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The First Human Settlement on the Moon by 2045: A Case Study

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The vision of living and working in space has been the topic of speculative fiction and non-fiction for some 150 years. More recently and with the advent of rocketry in the 1950s, there have been numerous studies of potential camps and outposts to be located on Earth's moon during the past 60-plus years. However, most considerations of longer- term human settlements – i.e., locations with semi-permanent habitation have focused on orbital habitats such as the so-called "O'Neill Cylinders" of the 1970s. During 2020-2021, the Architecture Working Group of the Moon Village Association (MVA) conducted a design reference architecture case study focused on the first human settlement on the Moon – to be established by 2045. Key considerations include access to resources (such as lunar ices), access to energy (e.g., sunlight, nuclear, etc.) and access to and recycling of essential materials (e.g., air, water, Carbon, Nitrogen, etc.).

This paper briefly summarizes the history of space settlements, and recent MVA-sponsored studies. The paper also describes in some detail the working results-to-date of the '2045 Settlement on the Moon Case Study', including physical, biological and economic considerations. The paper concludes with a discussion of suggested directions for future studies and requirements for research needed to realizing the vision of a settlement on Earth's nearest neighboring world.

Keywords
MVA, Moon Village, scenario-based planning, architectures, space systems

1. Introduction

Humanity is now extending to the Moon, including exploration, human presence and discovery, the development of key resources such as lunar polar ice, and potentially space settlement. During the past three years, the steps that might be taken toward a permanent human expansion to Earth's Moon have been evolving rapidly – driven in significant measure by emerging government plans related to the Moon, and also by commercial activities. The Moon Village Association (MVA), a non-governmental organization (NGO), based in Vienna, Austria was established to promote international cooperation and collaboration in the pursuit of this vision. The "Moon village" represents an overarching concept for an assortment of prospective activities on and near Earth's Moon and is not limited to a specific project, location or organization.

During 2020-2021, the Architecture Working Group of the MVA conducted a design reference architecture case study focused on the first human settlement on the Moon – to be established by 2045. Key considerations have included access to resources (such as lunar ices), access to energy (e.g., sunlight, nuclear, etc.) and access to and recycling of essential materials (e.g., air, water, Carbon, Nitrogen, etc.). Without narrowing scope to a particular implementation, an "International Moon Village Reference Architecture" analogous to what is sometimes called a "Design Reference Architecture" (DRA) has been developed by the MVA[1] Architecture Concepts and Considerations Working Group. This Reference Architecture encompasses activities in several "zones', including the South Polar Region of the Moon, low lunar orbit, cis-lunar space and Earth orbit. The systems and activities associated with these zones have been examined in three timeframes: 2025 (just following current plans for a human lunar return), 2035 (following the availability of low-cost lunar transportation systems and 2045 (when extensive lunar surface operations may have emerged).

This paper provides a status report on MVA studies of a '2045 Settlement on the Moon', including physical, biological and economic considerations. The paper discusses suggested directions for future studies and requirements for research needed to realize the vision of a settlement on Earth's nearest neighboring world.

2. Background

The Moon Village Association (MVA) is a non-governmental organization (NGO) focused on advancing humanity's expansion to the Moon over the coming years. The MVA comprises both individual and institutional members from more than 30 countries, and organizes thematic activities through an assortment of distinct working groups.

2.1 MVA Architecture WG Studies

During 2017-2019, the MVA Architectural Concepts and Concerns Working Group (aka, the "Architecture WG") has examined the technical aspects of humanities expansion into cis-lunar space and to the lunar surface over the coming decades. Figure 2-1 depicts an overview of the process flow for the several stages of the Case Study.

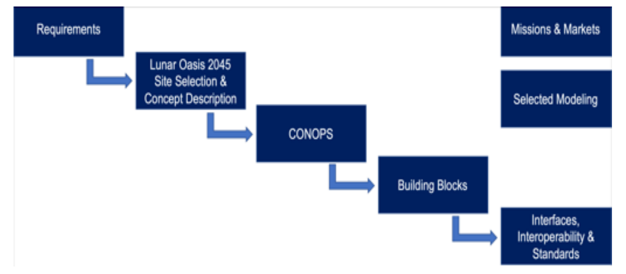


Figure 2-1 Moon Village Architecture Case Study Logic Flow

The approach to conducting the MV Architecture WG "case study" has involved: (1) definition of requirements for a settlement; (2) selection of a candidate site and preliminary description of the settlement concept; (3) development of a 'concept of operations' (CONOPS), including various prospective missions, commercial activities, and operations; (4) refinement of earlier-defined systems 'building blocks'; and (5) framing interfaces, inter-operability requirements and standards for the settlement. On this footing, potential government missions and commercial markets were further defined, and selected models developed and studies conducted.

A primary foundation for these MVA architecture studies was the 'Global Exploration Roadmap' (GER) created by the International Space Exploration Coordination Group (ISEC-G). From this foundation, the Architecture WG updated a set of potential scenarios (first defined in 2017-2018) for the how humanity's activities on and near the Moon might unfold – focusing on 'why', i.e., the purposes of lunar activities.

2.2 The Global Exploration Roadmap[2]

The ISEC-G, which comprises more than two dozen space agencies from around the world has worked for several years to coordinate disparate activities related to space exploration – and lunar exploration and development in particular. Figure 2-2 presents the August 2020 update of the group's "Global Exploration Roadmap".

The ISEC-G Roadmap establishes an official projection of the various missions to the Moon that will be undertaken through the first years of the 2030s. It is from this foundation that the MVA has updated its architecture studies during 2020-2021.

2.3 MVA 'Scenarios'[3]

It is impossible to know the future; however, a variety of techniques may be employed to better anticipate the potential pathways along which future events could unfold. During 2018, the MVA Architectural Concepts and Considerations Working Group (aka, the 'MV Architecture WG'), formulated a set of high-level scenarios for how lunar exploration, development and eventual settlement might proceed.

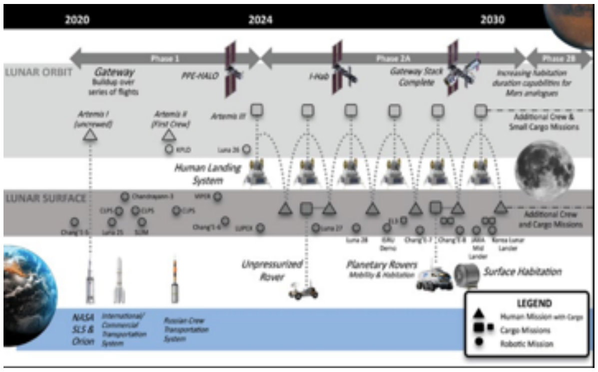


Figure 2-2 ISEC-G Global Exploration Roadmap (August 2020 Supplement)

Three scenarios (which span activities on the lunar surface, supporting activities in lunar orbit, etc.) were defined as follows:

- Scenario **Alpha** – Human Space Flight goal-driven lunar activities;
- Scenario **Beta** – scientific goal-driven lunar activities; and,
- Scenario **Gamma** – commercial opportunity driven activities.

In Scenario ALPHA, geopolitical interests are presumed to be the driving motivation for lunar surface and associated activities during the next 20 years; however, government funding levels are assumed to be approximately level projected forward from the present. Also, in this scenario, there are no breakthroughs in infrastructure, systems or technology for the coming 20 years; the only systems in use are those that are linear extrapolations of those in use or evidently available in 2018. Finally, although there are opportunities for commercial firms to support government-sponsored human space flight and related space programs, there is minimal commercial-to-commercial economic activity during the period.

In Scenario BETA, science and related exploration mission goals and interests are presumed to be the driving motivations for lunar surface and associated activities during the next 20 years. Government funding levels are assumed to decline modestly relative to the present. Also, in scenario BETA there are no breakthroughs in infrastructure, systems or technology for the coming 20 years. With the exception of major new lunar science capabilities, the only systems in use are those that are linear extrapolations of those in use or evidently available in 2018. Finally, although there are opportunities for commercial firms to support government-sponsored science programs, there is minimal commercial-to-commercial economic activity during the period.

In Scenario GAMMA, innovations that are now being undertaken are presumed to emerge from various commercial / private sponsors of space activity at present and to succeed in developing critical / revolutionary new capabilities (such as low-cost transportation, commercial habitable volume in orbit and lunar surface, ISRU, etc.). Enabled by these new capabilities, the driving motivation for lunar surface and associated activities during the next 20 years become profit oriented. However, government funding levels are assumed to be approximately level projected forward from the present, with both human space flight and ambitious science goals achievable due to lower costs.

There are opportunities for commercial firms to support government-sponsored human space flight and related space programs, and there is increasing commercial-to-commercial economic activity during the period.

2.4 Key Assumptions About the Future

During the past five years the pace and scope of lunar mission planning has accelerated and broadened to include more than a dozen countries. The ISEC-G has defined a government-focused 'global exploration roadmap' that frame the next decade. However, based on recent events, the MVA Architecture Working Group has made the following additional assumptions about the future:

First, that low-cost commercial access to low Earth orbit (LEO) will transform cis-Lunar space operations during the next decade; the only question being: precisely when? The assumption for this DRA case study is that such low-cost access to LEO will become available before 2030.

Moreover, it can be expected that massive new government mission opportunities and commercial market ventures will be the result of low-cost access to space; examples include (1) space-based global connectivity; (2) affordable megawatt power systems (solar, wireless and potentially nuclear); (3) development of physical space resources – beginning with the Moon (and initially focused on volatiles); and (4) sustainable permanent human presence in cis-Lunar space. From this foundation, the MVA Architecture WG has developed a lunar settlement case study.

3. A Reference Architecture for the Moon Village: Framework

The vast majority of lunar missions during the coming decade (orbiters, landers, landers with rovers, sample return missions, and human sorties and more) are targeting the south polar region of the Moon. A taxonomy of systems and capabilities has been defined to provide a technical framework within which a reference architecture may be defined. Figure 3-1, which provides an overview of this technical framework is accompanied by a quick summary of each MV architecture element (AE).

3.1 MV Architectural Elements

The following are the key architectural elements that frame the case study.

Earth-Based Architecture Elements (EB-AE). This MVAE (Moon Village Architectural Element) comprises mission control facilities for various lunar surface operations, development and testing capabilities (including analogues) and others.

Mission & Market Architecture Elements (MM-AE). These include a host of prospective capabilities, including lunar surface science systems and missions (e.g., lunar surface observatories, laboratories in cis-lunar space or on the surface, etc.). In addition, there are expected to be a range of novel commercial markets associated with future human expansion to the moon; these include public space travel and tourism, resources development and a range of activities related to future settlement (such as agricultural activities). A specific lunar activity that is often mentioned is the conduct on the Moon of R&D and analogue operations related to future human Mars missions.

