ppm, according to the Lunar Prospector data. If this hydrogen is concentrated in the cold trap areas, the hydrogen levels may be as high as 16,700 ppm. Most of this hydrogen could be recovered by heating the regolith to some required temperature. The required temperature depends on what form the hydrogen exists within the cold trap (physically vs. chemically bonded). The solar wind volatiles and oxygen recovery processes (as discussed earlier) also apply to this scenario.

3.3.2 Conceptual Design for ISRU Production Plant

Figure 14 and 15 show schematic diagrams of the ISRU production plants under Scenario #1 and #2. In both cases, regolith from the permanently shadowed cold traps is mined and placed in the regolith reduction reactor. The regolith is heated via concentrated solar energy. Any frozen gases or ices present in the regolith (Scenario #1) will be released through low heating (<100 C). These gases could be separated and further processed. For example, the ammonia can be separated into nitrogen and hydrogen through catalytic dissociation.

As the regolith is further heated, additional volatile gases would be recovered from the lunar regolith. Heating the regolith up to 1,200 C would produce H_2O, H_2S, CO, CO_2, NH_3, HCN, and noble gases (in both scenarios). These gases would be collected from the regolith reduction reactor and passed through a combustion chamber to produce H_2O, CO_2, N_2, SO_2, and noble gases [Haskin, 1988]. These product gases would then be separated and stored.

If the lunar regolith is further heated to ~1630 C, carbothermal reduction of the lunar silicates would produce oxygen. The carbothermal process consists of three steps: (1) the reduction of lunar silicate with methane gas to form carbon monoxide and hydrogen; (2) the reduction of carbon monoxide with hydrogen to form methane and water; and (3) the electrolysis of water to form hydrogen and oxygen. Methane gas is introduced into the regolith reduction reactor. Methane gas that makes contact with the molten regolith will instantly pyrolyze, depositing carbon and liberating hydrogen gas. The deposited carbon will carry out the desired reduction reactions, generating carbon monoxide product gas. The hydrogen gas should also contribute to the reduction process (e.g., FeO), producing gaseous water. Reduction of silica and iron oxide will occur, and, as previously mentioned, additional constituents of the lunar regolith may be reduced depending on the operating temperature produced by the solar energy collector.

Carbon monoxide product gas and hydrogen from methane pyrolysis will exit the reduction reactor along with any unreacted methane. These hot gases will enter a heat exchanger so that some of their thermal energy can be transferred to the incoming methane gas stream. After exiting the heat exchanger, the gases will need to be separated (gaseous or sweep diffusion, gas permeation, etc.) so that the methane can be recycled to the feed stream and so the carbon monoxide and hydrogen can be admitted to the CO reduction reactor in the optimal 4:1 ratio. This process reduces the iron and silicon oxides in the regolith which produces iron and silicon in addition to the oxygen. According to previous ORBITEC experiments, at least 9% of the regolith mass can be recovered as oxygen with virtually no loss of carbon (at 1630 C processing temperature) [Rice et al., 1996]. Higher processing temperatures may allow up to 28% of the regolith mass to be recovered. A recovery rate of 20% is assumed in this study.

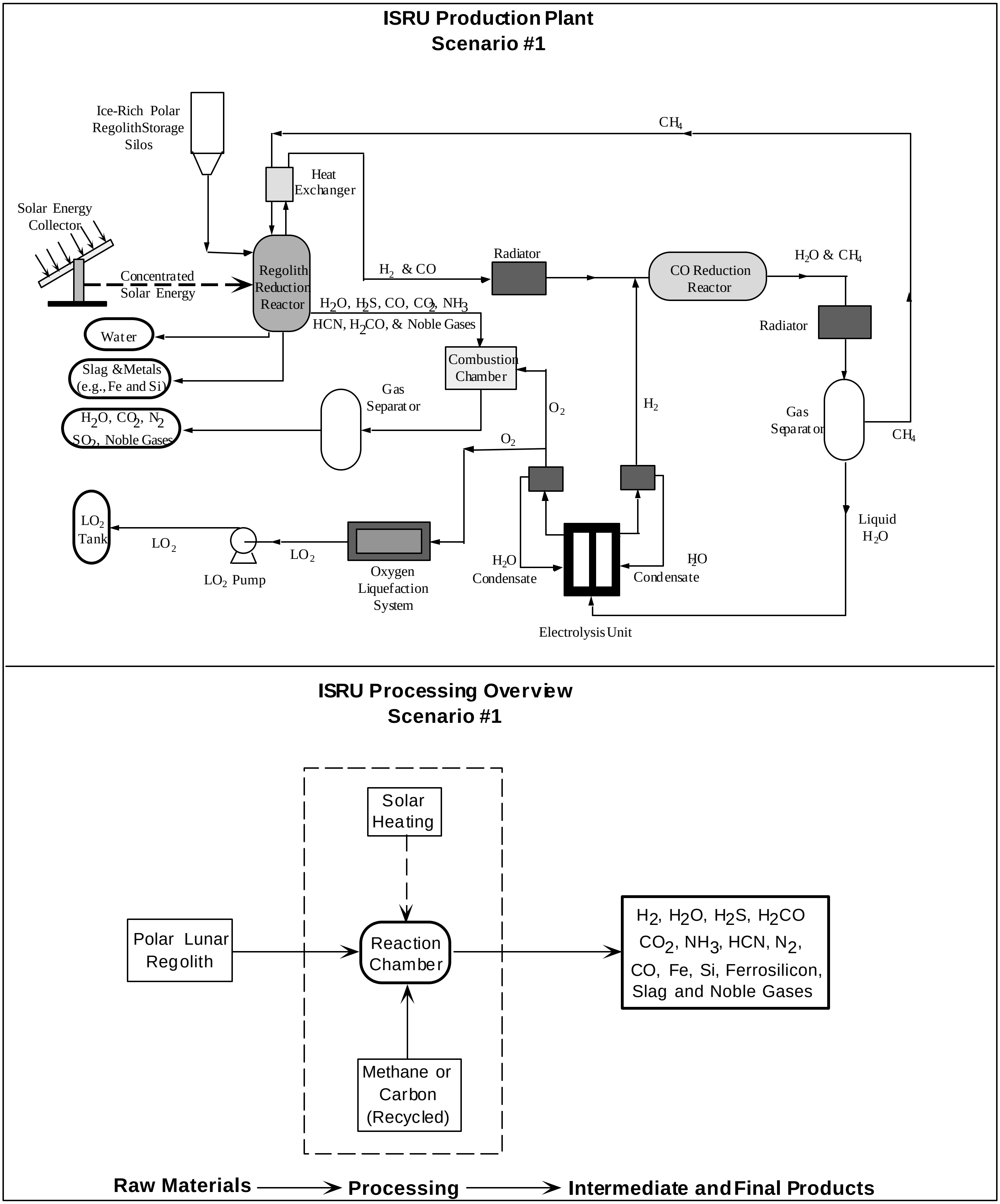
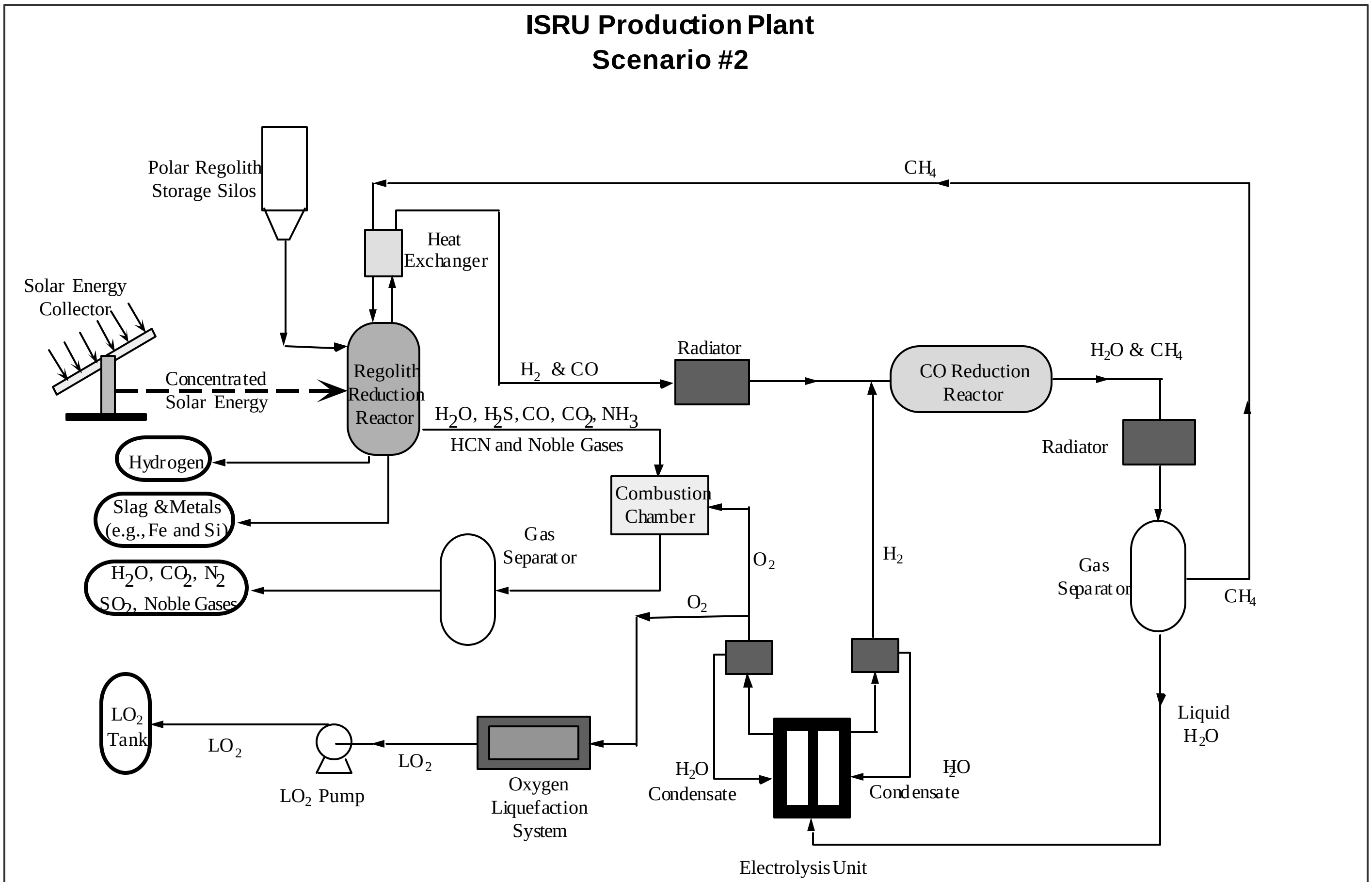


