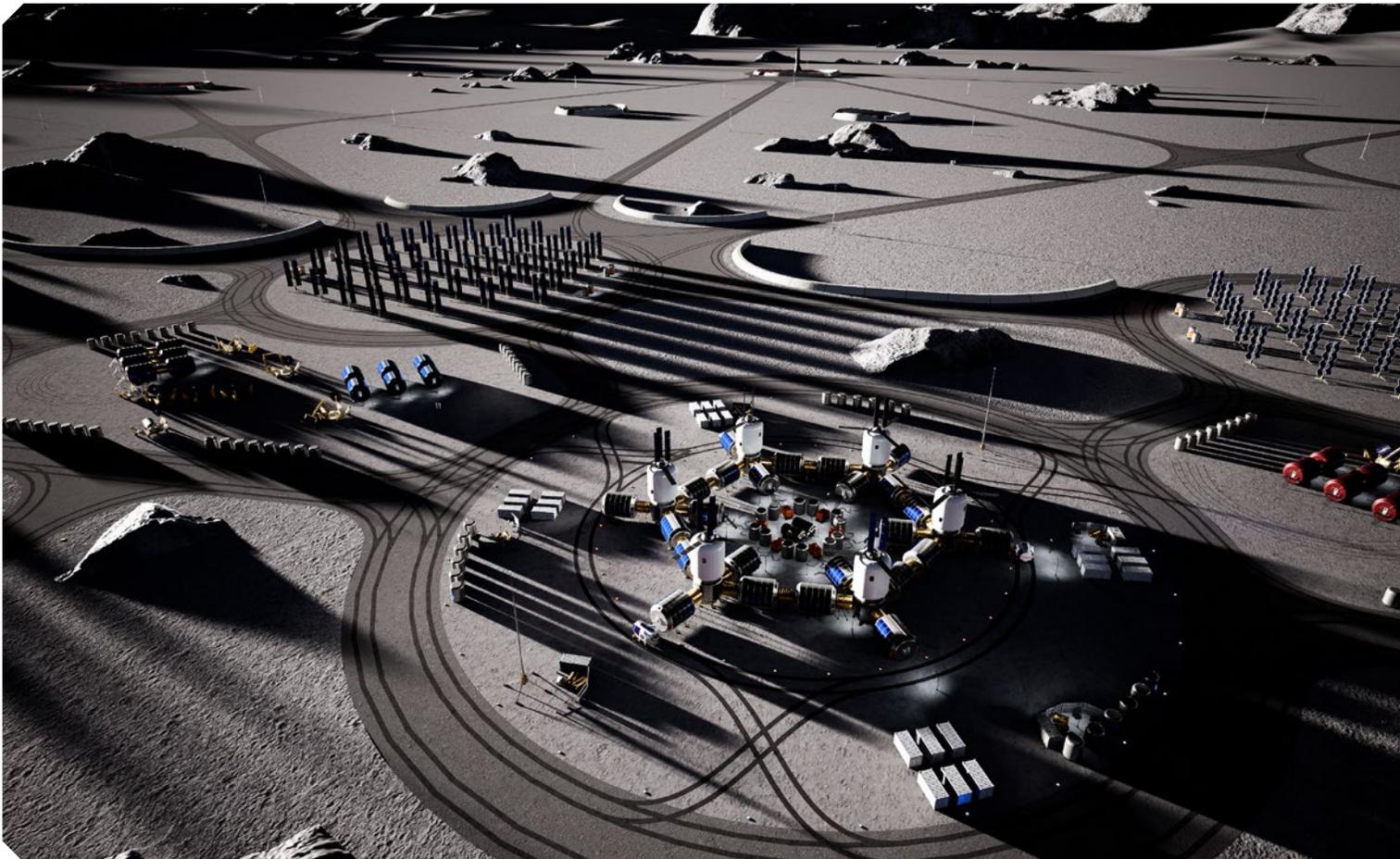




# Beyond Earth Institute Leadership Council

## 2024 Reports and Recommendations





# Beyond Earth Institute Leadership Council

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# 2024 Reports and Recommendations

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# Overview

## Overview of the 2024 Leadership Council Working Group Papers

By Courtney Stadd<sup>1</sup>

As a non-partisan think tank, the Beyond Earth Institute (BE) enlists the expertise of thought leaders in the public and private space sectors to generate analyses concerning the critical legal, regulatory, financial, economic and market challenges facing the creation of economically vibrant communities beyond Earth. We recognize that achieving this goal will take time and entail many daunting technical and policy challenges.

To that end, BE created the Leadership Council (LC) as the principal means for the BE stakeholder community to engage with each other, develop actionable findings for decision-makers, and ultimately help shape the policy priorities of the organization.

LC members are companies and entities that share the vision of BE, possess subject matter expertise, and sincerely wish to contribute to crafting a comprehensive policy and legal framework that will accelerate society toward a space migration future.

For additional details about the LC and how you might participate, please refer to:

<https://beyondearth.org/leadership-council/>

Over the past year, under the auspices of the LC, five Working Groups were formed to address major policy topics that encompass many of the fundamental issues and challenges associated with establishing large scale beyond Earth human presence.

- Commercial Space Stations
- Cislunar Economy
- Advanced Financing & Economics
- Reliability, Health, & Safety
- Large-Scale Habitats

Below is a high-level summary of the key findings from the resulting WG reports. Given their depth and scope, it is not possible to fully capture all the nuances of their key points in a brief summary. Because of this, we encourage you to read these investigations and their findings in their entirety. This overview highlights some of the more prominent findings and recommendations from the working groups. The intent is to encourage the interested reader to begin pondering the compelling insights which, seen in the aggregate, grapple with the technical, financial, and policy challenges associated with each of the following topics:

### Cislunar Economy Working Group

The Cislunar Economy WG recommends that the U.S. adopts a “go big and go now” approach to secure key lunar locations, access critical resources, and establish supporting infrastructure. With an eye on the aggressive investments being made by other nations, especially China, in establishing a major footprint on the Moon, the “go big and go now” approach will enable the U.S. to shape Cislunar norms, protect national security, strengthen international partnerships, and drive technological advancements for continued leadership in space, on Earth, and future U.S. commercial activity on the Moon. China’s aggressive pursuit of moon occupancy means if the US does not establish a permanent, early presence there, China surely will. China is not a signer of the Artemis Accords, and therefore may not play nice with other nations wanting access.

Further, the Cislunar Economy WG recommends that the U.S. government should leverage existing UN treaties and collaborate with like-minded nations through frameworks like the Artemis Accords to avoid conflicts, ensure lunar resource rights, and develop a shared infrastructure for a stable and sustainable Cislunar economy.

<sup>1</sup> Executive Vice President, Beyond Earth Institute

It is imperative that the U.S. focus on flexible regulation and minimal intervention, supporting Cislunar growth through a variety of measures including improving IP protections and ongoing service contracts. Also recommended is the continued pursuit of international coordination via the Artemis Accords and active participation in UN COPUOS to maintain U.S. leadership in the Cislunar economy. Finally, to support the Cislunar economy, the U.S. needs to continue to prioritize development and refinement of public-private partnerships.

#### **Key Takeaways Include:**

- Adopt a “Go Big and Go Now” Approach
- Collaborate with Like-Minded Nations
- Support the Cislunar Economy Development
- Focus on Establishing Scalable Infrastructure
- Flexible Regulation & International Coordination
- Expand Public-Private Partnerships
- Increase Space Budget for Cislunar Activities

### **Commercial Space Stations Working Group**

As the commercial space sector matures, the government’s role must evolve from heavy oversight to one that supports market-driven growth, balancing public and private interests. Further, the shift from government-led space stations to privately operated ones pose regulatory challenges that require ongoing Government support and adaptations. The success of commercial space stations hinges on contracting flexibility and regulatory clarity.

To ensure there is no gap in human and space laboratory capabilities, a seamless transition must be made from the International Space Station (ISS) to Commercial Space Stations. Through public-private partnership models, government agencies have a new approach to stimulate commercial endeavors.

With the pending decommissioning of the ISS, NASA is currently working with three commercial ventures through a public private partnership model to avoid any capability gap and stimulate new commercial markets.

By fostering public-private partnerships, adjusting regulatory frameworks, and implementing new liability protections, the government can support the commercial sector’s growth and help ensure the sustainability of human space activity beyond Earth.

#### **Key Takeaways Include:**

- Commercial Space Station providers should adopt a multi-contract approach to balance public and private needs.
- The Government should extend to Commercial Space Stations the commercial liability regime similar to the one currently in place at the FAA.
- The Government should establish Low Earth Orbiting (LEO) Accords as a normative mechanism for commercial space activity.

### **Reliability, Health, and Safety Working Group**

Safety, reliability and the health of space inhabitants are cornerstones of the emerging space-based economic revolution. Safety in operations for both space systems and humans living and working in space remains a primary demand of both government and commercial customers. Reliability is an essential element of reducing the cost of space and increasing the attractiveness of profitable space ventures. Over sixty years of space experience has revealed key health challenges of living in microgravity and exposure to radiation. Addressing these topics is an indispensable part of stimulating positive change in the nature of space business and the viability of human space expansion.