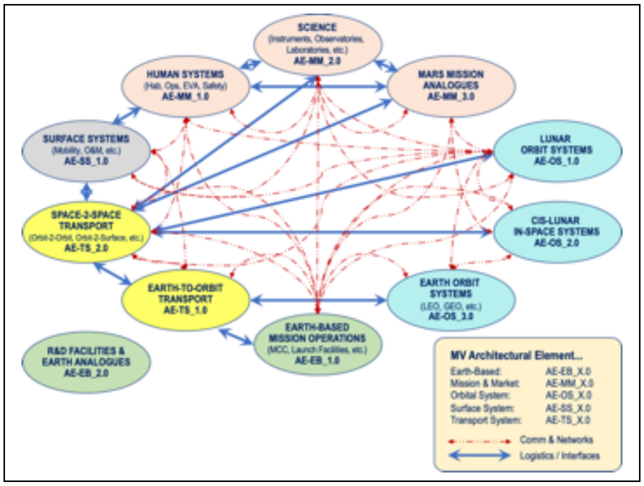


Figure 3-1 Technical Framework for the Moon Village Reference Architecture

Orbital Systems Architecture Elements (OS-AE). These MVAE relate to transportation nodes (the international Lunar Gateway is an example), as well as services-oriented platform. For example, OS-AE would include future lunar orbit refueling facilities. In the nearer term, this class of elements will also include communication, navigation and imaging services providing spacecraft.

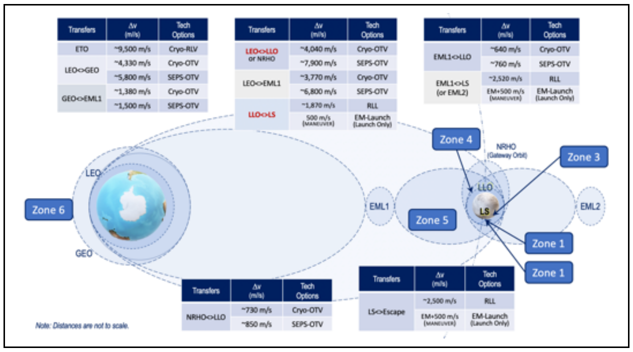
Surface System Architecture Elements (SS-AE). SS-AE are the canonical systems most often illustrated in graphics relating to a Moon Village – including habitats, EVA systems, surface power systems, rovers and robotic systems. These systems are distinguished from but related to the Mission and Market systems described earlier in that SS-AE are more generic, supporting capabilities.

Transport System Architecture Elements (TS-AE). Finally, transportation system-related architectural elements include a wide range of critical capabilities, beginning with Earth-to-orbit transport, in-space transport, orbit to surface transport etc.

3.2 Lunar Settlement Case Study "Zones"

As illustrated in Figure 3-2, the MVA architecture case study began by identifying six candidate zones in which settlement operations to be examined might occur. These included: (a) Zone 1, the lunar south polar region; (b) Zone 2, a permanently shadowed region (PSR) near Zone 1; (c) Zone 3, a site to be selected on the far-side of the Moon (for a lunar science observatory); (d) Zone 4, low lunar orbit (LLO); (e) Zone 5, cis-Lunar space (e.g., EM1 or an NRHO); and, (f) Zone 6, Earth orbit.

Although terrestrially-based activities (launch, mission operations, lunar analogues, etc.) are quite critical, of course, they were considered beyond the scope of the current study.



Transfers	Δv (m/s)	Tech Options
ETO	~9,500 m/s	Cryo-RLV
LEO<>GEO	~4,330 m/s	Cryo-OTV
	~5,800 m/s	SEPS-OTV
GEO<>EML1	~1,380 m/s	Cryo-OTV
	~1,500 m/s	SEPS-OTV

Transfers	Δv (m/s)	Tech Options
LEO<>LLO or NRHO	~4,040 m/s	Cryo-OTV
	~7,900 m/s	SEPS-OTV
LEO<>EML1	~3,770 m/s	Cryo-OTV
	~6,800 m/s	SEPS-OTV
LLO<>LS	~1,870 m/s	RLL
	500 m/s (MANEUVER)	EM-Launch (Launch Only)

Transfers	Δv (m/s)	Tech Options
EML1<>LLO	~640 m/s	Cryo-OTV
	~760 m/s	SEPS-OTV
EML1<>LS (or EML2)	~2,520 m/s	RLL
	EM+500 m/s (MANEUVER)	EM-Launch (Launch Only)

Transfers	Δv (m/s)	Tech Options
NRHO<>LLO	~730 m/s	Cryo-OTV
	~850 m/s	SEPS-OTV

Transfers	Δv (m/s)	Tech Options
LS<>Escape	~2,500 m/s	RLL
	EM+500 m/s (MANEUVER)	EM-Launch (Launch Only)

Figure 3-2 Moon Village Architecture Working Group Case Study "Zones"

4. Moon Village A Reference Architecture: Requirements & Site Selection

The following section discusses the requirements defined architecture for the Moon Village that is being examined during 2020-2021 by the MVA Architecture WG. It includes (1) a summary of requirements that such a settlement must satisfy, (2) a review of lunar surface locations at which a settlement might be developed, and (3) the selected site for a prospective settlement.

4.1 Settlement Requirements

Primary Requirements. There are a number of fundamental requirements that must be satisfied by any architecture for a lunar-surface MV settlement:

- Access to/from Earth. In other words, the settlement must be located in a place where it is possible to accomplish safe and timely vehicle landing and ascent.
- Available and Potential of Resources. Resources availability and potential includes proximity to volatiles and surface mobility access to PSR, and the opportunity to transmit energy to lunar PSRs / cold traps.

- Energy Flows. This includes the availability of significant amounts of energy and an environment that allows waste heat rejection.[*]
- CONOPS (concept of operations). This includes an acceptable surface 'smoothness' for mobility.

And others may be identified.

Secondary Requirements. The following are key secondary – largely biological – requirements that must be satisfied by any lunar settlement.

- Survival (including air, potable water, food, thermal management, waste disposal, radiation protection)
- Self-sufficiency (such as life support, agriculture, energy, etc.)
- CONOPS (Concepts of Operations) considerations (such as EVA, mobility, repair and maintenance, communications, etc.)
- Quality of Life issues (such as personal space – i.e., habitable volume, personal energy (for devices, lighting, etc.), personal communications and information access, etc.)

Tertiary Requirements. The following are some of the 'tertiary' but still important requirements that the MV architecture must satisfy.

- Local Sources. First, the maximum use of locally-sourced materials is important to cost-effective deployment and operations. In other words, the settlement as a whole should be like a living organism.
- Ability to Grow. This characteristic – to be like a living thing – encompasses the capability to 'grow' and to reproduce when appropriate.
- Accommodating Visitors. For reasons of economic viability, the settlement should also have the capability to accommodate and entertain visitors to the settlement, including 'space tourists' and other classes of individuals – particularly government employees.
- Support for Diverse Arriving and/or Departing Vehicles. The capability to support multiple types of transport vehicles arriving and departing; including; different types of vehicles; different countries of origin; and; different consumables as may be required.

4.2 Lunar Surface 'Siting'

There are many locations where a lunar settlement might be establishes. For purposes of the MVA Architecture WG case study, the south pole of the Moon was pre-selected as the general site of a prospective settlement – based on the availability of ice at the poles and the fact that many lunar missions – including those of the US, China, Japan, India, South Korea and others – are targeting the south pole. The question remains: where specifically? This case study has focused on a site that satisfies the requirements stated above.

Some requirements to be satisfied include:

(1) proximity to one or more PSRs and resources located there;
(2) availability of solar energy;
(3) local smoothness and slopes (i.e., terrain that can be traversed by people and machines);
(4) convenient surface access to locations nearby where landing and launch operations may be conducted; and,
(5) convenient use of regolith to provide critically-needed radiation protection.

In addition, to satisfy 'quality of life considerations' it is desirable that the settlement be placed in a location where the Earth will be visible. The figures that follow present a series of relevant images of the Moon's south pole that step one-by-one through these requirements.[†,4]

Figure 4-1 presents a topographical overview of the entire lunar south polar region, while Figure 4-2 indicates locations where the presence of ice has been strongly indicated.

However, the question remains: where exactly to locate the settlement? Availability of solar energy is a key discriminator. Figure 4-3 presents average temperature across a number of locations around the South Pole – which is a simple surrogate for the

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[*] It is likely that both solar energy and space nuclear power will continue to be used in the exploration and development of the Moon; however, only solar energy can provide the capabilities to both scale-up and deliver the sheer scale of the power required for (1) harvesting lunar resources, (2) manufacturing of all types, (3) processing and storage of lunar-derived propellants, and (4) self-sufficient bio-regenerative life support systems (BRLSS), including agriculture.

[†] These data are drawn in large measure from the results of the Lunar Reconnaissance Orbit (LRO) mission – particularly the LOLA instrument (Lunar Orbiter Laser Altimeter), and the Diviner Lunar Radiometer Experiment (DLRE), which measured surface temperatures.

average illumination of the various locations – i.e., the availability of solar energy.

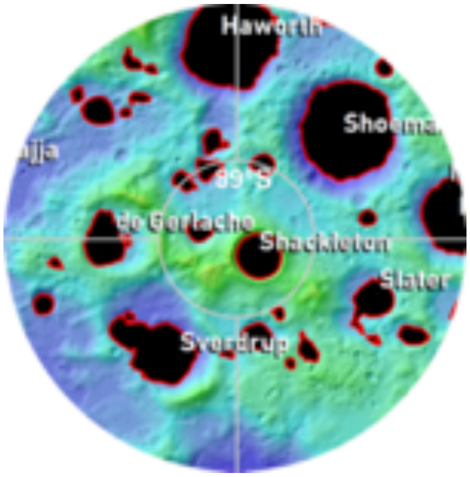

Figure 4-1 Topographical Overview of the Lunar South Pole and PSRs (Centered at South Pole, out to 87° South Latitude)

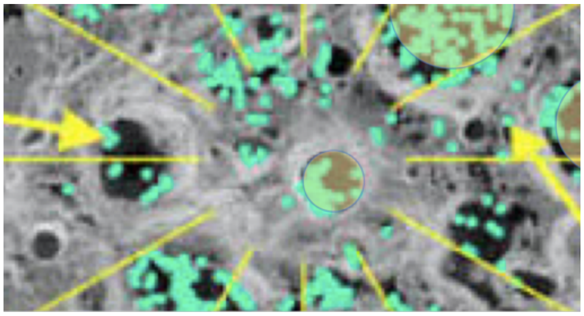

Figure 4-2 Lunar South Polar Region: Identified Ice Locations

Based on an assessment of the information provided by the LRO instruments as illustrated in Figure 4-1 through 4-3, a general location was chosen: the lunar south polar ridge, just to the left of Shackleton Crater as shown. In addition, Figure 4-4 presents slope data in that vicinity – demonstrating that the slopes near the ridge appear adequate for surface mobility.

