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Reference Scenarios, Architecture & Roadmap for the Moon Village

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ABSTRACT

Humanity – as represented by diverse countries, many companies of various sizes, academics around the world and individuals of many countries – is now moving to extend activities to the Moon. It is impossible to truly know the future; however, planning methodologies that take uncertainty into account in a structured fashion can provide useful insights that allow thoughtful preparations in the face of that inevitable ignorance. 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. During the past 12-18 months, the near-term potential steps that might be taken toward a permanent human expansion to Earth’s Moon have been changing rapidly – driven in a significant measure by the new NASA leadership and evolving plans related to US lunar plans.

Without narrowing scope to a particular implementation (for example, a specific “Moon Base” at in a particular location), but to still provide a consistent framework for the conduct of studies, research and development and business investments, a set of “Moon Village Reference Scenarios” (analogous to what are sometimes called “Design Reference Missions”) have been defined. These scenarios deliberately look to the far-term: from the present out to 2100, in order to place near-term projections in a larger context. Each of these three scenarios – if they were to become the future – would involve similar and distinct missions, systems and commercial markets. Within each of these scenarios, example architectural concepts have been defined that allow the scenarios to be more thoroughly and analytically examined. This paper will provide an overview of present international lunar exploration and Moon Village activities, including a discussion of the alternate scenarios described above. On that basis specific lunar systems and MV “reference architecture”, including missions and markets will be sketched and an integrated roadmap for framed. The working paper will conclude with a discussion of the common threads that span the alternative futures, it will highlight the most distinct aspects of each and it will identify some potential “signposts” that can be watched for that would indicate which path humanity will be taking to its lunar future.¹

Keywords : Moon Village, architecture, scenario-based planning, space systems

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 be a catalyst of 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 is a key factor for the peaceful future of humankind. It would 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

¹ NOTE: this paper reflects inputs received during (1) the 2019 Moon Village Workshop & Symposium in Tokyo & Kyoto, Japan, (2) the 2019 International Astronautical Congress in Washington DC, USA; (3) the 2019 International Symposium on Space Technology & Science in Fukui, Japan; and, (4) the 2019 International Space Development Conference in Washington DC, USA.

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Moon Village is its role as a proving ground for missions farther out in the solar system.

To turn this vision into 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 research network for the 21st century.

The Moon Village Association (MVA) plans over the coming years to provide coordination and communication among a number of organizations and individuals on diverse topics through focused working groups (WGs) and annual International Workshops.^[1,2] Topics being addressed through the WGs include Architectural Concepts and Considerations; Mission & Markets; Cultural Considerations; Participation, Cooperation and Coordination; Analogues; and others. Without narrowing scope to a particular implementation (a specific “Moon Base” at a particular location, for example), while still providing a consistent framework for the conduct of MVA Working Group activities, a set of “Moon Village Reference Scenarios” (analogous to what are sometimes called “Design Reference Missions”) have been defined.

2. Framing the Moon Village: Key Topics

There are a wide range of topics that must be explored as the Moon Village progresses, including issues related to the architectures and systems that will evolve over time, the missions and markets that may emerge, how expanding humanity’s presence to the Moon will impact human culture, and many others. For each topic, an MVA working group has been created. The following are some of these key questions.

2.1. Architectural Concepts & Issues.

A central issue to consider is that of what systems architectures will be developed and deployed, and when? There are a variety of alternatives, and the unfolding of these will strongly influence the opportunities ranging from scientific research and commercial ventures. How architectural options are examined, and what information is included in documenting such options will be of great importance.

Another question: what are the key functional elements that must be incorporated into any overarching lunar / Moon Village Architecture? For example, end-to-end transportation systems (including Earth-to-orbit (ETO), in-space, space to lunar surface); surface mobility and robotics (e.g., rovers, construction systems, etc.); power (including in-space, lunar surface in various locations, etc.); human habitation systems (e.g., in-space, lunar surface; e.g., fixed vs. mobile; etc.

And finally, how would the key functional elements (see above) of a lunar Architecture change from one Scenario to another? For example, in terms of capability, the timing of precisely when a given capability might be needed, etc.

Various types of prospective services might be critical in the near- to mid- term for future Moon missions & markets; these could include systems, operational services, etc. – including services on the lunar surface, in cis-lunar space, transportation (beginning on Earth), etc. A key question to consider, particularly for the longer-term: what are the prospective “critical services” that might be needed to support missions by government programs, commercial firms seeking to provide services to government programs, scientific researchers or other types?

2.2 Moon Village Standards.

A specialized topic within the general consideration of systems and architectures is that of “standards” for a Moon Village – such as the communications interfaces among various systems. Some standards are already being defined by extension from the ongoing International Space Station (ISS) program. However, a more general consideration is needed; for example, what are the broad topics in engineering for lunar systems where Standards will play an important role in making timely and cost-effective progress, including the near-, mid- and far- term? The creation of appropriate Standards could enhance future commercial and/or private sector development of services for a Moon Village, as could the adoption of terrestrial Standards where appropriate.