Building on past working group efforts, webinars and collective discussions surrounding the topic, this year’s WG identified two crucial hurdles for a thriving and permanent human presence beyond Earth: artificial gravity (AG) and radiation protection. The WG explored the use of AG as a potential holistic approach to solving the root cause of the deleterious effects of mid and long-term exposure to microgravity but found the lack of facilities providing relevant in-space experimental data on humans means we lack data to make informed decisions. The WG also investigated possible strategies to respond to the harmful effects of radiation, including protection, countermeasures, and operational architecture adjustments.

The future of commercial space settlements is trending toward a combination of human and robotic symbiosis. The increasingly capable digital assistance and the demonstrated use of semi-autonomous systems on the ISS are a model commercial ventures should strongly consider in their future plans. Such combinations offer new operational opportunities to create safer and more reliable working space environments.

As space exploration moves from a government-only endeavor to one that includes private enterprise (including space transportation, habitation, and potentially space real estate), there will be a critical need to establish comprehensively accepted personal health data privacy industry standards, as well as safety and health protocols.

<sup>2</sup> 10 CFR Part 20 (“Standards for Protection Against Radiation,” establishes the dose limits for radiation workers. Although the limits vary, depending on the affected part of the body, the annual total effective dose equivalent (TEDE) for the whole body is 5,000 mrem (5 rem)...).

### **Key Takeaways Include:**

- NASA needs to coordinate with academic researchers, space organizations (such as BE), and commercial enterprises, to identify the unknowns, develop experiment recommendations, and assist in engineering the technologies that define the requirements for a near-term commercial low Earth orbit artificial gravity laboratory.
- Methods for mitigating and countering damage caused by space radiation to long-term space inhabitants should strive to achieve levels closer to radiation levels around currently accepted industrial maximum yearly dose rates.<sup>2</sup>
- Beyond Earth and its members should actively monitor and participate in the debates and development of health data collection methods that assure privacy while serving marketplace needs.
- Beyond Earth and its members should actively monitor, participate in the debates, and present recommendations regarding regulatory oversight of space developments, facilities, and operations.

### **Advanced Financing & Economics Working Group**

The creation and implementation of a framework of governance for Cislunar investment and business development is needed for the viability and sustainability of both business and non-business lunar efforts. In pursuit of this goal, the WG focused on three key activities which have been identified as necessary to develop such an economy: (1) affordable, available—as well as safe and reliable—transportation; (2) actionable Lunar data; and (3) In situ resource utilization (ISRU).

Ultimately, large-scale involvement of public actors in transportation to lunar-space will likely be balanced in the coming years with increased involvement from the private sector.

Markets for lunar-specific data are expected to emerge including data focused on resources needed for the development of the Cislunar economy, and lunar environment data expected to consume the largest share of the lunar data market. In addition, markets for telemetry data, derived from lunar instruments and vehicles (exploratory data as well and data with terrestrial applications or “spin-off data”) are anticipated to evolve. Finally, markets for entertainment data, consisting of images, videos, and recordings, will be generated.

Having a sustained manned or unmanned presence on the moon opens the path for local resource extraction and utilization. Moreover, such resource extraction and utilization is likely to be integral to the establishment of not only a Cislunar economy, but for future space missions beyond lunar space (i.e. Mars and

deep space).

The absence of a more robust governing framework for Cislunar development promotes major concerns for both space sustainability and security. The Moon, like all other areas of space, does not contain equal resources. As a result, resource rich areas are at risk of land-grabs, possibly resulting in legal conflict between competing claims.

China’s comprehensive plan is significant because—should it succeed—it puts China strategically ahead of the game in developing the Cislunar economy, effectively making them the first mover. For a Western model to effectively compete with the Chinese model, Western actors should lean into the systems that have made the west strong. Specifically, a Western model should focus on wielding international support to enable private sector participation and, thus, ensure free market access to the Cislunar economy.

The Lunar Development Cooperative (LDC) concept was brought before the Working Group as a viable framework for Cislunar governance. The LDC would be a multi-national public-private partnership providing infrastructure, services, and a rules-based order for space users that opt-in to membership.

By ensuring the efficient creation of lunar infrastructure and responsible use of lunar sites, the LDC reduces potential conflicts and protects lunar resources. This structure is also scalable and transferable to other outer space domains (e.g. Mars, asteroids, and orbital facilities).

### **Key Takeaways Include:**

- The Advancing Economics and Financing Working Group has identified the LDC framework as a viable and strong candidate framework for space and Cislunar economic development, deserving aggressive investigation and refinement.
- The WG further recommends, encourages and supports soliciting grant-making institutions for financial support of these initiatives thus ensuring rigorous exploration and refinement of the LDC as a viable solution for ensuring the sustainable development of a free and open space marketplace to include public, private sector, and international cooperation.
- The WG will support further investigations of the LDC framework as a viable governance structure for Cislunar activities.

## Large-Scale Habitats Working Group

The development of large-scale surface habitats in space represents a pivotal step toward establishing a sustainable human presence beyond Earth. This report addressed many of the multifaceted challenges associated with these endeavors. The WG offers strategies that integrate advanced potential technology solutions, international policy frameworks, and economic sustainability considerations.

The Large-Scale Habitats WG Focused on investigating the system engineering and technological capabilities that will be needed for sustainable surface habitats on the Moon, Mars, in orbiting facilities and other celestial bodies in our solar system. As part of this review, attention was given to those socio-economic factors which are vital stimulants to space settlement.

Large-scale habitation capabilities and future settlements are defined as those accommodating 20 or more individuals, moving beyond the size of small research outposts, expected to include a diverse mix of professional astronauts, commercial occupants, and civilian visitors. The logistical challenges of transporting, housing, and supplying this larger group, combined with the associated costs, signify the transition to large-scale habitation.

The analysis was undertaken in the context of a historically proven sequence in opening new frontiers for human settlement. This sequence has three distinct phases: exploration phase, expansion phase, and permanent human activity establishment phase.

We are currently in the exploration phase. To move to the expansion phase, requires gaining insights and perspectives into the enabling aspects foundational to our civilization's extension into space.

Building and operating space development infrastructure requires industrial mastery of how to operate with acceptable safety and economy. This can only be accomplished with cooperation between participants to create common interfaces and accepted methods of governance. Of equal importance is a means to secure ongoing financing to manage, secure and operate these facilities.

Without the development of this industrial mastery, frontier opening stagnates in the exploration phase with only state sponsored research sites or the rugged individual settler outposts. It does not progress to expansive economic growth characterized by resource extraction, local industrialization, services settlements, and interconnected economic and social development.

The Artemis Program represents NASA's cornerstone initiative to establish a sustainable human presence on the Moon for NASA personnel by the late 2020s. The Artemis basecamp must have the support infrastructure and operational capabilities necessary to operate. The WG believes NASA should consider using public-private approaches to obtain and acquire infrastructure services.

By adopting a phased and iterative approach aligned with commercial needs, NASA's Moon to Mars Architecture can better serve as a blueprint for mitigating risks and enhancing the technical and operational capabilities needed to support long-duration human missions. The establishment of sustainable surface habitats on the Moon and Mars requires a unified effort across technological, economic, and policy domains.

### Key Takeaways Include:

- An independent commercial assessment should be made regarding the suitability of these developed technologies and systems within commercial lunar applications.
- NASA should consider and investigate the use of alternative commercial lunar infrastructure services.
- Continue and extend the development of international industrial standards through organizations like the International Organization for Standardization (ISO).
- Incorporate modular maintenance protocols. Facilitate collaborative development and sharing of infrastructure services. Design habitats for incremental expansion. Enable adaptable growth based on mission requirements. Support long-term planning forums and evaluations for efficient scaling. Simplify and publish interfaces to enhance maintenance and component replacement. Establish modular maintenance protocols. Standardize components and interfaces across modules. Enable technology integration and upgrades. Integrate bio-regenerative components like algae or engineered bacteria into ECLSS for efficient oxygen production and CO<sub>2</sub> removal.
- Incorporate hybrid structural designs that use multifunctional elements, such as double-walled structures filled with regolith or water, to provide both mechanical support and radiation protection.
- Consider employing phase-change materials (PCMs) within habitat walls to absorb and release thermal energy, maintaining stable internal temperatures.
- Design internal spaces to be reconfigurable to adapt to varying missions and crew sizes.
- Develop an understanding of the unknowns of partial and artificial gravity on human and biologic systems.
- Integrated health monitoring and predictive analytics.
- Implement physiological countermeasures. Develop psychological support systems.

Please note that the above takeaways are a subset of other detailed recommendations in the paper.