Finally, and as noted previously, an important – albeit secondary –question relates to the 'quality of life' for settlers and visitors is to be able to see Earth. Figure 4-5 provides an illustration (based on JAXA data from the Kayuga mission) of Earth in the sky as seen over Shackleton Crater.[5]

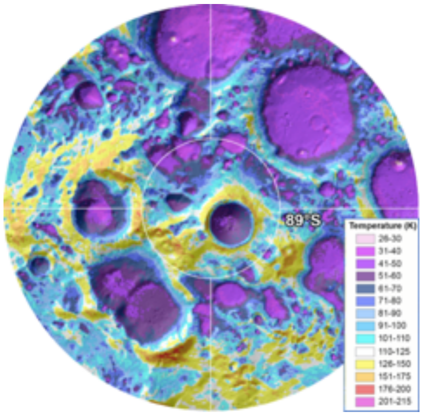

Figure 4-3 Lunar South Polar Region: Illustrating the Average Temperature of various Locations (as a surrogate for Illumination)

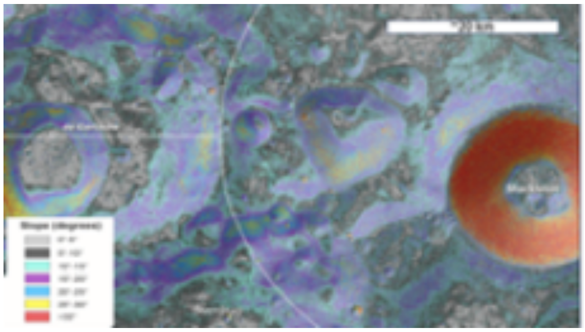

Figure 4-4 Lunar South Polar Region: Illustrating the Slopes Near the South Polar Ridge

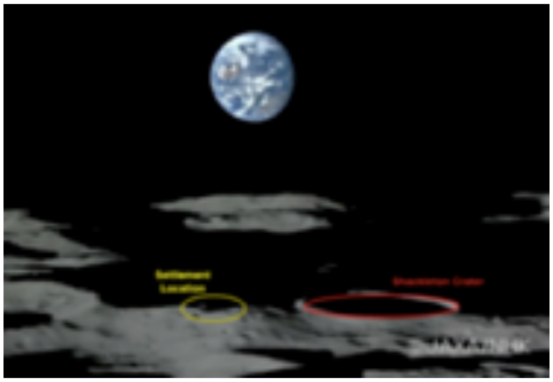

Figure 4-4 Lunar South Polar Region: View Across Shackleton Crater Toward Earth‡

4.3 The Selected Site

Based on the various factors discussed above, a location was been chosen. As illustrated in Figure 4-6, the lunar settlement would be located along the Earth-facing slope of the Lunar south polar ridge,

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‡ Image from JAXA Kayuga Mission; c. 2007.

along the upper edge of an approximately 800 m diameter crater there, facing downslope and toward Earth (which should be occasionally low on the south polar horizon).

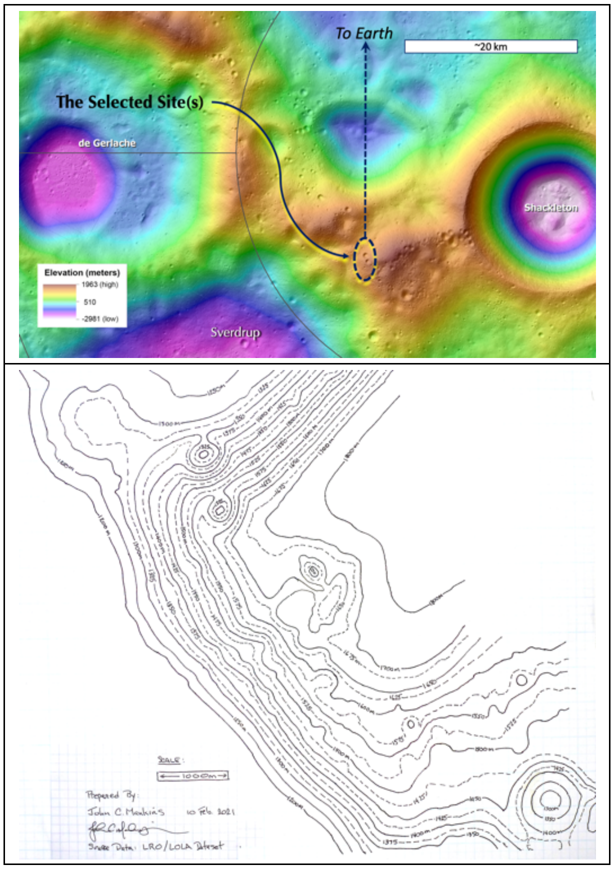


Figure 4-6 Moon Village Reference Architecture: Craters (from LRO LOLA data; Upper: Overall View of the Ridge Lower: close-up of the area & craters selected

This will afford an excellent view from the settlement of Earth, availability of solar energy, and access to resources. Landing and launch facilities would be located on the far-side of the south polar lunar ridge line, at a distance of approximately three kilometers to minimize the risks due to 'ejecta' produced during arrivals and/or departures from the settlement. The location of the notional MV settlement was chosen to facilitate access by surface transportation to permanently shadowed regions (PSR) where ice has been detected during recent years. However, key locations of the settlement would be linked by tunnels.

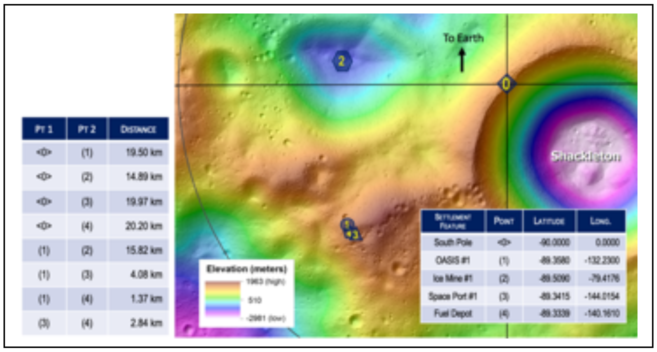
5 OASIS 2045: Settlement Description

The following section presents a high-level description of the concept under study: the first human settlement on Earth's Moon. The reference architecture settlement has been designated as "OASIS" – aka, '**O**ff-Earth **A**utonomous **S**elene-based **I**n-space **S**ettlement'. It is intended to be largely self-sufficient from Earth-based logistics once full-operations are achieved in the year 2045. At that point, the settlement would sustain a permanent population of 40 individuals and would accommodate more than 300 visitors from Earth each year, including scientists, government astronauts, tourists.§

5.1 OASIS 2045 Overview

The primary habitation systems for OASIS are anticipated to be located in the crater so-designated in Figure 4-5. These systems are presumed to include (in descending order of importance and volume): (1) an agricultural 'spiral' described below, (2) a chemical processing plant, (3) 'main street' settlement (comprising the central control center for the settlement, settler habitats etc.), (4) a visitor habitat, and (5) the settlement manufacturing center.

'Urban Planning'. Prospective locations for the above elements of the overall OASIS have been identified at several sites near the initially chosen crater (see Figure 4-6). Figure 5-1 provides the results of this 'urban planning' with a single graphic showing all of the major sites of settlement in 2045, the lunar latitude and longitude of each, and the linear distances between them (pairwise).



PT 1	PT 2	DISTANCE
<0>	(1)	19.50 km
<0>	(2)	14.89 km
<0>	(3)	19.97 km
<0>	(4)	20.20 km
(1)	(2)	15.82 km
(1)	(3)	4.08 km
(1)	(4)	1.37 km
(3)	(4)	2.84 km

SETTLEMENT FEATURE	POINT	LATITUDE	LONG.
South Pole	<0>	-90.0000	0.0000
OASIS #1	(1)	-89.3580	-132.2300
Ice Mine #1	(2)	-89.5090	-79.4176
Space Port #1	(3)	-89.3415	-144.0154
Fuel Depot	(4)	-89.3339	-140.1610

Figure 5-1 'OASIS' Key Sites

As presented, the primary habitation site will be located at Latitude of -89.358° and Longitude of -

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§ On the path to 120 or more, as discussed in Mankins, et al, "Biological Requirements of Truly Self-Sufficient Space Settlement."

132.230° – a distance of some 19.5 km from the lunar south pole (located on the rim of Shackleton Crater). The major sites include (1) the primary habitation site; (2) an initial prospective 'ice mining' site, aka, *Spudis PSR* (a permanently shadowed region named in 2021 for lunar scientist and author, Paul Spudis) at Latitude –89.5090°, Longitude –79.4176°; (3) a location for a Space Port to serve the transportation needs of the settlement at Latitude -89.3415°, Longitude -144.0154°; and, (4) a location for a naturally-cooled Cryogenic Propellant Depot at Latitude -89.3339°, Longitude -140.1610°. (Distances among these sites are provided in the figure.)

Leveraging Local Topography. Figure 5-2 below provides the local topographical context for the above noted elements of the OASIS settlement – including the crater where the primary habitation for the settlement is envisioned, the location of a planned 'OASIS Space Port' (OSP) and a "Cryogenic Fluids Depot (CFD)" in between those sites.