2.3 Human Factors.

Similarly, beyond the near-future there will be increasing numbers of missions that involve astronauts – leading eventually to the possibility of permanent human operations on the surface and in the vicinity of the Moon. A key question will be how best the engineering for lunar systems where human factors will play an important role can be accomplished in making timely and cost-effective progress toward realizing the Moon Village. This will include a wide variety of topics in the mid-term, such as radiation protection, partial gravity effects and countermeasures, dust effects and mitigation, extravehicular activity (EVA) systems, life support, emergency medical care, and so on. Similarly, in the far-term more advanced considerations in human factors must be considered, including major medical care, closed loop life support systems, waste recycling, agriculture, use of in situ resources, etc. And, because a Moon Village will include both surface and orbital operations, there will be key differences for human factors between surface and cis-lunar space human systems.

2.4 Moon Village & Exploration Analogues.

There are a wide variety of mission design decisions that will be difficult to make with only “paper studies” and computer modeling. This is the reason that establishing terrestrial Analogues is being considered. The goals for such an environment might include studying potential concepts of operations (CONOPS) – i.e., how to best and most safely accomplish specific science activities, in

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particular repair or maintenance activities, evaluating exploration procedures, including human-machine interfaces, and similar goals. Some of the key questions to be explored in the near-term include: what Analogue facilities already exist and where are these located? What new Analogue facilities are being considered, and where would these be located?

Another distinct, but related topic for consideration is how the emerging capabilities of the Moon Village in the near-, mid- and far- term provide an Analogue facility for testing of technologies and concepts for subsequent space exploration and operations, but in general and for Mars in particular?

2.5. Other Topics.

It would be very useful for the lunar community to have clear data sources for the planned, but not yet formally scheduled lunar missions during the near- to mid- term (e.g. out to about 2028), and to have projections for the mid- to far- term, as to what might be the principal types of Lunar missions / projects that are likely to be pursued by (a) government programs; (b) commercial firms seeking to provide services to government programs; (c) scientific researchers; or other types.

A diverse set of mechanisms will be needed to accomplish coordination and cooperation among participants in the Moon Village. Examples might include: multilateral agreements and treaties; specific agreements; establishing standards for key systems (discussed above), and others. There are, of course specific past mechanisms – such as the ISS agreement – some of which could help, and some of which might progress toward the goals of the Moon Village vision.

One legacy of the Apollo program and the first era of lunar exploration was the so-called “Overview Effect”, which had a profound impact on our shared perspective of humanity’s place in the universe. Along with the broad array of technical and programmatic topics, it is also important that cultural considerations associated with the extension of human activities to Earth’s Moon not be neglected. This includes both the extension of human cultural to the Moon, as well as the cultural ramifications of government, commercial and/or private operations at the Moon (surface and vicinity). Aspects related to the environmental impact on the Moon and from activities on Earth shall also be assessed.

Finally, it is extremely important that the general public be successfully engaged in humanity’s extension of activities to Earth’s Moon. Such outreach efforts should include identifying what non-space types of organizations and/or specific organizations could represent candidates in the near-term for engagement (e.g., broad sectors, such as mining or energy; and particular firms). Another issue is how best engagement of international “STEM” or “STEAM” activities could be undertaken. These might

well involve non-governmental organizations (NGOs) as well as particularly colleges and universities or other educational institutions.

3. Moon Village Scenarios

In order to provide a consistent framework for the conduct of MVA working group activities without narrowing scope to a particular implementation (a specific “Moon Base” at a particular location, for example), a set of “Moon Village Reference Scenarios” have been defined. See Figure 1.

For purposes of this definition of MVRS, three distinct scenarios have been defined: Scenario Alpha (Government / Human Space Flight Predominates); Scenario Beta (Government Space Science Predominates); and, Scenario Gamma (Private Venture Space Predominates). These scenarios deliberately look to the far-term: from the present out to 2100, in order to place near-term projections in a larger context. The paragraphs that follow present overviews of the three scenarios.

3.1. Scenarios Overview.

The MVRS are defined according to the following characteristics: Who, What, When, Where and Why:

- **WHO** – Who is driving the MV-related activity? What type of organization is the key player involved, including: government space Agencies, non-Space government Agencies, large commercial firms, small and medium-scale enterprises, academic organizations, non-profit organizations, and/or individuals.
- **WHAT** – What is the MV-related activity? For example, this might include lunar orbiters, mission-focused lunar landers, lunar surface mobility systems (e.g., “rovers”); transportation systems (ETO, in-space, to/from surface, etc.); lunar vicinity operational stations and infrastructure; lunar surface infrastructures; lunar surface stations/bases; sustainable lunar surface settlements; and others.
- **WHEN** – When might the MV-related activity occur? Defined for this purpose to involve three timeframes: (a) the Near-term (i.e., from 2018 until 2030); (b) the Mid-term (i.e., from 2031 to 2050); and, (c) the Far-Term (i.e., beyond 2051 but before 2100).
- **WHERE** – Where on the Moon will the primary activities take place? These might include general locations, such as “the Lunar South Pole” or “the Far Side of the Moon”, or a class of locations, such as “Sites of Lunar Scientific Interest” or “Lunar ice-bearing regions”, or specific locations, such as “Shackleton Crater” or “Apollo 11 Landing Site”, etc.
- **WHY** – Why would this MV scenario take place? In other words, what are the primary cultural or

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economic purposes that would drive the activity; these might include general purposes, such as “Commercial Market-Driven”; “Government-sponsored Science Missions”; “Commercial Services for Government Missions” or more focused mission/market purposes such as “a Lunar Radio Observatory”, “Public Space Travel” or “R&D for Future Mars / Solar System Exploration”.