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# To the Moon - Go Big and Go Now

## Policy Recommendations for the Cislunar Economy

*This paper is a product of the Cislunar Economy Working Group of the Beyond Earth Institute Leadership Council. While the paper represents a consensus of Working Group discussions, the views and recommendations do not necessarily represent those of the individual members or their respective organizations.*

By Francesca Giannoni-Crystal & Charles Horikami

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# Executive Summary

Interest in the Moon has grown over the past decade, both for its potential resources and its strategic value as a low-gravity launch point enabling further space exploration. This has caused several countries to renew their focus on the Cislunar Economy and increase their priority in its development. To address these developments, the Beyond Earth (BE) Institute Working Group on the Cislunar Economy has identified several key issues that, if unresolved, would prevent further successful development of the Cislunar environment and makes recommendations to overcome these challenges and ensure that the U.S. remains the preeminent leader in Cislunar development.

To this end, this report advocates a “go big and go now” approach, highlighting the urgency for the U.S. to take immediate and decisive action to maintain its leadership in lunar exploration that it originally achieved with the first human landing on the Moon in 1969. In short, we argue that a small, occasionally crewed lunar orbiting station and a few temporary base camps, as currently contemplated, are insufficient to maintain this leadership. Rather, with its Artemis partners, the U.S. must construct a lunar outpost and research center, as well as catalyze development of infrastructure capable of supporting a permanent human presence on the Moon. This outpost should be designed to expand into a lunar base able to support exploration missions beyond the Cislunar environment.

## I. Background

Several countries have shown growing interest in lunar exploration. China, in particular, made substantial investments and has achieved considerable success in its Chang’e program (established in 2007). To date, China has twice landed on the Far Side of the Moon and successfully returned lunar regolith samples.<sup>1</sup> Moving forward, China seeks to land humans on the Moon by 2030, establish a lunar base at the Moon’s South Pole by 2035, and extract lunar resources.<sup>2</sup> This project, the International Lunar Research Station (“ILRS”) is coordinated with several other countries (Russia being its co-founding partner).<sup>3</sup>

The United States renewed its focus on lunar exploration when it kick-started its Artemis Program in 2017. In 2022, an uncrewed Orion spacecraft on the Artemis I mission successfully completed a journey around the Moon and returned to Earth.<sup>4</sup> The program aims to return astronauts to the Moon by 2026, begin construction on a lunar orbital space station named “Lunar Gateway” by 2028, establish five temporary base camps on the lunar surface by 2032, and facilitate lunar mining activities for commercial partners.<sup>5</sup> To establish norms for lunar and cislunar exploration, the U.S. has entered into bilateral agreements with more than 40 countries (including existing space powers and emerging spacefaring nations such as Australia, Canada, India, Japan, the United Arab Emirates (UAE), and several members of the European Space Agency) known as the Artemis Accords.<sup>6</sup>

## II. Go Big and Go Now

**Recommendation: The U.S. should adopt a “go big and go now” approach to secure key lunar locations, access critical resources, and establish infrastructure.**

The “go big and go now” approach will enable the U.S. to shape Cislunar norms, protect national security, strengthen international partnerships, and drive technological advancements for continued leadership in space, on Earth, and future U.S. commercial activity on the Moon. There are several reasons why we recommend the “go big and go now” approach.

First, acting quickly and boldly will allow the U.S. to stake its claim by securing access to ideal locations on the Moon, thereby gaining strategic advantages and ensuring access to important lunar resources, which are crucial for the lunar economy and for supporting deep space missions into the Solar System. Second, it will boost the lunar economy by supporting commercial space companies, which need a strong backbone of infrastructure to operate successfully. Third, being first will enable the U.S. to set de facto norms and standards for cislunar activities, aligning them with democratic values and fostering a sustainable lunar economy. Fourth, it is essential that the U.S. protect its economic and national security interests by preventing competitors, such as China, from dominating this critical domain. Fifth, it will encourage international alliances and cooperation with the

<sup>1</sup> Katrina Miller, China Becomes First Country to Retrieve Rocks From the Moon’s Far Side, NEW YORK TIMES (June 28, 2024), <https://www.nytimes.com/2024/06/25/science/change-6-china-earth-moon.html>.

<sup>2</sup> Leonard David & Lee Billings, China Makes History with First-Ever Samples from the Moon’s Far Side, SCI. AM. (June 25, 2024), <https://www.scientificamerican.com/article/china-returns-first-ever-samples-from-the-moons-far-side/>.

<sup>3</sup> Lunar Space Cooperative Initiatives, SECURE WORLD FOUNDATION, <https://swfound.org/lunar-space-cooperation-initiatives/> (May 28, 2024) (showing 11 signatories as of April 2024).

<sup>4</sup> Rachel H. Kraft, View the Best Images from NASA’s Artemis I Mission, NASA (Dec. 21, 2022), <https://www.nasa.gov/humans-in-space/view-the-best-images-from-nasas-artemis-i-mission/>.

<sup>5</sup> Michael Abrams, NASA Plans to Retrace Apollo’s Footsteps, AM. SOC’Y MECH. ENGS. (May 4, 2021), <https://www.asme.org/topics-resources/content/nasa-plans-to-retrace-apollos-footsteps>.

<sup>6</sup> SECURE WORLD FOUNDATION, *supra* note 3 (showing 43 signatories as of June 2024).

Artemis Accords signatories by reassuring partners that the U.S. continues to be the preeminent leader in space, on the Moon, and indirectly, on Earth. Sixth, by acting quickly and boldly, the U.S. will boost advanced technologies and infrastructure on Earth, allowing the U.S. to maintain its technological edge, preserve its economic supremacy, and attract international partnerships.

## A. Expanding International Cooperation in the Cislunar Economy

**Recommendation: The U.S. government should leverage existing UN treaties and collaborate with like-minded nations through frameworks like the Artemis Accords to avoid conflicts, ensure lunar resource rights, and develop a shared infrastructure for a stable and sustainable Cislunar economy.**

As the Cislunar economy emerges, international collaboration becomes increasingly vital. While remaining vigilant in maintaining a competitive edge against nations such as China, like-minded space-faring free market countries should cooperate to establish shared goals and common objectives for the Moon, such as setting common safety standards, promoting sustainability in lunar activities, and enabling interoperable technologies. Collaborative efforts among nations will be key in avoiding conflicts over locations, resources, and interference. In addition, these like-minded countries need to develop a common robust Cislunar operating infrastructure to facilitate private companies' lunar activities. However, the cooperation should maintain healthy competition to foster innovation, ensuring diverse participation in lunar exploration.

Adopting a comprehensive international treaty would be complex, lengthy, and likely impossible in the current geopolitical climate. Instead leveraging existing UN treaties and arrangements such as the Artemis Accords can provide the basis to facilitate cooperation. Such frameworks help establish common understanding and cooperation for the exploration and utilization of Cislunar space. This ensures also that activities are conducted responsibly and sustainably. A cooperative approach to emerging issues will also enhance safety and security through common lunar traffic management, resource rights, and the long-term sustainability of Cislunar operations.

Finally, international coordination is important for commercial space enterprises to secure the resources vital for creating a thriving lunar economy and implementing the necessary infrastructure. It will be critical to create a stable, predictable and conflict-free lunar business environment that seamlessly integrates into an Earth-Moon ecosphere.

## B. U.S. Government as a Foundational Enabler and Catalyst

**Recommendation: The U.S. government should act as an enabler for the cislunar economy by helping to provide foundational infrastructure, which is necessary to encourage private investment.**

It is essential to establish a clear, minimal, and flexible legal and regulatory framework that fosters private investment and can adapt to industry changes. Additionally, we urge the government to provide financial support, including direct funding and reinsurance programs, to mitigate risks for space ventures and ensure the cislunar economy's growth.

Within the "go big and go now" approach, the U.S. should act as a foundational enabler and catalyst for the Cislunar economy, by advancing the necessary infrastructure, which is crucial to supporting commercial space companies' Cislunar projects. This includes helping to provide the foundational systems, such as landing pads, life support systems, communication, navigation, power, water, fuel, and food production. Not only will this give a boost to the development of the lunar economy, but it will also show industry participants the dedication the U.S. has towards continued commitment, thereby promoting further investment and development.

Space exploration and development has effectively gone through two phases. First, "space 1.0," when exclusively governments engaged in space activities; this is the phase that led to the Apollo moon landing in 1969.<sup>7</sup> Second, "space 2.0," beginning in the late 20th century and continuing to the present day, is a more collaborative and commercially oriented phase, with private space companies acting as both partners with governments as well as acting independently. This relationship offers space services such as launch, transport, and communications with the government continuing to be a primary end-use customer.<sup>8</sup> Until the space industry fully transitions to a "space 3.0" self-sustaining economic expansion, where commercial customers are the primary end-use customers, the role of the government as an enabler for the space industry remains fundamental, especially for a Cislunar economy.

