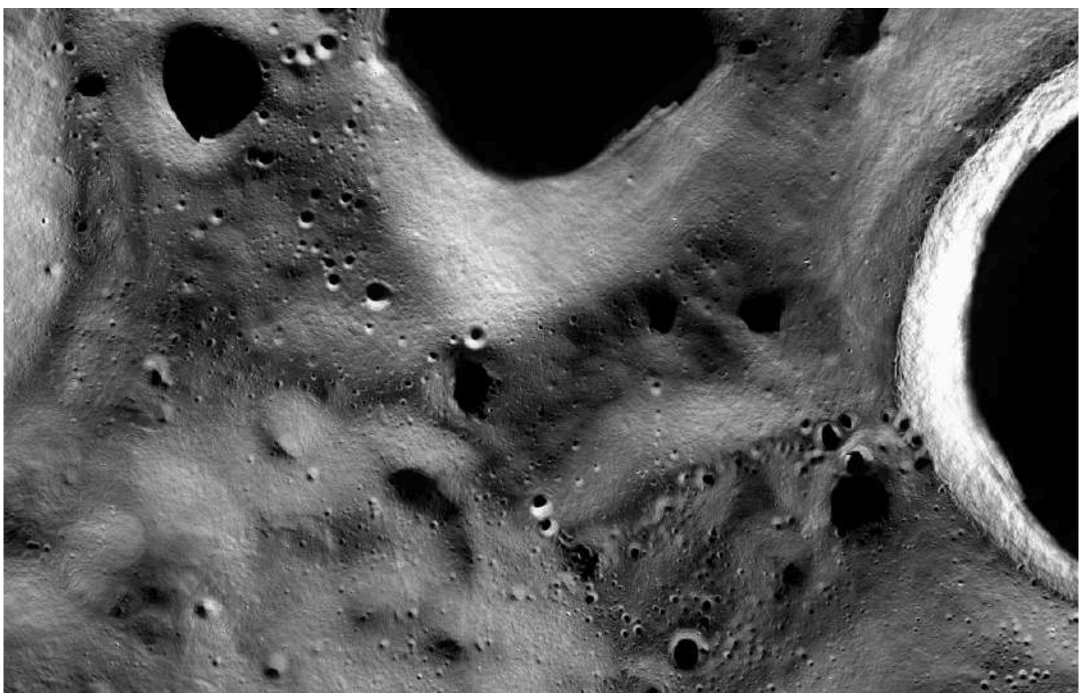
Architecture Working Group
2020 WORKSHOP FINAL REPORT



14-16 December 2020
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Moon Village Association

Architectural Concepts and Considerations Working Group

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SUMMARY

The Moon Village Association (MVA) is an international non-Governmental organization (NGO), based in Vienna and established for the purpose of advancing humanity's presence and activities on and near Earth's Moon. The MVA's Moon Village (MV) Architecture Working Group (WG) is conducting during 2020-2021 an "Architecture Reference Case Study" – addressing prospects for the first human settlement on the Moon, targeting the 2045 timeframe, but looking back toward the present (e.g., 2025 and 2035) and beyond to the further future. During 14-16 December 2020, the MVA Moon Village Architectural Concepts and Considerations Working Group (MV Arch WG) organized an online workshop.

This document is the final report from that workshop. It comprises several primary sections as well as 'annexes' that address specific details; the contents are described on the second page following.

Participants in the event included individuals from the Netherlands, France, Italy, Japan, Kuwait, The Netherlands, Ukraine and the USA, and other countries.

Co-organizers of the event included: Dr. Madhu THANGAVELU (Conductor, Graduate Space Concepts Studio, University of Southern California (USC), and North American Coordinator, Moon Village Association (MVA); INATANI, Yoshifumi (Member of the Board, MVA, and Co-Chair, MVA Moon Village Architecture Working Group); and, John C. MANKINS (Vice President, MVA, and Co-Chair, MVA Moon Village Architecture Working Group).

John C. MANKINS
Vice President, Moon Village Association
Co-Chair, MVA Moon Village Architecture Working Group

A REMEMBRANCE

In March 2021, a good friend and space visionary, Charles (Chuck) Lauer passed. His many valuable contributions toward realizing an ambitious future in space – at the December 2020 Moon Village Architecture Workshop and in other venues and activities over a lifetime of accomplishment – will be remembered.

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SECTION 1

INTRODUCTION

The "Moon Village" represents an encompassing concept for a diverse assortment of planned and prospective activities on and near Earth's Moon. It is not limited to a specific project, location or organization. The Moon Village is the ensemble of all efforts from the private sector, governments and others to explore and use the Moon in a sustainable manner. It is not a literal village on the Moon, it is not an "International Space Station on the Moon," and it is not a single science facility.

The Moon Village will rely on automatic, robotic and human-tended elements to achieve sustainable lunar orbital and surface operations, serving multiple purposes on an open-architecture basis. Additionally, the Moon Village could achieve multiple objectives: astronomy, fundamental research, science, communications, space resources utilization, manufacturing, arts, entertainment, tourism, discovery, human settlement etc. Moreover, it could stimulate new alliances between public and private entities, including non-space industries and operators. Additionally, the Moon Village could provide a strong inspirational and educational foundation for younger generations.

The Moon Village vision can be a key factor for the peaceful future of humankind. It could serve as a catalyst for government, scientific research, education and industry activities, stimulating a virtuous cycle of economic development by all and for all humankind. Industry will build infrastructures, with the assistance of government and private funding, and will also facilitate the creation of a governance and contractual framework to sustain the architecture and create new products, applications, services, and markets. Another significant value of the Moon Village is its potential role as a proving ground for missions farther out in the solar system.

To turn this vision into a reality, the space community should rally all sectors and disciplines and help put the Moon Village vision on the political agenda – as an innovation platform, inspiration and network for research during the 21st Century.

1.1 Moon Village Association Overview

Created in 2017, the Moon Village Association (MVA) is a non-governmental organization (NGO), dedicated to the goal of advancing humanity's exploration, utilization, development and eventual settlement of Earth's Moon. The organization has more than 500 members and participants in its activities, including individuals and organizations from countries around the world. The mission of the MVA is to: "Facilitate and catalyze the world-wide decision-making process for the creation of Moon Village infrastructure in/beyond LEO under sustainable and open-ended human and robotic programs, in partnership with space agencies, industry and society by creating a forum/platform", and in particular to:

- Consolidate a compelling shared vision that fosters a sense of belonging and inspires a group of people to create the Moon Village together.

- Coordinate space and non-space organizations in supporting the vision, creating a new open dynamic that includes ideas from space agencies, commercial space, donors, philanthropist and citizens.
- Stimulate global awareness of the prospective benefits of the Moon Village, with arguments about how Earth's citizens, regions, and the environment will benefit in the near and mid-term if humanity advances to establish a permanent base on the Moon.
- Coordinate discussions and workshops with financial industry experts and entities with the goal to establish the necessary financial infrastructure and means to support the development of the Moon Village and associated economic activities.
- Create a paradigm shift in how international space missions are being designed - in a fast, low cost, creative and collaborative manner.
- Foster the vision to the society at large to engage citizens worldwide.
- Act as representative of the civil society and international space community in the decision-making process.

The Moon Village vision encompasses a large variety of actors and motivations, and it is gaining support from a broad spectrum of stakeholders, including those beyond the usual space community: industrial verticals financial sector, scientific community, civil society, and others. As a consequence, it is necessary to implement new frameworks for discussion and cooperation, beside the on-going classical groups led by government Space Agencies and groups (such as the ISEC-G, ILEWG, LEAG, etc.). The intent is not to replace these groups which deliver important beneficial results, but to offer the opportunity to new non-governmental and non-space stakeholders to play a role in the definition of the concept.

1.2 MVA Architectural Concepts and Considerations Working Group

Within the MVA, there are various working groups; one of which is the Architectural Concepts and Considerations Working Group (the "Architecture WG"). The Architecture WG concerns itself with a variety of technical issues that pertain to the Moon Village concept, including scenarios, building blocks and case studies. The WG considers current government and industry plans, but looks beyond to the longer-term future on the Moon – as discussed in the paragraphs that follow.

1.2.1 Scenarios

The Moon Village Scenarios build upon the official government plans – for example, as documented in the 'Global Exploration Roadmap" (GER) by the International Space Exploration Coordination Group (ISEC-G). Where the GER only extends to the end of the coming decade, however; the MV Architecture WG considers activities that reach to the middle of this century and beyond. Moreover, both government and private sector circumstances and plans are constantly changing: it is impossible to know the future.

As a result, the Architecture WG defined a set of three possible high-level scenarios for how humanity's lunar activities may unfold over the coming years. These involve three distinct drivers for human activity at Earth's Moon. The first version of the scenarios (developed in 2018) has been updated during 2020 based on external events during 2019-2020, as well as working group activities. The new scenarios involve the following drivers: exploration, science and development. Annex B of this report provides a preliminary update of the Moon Village Scenarios.

1.2.2 Building Blocks

Another Architecture WG activity is the identification of candidate MV systems, including the so-called 'MV Building Blocks' as well as key interfaces and standards among the building blocks. The MV Building Blocks provide a useful reference for organizations and countries. One such activity has been MVA's PESC program ("Participation of Emerging Space Countries"), in which various teams in countries around the world have used the Building Blocks and the Scenarios as a framework for developing their own plans for prospective involvement in lunar activities.

1.2.3 Reference Case Studies

Finally, during 2020-2021 the Architecture WG is conducting its first design reference case study – focused on the idea of establishing the first human settlement on the Moon by 2045. This case study was the principal topic for discussion during the December 2020 workshop that is the subject of this report. Additional details regarding the current case study are discussed in Section 3.

1.3 The 2020 Moon Village Architecture Workshop

As noted above, the MVA's Moon Village (MV) Architecture Working Group (WG) is conducting during 2020-2021 an "Architecture Reference Case Study" – addressing prospects for the Moon Village, targeting the 2045 timeframe, but looking back toward the present (e.g., 2025 and 2035) and beyond to the further future.[1] USC, including the Viterbi School of Engineering has for years conducted well-known and respected academic programs in space systems engineering and architecture studies – during 2020 focusing in part on lunar surface developments.[2] The recorded zoom videos for the event are available from the MVA website at: https://moonvillageassociation.org/?s=moon+village+architecture+working+group+workshop

During the workshop and for several weeks following, inputs were invited from individual participants in the form of "ITBCs" – i.e., "issues to be considered", which were treated as though they were inputs to the discussion during the meeting. This report reflects the ITBC inputs received.[3]

1.4 This Report

This workshop report is organized into several major sections, including: Section 1, the introduction (i.e., this section); Section 2, which provides an overview of the workshop and its organization; Section 3 that summarizes the 'going in' version of the MV Architecture WG Case Study 'going into' the workshop; Section 4, which provides a brief synopsis of each day and session at the meeting; Section 5, presenting a synthetic summary of the results by theme; and Section 6, comprising key findings and the plan forward for the case study. In addition, there are several annexes, including a glossary of acronyms, a listing of workshop participants, an update of the MVA scenarios (discussed below), and a brief discussion of a new tool for assessing maturity of prospective lunar activities described as the Moon Village Readiness Levels (i.e., the "MVRLs").

1 See https://moonvillageassociation.org/about/working-groups/architectural-concepts/.

2 Please see https://sites.google.com/a/usc.edu/aste527/home.

3 Special thanks to everyone who provided an "ITBC" for the workshop – especially Mark Henley and Dallas Bienhoff.

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SECTION 2

WORKSHOP OVERVIEW

2.1 Workshop Goals & Objectives

2.1.1 Goals[4]

The goals of the 2020 MV Architecture Workshop included the following: (1) advance the implementation of 2020-2021 studies by the Moon Village Architecture Working Group (MV Architecture WG); (2) communicate MV Architecture WG 'work in progress', including updates of the 2018 "Moon Village Scenarios," updates of the 2019 Architecture WG studies, and the status and interim results from the MV Architecture WG "2045 Space Settlement Case Study" – including identification of key 'building blocks', interfaces and standards, etc. An additional goal included communicating and coordinating MV Architecture Working Group activities with those of the Moon Village Evolution Team.

Finally, two other goals of the meeting were to review through invited presentations global concepts and progress toward the key 'building blocks' and other related topics, and to review and update plans for 2021 MV Architecture WG activities.

2.1.2 Objectives

In order to accomplish the above goals, the detailed objectives of the MV Architecture Workshop were the following:

- Present the 2019-2020 MVA Architecture study results, focusing on the MV Architecture Reference Case Study;
- Communicate the results of recent studies related to lunar and cis-lunar exploration, development and settlement from various organizations, in the context of the MV Architecture Reference Case Study;
- Identify critical 'building blocks' for the Moon Village –in particular those that might emerge early and continue to play important functions in lunar development and settlement during the remainder of this century (including key interfaces and standards for interoperability);
- Examine in particular the potential role that extraterrestrial resources might play in lunar architectures, including assessing potential connections among international government and commercial programs now being undertaken.
- Identify and assess technology options, readiness and risks associated with the various systems concepts; and,
- Discuss important topics for further development during 2021 as the ongoing studies continue.

The paragraph that follows described the organization of the December 2020 workshop.

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[4] Note that neither the study to date, nor this workshop addressed the various important governance or cultural considerations that will, of course be associated with realizing a lunar settlement by 2045. Those topics may be considered in the second part of this study, and will be the topic of other, future MVA efforts.

2.2 Workshop Organization

The format for this online MVA event included four major types of sessions: (1) an opening session, presenting overview topics; (2) several working sessions, comprising presentations that address specific subjects important to the lunar exploration, development and settlement; (3) a number of online 'panels' at which specific previously identified questions were discussed; and, (4) a closing summary session, which included highlights from the meeting and plans going forward.

Several themes (corresponding to MV Architecture Working Group 'building blocks') were addressed, including:

- Theme 1*: In Situ* Fabrication of structural systems, including habitation systems;
- Theme 2: *In Situ* Resource Utilization (including propellant production);
- Theme 3: Life Support Systems (including air and water, food and agricultural systems, bioregenerative life support, recycling of biological materials, etc.);
- Theme 4: Reusable Space Transportation Systems (including vehicles for access to the Lunar Surface, refueling systems such as propellants, transportation to cis-lunar space, etc.);
- Theme 5: Power (including generation, storage and distribution); and,
- Theme 6: Lunar Market Development options, Lunar Surface Architectures, and other topics.

2.3 Workshop Logistics

Due to the ongoing COVID-19 Pandemic, a variety of online meeting tools have come into widespread use during 2020; these enable new modes of communications and information gathering. The technology chosen for this online meeting was "ZOOM". Participation was by invitation only, with a planned maximum of 50-60 individuals. The sessions were planned to be recorded to facilitate the use of the information presented for the development of an interim study report – planned to be completed (as a draft) during Winter 2020-2021. The meeting took place for several hours on each of 3 days to enable participation by individuals in Europe, North America and Asia.

Presentations involved both slides (which were requested ahead of time) and an online narration in real-time by the speaker. The time allotted for each presentation was approximately 15-20 minutes.

2.4 Workshop Deliverables

Planned workshop deliverables included the following:

- A written summary of the workshop; this document is that report.
- Copies of the presented materials (i.e., slide decks); those presented materials that are available were posted on the MVA website (see: https//www.moonvillageassociation.org).
- Recorded videos of the various sessions, which have also been posted to the MVA Website; see above.
- Updated planning for MVA Architecture Working Group in 2021; see Section 6 of this summary report from the workshop.
- Other products.

SECTION 3

2020-2021 MOON VILLAGE ARCHITECTURE CASE STUDY PROJECT

During 2020-2021, the Moon Village Architectural Concepts and Considerations Working Group ('Architecture WG') is conducting a focused Case Study on the topic of the first human settlement on the Moon, to be established by 2045. This study builds upon the foundation of the Moon Village Scenarios, which have also been updated during 2020 (see Annex D), and the Global Exploration Roadmap (GER) produced by the International Space Exploration Coordination Group (ISEC-G).

In addition to the Architecture WG case study, there is a parallel activity being conducted in Japan, under the leadership of the WG co-chair, Prof. Yoshifumi Inatani who is also the lead for 'MVA Evolution Studies.' A brief summary of Prof. Inatani's presentation on the Evolution Studies is provided below in paragraph 3.1.

3.1 MVA Evolution Team Study Summary

The MVA Evolution Team (focused in Japan and lead by Prof. Inatani) is conducting a study of the longer-term prospects for lunar settlement in parallel with the MV Architecture WG Case Study. During workshop Day 1 presentations (December 14, 2020), Prof. Yoshifumi INATANI provided an introductory overview of the various Moon Village activities that are ongoing in Japan.

These activities look to the latter portion of the 21st Century – well after the timeframe of the Moon Village Architecture Working Group (which is 2045). Prof. Inatani described various candidate elements of a 'value proposition' for a sustainable lunar settlement. He highlighted a potential 'analogue' in terrestrial economics: large scale mining in remote locations. Prof. Inatani recounted various details of ongoing lunar programs and activities – focusing on both architectural issues for sustainability (e.g., food production), and the exceptionally high-costs of transportation hat would be involved if a sustainable lunar human presence were to be founded on such ongoing systems.

A stand-alone, Japan-centric working group has been formed to formulate a 'reference model' for the Moon. Japanese activities are based on the presumption that for a sustainable society on the Moon, that high-frequency mass transport will be required. Such transport will of necessity involve dramatic reductions in cost, and that the reference model must generate the key requirements for such infrastructure.

The key assumptions for this reference model included the following: a population of 1,000 individuals to scope supply chain requirements; these would include residents, workers and immigrants. Several options are being considered for how this population might be realized, including (a) 1000 workers with a one-year duration stay (workers with ages from 30-50); (b) 1,000 population including workers and their families with a many-year duration stay; and (c) a population of 1,000 in a steady-state population (including a sustainable 'pyramid' of individuals of various ages). Other key questions that the group will consider will include the type and quality of habitation and the sources of revenues for the lunar activity, such as lunar resources mining and processing and lunar space tourism (with a baseline of 10,000 visitors from Earth per year).

Prof. Inatani stated that requirements and constraints are imposed by various technical and non-technical disciplines, and described how the team in Japan has organized to consider several factors, including:

1. An architecture working group examining infrastructure for sustainable human presence on the Moon has been formed in Japan. This group comprises various sub-groups, including systems, transportation, energy, construction, in situ resource utilization, and agriculture and life support.
2. A business working group has been formed that will examine economic activities that might create value on the Moon.
3. Also, a working group focused on regulatory issues (including rule-making and governance issues) has been formed.
4. Finally, a working group has been formed that addresses human and cultural anthropologic issues.

Also, many of the members of the various groups were indicated by Prof. Inatani.

Prof. Inatani summarized his remarks at the December workshop by noting that a reference model for a village and/or society on the Moon is now under discussion, and observed that various assumptions for such a reference model have been made. He noted that the interactions among other disciplines – such as legal, business and human aspects – will impose the requirements and constraints to architectural considerations. These will be necessary for studies to determine if and how a sustainable society may be achieved on the Moon.

As stated, the Japan-centered MVA Evolution Team activity is distinct from the Case Study, but the two activities are being coordinated.

3.2 The MV Architecture Case Study 2020-2021: First Lunar Settlement by 2045

As noted previously, the MVA Architecture Working Group has updated the scenarios, first published in 2018-2019; these are being published in parallel with this workshop report. During 2020-2021, the MVA Architecture Working Group is also conducting a focused ‘case study’ that examines in greater detail the potential consequences of a specific set of assumptions regarding the future course of events.

3.2.1 Key Assumptions

Key assumptions that provide a framework for this case study include the following:

- Assumption 1: Low-cost commercial access to low Earth orbit will transform cis-Lunar space operations during the next decade; the only question: precisely when?
  - Two options were considered: (a) that low cost launch might be available before 2025, or (b) that low cost launch might be available before 2030 – which is a less optimistic future.
  - The latter, ‘option b’ as described above is the assumption that has been made for purposes of this Case Study.
- Assumption 2: Massive government mission opportunities and commercial market ventures will be the result of the emergence of very low-cost launch; examples include:

- Space-based global connectivity through low Earth orbit (LEO) 'mega-constellations' (such as StarLink, Kuiper, OneWeb, etc.)
- These 'new space' systems will involve large-scale, low-cost production of modular space systems at costs radically lower than those of prior large space systems.

- As a result of these Assumptions, there will be several Consequences, including:
  - Consequence A: Affordable megawatt power systems (solar, wireless and potentially nuclear) will become possible, throughout cis-lunar space and the inner solar system given the market demand for powering mega-constellations.
  - Consequence B: Development of physical space resources – beginning with the Moon (and initially focused on volatiles) – will become affordable and feasible given large-scale production of modular flight hardware and large-scale power systems fabrication.
  - Consequence C: And, finally: given affordable hardware, then sustainable permanent human presence in cis-Lunar space will become technically feasible and financially viable – pending resolution of key biologically-derived questions.

3.2.2 The Economics of 'Settlement 2045'

Any lunar settlement must have a sound economic foundation. This includes but is not limited to government-sponsored lunar activities. For purposes of the MV Reference Architecture Settlement Case Study, it is assumed that in 2045 there will be a diverse set of market customers and providers for a wide range of goods and services. The following are the assumed elements of a settlement economy:

- 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'

And others, to be identified.

3.2.3 Primary Questions being Addressed

There are several important questions that are being addressed through the case study project; these include the following.

First: what do we mean by the term '**settlement'** and what is the difference between a base or camp and a settlement? Clearly, the International Space Station (ISS) is a 'base' – with resupply and no recycling of trash depending on Earth, no permanent or semi-permanent inhabitants, etc. Although much larger, the stations in Antarctica are also not settlements for similar reasons. For the purposes of this study, the following definition has been formulated:

> *"A 'space settlement' is an artificial environment located beyond Earth's biosphere in which an indefinite number of generations of healthy human beings are born, raised, live, work, and eventually die – without external inputs of materials from Earth beyond those that might be used in creating said settlement."*

Second, what is a reasonable, minimum **size** for a human lunar settlement? This topic has been examined in various papers, in many cases in the context of sizing of concepts for multi-generational interstellar vehicles. For purposes of the case study, the primary drivers are presumed to be human biology and skill-sets required for operational viability. In that framework, it is assumed that an initial more-or-less permanent population of settlers will be about *40 individuals*, with the goal to grow to an approximate steady population of about *120 individuals*.

Finally, there is the basic question of what is an optimal **location** for a human settlement on the Moon? Answering this question depends upon identifying a set of requirements for such an installation, including resources, operations, and other topics. The working set of these requirements are provided below.

3.2.4 Requirements

A set of requirements were defined as a first step to address the key questions indicated above; these included primary requirements, secondary / biological sustainability-focused requirements, and tertiary market / mission related requirements.

Primary Requirements. The primary requirements for a lunar settlement include the following:

- *Access from and to 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.
- *Energy Flows*; This challenge includes the availability of significant amounts of energy – particularly solar energy – and an environment that allows waste heat rejection.[5]
- *Concepts of Operations (CONOPS)* considerations, including an acceptable degree of surface 'smoothness' to enable surface mobility for various operations.
- *Resources considerations*, including proximity to volatiles, surface access to permanently shadowed regions (PSR), and the opportunity to transmit energy to the 'cold traps' in the PSRs.
- And, others to be identified.

Secondary / Biologically-Driven Requirements. The secondary human factors and/or biologically-focused requirements identified for a lunar settlement included the following:

- *Survival*; primarily, requirements for breathable air, potable (i.e., drinkable) water and for nutrition (food), as well as biological waste disposal
  - Also, requirements related to thermal management and radiation protection
- *Health*, which was include addressing the single greatest unknown – requirements related to the impact of partial gravity over the long-term on human health (including reproduction)

[5] 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 essential capabilities to both scale-up easily 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.

- *Self-sufficiency*, including again requirements for appropriate chemical cycles – including air (carbon dioxide, nitrogen, etc.) and water (including waste management), and others, such as
    - Including both personal and agricultural requirements
    - Biological Life Support / Ecosystem, including Agriculture (all species required, etc.)
    - Lighting / Energy Flows
    - Recycling (all sorts)
- *Concepts of Operations (CONOPS),* including extravehicular activity (EVA) systems, EVA mobility systems, and others such as repair and maintenance (both inside habitats and external to them), communications, and others.
- *Quality of Life* related requirements, including habitable volume (per person and for common spaces – including 'ceiling heights' etc. Other QoL requirements include:
    - Personal Energy (devices, lighting, thermal)
    - Communications / Info

Tertiary / Market Driven Requirements. Finally, the tertiary market and/or mission related requirements identified included the following:

- *Maximum use of locally-sourced materials* such that the settlement as a whole should be like a 'living thing' – including the capability to 'ingest' new materials, to 'digest' those materials and use them to manufacture materials and systems of value, to recycle and/or repair parts of the settlement when they need to be decommissioned, and finally to 'excrete' (i.e., to remove toxic or unusable materials from the settlement).
- *Capability to Grow*, which includes the ability to add more volume with more air, more soil, etc., and to do so largely or entirely independent of Earth.
- *Tourism Accommodations*, in particular the capability to support and/or entertain lunar tourists, as a primary market / economic opportunity to financially support the settlement. Such capabilities could include:
    - Availability of sports and/or athletics.
    - Access to the outside
    - Urgent medical care
    - Information / infotainment
    - Acceptable surface 'smoothness' for mobility
- *A Multi-Vehicle Spaceport*, including the capability to support both multiple vehicles, and different types of vehicles arriving and potentially departing, including
    - Different types, different countries, different fuels

3.3 Baseline Description of 'Settlement 2045'

3.3.1 Introduction

To begin the workshop, a baseline description of the MV 'Settlement 2045' Reference Architecture was distributed (and presented at the meeting); this concept encompasses activities in several zones, including the South Polar region of the Moon, low lunar orbit (LLO), 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).