Figure 14. ISRU Production Plant Design for Scenario #1



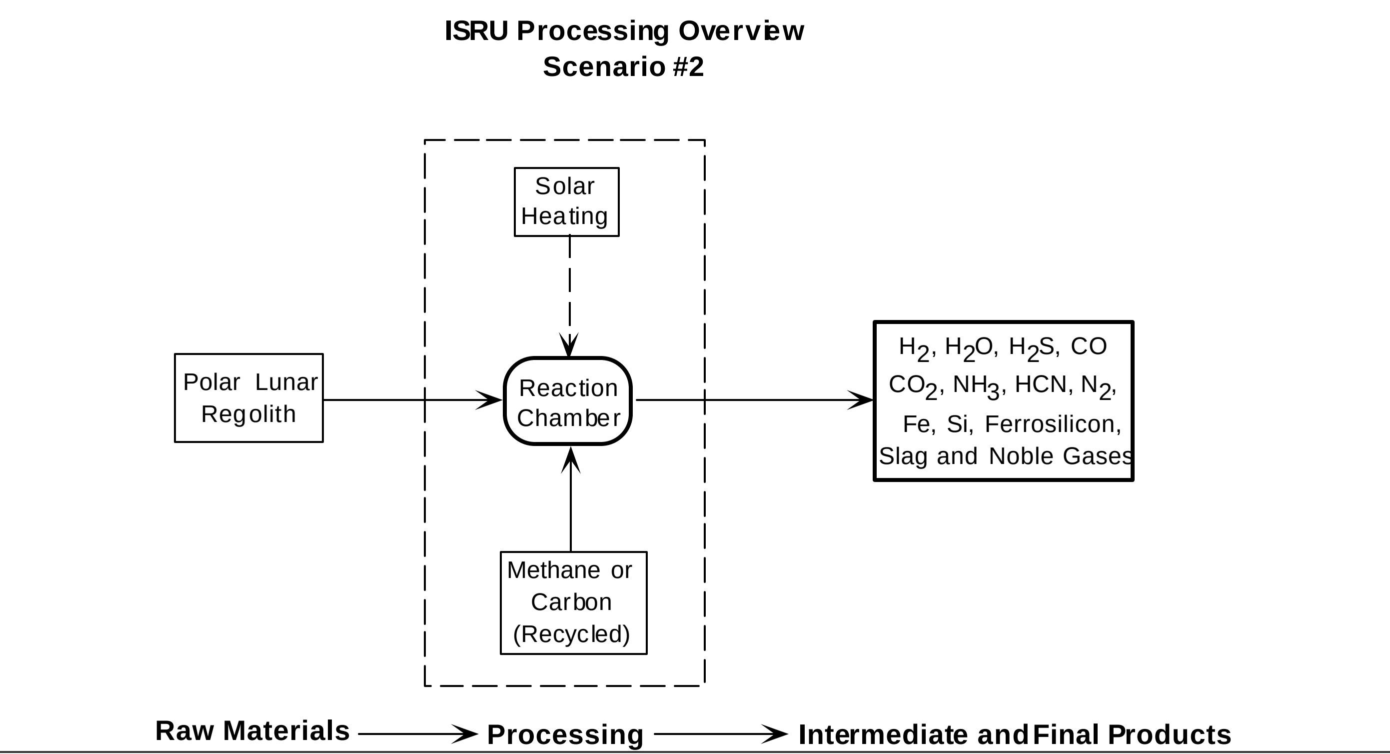


Figure 15. ISRU Production Plant Design for Scenario #2

3.3.3 Estimates of Lunar Regolith Requirements for ISRU Production

Figure 16 shows the amount of regolith that must be processed in each scenario to produce the make-up gases in the life support system for the SSLC. These calculations are based on the model developed under Task 2 (see Section 3.2.1) and the ISRU production plant design. The most striking difference between the processing scenarios is the amount of regolith needed to produce the make-up nitrogen gas. Under Scenario #1, approximately 44 metric tons of ice-rich regolith per day would need to undergo low temperature processing (<100 C) to recover the required amount of nitrogen. Under Scenario #2, approximately 4,382 metric tons of regolith per day would need to undergo medium temperature processing (~1,200 C) to recover the same amount of nitrogen. The presence of ice in the polar cold traps will have a large impact on determining the feasibility of such ISRU operations versus a direct nitrogen supply from Earth. In either scenario, processing enough regolith to produce the required amount of nitrogen will also produce excess amounts of oxygen, water, and carbon.

Scenario #1

Resource	Amount of Ice-Regolith Required
Water	0.9 metric tons/day
Oxygen	15.3 metric tons/day
Nitrogen	43.5 metric tons/day
Carbon	3.2 metric tons/day

Resource	Amount of Dry Regolith Required
Water	168.8 metric tons/day
Oxygen	1.0 metric tons/day
Nitrogen	4381.8 metric tons/day
Carbon	20.6 metric tons/day

Scenario #2

Resource	Amount of Hydrogen-Rich Regolith Required
Water	4557.7 metric tons/day*
Oxygen	*not applicable*
Nitrogen	4381.8 metric tons/day
Carbon	20.6 metric tons/day

Resource	Amount of Dry Regolith Required
Water	0.4 metric tons/day
Oxygen	1.0 metric tons/day
Nitrogen	4381.8 metric tons/day
Carbon	20.6 metric tons/day

Low Temperature (<100 C) Processing

The need for nitrogen requires the largest amount of regolith to be processed. Approximately 43.5 metric tons [mt] (or ~25 m^3) of ice-rich regolith must be processed each day to produce ~0.34 mt of nitrogen. This will also produce ~4.35 mt of water (or ~3.87 mt of oxygen and ~0.48 mt of hydrogen) and ~0.38 mt of carbon.

High Temperature (>2000 C) Processing

Some of the processed regolith can be further processed via carbothermal reduction to produce iron, silicon, and additional oxygen. If all of the regolith used in the low temperature processing were used, ~4.56 mt of iron, ~7.98 mt of silicon and ~7.60 mt of oxygen would be produced.

Medium Temperature (<1200 C) Processing

The need for nitrogen requires the largest amount of regolith to be processed. Approximately 4,382 metric tons (~2,504 m^3) of regolith must be processed each day to produce ~342 kg of nitrogen. This will also produce ~675 kg of carbon, ~7,318 kg of hydrogen, and perhaps ~88 kg of water (although this is not certain). * = Water was released at very low levels from lunar regolith, but it may be a result of terrestrial contamination. The excess hydrogen can be combined with oxygen from the high-temperature processing to form water. However, it is not included in this calculation.

High Temperature (>2000 C) Processing

Approximately 1 metric ton of regolith must be processed via carbothermal reduction to produce the oxygen required. If no water is produced during heating up to 1200 C, an additional ~0.4 metric ton of regolith must be reduced. This additional oxygen would be combined with excess hydrogen to produce water. Approximately 140 kg of iron and 210 of silicon would also be produced.

Figure 16. Amount of Lunar Regolith Required to be Processed Under Each ISRU Scenario

3.4 Define the Preliminary System Architecture

As discussed in the previous sections, the SSLC is intended to fully utilize lunar ISRU resources and minimize or eliminate the use of Earth-supplied materials and products. The SSLC will not only provide a permanent human presence on the surface of the Moon, but it will serve as a test bed of important technologies required for future excursions into our solar system, particularly Mars.

3.4.1 Location of the SSLC

Analysis of the data from the Clementine spacecraft has allowed the lighting conditions at the poles to be determine over the course of a lunar day [Bussey et al., 1999]. Areas that receive nearly continuous sunlight are of interest as potential locations for the SSLC solar photovoltaic arrays. Data from the Lunar Prospector has indicated the possible presence of frozen water ice, or at least bound hydrogen at both of the lunar poles in cold traps where the sunlight is severely limited or non-existent. This resource would provide a valuable feedstock for water, oxygen, and fuel to support lunar surface activities, provide life support consumables, and allow transportation back to the Earth. The ideal location for the SSLC would be in a well-illuminated area that is near a permanently shadowed region containing water or hydrogen deposits. Figure 17 shows the illumination map for the lunar south pole region. Figure 18 shows the illumination map overlaid on top of an Arecibo radar image.