To facilitate the Cislunar economy the government should first provide a consistent legal framework and regulatory clarity. This will encourage further private investment in emerging lunar technologies, especially in high-risk areas such as space resource utilization and in-space services, assembly, and manufacturing (ISAM). Extending the "learning period" for space regulations is one approach worth considering, as it could allow commercial and private industry participants to continue adapting to new challenges and learning from their experiences.<sup>9</sup>

<sup>7</sup> Freddie Wilkinson, The History of the Space Race, NAT'L GEOGRAPHIC (Aug. 20, 2024), <https://education.nationalgeographic.org/resource/history-space-exploration/>.

<sup>8</sup> Nikolai Khlystov & Gayle Markovitz, Space is Booming. Here's how to embrace the \$1.8 trillion opportunity, WORLD ECON. F. (Apr. 8, 2024), <https://www.weforum.org/agenda/2024/04/space-economy-technology-invest-rocket-opportunity/>.

<sup>9</sup> See Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, Art. VI, Jan. 27, 1967, 18 U.S.T. 2410, 610 U.N.T.S. 205 (entered into force Oct. 10, 1967) [hereinafter Outer Space Treaty].

However, the government should also ensure that it does not over-regulate or pre-emptively regulate in a way that hinders development of the Cislunar economy. Regulations should be simple, broad, and flexible, allowing for dynamic adaptation as the industry evolves. Such flexibility aligns with the adaptive governance model embedded in the Artemis Accords, which emphasizes principles of cooperation, flexibility, and evolving norms.<sup>10</sup> As industry participants develop new technologies, industrial capabilities, and explore new avenues of development in this new ecosystem, they will develop new standards and methods to deal with unforeseen problems, exploiting commercial flexibility to ensure that they can effectively resolve issues. Similarly, to promote certainty, encourage investment, and solidify state practice, the U.S. government should make it clear that its long-standing interpretation of Article II of the Outer Space Treaty<sup>11</sup> does not preclude private ownership of real property in outer space.

Second, the government's financial support needs to increase, taking several forms. While governmental support for space certainly exists, increased support by the government is vital for a smooth transition from government-led to commercial-led space. For new lunar companies to be successful and have viable lunar operations, they must avoid the "chasm of death," i.e., the critical period between securing startup funding and obtaining a large enough customer base to become self-sustaining. Until there is a self-sustaining marketplace with enough customers, the government must provide a solid customer base driving innovation and evolution of capability. Larger companies will also need sustained government procurements to justify investing and competing, and thus drive progress in the cislunar economy. This support is crucial for any private company navigating the financial risks of advanced space ventures until the market becomes commercially driven. Such increased government support will require that more budget be allocated to NASA, DoD, and other agencies to act as customers and not developers. Only an increase in U.S. space funding—especially for the Artemis Program—will ensure that the Cislunar economy will develop, grow, and thrive.<sup>12</sup> However, it is essential to remain mindful of cost-efficiency by leveraging competitive commercial space solutions alongside government-led initiatives, ensuring a balanced and sustainable approach.

The U.S. government's financial support should take the form of direct funding (e.g., contracts, grants, or loans) from government departments in the form of purchase commitments for goods, services and lunar resources. These departments should offer long-term procurement commitments, act as anchor tenants for lunar companies (e.g., resource utilization businesses, lunar

services, and manufacturing), and act as an insurance guarantor, or offer reinsurance programs.

Reinsurance would be a particularly effective—and less onerous way—to support and stimulate the lunar and space industry as a whole. Insurance for "new space ventures" —essentially all lunar projects—is difficult to secure. This is because insurance companies have limited data on the risks involved. This makes insurers hesitant to offer coverage, especially for new market ventures. This is why re-insurance for space insurance companies is vitally important as it transfers some of its insured risk to the reinsurer.

This is true not only for first-party insurance but also for third-party insurance. Both types of insurance are important for industry participants to obtain financing. First-party insurance provides protection for assets such as a company's spacecraft and lunar habitats, while third-party insurance provides liability coverage for damage caused to other entities. A model already exists for third party liability coverage under the Commercial Space Launch Act,<sup>13</sup> which provides protection of the launch and reentry industry. Among other actions, the government should help educate the insurance industry and propose potential legislative solutions, including liability caps.

A government reinsurance initiative—which could support large lunar initiatives, such as lunar bases or mining operations with varying numbers of participants—would lower barriers associated with the creation of new companies and technologies. It would also help mitigate risks associated with providing first- and third-party insurance by spreading financial risk across a broader base so that insurers can manage large claims and maintain market stability. Specifically, a reinsurance program for the Cislunar ecosystem would allow lunar industry participants to address the challenges in obtaining insurance for missions to the Moon.

Additionally, the government could offer additional opportunities for indemnification and waivers of liability and take other measures to cap liability to a commercially reasonable level.<sup>14</sup> Given that the commercial industry has little to no power to mitigate financial risk, to encourage new entrants and development of innovative technologies it is crucial that the government assist mitigate financial risk by taking steps that will help the insurance market, which is not expanding at the same rate as new entrants, to accommodate all these new entrants.

<sup>10</sup> R. Deplano, *The Artemis Accords: Evolution or Revolution in International Space Law?*, 70 INT'L & COMP. L.Q. 799, 799–819 (2021).

<sup>11</sup> Outer Space Treaty, *supra* note 9.

<sup>12</sup> Another possible funding project could be a Strategic Space Commodities Reserve, which the government could support as an anchor customer in the purchase of commodities like water, fuel, and metals mined from the moon.

<sup>13</sup> Commercial Space Launch Act, Pub. L. No. 98-575, 98 Stat. 3055 (1984).

<sup>14</sup> See discussion in Lauren Andrade et. al., *A Path Forward for Commercial Space Stations: Policy and Regulatory Considerations*, Beyond Earth Institute Working Group Report (2024).

## C. Infrastructure Planning and Technological Priorities

**Recommendation: We recommend the U.S. avoid a detailed, expansive, and fixed master plan for lunar infrastructure and instead focus on minimal, scalable, and adjustable infrastructure to support a human presence on the Moon.**

The government should prioritize building a commercial ecosystem by incentivizing industries like mining and manufacturing. We further recommend policies that promote infrastructure development, including reusable lunar transportation, tax incentives, long-term contracts, improved IP protection, and activation grants to support technological advances and workforce growth. To “go big and go now,” the Cislunar economy must avoid a detailed master plan. However, this does not mean going to the Moon without policy and economic objectives. Goals and priorities should focus on establishing the minimal, yet scalable infrastructure required to sustain a successful human presence on the Moon.

Whether this human presence initially finds itself in a centralized location (e.g., crater) branching out to other craters or begins dispersed amongst several occupying craters and then develops a common centralized hub might not matter. The crucial point is by avoiding an articulated master plan we help prevent delaying the initiation of a Cislunar economy. Instead of spending time articulating and attempting to gain acceptance of a master plan, U.S. government actions should focus on supporting the creation of a commercial ecosystem. This may start with scientists (recognizing the need to conduct exploratory prospecting and obtain a better understanding of the lunar environment) but it must quickly transition and expand to include various industries, such as mining, manufacturing, hospitality and agriculture. It is our opinion that one way to foster the creation of a minimal, scalable, and adaptable infrastructure to support human presence on the Moon is through Public-Private Partnerships (PPPs).<sup>15</sup>

The U.S. needs to opt for laws and policies that prioritize advancement and supporting infrastructure development in order to encourage continued investment to achieve a sustainable expansion of our gross national product through the Cislunar economy. In fact, without a sustainable return, investors will not invest. In this way we will not only ensure the economic success of lunar projects, but we will also lay the needed foundation for a viable infrastructure critical to sustaining a permanent human presence on the Moon.

To foster such a lunar infrastructure, the U.S. should prioritize and incentivize the creation of practical, safe and reusable lunar

launch and landing pads. This transportation infrastructure element prevents regolith diffusion and provides an established space port to conduct transportation activities. Exploratory prospecting missions will provide insights into the location and quality of natural lunar resources, identifying potential viable crater locations needed for infrastructure development and data to create extraction methods for in situ resource utilization.

Given that the technologies relevant for these activities require long-term investment and sustained revenue funding, it is imperative that the U.S. government, first, actively promote the development of these technologies by offering for example tax breaks and/or non-dilutive co-investments to companies engaged in such activities. Second, offer long-term and/or renewable contracts related to supplying these capabilities. Third, pass laws and adopt policies encouraging scientific and technological development through improvement of laws for continued robust IP protection measures. And fourth, create activation grants that leverage the investigative power of universities, thus stoking the pipelines for future technologies and a strong U.S. commercial space workforce.<sup>16</sup>

## D. U.S. Regulatory Framework and Coordination

**Recommendation: The U.S. should focus on flexible regulation and minimal intervention, supporting Cislunar growth through a variety of measures including improving IP protections, offering ongoing contracts. We also recommend international coordination via the Artemis Accords and active participation in UN COPUOS to maintain U.S. leadership in the Cislunar economy.**

The “go big and go now” approach needs to play prominently in the regulatory choices of the U.S. government and its coordination with the international community and industry participants. This is because the U.S. has a spectrum of choices towards securing continued leadership in the Cislunar economy. On one end of the spectrum, the U.S. could attempt to plan and regulate every possible lunar activity and even create a “Lunar Master Plan” similar to the “South Pole Station Master Plan” proposed by the National Science Foundation.<sup>17</sup> Any attempts to create such wide and premature sweeping regulations would inevitably meet with delays created by inter-agency conflicts on jurisdictional authority,<sup>18</sup> and partisan and/or regional favoritism.<sup>19</sup> Such attempts could also face challenges in court under, among others, the Major Questions Doctrine, which suggests that agencies cannot rely on vague or general statutory provisions to justify expansive regulatory actions on major

<sup>15</sup> See *infra*, discussion page 9–10.