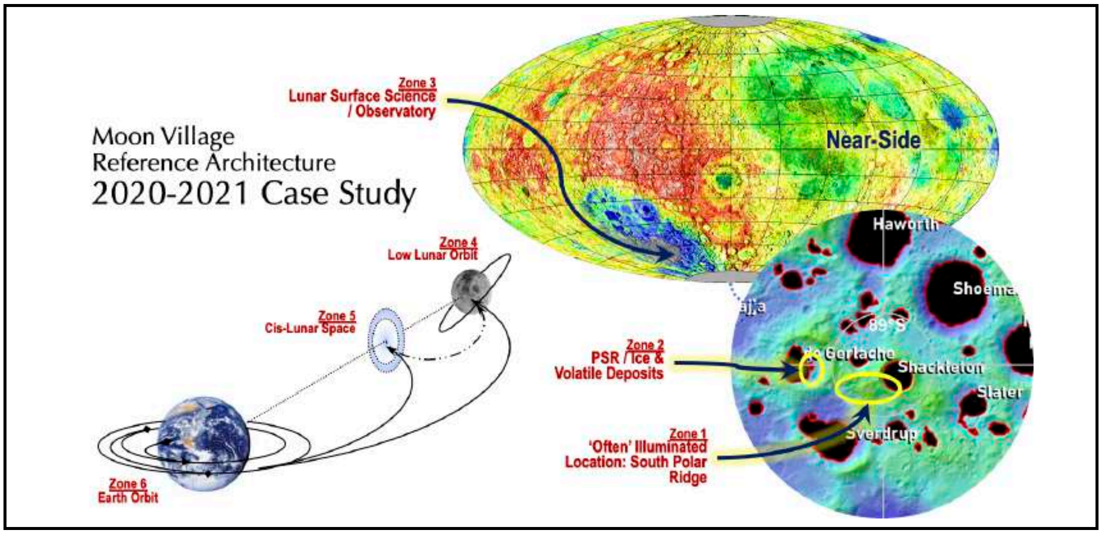

Figure 3.1 Overview of the Moon Village 2020-2021 Case Study Reference Architecture

The following are the zones referenced in the Case Study: Zone 1, south polar settlement habitation location; Zone 2, south polar ice mining and ISRU operations location (in a PSR); Zone 3, a science operations location on the far-side of the Moon (nomically in the South Polar Aiken Basin); Zone 4, LLO operations location; Zone 5, cis-lunar space operations location (nomically an Earth-Moon Libration point); and Zone 6, an Earth orbit operations location (nomically LEO). The primary focus for the discussions at the workshop was on the lunar surface zones, in order of time at the workshop involving Zone 1 (habitation), Zone 2 (mining and ISRU), and Zone 3 (science). The following paragraphs summarize the baseline 'Settlement 2045'.

3.3.1 Settlement Location

There are many locations where a lunar settlement might be established; the South Pole of the Moon may be pre-selected as the general site – 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 in on a site that satisfies the requirements stated in Section 3.2.4 above.

The key requirements that must 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 readily 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' (QoL) 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.

Figure 3-1 presents a topographical overview of the entire lunar south polar region, while Figure 3-2 indicates locations where the presence of ice has been strongly indicated.[6] However, the question remains: where exactly to locate the settlement? Availability of solar energy is a key discriminator. Figure 3-3 presents average temperature across a number of locations around the South Pole – which is a simple surrogate for the average illumination of the various locations – i.e., the availability of solar energy.

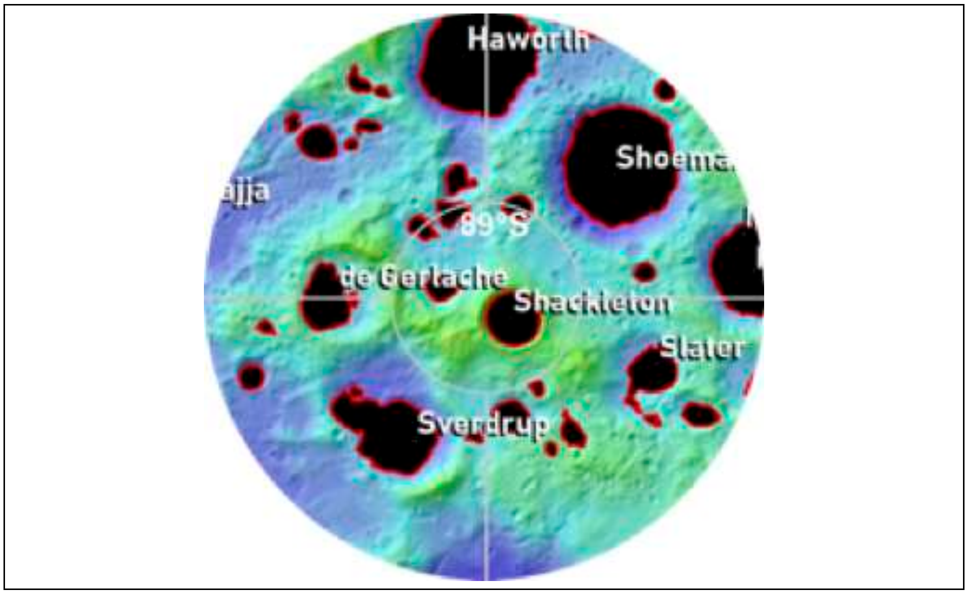

Figure 3-1 Topographical Overview of the Lunar South Pole and PSRs (Centered at South Pole, out to 87° South Latitude)

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

[6] 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.

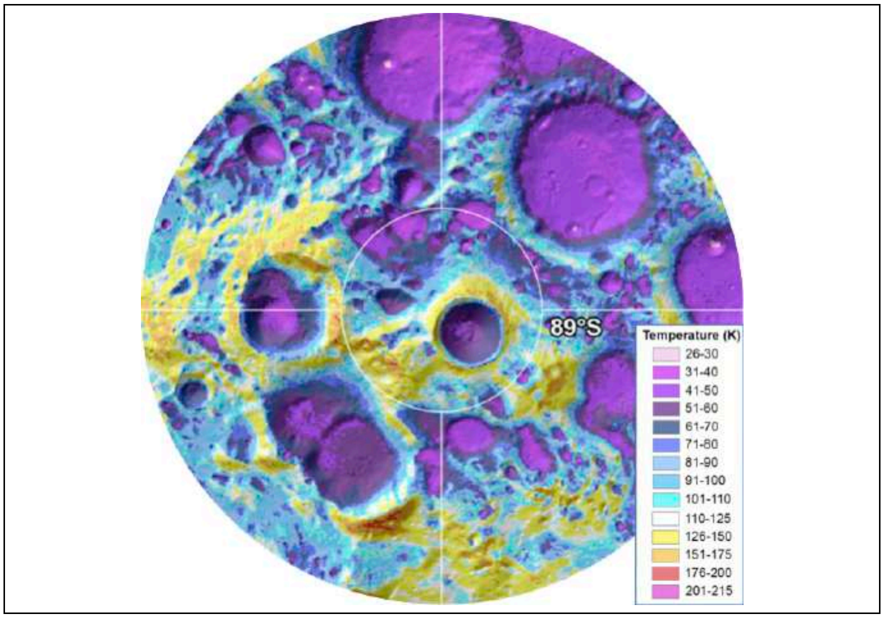

Figure 3-2 Lunar South Polar Region: Illustrating the Average Temperature of various Locations (as a surrogate for Illumination)

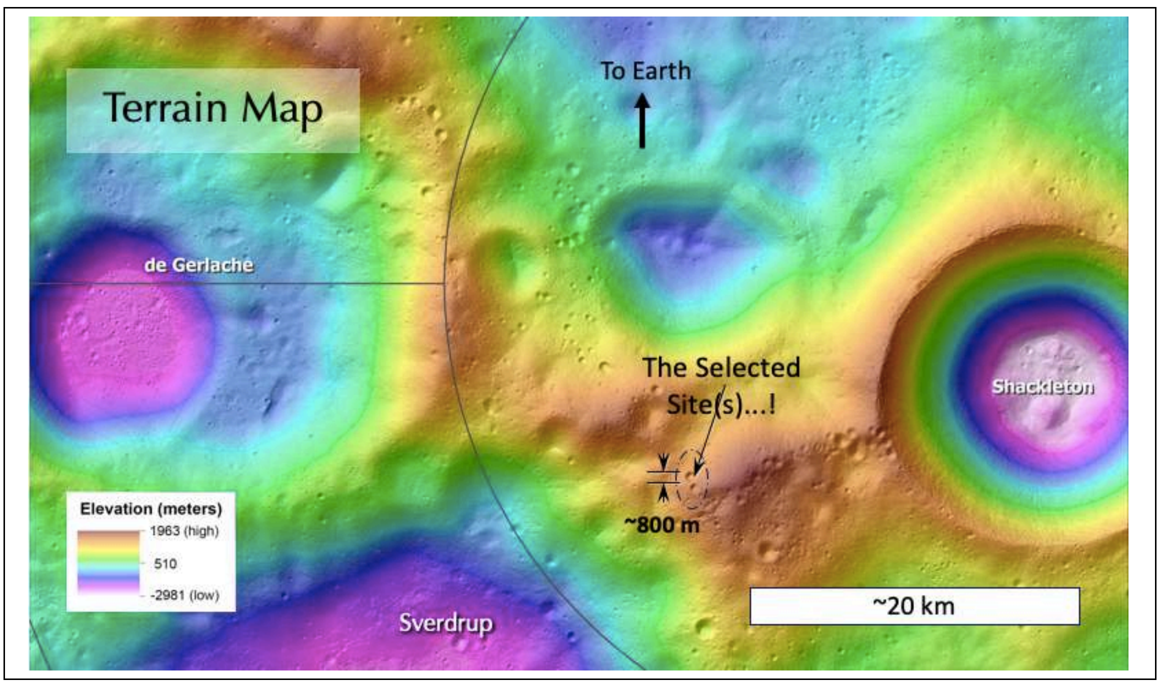

Figure 3-3 Lunar South Polar Region: Illustrating the Elevations Near Shackleton, Along the South Polar Ridge

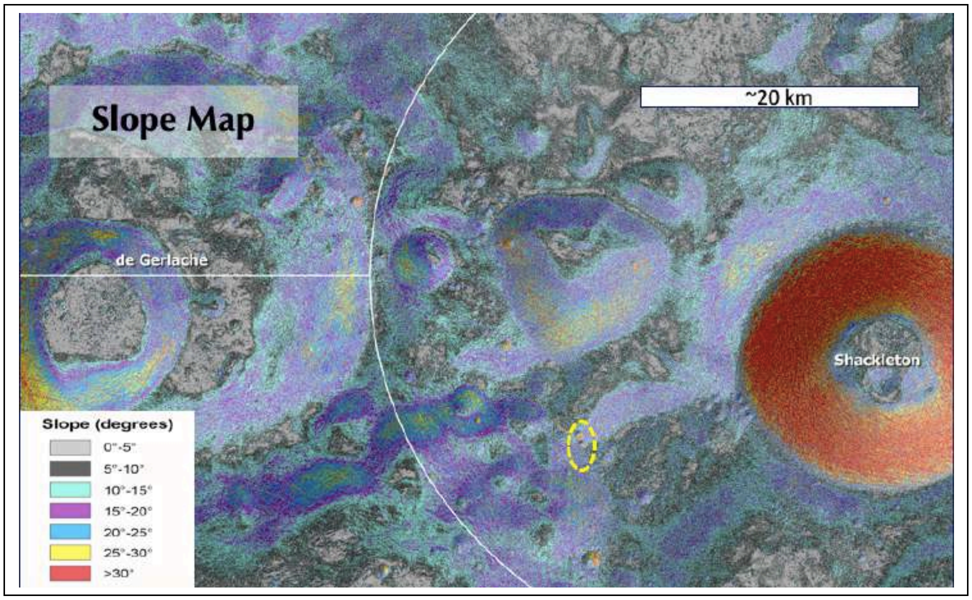

Figure 3-4 Lunar South Polar Region: Illustrating the Slopes Near the South Polar Ridge

Finally, as noted previously an important, albeit secondary question relates to the 'quality of life' for settlers and visitors is that of whether they will be able to see Earth. Figure 3-5 provides an illustration (based on JAXA data from the Kayuga mission) of Earth in the sky as seen over Shackleton Crater. In the figure, Shackleton Crater is in the lower right of the frame; the selected sites are on the shoulder of a ridge to the left of Shackleton just at the shadow's edge.

Figure 3-5 Lunar South Polar Region: View Across Shackleton Crater Toward Earth[7]

[7] Image from JAXA Kaguya Mission; c. 2007.

Based on the various factors, a specific location has been chosen. As illustrated in Figure 3-6, the lunar settlement would be located along the upper edge of crater 1, facing downslope and toward Earth (low on the south polar horizon). 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.

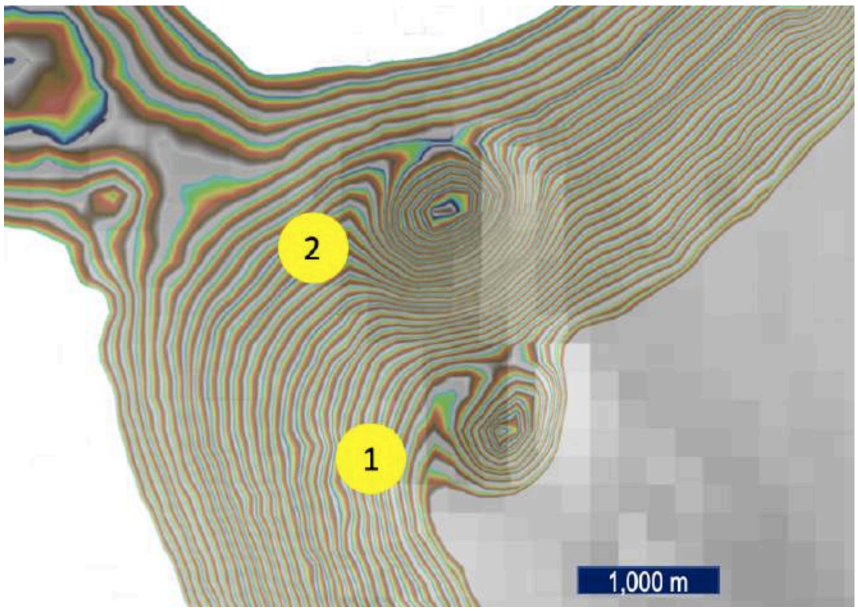

Figure 3-6 Moon Village Reference Architecture: Craters (Closeup from LRO LOLA Data)

The location of the notional MV settlement has been 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.

3.3.2 Settlement Functional Description

It is envisioned that Settlement 2045 will comprise several major segments, including functions related to habitation for the inhabitants, supporting infrastructures (including power systems), mission systems (such as surface science systems), and others. Figure 3-7 presents a preliminary high-level functional block diagram of the proposed Moon Village 2045 Reference Settlement Architecture.

As illustrated in this figure, this case study is approaching the question in a 'whole-of-system' fashion in which living organisms are a part of the system; hence the distinct functions include

- Habitation Systems, comprising both humans (residents and visitors) and the biosphere (which includes all other living organisms, air, water, soil, etc.)
- Energy Systems
- 'Air' Imports and Systems
- ISRU Systems, comprising regolith, ice/water/volatiles, and waste management
- Surface Operations Systems

- Surface Science Systems
- Space Transportation Systems
- In-Space Systems, and
- Various Cis-Lunar Markets.

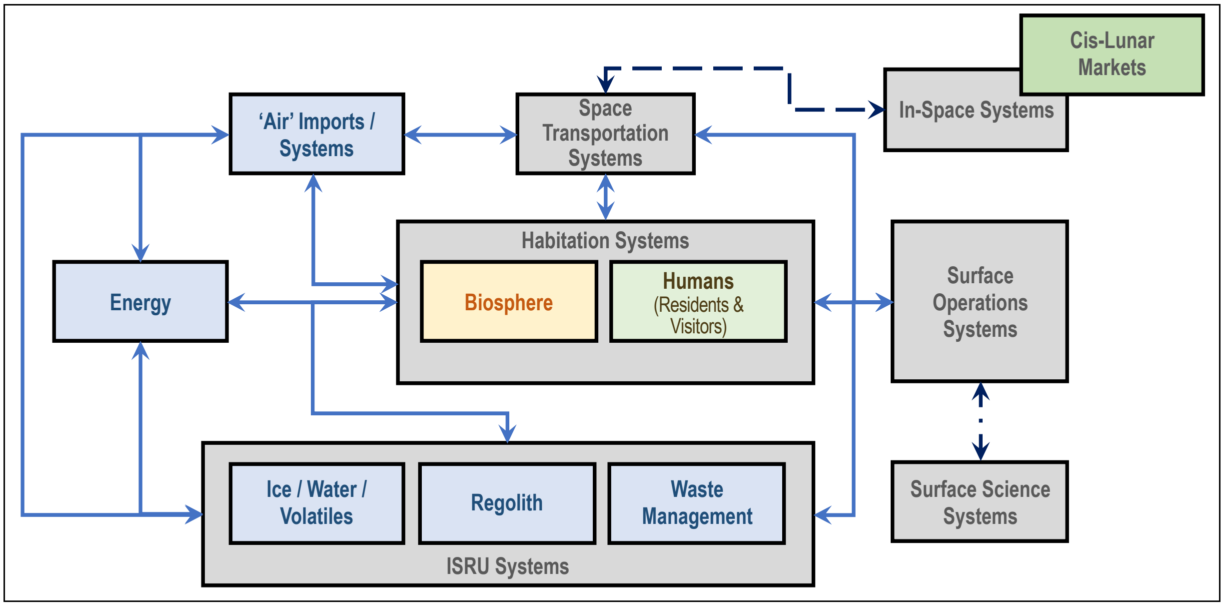

Figure 3-7 Moon Village Reference Architecture: Settlement

More detailed consideration of the nature of a lunar settlement at the selected location is needed; prospective activities during 2021 are discussed in Section 5 and Section 6.

Section 4 that follows presents a summary of the workshop results, organized by session, theme and speaker, including the several keynote speakers that started each of the three days of the meeting.

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SECTION 4

WORKSHOP RESULTS BY SESSION AND SPEAKER

The following section presents a brief summary of the presentations of each of the several speakers at the workshop, organized by day, session and theme.

4.1 Day 1

There were two primary topics discussed during Day 1: local manufacturing and construction and *in-situ* resource utilization. During Day 1 of the workshop, there were speakers from the USA, Japan, and The Netherlands. The paragraphs below summarize the speakers during Day 1 of the MV Architecture Workshop. The paragraphs that follow provide information on each of the sessions. To watch the Day 1 videos, please visit: https://www.youtube.com/watch?v=T-J35UUku3o

4.1.1 Day 1 Opening Plenary Session

The Day 1 opening session was the beginning of the workshop, comprising presentations on the working group activities, as well as the activities of the MV Evolution Study activity. Table 4.1.1 presents a summary of the speakers during the workshop opening plenary session.

Table 4.1.1 Speakers During the Day 1 Opening Plenary Session[8]

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
5:00	MANKINS, John C.	Opening & Introduction	MVA / NSS / IAA	USA
5:10	MANKINS, John C.	Moon Village Architecture Studies Overview	MVA / NSS / IAA	USA
5:30	INATANI, Yoshifumi	A reference model consideration for MV as a society on the Moon	MVA / ISAS	JAPAN
6:00	CLINTON, Raymond G. (Corky)	In Situ Fabrication, Keynote	NASA MSFC	USA

The following are brief summaries of the several presentations made during the opening session on Day 1 of the workshop. Illustrative slides from the latter two presentations are provided in Figure 4-1-1 and 4-1-2. (Images from the MV Architecture Studies overview are provided in Section 3.)

- John C. MANKINS, Prof. Madhu THANGAVELU and Dr. Yoshifumi INATANI made opening remarks at the beginning of the workshop.
- John C. MANKINS presented an overview of Moon Village Association (MVA) architecture studies during 2020-2021, providing the conceptual context for the workshop. (Note: this material is provided in some detail in Section 3 of this report.)

8 All 'times' in all tables are for Pacific Time, AM; for example, the meeting started at 5:00 AM on December 14, 2021 in California.

- Yoshifumi INATANI, Ph.D. gave a keynote presentation for the workshop.
  - TITLE: "A reference model consideration for Moon Village as a society on the Moon"
  - SUMMARY: A sustainable human activity and settlement on the Moon are the first challenge for building a society in outer space. In this context, how will this society look and how it is to be built are topics that must be considered in thinking about the further future. A reference model of relatively large human settlement as a society in comparison with the existing human space program is to be figured out, such as 1000 habitants and economical activities by resource utilization, tourism business, and so on. A background idea, basic assumptions and study status of the reference model were presented.

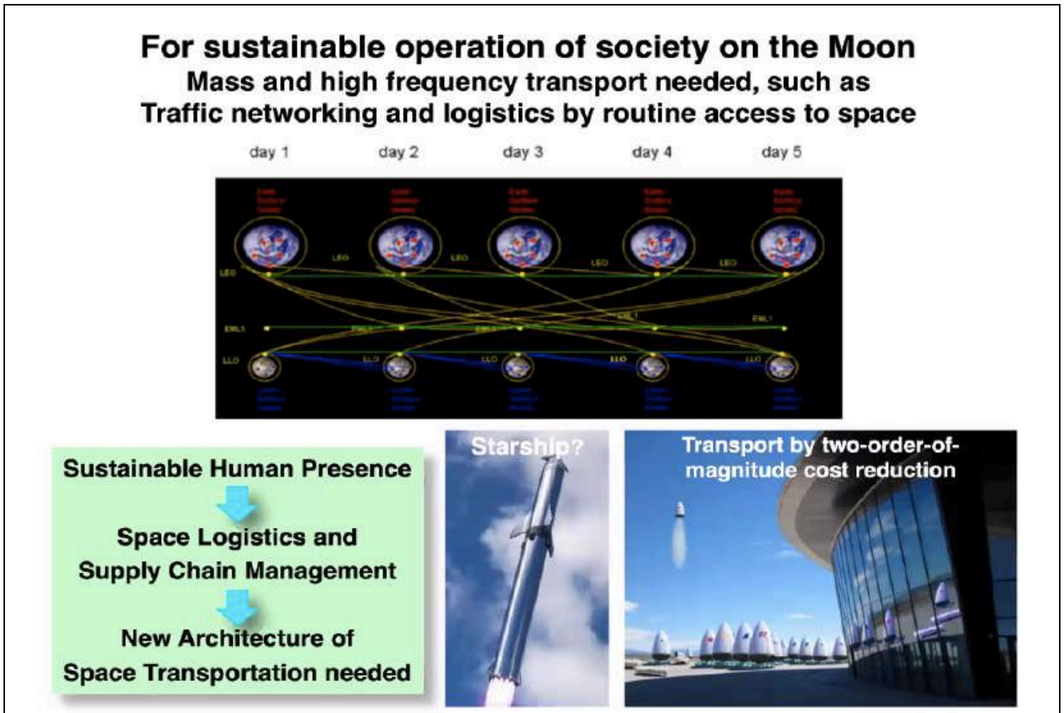


Figure 4-1-1 A reference model consideration for MV as a society on the Moon

- Raymond (aka, "Corky") CLINTON, Ph.D. gave a keynote presentation for the workshop.
  - TITLE: You Can't Always Take What You Want! In Space Manufacturing and Extraterrestrial Construction – Addressing the Exploration Logistics Challenges.
  - SUMMARY: NASA Marshal Space Flight Center's (MSFCs) first "proof of concept" experiment to assess additive manufacturing in a microgravity environment was conducted in 1999 on NASA's KC-135 reduced-gravity aircraft. Other milestones followed during the early 2000s, such as the *In-Situ* Fabrication and Repair (ISFR) Program Element (2004) supported by NASA's Office of Biological and Physical Research (OBPR) and formulated by the MSFC Exploration Science and Technology Division. The importance of such technologies was validated by analyses (Cirillo and Owens) for the International Space Station (ISS), leading to an early demonstration on ISS that involved fabrications of parts and tools from plastic feedstock.

During recent years, work related to additive manufacturing has evolved and expanded to involve new materials (metals), new fabricated items (electronics), new goals (such as ISRU, recycling and others) and new settings, primarily lunar surface fabrication and construction. The overall vision of current efforts at NASA MSFC, other NASA organizations and a range of academic and industry partners is to establish the capabilities needed to 'print' custom-designed expeditionary structures on-demand and in the field using locally-available materials. These efforts are now focused through 'MMPACT' – the Moon-to Mars Planetary Autonomous Construction Technologies activity (under NASA's Space Technology Mission Directorate (STMD) Lunar Surface Innovation Initiative, LSII) and were the topic of several talks during the current workshop.

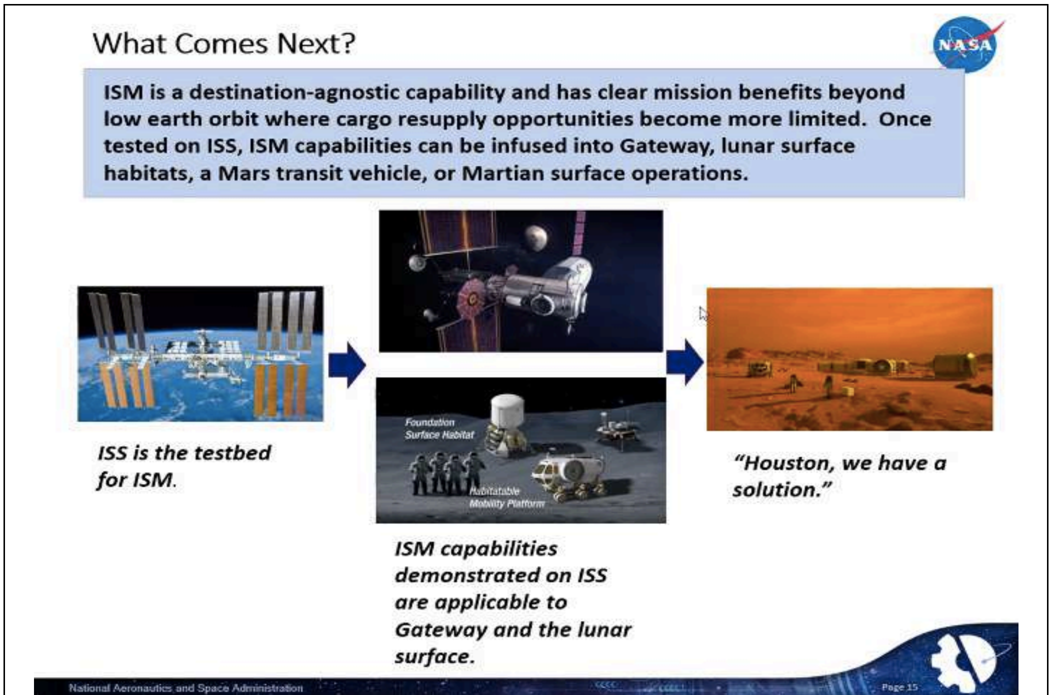


Figure 4-1-2 In Situ Fabrication, Keynote

4.1.2 Theme 1 Presentations

The topics of Theme 1 involved aspects of local manufacturing and construction including structural systems such as pressurized volume. Table 4.1.2 provides a summary of the speakers and topics during the Theme 1 session.