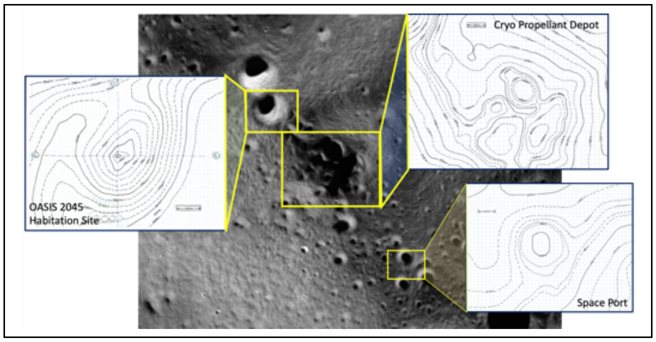
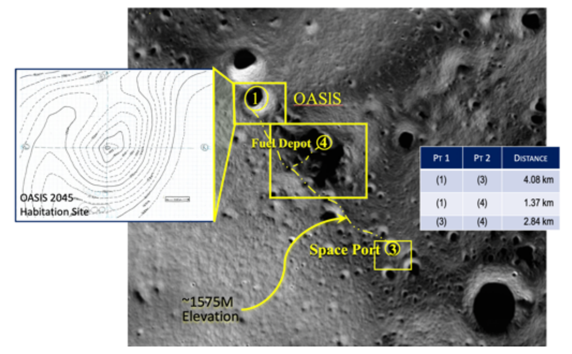


Figure 5-2 'OASIS' Local Topography – Close-up 1

As suggested by the features in Figure 5-2, a central strategy in the locations chosen is to leverage to the greatest degree possible the local topography. This is being accomplished in multiple ways. First, a crater was chosen for the site of the primary habitation to exploit the rim of the crater to provide 'free' radiation protection. Second, the Space Port is located at the far-side of the ridge so as to minimize the risk of ejecta during landing and launch operations impacting the habitats. Also, the CPD is located between the habitations and the Space Port for convenience, and in a naturally cool impact feature to reduce energy requirements for liquefaction and maintenance of cryogens. It is also expected that by placing the agricultural modules in a crater at a lower level than the primary habitation that waste management will be facilitated (e.g., through passive water flows). Finally, the sites chosen are all accessible from a single elevation at approximately 1575 m, as shown in figure 5-3.

It is anticipated that a terraced and paved roadway would be laid along the path at 1575 m – a distance of about 4 km from the primary habitation site to the Space Port, and about 2.8 km from the Space Port to the Cryogenic Fluids Depot.



Pt 1	Pt 2	Distance
(1)	(3)	4.08 km
(1)	(4)	1.37 km
(3)	(4)	2.84 km

Figure 5-3 Common Elevation for Access

5.2 Habitation Details

Figure 5-4 provides a 'close-up' of the primary site crater and the several habitation systems that might comprise the 'main settlement' at that location. Please note that the layout is indicative only; more detailed study, including thermal analysis, radiation modeling and other examinations is needed. However, as labeled in the future, it is envisioned that the following elements will comprise the main OASIS settlement:

(A) A set of primary pressurized volumes (sufficient living volume for a total of some 40 individuals);

(B) A primary Chemical Processing Plant (including waste treatment and toxic materials processing);

(C) A Logistics, Repair and Maintenance Center (including both pressurized and in-vacuum operations, with at least one large airlock)

(D) A Light Manufacturing Center (including metal working, 3D printing, fabrication of soft materials and fabrics, etc.;

(E) A 'spiral of Archimedes' that will house the principal agricultural operations of the settlement (this will involve multiple, semi-autonomous modular segments that can be isolated if necessary; each modular segment providing about 1000 m^2 of 'farm land'); and,

(F) Tourism and recreation pressurized volume, sufficient for a visitor population of not less that 20 nor more than 60, and including both individual accommodations and a common area (e.g., for sports, entertainment, etc.)

Overall, it is envisioned that the settlement will more closely resemble the cliff dwellings found in various parts of the world (such as the American Southwest Anasazi people) rather than a 'space station on the Moon'.[6] Finally, it is anticipated that these distinct pressurized volumes will be connected by a largely or entirely buried tunnel (shown in the figure connecting several areas). Not shown in the figure are required power and thermal systems.

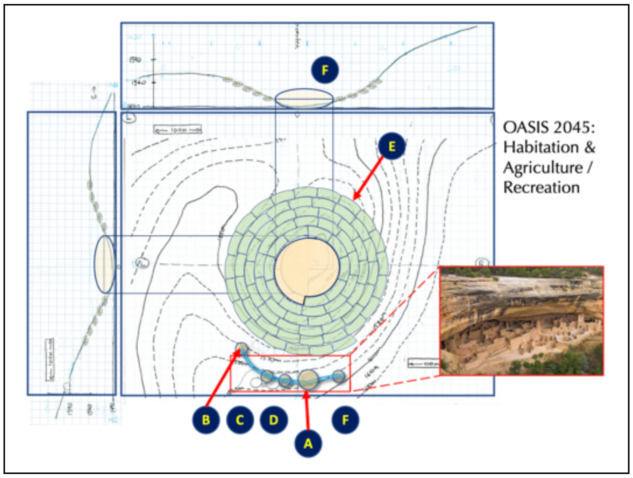


Figure 5-3 'OASIS' Local Layout (top and side views)

The Spiral. A proposed innovation presented in the figure above is the idea of constructing the primary agricultural volume for the settlement in the form of a 'Spiral of Archimedes', which resembles the shell of a chambered nautilus. As with the case of the cephalopod, the idea is to segment the volume into separate chambers that can be individually fabricated, one building upon the prior chamber from locally-sourced materials – and which would provide inherent defense against catastrophic decompression due to an outside threat, or the spread of a blight or other interior threat. As illustrated at the center of the spiral would be a single larger 'dome'. This location is intended to accommodate community gatherings, sporting events, etc. The construction of the spiral on the interior of a lunar crater would (1) facilitate radiation protection, (2) other protection against impact events; and would (3) provide a natural gravity gradient for drainage from the agricultural segments.

The central feature of OASIS is a substantial habitable volume dedicated to agriculture, including CO_2 removal, air regeneration, water purification, food production and waste management / recycling. This large volume would comprise multiple discrete but interconnected modules, constructed from local materials and supporting a self-sufficient local biosphere. A number of additional modules would be located adjacent to the biosphere and would serve as living quarters for the settlers, habitation for visitors, common areas, and functional areas such as a chemical processing plant, manufacturing facilities, etc.

5.3 Operations Sites

A fourth major site for the OASIS settlement is, of course the ice mining location (the vaguely 'diamond-shaped' PSR in Figure 5-5 just Earth-ward from the primary site.[**,7] A surface route to/from the Spudis PSR and the settlement crater is also shown (as is the topography of the PSR itself) – a distance of roughly 10-15 km.

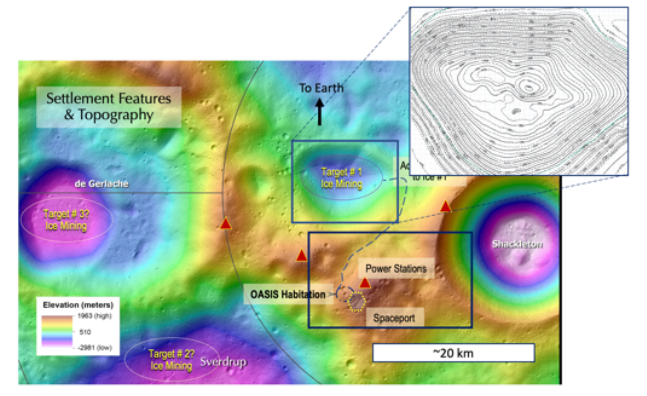


Figure 5-5 Operational Elements – including Candidate 'Ice Mining' Sites

Figure 5-5 also illustrates another important idea: that providing the megawatts of power that will be necessary for a sustainable lunar settlement will necessitate an extensive power generation capability and local power grid – envisioned here to be wireless in character.

6. Framing an Overall Concept of Operations

Abstracting from the above discussion, Figure 6-1 presents a 'metro-map diagram' of the OASIS and nearby installations and prospective 'missions and markets.' Together, these collectively reflect the 'concept of operations" (CONOPS) of the settlement.

[**] This feature has recently been designated as "Spudis crater" after the well-known lunar research – and a good friend before his passing – Paul Spudis.

(See the 'Legend' for an explanation of various symbols on the map.)

The 'metromap' view of OASIS highlights a number of additional elements. For example, the pathways that connect the primary habitation volumes with the various operational areas, the key nodes in the generation of power and its wireless transmission with various customers for that power, and the interconnections with various prospective missions and markets – including a prospective laboratory, a far-side science observatory, and other lunar surface installations (such as 'bases' established by various governments or commercial players.

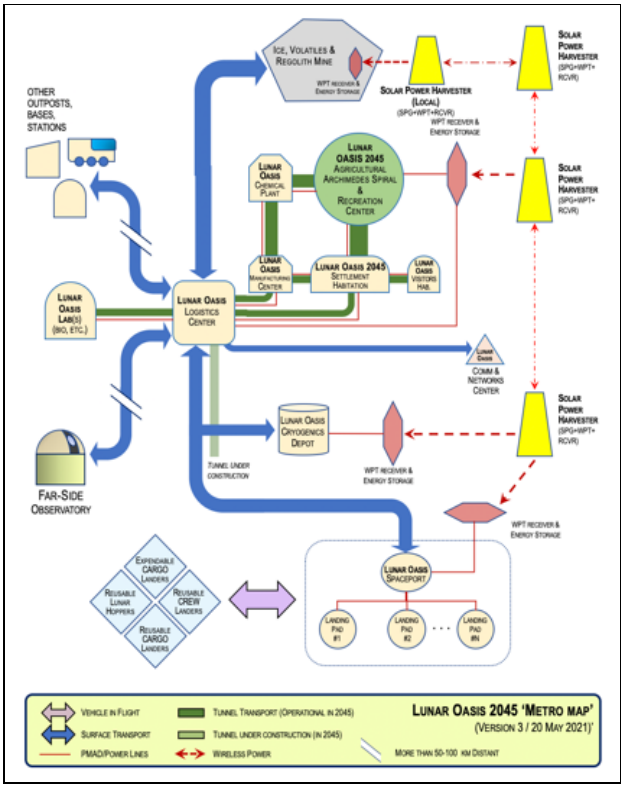


Figure 6-1 OASIS Reference Architecture CONOPS "Metromap" Diagram

The metromap also highlights the idea that there will be several different types of vehicles that operate out of the 'Space Port' – including one-way vehicles delivering cargo from orbit, Reusable Lunar Landers (RLLs) for both crew and cargo, and 'reusable lunar hoppers' that could use the availability of lunar propellants to enable cost-effective access by rocket propulsion to remote locations on the surface from the outpost.

7. OASIS 2045: A Systems Model and Building Blocks

Based upon the MV 2020-2021 Design Reference Architecture, a set of 'building blocks' have been identified; these represent major functional elements that will comprise both OASIS #1 and the overall settlement. These building blocks and the high-level interactions among them are presented in Figure 7-1, in the form of an overall 'systems model'.