<sup>16</sup> See GREG AUTRY & PETER NAVARRO, RED MOON RISING: HOW AMERICA WILL BEAT CHINA ON THE FINAL FRONTIER (2024).

<sup>17</sup> Request for Public Comment: Draft South Pole Station Master Plan, 89 Fed. Reg. 42, 904 (May 16, 2024).

<sup>18</sup> Leighton Brown & Paul Stimers, The FCC’s authority in regulating orbital debris, THE SPACE REVIEW (Nov. 6, 2023), <https://www.thespacereview.com/article/4687/1>.

<sup>19</sup> Emily Cochrane, The Loss of Space Command Headquarters Brings an Alabama City Down to Earth, NEW YORK TIMES (Aug. 5, 2023), <https://www.nytimes.com/2023/08/05/us/politics/huntsville-space-command-colorado-springs.html>.

issues,<sup>20</sup> and Loper Bright overturning the Chevron deference standard, which required courts to defer to an agency's own reasonable interpretation of their statutory authority to act.<sup>21</sup> Such delays would defeat the "go now" portion of this report's advocated approach to "go big and go now." Further, while many would argue that early regulatory action offers predictability, stability, and legal certainty, it would place U.S. industry at a severe disadvantage when compared with other countries (such as China), which do not have such sweeping regulations.

On the other end of the spectrum, the U.S. could adopt a Wild West approach and leave the Cislunar economy largely unregulated. Under current law, U.S. industry may operate in space without further licensing laws passed.<sup>22</sup> While this approach has the benefit of allowing U.S. companies to operate freely—so encouraging rapid development and innovation without bureaucratic barriers—U.S. companies would be operating without any rules, which could result in chaos, conflicts, and safety concerns.<sup>23</sup> An approach similar to the Defense Advanced Research Projects Agency's (DARPA) contract-based strategy with the LunA-10 companies, if adopted by more government departments, could be an effective and efficient way to getting us on the Moon "now."<sup>24</sup> However, such a strategy does not easily allow for effective coordination or protections for small industry participants and academic institutions, which are rarely granted such large contracts, leaving out a significant portion of the community, a diversity of perspectives, and the fresh insights to the field typical of smaller entities and academic researchers.

To ensure that the U.S. remains the world leader in outer space, the U.S. must create a flexible balance. Such an approach exploits the ingenuity, creativity and power of free market forces while selectively allowing for adopting industry standards and practices. As these standards, methods and practices become accepted in the market and industry, regulatory agencies will have the data needed to formulate appropriate regulations.

To create a business and regulatory environment appropriate for the Cislunar economy, several conditions are needed. First, ensure that robust intellectual property (IP) protection is maintained. This is critical for encouraging continued investment and enabling asset-based financing, using that IP as collateral for further investments. In particular, the U.S. – through IP laws and policies – should create a favorable commercial environment for private investment. Second, while maintaining a contract-based strategy, further support that strategy by offering continuing and ongoing government contracts to industry. This allows industry participants and customers to know there will be market stability

for their Cislunar project. This should include smaller companies, which by their nature do not have the business depth of more established companies and must rely on continuing contracts to remain solvent and viable competitors in the Cislunar economy.

Third, limit regulation implementation to what is needed at that time. Specifically, a wait and see approach rather than a knee-jerk or pre-emptive approach should be adopted. This prevents excessive, ineffective and inappropriate regulation which would stymie the U.S. Cislunar economy. Fourth, continue to expand international coordination with the Artemis Accords and encourage support of international trade associations, development self-regulating global standards, and/or multinational non-governmental organizations (NGOs) like INSTELSAT. Fifth, conduct proactive negotiations in recognized international fora, such as the United Nations Committee on the Peaceful Uses of Outer Space (UN COPUOS) with the primary objective to help establish a shared lunar legal framework and to help prevent international conflicts. Taking these steps will show the world that the U.S. continues to be a leader in the Cislunar economy and demonstrates to the marketplace and financing community that it supports innovation and development, both critical to ensure development and sustainment of the U.S. Cislunar economy.

In conclusion, this report advocates that while some regulation is needed to ensure that investment and industry participation continues to grow, a full regulatory master plan is unnecessary and would hinder development and growth.

## E. Public-Private Partnerships and Economic Sustainability

**Recommendation: The U.S. should expand public-private partnerships (PPPs), including small industry participants, and offer long-term contracts for propellant production, transportation, and lunar resource utilization.**

In the optic of risk sharing as the foundation of an effective PPP, guaranteeing initial demand for lunar resources and adjusting tax structures will reduce risks, stimulate investment, and support the growth of the Cislunar economy. Key to a strong Cislunar economy is the stability of lunar companies, including smaller ones and start-ups. Under current U.S. policy, stability of small companies does not seem to be a priority.<sup>25</sup> Indeed, U.S. governmental actors, such as NASA and the DoD have until now relied on contracts with the traditional large aerospace

<sup>20</sup> See, e.g., *West Virginia v. Environmental Protection Agency*, 597 U.S. 697 (2022), holding that when an administrative agency seeks to regulate matters of significant national importance with broad economic or political consequences, courts will require clear congressional authorization and finding that the EPA had overstepped its authority in regulating greenhouse gas emissions without clear authorization from Congress.

<sup>21</sup> *Loper Bright Enterprises v. Raimondo*, 144 S. Ct. 2244 (2024).

<sup>22</sup> See Laura Montgomery, *U.S. Regulators May Not Prevent Private Space Activity on the Basis of Article VI of the Outer Space Treaty*, Mercatus Working Paper (Mar. 28, 2018).

<sup>23</sup> See, e.g., *Titan Sub Implosion: What We Know About Catastrophic Event*, BBC News (June 26, 2023), <https://www.bbc.com/news/world-us-canada-65934887> (last visited Sept. 19, 2024). The implosion of OceanGate's private submarine, Titan, during its visit to the Titanic wreck—an incident claimed the lives of all five passengers on board—could serve as a stark reminder of the dangers of unregulated or lightly regulated activities in extreme environments.

<sup>24</sup> *Catalyzing an Integrated Lunar Economy: Initial Results of the LunA-10 Capability Study*, DARPA (May 10, 2024), <https://www.darpa.mil/news-events/2024-05-10>.

<sup>25</sup> Yaswant Devarakonda, *Legislation on Space Debris and Commercialization*, AM. ASTRONOMICAL SOC'Y (Nov. 16, 2023), <https://aas.org/posts/advocacy/2023/11/legislation-space-debris-and-commercialization>.

companies, such as Boeing and Northrop Grumman, which then have sub-contracted out portions of their projects to small industry participants and start-ups.<sup>26</sup> While this structure might appear to encourage quick development and implementation of aerospace technologies it is not always conducive to that goal as, among other reasons, risk sharing weighs heavily in favor of government and large corporate actors. Large companies often find it more cost-effective to acquire small companies that have already developed new technologies, rather than developing those innovations in-house. In addition, the lack of governmental on-going support and contracts for the subcontractors often stymie the further development of technologies by the smaller companies.<sup>27</sup>

Continued agency application of this preferential structure imposes an unfair and inefficient burden on the space industry. While it is true the market will naturally filter out less valuable technologies, the current imbalance disproportionately disadvantages smaller players, a situation leading to an unnecessary loss of potentially valuable innovations. More support for small companies is needed, risk must be shared to enable them to reach a point where the market can properly assess their innovations. When small industry participants and start-ups cannot rely on consistent contracts for a steady revenue stream and when all the risk is placed on them rather than shared with the government and larger contractors, then investors are discouraged from investing and these small companies often collapse. When companies collapse, the IP they have developed ceases to receive on-going support, and new companies, which develop their own IP, enter the market, it creates an environment with an abundance of technologies that are not cross compatible and which may, over time, become inaccessible.<sup>28</sup>

To support the Cislunar economy, the U.S. needs to continue to prioritize development and refinement of public-private partnerships. These partnerships must include startups and small industry participants as well as the big names in the industry. In other words, to foster investment in lunar activities, the U.S. government needs to share risks with industry rather than laying the burden solely on industry. Small industry participants and start-ups need some guarantee for revenue streams and customers in order to ensure that investors invest and assure the financing community participation. In fact, to attract investors, there must be a plausible return on investments. Government guaranteed contracts are an instrumental tool that bolsters financing confidence and defeats the “chasm of death” discussed earlier.