Table 4.1.2 Speakers During the Day 1 / Theme 1 Session

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
6:30	MANKINS, John C.	Introduction of Theme 1	MVA / NSS / IAA	USA
6:40	BALLARD, Jason	ICON Overview & Project Olympus	ICON	USA

Table 4.1.2 Speakers During the Day 1 / Theme 1 Session

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
7:00	DiMARZIO, Kevin	Manufacturing Lunar Infrastructure	Red Wire / Made-in-Space IMIS)	USA
7:20	IGNATIEV, Alex Ph.D.	ISRU & Energy	Lunar Resources, Inc.	USA
7:40	MORRIS, Michael	Lunar Lantern: Project Olympus Habitation & Landing Pads	Space Exploration Architecture; (SEArch+)	USA
	PALLES-FRIEDMAN, Rebeccah		Space Exploration Architecture; (SEArch+)	USA

The following are brief summaries of the several presentations made during Theme 1 on Day 1 of the workshop. Illustrative slides from the several of the presentations are provided in Figure 4-1-3 through 4-1-5.

- John C. MANKINS gave an introduction of the topics to be discussed under workshop Theme 1 as well as introductions for the several speakers. One key observation: there are topics discussed during each 'Thematic' portion of the workshop that also applied to / were discussed in other portions.
- Jason BALLARD, CEO of ICON, Inc. gave a presentation on 'Project Olympus', an effort under the auspices of MMPACT (see above).
  - TITLE: "ICON Overview and Project Olympus".
  - SUMMARY: Project Olympus is advancing architectural concepts and technologies for space-based construction system to support future exploration of the Moon. These include systems concepts involving quite large additive manufacturing machines using layered construction techniques, that can be used for structural fabrication both on Earth and on the Moon. Terrestrial applications include commercial building, military structures and homes in diverse settings. Past efforts related to extraterrestrial applications have addressed potential Mars surface habitats. More recently under the MMPACT program, efforts have addressed lunar surface pressurized structural systems – i.e., habitats. In all cases, a major strategic benefit is envisioned to be the use of locally-source materials, rather than importation from Earth.

    The goal of "Olympus" is to develop an autonomous construction system capable of delivering landing pads, roads, habitats and other forms of construction the lunar surface by 2025 using a 3D printing / additive construction paradigm with a strong bias toward *in situ* resources. Moreover, these systems must be extensible and designed with an eye toward multiple deposition subsystem usage and eventual Martian operations.

    The environment of the Moon is quite different from that of Earth, and a wide variety of different 3D printing machine approaches have been examined, including gantries, rovers, robotic arms, towers with booms (like terrestrial construction site cranes), and the 'flying delta' (a cable suspension systems, like the Arecibo receiver suspension). Within this framework, there are several potential techniques for sintering – i.e., heating and fusing the regolith – including both lasers and microwave heating. A variety of nearer-term experiments have been conducted, and are continuing. R&D is ongoing, including examination of various concepts of operations (CONOPS).

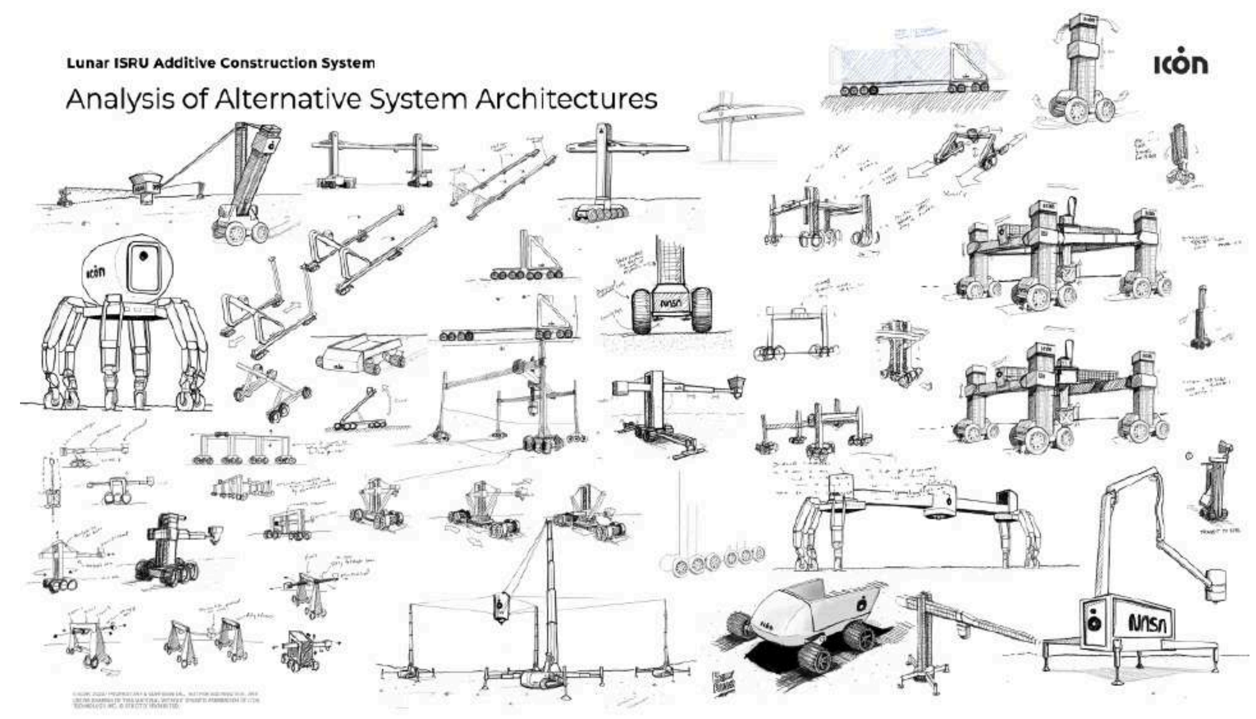


Figure 4-1-3 ICON Overview & Project Olympus

- Kevin DiMARZIO of Redwire / Made-in-Space (MIS) gave a catalytic presentation providing an overview of business activities and relevant technical R&D activities.
  - TITLE: "Manufacturing Lunar Surface Infrastructure".

    SUMMARY: Redwire (aka / formerly Made-in-Space) comprises a wide range of capabilities including on-orbit servicing, assembly and manufacturing; low Earth orbit (LEO) commercialization; advanced sensors and components; space domain awareness and resiliency; and, digitally engineering spacecraft. Redwire's in-space manufacturing and robotic assembly technology enable remote construction of large complex structures and space-optimized assets that transform the future of mission architecture and lunar surface infrastructure. These in-space manufacturing technologies and ISRU capabilities will deliver the resilient infrastructure needed for humans to sustainably venture farther from Earth than ever before on critical missions. Relevant space exploration solutions address next-generation capabilities for deep space exploration, including space-based science, ISRU, and sustainable mission campaigns (including at the Moon and Mars). Current R&D includes "RegISS" – a first-of-a-kind technology demonstration of 3D printing technology on the ISS with a polymer and regolith simulant. Other R&D efforts are developing concepts and technology for future lunar surface landing pads using locally-fabricated brick ("Regobricks"), as well as orbital metallic welding systems for potential use in cis-Lunar space.

- Alex IGNATIEV of Lunar Resources, Inc. gave a catalytic presentation addressing a diverse set of ISRU-related topics. See Figure 4-1-4 for an illustrate slide from the projection.
  - TITLE: "Lunar Surface Manufacturing".
  - SUMMARY: The fundamental stages in lunar *in situ* resource utilization comprise: (1) resource extraction and refining; (2) production of raw materials (i.e., feedstocks); and, (3) manufacturing of final products. These stages begin with the lunar regolith – a powdery mixture of metal oxides formed over billions of years of impacts and deposited to a depth of 5m-15m across the entire surface of the Moon. With a fair degree of uniformity, the regolith comprises various Oxides: Silicon, Iron, Aluminum, Calcium, Magnesium and other elements such as Titanium; missing are the lighter elements (such as Hydrogen, Carbon, Nitrogen, and so on). The key challenge for making various feedstocks is to break apart the oxygen bonds. One simple technique is that of molten regolith electrolysis (MRE) using high-temperature electrodes – e.g., about 2,000 °C – which has the advantage of requiring no reagents or secondary processing, but which does require a great deal of electricity.

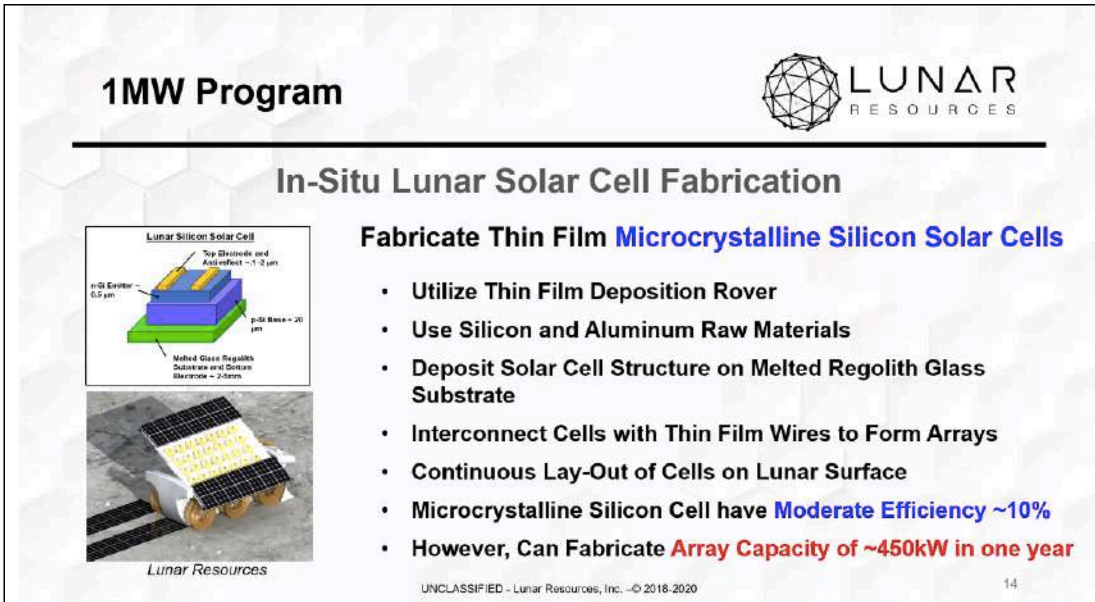


Figure 4-1-4 Lunar Surface Manufacturing

Industrial scale MRE is readily feasible and can produce not only metallurgical grade metals and semiconductor grade Silicon but also Oxygen. Power requirements for a nominal 1 m^3 MRE reactor with an annual capacity to process 64,000 kg (64 MT) per year would require some 1500 Amps (i.e., 150 kW at 100 Volts – or 1.3 x 10^6 kWh over one year) to produce approximately: (1) 13 MT of Iron; (2) 3.7 MT of Oxygen; and, (3) 3.2 MT of Silicon – along with other elemental materials in lesser amounts. Specific products will depend on the composition of the regolith used, of course.

Several R&D efforts are underway with varying objectives. For example, the 'Magma Program' will produce structural elements such as rebar, conduits, conductors, etc. from Aluminum, Iron and other elements. And, in conjunction with the hard vacuum found on the

Moon (10^{-9} torr), the Magma Program will also produce metals and semiconductors for vacuum deposition (e.g., thin film solar cells, Aluminum electrodes and wires, battery components, etc.). In contrast, the 'Farview Program' will enable the construction of one or more exceptionally large-scale radio telescopes on the lunar surface (through direct deposition). This option will involve the use of a properly configured surface rover, that can accomplish the deposition of thin-film materials and then move on – tracing out a large antenna over time. A similar rover system would be involved in the "1MW Program", but would fabricate solar cells from lunar regolith, while still on the surface and deposit needed electrical wires to produce PV arrays. The goal of this effort would be to enable 1MW of power generation capacity by 2030, as well as lunar ISRU-based battery systems.

In summary, the fabrication of both structural materials and functional materials can readily be accomplished with sufficient power / energy – and through processes that will produce significant Oxygen as a bi-product.

- Michael MORRIS and Rebecca PALLES-FRIEDMAN of Space Exploration Architecture (SEArch+), presented a variety of architectural concepts for lunar surface fabrication (as part of the ICON Project Olympus). See Figure 4-1-5 for an illustrative slide from the presentation.
  - TITLE: "The Lunar Lantern for ICON's *Project Olympus*".
  - SUMMARY: Space Exploration Architecture (SEArch+) introduces the "Lunar Lantern", designed for ICON's Project Olympus, a research and development initiative for a space-based construction system to support future exploration of the Moon.

Figure 4-1-5 Lunar Lantern: Project Olympus Habitation & Landing Pads

SEArch+'s Lunar Lantern survey presentation included a discussion of habitat, sheds, landing pads, blast walls, and roadway proposals. Key elements of the Lunar Lantern (which resembles a very large, old-style lantern) include not only the overall design but also detailed elements of the interior layout, a multifunctional wall system, the construction approach, and more. The Lunar Lantern project comprehensively aims to exceed the factors of safety for its inhabitants in support of mankind's first extended mission on the Moon's surface.

4.1.3 Theme 2 Presentations

Theme 2 comprised various aspects of *in situ* resource utilization (ISRU), including materials process and precursor activities such as mining, resource extraction, and others. Table 4.1.3 provides a summary of the speakers and topics during the Theme 2 session.

Table 4.3 Speakers During the Day 1 / Theme 2 Session

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
8:10	MANKINS, John C.	Introduction of Theme 2	MVA / NSS / IAA	USA
8:20	ABBUD-MADRID, Angel	Overview of School of Mines Activities	Center for Space Resources, Colorado School of Mines	USA
8:40	UYAMA, Naohiro	Future Lunar Construction	Shimuzu Corporation	JAPAN
9:00	KERAVALA, Jim	Offworld, Inc. Robotic Mining	OffWorld, Inc	USA

The following are brief summaries of the several presentations made during Theme 2 on Day 1 of the workshop. Illustrative slides from the latter three presentations are provided in Figure 4-1-6 through 4-1-8.

- John C. MANKINS gave a brief introduction of Theme 2 – *in situ* resource utilization (ISRU) – and the planned speakers for the session. One key observation: there are topics discussed during each 'Thematic' portion of the workshop that will also apply to / be discussed in other portions.
- Angle ABBUD-MADRID, Director of the Center for Space Resources at the Colorado School of Mines and Director, Space Resources Graduate Program made the initial catalytic technical presentation during Theme 2 discussion.
    - Title: "Lunar ISRU activities at Colorado School of Mines".
    - SUMMARY: In recent years, space agencies and the private sector have increasingly realized that further robotic and human exploration, as well as growth of commercial opportunities in cislunar space and the Moon will require extraction of materials, production of propellants and human consumables, and power generation from in situ lunar resources. This will result in more affordable and flexible transportation, facilities construction, manufacturing of parts, energy production, and life support systems.

      In addition to its long-standing educational programs, the Colorado School of Mines (CSM) is currently involved in a variety of projects in all aspects of the lunar resources value chain, including fundamental studies of lunar regolith properties, excavation, drilling, extraction, processing, manufacturing, and construction, as well as the important legal, economic, social, and education aspects of this rapidly developing field. Specific developments are being pursued in areas such as thermal 'ice mining', 3D printing of habitats, regolith sintering, metal and oxide extraction, and others. CSM has also pursued studies of the economics of commercial propellant production, involving multiple companies.

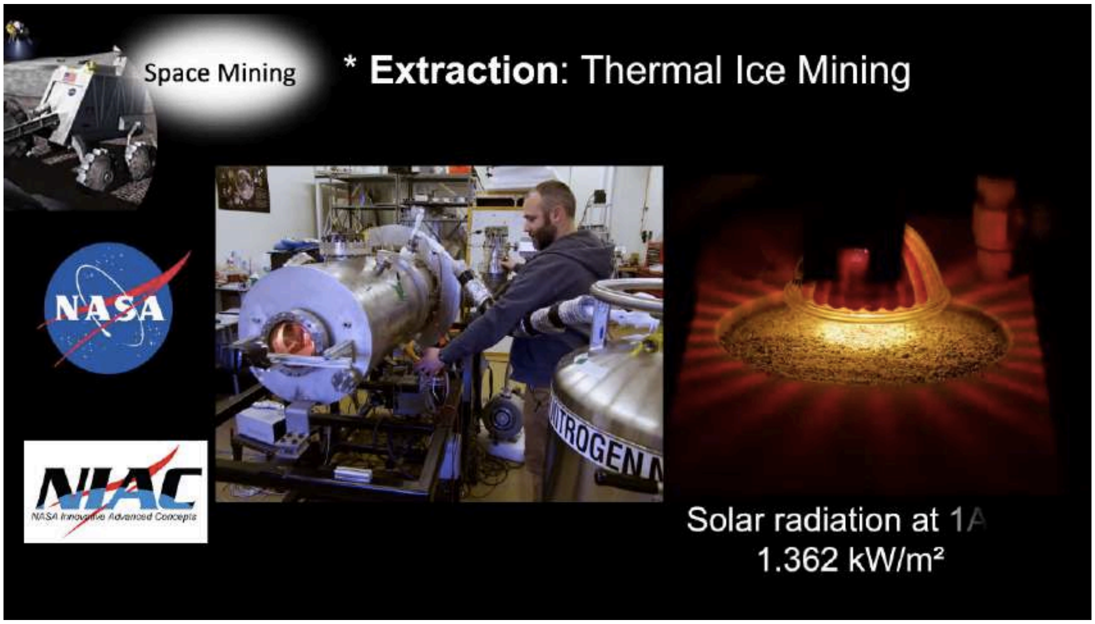


Figure 4-1-6 Colorado School of Mines Activities: Thermal Ice Mining Experiments

- Naohiro UYAMA of Space Programs, Emerging Frontiers Division, Shimizu Corporation gave a catalytic presentation.
  - TITLE: "Future Lunar Construction Concepts and Related Studies".
  - SUMMARY: Living on the Moon needs safe, comfortable and sustainable habitats. In-Space Architecture beyond the International Space Station (ISS) has not been achieved yet and is a big challenge for expanding human presence beyond the Earth. We have been working on the realization of lunar construction from future concepts to research and development. In this presentation, various concepts were presented involving lunar construction and Shimizu studies on various topics of construction-related *in situ* resources utilization, terra-mechanics, and lunar habitats.

    The presentation began with an introduction to Shimizu Corporation (founded in 1804, more than 200 years ago), and discussion of Shimizu's space programs, which go back to the latter 1980s. It also included a discussion of general topics of lunar construction, including comparison of environment, examples of lunar habitat architecture, and a summary of the factors that make lunar construction challenging. The presentation them presented a brief review of Shimizu's R&D activities, including ISRU, terra-mechanics, and inflatable structures. Activities are ongoing in production of lunar regolith simulants, lunar regolith-targeted 'basalt casting' using a solar concentrator, production of lunar concrete, production of O_2 and water from regolith with imported / recycled H_2 (not ices), mechanics and drilling in a vacuum, inflatable structures, and more.

Figure 4-1-7 Future Lunar Construction at Shimizu: Inflatable Structures R&D with TUS & JAXA

- James KERAVALA of OffWorld, Inc. gave a catalytic presentation on developments in all-electric / robotic mining technologies and systems applicable to both terrestrial and extraterrestrial mining opportunities.
  - TITLE: "Toward an AI-Powered Industrial Lunar Mining & Construction Robotic Workforce".
  - SUMMARY: There are extensive developments underway at OffWorld, Inc. vis-à-vis robotic mining and operational systems for a variety of heavy-duty industrial operations. There are a number of reasons why humans living off the Earth is an important option that must be enabled: first, as a life insurance policy again catastrophe affecting Earth; second, to support ongoing sustainable development here on Earth; and, third, because space is a new frontier for human exploration and settlement. However, settlement has always been difficult. Limited supply chains and harsh environments have in past centuries resulted in many instances in recourse to forced labor.

    Space development and settlement will be even more challenging. Various difficult tasks must be accomplished by future machine systems: building landing pads, excavating underground habitats, extracting water ice and other materials, making consumables (including drinkable water, breathable air and rocket propellants), manufacturing basic structures and functional systems (such as solar cells / arrays), producing electricity; and, eventually self-replicating.

    Developing the needed systems will take time and resources; one strategy is to begin by reinventing how we mine, process, manufacture and undertake logistics here on Earth. To accomplish this, we need not start from scratch – instead we can draw on lessons learned over decades of experience in remote location. On that basis, while humans remain safe, we can develop the means to settle space using a new generation of AI-based industrial workforce involving ultra-low cost, thousands of modular robotic systems within 'solar system wide' standards.

Figure 4-1-8 OffWorld, Inc. R&D involving AI / Learning / Avatar based modular robotic systems

To accomplish this, technical and economic goals must be ambitious: (1) to reduce total cost of operations by 10-fold; (2) to create fully-scalable solutions (valid across a range of industries); and, (3) to choose only options that can accelerate improvements in industrial productivity over the coming years. And, there are design constraints for the needed developments; these including first, no infrastructure (no facilities, no large-scale external power, etc.); second, no human involvement on site (only oversight); third, no long-term foot print (sites must be returned to their pre-existing format to the degree feasible; and fourth, no imported consumables can be used (unless fully recycled).

A simple set of modular robotics can accomplish – with changing tools and extensions – a wide variety of specific objectives, ranging from mining to tunneling to repair operations and more, on the Moon and beyond. The key is AI-driving operations, with extensive reliance on machine learning.

4.2 Day 2

There were two primary topics discussed during Day 2: regenerative life support systems (RLSS) and agricultural systems (including food projection), and reusable space transportation systems (RSTS), including both vehicles and required infrastructure systems. During Day 2 there were speakers from the USA, Italy, Japan and Ukraine. See Table 4.2.1 for a summary of the speakers who presented during the Day 2 opening plenary and technical sessions.

To watch the Day 2 videos, please visit: https://www.youtube.com/watch?v=qVqdDq3NHjA.

4.2.1 Day 2 Opening Plenary Session

The following are brief summaries of the presentations made during the opening plenary session on Day 2 of the workshop. Illustrative slides from the latter two presentations are provided in Figure 4-2-1 and 4-2-2.

Table 4.2.1 Speakers During the Day 2 Opening Session

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
5:00	MANKINS, John C.	Opening Remarks, Start of Day 2	MVA / NSS / IAA	USA
5:10	SHERWOOD, Brent	Keynote: "On Our Way ... to the Moon" (Blue Origin Lunar Exploration Activities)	Blue Origin	USA
5:40	MOORE, Christopher	Keynote: NASA Life Support R&D	NASA HQ	USA

- John C. MANKINS presented introductions of the two keynote speakers: Brent Sherwood of Blue Origin, and Chris Moore of NASA HQ / HEOMD.
- Brent SHERWOOD, Blue Origin (Advanced Programs) presented a keynote address on Day 2 of the workshop.
  - TITLE: "On Our Way ... to the Moon".
  - SUMMARY: The achievable human destinations in space aren't equal in terms of challenge or reward. Among them, only the Moon advances all Four Futures (explore, experience, extract, and expand). Opening the Moon will be more complex than building and using the International Space Station, so public-private partnerships and commercial business outside of government contracting are needed to progress through four stages of growth at a rate we would all like. The very first step is getting there and back. The National Team has submitted its proposal for the Artemis Human Landing System (HLS) to NASA. Blue Origin, Lockheed Martin, Northrop Grumman, and Draper have designed a modular vehicle system for an accelerated schedule and a sustainable future of routine lunar transportation.

    There are several phases to the extension of humanity on the Moon; these include science-driven exploration, reducing discoveries to practical applications, developing industrial-scale operations, and finally the possibility of settlement of the Moon. Operations at the Moon are significantly more complex than operations at the ISS in LEO. Writ large, the former involves up and down 'shuttle' flights, power, laboratories and habitats. However, the Moon will involve all of these as well as transportation to/from the LLO, transportation from LLO to/from the lunar surface, surface mobility and construction, and resource utilization (ISRU).

    Public-Private partnerships will play a key role in humanities lunar activities, including: science program sponsors spacefaring customers, and in the farther term terrestrial markets (including media, travel, energy and materials). Blue Origin activities in the nearer term will leverage the capabilities inherent in the HLS that will support multiple important capabilities, including cargo delivery, reuse of systems, life after landing, and supporting establishing a lunar water economy – all targeting the realization of sustainable lunar operations.

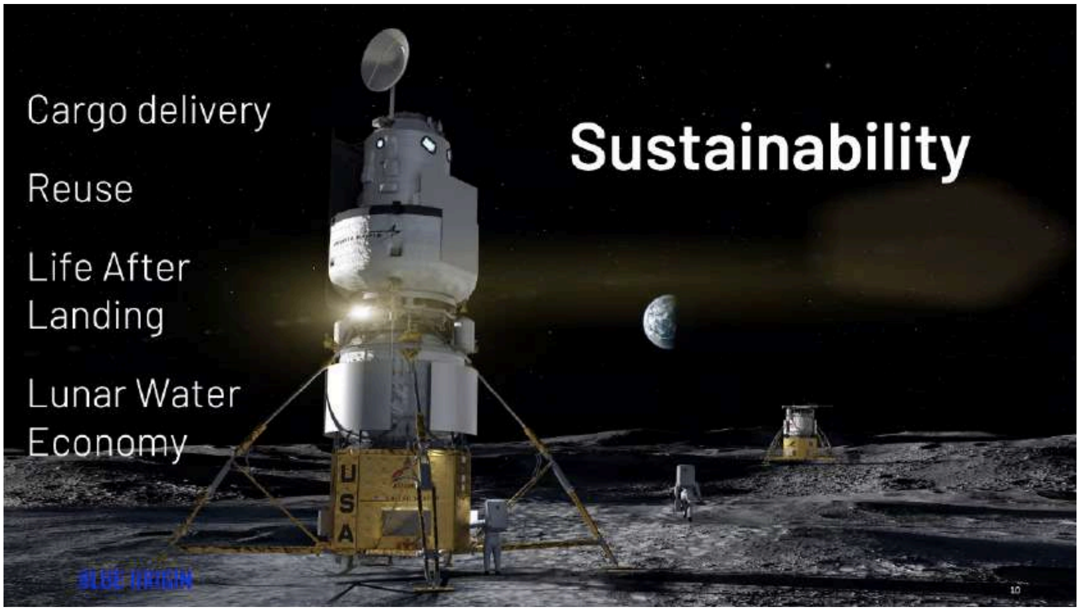


Figure 4-2-1 "On Our Way...to the Moon" (Blue Origin Lunar Exploration Activities)

- Christopher MOORE, NASA HEOMD (Human Exploration and Operations Mission Directorate) presented a keynote address on Day 2 of the event.
  - TITLE: "Life Support Systems for Human Exploration".
  - SUMMARY: NASA's Artemis Program is working to achieve a human return to the Moon by 2024, with the goal of establishing a foundation for later human missions to Mars during the 2030s. Life support systems – particularly regenerative life support systems (RLSS) – will be critical for safe, affordable long-duration human space exploration. A foundation for future RLSS is being established by the life support systems programs of the International Space Station (ISS) – both the current systems as well as R&D for future systems now underway.