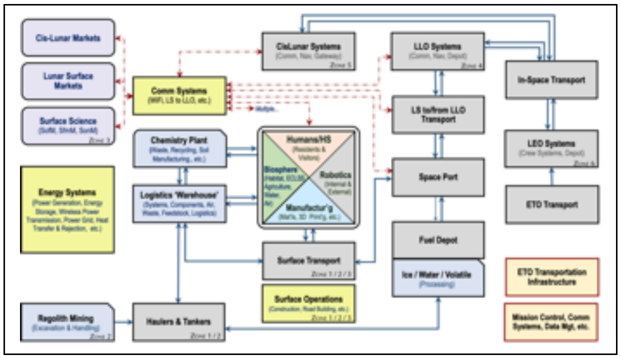


Figure 7-1 'OASIS' Reference Architecture Systems Modeling Diagram

7.1 Interoperability

It is clear that the various building blocks must be capable of working together – and with other systems that may be operating on the Moon that are external to the "Moon Village Settlement". Hence, 'Interoperability' will be an *essential* characteristic of any future lunar settlement. However, the precise meaning of this term for lunar and cis-lunar systems appears somewhat fluid at present, usually focusing on interoperability for data systems and networks, and sometimes documented at the detailed level – but without a clear conceptual framework.[8] For purposes of the MV Architecture WG studies during 2020-2021, efforts will adhere to the following definition:

> *"**Interoperability** is the capability of space systems of all types to interact, communicate and cooperate safely, efficiently, cost-effectively and securely – including but not limited to computing, positioning and navigation, imaging, physical systems and interactions, and living systems & their interfaces."*

For purposes of the MV Architecture WG, Interoperability comprises the full range of functions and interfaces of diverse systems – including data systems, power systems, mechanical systems (such as airlocks), fluids (such as atmospheres – pressures and composition), fire safety, living species interactions, and more.

7.2 Building Blocks

These building blocks (which have been updated from the 2019 version) include the following:

- *Human Operations & Health*, including humans themselves, EVA systems; airlocks; EVA Suits; personal mobility systems; EVA maintenance systems; medical care systems (urgent care, immunology, surgical care, etc.); and, lunar-gravity mitigation.
- *Habitation / Self-sustaining 'Biospheres'*, including habitable volume (pressure vessel, air, water, lighting, thermal management, etc.); radiation protection; agricultural systems; biological waste processing & recycling
- *Robotic Systems* (e.g., surrogates and human augmentation systems, including a wide variety of robotic systems essential to the development and subsequent operations of the settlement – both as surrogates for human actors and to augment or support them.
- *Utilities* including communications & network systems; position location and navigation; imaging & operational sensing; computing and data management; and, power generation & energy.
- *Operations* building blocks, including dust mitigation; construction systems; physical waste processing and recycling; tunneling; and, manufacturing.
- *Resources*-related building blocks such as capabilities related to lunar regolith, such as exploration for and characterization of resources; mining systems & resources extraction capabilities; and, resource processing & handling systems.
- *Transport & Logistics* building blocks including Space Transport Vehicles (Expendable, Reusable, etc.); Spaceport Systems; a Fuel Depot; Advanced Lunar Launch Concepts; and, Surface Transport Systems (including transportation of crew, cargo and materials).
- Various *In-Space Capabilities*, including building blocks in LEO, LLO and cis-Lunar space.
- *Science Missions / Payloads* including three categories: (1) Science of the Moon (e.g., geophysics); (2) Science from the Moon (such as astrophysics); and, (3) Science on the Moon (e.g., research laboratories and Mars testbeds).
- *Lunar Surface Markets,* including several candidate markets such as operational bases of various space-faring countries or companies; these would involve supplying propellants, products (e.g, habitable volume, tankage, solar arrays, etc.), services (such as Cloud services, communications, power, etc.), and or logistics (e.g., feedstocks).
- *Cis-Lunar Markets*, involving supplying propellants, products (e.g, tankage, solar arrays, etc.), and or logistics (e.g., feedstocks) to customers in cis-lunar space (such as the Earth-Moon Libration points).

7.3 Interfaces and Standards

With the above definition of Interoperability and the identified Building Blocks, a set of interfaces and standards may be defined. A handful of draft 'deep space interoperability standards' have been identified by a sub-set of ISS participants.[9] However, there are diverse additional interfaces and interface standards that must be considered in greater detail – even though they will not be finalized for years. Such earlier insight can inform decisions by both entrepreneurs and space agencies (and their contractors) in the nearer term. Some of the likely interfaces will include:

- Communications systems related interfaces and standards (e.g., spectrum use, non-interference, standards and protocols for networks, etc.).
- Human systems related interfaces (e.g., atmospheres, airlocks, EVA systems, medical care systems and coordination, and many others).
- Transportation systems interfaces and standards (including especially propellants, supporting services, landing and launch installations and 'space traffic control' and others).
- Agricultural and bio-systems standards and coordination (including protection of individual habitats from inadvertent contamination and/or invasive species, and more).
- Energy systems and standards (including access to solar energy, use of wireless power transmission (WPT), power lines and specifications (e.g., voltage, AC or DC, etc.).

8. Settlement Economic Viability

It is highly likely that 'outposts' – of which the International Space Station (ISS) is an example – may be deployed in cis-lunar space and perhaps on the lunar surface in the coming 10-20 years. However, at present it seems unlikely that governments will invest the necessary funds to deploy and maintain a space settlement for policy reasons. As a result, in addition to technical feasibility, a lunar settlement must also be economically viable. For purposes of the MV Reference Architecture 'Settlement Case Study, it was assumed that in 2045 there will be a diverse set of market customers and providers for a wide range of goods and services. These will include:

- Contracting to Government Projects
- Providing Goods and/or Services to Government Missions
- Providing Goods and/or Services to Commercial Markets
- Contracting to Commercial Firms
- Providing Goods and/or Services to Private Individuals
- Selling to "Visitors" (e.g., government or commercial sponsored visitors)
- Selling to Public Space Travelers or "Tourists" (e.g., personally financed visitors)
- Selling to "Settlers" (i.e., those who intend to stay)
- Providing Goods and/or Services to 'the Settlement'

As noted elsewhere, there only a few of these will be 'primary markets' for a lunar surface settlement. These will certainly be focused for many years on providing goods and services to government-sponsored activities (both human space flight related and science oriented). However, from early in the development of the Moon Village it can be expected that there will also be commercial activities related to providing goods and services to private visitors to the Moon – particularly if the key assumption of this case study regarding low-cost transportation emerge.

Some of the promising economic activities projected for a lunar settlement are:

(1) Lunar fuel / consumables production and sales on the lunar surface (including both government and commercial transportation services);
(2) Providing Space Port Services (including personnel transportation between the Space Port and OASIS, refueling services for reusable landers and hoppers, cargo and refueling transport services);
(3) Lunar propellant services in Lunar orbit;
(4) Lunar travel and tourism accommodations and services (including government and corporate visitors);
(5) Generation and delivery of power to lunar surface markets and missions;
(6) Providing a biosphere for lunar settlers, up to a total of 1,000 m^2-1,500 m^2 of land per settler (including habitable volume, 'Earth-normal' air, 'agricultural land' and agricultural water); and,
(7) Support for a lunar surface scientific research station (presumed to be an observatory on the far-side of the Moon).

An initial exploration of each of these market opportunities – including preliminary 'use cases' is presented in the paragraphs that follow.

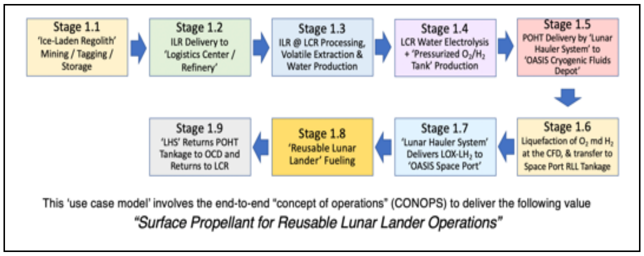
8.1 Lunar Surface Fuel / Consumables Production and Sales

Lunar fuel / consumables production and sales on the lunar surface (including both government and commercial transportation services) are inherent in all discussions of lunar 'ice mining and propellant production.'

Preliminary Use Case. Figure 8-1 presents at a high-level a preliminary use case for lunar surface power. Due to the complexity of the operation, this use case involves a number of high-level stages. The use case involves several stages, beginning with (1.1) cold ice-laden regolith (CILR) mining, tagging and storage (in a PSR); (1.2) CILR delivery from the PSR to the OASIS 'logistics center and refinery' (LCR); and, (1.3); CILR processing at the LCR, including heating under controlled conditions in a pressure vessel, resulting in volatile extraction and water production and separation[††]

Next, (1.4) water electrolysis is performed at the LCR resulting in production of gaseous Oxygen and Hydrogen, and 'Pressurized O_2 and H_2 Tank' (POHT) production; (1.5) transfer of the POHT to a Lunar Hauler System (LHS) for transportation to the OASIS Cryogenic Fluids Depot (CFD); and, (1.6) liquefaction of gaseous H2 and O2 takes place at the CFD, ending in transfer to (RLL-capable Cryogenic Tankage).

[††] Processes dealing with non-water volatiles will also be required; however, these are not included because they are not part of this specific use case.



This 'use case model' involves the end-to-end "concept of operations" (CONOPS) to deliver the following value

"Surface Propellant for Reusable Lunar Lander Operations"

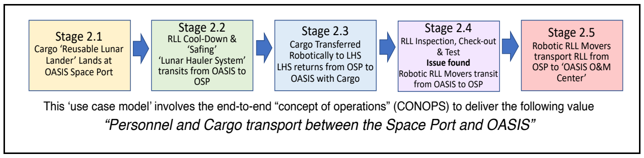
Figure 8-1 Use Case Diagram: Lunar Fuel and Consumables

Finally, (1.7) the LHS transports the now LH_2/LOx-bearing RCT to the Space Port; (1.8) Fueling of the Reusable Lunar Lander (RLL) by the LHS+RCT; and, (1.9) in the final stage, the LHS returns the RCT to the CFD, and the POHT from the CFD to the OASIS LCR. At this point, all systems have returned to their starting positions and the process begins again for the next RLL fueling.

8.2 Lunar Surface Space Port Services

Providing Space Port Services (including personnel transportation between the Space Port and OASIS, refueling services for reusable landers and hoppers, cargo and refueling transport services).

Preliminary Use Case. Figure 8-2 presents at a high-level a preliminary use case for services that might be provided at a lunar surface Space Port. In particular, the emphasis is on a uniquely Space Port' type of service: dealing with a Reusable Lunar Lander (RLL) that has a problem following landing and which must be removed for repair and/or recycling.