What type of renewable and long-term government contracts would both support U.S. policy goals and be attractive to private investors? Contracts for propellant and power production, transportation, and in-situ lunar resource utilization would be key areas for such support. For example, government contracts that guarantee the purchase of lunar propellant and power can act as a catalyst for the Cislunar economic development. By guaranteeing the initial demand for lunar resources (e.g., water, oxygen), the U.S. government can reduce revenue risks, stimulate development of lunar infrastructure and attract private investment. With consistent production assurance, private commercial participants can enter the market with confidence, utilizing established producers.

Once market demand for key services is primed by the U.S. government, a space commodities exchange could be established, allowing for future contracts on the purchase and delivery of various lunar commodities and other services at various points in space and time. As the Cislunar economy expands, these types of contracts offer the added benefit of fueling increased private investment in lunar facilities to utilize lunar resources and create supporting products and services.

Additionally, by extending or modifying current laws, tax structures and regulations that encourage and enhance financing for space companies, the U.S. can be an ally promoting the economic sustainability and stability of the Cislunar economy. Such risk sharing and support will help stimulate lunar economic expansion and an on-going development of industry standards, technological advancements, supply chain coordination, and the lunar infrastructure.

## F. U.S. National Interest

**Recommendation: We recommend that to maintain a first-mover advantage and to lead globally that the country's budget for space needs to grow to a level sufficient to develop cislunar space and establish a permanent lunar presence.**

Leveraging both government and private efforts can accelerate cislunar progress, counter China's growing space investments, and ensure the U.S. maintains its strategic advantages, with a strategy focused on establishing a permanent presence on the Moon. We further recommend that the U.S. clearly communicate to the public that the “go big and go now” approach is essential for national security, and global leadership.

<sup>26</sup> Compare Rachel Jewett, Boeing Receives US Space Force Contract for WGS-12 Satellite, VIA SATELLITE (March 5, 2024), <https://www.satellitetoday.com/government-military/2024/03/05/boeing-receives-us-space-force-contract-for-wgs-12-satellite/>, with Jim Destefani, A Look at Boeing's Outsourcing Strategy, SOC'Y MFG. ENG'RS (May 20, 2024), <https://www.advancedmanufacturing.org/industries/aerospace-defense/a-look-at-boeing-s-outsourcing-strategy/article.8732477e-16ab-11ef-9078-a3d8acf55279.html>.

<sup>27</sup> See Small Business Innovation Research (SBIR), <https://www.sbir.gov/> (last visited Sept. 19, 2024). The Small Business Innovation Research (SBIR) process provides a relevant example of the challenges faced when technologies are successfully developed to a specific Technology Readiness Level (TRL) but due to a lack of sustained investment or support, are not pursued for further development or commercialization, and therefore never reach the market.

<sup>28</sup> See Sean Bryant, How Many Startups Fail and Why, INVESTOPEDIA (June 24, 2024), <https://www.investopedia.com/articles/personal-finance/040915/how-many-startups-fail-and-why.asp> (last visited October 17, 2024).

The “go big and go now” approach is consistent with national interest. Historically, space exploration has been symbolic, as exemplified by the Apollo missions.<sup>29</sup> After being the first and only country to land humans on the Moon, establishing the first permanent and conspicuous lunar presence should also be a matter of national interest and global leadership.

More importantly, being the first to establish a permanent presence on the Moon represents a critical component of national security strategy, as it will be a vital part of the future of global military power and economic influence. It would signal the country’s commitment to maintaining its leadership in space, thereby enhancing national security and reinforcing U.S. global standing vis-à-vis allies and adversaries, and those in between.

Additionally, a robust U.S. presence on the Moon allows the U.S. to establish our rules of engagement for future space activities. It would help ensure that the U.S. maintains its strategic advantages in space and on Earth. It would preserve our lunar cultural heritage, which is part of history and continued national power. The leadership of the U.S. presence on the Moon would be a template for other like-minded spacefaring nations offering them encouragement to adopt those same rules of engagement. Ultimately, this second race to the Moon is not just about exploration; it is about securing the future of global and interstellar power for us and our like-minded allies.

The Moon is rich in strategic valuable resources such as water, metals, and helium-3;<sup>30</sup> control over these critical resources could grant a significant economic and technological edge for future space exploration. Moreover, the Moon, as a launching site and as a source of resources, will serve as a critical gateway for further space exploration to Mars and beyond. For the U.S., establishing a significant presence on the Moon is crucial to maintaining geopolitical balance. If another non-allied nation were to control the most valuable lunar locations, it could monopolize and set terms for access to these critical resources, thereby exerting undue influence over other nations’ lunar activities.

If China is the first to establish a lunar base, it may well be the first to use the Moon as a layover hub to further destinations in the Solar System. China’s rapid advancements in lunar exploration highlight its growing skills, ambitions and its primacy on the Moon. This could lead to a shift in the terrestrial geopolitical order. Securing a U.S. presence on the Moon before China is a strategic imperative to prevail in any U.S.-China competition on Earth. By establishing and sustaining a lunar presence early, the U.S. can safeguard its national interests,

maintain global leadership, and prevent China—with its growing skills and ambitions of primacy on the Moon—from gaining a strategic advantage that could alter the global power structure.

Private companies have already committed substantial resources to programs such as the Human Landing System (HLS), while numerous others are investing heavily in critical technologies for lunar exploration. These commercial investments complement government initiatives, reinforcing the notion that leveraging both public and private efforts can expedite progress in space. Considering the commitment of its national companies, the U.S. must increase its budget to ensure that these efforts are fully supported and aligned with the country’s strategic objectives, particularly in establishing a permanent lunar presence and maintaining global leadership in space.

The U.S. must increase its space budget (especially the portion directed towards Cislunar) in order to maintain strategic leadership in space and terrestrially. To provide context: the 2024 U.S. combined space related budget for NASA and the Department of Defense (DoD) (Space Force) is ~\$51 billion (with ~\$7 billion allocated to the Artemis program by NASA).<sup>31</sup> In contrast, China’s 2024 estimated space budget, while opaque, is likely in the neighborhood of ~\$14 billion; when adjusted for Purchasing Power Parity estimated to be between 1.8 and 2.0, China’s 2024 space budget could effectively be between \$24 and \$28 billion.<sup>32</sup> While the U.S. retains a lead in absolute spending and technological infrastructure, in the decade between 2014 and 2024, China has more than doubled its budget (in 2014, China’s space budget was estimated to be ~\$6 billion),<sup>33</sup> while the U.S. has not (in 2014, the combined budget for NASA and the DoD—before the Space Force—was ~\$39 billion).<sup>34</sup> China’s continued increasing investment underscores commitment to meeting its space objectives. In the face of such competition, there is a need for the U.S. to also substantially and strategically increase its investment for space exploration, activate the emerging space and Cislunar economy, and develop the Moon’s resources. While increasing the budget is important, leadership is defined not by the amount spent but by how effectively those resources are allocated. This makes it essential to focus on the strategic use of funds, particularly in establishing a permanent lunar presence.

<sup>29</sup> Jessie Kratz, The Eagle Has Landed: The Apollo 11 50th Anniversary, NAT’L ARCHIVES (July 19, 2019), <https://prologue.blogs.archives.gov/2019/07/19/apollo-11-50th-anniversary/>.

<sup>30</sup> Jianjun Liu et al., Evidence of Water on the Lunar Surface from Chang’E-5 in situ spectra and returned samples, 13 NATURE COMM’NS 3119 (2022).

<sup>31</sup> JENNIFER DIMASCO, CONG. RSCH. SERV., IF12610, DEFENSE PRIMER: THE UNITED STATES SPACE FORCE, (2024); RACHEL LINDBERGH, CONG. RSCH. SERV., R43419, NASA APPROPRIATIONS AND AUTHORIZATIONS: FACT SHEET (2024).

<sup>32</sup> Jeffery Kluger, Why China Might Beat the U.S. Back to the Moon, TIME (April 1, 2024), <https://time.com/6962362/china-space-program-moon/>.

<sup>33</sup> ORGANISATION FOR ECONOMIC CO-OPERATION AND DEVELOPMENT, THE SPACE ECONOMY AT A GLANCE 2014, at 42 (2014).

<sup>34</sup> Id., at 139.

### III. Conclusion and Summary of Recommendations

The U.S. stands at a critical juncture in the race to secure its status as the preeminent leader in the Cislunar economy. A bold, forward-thinking strategy is essential for securing key lunar locations, accessing valuable resources, and establishing the necessary infrastructure. By acting decisively, the U.S. can protect its national security and foster international alliances, all while shaping the norms and standards for Cislunar activities. In contrast to a rigid and overly detailed plan, a flexible, scalable approach that prioritizes public-private partnerships and international cooperation will enable sustainable growth and allow the U.S. to stay ahead of its competitors, particularly China. The following recommendations provide a roadmap for the U.S. to secure its leadership on the Moon and foster a thriving lunar economy.