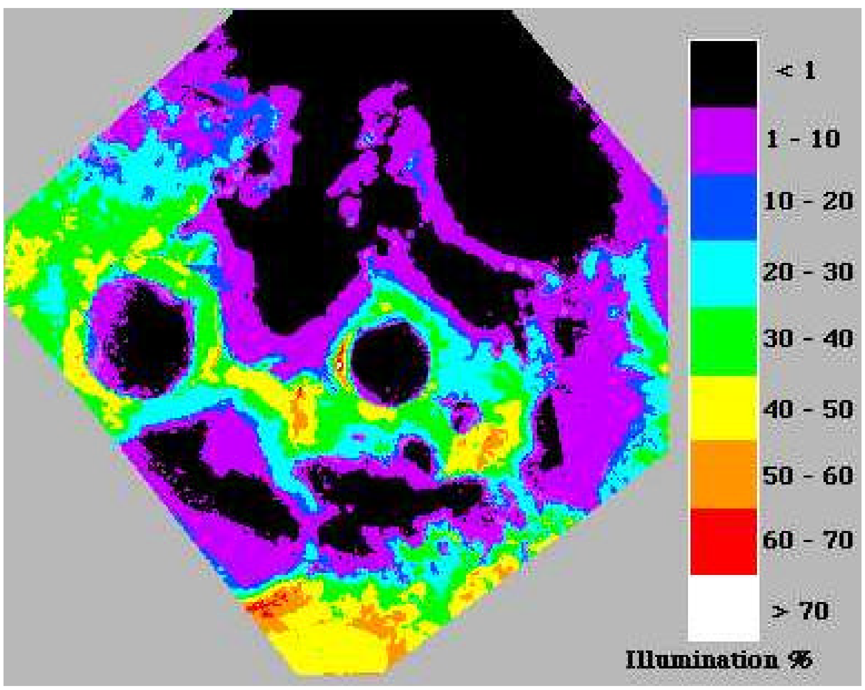


Figure 17. Illumination Map of Lunar South Pole Region [Bussey, et al., 1999]

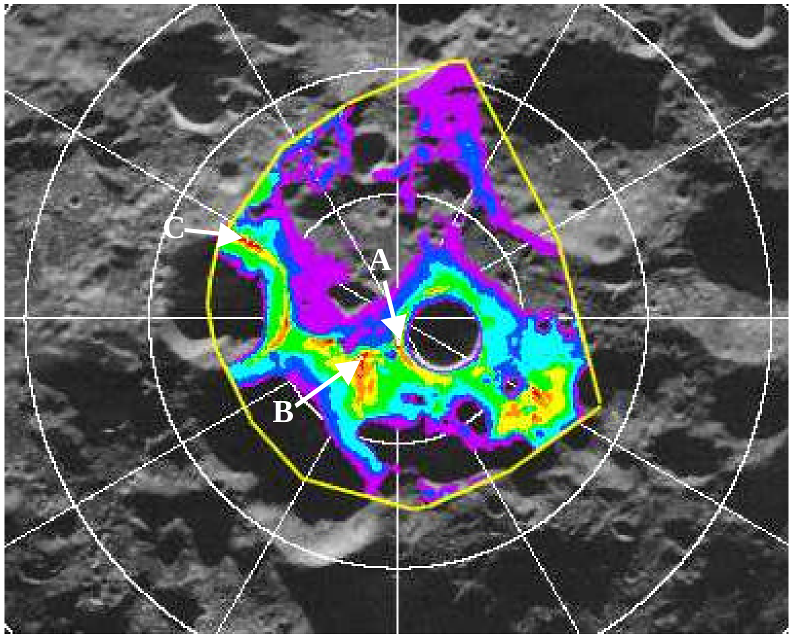


Figure 18. Illumination Map Overlaid on an Arecibo Radar Image [Stacy et al., 1997]

Three well-illuminated areas are labeled as A, B, and C in Figure 18. Figure 19 is a diagram that shows the illumination history during a lunar day as a function of subsolar longitude for these three places. Area A lies on the rim of Shackleton crater and is the most illuminated region near the south pole. This area received ~80% sunlight during the southern winter and even more during the southern summer. Areas B and C are both illuminated for more than ~70% of the lunar day. Area B lies on a ridge that originates along from the rim of Shackleton crater and roughly trends along the 124° W meridian. Area C is on the rim of the 30 km diameter crater centered at 88.5° S, 90° W. None of these areas receive permanent illumination, although all of them have the potential for continuous sunlight during the lunar summer. However, there is only a period of 10 hours (out of 708 hours in a lunar day) when neither areas A and B are in sunlight. If solar arrays were placed in both areas and connected by a link (either microwave or cable), the SSLC could be located at either site and receive near constant (~98%) solar energy [Bussey, et al., 1999]. Since areas A and B are only 10 km apart, this appears to be an excellent region for the SSLC and the solar photovoltaic arrays.

The locations not only offer a near continuous source of solar energy, but they also provide a relatively benign temperature environment. It has been estimated that the temperatures in the permanently lit areas (such as areas A and B) are approximately –53 C +/- 10 C [Heiken et al., 1991]. Other places on the Moon, outside of the poles, can see temperature swings over 400 C during lunar day to night cycle. Area A will serve as the baseline location for the SSLC with a secondary solar photovoltaic array located at Area B. It should be noted that information regarding the illumination conditions is preliminary and needs to be verified before selecting the final SSLC location.

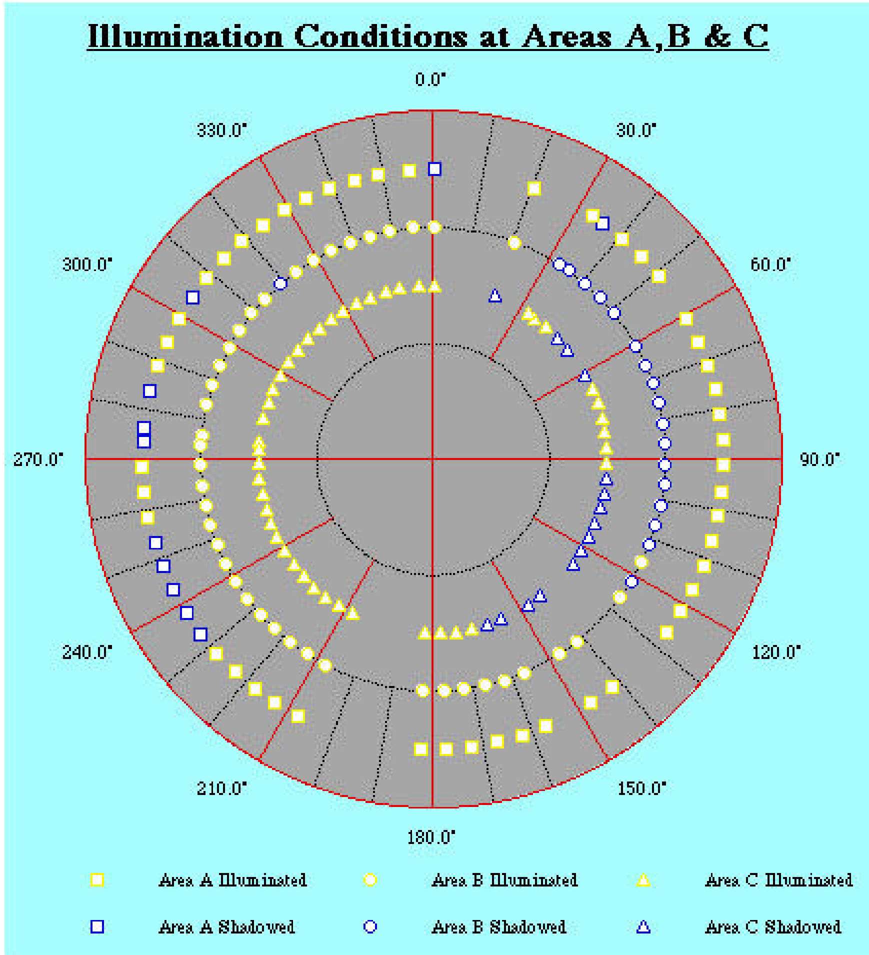


Figure 19. Illumination History During Lunar Day [Bussey et al., 1999]

3.4.2 SSLC Crew Radiation Protection Considerations

The US Federal Government sets radiation standards for radiation workers and the general public; there are also guidelines for space crews. For radiation workers working in US industries where exposure to radiation is apt to occur, the standard is 5 rem/yr (where rem is roentgen equivalent man). For the general public, the standard is less than 0.5 rem/yr. There is evidence that exposures to steady levels of radiation that produce up to 50 rem/yr will result in no detectable damage. Most places on Earth have a background of about 0.1 rem/yr.

The assessment of radiation risks in space dates back to 1961 when an ad hoc working group was set up by the Space Science Board of the National Academy of Sciences. Three years later, this group proceeded to make the first full systematic examination of the scientific and philosophical bases for establishing radiation protection for manned space flights. Basically, the whole body limit was set as 400 rem for an astronaut career. NASA's radiation protection program has involved planning to ensure that the radiation exposures of each astronaut be kept As Low As Reasonably Achievable, the principle known as ALARA.

Because of the increase in relevant data and understanding of radiation protection, the National Council on Radiation Protection and Measurements took on a complete review of radiation received in space activities in 1989 (NCRP, 1989). Table 4 lists the NCRP recommended space radiation limits.

Table 4. Career Whole Body Doses (BFO - based on 10-year exposure duration):

Age	**25**	**35**	**45**	**55**
Male	150 rem	250 rem	325 rem	400 rem
Female	100 rem	175 rem	250 rem	300 rem

The primary sources of radiation in space are conventionally classified into trapped particle radiation, galactic cosmic radiation (GCR) and solar particle radiation. The highest skin dose to crew during Apollo was 1.14 rem (Apollo 14). The highest dose during Skylab (90 days) was 7.74 rem. Typically, the highest doses to Shuttle crews for 7 to 8 day missions have been about 0.5 rem.