This 'use case model' involves the end-to-end "concept of operations" (CONOPS) to deliver the following value

"Personnel and Cargo transport between the Space Port and OASIS"

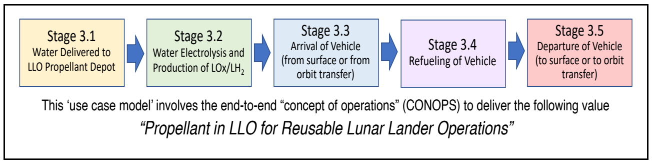
Figure 8-2 Use Case Diagram: Lunar Surface Space Port Services

The use case involves the following stages: (2.1) a cargo-bearing Reusable Lunar Lander (RLL) arrives at the OASIS Space Port (OSP) from LLO; (2.2) following RLL 'cool-down' and safeing, a Lunar Hauler System (LHS) transits from OASIS to the OSP; (2.3); Cargo is transferred robotically from the RLL to the LHS and the LHS returns to the OASIS; (2.4) RLL inspection and check-out is performed, resulting in the discovery of an issue with the RLL; a robotic RLL movers (RRMs) transit from the OASIS logistics center (OLC) to the OSP; and, (2.5) finally, the RRMs fix to the RLL and transport it to the OASIC OLC for repair and maintenance.

8.3 Lunar Orbit Propellant Services

Lunar propellant services in Lunar orbit represent one of the 'canonical' commercial services opportunities expected to be involved in lunar settlement operations. These services are fundamental to establishing Reusable Lunar Lander (RLL) operations – which are in turn essential for affordable access to the lunar surface.

Preliminary Use Case. Figure 8-3 presents at a high-level a preliminary use case for lunar orbit propellant services. The use case involves several stages: (3.1) water delivery to the low lunar orbit (LLO) propellant depot; (3.2) electrolysis of the delivered water takes place, followed by liquefaction and production of LOx and LH_2; (3.3); the vehicle that will require refueling arrives as scheduled; (3.4) vehicle refueling is accomplished; and, (3.5) the vehicle departs the LLO Propellant Depot (for either surface or for an orbit transfer).



This 'use case model' involves the end-to-end "concept of operations" (CONOPS) to deliver the following value

"Propellant in LLO for Reusable Lunar Lander Operations"

Figure 8-3 Use Case Diagram: Lunar Orbit Propellant Services

8.4 Lunar Visitors

Lunar travel and tourism accommodations and services (including government and corporate visitors) will likely be a primary 'direct market' for a lunar settlement; however, it is likely that essentially all materials involved in servicing this business must be 100% recyclable.

Preliminary Use Case. Figure 8-4 presents at a high-level a preliminary use case lunar travel and tourism, focusing on the recycling of consumables associated with the individual visitors to the Moon. The use case involves several stages: (4.1) Visitor consumables are delivered and transferred to OASIS; (4.2) consumables (including air, water and food) are delivered from OASIS to visitors for consumption; (4.3) visitor-produced materials (CO_2, water vapor, waste and trash) are collected by OASIS systems; (4.4) chemical and thermal processing and recycling of all waste streams is performed; and, (4.5) the settlement biosphere accomplishes recycling of any remaining waste streams through agriculture and/or other means (e.g., bio-digestors).

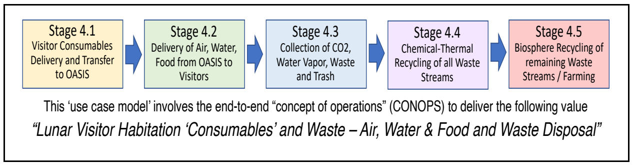


Figure 8-4 Use Case Diagram: Lunar Visitor Habitation Consumables Services

8.5 Surface Power

Generation and delivery of power to lunar surface markets and missions represents a essential capability for a lunar settlement. And, lunar surface power must be delivered at levels dramatically greater than any prior to the settlement: megawatts will be required, not kilowatts. Although there will certainly be government power systems, it is presumed that commercial vendors, perhaps working through public-private partnerships will be involved in delivering large-scale power, particularly for largely or partially commercial ventures (such as mining).

Preliminary Use Case. Figure 8-5 presents at a high-level a preliminary use case for lunar surface power. Due to the scale of power required, the need for rapid growth and the topography of the south polar region, it is presumed here that this commercial activity will involve solar power generation and wireless power transmission. The use case involves several stages: (5.1) a specific OASIS load system (OLS – a power consumer) identifies that it requires energy to recharge local storage and transmits a request; (5.2) the OASIS Power System (OPS) responds and coordinates delivery of power with the OLS; (5.3); OLS transmits a coded 'pilot signal' and the OPS begins wireless power transmission (WPT); (5.4) OLS receives and stores energy until 'full', then signals the OPS to stop WPT, which the OPS confirms before action; and, (5.5) finally, the OPS stops WPT and the OLS begins providing power to 'users'.

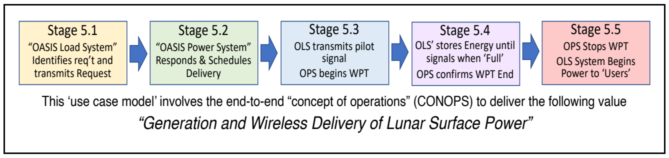


Figure 8-5 Use Case Diagram: Generation and Wireless Delivery of Lunar Surface Power

8.6 Habitable Volume and 'Agricultural Land'

Providing a biosphere for lunar settlers will be a critical but tremendous challenge, requiring to a total of 1,000 m^2-1,500 m^2 of area per settler (including habitable volume, 'Earth-normal' air, 'agricultural land' and agricultural water).

Preliminary Use Case. Figure 8-6 presents at a high-level a preliminary use case for lunar habitable volume and agricultural operations – focusing on a key issue: water.

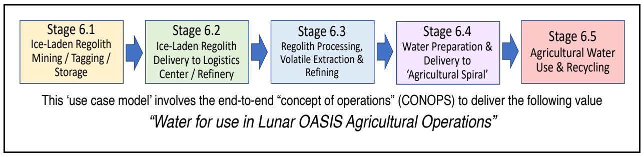


Figure 8-6 Use Case Diagram: OASIS Agricultural Complex: Water Cycle.

The use case involves several stages: (6.1) cold ice-lading regolith (CILR) mining and tagging; (6.2) CILR delivering to the Logistics Center & Refinery (ICR); (6.3); regolith processing, heating and volatile extraction (including water and other volatiles); (6.4) water preparation (including sanitation) and delivery to the agricultural spiral; and, (6.5) agricultural water use and delivery to the recycling system.

8.7 Lunar Surface Science Station

Support for a lunar surface scientific research station (presumed to be an observatory on the far-side of the Moon) will represent an important potential government contracting market for a lunar settlement.

Preliminary Use Case. Figure 8-7 presents at a high-level a preliminary use case for a lunar science station. Due to the distances involved (from the settlement to the remotely-located science station) and the topography of the south polar region, it is presumed here that this commercial activity will involve a 'reusable hopper' for transportation (cargo, crew, robotics, systems) to and from the science station.

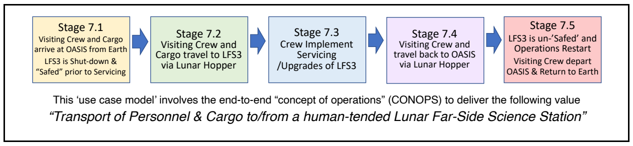


Figure 8-7 Use Case Diagram: Lunar Far-Side Science Station Services

The use case involves several stages: (7.1) visiting crew and cargo arrive at OASIS from Earth and the Lunar Far-Side Science Station (LFS3) is shut-down and 'safed' prior to servicing; (7.2) visiting crew travel with required cargo (e.g., spare parts, logistics) to the LFS3 via Reusable Lunar Hopper (RLH); (7.3) visiting crew verify LFS3 status, and as appropriate implement servicing and/or upgrades of the LFS3; (7.4) visiting crew travel back to OASIS via RLH; and, (7.5) LFS3 is 'un-safed' and operations restart; visiting crew depart OASIS and return to Earth.

9. Preliminary System / Cost Modeling

A final step in the case study is to develop high-level models, and at least preliminary estimation of potential costs. Figure 9-1 presents a notional approach to preliminary modeling and cost-estimation for the OASIS 2045 settlement. As shown, the methodology begins with identification of prospective missions and markets (e.g., the areas of interest for the use cases described above). This is followed by definition of the overall architecture and individual systems, and framing CONOPS (concepts of operations) for particular use cases.

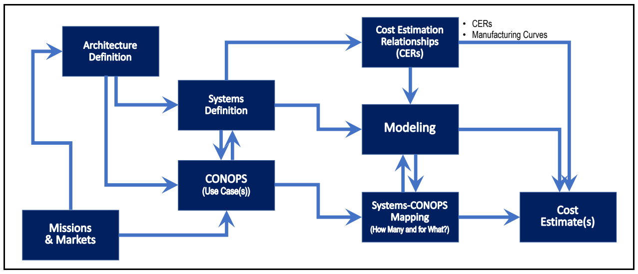
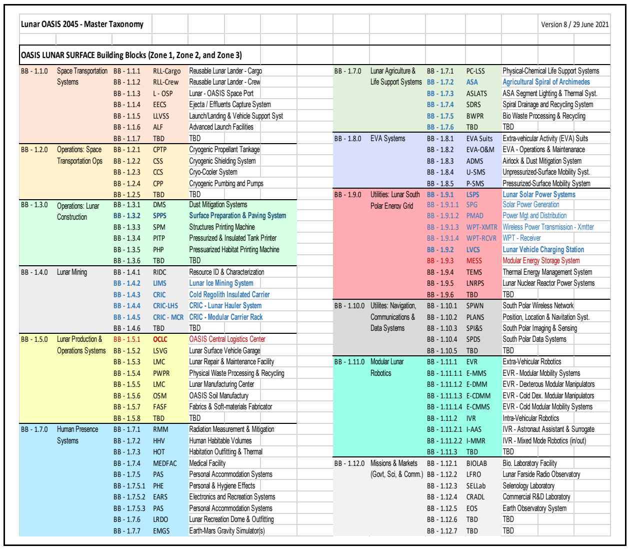


Figure 9-1 Case Study System Modeling and Cost Estimation Approach

Based on the Systems and the CONOPs, simple, spread-sheet models that analytically and numerically describe the relationships among the systems and the CONOPS (including cost estimation relationships, CERs) may be formulated. Figure 9-2 provides a screen shot from the model, indicating the variety of systems that have been considered thus far in the modeling effort.