From this set of characteristics, specific choices have been made to formulate an initial set of three overarching Moon Village Reference Scenarios (MVRS). Note that NONE of the MVRS are intended to be considered as the actual future that will unfold. In fact, almost certainly the actual future will be some combination of the MVRS described below (just as a particular recipe for curry represents some combination of ingredients). However, the Scenarios are designed to explore the technical, cultural and market implications of various plausible “potential futures” – allowing the MVA to better serve the interests of its members in making individual decisions in the near term.

3.2. Scenario ALPHA: Government-Sponsored / Human Space Flight Predominates.

In ALPHA, geopolitical interests are presumed to be the driving motivation for lunar surface and associated activities during the next 20 years; however, government funding levels are assumed to be approximately level projected forward from the present. Also, in this scenario, there are no breakthroughs in infrastructure, systems or technology for the coming 20 years; the only systems in use are those that are linear extrapolations of those in use or evidently available in 2018.

Finally, although there are opportunities for commercial firms to support government-sponsored human space flight and related space programs, there is minimal commercial-to-commercial economic activity during the period. The figure above provides a high-level definition of the scenarios by timeframe; the leftmost column summarizes the scenario described in this paragraph.

Key features: Early government-sponsored lunar surface human sortie missions; government-sponsored orbital facilities near the Moon; two or more permanently-crewed bases on the lunar surface by the far-term, established by various countries working in two or more coalitions; primarily government launchers supplemented by innovative commercial cargo contracting; and, minimal “new space” type business activities until post 2050.

This update of the 2018 initial MV scenarios includes the March 2019 announcement by NASA that the US space program has established a goal of an initial human return to the Moon by 2024.

3.3. Scenario BETA: Government-Sponsored Space Science Predominates.

In this scenario, science and related exploration mission goals and interests are presumed to be the driving motivations for lunar surface and associated activities during the next 20 years. Government funding levels are assumed to decline modestly relative to the present. Also in this scenario, there are no breakthroughs in infrastructure, systems or technology for the coming 20 years; with the exception of major new lunar science capabilities, the only systems in use are those that are linear extrapolations of those in use or evidently available in 2018. Finally, although there are opportunities for commercial firms to support government-sponsored science programs, there is minimal commercial-to-commercial economic activity during the period. The figure above provides a high-level definition of the scenarios by timeframe; the center column summarizes the scenario described in this paragraph.

Key features: Extended period of robotic only (government-sponsored) science and exploration lunar missions including orbiters, landers and rovers; two or more major science installations (e.g., a far-side lunar radio telescope); one or more human-tended encampments on the lunar surface by the far-term, established by various countries and focused on science goals; primarily government launchers supplemented by innovative commercial cargo contracting; and, minimal “new space” type business activities until post 2050.

3.4. Scenario GAMMA: Commercial / Privately-Sponsored Space Predominates.

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

There are opportunities for commercial firms to support government-sponsored human space flight and related space programs, and there is increasingly non-government commercial-to-commercial economic activity during the period. The figure above provides a high-level definition of the scenarios by timeframe; the rightmost column summarizes the scenario described in this paragraph.

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Figure 1 Moon Village Scenarios (Summer 2019 Update)