#### Summary of Recommendations:

1. **Adopt a “Go Big and Go Now” Approach:** Adopt a “Go Big and Go Now” approach to help secure key lunar locations, access critical resources, build infrastructure to shape Cislunar norms, protect security, and maintain U.S. leadership in space.
2. **Collaborate with Like-Minded Nations:** Work through international frameworks to ensure access to resources, avoid conflicts, and build shared infrastructure for a sustainable Cislunar economy.
3. **Support the Cislunar Economy:** Provide foundational infrastructure, flexible regulations, and financial support to foster private investment and mitigate risks for space ventures.
4. **Focus on Scalable Infrastructure:** Prioritize a flexible ecosystem with incentives for industries like lunar resource utilization, lunar transportation, tax benefits, and long-term contracts to ensure continued growth in the Cislunar environment.
5. **Flexible Regulation & International Coordination:** Promote adaptable regulation, cooperate within the Artemis Accords framework and collaborate with international bodies UN COPUOS to support Cislunar growth.
6. **Expand Public-Private Partnerships:** Engage small industry players with long-term contracts for propellant production, transportation, and resource utilization, while adjusting tax structures to stimulate investment.
7. **Increase Space Budget for Cislunar activities:** Boost funding for Cislunar activities—in particular, for a permanent lunar presence—to counter China’s investments and maintain U.S. strategic advantages.



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# A Path Forward for Commercial Space Stations

## Policy and Regulatory Considerations

*This paper is a product of the Commercial Space Stations Working Group of the Beyond Earth Institute Leadership Council. While the paper represents a consensus of Working Group discussions, the views and recommendations do not necessarily represent those of the individual members or their respective organizations.*

By Lauren Andrade, Kelsey Wu, and Elena Graham (Contributing Editor)

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# Executive Summary

Space exploration is rapidly transitioning from being primarily Government-led to a more commercially driven endeavor, aimed at affordable space settlement. As the International Space Station (ISS) approaches decommissioning, public-private partnerships are crucial to ensure continuous space laboratory capabilities. However, as the commercial space sector matures, the government's role must evolve from heavy oversight to one that supports market-driven growth, balancing public and private interests. Further, the shift from government-led space stations to privately operated ones poses regulatory challenges that require ongoing Government support and adaptation. The 2024 Commercial Space Stations Working Group has found that the success of commercial space stations hinges on contracting flexibility and regulatory clarity.

## I. Background/Context

As the fabric of space activity has evolved and expanded, space exploration is expanding beyond the limits of the government. We've entered the commercial space age that is driving to realize a vision of affordable space settlement as the end goal.<sup>1</sup> The implications of this ongoing shift toward commercialization have been and will continue to be profound for business, policy, and society sectors.

This year alone, private companies have made significant strides in space exploration. SpaceX has successfully deployed 67 missions by mid-2024 and is aiming for 135 launches by the end of the year.<sup>2</sup> Among their notable achievements was the fifth test flight of SpaceX Starship, which completed a successful "catch" of the Super Heavy booster, marking a significant milestone in enabling space commercialization and exploration.<sup>3</sup> Intuitive Machines built the lunar lander Nova-C, designed to deliver small commercial payloads, including experiments and equipment, to the crater Malapert A near the moon's south pole.<sup>4</sup> The IM-1 mission, which launched on February 29th, 2024, had a multi-day window that began in mid-February and concluded seven days after landing.

Private astronaut missions have experienced significant growth this year as well. The Polaris Program is pushing forward with the Polaris Dawn mission, the first of three planned missions led by Jared Isaacman in partnership with SpaceX. In September, Polaris Dawn launched aboard a SpaceX Crew Dragon spacecraft atop a Falcon 9 rocket, making history with the first commercial spacewalk.<sup>5</sup> The mission marks another key achievement

in private spaceflight, pushing the boundaries of what non-government space missions can achieve. To date, Axiom Space has flown three private astronaut missions to the ISS, with a fourth scheduled for early 2025.<sup>6</sup> Blue Origin also experienced a successful flight for the New Shepard Program in August, with the NS-26 flight.<sup>7</sup>

To ensure there is no gap in human and space laboratory capabilities, a seamless transition must be made from the International Space Station (ISS) to future Commercial Space Stations. However, strictly relying on the government's ability alone to support the type of expansive growth in space facility use is untenable as it alone can not maintain the free world's leading role in the emerging space econosphere. Through public-private partnership models, government agencies are now helping to stimulate commercial endeavors by imparting the wisdom of decades of development experience into private companies which are willing and able to advance the space industry at a much faster rate. The public-private partnership model operates on a symbiotic relationship between both parties which allows the entities to share decision-making power.

In the nascent years of Commercial Space Stations, it is likely that Government participation and support as anchor tenant will be a necessary stimulant. As is often the case with new and emerging commercial markets, these markets need to be fostered and supported by the Government until maturation to the point of long-term sustainability.

<sup>1</sup> Matthew Weinzerl & Mehak Sarang, The Commercial Space Age Is Here, HARVARD BUS. REV. (Feb. 12, 2021), <https://hbr.org/2021/02/the-commercial-space-age-is-here> (last visited Oct. 17, 2024).

<sup>2</sup> Alejandro Alcantarilla Romera, SpaceX continues record-breaking year with Starship's full success and Falcon milestones, NSF (July 1, 2024), <https://www.nasaspaceflight.com/2024/07/spacex> (last visited Oct. 17, 2024).

<sup>3</sup> Jeff Foust, SpaceX launches fifth Starship, catches Super Heavy booster, SPACENEWS (Oct. 13, 2024), <https://spacenews.com/spacex-launches-fifth-starship-catches-super-heavy-booster/> (last visited Oct. 22, 2024).

<sup>4</sup> IM-1 Mission, INTUITIVE MACHINES, <https://www.intuivemachines.com/im-1> (last visited Oct. 17, 2024).

<sup>5</sup> Justin Davenport, Polaris Dawn returns home after landmark commercial spaceflight, NSF (Sept. 14, 2024) <https://www.nasaspaceflight.com/2024/09/polaris-dawn-splashdown/> (last visited Oct. 17, 2024).

<sup>6</sup> Jeff Foust, Companies seek more opportunities to send private astronaut missions to ISS, SPACENEWS (Oct. 2, 2024), <https://spacenews.com/companies-seek-more-opportunities-to-send-private-astronaut-missions-to-iss/> (last visited Oct. 17, 2024).

<sup>7</sup> Blue Origin Completes 26th Mission to Space with Six Crew Onboard, BLUE ORIGIN (Aug. 29, 2024), <https://www.blueorigin.com/news/new-shepard-ns-26-mission> (last visited Oct. 17, 2024).

## A. Commercial Space Stations: Filling the ISS Void

The impending decommissioning of the ISS within the next decade presents both challenges and opportunities for growth of the commercial space sector.<sup>8</sup> The ISS has historically been unparalleled in providing an incubator for premium space technology and knowledge. It has operated for almost three decades as a large orbiting microgravity experimentation and technology laboratory, serving as a hub for astronauts and cosmonauts, all while doubling as a commercial test bed as well.

The decommissioning of the ISS has the National Aeronautic and Space Administration (NASA) currently working through a public private partnership model to avoid any capability gap. In February of 2020, NASA made an agreement with Axiom Space to develop an orbital segment that initially would be attached to the ISS and ultimately would operate as part of a fully commercial space station.<sup>9</sup> The next year NASA additionally entered into agreements with a variety of space companies including Blue Origin and Nanoracks LLC to build independent (non-government affiliated) space stations. Then, in January 2022 NASA issued the ISS space station transition report outlining the plan to support commercial growth in LEO via Commercial Low Earth Orbit (LEO) Destinations (CLDs) by 2030 to help fill the void left by the planned decommissioning of the ISS. Within the report, NASA stated their commitment to fully transitioning to commercially-operated space stations.<sup>10</sup> However, how and on what timetable that NASA plans to scale back Government oversight remains to be determined.

In addition to NASA's CLD partner organizations, other private space companies have also committed to create and deploy commercial first space habitats.<sup>11</sup> Vast's Haven-1 singular module space station is planned to launch by 2025.<sup>12</sup> Similarly, Starlab, a joint venture between Voyager Space, Airbus, Mitsubishi, MDA Space, Palantir Space, Hilton, Northrop Grumman, and Ohio State University has plans for a 2028 launch of a commercial space station that offers the "first science park in space."<sup>13</sup>

## B. 2023 Working Group Findings

At the conclusion of the 2023 Leadership Council Working Group on Commercial Space Stations, the Working Group members identified two central challenges to the prospect of successful implementation of commercial space stations.<sup>14</sup> Amidst a lack of clear direction from the Administration and Congress, the future of commercial space habitats faces significant challenges, including regulatory obstacles in that there is a lack of ability to effectively mitigate liability exposure exacerbated by the absence of readily available commercial insurance.