Lunar OASIS 2045 - Master Taxonomy

Version 8 / 29 June 2021

OASIS LUNAR SURFACE Building Blocks (Zone 1, Zone 2, and Zone 3)

BB - 1.1.0	Space Transportation Systems	BB - 1.1.1	RLL-Cargo	Reusable Lunar Lander - Cargo
		BB - 1.1.2	RLL-Crew	Reusable Lunar Lander - Crew
		BB - 1.1.3	L - OSP	Lunar - OASIS Space Port
		BB - 1.1.4	EECS	Ejecta / Effluents Capture System
		BB - 1.1.5	LLVSS	Launch/Landing & Vehicle Support Syst
		BB - 1.1.6	ALF	Advanced Launch Facilities
		BB - 1.1.7	TBD	TBD
BB - 1.2.0	Operations: Space Transportation Ops	BB - 1.2.1	CPTP	Cryogenic Propellant Tankage
		BB - 1.2.2	CSS	Cryogenic Shielding System
		BB - 1.2.3	CCS	Cryo-Cooler System
		BB - 1.2.4	CPP	Cryogenic Pumbing and Pumps
		BB - 1.2.5	TBD	TBD
BB - 1.3.0	Operations: Lunar Construction	BB - 1.3.1	DMS	Dust Mitigation Systems
		BB - 1.3.2	**SPPS**	**Surface Preparation & Paving System**
		BB - 1.3.3	SPM	Structures Printing Machine
		BB - 1.3.4	PITP	Pressurized & Insulated Tank Printer
		BB - 1.3.5	PHP	Pressuarized Habitat Printing Machine
		BB - 1.3.6	TBD	TBD
BB - 1.4.0	Lunar Mining	BB - 1.4.1	RIDC	Resource ID & Characterization
		BB - 1.4.2	**LIMS**	**Lunar Ice Mining System**
		BB - 1.4.3	**CRIC**	**Cold Regolith Insulated Carrier**
		BB - 1.4.4	**CRIC-LHS**	**CRIC - Lunar Hauler System**
		BB - 1.4.5	**CRIC - MCR**	**CRIC - Modular Carrier Rack**
		BB - 1.4.6	TBD	TBD
BB - 1.5.0	Lunar Production & Operations Systems	BB - 1.5.1	**OCLC**	OASIS Central Logistics Center
		BB - 1.5.2	LSVG	Lunar Surface Vehicle Garage
		BB - 1.5.3	LMC	Lunar Repair & Maintenance Facility
		BB - 1.5.4	PWPR	Physical Waste Processing & Recycling
		BB - 1.5.5	LMC	Lunar Manufacturing Center
		BB - 1.5.6	OSM	OASIS Soil Manufactury
		BB - 1.5.7	FASF	Fabrics & Soft-materials Fabricator
		BB - 1.5.8	TBD	TBD
BB - 1.7.0	Human Presence Systems	BB - 1.7.1	RMM	Radiation Measurement & Mitigation
		BB - 1.7.2	HHV	Human Habitable Volumes
		BB - 1.7.3	HOT	Habitation Outfitting & Thermal
		BB - 1.7.4	MEDFAC	Medical Facility
		BB - 1.7.5	PAS	Personal Accommodation Systems
		BB - 1.7.5.1	PHE	Personal & Hygiene Effects
		BB - 1.7.5.2	EARS	Electronics and Recreation Systems
		BB - 1.7.5.3	PAS	Personal Accommodation Systems
		BB - 1.7.6	LRDO	Lunar Recreation Dome & Outfitting
		BB - 1.7.7	EMGS	Earth-Mars Gravity Simulator(s)
BB - 1.7.0	Lunar Agriculture & Life Support Systems	BB - 1.7.1	PC-LSS	Physical-Chemical Life Support Systems
		BB - 1.7.2	**ASA**	**Agricultural Spiral of Archimedes**
		BB - 1.7.3	ASLATS	ASA Segment Lighting & Thermal Syst.
		BB - 1.7.4	SDRS	Spiral Drainage and Recycling System
		BB - 1.7.5	BWPR	Bio Waste Processing & Recycling
		BB - 1.7.6	TBD	TBD
BB - 1.8.0	EVA Systems	BB - 1.8.1	EVA Suits	Extra-vehicular Activity (EVA) Suits
		BB - 1.8.2	EVA-O&M	EVA - Operations & Maintenanace
		BB - 1.8.3	ADMS	Airlock & Dust Mitigation System
		BB - 1.8.4	U-SMS	Unpressurized-Surface Mobility Syst.
		BB - 1.8.5	P-SMS	Pressurized-Surface Mobility System
BB - 1.9.0	Utilities: Lunar South Polar Energy Grid	**BB - 1.9.1**	**LSPS**	**Lunar Solar Power Systems**
		BB - 1.9.1.1	SPG	Solar Power Generation
		BB - 1.9.1.2	PMAD	Power Mgt and Distribution
		BB - 1.9.1.3	WPT-XMTR	Wireless Power Transmission - Xmtter
		BB - 1.9.1.4	WPT-RCVR	WPT - Receiver
		BB - 1.9.2	**LVCS**	**Lunar Vehicle Charging Station**
		BB - 1.9.3	MESS	Modular Energy Storage System
		BB - 1.9.4	TEMS	Thermal Energy Management System
		BB - 1.9.5	LNRPS	Lunar Nuclear Reactor Power Systems
		BB - 1.9.6	TBD	TBD
BB - 1.10.0	Utilites: Navigation, Communications & Data Systems	BB - 1.10.1	SPWN	South Polar Wireless Network
		BB - 1.10.2	PLANS	Position, Location & Navitation Syst.
		BB - 1.10.3	SPI&S	South Polar Imaging & Sensing
		BB - 1.10.4	SPDS	South Polar Data Systems
		BB - 1.10.5	TBD	TBD
BB - 1.11.0	Modular Lunar Robotics	BB - 1.11.1	EVR	Extra-Vehicular Robotics
		BB - 1.11.1.1	E-MMS	EVR - Modular Mobility Systems
		BB - 1.11.1.2	E-DMM	EVR - Dexterous Modular Manipulators
		BB - 1.11.1.3	E-CDMM	EVR - Cold Dex. Modular Manipulators
		BB - 1.11.1.4	E-CMMS	EVR - Cold Modular Mobility Systems
		BB - 1.11.2	IVR	Intra-Vehicular Robotics
		BB - 1.11.2.1	I-AAS	IVR - Astronaut Assistant & Surrogate
		BB - 1.11.2.2	I-MMR	IVR - Mixed Mode Robotics (in/out)
		BB - 1.11.3	TBD	TBD
BB - 1.12.0	Missions & Markets (Govt, Sci, & Comm.)	BB - 1.12.1	BIOLAB	Bio. Laboratory Facility
		BB - 1.12.2	LFRO	Lunar Farside Radio Observatory
		BB - 1.12.3	SELLab	Selenology Laboratory
		BB - 1.12.4	CRADL	Commercial R&D Laboratory
		BB - 1.12.5	EOS	Earth Observatory System
		BB - 1.12.6	TBD	TBD
		BB - 1.12.7	TBD	TBD

Figure 9-2 Lunar Oasis 2045: Definition of Systems

Ultimately, specific cost estimations may be developed. This modeling is not comprehensive, but will provide a quantitative 'slice' through the total trade space for the OASIS – allowing an initial understanding of costs and systems trades for various operations and concepts.

10. Some Working Results

The following are working results and findings of the case study to date, including both some key issues related to the 'building blocks' and the question of how a settlement might be realized (i.e., getting from now to then).

10.1 An Example: The Relationship to Lunar Surface Transportation Usage to Power Requirements

A number of analyses are now in progress. One of these involves a key systems trade study: how much power will be needed to support lunar surface transportation operations? There are a variety of key technologies involved, of course, however, there are also several important 'independent variables' that will influence the results. One of these is the percentage of water ice per metric ton of ice-bearing PSR regolith to be processed. Another is the number of trips per unit time: once a week, once a month, etc. First however, some key assumptions must be made:

- Propulsion systems are LOx/LH_2 based
- The transportation system is a 'Reusable Lunar Lander" (RLL)
- For this analysis, the RLL is based on the lunar surface (and refueled there)
- Delta-Velocity from the lunar surface to / from low lunar orbit (LLO) is taken to be 1,860 meters per second.
- Propellant is produced by an integrated ice mining-propellant production CONOPS (see Use Cases in this paper)

Also, a number of preliminary analyses have been performed that will not be presented in this paper. These include sizing of the RLL, estimation of the power required for ice mining operations, for water production, and for propellant production from that water. Based on these analyses, the following KPPs have been specified for this example:

- Propellant required is 8,000 kg per RLL round-trip, with 7,111 kg of Oxygen, and 889 kg of Hydrogen

- Payload per RLL round-trip is about 8,000 kg, including the propellant for the return to the lunar surface from LLO
- Specific energies for key operations:
    - Specific Energy for Mining Regolith: 1.5 kWh / kg-regolith
    - Specific Energy for Regolith Transport @ 0.375 kWh / kg-regolith
    - Specific Energy for Water Extraction @ 0.76 kWh / kg-regolith
    - Specific Energy for Water Electrolysis @ 5.56 kWh / kg-Water
    - Specific Energy for Prop. Liquifaction @ 2.11 kWh / kg-LOx-LH_2

Figure 10-1 and 10-2 present some key results of the system modeling and analysis thus far. First, 10-1 presents the relationship between the percentage of ice in the regolith being processes and the power required to obtain propellant from that ice. Figure 10-2 presents the relationship between the cost of energy on the Moon ($ per kWh) and the cost of transportation per lunar surface flight.

Findings to Date. The power required for lunar propellant production will be highly dependent on the percentage of ice actually available in the ice-bearing PSR 'cold' regolith processed. A prospective 'lower limit' for initial economic viability appears to be about 3%. Also, the cost of lunar surface electricity will directly drive the cost of lunar orbit to lunar surface transportation. If a cost per flight of $10,000 is to be achieved, then the cost of electricity must be about 10¢ per kWh. If the cost of electricity is on order $60 per kWh – similar to the ISS – the cost of access will be roughly $10M per flight.