    ISS life support comprises a variety of key functions, including CO_2 scrubbing, Oxygen generation, water / brine recycling and waste management and disposal. In addition, continuing and accurate environmental monitoring is crucial to the operation of all of these systems; sensor systems consider air quality, airborne particulates, radiation monitoring, and others. Another important component of the ISS life support system is fire detection and suppression. For the longer-term, R&D activities are now underway to develop bioregenerative life support systems capabilities, including plant growth, bioreactors for waste management and others.

    ISS-based R&D is also working to reduce the logistics footprint of human exploration activities in space. These include in-space manufacturing using additive manufacturing techniques, waste 'destruction' via heating-melting and compaction, and the development of autonomous logistics management systems.

    A wide range of topics are being pursued by HEOMD in support of future exploration goals. These include surface habitats, advanced life support systems, logistics reduction, crew mobility systems, exercise equipment, food production, radiation and protection and fire safety. In addition, working with the NASA Space Technology Mission Directorate (STMD), HEOMD is pursuing diverse important additional capabilities for human exploration and operations, including autonomous systems, precision landing, surface power systems, *in-situ* resource utilization, cryogenic fluid management, lunar dust mitigation, access to extreme environments, and excavation and construction.

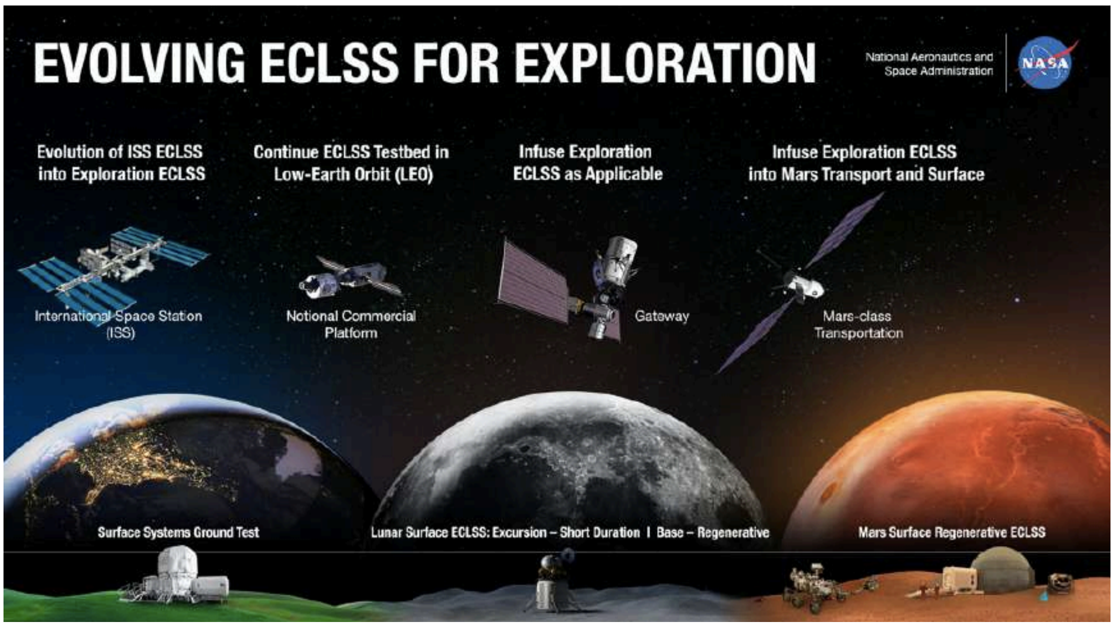


Figure 4-2-2 NASA Closed Life Support R&D

4.2.2 Theme 3 Presentations

Theme 3 involves regenerative life support systems (RLSS) and agricultural systems (including food projection). Table 4.2.2 indicates the order and timing of the presentations given.

Table 4.2.2 Speakers During the Day 2 / Theme 3 Session

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
6:10	MANKINS, John C.	Introduction of Theme 3	MVA / NSS / IAA	USA
6:20	IGARASHI, Iwao	Experimental Study on Reclamation in Closed System for Sustainable Human Presence on the Moon	Mitsubishi Heavy Industries	JAPAN
6:40	KITAYA, Yoshiaki	Space agriculture in the center of material circulation in Moon Village	Osaka Prefecture University; Environmental Sciences & Technology	JAPAN
7:00	PERINO, Maria Antonietta	Deep Space Habitats	Thales Alenia Space Italia	ITALY

Table 4.2.2 Speakers During the Day 2 / Theme 3 Session

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
7:20	PINO, Paolo	SGAC 'Biosphere Studies'	Space Generation Advisory Council (SGAC)	ITALY
7:35	SALMERI, Antonino	"T.U.R.T.L.E."	Space Generation Advisory Council (SGAC)	ITALY

The following are brief summaries of the several presentations made during Theme 3 on Day 2 of the workshop. Illustrative slides from the latter five presentations are provided in Figure 4-2-3 through Figure 4-2-7.

- John C. MANKINS presented a brief overview of the planned Theme 3 discussion, including introductions of the several speakers.
- Iwao IGARASHI of the Space Division of Mitsubishi Heavy Industries (MHI) made a catalytic presentation.
    - TITLE: "An Experimental Study on Reclamation in Closed System for Sustainable Human Presence on the Moon"
    - SUMMARY: Environmental Control and Life Support System (ECLSS) is an essential element for human activities in Space. It is self-sustaining, especially in the remote and faraway places like the Moon. This presentation shows our past experiment on oxygen reclamation from carbon dioxide in a closed system, so-called regenerative oxygen. Experiments and tests were done in a facility of a closed environment system in Tohoku Japan, operated by the Institute for Environmental Sciences. Based on the findings and conclusion, substantive discussions are to be considered to overcome the challenges, e.g. cleaning-up carbon inside the system, in achieving fully sustainable ECLSS in the future. Stress will be placed on building sustainable settlement on the Moon.

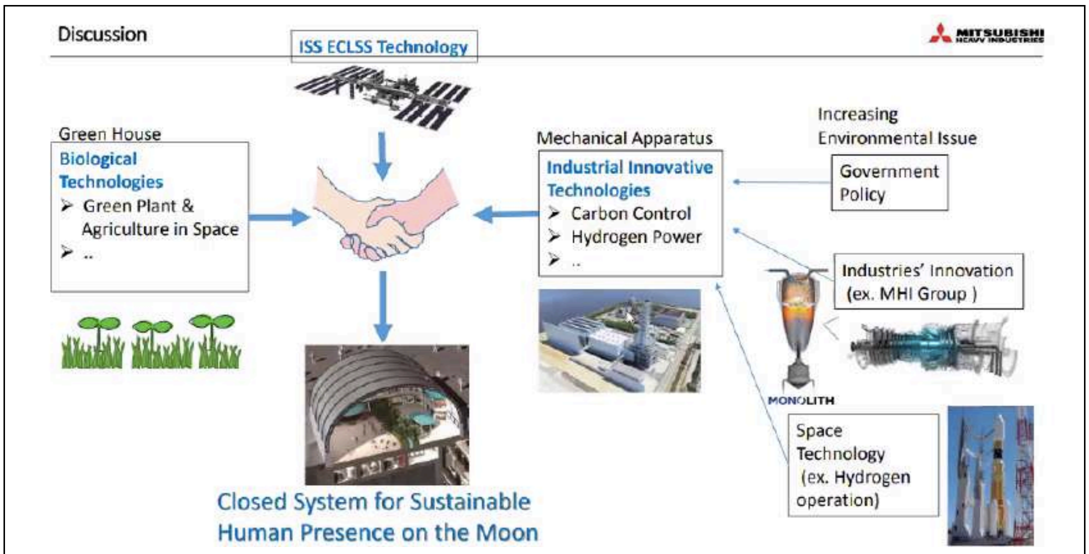


Figure 4-2-3 Reclamation in Closed System for Sustainable Human Presence on the Moon

- Yoshiaki KITAYA of Environmental Sciences & Technology, Graduate School of Life and Environmental Sciences, Osaka Prefecture University made a catalytic presentation.
    - TITLE: “Space agriculture in the center of material circulation in Moon Village”.
    - SUMMARY: Human habitation on the Moon will be highly dependent on self-sufficiency in the production of food, atmospheric O_2 and clean water – which will only be accomplished through space farming in bio-regenerative life support systems. Plants play important roles in food production, CO_2/O_2 conversion, water purification, etc. and are at the center of material circulation. Space agriculture is essential for long-duration human habitation on the Moon and its contribution to construction of a sustainable human society consisting of 1000 people on the Moon (the target for the Moon Village Evolution study team – discussed above).

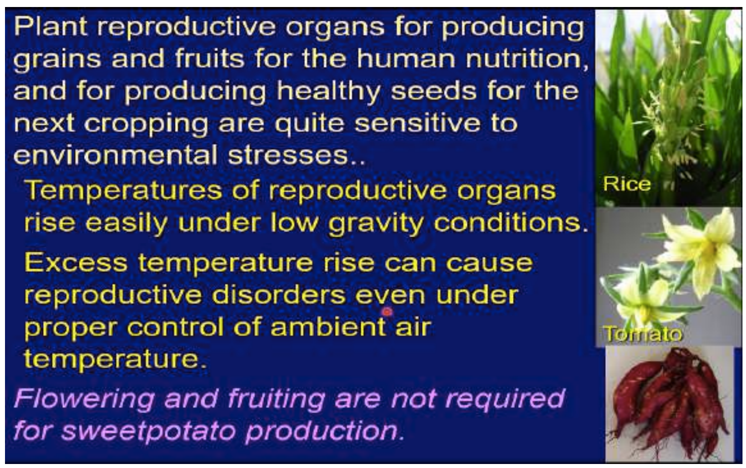


Figure 4-2-4 Space Agriculture for Essential Materials Circulation in a Lunar Settlement

An important issue to be considered further will be that of thermal management for the plants involved – particularly the sexual organs of the plants – due to the sensitivity of these organs to heating. In low or partial gravity, thermal convection will be reduced – and the temperature of various plant organs may be increased beyond acceptable limits. One option could involve the selection of plants that do not have temperature-sensitivity sexual organs – such as specific types of sweet potatoes, that have many (if not all) of the nutrients needed for human sustenance.

- Maria Antonietta PERINO of Thales Alenia Space Italia make a catalytic presentation on the topic of deep space habitats R&D.
    - TITLE: “Deep-Space Habitats”.
    - SUMMARY: Human space exploration is being pursued in a step-wise approach as described in the Global Exploration Roadmap (GER), which includes enabling technology developments, robotic preparatory missions, and developing early orbital and surface planetary outposts before introducing humans ‘in the loop’. A key element of the GER, which involves more than a dozen space agencies is the plan to develop and deploying a lunar orbital platform – aka, the “Gateway” in cis-lunar space. In the frame of this program, the European Space

Agency (ESA) will be providing the European Service Module (ESM) to support NASA's multi-mission Orion capsule for travel beyond LEO

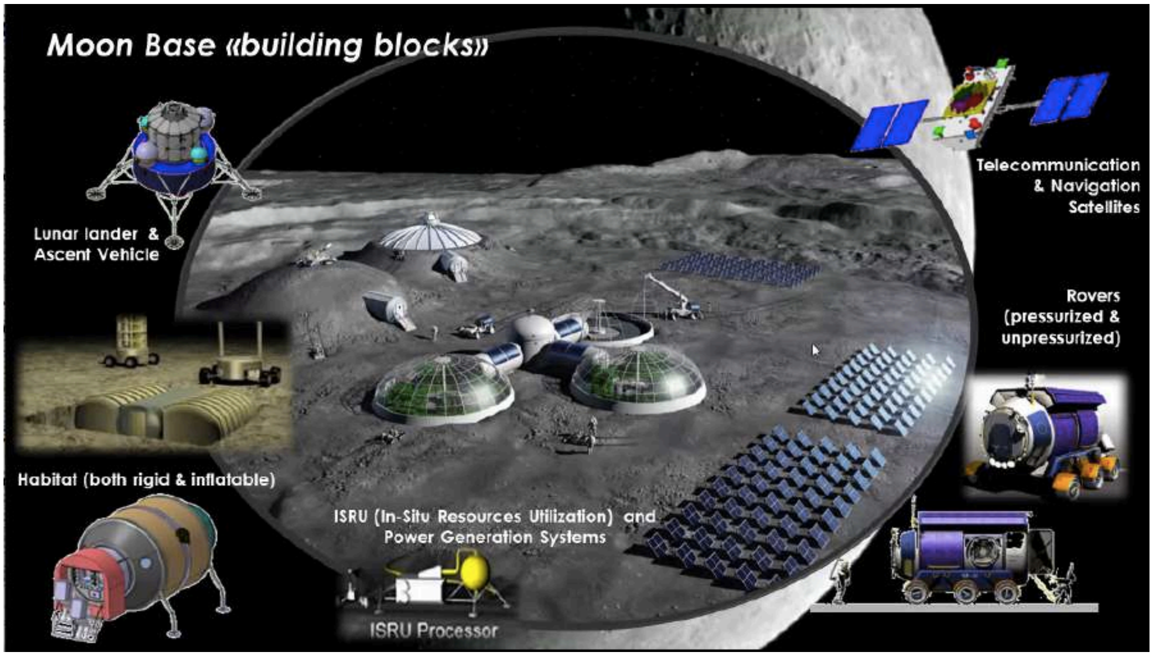


Figure 4-2-5 Thales Alenia Space Italia identified 'building blocks' for lunar exploration

The Gateway program in cis-lunar space will both validate key technologies for human missions to Mars as well as allowing the study of psycho-physiological factors during long-duration missions in deep space, including radiation protection, psychological effects, deep-space extravehicular activity (EVA), etc. The Gateway program will also enable testing of new autonomous systems and operations (such as RLSS and in-situ diagnostic and maintenance capabilities) as well as demonstrations of remote teleoperations on a planetary surface (in preparation for future Mars missions). The first elements of the lunar Gateway will comprise the Power and Propulsion Element (PPE) and the Habitat and Logistics Outpost (HALO) for which the structure and radiation protection are being provided by Thales Alenia Space. Later elements (after 2024) will include the I-HAB (International Habitat) and ESPRIT (European System Providing Refueling, Infrastructure and Telecommunications), both being provided by Thales Alenia Space (in Italy and France respectively).

The experience from the ISS program will inform planning and development for future deep-space habitats. One potential issue: how crowded space habitats can become over time. New module developments for the Lunar Gateway incorporate a range of differences – including lower mass, new docking ports, autonomous thermal control, modular avionics and others. One difference will be incorporation of water for radiation shielding in the crew quarters. Another will be the application of 'human-centered' design philosophy throughout – including interior design, access to augmented and virtual reality (VR) techniques, provision of relaxation areas, and environmental controls.

Lunar surface human missions are planned to begin as early as 2024 with NASA's Artemis Program; Thales Alenia Space is a part of this effort. Key 'building blocks' for future lunar surface activities will include lunar landers / ascent vehicles, habitats, rovers (pressurized and unpressurized), telecommunications systems, ISRU systems, and power systems. Ongoing R&D including development of extensible / inflatable crew airlocks for use on the Moon, pressurized rovers, a lunar greenhouse, and other capabilities. The key challenges for the Moon include operations in 1/6th gravity, lack of atmosphere, exposure to micro-meteors and radiation, limit solar power and extreme temperatures at the polar regions, and the use of regolith for use in 3D printing of habitats.

- Paolo PINO, et al. of the Space Exploration Program Group (SEPG) of the Space Generation Advisory Committee (SGAC) made a catalytic presentation on the topic of biosphere studies.
  - TITLE: "Lunar Biosphere".
  - SUMMARY: The goal of this research is to evaluate a sustainable ecosystem that could allow the establishment of a human colony on the lunar surface to be settled around the rim of the Shackleton Crater, including a preliminary assessment of the challenges and opportunities to leverage local resources and an analysis of plants compatible with the environment and ecosystem. Near-term efforts are focused on processing regolith to turn it into living soil, and an 'equivalent system mass' study. In particular, the project is examining crop selection by evaluating and comparing species which survive in hostile environment, and evaluating possible factors to enhance the fixation of nitrogen (fungi and bacteria) and support the ecosystem (insects).

Figure 4-2-6 SGAC Space Exploration Program Group – Example Biosphere Plant Selections

Key factors being examined vis-à-vis crop selection include: (1) partial pressure of CO_2, (2) humidity, and (3) temperature. Examples of crop selection include Nitrogen-fixing crops (such as annual clovers, which can grow in a dry environment and stony soil) and edible plants (for example, tomato plants that grow easily in soil, organic substrates, soilless mixes, perlite, sand or hydroponics).

The equivalent system mass study is examining two options: (1) using lunar regolith as living soil, and (2) aquaponics. The goal is to quantify benefits and opportunities, and to understand the impact of *in-situ* manufacturing and resources utilization.

- Paolo PINO (speaking on behalf of Antonino SALMERI) of the Space Exploration Program Group (SEPG) of the Space Generation Advisory Committee (SGAC) made a catalytic presentation on the topic of "T.U.R.T.L.E.".
  - TITLE: "T.U.R.T.L.E." (Technical Unit for Research for a Thriving Lunar Ecosystem)

    SUMMARY: The purpose of this research is to solve multidisciplinary technological challenges for the fair and sustainable development of the Moon. Goals include: (1) assessing development scenarios; (2) identifying sustainable technologies; (3) developing pragmatic solutions; and, (4) involving relevant stakeholders. The "T.U.R.T.L.E." team involves some 15 members across 5 countries. It is targeting three important areas: landing sites and systems (i.e., sites mapping and classification, spaceports development, and traffic control), logistics and architecture (e.g., assessing strategic areas and activities for shared infrastructure and logistics, and creating alternative scenarios to discover potential conflict areas in a collaborative workshop), and power systems (including technology 'landscaping' and trade-offs, interoperability as figure of merit and site-solution matching).

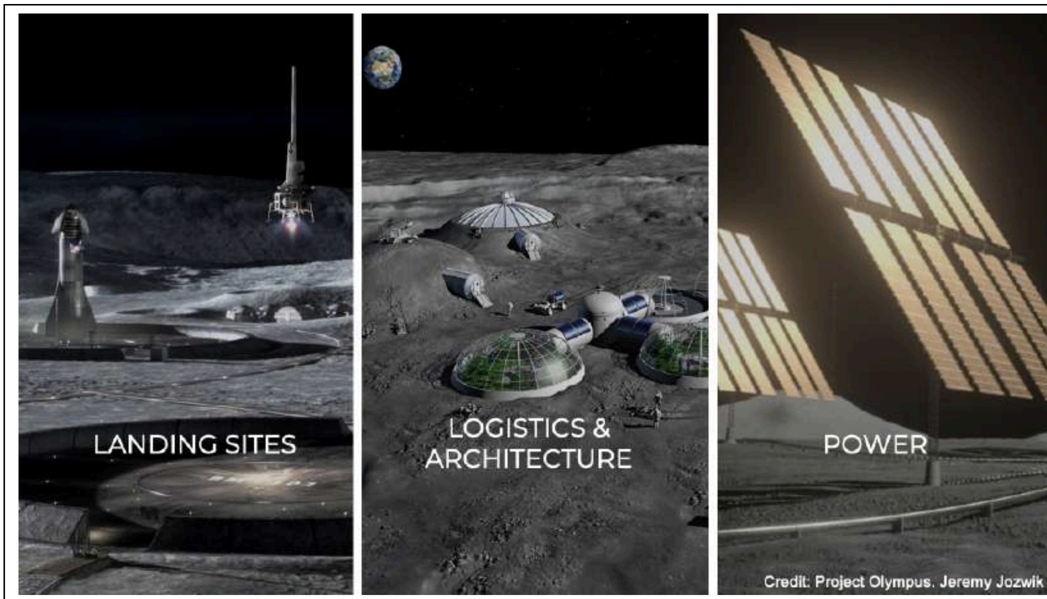


Figure 4-2-7 "T.U.R.T.L.E." topics being examine by the Team...

4.2.3 Theme 4 Presentations

During the latter portion of Day 2 of the workshop, the discussion of 'Theme 4' occurred – involving reusable space transportation systems and related infrastructure. Table 4.2.3 below summarizes the order and timing of the several speakers who spoke about the theme.

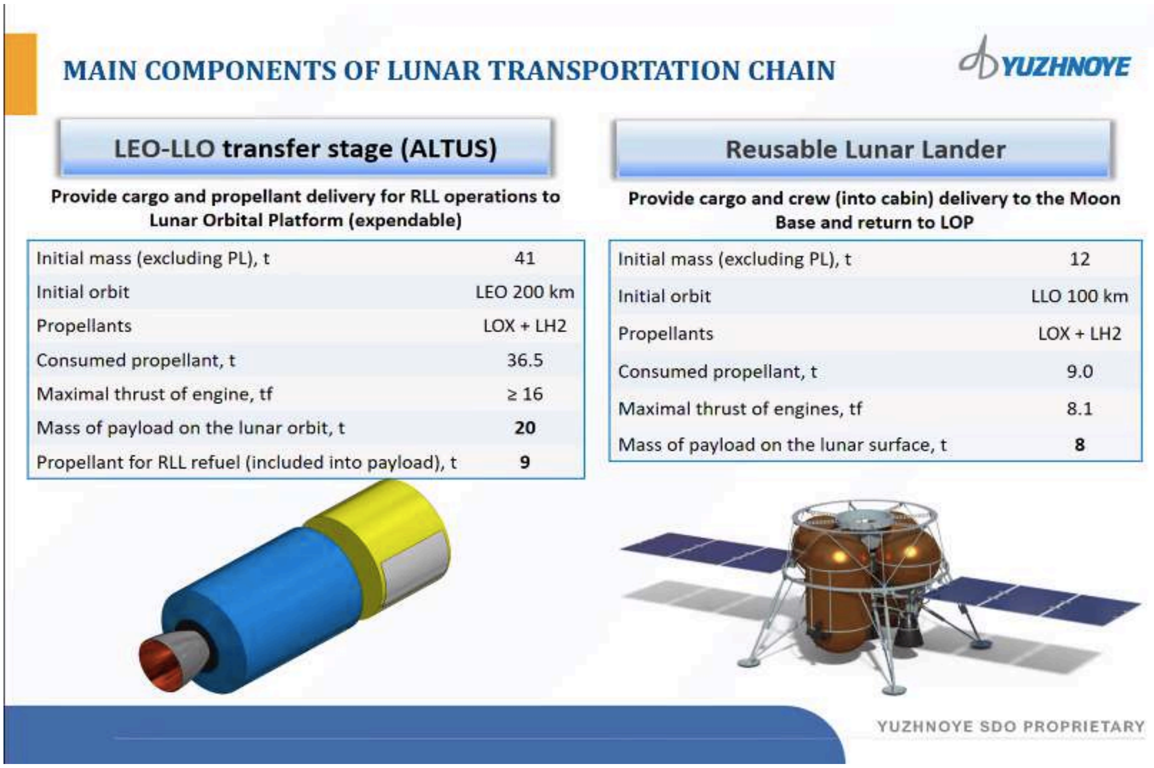
Table 4.2.3 Speakers During the Day 2 / Theme 4 Session

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
7:55	MANKINS, John C.	Introduction of Theme 4	MVA / NSS / IAA	
8:00	BERDNYK, Oleksandr	Reusable Space Transportation	Yuzhnoye State Design Office	UKRAINE
8:30	EFFINGER, Michael	Microwave Sintering – Landing Pads	NASA MSFC	USA
8:50	BIENHOFF, Dallas	Space Transportation	Cislunar Space Dev. Co., LLC	USA
9:10	IWASAKI, Akhiro Ph.D	Space Traffic & Supply Chain Management	Yspace	JAPAN
9:10	SAKATOMO, Yuki		Japanese Rocket Society (JRS)	JAPAN
9:30	KOBAYASHI, Hiroaki	Hydrogen will realize a sustainable society on the Moon for future humankind	Japanese Rocket Society (JRS) / ISAS (JAXA)	JAPAN

The following are brief summaries of the several presentations made during Theme 4 on Day 2 of the workshop. Illustrative slides from the latter two presentations are provided in Figures 4-2-8 through 4-2-12.

- John C. MANKINS presented a brief overview of the planned Theme 4 discussion, including introductions of the several speakers.
- Oleksandr BERDNYK of the Yuhnoye State Design Office, an Institutional Member of the MVA, made the opening catalytic presentation on the topic of space transportation during the discussion of Theme 4 of the workshop.
    - TITLE: “Reusable Space Transportation and Supporting Infrastructure”.
    - SUMMARY: In the 50 years of the space era, humanity has been overcoming many parries to the exploitation of near-Earth space and exploration of the Solar System. However, a new technological foundation will be needed to implement the next step: exploration of extraterrestrial energy and raw materials resources – enabling expansion of human habitation at first to the Moon and then to Mars and other locations. A critical issue now being addressed by R&D is that of affordable cargo and crew delivery from Earth to near-Moon orbits and the lunar surface. The key technology for this objective is the transition from expendable vehicle to reusable and refuelable vehicles, and the in-space production of propellent.

      Various concepts are now being studied, including a lander-hopper that could transport 50 kg of payload through point-to-point flight (up to 3 locations) or 150 kg one way to the surface, a LOX-H_2 fueled reusable lunar lander (RLL) that could transport payloads to/from the lunar surface and LLO. Two modes of operation have been examined for a 3 MT dry-mass vehicle. First, with fuel from a depot in LLO; in which case a vehicle with propellant load of 9 MT could deliver 8 MT to the surface one way, or could deliver a 3.2 MT payload to the surface and return to LLO after delivery.