	Scenario Alpha Gov't: Human Space Flight Predominates	Scenario Beta Gov't: Space Science Predominates	Scenario Gamma Private Venture Space Predominates
Near-Term	Present-to-2030^I	Present-to-2030	Present-to-2030
Who?	<ul style="list-style-type: none"> Government Space Agencies Commercial Services Providers 	<ul style="list-style-type: none"> Government Space Agencies University Space Science Labs Commercial Services Providers 	<ul style="list-style-type: none"> Private Ventures / Firms Government Space Agencies
What?	<ul style="list-style-type: none"> Robotic Orbiters, Landers, Rovers First Human Sortie Mission by NASA c. 2024-2025 Early Resources Utilization First Human Mission by others by 2029-2030 Cis-Lunar "Gateway" Facility 	<ul style="list-style-type: none"> Robotic Orbiters, Landers, Rovers Science mission technology demonstrations 	<ul style="list-style-type: none"> Robotic Orbiters, Landers, Rovers Low-Cost Earth-to-Moon Transport Early Resources Development for Markets & Govt Missions Near Moon "Gateway" Facility(ies), including a Propellant Depot
Why?	<ul style="list-style-type: none"> Resource Exploration Demonstration of Capabilities for later Humans-to-Mars Missions 	<ul style="list-style-type: none"> Science-of-the-Moon Science-on-the-Moon Science-from-the-Moon 	<ul style="list-style-type: none"> For-Profit Business Ventures Lunar Resources Use for Cost Reduction Demonstration of Capabilities
Where?	<ul style="list-style-type: none"> Lunar Surface Lunar Vicinity Orbit 	<ul style="list-style-type: none"> Lunar Surface Areas of Research Interest (e.g., Lava Tubes, etc.) 	<ul style="list-style-type: none"> Lunar South & North Poles / Shadowed Regions
Mid-Term	2031-2050^{II}	2031-2050	2031-2050^{IV}
Who?	<ul style="list-style-type: none"> Government Space Agencies Commercial Services Providers 	<ul style="list-style-type: none"> Government Space Agencies Commercial Services Providers 	<ul style="list-style-type: none"> Private-Firm Ventures Government Space Agency Services Customers
What?	<ul style="list-style-type: none"> Small-scale Lunar Base Lunar Resource Development / ISRU Demonstrations Transition to Privatized Operations 	<ul style="list-style-type: none"> Demonstration of Capabilities for later Humans-to-Mars Missions Lunar Surface-based Observatory 	<ul style="list-style-type: none"> Lunar Resources Outpost (ISRU, Manufacturing, etc.) Low-Cost transport throughout cis-Lunar space using lunar resources Human Lunar Base
Why?	<ul style="list-style-type: none"> Geopolitical Policy-Driving International Cooperation 	<ul style="list-style-type: none"> Science-of-the-Moon Science-on-the-Moon Science-from-the-Moon 	<ul style="list-style-type: none"> For-Profit Business Ventures Resources Development Settlement Tech Demos Local Manufacturing for Cost Reduction
Where?	<ul style="list-style-type: none"> Lunar Mare (e.g., Apollo Sites) 	<ul style="list-style-type: none"> Lunar Far-Side 	<ul style="list-style-type: none"> Lunar South & North Poles / Shadowed Regions
Far-Term	2051-2100	2051-2100^{III}	2051-2100^V
Who?	<ul style="list-style-type: none"> Government Space Agencies Commercial Services Providers Private Ventures Firms 	<ul style="list-style-type: none"> Government Space Agencies Commercial Services Providers 	<ul style="list-style-type: none"> Private-Firm Ventures Gov't Space Agencies (buying Services)
What?	<ul style="list-style-type: none"> Human Lunar Surface Base (Rotating Crews) 	<ul style="list-style-type: none"> Human-Tended Lunar Surface Science Camp (Occasional Sorties) 	<ul style="list-style-type: none"> Self-Sustaining Human Lunar Settlement Commercial products into cis-Lunar economy (e.g., SPS)
Why?	<ul style="list-style-type: none"> Permanent Human Presence Beyond Earth 	<ul style="list-style-type: none"> Science-on-the-Moon (e.g., bio labs) Large-scale radio-astronomy 	<ul style="list-style-type: none"> Large-scale commercial development of the Moon Permanent Expansion of Humanity Beyond Earth
Where?	<ul style="list-style-type: none"> Lunar Mare (e.g., Apollo Sites) 	<ul style="list-style-type: none"> Lunar Far-Side 	<ul style="list-style-type: none"> Lunar South & North Poles / Shadowed Regions
Scenario Notes	<p>^I All characteristics in a given timeframe persist to later timeframes</p> <p>^{II} First Humans-to-Mars Missions occur during this timeframe</p>	<p>^{III} First Humans-to-Mars Missions occur during this timeframe</p>	<p>^{IV} First Humans-to-Mars Missions occur during this timeframe</p> <p>^V Human Settlement on Mars Established in this timeframe</p>

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Key features: Early commercial / privately-supported revolutionary new capabilities emerge; government- and non-government- sponsored lunar surface human sortie missions; commercially-sponsored orbital facilities (including fuel / logistics depots) near the Moon; two or more permanently-crewed bases on the lunar surface by the mid-term, established by various countries working in two or more coalitions; and a permanently inhabited human settlement by the far-term; primarily commercial launchers supplemented (where required) by government lifters; and, robust “new space” type business activities until post 2030.

4. MV Architectural Elements

Across the several scenarios, a comprehensive “work breakdown structure” of MV “architectural elements” (MVAEs) has been defined; this WBS is listed below.