For a lunar mission, the crew radiation exposure would arise from: (1) two days spent first in low Earth orbit at the ISS; (2) the passage of their transport vehicle through the inner and outer Van Allen Belts; and (3) the GCR exposure during transit to the Moon and during the stay on the lunar surface. Exposure during the low Earth orbit and one-way Van Allen Belt transit phase and return would be about ~4 rem (for blood forming organs – BFO). The trip from outside the Van Allen Belts to the lunar surface and return would be 0.3 rem BFO. For a 52-month stay on the lunar surface (assuming no solar event) the dose would be 5.8 rem BFO. Thus, the total (without a solar event) would be 10.1 rem BFO. However, one solar event with no shielding, could result in an additional dose of ~ 60 to 400 rem BFO! One meter of lunar regolith shielding over a habitat where the crew is located would reduce these additional solar event doses to a maximum of from 0.1 to 5 rem BFO (Nealy, et al. 1988).

Radiation shielding and protection during transport and surface operations/stay is a very important consideration in the development of the SSLC architecture. Trade studies that would investigate shielding thickness for the different areas of the base occupied by crew versus the overall cost are needed.

3.4.3 SSLC Elements and Layout

The specifications for the pressurized modules of the SSLC are summarized in the Table 5. These specifications represent the minimal requirements that must be satisfied to accommodate 100 persons in the SSLC for extended periods of time. It should be noted that some of the spaces identified could be combined into common areas. For example, some of the plant growth and animal areas could be integrated into public open spaces (parks). This would provide the colonists important interaction with plants and animals. The table is intended to determine the overall scale of the pressurized volumes within the SSLC. Once specific designs are created for these areas, these dimensions will certainly change. Figure 20 shows the general layout of the major SSLC elements.

Table 5. Summary of Pressurized Module Requirements of the SSLC

Use of Space	Surface Area Required (m^2)	Estimated Height (m)	Volume (m^3)
COMMAND & CONTROL CENTER	**500**	**3**	**1,500**
HABITATATION	**16,190**	**--**	**79,010**
Personal Habitats	***4,900***	***3***	***14,700***
Public Habitats	***3,090***	***--***	***27,410***
Business, Shops, Offices	340	4	1,360
Hospital/Clinic	150	3	450
Assembly (churches, halls)	150	5	750
Recreation and Entertainment	500	3	1,500
Public Open Space (park)	1,000	20	20,000
Service Industry	400	3	1,200
Transportation	200	3	1,200
Mechanical Subsystems	50	1	50
Miscellaneous	300	3	900
Storage Areas	***1,500***	***3***	***4,500***
Repair and Maintenance	***1,000***	***10***	***10,000***
CELSS Facilities	***5,700***	***-***	***22,400***
Environmental Control	400	3	1,200
Waste Recycling	800	4	3,200
Plant Growing Area	2,500	4	10,000
Animal Areas	1,000	4	4,000
Food Processing, Storage	500	4	2,000
Agriculture Drying Areas	500	4	2,000
ISRU/RAW MATERIALS PRODUCTION	**2,500**	**10**	**25,000**
PRODUCT MANUFACTURING	**1,500**	**10**	**15,000**
POWER GENERATION, STORAGE, & DISTRIBUTION	**250**	**4**	**1,000**
SCIENCE AND TECHNOLOGY LABORATORY	**TBD**	**TBD**	**TBD**
LAUNCH & LANDING AREA	**--**	**--**	**--**
TOTAL SSLC	**20,440**	**--**	**121,510**

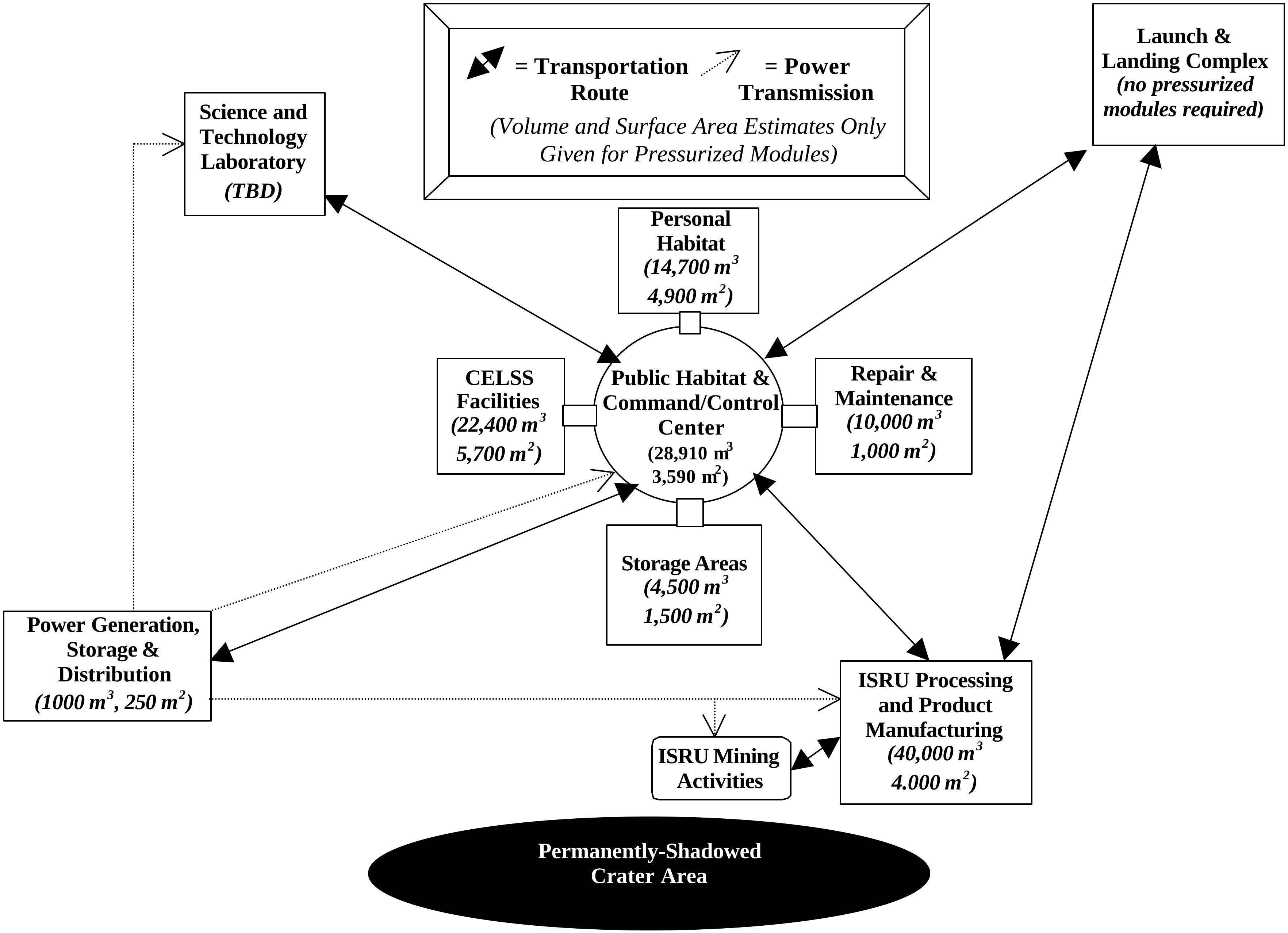


Figure 20. Preliminary Layout for SSLC

The public habitat areas would occupy the central location of the SSLC along with the central command and control center. The ISRU production facility is the primary structure to be established after the initial habitat areas are in place. Power generation (nuclear reactor and solar photovoltaic arrays) are located for at an optimum distance from the habitat areas and a safe distance from the launch and landing complex. The nuclear reactor must be located far enough away from the rest of the SSLC to ensure safety while the solar arrays must be far enough from any dust generating activities.

Even though the colony is designed to be self-sustaining, it still requires an on-going transportation system to and from the Earth. Space transportation is provided in the form of a lunar transfer vehicle, which can be operated between the surface and an orbiting station located in orbit, at a libration point, or as a cis-lunar cycler that is staged from the ISS. The launch and landing facilities for the SSLC should be located at a distance of between 1km to 5km from the other areas of the SSLC because of blast debris [Larson, et al., 2000]. They would be connected via surface or tunnel access as determined by the radiation considerations. The propellants generated by the ISRU production facility must be transported to the launch and landing complex via conduit connections. The surface transportation system would move colonists and cargo within the SSLC and the surrounding areas; it may be a fully robotic operation.

The CELSS would provide all the atmospheric requirements for living on the Moon. The food acreage sized to support 100 people and will 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. 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.

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, ISRU 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.

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. All airlocks would be designed with a dust control system. Each airlock will probably require a cleaning stage for reentering the colony, which totally cleans the dust from space suits and other items.

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 that the mean time to failure of much greater than 52 months.

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.

3.4.4 SSLC Functional Architecture and System Options

Table 6 lists the functional architecture of the SSLC. It is comprised of the major elements of the SSLC, followed by specific functions related to the main element. Table 7 lists the SSLC system architecture options. Each main element of the SSLC is identified along with sub elements. Some of the options considered for these sub-elements are listed. When more than one option is identified, the baseline option is listed first.