Initial mass (excluding PL), t	41
Initial orbit	LEO 200 km
Propellants	LOX + LH2
Consumed propellant, t	36.5
Maximal thrust of engine, tf	≥ 16
Mass of payload on the lunar orbit, t	**20**
Propellant for RLL refuel (included into payload), t	**9**

Initial mass (excluding PL), t	12
Initial orbit	LLO 100 km
Propellants	LOX + LH2
Consumed propellant, t	9.0
Maximal thrust of engines, tf	8.1
Mass of payload on the lunar surface, t	**8**

Figure 4-2-8 Reusable Space Transportation and Supporting Infrastructure

Second, the same vehicle with refueling on the lunar surface could deliver 8 MT to LLO from the surface, or 5.25 MT from LLO to the surface, or 3.2 MT round-trip. With this foundation, the key elements of an Earth-Moon transportation system have been defined as including:

- A heavy lift launch vehicle with a reusable first state (54-61 MT) such as the Falcon 9 Heavy (FH) or the New Glenn launch vehicle.
- A reusuable and re-fuelable in-space 'tug' (such as the Yuzhnoye ALTUS concept, for delivering of 17-20 MT payloads from LEO to LLO
- A reusable lunar lander (RLL) using LOX-LH_2 (described previously)
- Refueling stations (in LLO initially and later on the lunar surface); and,
- Crew spacecraft.

The ALTUS reusable LEO-LLO 'tug' concept might involve LOX-LH_2 propellants, and about 36 MT of propellant in LEO to deliver a payload of 20 MT to LLO (including 9 MT of fuel for the RLL and 11 MT of RLL-payload and fuel for Earth-return). With this foundation, a wide variety of payloads could be delivered to locations on the lunar surface, including crew vehicles, surface habitation modules, etc.

Of course, ISRU and propellant production will be required for this architecture, including exploration for materials, delivering of raw materials to processing facilities, processing (including extraction and purification of water and production of LOX-LH2 propellants, and storage and transfer of lunar propellant to customers). All of these functions will require specific systems – ranging from power supplies to transportation vehicles, equipment for electrolysis and liquefaction, contactors etc. And, in the farther-term ongoing transportation systems R&D will pursue advanced rocket systems (e.g., reusable nuclear propulsion, reusable electric propulsion systems, etc.) and non-rocket transportation concepts (such as electromagnetic launchers, etc.).

- Michael EFFINGER of NASA MSFC made a catalytic presentation on the topic of microwave sintering in general, and landing pads and related infrastructures in particular.
  - TITLE: "Microwave Sintering Lunar Landing Pads & Horizontal Infrastructure".
  - SUMMARY: There are a variety of potential uses for the lunar regolith in the manufacturing of local infrastructure. NASA MSFC is exploring a variety of these, with goals that include maturing the technology and capability to emplace *in-situ* based construction materials on the Moon to form *horizontal* infrastructure elements (e.g., landing pads, roads, etc.), and developing and demonstrating microwave sintering of lunar simulants that can be used to form infrastructure on the Moon for a mid-sized payload (e.g., a 2MT microwave paver vehicle).

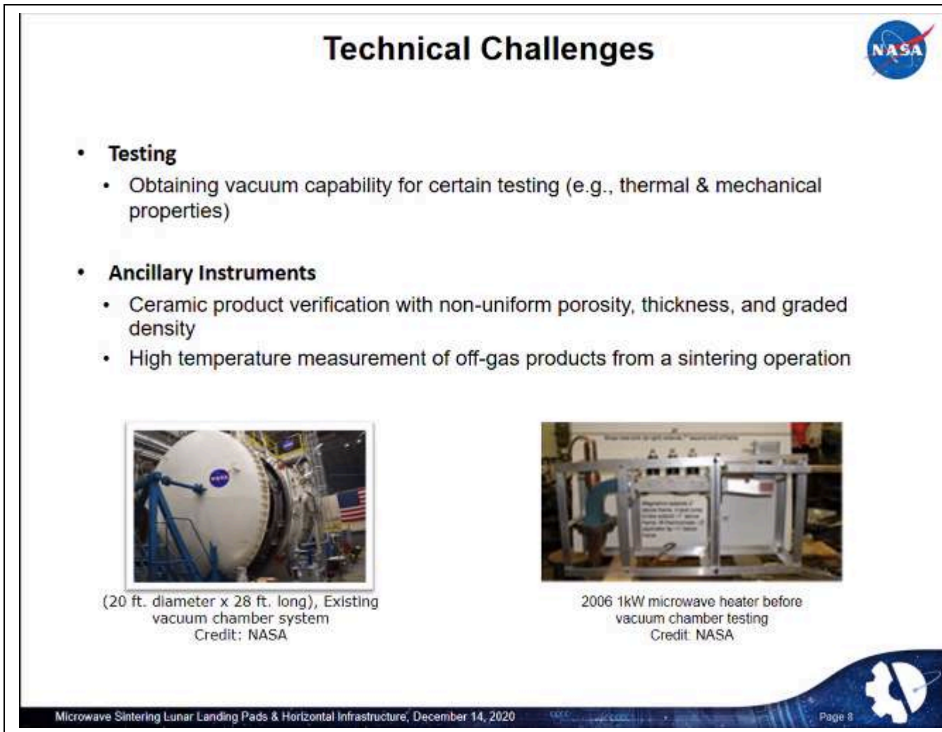


Figure 4-2-9 Microwave Sintering Lunar Landing Pads

Achieving these goals will require overcoming a number of disparate challenges, involving (1) developing a concept of operations (CONOPS); (2) availability of relevant simulant and other materials for R&D purposes; (3) technical issues involving site preparation and design; (4) accomplishing microwave sintering; and, (5) developing testing and requirements for ancillary instruments. Work is ongoing, and will address redundant paths to timely success.

- Dallas BIENHOFF of Cislunar Space Development Company, LLC made a catalytic presentation on transportation systems and infrastructure.
    - TITLE: "Reusable Cislunar Transportation Architecture".
    - SUMMARY: Cislunar Space Development Company, LLC is developing a reusable cislunar transportation architecture to operate from low Earth orbit to the Moon and all points in between. This presentation describes one potential growth path from a minimally viable capability to full operational capability as well as paths matched to the Moon Village Architecture Working Group Scenarios Alpha, Beta and Gamma. The architecture includes space tugs, Moon shuttles, propellant depots, Earth-to-orbit refuelers, space tanker elements and personnel module elements. The architecture is sized to deliver up to 25 metric tons to any point on the Moon's surface from its Earth Moon L1 propellant depot and 25 MT to Earth Moon L1 from low Earth Orbit.

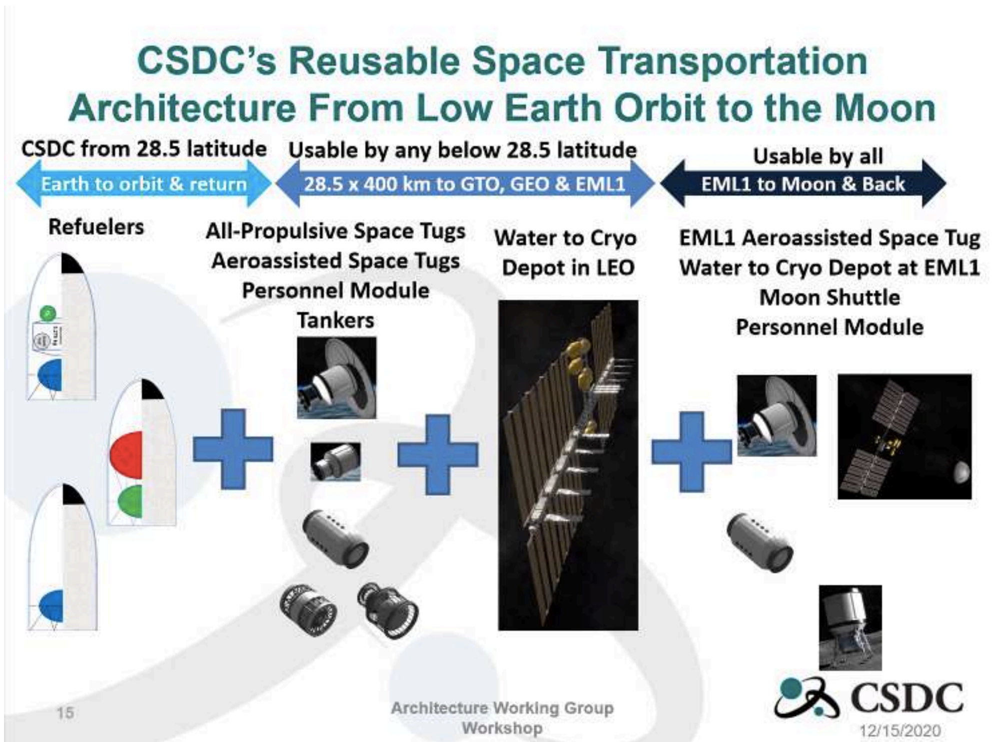


Figure 4-2-10 Reusable Cislunar Transportation

- Yuki SAKAMOTO of the Japan Rocket Society (JRS) and Dr. Akhiro IWASAKI of YSpace made a catalytic presentation concerning supporting operational capabilities in association with reusable space transportation.
    - TITLE: "Space Traffic & Supply Chain Management".
    - SUMMARY: The importance of expanding the human frontier into space will increase. Considering the entire process of space exploration, the space-transportation-network will determine the architecture. Concept studies have been started of a space transportation

network including utilization of the lunar water ISRU assuming there is a village of a thousand people on the Moon. The study aims to contribute insight to support the eventual construction of routine and sustainable space logistics. This presentation reported the status of studies on the Earth-Moon-Mars transportation network.

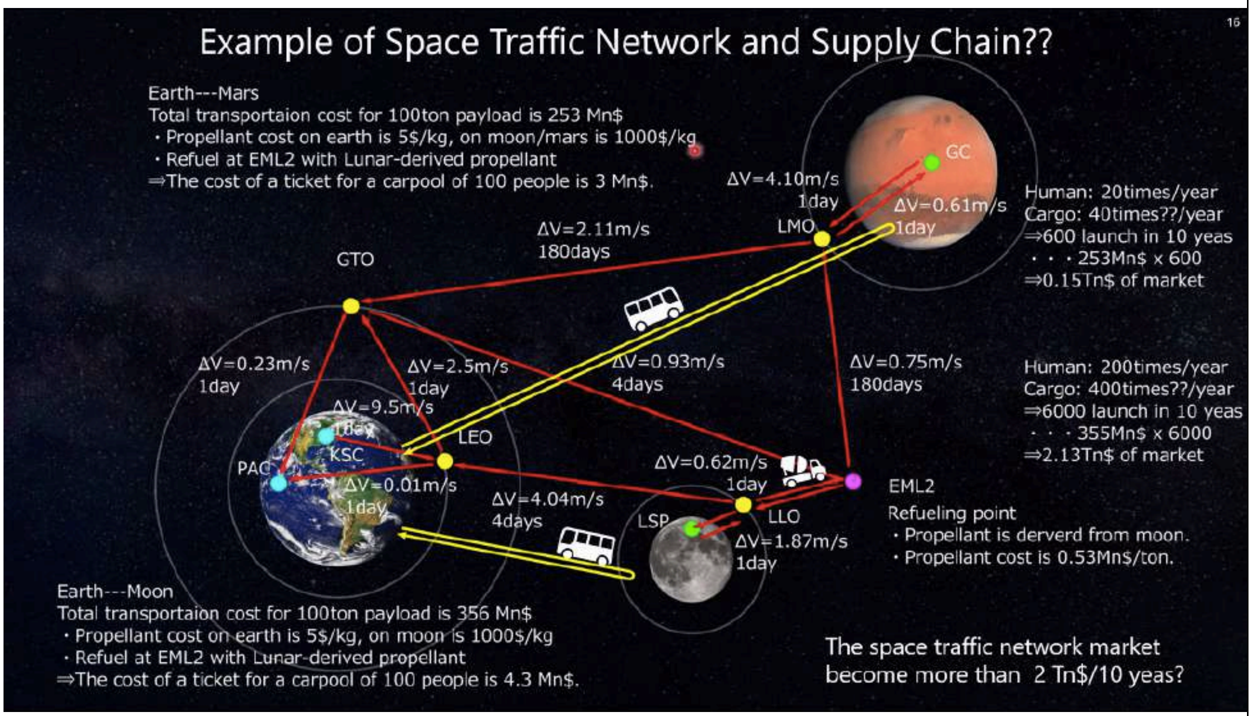


Figure 4-2-11 Space Traffic & Supply Chain Management

- Hiroaki KOBAYASHI made a catalytic presentation on hydrogen technology and applications for lunar and terrestrial applications.
    - TITLE: "Hydrogen will realize a sustainable society on the Moon for future humankind".
    - SUMMARY: We have been conducting research of hydrogen energy-related technology utilizing a large-scale hydrogen handling technology cultivated over many years of rocket development. As a result of the recent Moon exploration, the possibility that water or hydrogen is present on the lunar surface has been increased, and studies on using this for a continuous space exploration have been conducted in various areas.

      Specifically, it is envisaged that mining water on the Moon's surface, liquefying and storing hydrogen and oxygen generated by solar power generation and water electrolysis equipment, and using this as a propellant and a chemical material. The process of creating Hydrogen for use will be energy intensive – including electrolysis of lunar water and liquefaction of Hydrogen gas produced. This concept is to create a hydrogen energy-based society on the Moon, so it is expected that Japan's hydrogen technology acquired so far can be applied.

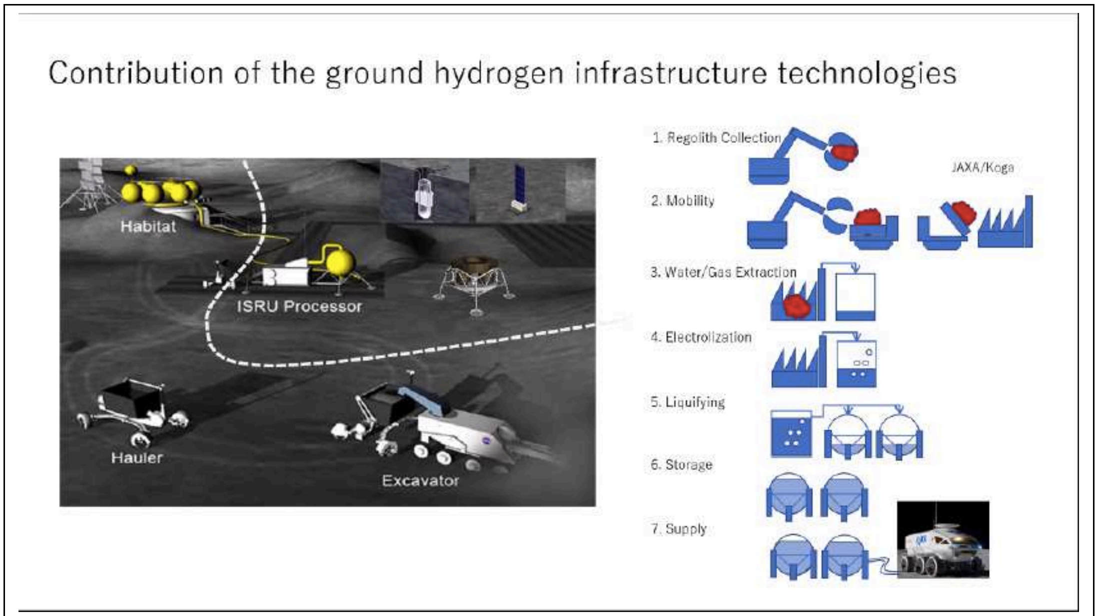


Figure 4-2-12 Hydrogen enables a Sustainable Society on the Moon

In the use of hydrogen in the Moon, it is necessary to realize more efficient equipment and hydrogen storage and utilization systems than the earth. These activities are expected to greatly contribute to the realization of the 'hydrogen society' on Earth.

4.3 Day 3

The final day of the workshop addressed topics related to surface power systems and related infrastructure, as well as Moon market development and final topics concerning lunar architectures. Speakers included individuals from the US, Italy, Japan, Kuwait, Ukraine, and the Netherlands. To watch the Day 3 videos, please see: https://www.youtube.com/watch?v=uOTGsmeaWvk

4.3.1 Day 3 Opening Plenary Session

The opening of the third and final day of the Workshop 5 involved a brief review of the workshop to date, as well as a discussion of various lunar surface operations concepts during the past century and more. Table 4.3.1 indicates the two speakers during this portion of the workshop.

Table 4.3.1 Speakers During the Day 3 Opening Session

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
5:00	MANKINS, John C.	Opening Remarks, Start of Day 3	MVA / NSS / IAA	USA
5:10	THANGAVELU, Madhu	Past Visions of Lunar Operations & Outposts	USC / NSS / MVA	USA

The following are brief summaries of the two presentations made during the opening session on Day 3 of the workshop. Illustrative slides from the latter presentation are provided in Figure 4-3-1.

- John C. MANKINS presented opening remarks for the third and final day of the workshop, and introduced the final day keynote speaker, Dr. Madhu Thangavelu.
- Dr. Madhu THANGAVELU. Conductor of the ASTE527 Graduate Space Concept Synthesis Studio in the Department of Astronautical Engineering within the Viterbi School of Engineering and the Arch599 Space Architecture and Extreme Environment seminar for graduate students in the School of Architecture at the University of Southern California.
    - TITLE: "Past Visions of Lunar Operations and Outposts".
    - SUMMARY: Imagination and creativity are the faculties that distinguish our species from the other beautiful creatures of Nature. The ability to Dream, project Visions and then persuade large and diverse groups of talented professionals to work together to manifest complex missions is as much an art form as it is a multi-pronged, cutting-edge scientific and technology effort. Dreams and Visions precede all human endeavor, and space exploration and human space activity is no exception. This talk depicted a wide variety of the dreams and visions of lunar missions and settlements from before the dawn of the space age, through the earliest years of the space age to the present. One of the first such visions was that of Jules Verne in his late-19th Century novel, "From Earth to the Moon".

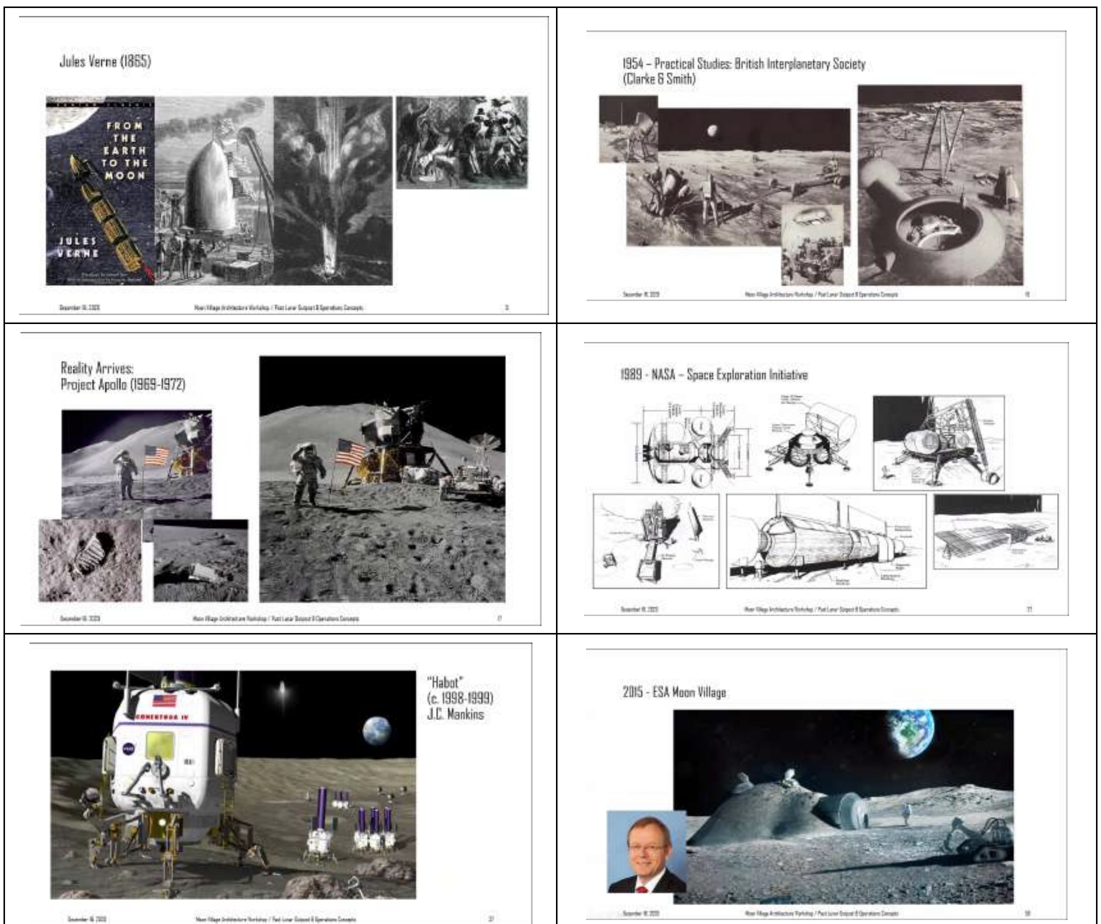


Figure 4-3-1 Past Visions of Lunar Operations and Outposts

4.3.2 Theme 5 Presentations

Workshop Theme 5 concerned lunar surface power systems, and related surface operations and systems. Table 4.3.2 indicates the several presentations (order and timing) during this portion of the workshop.

Table 4.3.2 Speakers During the Day 3 / Theme 5

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
5:40	MANKINS, John C.	Introduction of Theme 5	MVA / NSS / IAA	USA
5:50	EDWARDS, Christine	Power Distribution	Lockheed Martin Company	USA
6:10	SHINOHARA, Naoki	Solar power and WPT utilization to sustainable human society on the Moon	Kyoto University	JAPAN
6:30	FOING, Bernard	Lunar Science / ILEWG / Analogues	ESTEC	Netherlands
6:50	LAUER, Charles, & TANASYUK, Pavlo	Surface Robotics	SPACE BIT	UK

The following are brief summaries of the presentations made during Theme 5 on Day 3 of the workshop. Illustrative slides from the latter presentations are provided in Figure 4-3-2 through 4-3-4.

- John C. MANKINS made introductory remarkets for the beginning of the final day and second-to-last session of the workshop.
- Christine EDWARDS, Deputy Exploration Architect of Lockheed Martin Corporation / Space presented recent activities related to power systems for lunar polar exploration and operations.
  - TITLE: "Power Architecture for Sustainable Lunar Presence".
  - SUMMARY: The Global Exploration Roadmap (GER) published by the International Exploration Coordination Group (ISEC-G) presents a series of planned advances in lunar capabilities over the coming decade. These comprise from the first human landing a variety of surface systems (e.g., rovers, EVA systems, science payloads, etc.), as well a several power systems. However, when ISRU operations begin in earnest, demand could exceed supply. Peak loads can be managed to help manage and balance supply and demand – for example, by restricting ISRU operations to hours when there is sunlight available.

    For missions and infrastructure planned for the post-2030 timeframe, additional power will be required. A diverse, modular and interoperable 'ecosystem' can be built through international partnerships; including habitation systems, ISRU, and both solar and nuclear surface power systems. A flexible and resilient lunar surface power architecture should comprise solar power generation, space nuclear power systems coupled through local power distribution to energy storage, with charging stations for rovers and other mobile systems – and to stationary loads including habitation systems, ISRU and others.

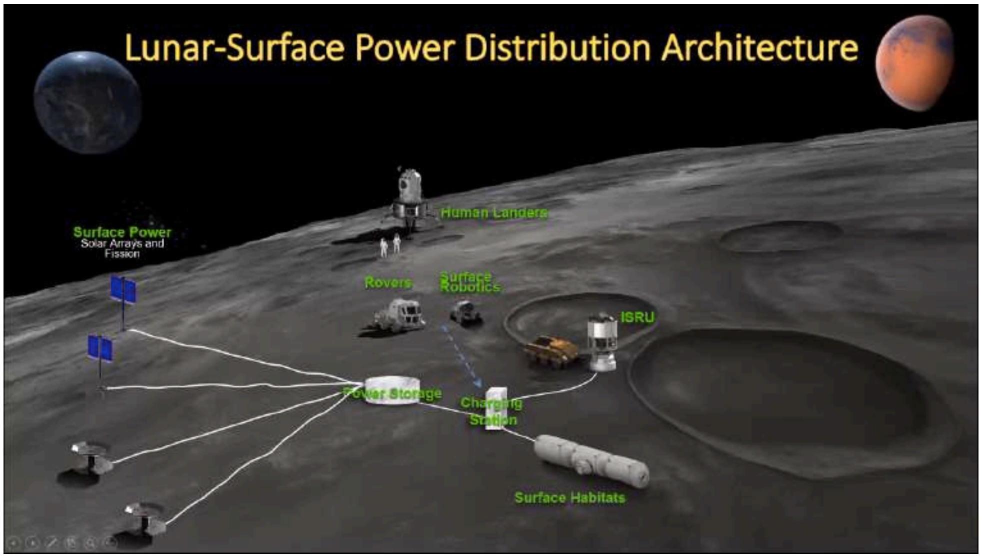


Figure 4-3-2 Power Architecture for Sustainable Lunar Presence

- Dr. Naoki SHINOHARA of Kyoto University made a catalytic presentation concerning wireless power transmission for lunar development.
  - TITLE: "Solar power and wireless power transfer utilization to sustainable human society on the Moon".
  - SUMMARY: One of problems for sustainable human society on the Moon is energy management. We propose utilization of wireless power transfer (WPT) technology via radio waves and space solar power with the WPT.

Figure 4-3-3 Solar Power and Wireless Power Transfer

WPT can manage the electricity not only on the Moon but also from Moon orbit without extra power lines. It also can drive a rover and a drone on the Moon. The WPT is recently well developed as commercial products, however, it's a problem that there were few experiments only. In this talk, he introduced recent wireless power transmission research and development (R&D) and discussed its utilization on the Moon.