- AE_1.0 / MV RESEARCH & DEVELOPMENT / TEST SYSTEMS. This category comprises a range of facilities that are to be used for lunar related R&D testing / experiments.
- AE_2.0 / MISSION SUPPORTING GROUND SYSTEMS. This category comprises a range of systems and facilities that are to be used for lunar-related ground systems (e.g., launch, mission control, etc.).
- AE_3.0 / SPACE TRANSPORTATION SYSTEMS. This category comprises a range of vehicles and facilities that are to be used for transporting lunar-related missions / systems to space, in space and to/from the surface of the Moon Various Examples will be given; these will be linked to the Scenarios and timeframes.
- AE_4.0 / EARTH-ORBITAL SYSTEMS. This category comprises a range of vehicles and systems operating in Earth orbit (typically LEO, MEO and/or GEO) that support lunar-related missions / systems operations and capabilities.
- AE_5.0 / MOON / CIS-LUNAR ORBITAL SYSTEMS. This category comprises a range of vehicles and systems operating in cis-Lunar orbit (typically a libration point, lunar orbit, etc.) that support lunar-related missions / systems operations and capabilities.
- AE_6.0 / SCIENTIFIC RESEARCH SYSTEMS. This category comprises a wide range of systems, payloads and capabilities in space that accomplish scientific research programs, including those operating in Earth orbit, cis-Lunar space, or the lunar surface.
- AE_7.0 / LUNAR SURFACE SYSTEMS. This category comprises a wide range of systems, payloads and capabilities delivered to and/or operating on the surface of the Moon that accomplish various functional requirements for scientific, commercial and/or human exploration focused programs and/or projects.
- AE_8.0 / HUMAN OPERATIONS & SAFETY SYSTEMS. This category comprises diverse systems, payloads and capabilities in space that enable safe / affordable human presence and operations, including those operating in Earth orbit, cis-Lunar space, or the surface.
- AE_9.0 / LUNAR & EXPLORATION ANALOGUES. This category comprises "analogue" testbeds -- which are specialized capabilities to test concepts of operations – including habitation human-systems design concepts, etc.
- AE_10.0 / MV MISSION / MKTS REQTS DATA. This category comprises management of Moon Village mission and markets requirements data.
- AE_11.0 / STANDARDS. This category comprises standards, including interface standards for the full-spectrum of systems and capabilities and operations involved in the Moon Village.

Working across these MVAEs, an integrated evaluation has been undertaken – with the objective of determining which specific elements should be examined in greater detail during 2019-2020, while the examination of others may be deferred. The following is a preliminary listing:

- Extravehicular Activity (EVA) systems,
- Lunar surface science systems: radio science observatories,
- *In situ* resource utilization (ISRU) systems: volatiles mining systems;
- Locally-fabricated surface habitation systems,
- Cis-Lunar propellant depot systems; and,
- Bio-regenerative life support / agricultural systems.

For these specific MV architectural elements, various topics will be considered, including standards, concepts, and others.

5. Progress Toward the Moon Village

During the past three years there has been real progress toward the realization of the Moon Village. The following section will examine four specific examples: (1) current missions now planned; (2) scenarios for future Moon missions and markets; (3) an approach for capturing data on both current missions and future markets and missions; and (4) recent developments that have the potential to transform both the near and the further term.

4.1 Recently Past Missions Overview.

To begin an assessment of current missions planned, it is useful to reflect on where global lunar activities stood just

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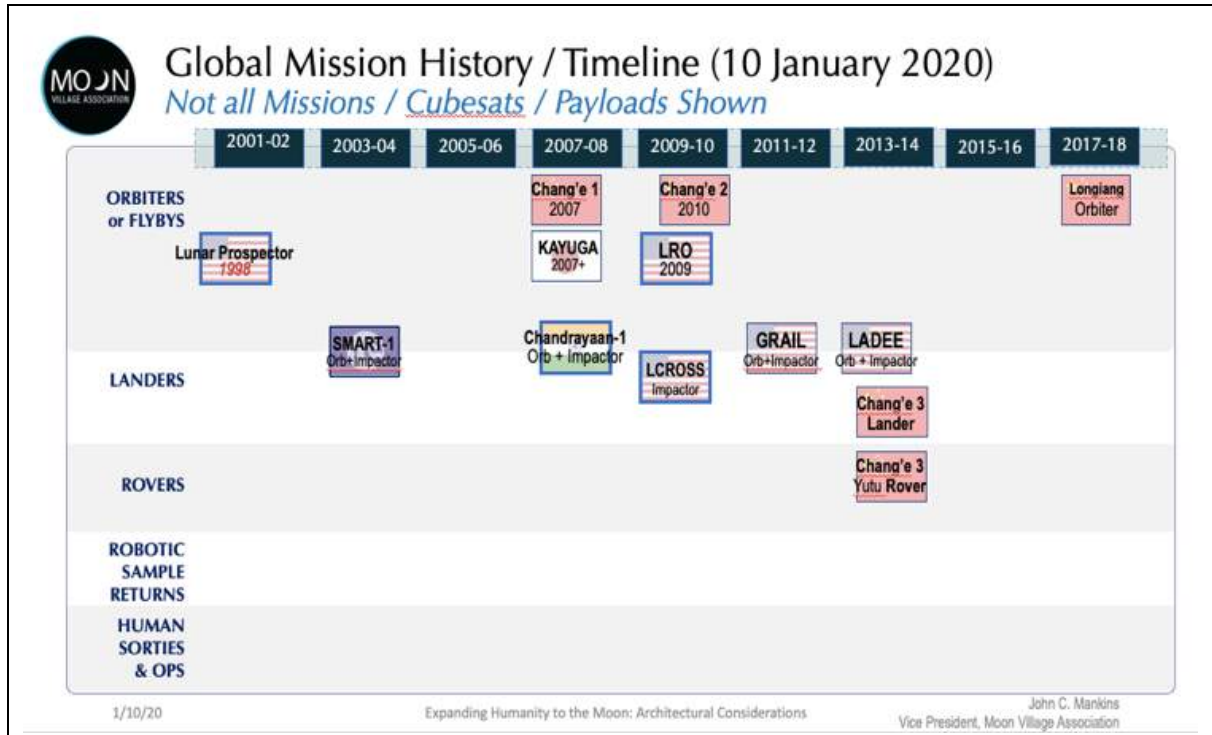
a few years ago. Figure 2 presents a summary of major lunar missions during the period 2000-2018.