Table 6. Functional Architecture of the SSLC

Base Command and Control Center
Power Generation, Storage and Distribution
CELSS (Closed Ecological Life Support System) • Agriculture/Food Production • Food/Biomass Processing • Waste Processing • Environmental Control
Personal Habitat (Living Quarters) • Sleeping • Eating • Hygiene • Entertainment/Social Interaction • Communications • Relaxation
Public Habitat • Eating • Hygiene • Entertainment/Social Interaction/Movies • Communications • Relaxation

• Recreation/Sports • Working • Medical/Health Services/Dental • Shops • Assembly/Meeting Areas • Park Area • Transportation/Elevators
ISRU Processing
Product Manufacturing
ISRU Mining
Storage
Repair and Maintenance
Launch and Landing Complex
Transport Systems
Science and Technology Laboratory

Table 7. SSLC Architecture System Options

Base Location • South Pole on Permanently Sunlit Crater Rim Area • Equatorial • Other
Base Command and Control Center <u>Architecture</u> • Distributed Monitoring and Control, with Central Monitoring and Override Capability • Distributed Monitoring and Control • Central Monitoring and Control <u>Approach</u> • Fully Automated with Human Override • Partially Automated with Human Override • Primary Human Control with Limited Automated Assistance
Power Generation, Storage and Distribution <u>Main Power Generation</u> • Dual Nuclear Reactors with Solar Photovoltaic Distributed Systems • Tri-Nuclear Reactors • Multiple Solar Photovoltaic Distributed Systems • Multiple Solar Dynamic Systems <u>Auxiliary Power Generation</u> • Chemical   ▪ Fuel Cell

▪ Turbine ▪ Internal Combustion Engine • Mechanical ▪ Electrical Generator ▪ Gas Turbine • Chemical Thermal ▪ Thermoelectric • Solar Thermal ▪ Dynamic Cycle • Solar Photovoltaic <u>Power Storage</u> • Chemical- H/O • Battery – Li or H/Ni, etc. • Superconducting Magnetic Energy Storage (SMES) • Mechanical – flywheel, gravity potential, etc. • Thermal <u>Electrical Power Distribution</u> ▪ Cables/Wires – above, on surface, or below ground ▪ Microwave Beaming
CELSS <u>Plant Agriculture</u> • Lighting ▪ Indirect Solar ▪ Indirect Solar and Artificial ▪ Artificial ▪ Direct Solar • Nutrient Delivery ▪ Hydroponic-Fully Liquid Approach ▪ Lunar Soil–Based Approach ▪ Biomass Substrate-Based Approach ▪ Hydroponic - Gas/Liquid Approach ▪ Semisolid Substrate – Foam Approach • Harvesting ▪ Mostly Automated ▪ Human Hand <u>Animal Agriculture</u> • Lighting ▪ Artificial ▪ Indirect Solar ▪ Indirect Solar and Artificial

- Nutrient Delivery
  - Automated
  - Human
- Animal Habitat
  - Cages
  - Open Areas
- Harvesting
  - Mostly Automated
  - Human Hand

Food/Biomass Processing

- Mostly Automated
- Human Hand

Waste Processing

- Total Recycling, Except for Unavoidable Losses that Must Be ISRU or Earth-Supplied

Environmental Control

- Approach - Total Integrated Environmental Control and Usage
  - Pressure
    - 10 psia (69 kPa)
    - 14.7 psia (101 kPa)
- Composition
  - 10 psia (69 kPa) Atmospheric Pressure
    - 3.1 psia (21.4 kPa) O_2, 6.7 (46.2 kPa) psia N_2, 0.15 psia (1 kPa) H_2O, 0.06 psia (0.4 kPa) CO_2
  - 14.7 psia (101 kPa) Atmospheric Pressure
    - 3.1 psia (21.4) O_2, 11.5 psia (79.3 kPa) N_2, 0.15 psia (1 kPa) H_2O, 0.06 psia (0.4 kPa) CO_2
  - N_2 Substitute – Inert Gases
    - He
    - Ar

Personal Habitat (Living Quarters)

Depth/Radiation Protection

- 3 Meters of Regolith Shielding Minimum (Low Radiation Dose)
- 1 Meters of Regolith Shielding (Medium Radiation Dose)
- 0 Meters of Regolith Shielding (High Radiation Dose)

Design Type

- Earth-Constructed
  - Inflatable (with or without regolith radiation shield)
  - Inflatable with Rigid Components or Reinforcement (with or without regolith radiation shield)
  - Fully Rigid Modules (with or without regolith shield)

- Partially Earth-Constructed
  - Inflatable (with or without regolith radiation shield)
  - Inflatable with Rigid Components or Reinforcement (with or without regolith radiation shield)
  - Fully Rigid Modules (with or without regolith shield)
  - Buried in an Existing Crater
  - Buried in an Existing Lava Tube
  - Buried in a "Sealed Mine Shaft"

Public Habitats

Depth/Radiation Protection

- 3 Meters of Regolith Shielding Minimum (Low Radiation Dose)
- 1 Meters of Regolith Shielding (Medium Radiation Dose)
- 0 Meters of Regolith Shielding (High Radiation Dose)

Design Type

- Earth-Constructed
  - Inflatable (with or without regolith radiation shield)
  - Inflatable with Rigid Components or Reinforcement (with or without regolith radiation shield)
  - Fully Rigid Modules (with or without regolith shield)
- Partially Earth-Constructed
  - Inflatable (with or without regolith radiation shield)
  - Inflatable with Rigid Components or Reinforcement (with or without regolith radiation shield)
  - Fully Rigid Modules (with or without regolith shield)
  - Buried in an Existing Crater
  - Buried in an Existing Lava Tube
  - Buried in a "Sealed Mine Shaft"

ISRU/Raw Materials Production Facility

Depth/Radiation Protection

- 3 Meters of Regolith Shielding Minimum (Low Radiation Dose)
- 1 Meters of Regolith Shielding (Medium Radiation Dose)
- 0 Meters of Regolith Shielding (High Radiation Dose)

Design Type

- Earth-Constructed
  - Inflatable (with or without regolith radiation shield)
  - Inflatable with Rigid Components or Reinforcement (with or without regolith radiation shield)
  - Fully Rigid Modules (with or without regolith shield)
- Partially Earth-Constructed

▪ Inflatable (with or without regolith radiation shield) ▪ Inflatable with Rigid Components or Reinforcement (with or without regolith radiation shield) ▪ Fully Rigid Modules (with or without regolith shield) ▪ Buried in an Existing Crater ▪ Buried in an Existing Lava Tube ▪ Buried in a "Sealed Mine Shaft" <u>Products</u> • O_2 • H_2O/H_2 • N_2 • CO/CO_2 • He • Ar and other Nobel Gases • Si • Fe • Ti • SO_2 • NH_3 • CH_2O • CH_4 • C_2H_5OH • Concrete • Other <u>ISRU Processes</u> • Carbothermal Reduction • Hydrogen Reduction • Solar Heating (ice and volatile gas extraction) • Magma Electrolysis • Plasma Processing • Others (TBD)
Product Manufacturing • Solar Cells • Others TBD
Mining
Storage
Repair and Maintenance
Launch and Landing Complex
Transport Systems
Science and Technology Laboratory
Steady State Earth-Supplied Resources and Products

3.4.5 Implementation Schedule for the SSLC Concept

Figure 21 gives an overall schedule for implementing the self-sustaining colony concept, including the development of a prototype system on Earth (Phase 1), the self-sustaining colony at the south pole of the Moon (Phase 2), and an eventual self-sustaining Mars colony (Phase 3). Several major engineering activities are conducted during each phase of the work towards an eventual SSLC and SSMC (self-sustaining Mars colony). Earth-based prototype systems would be designed for both the lunar and martian facilities to test integrated subsystems and increase their Technology Readiness Levels (TRL's). After the design work is underway, construction would begin on the Earth based prototype systems. A period of test and evaluation would follow the IOC (initial operational capability) for each prototype system. This testing allows for improved systems integration and uncovers changes that are necessary in the SSLC and SSMC designs. Once these changes are designed into the system, construction begins on Earth on the facilities needed for each respective colony. After the first components are finished for the colonies, the buildup phase begins and routine missions are conducted to transfer the components to the colonies. During the buildup phase, components are integrated at the colony site and any in-situ construction is also conducted. In the case of the SSLC, a design modification and retrofit is included to outfit the colony with newer technology or to correct shortcomings in the design in anticipation for the step to Mars. The retrofit is also intended to prepare the colony for commercial operations that can include lunar-based astronomy and mining of propellants for a refueling station.