- Professor Bernard FOING (with multiple co-authors) of the European Space Agency / ESTEC and the International Lunar Exploration Working Group (ILEWG) presented on the topic of lunar science and Analogues.
  - TITLE: "Together on the Moon: Missions, Science, Technology, Simulations, Inspiration and Diversity".
  - SUMMARY: The presentation began with a review of various topics in lunar science as well as a review of an early lunar missions of the European Space Agency (ESA), SMART-1 (aka, 'Small Missions for Advanced Research and Technology') that included a demonstration of solar electric propulsion (SEP) for the Moon. This mission captured an early (2006) elevation map of the lunar South Pole ridge – now under consideration as the location of the MVA's "Lunar Settlement 2045" case study. The talk also reviewed activities by the International Lunar Exploration Working Group, including the definition of various science questions that may be used to drive lunar exploration planning and the formulation of a high-level roadmap for the Moon comprising both robotic missions and later human sorties.

Figure 4-3-4 Preparing for Humans on the Moon: Requirements and Simulations on Earth

The second half of the presentation focused on ongoing lunar analogue activities in various countries, including robotic demonstrations. Challenges for implementation of the Moon Village concept were discussed, including robotics, human operations, transportation, communications, mobility systems and others. A number of ILEWG organized campaigns implemented during 2009-2019 were discussed. The presentation concluded with a discussion of prospective activities to prepare for the Moon Village, including both robotic village and human base related requirements.

- Charles LAUER and Pavlo TANASYUK of SpaceBit made a catalytic presentation concerning novel lunar robotic mission concepts and systems (Mr. Lauer speaking).

- TITLE: "SpaceBit; Space Robotics for Lunar Exploration".
- SUMMARY: Mr. Lauer presented a brief history of the SpaceBit firm, which was organized in the UK in 2014 and has operations in the USA, the UAE, Ukraine, Poland and Israel. A commercial firm, SpaceBit plans to fly on multiple upcoming "CLPS' landers of NASA (Commercial Lunar Payload Services) beginning in 2021 as well as other robotic lunar lander missions over the coming several years. Missions to the International Space Station (ISS) are also planned for technology demonstration and verification. Both legged and wheeled very small-scale lunar rovers are under development – with a form factor similar to orbital 'cubesats'. These will evolve and conducted expanded lunar exploration, including a range of sensors and mobility operations; the latter including prospects for sub-surface exploration in the next 4-5 years.

4.3.3 Theme 6 Presentations

Workshop Theme 6 concerned various lunar market development options, as well as several different lunar surface architecture concepts. Table 4.3.3 indicates the speakers and topics during this portion of the workshop.

Table 4.3.3 Speakers During the Day 3 / Theme 6

TIME	NAME	TOPIC / PRESENTATION	ORGANIZATION	COUNTRY
7:20	MANKINS, John C.	Introduction of Theme 6	MVA / NSS / IAA	USA
7:30	VENTSKOVSKY, Oleh	*En route* to the Moon Market	Yuzhnoye SDO, MVA Moon Market	UKRAINE
7:50	ALOTAIBI, Ghanim	PESC & Building Blocks	MVA PESC Project	KUWAIT
8:10	RUSSO, Gennaro Ph.D.	Lunar Habitat Architecture Studies	Italian Institute for the Future; Center for Near Space	ITALY
8:30	OCAMPO SALAZAR, Julian	Project Olympus: the emerging vernacular of Lunar habitat architecture	BIG – Bjarke Ingels Group	USA / DENMARK
9:00	MANKINS, John C.	END of the Workshop Remarks	MVA / NSS / IAA	USA

The following are brief summaries of the several presentations made during Theme 6 on Day 3 of the workshop. Illustrative slides from the latter 4 presentations are provided in Figures 4-3-4 through 4-3-7. Images from the final presentation ("End of the Workshop Remarks") are in Section 6.

- John C. MANKINS made introductory remarkets for the beginning of this, the final session and the workshop.
- Oleh VENTSKOVSKY, member of the MVA Board of Directors and the Representative of Yuzhnoye Design Bureau in Brussels, made a presentation concerning Moon Village market development.
  - TITLE: "*En route* to the Moon Market".

- SUMMARY: Mr. Oleh Ventskovsky presented a high-level summary of the MVA 'Moon Market' development effort, including identification of the some twenty-six (26) institutional members of the Association; these institutional members included major aerospace firms (such as Lockheed Martin, Yuzhnoye Design Bureau), new space firms (such as ASTRAX, academic organizations, such as the Colorado School of Mines and the Kepler Space Institute, as well non-Governmental organizations (NGOs), such as 'For All Moonkind' and the Open Lunar Foundation.

Figure 4-3-4 *En route* to the Moon Market

The discussion of Moon Market activities included a description of a working session on non-space businesses and the Moon that was jointly organized with the European Space Agency (ESA), and planning for events to be organized during 2021. The presentation concluded a description of a new MVA working group under the chairmanship of Derek Webber, focusing on the future of 'Lunar Commerce and Economy'.

- Ghanim ALOTAIBI made a presentation on the subject of "Participation of Emerging Space Countries (PESC) & Building Blocks.
  - TITLE: "Participation of Emerging Space Countries (PESC)".
  - SUMMARY: Mr. Ghanim Alotaibi presented an overview of the Moon Village Association's PESC program, along with a summary of various recent events (during 2019-2020). He also focused on the actions assigned to various teams, primarily the definition of country-centric Moon Village roadmaps organized around the 'building blocks' that had been earlier defined by the Architecture Working Group. The PESC process, which began during summer 2020 comprised identifying various prospective MV activities in each country, according to the

building blocks and the high-level MV scenarios created by the MV Architecture WG. Mr. Alotaibi also presented an example of a PESC roadmap and discussed future plans for the program.

Figure 4-3-5 Participation of Emerging Space Countries (PESC)

- Gennaro (aka, 'Rino') RUSSO, presenter; with co-authors G. De Martino, R. Minichini, M. Pica Ciamarra (Center for Near Space, Italian Institute for the Future).
  - TITLE: "OrbiTecture: New Paradigms for Space Habitats".
  - SUMMARY: The Center for Near Space of the Italian Institute for the Future focused its activity on the conviction that the era of the Expansion of Humanity in Space has actually begun and that its evolution requires the development of adequate private / commercial component.

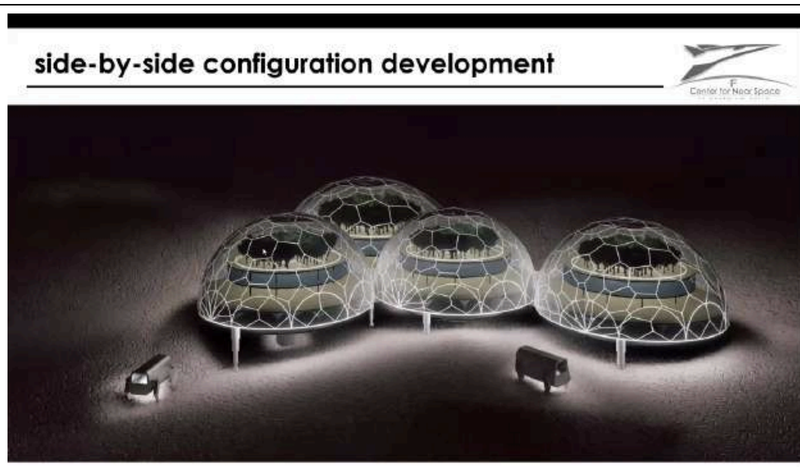


Figure 4-3-6 New Paradigms for Space Habitats

The OrbiTecture Working Group is presently investigating long-term lunar habitats. With reference to the previously-studied Cislunar City vision, a 100-person Moon settlement is thought to be mainly devoted to industrial activities such as mining or separation of constituent elements or construction of semi-finished products. A group of young engineering, physicists and students is actively participating in the WG studies, contributing with various ideas and analysis.

- Julian OCAMPO SALAZAR of BIG (aka, the Bjarke Ingels Group) presented selected results from recent lunar architecture studies.
    - TITLE: "Project Olympus: the emerging vernacular of Lunar habitat architecture".
    - SUMMARY: Shipping building materials from Earth to the lunar surface would be a prohibitively expensive undertaking. As a result, some approach to living off the land will be essential to affordable lunar development and habitation.

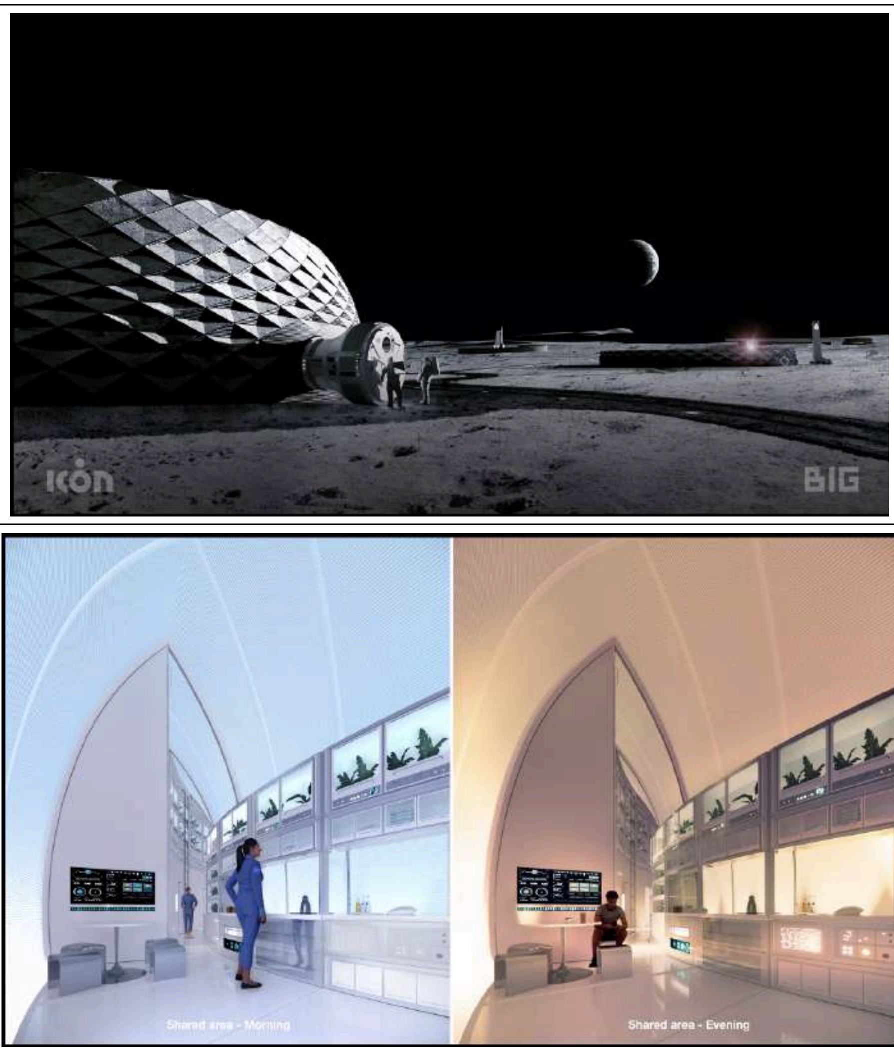


Figure 4-3-7 Project Olympus: the emerging vernacular of Lunar habitat architecture

There are various examples on Earth from which we might learn – such as igloos cut from ice to insulated against the cold in the far north or underground / troglodyte homes cut into the cooler rock below hot and arid climes. On the Moon, we must work with the local regolith for structures, thermal insulation, radiation protection, etc. R&D is advancing technologies that could be used to shape and create structural systems from the regolith. The strategy is to employ the concept of 3D printing of local materials so as to minimize transportation and equipment requirements.

Beginning with a flat surface on which to do construction, there are several possible geometric shapes that might make sense – such as cylinders, domes / spheres and doughnuts (i.e., a torus), of which the latter appear to better optimize access for 3D printing and use of materials (surface to volume, etc.). Design analysis suggests that for areas of 100 m^2 or less, that a conical dome is more efficient, while for areas of 100 m^2 or more, that a torus is more efficient. Moreover, these design concepts must deal with a range of hazards, including meteorite impacts, lunar dust, the radiation environment (solar particles and galactic cosmic rays), extremes of temperature, vacuum, and moon-quakes. The manner of construction also matters – and for fully 3D printed structures, an approximately (somewhat rounded) triangular cross-section with a particular taper is optimal. An overcover of regolith to protect against micrometeorites is also needed; the same overcover can also – if thicker – provide protection from radiation. All in all, the current R&D suggests a modified conical cross-section including a diamond-pattern to increase strength with an externally-supported regolith overcover.

Internal accommodations are also needed, and should be designed to reflect the geometry of the habitat, with adjustments to the interior lighting being provided as appropriate to the time of day vis-à-vis Earth.

4.3.4 Closing Session

During the final, closing session of the workshop, Mr. Mankins presented several observations and updates on the topic of the MV Architecture Case Study, based on the interim findings and conclusions presented during the three-day event. These closing observations are reflected in Section 5, which follows.

SECTION 5

WORKSHOP RESULTS BY THEME

The following section presents the summary results of the workshop, organized according to the principal themes discussed at the meeting, but does not highlight the specific presentations or speakers. (That information is provided in Section 4.) Please note that during the meeting, presentations were organized predominantly according to the various Themes; however, some presentations included information from more than one theme while others were accommodated at a time / in a theme where they fit best because of time constraints of the speaker.

The summary of each workshop theme includes both a synthesis of the results and integrated assessment of how each topic stands as of December 2020. This assessment (presented in tabular form) comprises four areas: (1) Requirements (i.e., what are the requirements in this Theme for a 2045 Settlement?); (2) Capabilities (in other words, what Capabilities are needed by 2045 to satisfy those requirements); (3) Players (i.e., who kinds of organizations are, or will be involved in realizing those capabilities?); and, (4) Maturity (in this discussion, what is the 'Moon Village Readiness Level" (MVRL) for the Theme?). Annex D presents current, high-level definitions of the MVRLs – which are a newly-proposed maturity scale, related to the TRLs but addressing a broader set of considerations than technology and focused on the Moon Village concept.

5.1 Theme 1: Local Manufacturing and Construction

Theme 1 of the Moon Village Architecture Workshop concerned local manufacture and construction of structural systems on the Moon. Although they would not be required for a base on the Moon, such capabilities are essential – a *sine qua non* – for a human lunar settlement. The workshop discussion indicated that that local manufacturing of diverse products and local construction of various structural systems using either imported and/or locally-sourced materials <u>are</u> technically feasible and should be available by the 2030s, in time to support the Settlement 2045 concept. A variety of systems can be locally manufactured and/or constructed on the lunar surface either from imported materials or from the lunar regolith. See Table 5-1 for a summary assessment of this area.

For example, construction includes structural systems such as habitat pressure vessels, landing pads and roads (and other planar structures), tunnels, and others. If local material is used, then local manufacturing and construction might be accomplished with largely untransformed regolith – without extraction or processing to produce interim feedstocks. One process for such regolith-based manufacturing – beyond 'Earth moving' and sculpting – is known as 'sintering'; i.e., the heating of regolith with lasers or microwaves.

In addition, lunar regolith may be processed – for example using high-temperature electrolysis – to produce elemental feedstock materials, including Oxygen from the oxides (FeO_2, SiO2, etc.) that make up a large percentage of the regolith. Alternatively, imported 'binding agents' might be imported and used in construction such as polymer resins. Also, concrete might be produce using recycling of water and other agents needed to achieve the relevant chemical reactions.

Table 5-1 Settlement 2045 / Theme 1 Summary Assessment[9]

THEME	Local Manufacturing and Construction (Theme 1)
REQUIREMENTS?	• Local manufacturing and construction are enabling for a future Lunar Settlement, but not necessarily for an inhabited base or camp on the Moon (which could be accomplished with an imported pressurized module and then provided with radiation protection locally).
CAPABILITIES?	• Construction of habitat and other pressure vessels (such a fuel tanks), landing pads, roads, tunnels are all the subject of ongoing R&D.
PLAYERS?	• Diverse space agencies, particular in the US, Japan and European organizations • Multiple companies, including 'majors' and new space firms
MATURITY?	• Concepts exists and R&D is being conducted, but is still at the laboratory level of testing / experiments. • More analytical modeling needed to test 'economic viability' for Settlement 2045. • Maturity = MVRL 3, approximately. (See Annex D)

With appropriate feedstocks high-quality electronics such as photovoltaic (PV) cells and arrays, electrical wiring and devices (such as electromagnetic devices), components for batteries and other systems can be fabricated on the Moon, perhaps with selected imported materials or components. Relatively small fabrication systems – including either fixed or mobile systems – might be used to accomplish this kind of fabrication if energy is provided, due in part to the ambient 'hard' vacuum environment on the Moon. Moreover, extremely large-scale (10s of kilometers) radio telescopes might also be manufactured by roving fabricators – enabling unprecedented observations of the universe.

5.2 Theme 2: *In Situ* Resource Utilization

Theme 2 addressed a topic closely related to local manufacturing and construction, namely *in situ* resource utilization, also known as 'ISRU'. The resources of the Moon are diverse and promise a wide variety of highly useful materials as feedstocks for local processing and manufacturing. Research and development (R&D) of various specific approaches to ISRU have been ongoing for decades, generally-speaking using lunar regolith simulants. The discovery of water ice at the Moon's poles opened new avenues for ISRU that are only now being explored. The workshop discussion validated that ISRU is technically feasible and can be available by the 2030s and to support the Settlement 2045 concept. See Table 5-2 for a summary assessment of this area.

However, typically the regolith must first be excavated, processed and transformed – and the resulting materials purified and, in some cases further processed and stored. For example, since the Apollo

9 As noted above, the "Moon Village Readiness Levels" (MVRLs) are discussed in Annex D as a proposed, discipline-independent scale for evaluating the maturity of various capabilities, missions, systems, etc. vis-à-vis the Settlement 2045 concept. The assessments presented in Section 5 are entirely preliminary in character, and will be updated.

era, it has been known that the regolith comprises a number of metal and semiconductor oxides. If the oxides are 'cracked' – for example by means of high-temperature electrolysis – then only electricity will be required to produce Oxygen (O_2), Iron (Fe), Aluminum (Al), Silicon (Si) and a host of other materials. During the past the two decades the presence of water ice in the permanently shadowed regions (PSRs) of the Moon's polar regions has been confirmed by various spacecraft. This discovery opened up entirely new opportunities for ISRU – and relevant technologies – both in terms of required systems and the operational environments involved.

Considerably more information is still to be gathered regarding the details for the physical characteristics of the water ice-bearing regolith in the permanently shadowed regions (PSRs). And, the specific chemical composition of regolith in the vicinity of the poles needs to be better understood to refine plans and processes for its use.

Table 5-2 Settlement 2045 / Theme 2 Summary Assessment

THEME	*In Situ* Resource Utilization (ISRU) (Theme 2)
REQUIREMENTS?	• ISRU for key materials – particularly production of water, Oxygen, propellants, etc. – are enabling for a Lunar Settlement, but are only high-leverage for an inhabited base or camp on the Moon (i.e., reducing costs, risks, etc.).
CAPABILITIES?	• ISRU of various types is the subject of R&D, often in close conjunction with manufacturing R&D in particular.
PLAYERS?	• Diverse space agencies, particularly in the US, Japan and European organizations. • Various universities – particularly CSM. • Multiple companies, including 'majors' and new space firms; however, corporate research in many cases appears less comprehensive / mature than that at universities.
MATURITY?	• More information is needed regarding the details of ices in the PSRs and the composition of polar regolith • Concepts exists and R&D is being conducted, but is still at the laboratory level of testing / experiments. • More analytical modeling needed to test 'economic viability' for Settlement 2045 and potential commercial applications. • Maturity = MVRL 2, approximately. (See Annex D)

5.3 Theme 3: Life Support Systems & Agriculture

Workshop Theme 3 life support systems and agriculture – the local recycling of various elements through bioregenerative means. The discussion indicated that significant advances beyond the foundation on those currently operating on the ISS (and other LEO space stations) are possible, but significant issues remain if agriculture is to be available by the 2030s, in time to support the Settlement 2045 concept. See Table 5-3 for a summary assessment of this area.

Many of the regenerative life support systems (RLSS) now in use onboard the International Space Station (ISS) depend upon consumable materials, such as filters and process chemistry-based systems. Such systems are practical only because the ISS can be resupplied regularly from Earth. The realization of a biologically-sustainable settlement on Earth's Moon will depend upon the capacity to, without recourse to filters or systems imported from Earth:

1) locally regenerate air;
2) locally deliver fresh water indefinitely to people, other animals, plants, etc.);
3) locally produce a diverse variety of nutritious food, sufficient for indefinite habitation; and
4) recycle indefinitely biological and physical waste associated with human society.

Fundamental necessities for all of the above will be (a) the local fabrication, construction, repair and expansion of structural systems – including pressurized habitable volumes, (b) the production of viable soil locally from a feedstock comprising primarily lunar regolith, (c) the production of both Earth-like air and potable water.

Table 5-3 Settlement 2045 / Theme 3 Summary Assessment

THEME	Life Support and Agriculture (Theme 3)
REQUIREMENTS?	• Regenerative ECLSS is essential for affordable long-duration human missions beyond LEO. • Bio-regenerative life support systems involving food growth and use of living systems in air recycling, waste processing, etc. is essential.
CAPABILITIES?	• ECLSS of various types is the subject of many government-sponsored R&D, particularly in the context of the ISS, and planning for the soon-to-be-deployed Chinese space station.
PLAYERS?	• Diverse space agencies, ISS partners particularly – including the US, Europe, Japan, Russian Federation, China, and others. • Only selected companies appear to be strong players, including some 'majors' and few new space firms. • Various universities are involved, but typically in plant research.
MATURITY?	• Fundamental understanding is lacking regarding plant growth and animal species in $1/6^{th}$ gravity. • Concepts exist and R&D is being conducted, but is still at the laboratory level of testing / experiments, typically with individual plant species. • More analytical modeling needed to verify the technical feasibility for Settlement 2045. • Maturity = MVRL 2, approximately. (See Annex D).

In appears entirely feasible to accomplish these functions; however, the system-of-systems required will be exceptionally complex and involve 'emergent' behaviors difficult to discern – much less understand – in simulations, sub-scale / partial testbeds or similar environments. Moreover, an 'unknown-unknown' in all of this involves the detailed effects of lunar gravity at 1/6th Earth normal on the various species in the settlement biosphere.

5.4 Theme 4: Reusable Space Transportation Systems

Affordable, regular and reliable transportation to and from a lunar settlement will be extremely important for both physical and economic sustainability. Such transportation will certainly require reusability of vehicle systems – at least for human-rated, passenger-carrying vehicles; and, of course reusability depends upon the ability to refuel vehicles. The workshop discussion indicated that reusable and therefore refueled space transportation are technically feasible and should be available by the 2030s, in time to support the Settlement 2045 concept. See Table 5-4 for a summary assessment of this area.

Table 5-4 Settlement 2045 / Theme 4 Summary Assessment

THEME	Reusable Space Transportation (Theme 4)
REQUIREMENTS?	• Low cost space transportation from Earth to the Moon and back is essential for a lunar settlement – and reusable space transportation for each segment is required. o to/from LEO, to/from LLO, to/from the lunar surface
CAPABILITIES?	• Reusable space transportation systems have been proven for ETO transport – the most difficult segment; • Both in-space and orbit-to-surface transportation is the subject of ongoing R&D.
PLAYERS?	• Diverse space agencies, ISS partners particularly – including the US, Europe, Japan, Russian Federation, China, and others. • Only selected companies appear to be strong players, including some 'majors' and few new space firms. • Various universities are involved, but typically in plant research.
MATURITY?	• Concepts exists and R&D is being conducted, but is still at the laboratory level of testing / experiments. • More analytical modeling needed to test 'economic viability' for Settlement 2045 and potential commercial applications. • Maturity = MVRL 3, approximately.[10] (See Annex D)

The deployment of Earth-supplied lunar orbit-surface-orbit vehicles, based and refueled in LLO (or cis-lunar space) would continue the sequence. This would be followed by the development of lunar surface systems for ice 'mining', extraction, and processing – followed by 'cracking' of the purified water to produce O_2 and H_2, followed by liquefaction and LOx-LH_2 propellant storage and use. At this point, lunar surface based (and refueled) RSTS will become possible – enabling truly low-cost access to the Moon. Lunar surface refueling of RSTS will depend upon ISRU, discussed previously.

[10] The maturity assessment if for the RSTS vehicle systems; there are closely related capabilities re: ISRU that are less maturity (due to the need for more information about the PSR ices) and operations (due to the need for local servicing and maintenance of vehicles).

5.5 Theme 5: Power & Operations

The discussion related to Theme 5 addressed both space power and a number of operations associated with the settlement concept. The workshop discussion indicated that advances beyond current power systems – particularly for solar power – are technically feasible and should be available by the 2030s, in time to support the Settlement 2045 concept. See Table 5-5 for a summary assessment of this area.

In order to accomplish a biologically and economically self-sufficient settlement on the Moon a significant advance in current capabilities for space power is essential. The ISS has an onboard power system capable of generating (peak) some 150 kW, and delivering (using battery systems) an average of about 100 kW – representing about 24 kW per person for a crew of 4. Taking into account the system development cost, the operations costs, repair and maintenance, and the lifetime of the ISS power system, the cost for this power may be estimated at approximately $50 per kilowatt-hour. This is very roughly 100-times greater than the cost of power in the US, for power equivalent to a small suburban neighborhood. Dramatically more power, and a much, much lower cost will be required to realize a sustainable space settlement on the Moon.

Table 5-5 Settlement 2045 / Theme 5 Summary Assessment

THEME	Power and Operations (Theme 5)
REQUIREMENTS?	• Significant power – in the multiple MW – is essential for the Settlement 2045 concept. Moreover, significant power must be delivered to the PSR to enable ice mining operations. • A variety of advanced 'CONOPS' are also essential, including surface transportation, local servicing of systems, etc.
CAPABILITIES?	• The capabilities of the ISS represent a baseline for both power and operations for the Moon • However, a variety of other capabilities are also in development – particularly large-scale mass production of power systems 'mega-constellations' • Power for the PSRs is a special issue; but developments of WPT and space nuclear power systems are both underway.
PLAYERS?	• Systems are being developed by a diverse set of space agencies, including the US, Europe, Japan, Russian Federation, China, the UK and others. • In addition, a number of companies appear to be strong players, including both 'majors' and new space firms. • Various universities are involved, but typically in plant research.
MATURITY?	• Concepts exists and R&D is being conducted, but is still at the laboratory level of testing / experiments. • More analytical modeling needed to test 'economic viability' for Settlement 2045 and potential commercial applications. • Maturity = MVRL 3, approximately. (See Annex D)

One of the fundamental assumptions of the current case study is that affordable, megawatt-class space power system are now being enabled – as a result of the mass production of solar powered spacecraft as a result of the deployment of mega-constellations in LEO.