As illustrated, there were a number of lunar missions – but a turning point was reached in interest in and a focus on the Moon with the discovery and later confirmation that there is significant hydrogen – most likely in the form of water ice – on the Moon in the permanently shadowed regions at the poles.

The key missions in this regard were Lunar Prospector (USA, 1998) and SMART-1, both of which found evidence

of lunar surface hydrogen, Chandrayaan-1 with an impactor (India, c. 2008) that confirmed the likely presence of water ice, and Lunar Reconnaissance Orbiter (LRO) along with the LCROSS impactor (USA, 2009) that confirmed the presence and characteristics of the ice as well as providing spectrum information about the composition (including non-water elements) of the materials. It is worth noting that the total lunar activity from 1998-20018 involved only one proper lander with rover (Chang’e-3 and Yutu, of China).

Figure 2. Past Major Moon Missions – 2000-2018



4.2 Forecast of Current Missions.

The MVA has conducted a twice-per-year assessment of the planned Moon mission plans and projects for the past several years. Figure 3 illustrates the results of the most recent version of this assessment.^[3] After the end of the 2008-2012 economic downturn, and the internalization of the potential impact of volatile deposits at the lunar poles, there has been a dramatic evolution in lunar mission planning and market opportunities.

Now numerous organizations are planning missions to the Moon over the coming handful of years, including

governments, so-called “new space” companies and major industry player. These include Canada (private), China (government), Germany (private), India (government & private), Japan (government & private), the Russian Federation (government) and the USA (government and private). The following list presents just some of the many planned missions that represent the first steps beyond Earth orbit and toward the vision of the Moon Village.

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Figure 3 Planned Missions – 2019-2027+



2019 began with the successful landing of China's "Chang'e 4 – a lander and rover mission – that was the first to target the South Pole Aiken Basin on the Moon's far side.^[4] Israel's "Sparrow" lander, which was planned to land on the lunar surface in the first quarter of 2019 failed. 2019 also saw the launch of Chandrayaan-2 (by ISRO), which resulted in another lunar orbiter after an attempted later with rover failed on landing).^[5] In 2020, the Chinese Lunar Exploration Program (CLEP) plans to accomplish another milestone: the Chang'e 5 mission, which will involve a lander capable of collecting and returning up to 2 kilogram of sample materials to Earth.^[6]

The lunar years of 2020-2023 will likely continue to be extremely busy, with the launch of missions developed by various private firms, including ISpace (Japan), and PTScientists (Germany). The year should also see Japan's SLIM mission launch – testing precision lunar landing technologies. And, it will include a major mission by NASA: "EM-1", which will involve not only the first launch of the SLS vehicle, but also the first (unpiloted) flight of the Orion Capsule and deployment of a range of highly-focused cubesats to the Moon.^[7]

And, in 2021, Roscosmos plans to launch Luna 25 mission (of the Russian Federation) to deploy a lander to the vicinity of the South Pole of the Moon.⁸ This mission is planned to be followed in 2022 by the Luna 26 orbiter mission and in 2023 by another lander, Luna 27. With

additional missions in later years. After 2021, the number of "definite" missions per year drops, but there are continuing plans. These include, in 2023, the first crewed demonstration of the SLS and Orion capsule should be accomplished by NASA (EM-2 mission).

In addition to the above individual missions, there is also a major planned program addressing human activities in cis-Lunar space (in particular, in a lunar polar orbit): the US-led planning for a Lunar Orbital Gateway – which now appears likely to involve a range of US and international modules developed in a far-reaching collaboration among the countries now involved in the ISS program. The first element of the Gateway (the propulsion and energy module) is currently scheduled for launch in 2022. However, completion of the platform is likely to be deferred until after the first US lunar surface mission with crew (targeted for 2024).

4.3 Summary

At this time, a wide range of lunar orbiters, landers and rovers are planned for the coming 5-7 years, including the beginning of human missions to the vicinity of the Moon, and of human sortie missions – particularly for the first time to the lunar south pole. These will result in a much better understanding of the resources at the poles and elsewhere on the Moon – as well as the beginnings of diverse internationally-sourced infrastructures on the surface and in the lunar vicinity. It is important to observe that all of these missions have both distinct as

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well as shared goals – together contributing to progress toward the Moon Village.

5. Moon Village Reference Architecture

5.1 Key Assumption & Drivers

It is clear that a major investment in lunar access and operations will be made by many countries and companies during the next decade. There are some critical assumptions that can now be made with increased confidence regarding what will likely happen soon.