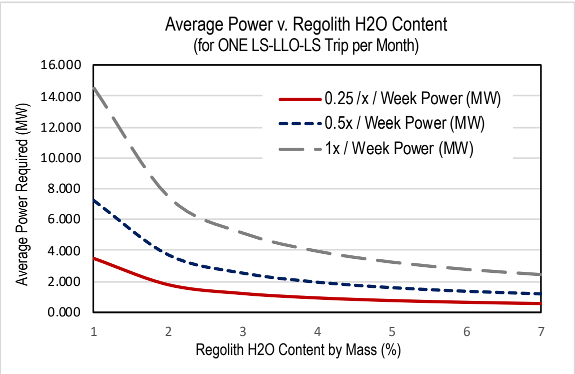


Figure 10-1 Relationship of Ice Percentage in Regolith and Power Required

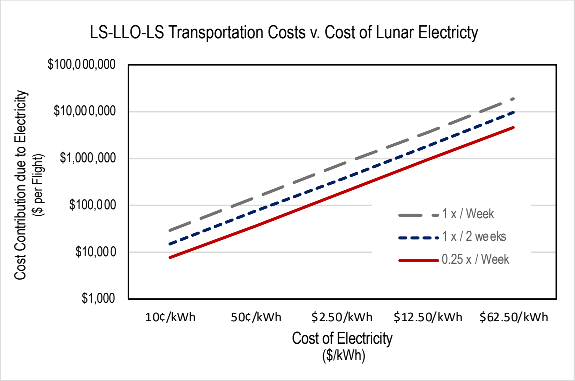


Figure 10-2 Relationship of Cost of Lunar Electricity and the Cost of Lunar-Propellant Based

The number of trips per month is also a key consideration: the greater the trips, the more power will be required. A baseline 'solution' to the problem: if ice is 5% per mass of regolith, with the LOx-LH2 RLL considered here, and a flight rate of 1 trip per week is desired, then the total power required for this 'market' will be about 3 MW. The question of where to refuel and how to provide the propellant is a key question. Refueling at both the lunar surface and in lunar orbit would provide the greatest payload-carrying capacity for the RLL. However, there will be two options for providing propellant for refueling in LLO: from the lunar surface and from LEO. In the latter case, the issue to be considered is then: how to accomplish this transportation?

These are the sorts of analysis that is needed in a variety of areas to better understand the key drivers for the viability of a future lunar settlement.

10.2 Building Blocks

10.2.1 *Utilities*. Three primary topics need to be examined: (1) the location of solar power generation (SPG) systems; (2) the requirements for wireless power transmission (WPT) from SPG to users of power; and (3) the use of *in situ* materials for regenerative fuel cell (RFC) reactants to store energy as needed on the lunar surface.

10.2.2 *Transport & Logistics*. The general concept for space transportation in the era of OASIS (Settlement 2045) is the following:

(1) dramatically lower the cost of transportation for cargo and crew to/from/to Earth and the Moon;

(2) to achieve cost reductions, use reusable systems, with refueling at optimum locations, including LEO, LLO and the lunar surface as appropriate;

(3) use high-thrust systems for crews and time-critical cargo and low-thrust-systems for non-time critical cargo (e.g., propellants); and,

(4) Integration of transportation and transported materials into the overall ‘ecology’ for the settlement systems.

10.2.3 *Operations*. There are three primary types of surface mobility operations that will be needed: (1) mobility systems to provide haulage of mined regolith back to OASIS for processing; (2) mobility systems to provide transport of electrolyzed water products (pressurized Hydrogen and Oxygen gasses) from OASIS to the cryogenics depot; and, (3) transport of cryogens from the depot to the Space Port. In addition, logistics transportation will be needed to and from the Space Port and OASIS (cargo, settlers, visitors, waste produced during transit from LEO to LLO, etc.). Lastly, Reusable Lunar Landers (RLLs) as describe above will need to be moved off the primary landing pad to a staging area at the *Space Port*.

10.2.4 *Resources*. The key issues related to resources involve the permanently shadowed regions (PSRs) and prospects for ice mining and derived *in situ* propellant production (ISPP). For the purposes of this case study, there are four primary categories of requirements for regolith mining in the permanently shadowed regions (PSR): (1) water for the biosphere of the OASIS #1 lunar settlement (described in sub-section 5.5 below); (2) propellants for the lunar travel and tourism (LTT) industry; (3) propellants for settler transportation (at the beginning of operations); and (4) reactants for energy storage.

There are four central questions associated with PSR resources: (1) how and where to process the ice-laden regolith? (2) how and where to process the extracted water? (3) how and where to make cryogens? And, finally (4) how to transport the materials at each step? In addition, there are the closely related questions of how and where to generate the required power and how to dissipate the resulting ‘waste’ heat?

10.2.5 *Habitation / Self-sustaining ‘Biospheres’*. Many (perhaps most) conceptual studies of habitation on the Moon, Mars or elsewhere presume that habitation systems will be fabricated on Earth, transported to the target destination and installed (e.g., buried) for use. However, in order for large-scale agriculture to be undertaken – a central requirement for self-sufficient human settlement – the use of local materials seems essential. The scale, configuration, materials and structural design of habitable volume is an important issue to be resolved.

In addition to the pressure vessel of the settlement and its ‘farm’, other key issues with establishing a self-sustaining biosphere are manifold and revolve around establishing key cycles: air, water, energy, waste (Carbon, Nitrogen, etc.), managing the ‘biome’ of the biosphere (virus, microbial life, fungi, plants, insects, other animals, etc.).

Some central issues involve sourcing Nitrogen for the atmosphere, creating soil (primarily, but not exclusively from regolith), delivering energy and removing waste heat, and others. This will certainly require a holistic and adaptive approach to design and development and not a deterministic one: a biosphere is not a computer, microbes and fungi are not ‘code’, etc. A program of tiered design, development, prototyping, testing and documenting results – and increasing degrees of fidelity to the final objectives of the system – will almost certainly be needed.

10.2.6 *Human Operations & Health*. An array of in-space human health and operations issues have been explored on the ISS during the past two decades. This knowledge will provide a strong foundation for establishing a self-sufficient human settlement on the Moon. However, numerous additional issues must be addressed; these will include known problems and supposed solutions, unknown challenges associated with known problems, and current mysteries that are described as ‘unknown unknowns.’ Some problems – such as radiation effects and protection outside Earth’s protecting magnetic field – are well-known and can be addressed through focused R&D. However, it is likely that many of the challenges will only be fully resolved once the development and deployment of a settlement has begun.

10.2.7 *Robotic Systems.* There are a number of clear issues associated with robotic systems to be used in the development and operation of a lunar settlement. Some of these will involve the degree to which the settlement is deployed by robotic surrogates, rather than by human astronauts; this will likely be extremely important early in the process. Another issue that will be novel to a settlement will be the balance between internal robotics, i.e., inside the pressurized volume an those external to it. (This is similar to the situation on the ISS.) However, there may also be robotic systems that move back and forth between the two environments – just a astronaut-settlers will.

10.2.8 *Science Missions / Payloads*. There are a variety of operational questions related to science at a permanent lunar settlement. Where will science missions and payloads be deployed, and how? What investigations will be prioritized earlier (during settlement development) and which are likely to be delayed until later?

10.3 Getting from Now to Then

The evolution from early lunar exploration and technology development activities (as illustrated in the GER from the ISEC-G earlier) is a key question that must be resolved. In order for 'OASIS 2045' to be realistic, the path from the early-2030s to the mid-2040s must be tractable and affordable.

The major changes that must occur in the transition from current plans (2025), to an early lunar outpost (c. 2035) to a proper settlement (c. 2045) can be expected to involve evolution of the early marketplace from primarily government and selected commercial markets to a much more diverse, and private sector focused marketplace (including individual settlers). This will involve:

- c. 2025: an initial human landing (planned), as well as intensifying robotic missions to multiple sites for scientific and technological objectives.
- c. 2035: government contracting, goods and/or services for government markets, goods and/or services for commercial markets, and goods and/or services for individual visitors (e.g., public space travel customers).
- c. 2045: as described above in this paper.

Detailed modeling and analysis are required to better understand the likely economics of a lunar settlement in general, and various specific markets in particular. This must include an integrated input-output matrix for various needed goods and services to determine the expected cost for such market contributions.

Nevertheless, there are several critical 'evolutionary' goals that must be carefully addressed and aligned with economical drivers in order for them to be achieved. These include (1) establishing a modular and scalable energy infrastructure to power all other objectives; (2) the economically-sustainable establishment of lunar resource utilization (particularly ice mining and propellant production) to enable low-cost access to the Moon; (3) the phased and affordable creation of habitable volume on the Moon for settlement, including the creation of water and soil for agriculture; and (4) the timely and profit-driven importation of both Carbon and Nitrogen to the emerging OASIS – a process that will likely require decades to achieve.

11. Summary

During the recent years, plans and activities that will lead to permanent human expansion to Earth's Moon have been changing rapidly. Commercial activities are progressing far more rapidly than ever before. Humanity is now extending activities to the Moon, including exploration, human presence and discovery and potential development of key resources, such as lunar polar ice. The "Moon Village" concept provides a framework for prospective activities in space, near and on Earth's Moon. In terms of the requirements identified, a lunar settlement appears to be technically feasible, however there are some significant unknowns that must still be resolved. For example, the biological feasibility of long-term healthy human life in a low-gravity environment, such as that of the Moon (at approximately 1/6th gravity) must still be established. The same is true for healthy existence of other animals, plants, fungi and other species that are essential to establishing a sustainable biosphere.

Of course, additional work remains to be done even in completing an initial 'case study' of a potential human settlement at the lunar south pole. However, good progress has been accomplished and the ground prepared for numerous more detailed assessments and R&D in future.

12. Glossary of Acronyms

Architecture WG	MVA Architectural Concepts and Concerns Working Group
BRLSS	Bio-Regenerative Life Support Systems
CFD	Cryogenic Fluid Depot
CLPS	Commercial Lunar Payload Services
CONOPS	Concept of Operations
DLRE	Diviner Lunar Radiometer Experiment ("Diviner")
DRA	Design Reference Architecture
ESA	European Space Agency

EMU	Extravehicular Activity (EVA) Mobility Unit
ETO	Earth-to-orbit (transportation)
EVA	Extravehicular Activity (Systems)
GER	Global Exploration Roadmap
ISEC-G	International Space Exploration Coordination Group
ISPP	*In Situ* Propellant Production
ISRU	*In Situ* Resource Utilization
JAXA	Japan Space Exploration Agency
kg	kilograms
km	kilometers
LFS^3	Lunar Far-Side Science Station
LIMS	Lunar Ice Mining System(s)
LLO	Low Lunar Orbit
LOLA	Lunar Orbiter Laser Altimeter
LRO	Lunar Reconnaissance Orbiter
LTT	Lunar Travel and Tourism
m	meters
MT	metric tons
MV	Moon Village
MVAE	Moon Village Architecture Element
MVA	Moon Village Association
MW	megawatt
NASA	National Aeronautics and Space Administration
NGO	Non-Governmental Organization
NRHO	Near-Rectilinear Halo Orbit
OASIS	Off-Earth Autonomous Selene-based In-space Settlement
OCD	OASIS Cryogen Depot
OSP	OASIS Space Port
OTV	Orbital Transfer Vehicle
PSR	(Lunar) permanently-shadowed region
RFC	Regenerative Fuel Cell
RLL	Reusable Lunar Lander
R-OTV	Reusable OTV
SEPS	Solar Electric Propulsion System
SPG	Solar Power Generation
SSP	Space Solar Power
TBM	Tunnel boring machine
WG	Working Group
WPT	Wireless Power Transmission

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