5.6 Theme 6: Architectural Concepts & Markets

This final session addressed two cross-cutting topics: architectural concepts and markets. The workshop discussion indicated that a variety of activities are underway, exploring diverse architectural concepts for the Moon that could be relevant to a future lunar settlement. Markets are also emerging with new players (e.g., MVA's PESC program), and communications being coordinated through means such as the MVA 'moon market' activity and the economics working group. However, additional work is needed to better reflect the special character of the lunar polar regions and the opportunities that will emerge through accomplishing Settlement 2045. See Table 5-6 for a summary assessment of this area.

Table 5-6A Settlement 2045 / Theme 6A Summary Assessment

THEME	Architectural and Related Concepts (Theme 6A)
REQUIREMENTS?	• Architectural concepts appropriate to the lunar polar regions are essential to the Settlement 2045 concept. • These must address not just traditional 'architecture' – i.e., buildings – but also urban planning, power engineering, etc.
CAPABILITIES?	• There is a rich history of design and planning for lunar surface installations, going back to the 1950s. • R&D is ongoing, with multiple studies. However, these tend to not be focused on the lunar polar region.
PLAYERS?	• Diverse space agencies, ISS partners particularly – including the US, Europe, Japan, Russian Federation, China, and others. • Only selected companies appear to be strong players, including some 'majors' and few new space firms. • Various universities are involved, but typically in plant research.
MATURITY?	• Concepts exists and R&D is being conducted, but is still at the laboratory level of testing / experiments. • More analytical modeling needed to test 'economic viability' for Settlement 2045 and potential commercial applications. • Maturity = MVRL 3, approximately. (See Annex D)

The discipline known as 'architecture' is defined as referring to 'the art or science of building' in general, and more specifically 'the art or practice of designing and building structures and especially habitable ones.'[11] Designing a lunar settlement must involve a wide variety of disciplines – including not only 'architecture', but also lunar geophysics, space systems engineering, electrical engineering and many

[11] See: https://www.merriam-webster.com/dictionary/architecture, downloaded on 23 December 2020.

others.[12] There is a general consensus for a lunar settlement to be 'sustainable', it must be sustainable not only in terms of the physical aspects of the installation, but also with regards to its economics. Only a handful of market opportunities have been identified that suit the capabilities of a lunar settlement during the coming several decades and which also technically feasible.

Table 5-6B Settlement 2045 / Theme 6B Summary Assessment

THEME	Market Development (Theme 6B)
REQUIREMENTS?	• A settlement on the Moon must not only be technically feasible, it must also be economically viable; this will depend upon the early • Establishing a permanent settlement on Earth's Moon must be a peaceful endeavor of all humanity – hence broadening the base of global participation is a key requirement
CAPABILITIES?	• Only very limited concepts have emerged for a viable 'economy of the Moon'. • There are ongoing efforts – particularly by the MVA – to broaden international participation in lunar programs.
PLAYERS?	• Diverse space agencies, ISS partners particularly – including the US, Europe, Japan, Russian Federation, China, and others. • Only selected companies appear to be strong players, including some 'majors' and few new space firms. • Various universities are involved but studies are limited.
MATURITY?	• Concepts exists and R&D is being conducted, but is still at the laboratory level of testing / experiments. • More analytical modeling needed to test 'economic viability' for Settlement 2045 and potential commercial applications. • Maturity = MVRL 1-2, approximately. (See Annex D)

Section 6, which follows presents closing observations, including an update of the baseline Settlement 2045 concept and the plan forward.

12 As a 'term of art' to reflect this diverse of disciplines and skills the following is suggested: "Lunatect" as someone who practices the art and science of 'Lunatecture' – including the diverse and dynamic combination of skills, modeling tools, etc. etc. that must be employed to create a new biosphere on Earth's satellites.

SECTION 6

KEY FINDINGS & PLAN FORWARD

6.1 High-Level Findings

The following are some of the key findings and potential actions that could be taken both for the remainder of the current ongoing Case Study, as well as after its completion. The topics addressed include: (1) settlement technical feasibility; (2) the importance of terrain near the chosen location; (3) long-distance operational mobility; (4) the building blocks needed; (5) interfaces that must be defined; (6) promoting interoperability; (7) settlement economic viability; and, (8) assessing 'readiness' to accomplish these goals. The section also identifies selected updates of the Reference Architecture that are needed. Each of these is addressed in the paragraphs that follow.

6.1.1 Settlement Technical Feasibility

In terms of the requirements identified by the Case Study (see Section 3), a lunar settlement located near the south pole of the Moon appears to be technically feasible. Habitable volume manufactured locally, power and thermal systems, reusable (i.e., refueled) space transportation, communications, in-situ resource utilization, radiation shielding, etc. all appear achievable. However, there are some significant unknowns that must still be resolved.

First and foremost, the most important 'known unknown' involves 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 the many other animals, plants, fungi and other species that are essential to establishing a sustainable biosphere. And, for agriculture to be realized, an affordable source of large amounts of Nitrogen and Carbon (which are not meaningfully available in the lunar regolith) must be identified. Moreover, there are other 'unknown unknowns' associated with the lunar polar environment itself, as contrasted with the lunar environment at the Apollo landing sites. The structure of the regolith in the PSRs has not been determined in detail, nor has the chemical composition of the ices that have been discovered.

Although a settlement appears technically feasible (with the exception of various unknowns, such as those mentioned above) a wide variety of technologies and systems still must be developed or adapted from terrestrial applications by not later than the mid-2030s if a settlement is to be accomplished by 2045. The outstanding issues concerning technical feasibility will be examined in greater detail by the ongoing Case Study in 2021.

6.1.2 The Importance of Terrain

The current focus of international and commercial interest in the Moon is on the poles of the lunar surface – primarily the south polar region – due to the presence of water ice in the permanently shadowed regions (PSRs). The existence of PSRs is due to the extremes of terrain at the poles. For example, the difference in elevation from the rim of Shackleton Crater to its floor is approximately 5,000 meters, a change that occurs over a linear distance of only some 5-6 km. For comparison, recall that the depth of the Grand Canyon in the US is only a little more than 1,800 meters.

Many lunar surface habitat architecture studies have been conducted over the years, addressing a wide range of variations – including buried ISS-like modules, locally fabricated domes, mobile habitats, and other concepts. however, most of these have addressed generic locations, typically similar to the Apollo landing sites, which were quite 'flat' or sometimes involving lava tubes. And only a few have looked at using the Moon's most common feature – craters – in a habitation design. However, none of the typical concepts are especially suitable as points of comparison for the majority of the lunar south polar region, which is quite rugged.

Additional factors in a lunar settlement that are impacted by terrain include power supplies, launch and landing sites, and others. Again, few past studies have been set in a terrain model similar to that at the Moon's south pole – although recent consideration has been given to often-illuminated high-elevation locations (e.g., ridgelines, crater rims, etc.) for solar power generation. Also, cost-effective transportation among the various operational locations of a settlement will be on the surface – and hence the terrain will be extremely important.

6.1.3 Long-Distance Operational Mobility

As noted in the prior paragraph, little R&D has been done concerning long-distance traverse mobility over rugged terrain – such as exists at the lunar south pole – for operational purposes (e.g., mining, transporting cargos or crews over 10s of km) in the south polar region. Many countries have developed robotic 'rovers' for scientific purposes, including both the Moon and Mars; and, building on the Apollo program R&D is being conducted to develop both unpressurized and pressurized astronaut mobility systems. For a lunar settlement, it is likely that 'trucks' to move regolith (or water) from a mining site to the location of a processing plant will likely need to traverse tens of kilometers daily, 100s of km per month and 1,000s per year, and to do so while hauling up to tons of material. Dust will be a major issue, of course; and its mitigation for surface mobility systems essential. However, the fabrication of roadways (e.g., pavement or paving stones that together comprise a roadway) by sintering regolith may accomplish this objective. During 2021, further characterization will be pursued of mobility requirements, concepts and technologies.

6.1.4 Building Blocks Needed

One key result of the current case study was the development of a set of 'building blocks' (mentioned above) that will be important to the realization of the reference architecture, these address the issues identified above and many others. These are sketched in the paragraphs that follow, along with preliminary plans for additional work to be pursued during 2021.

Utilities. 'Utilities' building blocks include communications & network systems; Position location and navigation; Imaging & Operational Sensing; computing and data management; and, power generation & energy systems. More information is needed on the requirements to be satisfied by the various utilities; for example, power for life support systems, waste heat to be dissipated, etc. Clearly solar power generation systems will be located either at a system user or in a sunlit location within reach by power transmission (wired or wireless). However, space nuclear power generation system siting is somewhat less straightforward as it will involve sizing for transportation, choosing an appropriate thermal environment, planning for the system once it is radioactive, and other topics. Various utilities – but especially power – will be considered in greater detail during 2021.

Transport & Logistics. 'Transport & logistics' building blocks include *Space Transport Systems* (including surface-to-surface transportation – i.e., 'hoppers'); *Space Transport Vehicles* (Expendable, Reusable, etc.); *Landing Systems & Vehicle Support Systems*; *Advanced Lunar Launch Concepts*; and, *Surface Transport Systems* (including transportation of crew, cargo and materials). In addition, harvesting residual propellants from landers will be an important source of consumables. Recycling of one-way expendable vehicles will be a key function for both the 'Transport & Logistics 'and 'Operations' Building Blocks. Also, it is unlikely that vehicles will be able to arrive at will at a spaceport near a settlement. Schedules will be impacted by orbital locations of facilities in space, flight paths on the lunar surface, access to facilities, and other factors. Integrated analysis of traffic models is needed – coupled to systems studies of both space transportation systems, and surface-based capabilities (such as ISRU, ISPP, CPDs, space ports and surface transportation).

Operations. A wide range of building blocks fall under the general category of 'operations', including dust mitigation; construction systems; physical waste processing and recycling; and, manufacturing. Another critical 'Operations' building block for the lunar settlement reference case study will be Tunnel Boring Machines (TBMs) that are capable of full dry tunneling and producing sealed tunnel structural systems.

Resources. These building blocks involve all manner of systems and capabilities related to lunar surface resources, such as exploration for and characterization of lunar resources (including ice and other volatiles, minerals in the regolith, etc.); mining systems & resources extraction capabilities; resources processing & handling systems; and the production of pure feedstocks for use in habitation and transportation operations (e.g., pure water, pure O_2, pure H_2, etc.). Integrated assessment and analysis of resources-related considerations in the context of the other Building Blocks will be pursued during the remainder of the Case Study.

Habitation / Self-sustaining 'Biospheres'. Including habitable volume (pressure vessel, air, water, lighting, thermal management, etc.); radiation protection; agricultural systems; biological waste processing & recycling. Options of the integration of possible low-gravity mitigation systems (e.g., a centrifuge) in the habitation systems are needed. Having multiple habitats appears to be an excellent risk-mitigation strategy for a lunar settlement (i.e., not putting all of one's 'eggs in one basket'). However, connecting these places where people will live without requiring individuals to go outside into the vacuum will be essential. (The same issue arises in many communities on Earth where the weather is too hot or too cold during much of the year, and is solved by elevated walkways and/or tunnels.) These factors will be examined during 2021.

Human Operations & Health. Human operations and health related building blocks include EVA systems; airlocks; EVA Suits; personal mobility systems; EVA maintenance systems; medical care systems (including urgent care, immunology, surgical care, dental care systems, etc.). Lunar gravity mitigation is a closely-related consideration. All of these systems must be able to be fabricated locally in large measure, if not entirely for a settlement to be 'self-sufficient'. In 2021, the Case Study will examine these considerations.

Robotic Systems (Surrogates / Augmentation). A wide variety of robotic systems will be essential to the successful development and subsequent operations of the Moon Village – both as surrogates for human actors and to augment or support them. These include robotic systems that will operate inside human habitation systems, those that may operate either on the interior or the exterior of habitats (just as humans do), and those that are restricted to operations exterior to habitats (and perhaps at locations remote from them (such as mining sites).

Science Missions / Payloads. Science Missions and/or Payloads include three major categories of science: (1) Science of the Moon (for example, geophysics); (2) Science from the Moon (such as astrophysics); and, (3) Science on the Moon (for example, generic research laboratories as well as focused research installations, such Mars mission testbeds on the Moon).

6.1.5 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.[i] 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.).

The closely related topic of 'interoperability' is discussed in the paragraph that follows.

6.1.6 Promoting 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 important 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.[ii] 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.

6.1.7 Settlement Economic Viability

It is highly likely that 'outposts' – of which the International Space Station (ISS) is an example – may be deployed in Earth orbit, in cis-lunar space and perhaps on the lunar surface in the coming 10-20 years. However, at present it seems unlikely that governments for policy reasons will invest the necessary funds to deploy and maintain a space settlement. As a result, in addition to technical feasibility, a lunar settlement must also be economically viable.

As noted elsewhere, there are only a few '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). 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 assumptions of this case study regarding low-cost transportation emerge. In addition to scientific exploration and preparation for later Mars missions, the Moon may also be an important R&D facility for future lunar capabilities. For example, a biosphere on the Moon may well be the best possible facility for may sorts of partial gravity biological research.

During 2021 the potential markets for a lunar settlement will be examined in terms of the several 'building block' capabilities identified during 2020. Potential services that might support these (for example, related to space tourism) will be identified and assessed.

6.1.8 Assessing Readiness

There are diverse programs and projects around the world relating to future human activities on and near the Moon. One thing that was apparent from the numerous presentations and resulting discussion at the workshop was that some standardize way of assessing the 'readiness' for different lunar-focused activities to begin / proceed might be very helpful. If activities only involved technology, the already standard "technology readiness levels" (TRLs) would be sufficient, of course. However, lunar activities involve technologies, systems, analogues and other facilities, market developments and more.

6.2 Actions and Plan Forward

6.2.1 Current Implementation Planning

The current implementation plan involves:

- Already Achieved: During 2020, preliminary studies and modeling
  - Selected results were presented at the online International Astronautical Congress (IAC) in October 2020
  - 2020 September – Initial 'Webinar' on MV Architecture Studies
  - 2020 November – Preliminary inputs presented at the MVA 2020 Online Symposium
  - 2020 December – An online MVA Workshop focusing on the MV Reference Architecture will be jointly organized; this meeting is that online event
- Ongoing
  - Interim reports are being developed and posted to the MVA website in early 2021

- Future: During 2021, further studies and meetings, including
  - MV evolution in terms of international cooperation, business society and legal considerations will be jointly organized during late Spring 2021.
  - Case Study 2nd workshop during Spring/Summer
  - Possible ESTEC Concept Development Facility-type (CDF) studies
  - 2021 Fall/Winter – Working results will be presented at IAC 2021 and at the 2021 Moon Village Association Workshop and Symposium
  - 2022 January – Final reports will be developed and posted to the MVA website

6.2.2 Settlement 2045 Reference Updates

This section has presented a number of topics that will be considered in framing prospective updates to the Settlement 2045 reference based on the Case Study thus far. These included the various issues related to each of the Building Blocks, as well as cross-cutting technical and programmatic matters – ranging from evaluating the economic viability of a lunar settlement in 2045 to assessing in the near-term the readiness to accomplish essential capabilities. During 2021, two updates of the Settlement 2045 are planned – one in the summer and a second update prior to the planning final workshop.

6.2.3 A Few Other Factors

A number of additional factors have been identified in the context of the December 2020 workshop. For example, the view of Earth from the current target location for a settlement will vary over the course of a lunar month and year – with the Earth moving up and down near and likely below the horizon. Will that be acceptable, or should another location be considered – perhaps one just for viewing our home? Also, the candidate location for Settlement 2045 was chosen with a view toward avoiding clear issues of public concern (such as a settlement exactly at the lunar south pole of the Moon – a unique location). However, what other concerns should be taken into account, particularly with respect to changes to the nearly permanent record of the Moon's regolith that might result from mining operations?

In addition, the MVA Evolution Team (based in Japan) is considering the longer-term future of humanity on the Moon, beyond 2045. How might such later-21st Century considerations more correctly influence the 2045 Reference Concept? These and other factors will be considered during the remainder of 2021.

6.2.4 Signposts?

The workshop comprised a discussion of the various global studies and R&D activities. These represented common threads that spanned various Moon Village scenarios, but were generally focused on the current Case Study and highlighted a preliminary vision for a MV Reference Architecture – including a candidate settlement at the south pole of the Moon to be established by 2045. The current Case Study is founded on a set of specific assumptions about the future course of events. However, these may not be correct. How then to judge the best course for government planning, future R&D and business developments?

There may well be 'signposts' during the coming several years that will indicate which path humanity will be taking to its lunar future.

One signpost could well be the beginning of ETO services by two or more reusable launch vehicle service providers (rather than only one). If this occurs, the key question will be the impact of multiple service providers on ETO prices for a range of customers? If prices drop as seems likely, then the cost of operations throughout cis-Lunar space could be significantly reduced. Another important indicator of future directions will be the detailed results from various lunar polar missions – particularly rovers and sample returns. This will indicate the physical character of volatiles already detected at the Moon's poles, thereby enabling planning for and development of ISRU systems to proceed.

Many such signposts exist; however, one final indicator of future directions must be mentioned. What will be the disposition in practiced law of the ownership of 'processed' materials on the lunar surface? At the moment, the indication is that the major space-faring countries (e.g., the US, China, etc.) will assign ownership of "a fish" to the "fisherman who caught it" (metaphorically speaking). When – and if – the first lunar rock is 'owned' by a firm that collects it, that will be a significant signpost of which lunar path we are on.

It is the hope of the MVA Architecture Working Group that the current Settlement 2045 Case Study will provide a framework for evaluating the potential consequences of these and other future developments – and inform timely decisions regarding prospective courses of action by governments, companies, universities and individuals.

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ANNEX A

GLOSSARY OF ACRONYMS

AI	Artificial Intelligences
BIG	Bjarke Ingels Group
CDF	(ESA) Concept Development Facility
CLPS	(NASA) Commercial Lunar Payload Services program
CNS	(IIF) Center for Near Space
CO2	The chemical formula for Carbon Dioxide
CONOPS	Concept of Operations
CSM	Colorado School of Mines
ECLSS	Environmental Control and Life Support System
ESA	European Space Agency
ESPRIT	(Lunar Gateway) European System Providing Refueling, Infrastructure and Telecommunications
ESTEC	ESA Science and Technology Engineering Center
ETO	Earth-to-orbit (transportation)
EVA	Extravehicular Activity
GER	(ISEC-G) Global Exploration Roadmap
H_2	The chemical formula for Hydrogen
H_2O	The chemical formula for water
HALO	(Lunar Gateway) Habitat and Logistics Outpost
HEOMD	(NASA) Human Exploration and Operations Mission Directorate
HLS	(NASA) Human Landing System
IAA	International Academy of Astronautics
I-HAB	(Lunar Gateway) International Habitat
IIF	(Italian) Institute for the Future
ILEWG	International Lunar Exploration Working Group
ISAAC	In Space Assembly and Construction
ISAS	(JAXA) Institute of Space and Astronautical Science
ISEC-G	International Space Exploration Coordination Group
ISRU	*In situ* resource utilization
ISS	International Space Station
JAXA	Japan Aerospace Exploration Agency
JRS	Japan Rocket Society
kg	kilogram
km	kilometer
kW	kilowatt
kWh	kilowatt-hour
LEAG	Lunar Exploration Advisory Group
LEO	low Earth orbit
LH_2	Liquid Hydrogen
LLO	low lunar orbit
LOX	Liquid Oxygen
LSII	(NASA) Lunar Surface Innovation Initiative
m	meter(s)
MIS	Made-in-Space

m^2	'meters-squared', aka 'square meters'
MMPACT	Moon-to-Mars Planetary Autonomous Construction Technology
m^3	meters-cubed
MRE	Molten Regolith Electrolysis
MSFC	(NASA) Marshall Space Flight Center
MT	Metric Tons
MVA	Moon Village Association
MVRL	Moon Village Readiness Level(s)
MW	megawatt
MWh	megawatt-hour
MV Architecture WG	Moon Village Architectural Concepts & Considerations Working Group
MW	megawatts
N_2	The chemical formula for Nitrogen gas
NASA	National Aeronautics and Space Administration
NGO	non-Governmental organization
NSS	National Space Society
O_2	The chemical formula for Oxygen gas
PESC	(MVA) Program for Emerging Space Countries
PPE	(Lunar Gateway) Power and Propulsion Element
PSR	Permanently Shadowed Region
R&D	research and development
RLL	Reusable Lunar Lander
RLSS	Regenerative Life Support Systems
RSTS	Reusable Space Transportation Systems
SDO	(Yuzhnoye) State Design Office
STMD	(NASA) Space Technology Mission Directorate
TBD	to be determined
TBM	Tunnel Boring Machine
Team X	(NASA) 'Team-X'
TRA	Technology Readiness Assessment
TRL	Technology Readiness Level(s)
TRRA	Technology Readiness and Risk Assessment
TUS	Tokyo University of Science
UAE	United Arab Emirates
USA	United States of America
USC	University of Southern California
VR / AR	Virtual Reality / Augmented Reality
WG	working group

ANNEX B

WORKSHOP PARTICIPANTS

The following Annex table presents a summary listing of the registered participants of the MV Architecture WG Workshop (14-16 December 2020).

NAME (LAST, FIRST)	COUNTRY	ORGANIZATION	ROLE
ABBUD-MADRID, Angel	USA	Center for Space Resources, Colorado School of Mines	Participant, Speaker
ALOTAIBI, Ghanim	KUWAIT	MVA PESC Project	Participant, Speaker
ASAZUMA, Taro	JAPAN	Ispace	Participant
BALLARD, Jason	USA	ICON	Participant, Speaker
BARNHARD, Gary	USA	XISP, Inc.	Participant
BAYCAN, Serdar	AUSTRALIA	Tectura	Participant
BERDNYK, Oleksandr	UKRAINE	Yuzhnoye State Design Office	Participant; Speaker
BIENHOFF, Dallas	USA	Cislunar Space Dev. Co., LLC	Participant; Speaker
BURKE, James D. (Jim)	USA	JPL, Retired; MVA	Participant
BURKE, Margaret (Margie)	USA	Jim Burke's Daughter	Participant
CARRELI, Paolo	UAE	College of Engineering; Abu Dhabi University	Participant
CHEUVRONT, David	USA	NSS	Participant
CLINTON, Raymond G. (Corky)	USA	NASA MSFC	Participant, Speaker
CLINTON, Trey	USA	Red Wire / Made-in-Space	Participant
COLE, Troy	USA	MVA Member	Participant
DAVID, Leopard	USA	Participant, Media	Participant
DE CHIARA, Giuseppe	ITALY	IIF	Participant
DE MARTINO, Guido	ITALY	IIF	Participant
DEEPAK, Adarsh	USA	Taksha Insittute	Participant
DEEPAK, Ravi	USA	Taksha Insittute	Participant
DiMARZIO, Kevin	USA	Red Wire / Made-in-Space	Participant, Speaker
EDMUNDSON, Jennifer	USA	NASA MSFC	Participant
EDWARDS, Christine	USA	Lockheed Martin Company	Participant, Speaker
EFFINGER, Michael	USA	NASA MSFC	Participant, Speaker
ENLOE, Sandy	USA	Blue Origin	Participant
FISCHER, Richard T.	USA	NASA MSFC	Participant
FISKE, Mike	USA	NASA MSFC	Participant
FOING, Bernard	Netherlands	ESTEC	Participant, Speaker

Name (Last, First)	Country	Organization	Role
FOUST, Jeff	USA	The Space Review / Space.com	Participant; Media
FUKUNAGA, Mihoko	JAPAN	IHI	Participant
FUKUSHIMA, Sho	JAPAN	Shimizu Corporation	Participant
GOTO, Takuya	JAPAN	Doshisha University	Participant
GRISSIM, Robert	USA	Drake State University	Participant (Future Lunar Construction)
HENLEY, Mark	USA	Boeing (Retired)	Participant
HIGUCHI, Kiyoshi	JAPAN	former IAF president, JAXA vice president	Participant
IGARASHI, Iwao	JAPAN	Mitsubishi Heavy Industries	Participant, Speaker
IGNATIEV, Alex Ph.D.	USA	Lunar Resources, Inc.	Participant, Speaker
INATANI, Yoshifumi	JAPAN	MVA / ISAS	Co-Chair, Keynote
INATOMI, Yuko	JAPAN	JAXA	Participant
IWASAKI, Akhiro Ph.D	JAPAN	Yspace	Participant; co-Speaker
KERAVALA, Jim	USA	OffWorld, Inc	Participant, Speaker
KITAYA, Yoshiaki	JAPAN	Osaka Prefecture University, Environmental Sciences & Technology	Participant, Speaker
KOBAYASHI, Hiroaki	JAPAN	Japanese Rocket Society (JRS) / ISAS (JAXA)	Participant; Speaker
LAUER, Chuck	UK / USA	SPACE BIT	Participant
MANKINS, John C.	USA	MVA / NSS / IAA	Co-Chair, Keynote, Speaker
MESSINA, Piero	FRANCE	ESA HQ	Participant
MINICHINI, Raffaele	ITALY	IIF	Participant
MITSUI, Masami	JAPAN	JAXA	Participant
MIYAJIMA, Hiroyuki	JAPAN	International University of Health and Welfare	Participant
MOORE, Christopher	USA	NASA HQ	Participant, Day 2 Keynote
MORITA, ken	JAPAN	Takasago Thermal Engineering	Participant
MORRIS, Michael	USA	Space Exploration Architecture; (SEArch+)	Participant, Speaker
OCAMPO SALAZAR, Julian	USA / DENMARK	BIG – Bjarke Ingels Group	Participant, Speaker
OKAMOTO, Yuki	JAPAN	IHI AEROSPACE	Participant
ONUKI, Misuzu	JAPAN	SpaceAccess	Participant
PALLES-FRIEDMAN, Rebeccah	USA	Space Exploration Architecture; (SEArch+)	Participant, Speaker
PELKEY, Tina	USA	Blue Origin	Participant
PERINO, Maria Antonietta	ITALY	Thales Alenia Space Italia	Participant, Speaker
PICA CIAMARRA, Massimo	ITALY	IIF	Participant

NAME (LAST, FIRST)	COUNTRY	ORGANIZATION	ROLE
PINO, Paolo	ITALY	Space Generation Advisory Committee	Participant, Speaker
REIBALDI, Giuseppe	The Netherlands	Moon Village Organization	Participant
RUSSO, Gennaro Ph.D.	ITALY	Italian Institute for the Future; Center for Near Space	Participant, Speaker
SAITO, Akio	JAPAN	IHI AEROSPACE	Participant
SAITO, Akio	JAPAN	IHI AEROSPACE	Participant
SAKATOMO, Yuki	JAPAN	Japanese Rocket Society (JRS)	Participant; co-Speaker
SALMERI, Antonino	ITALY	Space Generation Advisory Committee	Participant, co-Speaker; with P. Pino
SASAMURA, Mami	JAPAN	JAXA	Participant
SATO, Naoki	JAPAN	JAXA space exploration Center	Participant
SATTLER, Antoniia	GERMANY	Student; DLR; Space Architect dot Org	Participant
SCARSPI, Floriana	ITALY	Space Gen. Advisory Committee / Lunar Biosphere Project	Participant / Speaker (Life Support & Habitation)
SHERWOOD, Brent	USA	Blue Origin	Participant, Day 2 Keynote
SHINOHARA, Naoki	JAPAN	Kyoto University	Participant, Speaker
STONE, Dennis	USA	NASA JSC	Participant
STRASHKO, Vitalii	UKRAINE	Dnieper State Academy of Civil Engineering and Architecture	Participant
TAKAHASHI, Akihisa	JAPAN	Gunma University	Participant
TANASYUK, Pavlo	UK	SPACE BIT	Participant & Speaker
THANGAVELU, Madhu	USA	USC / NSS / MVA	Co-Chair, Keynote
UCHIDA, Atsushi	JAPAN	Mitsubishi Research Institute	Participant
UYAMA, Naohiro	JAPAN	Shimuzu Corporation	Participant, Speaker
VENTSKOVSKY, Oleh	UKRAINE	Yuzhnoye SDO, MVA Moon Market	Participant, Speaker
WERKHEISER, Niki	USA	NASA HQ / Lunar Surface Innovation Initiative (LSII)	Participant, TBD?
YASHAR, Melodie	USA	San Jose State University	Participant

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ANNEX C

Moon Village Architectural Concepts and Concerns

MOON VILLAGE SCENARIOS / VERSION II

v.2 | 17 December 2020

C.1. Introduction

The Moon Village Association (MVA) is dedicated to advancing the goal of humanity's expansion to the Moon (comprising in-space, and lunar surface) systems, missions and operations) under the rubric of the 'Moon Village' (MV) concept. Within the MVA, the MV Architectural Concepts and Considerations Working Group (MV Arch WG) is responsible for conducting technical studies that build upon current government and private sector lunar plans. During 2018, the MV Arch-WG developed and published a set of three high-level 'MV Scenarios' that encompassed a wide range of potential lunar goals, programs and accomplishments.