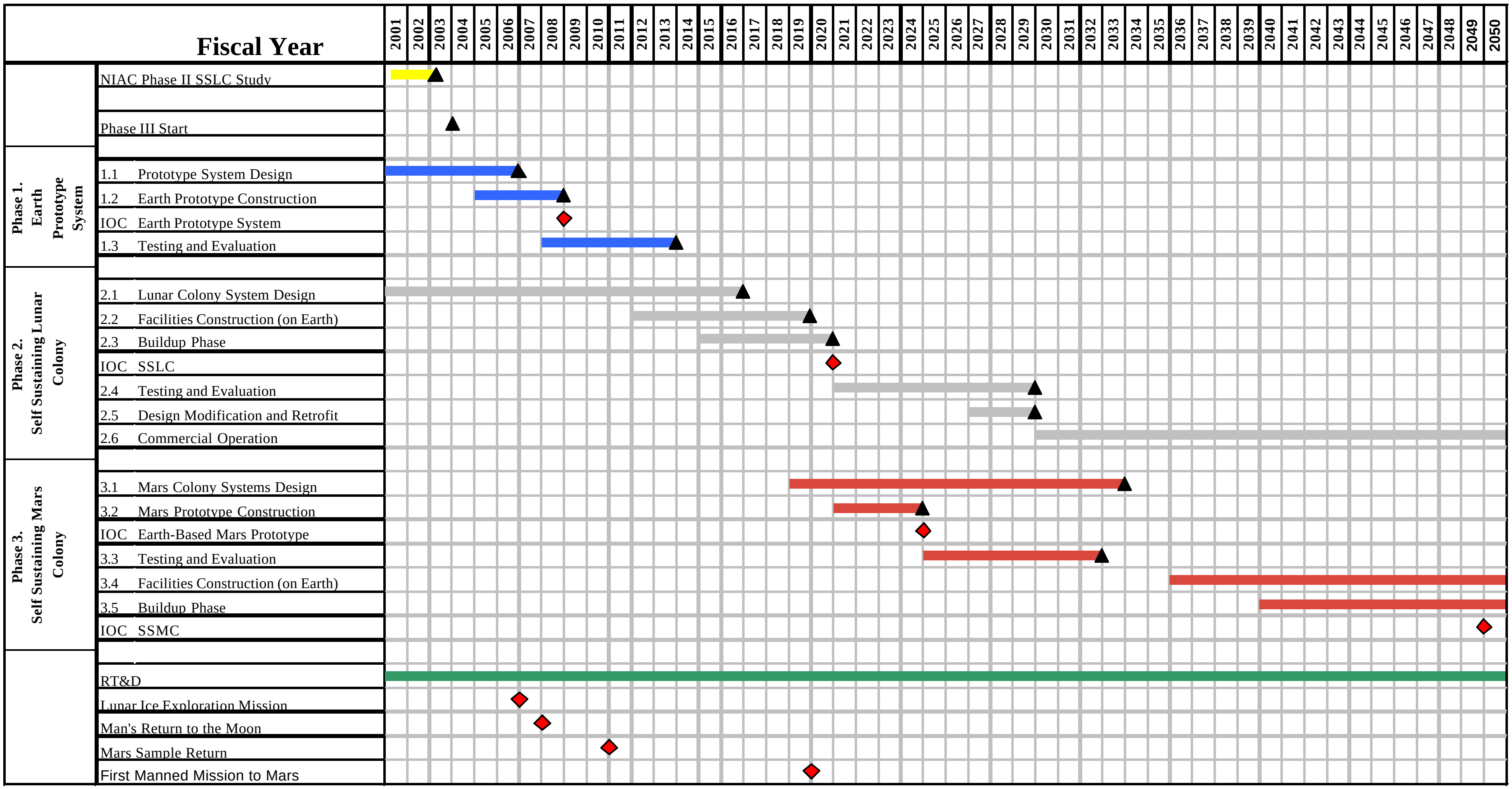


Figure 21. Overall Schedule of the Self-Sustaining Colony Concept

3.5 Create Multidisciplinary Consortium of Contributors for Lunar Colony

The purpose of this work task was to establish a multidisciplinary consortium or network of experts for further developing the SSLC system architecture. The consortium was created by compiling a directory of technical and business contacts at companies, universities, government agencies, and institutes from around the world that may be willing to participate and contribute to the SSLC study in the NIAC Phase II effort and beyond. Table 8 shows the current list for the consortium, including name, affiliation, and area of expertise. There is a database of contact information for all consortium members (including phone number, fax number, mailing address, email address, etc.), but it is not included in this public report. In Phase II, we will use the knowledge and expertise of this consortium as a resource base to develop a detailed system architecture for the SSLC. Specific technology needs and research questions will be identified early in the Phase II effort, based on the results of this Phase I study. A SSLC web page will be created and hosted by ORBITEC to facilitate communication between the project team members, members of the consortium, and the general public. The needs and questions identified will be posted on the web page and participation will be solicited via various methods. The goal is to excite the consortium members and the general public about the SSLC concept and to encourage participation in the Phase II architecture development. A workshop will be held early in the Phase II effort to facilitate the participation of the consortium members and other contributors. The results of the workshop would be posted on the SSLC web page.

Table 8. Multidisciplinary Consortium of Contributors for SSLC

Name	Affiliation	Area of Expertise
Dr. Eric Rice	ORBITEC	ISRU, Propulsion
Dr. Doug O'Handley	ORBITEC	Human Exploration, Astrobiology
Robert Gustafson	ORBITEC	ISRU
Dr. Martin Chiaverini	ORBITEC	Propulsion
Daniel Gramer	ORBITEC	Propulsion
Jerry Hanley	ORBITEC	Systems Engineering
Dr. Jim Jordan	ORBITEC	Lunar Resources
Bill Knuth	ORBITEC	Propulsion, System Design
Dr. T. D. Lin	ORBITEC	Lunar Concrete
Matt Malecki	ORBITEC	Propulsion
Dr. Bob Morrow	ORBITEC	Plant Growth, CELSS
Pete Priest	ORBITEC	Systems Engineering, Propulsion
Ron Teeter	ORBITEC	Propulsion, Automation/Robotics
Brant White	ORBITEC	ISRU
Dr. Leslie Gerstch	ORBITEC	Space Mining
Dr. Richard Gerstch	ORBITEC	Space Mining
Tom Crabb	ORBITEC	Human Exploration, CELSS, Crew
Dr. Larry Diehl	ORBITEC	Propulsion, Transportation
Dr. Eligar Sadeh	ORBITEC	Inflatable Habitats
Dr. Lawrence Taylor	ORBITEC	Lunar Regolith, Dust Control
Bob Cataldo	NASA/GRC	Space Power
Diane Linne	NASA/GRC	ISRU Propulsion
Bryan Palaszewski	NASA/GRC	ISRU Propulsion

Jerry Barna	NASA/GRC	Exploration
Stan Borowski	NASA/GRC	Space Nuclear Power, Propulsion
Dr. Subramanian Sankaran	NASA/GRC	Space Exploration
Wendell Mendell	NASA/JSC	Human Lunar Exploration
Dr. Tom Sullivan	NASA/JSC	ISRU, ISS
Dr. Dave McKay	NASA/JSC	Astrobiology
Jerry Sanders	NASA/JSC	ISRU, Propulsion
John F. Connolly	NASA/JSC	Mars Exploration and ISRU
Debra Neubek	NASA/JSC	ISRU
Hum Mandell	NASA/JSC	Human Exploration
Don Henninger	NASA/JSC	CELSS
Doug Cooke	NASA/JSC	Human Exploration
David Kaplin	NASA/JSC	ISRU
Kent Joosten	NASA/JSC	Lunar Exploration
Al Behrend	NASA/JSC	Life Support
Doug Ming	NASA/JSC	Life Support
Mike O'Neal	NASA/KSC	Human Exploration, Logistics
Bill Larson	NASA/KSC	Human Exploration, Logistics
Dr. Dale Lueck	NASA/KSC	ISRU
Dr. Clyde Parrish	NASA/KSC	ISRU
Dr. John Sager	NASA/KSC	Food Production, CELSS
Dr. Geoff Briggs	NASA/ARC	Robotic Mars Exploration
John E. Finn	NASA/ARC	Life Support, ISRU
Mark H. Kliss	NASA/ARC	Life Support, CELSS
Dr. Chris McKay	NASA/ARC	Mars Terraforming, Human Expl.
Dr. K. R. Sridhar	NASA/ARC/UA	ISRU
Steve Cook	NASA/MSFC	Propulsion, Space Transportation
Peter Curreri	NASA/MSFC	ISRU, Materials
Ann Trausch	NASA/MSFC	ISRU
John Cole	NASA/MSFC	Advanced Propulsion
Robin Henderson	NASA/MSFC	Microgravity Research
Hank Kirchmyer	NASA/MSFC	Space Transportation
Dr. Mark Craig	NASA/SSC	Human Exploration
Alex Pline	NASA/HQ	Space Exploration
Dr. B. J. Bluth	NASA/HQ	Human Factors
John Mankins	NASA/HQ	Engineering, Space Technology
Peter Ahlf	NASA/HQ	ISS Technologies
Dr. Bryant Cramer	NASA/GSFC	Systems Engineering, Life Science, Data Systems
Joe Loftus	NASA/JSC (retired)	Human Exploration
William Smith	NASA/LaRC (retired)	Human Space Exploration
Dr. George Miley	UI	Power Generation
Dr. Mike Duke	CSM	Moon & Mars Exploration, ISRU
Dr. Jerry Kulcinski	UW-Madison	ISRU – Helium-3
Dr. Robert Cassanova	NIAC	Advanced Space Concepts

Dr. John Olds	Georgia Tech	Systems Engineering
Dr. Bob Ash	Old Dominion U.	ISRU
Dr. Harrison Schmitt	Univ. of Wisconsin-Madison	Lunar Energy Recovery, Astronaut
Prof. David Criswell	Univ. of Houston	Lunar Power Generation
Prof. Madhu Thangavelu	University of Southern California	Human Exploration
Prof. George Morgenthaler	Univ. of Colorado (Boulder)	Human Exploration, CELSS
Prof. Keith Prisbrey	University of Idaho	ISRU, Lunar Launch Concepts
Prof. Haym Benaroya	RUTGERS University	ISRU, Space Structures
David G. Schrunk, MD	N/A	Lunar Development, Nuclear Medicine
Dr. Paul Spudis	LPI	Lunar Exploration and Resources
John Hunt	USDA/FPL	Biomass Products
Dr. Ed McCullough	Boeing	ISRU
Bill Siegfried	Boeing	Lunar Exploration, Space Transportation
Mark Prado	Permanent	Space Exploration
Laura Powers	CTL	Concrete, Cement
Buzz Aldrin	Starcraft Enterprises	Astronaut, Lunar Transportation
Bonnie Cooper	OSS	ISRU
Dr. Takashi Nakamura	PSI	Direct Solar Energy
David P. Gump	Luna Corp	Lunar Exploration
Will Reynolds	Lunar Cities	Lunar Architectures
Larry Bell	Retired	Space Exploration
Dr. Don Bliss	Mid-America AG Research	Animal Husbandry
Peter Maricich	Boeing	Systems Engineer
Mark Jacobs	SAIC	ISRU
Carlton C. Allen	Lockheed Martin	ISRU
Dr. Benton Clark	Lockheed Martin	Space Exploration
David R. Scott	Scott Science and Technology	Astronaut, Engineer
Mike Stancati	SAIC	Space Exploration
Dr. Bob Zubrin	Pioneer Astronautics	Mars ISRU and Exploration
Dr. Robert S. Wegeng	Pacific Northwest National Lab	Micro Channel Chemical Processors
Jim Benson	SPACEDEV	Space Exploration
Robert R. Zimmerman	Rand Corp - SEI Effort	Space Exploration
Mark W. Henley	Boeing - Advanced Engineering	Space Exploration
Dan Greenwood	Netrologic	Lunar Power
Brent Sherwood	Boeing - Strat. Arch.	Space Exploration
George Erickson	Los Alamos	Lunar Base Architecture
Steve Durst	Lunar Enterprise Corporation	Public Relations, Publishing
Roxanne Phillips	Falcon's Court	Birds
James V. Zimmerman	International Space Services	Engineer, International