First, low-cost commercial access to low Earth orbit (LEO) is now almost a certainty (i.e., via SpaceX and Blue Origin systems). Others – particularly government programs in China, Europe – are likely to pursue cost reduction as well. Together, these capabilities will transform cis-Lunar space operations during the next decade; the only question: precisely when? It is possible that such a transformation will occur before 2025 (Figure 3 reflects this possibility); however, it will certainly be before 2030.

On the basis of very low-cost launch to LEO, costs for lunar access will also drop – and massive government mission opportunities and commercial market ventures will be the result; examples include space-based global connectivity; affordable megawatt power systems (solar, wireless and potentially nuclear); the development of

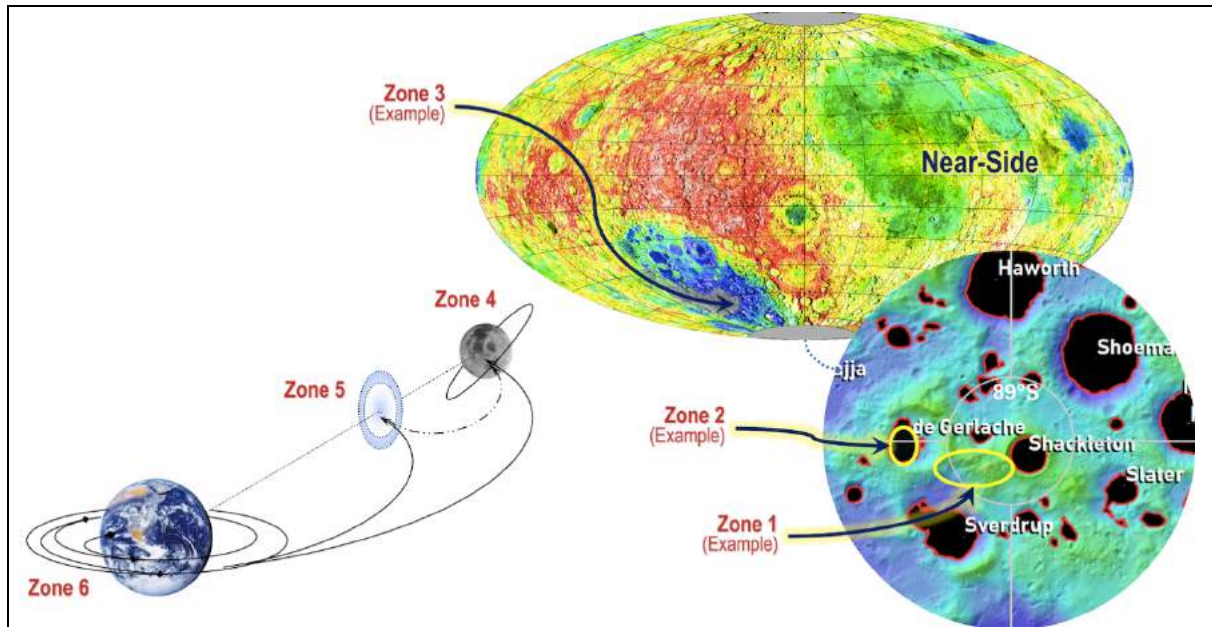
physical space resources – beginning with the Moon (and initially focused on volatiles); and, the emergence sooner rather than later of sustainable permanent human presence in cis-Lunar space.

As noted above, during the past 20 years, various missions / probes have validated that vast amounts of volatiles – particularly water, probably in the form of ice – are captured in the extremely cold, permanently-shadowed regions at the North and South poles of the Moon. The Moon’s polar deposits of volatiles can be mined, and transformed into both propellants (Oxygen and Hydrogen) and life support logistics (air, water, etc.); as a result, they represent a significant potential resource for future exploration, commercial development and eventual settlement. The US, China, Japan, India, Europe and others are all examining options for exploration and later extraction / use of these resources. This may be assumed to be the focus for a Moon Village (MV) Reference Architecture.

5.2 The MV Reference Architecture

The MV Reference Architecture (see Figure 4) represents a series of “zones” for activities related to the Moon Village – it is not a specific concept for a ‘base’, however it does encompass all of the several aspects of the Moon Village Scenarios described earlier.

Figure 4 Moon Village Reference Architecture Zones



The following are the “Zones” of activity that comprise the reference architecture:

- **Zone 1:** the “Peak of Eternal Light” (PEL) near Shackleton Crater at the lunar south pole.
- **Zone 2:** the Permanently Shadowed Regions (PSR) of the lunar south pole.
- **Zone 3:** The South Polar Aiken Basin on the far-side of the Moon – including locations near the

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south pole, but at which radio interference from Earth would be minimized.

- **Zone 4:** Low lunar orbit (LLO) – including in particular the so-called “frozen” lunar orbit that passes regularly over the south pole.
- **Zone 5:** Cis-lunar space, including but not limited to both the Earth-Moon Libration Points and/or the orbit planned for NASA’s lunar Gateway platform.
- **Zone 6:** Earth orbit, and in particular low Earth orbit (LEO) – including the ISS and/or other LEO platforms that may be involved in lunar operations.