This update of the Moon Village Architecture Working Group 'Scenarios' for lunar exploration, development and (eventual) settlement represents a major revision of the initial scenarios, developed during and published at the end of 2018. Over the past several years, there have been significant policy and program planning changes (particularly in the US space program) as well as meaningful technology advances. Some of these changes are ongoing as management changes in the US program are imminent. Moreover, the August 2020 version of the Global Exploration Roadmap (GER) released by International Space Exploration Coordination Group (ISEC-G) provides a common set of events over the next 8-10 years that should be reflected in all MV Architecture Working Group (MV Architecture WG) scenarios.[1]

The updated MV scenarios continue to comprise three (3) alternative visions of the future, but with revisions in their definitions to better correspond with recent developments, described above. In addition, the MV Arch. WG 'case study' being conducted during 2020-2021 has produced useful interim results (e.g., the MV 'Building Blocks') that are incorporated into the updated scenarios. The following are the new scenarios:

- Scenario Alpha: Exploration-Driven.
- Scenario Beta: Science-Driven.
- Scenario Gamma: Development-Driven.

The paragraphs that following provide additional details on each of these; these are organized according to the classic questions: who? what? when? where? and why" (just as was true in Version I of the Scenarios). A prospective schedule of major milestones for each scenario is identified in terms of for timeframes: near-term (2021-2030), mid-term (2031-2040), far-term (2041-2050); and far-future (post 2051).

C.2. Scenario Turning Points

The actual future of human space activities will almost certainly not be any one of the three scenarios outlined here. Rather, the future may very well involve a combination of all them, with the 'level' of each's

1 For information on the ISEC-G and the GER, see: https://www.globalspaceexploration.org/wordpress/?cat=1 (downloaded on 22 November 2020), and 2020 Supplement: Global Exploration Roadmap Supplement – Lunar Surface Exploration Scenario Update (also downloaded on 22 November 2020).

contribution depending on identifiable 'turning-points' that may occur during the remainder of the 2020s. Along with the descriptions below, following each are suggested example 'turning-points' for each of the three scenarios; each turning point comprises a statement of a potential future event, including selected details of what might be entailed.

C.3. Scenario Alpha: Exploration Goals & Objectives-Driven Lunar Activities

In this alternative future, lunar activities will be planned and implemented to best support the goals of national government-sponsored space exploration programs, focused on or using the Moon. Human Space Flight (HSF) – the focus of Scenario Alpha in Version I of the MVA Scenarios – plays a large role in this new scenario, but robotic exploration is also emphasized. Primary activities will be conducted by contractors, working for government managers, and to a lesser extent in proportion by university researchers, although the total amount of effort will depend upon the overall funding for any program. Eventual human missions to Mars (HMM) are an over-arching motivation for a wide range of programs under this scenario during the 2020s and 2030s.

Within Scenario Alpha, major science goals will be accomplished, but typically this will occur as they are enabled by exploration programs (rather than as science goals in and of themselves). Similarly, important space development milestones will be realized; however, these will be primarily pursued for the benefits that new capabilities can deliver to exploration programs, or by providing useful ongoing services as required. Space 'development' might have commercial benefits, but these would not the purpose of government support for such efforts.

A primary purpose of government-sponsored exploration activities involving the Moon under Scenario Alpha will be preparation for later human Mars Missions (HMM). This purpose will result in the development and demonstration of various new capabilities – such as very long-range mobility, very long-duration (but limited capacity) habitation systems, and multi-use, locally maintained extravehicular activity (EVA) systems. Table 1 provides a schedule of major milestones that might results from Scenario Alpha occurring.

Scenario Alpha (Exploration-Driven) Turning Points

The following are 'turning points' that – if they occur in the near-term – would indicate that Scenario Alpha is likely to be a strong part of humanity's future vis-à-vis the Moon.

- Turning Point A.1 / Policy makers in a number of space-faring countries continue to support steady ongoing funding for lunar robotic missions (including orbiters, landers, rovers and sample return missions).
- Turning Point A.2 / Policy makers in major space-faring countries support significant additional resources for lunar exploration programs (particularly in the US, China, Europe and/or the Russian Federation). These might include a permanent outpost on the Moon or the significant use of the Moon as a testbed for later Mars missions.
- Turning Point A.3 / Policy makers in major space-faring countries support significant resources during the 2020s to develop capabilities for later human Mars Missions.

Table D.1: Scenario Alpha (Exploration) Schedule of Major Milestones (Version II)

When? (Years)		What? & Where? (Milestone Summary[Note_1])	Who? & Why?
Near-Term (2021-2030)	Multiple	Ongoing / multiple robotic exploration missions, including orbiters, landers, rovers and sample return. (GER[Note_2])	**Who?** Government Space Agencies Commercial Services Providers Universities, etc. <u>After the Mid-Term</u> Private Ventures (Increasingly)
	Multiple	Lunar surface and orbital technology demonstrations	
	Multiple	Lunar surface / orbit comm and nav systems deployed	
	c. 2024-2026	Lunar 'Gateway' Operational in cis-Lunar space (GER)	
	c. 2024-2026	US-Partners Human Mission to the Moon's South Polar Region (GER)[Note_3].	
	c. 2024-2026	Advanced Lunar EVA Operational (GER)	
	c. '24, '26, '29	Launch of Robotic Mars Sample Return Mission	
	c. 2028-2029	Long-Range Pressurized Rover Operational (GER)	
	c. 2028-2029	Lunar Surface Mars Habitation Systems (GER)	
	c. 2028-2029	Large-scale (350 kW) Power Emplaced on Surface (GER)	
	c. 2029-2030	Fuel Production Systems Emplaced on Surface (GER)	
	c. 2029-2030	Human Moon Missions by Others Begin, including to the Moon's South Polar Region	
Mid-Term (2031-2040)	Multiple	Ongoing / multiple robotic exploration missions, including orbiters, landers, rovers and sample return missions.	
	c. 2031-2032	Fuel Production @ 50 MT / year on Surface (GER)	
	c. 2031-2032	500-day Mars Habitation Demonstration (GER)	**Why?** National Policy Geopolitical Policy-Driven International Cooperation Resource Exploration & Exploitation to reduce costs Near-Term & Mid-Term: Demonstration of Capabilities for Humans-to-Mars Missions <u>After the Mid-Term</u> Profit Motives (Increasingly)
	c. 2031-2035	Various Lunar Mars Mission Simulations & Demos (GER)	
	c. 2035-2042	First Human Mission to Mars (HMM)[Note_4]	
Far-Term (2041-2050)	c. 2042-2046	Second Human Mission to Mars (HMM)[Note_4]	
	c. 2043-'44	Small-scale Lunar Outpost Established at the Lunar South Polar Region (Human Tended)	
	c. 2046-'48	Small Lunar Far-side Observatory Established	
	c. TBD	Lunar Space Tourism and Travel Begins	
Far-Future (2051-2100)	c. 2051-'53	Larger Lunar Outpost Established at the South Polar Region (Permanent Staff)	
	c. 2054-'58	Third Human Mission to Mars (HMM)	
	c. 2060-2070	Private / Commercial Lunar Outpost for Tourism	
	c. 2070-2080+	Permanent Lunar Settlement Established (Location depends on Markets-supported)	

<u>**Notes**</u>:

Note 1: Ongoing operations (e.g., the Gateway in the Mid-term) are not shown as milestones.

Note_2: "GER" indicated that this Scenario Milestone is included in the ISEC-G Global Exploration Roadmap supplement of August 2020.

Note_3: this GER milestone requires an immediate and significant increase in funding in the US and partnering countries to remain on its November 2020 schedule.

Note_4: this milestone depends on the dates / funding for the Mars Sample Return in the Near-Term.

C.4. Scenario Beta: Hypothesis-Based Science- Driven Lunar Activities

In this version of the future of human lunar activities, hypothesis-driven science goals and objectives will motivate lunar programs, again largely funded by government programs, but now involving a greater proportion of university-led science instruments and investigations relative to contractor implemented projects. (Again, the total scope of any program will determine whether a greater or lesser amount of contracted but government-funded work is ultimately performed.) In this scenario, steady resources over long periods is presumed, without dramatic surges in government spending or development of new capabilities. The several international science stations in Antarctica,[2] as well as major ground-based international observatories (such as the Square Kilometer Array[3]) or major facilities class international instruments such as the Large Hadron Collider (LHC)[4] represent models for envisioned science-drive lunar activities under This scenario.

Human space flight plays a more modest role in overall activities under Scenario Beta, with major new missions achieved only occasionally. A human Mars mission (HMM) would still occur, but probably later and only in the context of other science-driven goals and objectives. Periodic, regularly-funded small and medium scale science mission may be more typical. Development of space milestones are realized, but these are more typically in the form of services to ongoing science facilities and programs, rather than in the context of developing new capabilities for economic benefits. Permanent, but possibility human-tended outposts on the Moon man play a role – particularly if they can cost-effectively support science program requirements. Table 2 provides a schedule of major milestones for Scenario Beta.

Scenario Beta (Science-Driven) Turning Points

The following are 'turning points' that – if they occur in the near-term – would indicate that Scenario Beta is likely to be a strong part of humanity's future vis-à-vis the Moon.

- Turning Point B.1 / Policy makers in a number of space-faring countries continue to support steady ongoing funding for lunar robotic missions (including orbiters, landers, rovers and sample return missions).
- Turning Point B.2 / The international scientific community embraces a coordinated (not necessarily joint) family of major initiatives for lunar science – e.g., analogous to the "Great Observatories" model of the 1990s NASA, and policy makers in involved space-faring countries must support funding for these initiatives.[5]

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2 As an example of an Antarctic research station, (downloaded on 22 November 2020), see: https://en.wikipedia.org/wiki/Amundsen%E2%80%93Scott_South_Pole_Station.

3 For additional information about the Square Kilometer Array, see: https://www.skatelescope.org/ (downloaded on 22 November 2020).

4 For additional information about the Large Hadron Collider, see: https://home.cern/science/accelerators/large-hadron-collider (downloaded on 22 November 2020).

5 For information about the so-called "Great Observatories", see: https://en.wikipedia.org/wiki/Great_Observatories_program (downloaded on 22 November 2020).

Table D.2: Scenario Beta (Science) Schedule of Major Milestones (Version II)

<table>
<tr><th colspan="2">WHEN? (YEARS)</th><th>WHAT? & WHERE? (MILESTONE SUMMARY[NOTE_1])</th><th>WHO? & WHY?</th></tr>
<tr><td rowspan="8">Near-Term
(2021-2030)</td><td>Multiple</td><td>Ongoing / multiple robotic exploration missions, including orbiters, landers, rovers and sample return. (GER)[NOTE_2]</td><td rowspan="12">WHO?
Government Space Agencies
Commercial Services Providers
University Space Science Labs, etc.
<u>After the Mid-Term</u>:
Private Ventures Increasingly</td></tr>
<tr><td>Multiple</td><td>Lunar surface and orbital technology demonstrations</td></tr>
<tr><td>Multiple</td><td>Lunar surface / orbit comm and nav systems deployed</td></tr>
<tr><td>c. 2024-2026</td><td>Lunar 'Gateway' Operational in cis-Lunar space (GER)</td></tr>
<tr><td>c. 2027-2028</td><td>Human Mission to the Moon (GER)[NOTE_3].</td></tr>
<tr><td>c. 2027-2028</td><td>Advanced Lunar EVA Operational (GER)</td></tr>
<tr><td>c. '24, '26, '29</td><td>Launch of Robotic Mars Sample Return Mission</td></tr>
<tr><td>c. 2029-2030</td><td>Long-Range Pressurized Rover Operational (GER)</td></tr>
<tr><td rowspan="8">Mid-Term
(2031-2040)</td><td>Multiple</td><td>Ongoing / multiple robotic exploration missions, including orbiters, landers, rovers and sample return missions.</td></tr>
<tr><td>c. 2031-2032</td><td>Lunar Surface Mars Habitation Systems (GER)</td></tr>
<tr><td>c. 2032-2035</td><td>Various Lunar Mars Mission Simulations & Demos (GER)</td></tr>
<tr><td>c. 2033-2034</td><td>Large-scale (350 kW) Power Emplaced on Surface (GER)</td></tr>
<tr><td>c. 2034-2035</td><td>Fuel Production Systems Emplaced on Surface (GER)</td><td rowspan="12">WHY?
<u>Science Goals:</u>
Science-on-the-Moon
Science-of-the-Moon
Science-from-the-Moon
Geopolitical Policy-Driven International Cooperation
Resource Exploitation to reduce costs
Near-Term & Mid-Term: Demos for Humans-to-Mars Missions
<u>After the Mid-Term</u>:
Profit Motives (Increasingly)</td></tr>
<tr><td>c. 2036-2037</td><td>500-day Mars Habitation Demonstration (GER)</td></tr>
<tr><td>c. 2036-2037</td><td>Fuel Production @ 50 MT / year on Surface (GER)</td></tr>
<tr><td>c. 2037-'2039</td><td>First Human Mission to Mars (HMM)[NOTE_4]</td></tr>
<tr><td rowspan="4">Far-Term
(2041-2050)</td><td>c. 2042-'43</td><td>Small Lunar Far-side Observatory Established</td></tr>
<tr><td>c. 2044-'45</td><td>Human-Tended Lunar Laboratory Established at the Lunar South Polar Region</td></tr>
<tr><td>c. 2046-2048</td><td>Second Human Mission to Mars (HMM)</td></tr>
<tr><td>c. 2050</td><td>Lunar visits per year continues to increase</td></tr>
<tr><td rowspan="4">Far-Future
(2051-2100)</td><td>c. 2050-2055</td><td>Permanent-inhabited human outpost established</td></tr>
<tr><td>c. 2054-2056</td><td>Third / Final Human Mission to Mars (HMM)</td></tr>
<tr><td>c. 2070</td><td>Large Lunar Far-side Observatory Established</td></tr>
<tr><td>c. 2070-2080</td><td>Lunar sourced logistics (e.g., propellants) begin sales in the cis-lunar economy</td></tr>
</table>

NOTES:
Note_1: Ongoing operations (e.g., the Gateway in the Mid-term) are not shown as milestones.

Note_2: "GER" indicated that this Scenario Milestone is included in the ISEC-G Global Exploration Roadmap supplement of August 2020.

Note_3: this GER milestone requires an immediate and significant increase in funding in the US and partnering countries to remain on its November 2020 schedule.

Note_4: this milestone depends on the dates / funding for the Mars Sample Return in the Near-Term.

C.5. Scenario Gamma: Development- Driven Lunar Activities

The third and final scenario is the most divergent from class models of space and/or lunar activities, however in comports most closely with events that have occurred in near-Earth space during the past several decades. Scenario Gamma presumes that the development of new capabilities and services – both by commercial firms for profit or by government agencies for economic reasons lunar development will drive activities on, near or for the Moon. These will include development of a wide range of novel systems, access to new resources and delivery of new services.

Government-sponsored exploration and science programs will play 'turn-key' roles in supporting and enabling lunar development, including buying services analogous to NASA's Commercial Cargo Program for the International Space Station (ISS) to incentivize the creation of important new capabilities. These could include more affordable transportation systems for LEO-to-LLO, lunar surface access, etc. Such a 'turn-key' role might also involve establishing international frameworks for regulation, cooperation and standards among others.

Under Scenario Gamma, it is presumed that activities will be predominantly commercial in character; however, government-sponsored programs may also play important roles, particular in resource-focused exploration and prospecting, development of new technologies, etc. Establishing permanent human outposts – leading to one or more settlements in the longer term – are expected to result in cost-effective means to supporting both operational needs (e.g., resource mining, extraction, etc.) and commercial opportunities (e.g., private lunar space travel and tourism). Both exploration and science government-sponsored programs are expected to benefit dramatically in the mid- to later- term due to lower-cost services and systems, and the availability of *in situ* resources.

<u>Scenario Gamma (Development-Driven) Turning Points</u>

The following are 'turning points' that – if they occur in the near-term – would indicate that Scenario Gamma is likely to be a strong part of humanity's future vis-à-vis the Moon.

- Turning Point C.1 / Very low-cost transportation to low Earth orbit (LEO) becomes available for commercial and government customers, at less than $600-$1,000 per kilogram to LEO.
- Turning Point C.2 / Affordable megawatt-class solar power becomes available through cis-lunar space at less than 25¢ to 50¢ per kilowatt-hour.
- Turning Point C.3 / Reusable space transportation systems provide affordable service from LEO to low Lunar orbit (LLO), to/from the lunar surface, etc.
- Turning Point C.4 / Fuels and structural systems can be created affordably from lunar materials.

Table D.3: Scenario Gamma (Development) Schedule of Major Milestones (Version II)

When? (Years)		What? (Milestone Summary[Note_1])	Who? & Why?
Near-Term (2021-2030)	Multiple	Ongoing / multiple robotic exploration missions, including orbiters, landers, rovers and sample return. (GER[Note_2])	**Who?** Government Space Agencies Commercial Services Providers Universities, etc. <u>After Near-Term</u> Private Ventures / firms (Increasingly)
	Multiple	Lunar surface and orbital technology demonstrations	
	Multiple	Lunar surface / orbit comm and nav systems deployed	
	c. 2023-2024	First launch of operational very low-cost ETO system, with costs less than $1,000 per kilogram	
	c. 2024-2026	Lunar 'Gateway' Operational in cis-Lunar space (GER)	
	c. 2024-2026	Human Mission to the Moon (GER)[Note_3].	
	c. 2024-2026	Advanced Lunar EVA Operational (GER)	
	c. 2024, '26,,'29	Launch of Robotic Mars Sample Return Mission	
	c. 2026-2027	First affordable reusable space transport system to the Moon, with costs less than $25,000 per kilogram	
	c. 2028-2029	Long-Range Pressurized Rover Operational (GER)	
	c. 2028-2029	Lunar Surface Mars Demo Habitation Systems (GER)	
	c. 2028-2029	Large-scale (350 kW) Power Emplaced on Surface (GER)	
	c. 2029-2030	Fuel Production Systems Emplaced on Surface (GER)	
Mid-Term (2031-2040)	c. 2031-2032	Fuel Production @ 50 MT / year on Surface (GER)	
	c. 2031-2032	500-day Mars Habitation Demonstration (GER)	
	c. 2033-'34	Surface Refueled Space Transport @ <$10,000 / kg	
	c. 2031-'35	Various Lunar Mars Mission Simulations & Demos (GER)	**Why?** National Policy Geopolitical Policy-Driven International Cooperation Resource Exploration & Exploitation to reduce costs <u>After the Near-Term</u> Profit Motives (Increasingly) Science Goals (Increasingly)
	c. 2033-'34	Cis-Lunar Space / LLO Propellant Depot Deployed	
	c. 2035-2036	Private / Commercial Lunar Outpost for Tourism	
	c. 2035 or '37	First Human Mission to Mars (HMM)[Note_4]	
	c. 2039-2040	Lunar Radio Far-Side Telescope Deployment	
Far-Term (2041-2050)	c. 2041	Lunar Pole Permanently-Staffed Solar Polar Outpost	
	c. 2042-2043	Large-Scale Lunar Manufacturing from Local Materials	
	c. 2045	First lunar settlement (40 residents) at the South Pole	
	c. 2039+	Human Missions to Mars at each Opportunity (@ 26 mos)	
Far-Future (2051-2100)	c. 2051	Second lunar settlement (80 residents) at the South Pole	
	c. 2070	Third lunar settlement (>200 residents) – Location TBD	
	c. 2080-2085	Electromagnetic Lunar Launcher Operational @ <$1K / kg	
	c. 2085+	Commercial Products for cis-Lunar Space (e.g., SPS)	

<u>**Notes**</u>:

Note_1: Ongoing operations (e.g., the Gateway in the Mid-term) are not shown as milestones.

Note_2: "GER" indicated that this Scenario Milestone is included in the ISEC-G Global Exploration Roadmap supplement of August 2020.

Note_3: this GER milestone requires an immediate and significant increase in funding in the US and partnering countries to remain on its November 2020 schedule.

Note_4: this milestone depends on the dates / funding for the Mars Sample Return in the Near-Term.

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ANNEX D

MOON VILLAGE READINESS LEVELS (MVRLS)

D.1 Introduction

The 2020 Architecture Workshop demonstrated that a wide variety of activities are now ongoing that will contribute to the eventual realization of a lunar outpost – and perhaps a settlement on the Moon. However, a central question also emerged: how best to evaluate in a consistent fashion the diverse activities, which involve much more than simply technology? For R&D programs, the 'technology readiness levels" (TRLs) can be employed through technology readiness assessments (TRAs). TRLs were first defined in the late 1960s / early 1970s as an R&D analogue to NASA's "flight readiness reviews" (FRRs), and were codified in detail in 1995. Since then, a wide variety of derivative 'readiness level" scales have been defined – including manufacturing readiness levels (MRLs), integration readiness levels (IRLs), etc.

D.2 The MVRL Scale[1]

Emerging from the discussions at and following the MV Architecture WG workshop, an issue to be considered (ITBC) identified the need for a maturity assessment tool for Moon Village related activities and capabilities. The "MVRL" (Moon Village Readiness Level) scale was identified to meet this need; it is a readiness level scale that is allows the discipline-independent evaluation of the 'maturity' of diverse lunar activities – including not just systems development, but also markets and missions, etc.

Table D-1 on the page following presents a preliminary set of MVRL definitions.

D.3 Difference between the TRLs and the MVRL Scale

The Technology Readiness Level (TRL) was created in the 1960s-1970s, and codified in 1995 to enable assessment of the maturity of a technology or group of technologies being developed and for an application. See: https://www.researchgate.net/publication/247705707_Technology_Readiness_Level_-_A_White_Paper. Technology Readiness Levels (TRL 1 through TRL 9) are equally valid for applications in Earth orbit for a satellite or a space station, for a Mars orbiter or lander, or for a lunar rover. However, scale does not address considerations such the definition and validation of a 'concept of operations' (CONOPS), testing in an analogue, market identification, etc.

The MVRL scale (MVRL 1 through MVRL 7) other the other hand address only lunar-focused activities and addresses not only technology and/or systems, but also CONOPS, markets, missions, analogue testing and other topics essential to the realization of a particular capability for the Moon Village vision.

D-1 The MVRL scale, including the definitions here, was created and applied in Section 6 by J.C. Mankins in response to a suggestion (an "ITBC") made by G. Reibaldi in discussions immediately following the Workshop.

Table D.1 Definitions of the MVRL Scale (04 April 2021 Version)

Moon Village Readiness Level	*DRAFT* – MVRL Description / Definition – *DRAFT*
MVRL 1	Basic market, environmental and/or physical information known relating to the Moon and/or cis-lunar space.
MVRL 2	Functional, physical or economic concept formulated for a market and/or mission activity on the Moon or in cis-lunar space, including systems and/or services.
MVRL 3	Essential characteristics of the prospective Moon Village system and/or service experimentally and/or analytically identified and/or modeled for a general class of market and/or mission activities concerning the Moon (surface or Earth-Moon space).
MVRL 4	Essential and selected additional characteristics for a potential market segment and/or mission activity concerning the Moon (surface, LLO, cis-lunar space or Earth orbit), modeled in an integrated environment and/or experimentally validated in a laboratory or analogue environment, including systems and/or services.
MVRL 5	All relevant characteristics for a specific market and/or mission activity modeled in an integrated environment or demonstrated in a relevant simulated and/or analogue environment, including systems and/or services.
MVRL 6	Market and/or mission activity demonstrated at the 'prototype level' in the expected operational environment (e.g., on the Moon and/or in cis-lunar space), including systems and/or services.
MVRL 7	Highest MVRL; market and/or mission activity fully operational on the Moon or in cis-lunar space, including systems and/or services.

Comments on this DRAFT concept for "MVRLs" will be invited during 2021. A final definition is planned by the end of the current Case Study.

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