		Cooperation
Bradley C. Bourne	Spar - VP Marketing	Engineering, Robotics
Dr. Niklas Jarvstrat	Literati	Technology Requirements Breakdown, Lunar Bases
Greg Bennett	Bigelow	Space Exploration
Peter Eckart	TU Munich	Lunar Bases
Dr. Maria Nystrom	Lund Inst. of Tech.	Space Exploration
Gernot Groemer	University of Innsbruck	Public Relations, Astrophysics, Space Exploration
Prof. Ignasi Casanova	Universitat Politecnica de Catalunya	Lunar Resources, Construction Materials
Dr. Claes-Gustaf Nordquist	N/A	Aerospace Medicine, Radiation Protection
Dr. Christen Sallaberger	McDonald Detweilder	Engineer, Human Lunar Exploration

4.0 CONCLUSIONS

The SSLC Phase I study has produced a number of conclusions. The south pole of the Moon was chosen as the location for the SSLC because of the moderate temperatures swings, the availability of nearly continuous solar power, and the significant quantities of hydrogen or other frozen volatiles located in permanently shadowed polar craters. However, this location creates a transportation challenge due to the more difficult task of landing there. The advantages of a location at the pole appear to far outweigh these transport difficulties.

The study did not consider an explicit purpose for the SSLC, other than to establish a permanent human presence of the Moon with a minimum need for Earth supplies and to serve as a test bed for technologies in common with an eventual human base on Mars. We selected the period of 52 months for demonstration of being self-sustaining. This 52-month period reflects a scenario on Mars with one missed supply opportunity from Earth. If one can survive on the Moon for this period without supplies or physical interaction with the Earth, then we can begin the pursuit of human exploration of Mars with confidence.

Some other specific conclusions are listed below:

- The SSLC concept appears to be a feasible approach to establishing a permanent human presence outside of the Earth, not only on the Moon, but eventually on Mars.
- A closed ecological life support system (CELSS) is required to make the SSLC a reality.
- Nitrogen appears to be the most difficult life support consumable product to recover from the local lunar resources, due to its low concentrations in the lunar regolith.
- Significant amounts of frozen gases in the permanently shadowed regions of the south pole would provide an important resource for the SSLC, including a source of nitrogen.
- Proper consideration of crew radiation dose and crew shielding during transport, above surface operations, and within the base, require careful assessment. Proper "safe haven" shielding for solar flare events appears to be the main design driver. Consideration of from 1 to 3 meters of regolith or equivalent shielding appears to be warranted.
- There are no data on the long-term effects of lunar gravity on the human body. The short lunar surface stays during the Apollo missions do not provide any useful data. This study has assumed the need for regular exercise for the lunar colonist, especially for colonists returning to Earth. However, it would be virtually impossible to gain these data before we establish a permanent lunar base.
- The long-term effect on the human immune system from living in the closed environment of the SSLC for long periods of time is unknown. The human immune system builds up its defenses to viruses and bacteria through constant exposure here on Earth. The controlled environment of the SSLC may become problematic. The immune systems of long-time lunar colonists returning to the Earth may not be able to cope with new mutations of viruses and bacteria. Likewise, perspective lunar colonists arriving from Earth may carry new viruses and bacteria that could infest the SSLC. This problem could be studied on the Earth in controlled environments that simulate the SSLC.

- The long-term effects of reduced atmospheric pressures with elevated levels of oxygen on the human body are not understood. Lower interior pressure in the habitat modules of the SSLC would help to minimize gas losses. The partial pressure of oxygen at sea level on Earth can be maintained to minimize the effects of the lower atmospheric pressure on the human inhabitants. This could be studied on the Earth in controlled environments that simulate the SSLC.
- The long-term effects of replacing atmospheric nitrogen with other inert gases on the human body are not understood. Nitrogen does exist on the Moon, but in relatively low concentrations. Therefore, a large amount of regolith must be processed to provided to replace nitrogen that has leaked from the pressurized modules. If other lunar-derived inert gases could be safely substituted for nitrogen, it would reduce the amount of regolith that would need to be processed. This could be studied on the Earth in controlled environments that simulate the SSLC.
- The long-term effects of reduced atmospheric pressures with elevated levels of oxygen and/or replacing atmospheric nitrogen with other inert gases on plant growth is not known. Although some plants will be grown within the human habitat, significant reductions in gas losses may be possible by growing some of the needed plants under more extreme conditions (reduced pressures and nitrogen levels). It is possible that plants are more sensitive to low nitrogen levels than humans or animals. This could be studied on the Earth in controlled environments that simulate the SSLC.
- The gas leakage rates for the pressurized modules in the SSLC directly impact the ability to close the life support loop in the colony. A previous NASA study [Sridhar et al., 2000] indicates the gas losses from airlock operations are much higher than the gas losses from module leakage. The gas losses must be replaced from ISRU products or supplies from Earth, so they have a large effect on the system architecture. Reducing the gas permeability of module walls and seals would provide a large reduction in the amount of lost SSLC atmospheric gases. Current airlock designs need to be improved for use in the SSLC.
- An accurate estimate of the costs to recover local lunar resources is needed to determine the economic feasibility of various ISRU products. For example, if the cost of shipping nitrogen to the SSLC is less than the cost to produce it locally, nitrogen is not an economically feasible ISRU product. This type of analysis would determine the key ISRU products and technologies that need to be developed and optimized.

RECOMMENDATIONS

This section presents ORBITEC's study recommendations that have been based on the completed Phase I work. Our recommendations are:

1. NIAC fund ORBITEC's proposed Phase II effort;
2. Gain participation and interest of key NASA staff in the conduct of the Phase II SSLC architecture study and its resulting outputs/products;
3. Gain participation of Dr. Robert Cassanova, NIAC Director, in the development of the Phase II SSLC architecture study;
4. Refine the SSLC requirements developed in the Phase I effort;
5. Develop a complete system architecture for the SSLC;
6. Create solid models of the SSLC elements and simulation models of the SSLC operations;
7. Create a cost model of the SSLC, including implementation and operation;
8. Further assess the radiation environment and shielding options for the SSLC;
9. Develop a conceptual design for the CELSS facility in the SSLC;
10. Develop a conceptual design for the integrated SSLC power system;
11. Develop a conceptual design for the SSLC habitats and structures;
12. Determine the ISRU products and minimum Earth-Supply requirements for the SSLC;
13. Develop a conceptual design for the ISRU production and manufacturing facility;
14. Define the research and technology development activities for the SSLC and those that relate to an eventual Mars base;
15. Define the transportation and logistics needs of the SSLC;
16. Create a strategic plan to implement the SSLC and develop a technology development roadmap;
17. Define an Earth prototype SSLC system;
18. Develop a communication and outreach activity to educate and excite the public about the SSLC concept.

Recommendations for a specific work plan, including individual work tasks can be found in the Phase II proposal submitted with this final report.

APPENDIX A. BIBLIOGRAPHY

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APPENDIX B. WORKSHOP SUMMARY

WORKSHOP SUMMARY

on

SYSTEM ARCHITECTURE DEVELOPMENT FOR A SELF-SUSTAINING LUNAR BASE

TECHNICAL SUMMARY REPORT ON PROJECT WORKSHOP

Held
22-23 June 2000
Madison, Wisconsin

Research Contract 07600-052 (Prime Contract NAS5-98051)
OTC-G097-TR-2000-1

Prepared for:

NIAC
Universities Space Research Association (USRA)

27 November 2000

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INTRODUCTION

A NIAC/ORBITEC project workshop was held in Madison, Wisconsin from, June 22-23, 2000 to gain valuable interaction between certain exploration/ISRU experts and the ORBITEC study team (the agenda is given as Attachment A). The effort involved the NASA/NIAC/ORBITEC funded study: "System Architecture Development for a Self-Sustaining Lunar Base." The workshop focused on two tasks: (1) introducing the concept of the new NIAC study to the participants and (2) discussing all of the possible aspects of beginning the study and identifying the technological considerations.

The participant's list is located in Attachment B.

Dr. O'Handley began the workshop with an overview of the study task and Dr. Niklas Jarvetrat outlined the underlying philosophy. This was nearly identical to the presentation made at Goddard in early June by Dr. Eric Rice.

The major agenda item for the afternoon was the "Requirements Development Workshop." It became obvious to all that the definition of what it meant to be self-sustaining varied among most of the participants. The resulting definition was selected out of the proposal and finally became the working definition.