The general types of systems and operations at each of these Zones are expected to fall into the general categories of the MV Architectural elements described above.

5.3 MV Reference Architecture Roadmap

The pieces are now available from which to construct a prospective roadmap for the Moon Village. These include (1) the scenarios, (2) the current forecast of global lunar missions over the coming 5-7 years, summarized above and (3) the framework of the MV Reference Architecture (including the several MV Architectural Elements). The following then is a potential roadmap for the Moon Village, stated in terms of potential zone-by-zone activities in three timeframes: 2025, 2035 and 2045.

6. Conclusions

The concept of a “Moon Village” (MV) is one that encompasses a wide range of prospective future human activities on the Moon – comprising early landers and orbiters, initial human and robotic exploration missions in the mid-term and eventual ambitious government and commercial operations (including eventual human settlements) in the far-term.

It seems likely that the coming years will see a wide range of additional and accelerating developments to realize the Moon Village. These will include both government and private sector missions that are already planned. In addition, future plans are certain to be shaped by the results from early lunar landers (e.g., seeking polar ice deposits on the Moon), from evolving international plans (e.g., vis-à-vis the LOP-G), and the prospect for ambitious private developments (such as the BFR and others).

Moon Village Association activities will evolve as well, focusing on finding for all stakeholders’ common goals to contribute to the vision of the Moon Village for the benefit of humankind, regardless of their national / international programs, and to better engage the general public internationally in the realization of the Moon Village Vision.

A set of specific Moon Village Architectural Elements is being selected upon which the MVA architectural working group will focus its attention during the coming year. These include systems concepts across multiple timeframes and alternative scenarios describing how the future may unfold. During the coming months, these will be further defined and detailed studies undertaken.

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Glossary of Acronyms

<i>ISRO</i>	: Indian Space Research Organization
<i>ISRU</i>	: <i>In Situ</i> Resource Utilization
<i>ISS</i>	: International Space Station
<i>JAXA</i>	: Japan Aerospace eXploration Agency
<i>LEO</i>	: Low Earth Orbit
<i>LLO</i>	: Low Lunar Orbit
<i>MV</i>	: Moon Village
<i>MVA</i>	: Moon Village Association
<i>MVRS</i>	: Moon Village Reference Scenario(s)
<i>MVAE</i>	: Moon Village Architectural Element(s)
<i>NASA</i>	: National Aeronautics and Space Administration
<i>PEL</i>	: Peaks of Eternal Light
<i>PSR</i>	: Permanently Shadowed Regions
<i>SPAB</i>	: South Polar Aiken Basin

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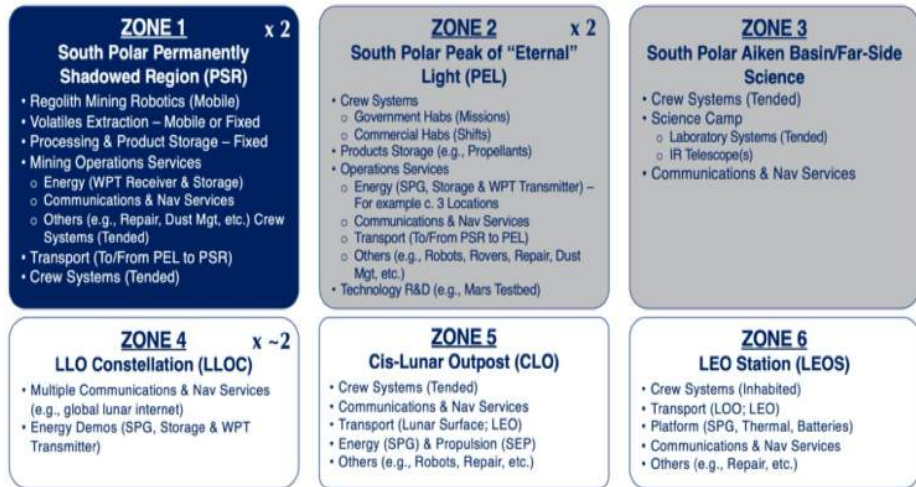
2025: The beginnings of surface operations; extensive international surface exploration and prospecting along with early technology demonstrations related to lunar *in situ resource utilization* (ISRU); surface crew operations limited to US sortie mission(s) – depending on progress to current schedule for government and commercial projects.
See Figure 5.

Figure 5 MV Reference Architecture Roadmap - 2025



2035: Major expansion of surface operations; extensive international operations, including crew mission by multiple countries and companies; ISRU full underway with fuel being produced for local use (i.e., access to the Moon’s surface); US and international use of the Moon as a testbed for Mars underway.
See Figure 6.

Figure 6 MV Reference Architecture Roadmap – 2035



2045: US Government NASA programs focused on Mars exploration; ongoing international operations, including crew missions, lunar tourism and a lunar surface ‘settlement’ with long-duration habitation; lunar-derived resources and products in use beyond the local vicinity of the Moon.
See Figure 7.

Figure 7 MV Reference Architecture Roadmap - 2045