"The purpose of this task is to develop the basic architecture design requirements for the survival of an isolated group of humans on the lunar surface over an indefinite period of time that fully utilize lunar in situ resources and minimize the use of Earth-supplied materials and products"

Self-Sufficient vs. Self-Sustaining

The initial discussions revolved around a discussion of what was meant by "self-sufficient" vs. "self-sustaining." What are the minimum requirements to survive? This assumes at some point there is no input from the Earth. This implies production on the moon of all food, air, and water. This also implies the ability to have population growth independent of the Earth. Self-sufficiency was also thought to exist for a period of four to twenty[1] years. Another dimension of self-sufficiency was that machines used on the base would be able to be repaired and replaced independent of the Earth for parts or materials. Another thought, which was introduced, was that one could define the base, as self-sufficient if the export was greater than the input. (Mass or monetary).

An assumption was stated that under all circumstances there would be communications with Earth not isolation from it even if the base were totally self-sufficient.

Colony Initial Size:

Number of People: The numbers discussed ranged from a low of 6 to a high of 2000 in order to have self-sufficiency. For total independence 6 is too low to fulfill the requirements set out above. The maximum size seemed to be centered at 1000 people. A figure from Navy submarines gave a figure of 150. This was felt to be adequate for a ship but not if one had to add

[1] See below on the Mars base assumptions.

agriculture and repair of the base without help from external sources.[2] Then a discussion pursued as to the distribution of skills required for self-sufficiency. The skill mix included miners, mechanics, farmers, and medical types.[3] Although not compete the overall consensus was that most people would have cross training in a few areas.

Minimum:

The discussions then looked at the initial re-supply rate to establish the steady state. There was no consensus on how many tons/year this might represent. Replacing losses was considered to be the significant pacing quantity.

A discussion of power requirements established a minimum of 6 KW/person/day. This number would have to be verified and documented.

Lunar Base Sites:

The discussions then turned to where a self-sufficient lunar base would be located. The two generic locations were the near equator or at the poles.

Equator – Most challenging as a consequence of 14 days of lunar night
Most extremes of temperatures – Suits, habitats, rovers
Water must be gotten from a process of extraction

Poles - Almost eternal sunlight
Possible water available in the form of ice
Moderate temperature extremes

The conclusion of the workshop led to the following assumptions and approach to the beginning of the study.

- To make this study more meaningful, C. C. (Pete) Priest suggested that the study should be linked with human Mars exploration; i.e., we are defining a self-sustaining "Mars test bed" located on the moon. It becomes a precursor to the eventual Human Missions to Mars. This will then determine the timing (2020?).
- The test bed time goal should be defined around an equivalent Mars re-supply capability and assume you might miss one opportunity – minimum of 52 months
- Crew size should initially be done parametrically to drive out of the study the optimum/preferred crew size.
- The study approach should identify major re-supply requirements and define approaches to minimize these requirements supplied from Earth – goal is to provide *in-situ* production of food, air, water, and fuel for both land transportation and eventually transport back to Earth.
- Study must recognize that a huge investment was made to develop an Earth-Moon transportation system (communications system too) and to suddenly shut it down doesn't

[2] See "First Lunar Concrete Structures for further discussion. Page. B-6
[3] See page B-5 for distribution of skills

make sense. Continued flights to and from the Moon will be made regardless of whether or not there is an independent base on the Moon.

- Assume that the base is fully developed prior to attaining self-sufficiency. No further build-up flights. No transportation consideration will be carried out.

Additional Suggestions:

- No nuclear power baseline at this time for political reasons
  - This implies location at the south pole to use the continuous sunlight available
- Presence or development of water
  - This also implies the favored location at the south pole if water is confirmed there.
- Planetary Quarantine at the moon for Earth visitors coming to the station?
- Research, Quality Assurance, and Service
  - Initial logistics
  - Initial verification and validation
    - Shuttle 16 days / Skylab 84 days / MIR?? / ISS

Ground Rules:

Automation and robotics used extensively for surface operations
Manufacturing – maintenance and repair or replace trade off
Self-replicating systems should be considered
Power rich (night power strategy)
Location – underground for radiation protection (~30 m of regolith)
Communications – free flow from Earth.

Distribution of Jobs:

Health / disease
    Medical doctor part of crew
        Telemedicine
    Average life span
    Age distribution
    Beginning   not considered
    Permanence   50/50 natural distribution?
Escape requirements (size) self-sufficiency - redundancy
Quality of life
External capabilities – transportation.

Additional persons and organizations to be listed as members of the Multidisciplinary Consortium of Contributors to the Lunar Colony

- Health care professional – JSC flight surgeon
- Naval Research Labs – MIMS
- Sandia - Rapid prototyping
  - Metals
  - Ceramics
  - Wood
  - Plastics
- Self-replicating – David Criswell (Houston)
- Bechtel/Flour Daniels – Andy Franklin
- KSC – Plant growth
- JPL – Thermophyles – Ken Nielson
- AARC (Alternate Agriculture Research Center)

First Lunar Concrete Structure

Size:	30’ X 40’ X 10’ for 12 people
Number of precast elements ~	150 pieces
Time needed for casting Assuming 2 days / pcs	2 X 150 = 300 days
Safety factor	3.5
Total time	1050 days ~ 3 years
Technology development Full-scale construction Demonstration on Earth	5 years
Lunar cement production	4 years
Water production	
Total time	12 years

T.D. Lin (ORBITEC) Presentation

Preliminary System Architecture

Excavation and tunnel (s)
Stabilizing the structure and protection from radiation.[4]

As a minimum this workshop introduced the participants to the scope and existence of the study. Further interaction and comments were requested from all of the participants.

[4] Gertsch, Richard E. and Gertsch, Leslie E., “Lunar Surface Mines and Mining Machinery: Design Criteria,” Engineering, Construction, and Operations in Space, Proceeding Space90, ASCE, June, 2000

ATTACHMENT A

MOON AGENDA (6/21/2000)
SYSTEM ARCHITECTURE DEVELOPMENT FOR A SELF-SUFFICIENT LUNAR BASE (SSLB) REQUIREMENTS DEVELOPMENT WORKSHOP

Orbital Technologies Corporation, Space Center, 1212 Fourier Drive, Madison, Wisconsin 53717
Phone: 608.827.5000, FAX: 608.827.5050
June 22-24, 2000

Thursday, June 22, 2000

1:30 Welcome to ORBITEC - Eric Rice, ORBITEC President and CEO
1:45 Overview and Purpose of the NIAC/ORBITEC SSLB Workshop - Doug O'Handley (PI)
2:00 Participant Introductions - All
2:15 Basis of the SSLB Concept -- Underlying Thoughts - Niklas Jarvetrat
2:30 Project Overview - Doug O'Handley
3:00 Break/Informal Communications
3:30 Requirements Development Discussion - Doug O'Handley

- Implementation time frame
- Colony initial size
- Colony growth rate
- Basic ground rules
- Self-sufficiency categories and needs

5:00 Adjourn

Friday, June 23, 2000

7:30 Donuts, Fruit, Coffee, Juice
8:00 SSLB Requirements Recap/Consensus - Doug O'Handley
9:00 Study Task Related Discussions

- Define Minimum Earth-Supply Requirements - Ron Teeter
- Examples of Lunar ISRU Production Activities and Products - Bob Gustafson
- Define Preliminary System Architecture - Doug O'Handley
- Multidisciplinary Consortium of Contributors to Lunar Colony - Doug O'Handley

10:00 Break/Informal Communications
10:30 ORBITEC Tour and Demonstrations (ISRU processing, engine firing, other)
12:00 Onsite Lunch
1:30 Suggested Technical Discussions/Presentations (~10 minutes each)

- Paul Spudis (LPI) - Political Will and Reasons for a SSLB
- Niklas Jarvetrat (LiTeRaTi) – International Collaboration
- Mike Duke (LPI/CSM) - Lunar Resources
- Jim Jordan (ORBITEC/Lamar Univ.) - Lunar Volatiles
- Richard Gertsch (ORBITEC/MTU) – Selecting ISRU Extraction Machinery
- William Knuth (ORBITEC) – Concepts for Lunar Material Processing
- TD Lin (ORBITEC) - Use of Lunar Concrete
- Ron Teeter (ORBITEC) - Use of Lunar Basalt
- Brant White (ORBITEC) – Carbothermal Reduction for O, Fe, Si, and other materials

3:00 Break/Informal Communications
3:30 Suggested Technical Discussions/Presentations Continued (~10 minutes each)

- Ed McCullough (Boeing) – ISRU Lunar Processing Overview
- Bob Gustafson (ORBITEC) - Extraction and Use of Lunar Water
- Robert Morrow (ORBITEC) – Growing Plants for Food and other Life Support
- John Hunt (USDA/FPL) - Biomass Use in Products
- Martin Chiaverini (ORBITEC) - Lunar ISRU Propulsion
- Bob Gustafson (ORBITEC) - Lunar Inflatable Habitats

4:30 Wrap-up Discussions
5:00 Adjourn

ATTACHMENT B

Participants

ORBITEC

DR. ERIC RICE
DR. DOUG O'HANDLEY
ROBERT GUSTAFSON
DR. MARTI CHIAVERINI
DAN GRAMER
JERRY HANLEY
DR. JIM JORDAN
BILL KNUTH
DR. T. D. LIN
MATT MALECKI
DR. BOB MORROW
PETE PRIEST
RON TEETER
BRANT WHITE
DR. LESLIE GERSTCH
DR. RICHARD GERSTCH

NASA

MIKE O'NEAL

UNIVERSITIES

DR. MIKE DUKE
DR. JERRY KULCINSKI

INDUSTRY/EURO/OTHER

DR. NIKLAS JARVSTRAT
DR. PAUL SPUDIS
JOHN HUNT
DR. ED McCULLOUGH