In response to these concerns, the 2023 Working Group offered five key recommendations. First, it advocated for centralizing the regulation of on-orbit activities under a single governing body. Second, it suggested that the Department of Commerce is well-suited to serve as the coordinating regulator. Third, it recommended using the U.S. State Department's Circular 175 model for coordination across the Federal government. Fourth, it proposed a milestone-based approach to enforcement. Lastly, due to the difficulty of obtaining insurance for space activities, it expressed that the U.S. government should support the insurance industry by offering expertise and providing third-party indemnification coverage to the private sector.

## II. Challenge: What Does It Mean to Be A Commercial Space Station?

With the private sector entering the domain of habitable space stations and other novel space activities, the government has recognized the pressing need for a regulatory scheme which supports growth. In conceptualizing the regulation and functionality of a fully commercial space venture like a CLD, the lingering question is: What does it actually mean to function as a CLD?

<sup>8</sup> FAQs: The International Space Station Transition Plan, NASA, <https://www.nasa.gov/faqs-the-international-space-station-transition-plan/> (last visited Oct. 17, 2024).

<sup>9</sup> NASA Selects First Commercial Destination Module for International Space Station, NASA (Jan. 27, 2020), <https://www.nasa.gov/press-release/nasaselects-first-commercial-destination-module-for-international-> (last visited Oct. 17, 2024); Axiom Station, AXIOM SPACE, <https://www.axiomspace.com/axiom-station> (last visited Oct. 17, 2024).

<sup>10</sup> International Space Station Transition Report, NASA, 1,3 (January 2022).

<sup>11</sup> Commercial Destinations in Low Earth Orbit, NASA, <https://www.nasa.gov/humans-in-space/commercial-space/low-earth-orbit-economy/commercial-destinations-in-low-earth-orbit/> (last visited Oct. 17, 2024).

<sup>12</sup> Roadmap, VAST SPACE, <https://www.vastspace.com/roadmap> (last visited Oct. 17, 2024).

<sup>13</sup> Starlab Space, STARLAB SPACE, <https://starlab-space.com/> (last visited Oct. 17, 2024).

<sup>14</sup> Lauren Andrade, A Framework For The Effective Implementation Of Commercial Space Stations: Policy Considerations and Recommendations, Beyond Earth Institute Working Group Report (2023), <https://beyondearth.org/wp-content/uploads/2023/10/Lauren-Article.pdf>.

## A. Shifting Toward A Commercial Model

The shift toward the CLD model is one that has ongoing Government support, but is not without growing pains. It is clear from the passage of legislation including the 2015 Commercial Space Launch Competitiveness Act, also commonly referred to as the Spurring Private Aerospace Competitiveness and Entrepreneurship Act (SPACE Act), that US citizens are authorized to “engage in commercial exploration for and commercial recovery of space resources free from harmful interference.”<sup>15</sup> The SPACE Act expands the framework outlined in the Commercial Space Launch Act of 1984 (CSLA) and supports the commercial sector through regulatory and liability protections.<sup>16</sup> Despite the ongoing support for commercial space enterprise, the shift toward a fully commercial space station highlights the need for clear Government support of commercial space business models.

### i. Commercial Contracting

As its name suggests, the public-private partnership model allows for a symbiotic relationship between Government and commercial entities. Combining public sector support and oversight with private sector capital, efficiency, and ability it seeks to tap into innovation and ensure U.S. competitiveness in the space market. Indeed, this Beyond Earth working group sees public sector support of CLD as essential to its success.

The shift away from government-funded and operated space stations like the ISS results in the necessary reliance on commercial enterprises to provide needed capability and support. However, the Government has yet to demonstrate a clear willingness to support commercial contract terms. This creates and presents significant challenges for the private sector. The result of this commercial contract reluctance puts CLD operators in a bind. Moreover, the NASA view of what constitutes a commercial transaction is fundamentally different from a traditional commercial venture between two non-government entities. On one hand NASA is used to greater levels of oversight and control afforded to them under traditional government managed contracts. On the other hand they also seek to obtain the cost advantages of being one of many “customers” of commercially-owned and operated space stations.<sup>17</sup> Ultimately, if the Government wishes to benefit from the CLD effort, there needs to be a clear willingness to operate within a commercial market and business framework. This means letting commercial vendors know their customer needs but operating as they have in the past executing traditional government contracts. The commercial vendors must then decide if they want to make the investments to meet this customer’s needs.

### ii. Multi-Interest Considerations

One important aspect of the CLD model is that commercial providers are by and large free to enter into contractual

arrangements with a myriad of parties. This will likely result in multi-interest facilities capable of hosting missions with both Government and non-Government parties. This gives rise to additional questions about CLD functioning and Government customer interaction. Addressing mixed-occupant/payload missions, the CLD Working Group identified several key scenarios that must be addressed.

These identified scenarios recommended for further consideration include situations where NASA is not the primary customer and Government interest may be secondary, raising the question: What happens when a multi-customer mission with NASA participation but another customer is a larger stakeholder? Further, how will CLD handle NASA-astronaut tended third party payloads? Additionally, where the CLD contains independent non-human tended payloads, the CLD Working Group identified the need to articulate the protections and rights of the human versus payload stakeholders.

The common theme present in each of these scenarios is that trust in the CLD provider is essential to its success. From development, to NASA qualification for facility use, to their ultimate ability to provide commercial customer services, a CLD cannot function without the shared trust of both public and private stakeholders in its efficacy.

## III. Recommendation: Commercial Space Station providers should adopt a multi-contract approach to balance public and private needs.

For CLD to function, both public and private customers need to trust the provider’s ability to provide needed services, and thus there is necessarily a need to balance both public and private concerns. This need for a mechanism that fosters customer confidence is essential and relies on ongoing Government support of CLD providers. To that end, the CLD Working Group recognizes the key role NASA plays in the development and growth of CLD. As an established and proven globally-trusted leader in space activity, NASA’s contribution to the CLD model builds commercial operators’ credibility with regulators, which is critical to mission authorization and licensing. Taking into account the necessity of balancing both public and private interests, the CLD Working Group recommends a more simplified multi-contract approach to the CLD model. In order to adequately attend to the unique needs of a CLD at development, during qualification, and when providing services, the CLD Working Group recommends the implementation of a minimum of three complementary services type contracts that support the entire life cycle of the CLD.

<sup>15</sup> US Commercial Space Launch Competitiveness Act, Pub. L. No. 114-90.

<sup>16</sup> 51 U.S.C. 50901 - 50923.

<sup>17</sup> NASA, supra note 11.

## A. A Multi-Contract Approach

To attract investment opportunities, commercial companies need to be able to demonstrate they will have customers that can provide a return on investment. Key questions arise regarding the Government's role in this process. This includes things such as whether the agency will guarantee a minimum purchase of services and if it can provide enough business to a sufficient number of operators to make commercial space station ventures viable. The multi-contract approach allows for the gradual lessening of Government involvement in the CLD framework, to ensure that Government concerns are addressed throughout the development and qualification of the CLDs. Moving toward a lessening of Government involvement in the Services (operations) phase of the CLD.

## B. Building Private Sector Trust

It is clear that the reliance on commercial space providers is by no means novel. In May 2009, President Barack Obama via the Office of Science and Technology Policy ("OSTP") created the Review of U.S. Human Spaceflight Plans Committee (or "Augustine Committee") to assess US involvement in the ISS, future missions outside of low Earth orbit, and the future of the commercial space industry.<sup>18</sup> The retirement of the space shuttle fleet placed reliance on America's ISS partners—in particular Russia but also the European Space Agency, and Japan—for station transport.<sup>19</sup> In response, NASA Administrator Charles Bolden stated that NASA "will foster a growing commercial space transportation industry that will allow NASA to focus our efforts on executing [the] direction in the act to start work on a heavy-lift architecture to take astronauts beyond low-Earth orbit, and to develop a multipurpose crew vehicle for use with our new space launch systems."<sup>20</sup>

### i. What Does It Mean to Be Commercial? – The NASA Commercial Crew Model

Since 2020, NASA has relied on SpaceX to provide commercially operated transportation to and from the ISS through the Commercial Crew Program (CCP).<sup>21</sup> Prior to the implementation of the CCP, NASA funded and managed such programs, being fully involved in every detail of spacecraft development from initial design through construction and operation. By contrast, the CCP approach allows NASA to collaborate with the private sector to identify needs while allowing companies to design and construct spacecraft to their own specifications. Through this process, the private company maintains complete ownership and operational control of its spacecraft; however NASA imposes requirements during the development and qualification phases to ensure that the commercial spacecraft meets the required

standards. However, absent a formal commitment, NASA has been unclear about what it plans to purchase from the commercial sector. This has led to a lack of clarity regarding what the actual return on investment will be for CLD operators.

Further, given the nascent state of current commercial demand, it is yet to be seen how the CCP model translates to other corporations. For SpaceX, a private entity already focused on space development without government incentivisation, the model worked effectively. However, the Boeing Starliner public-private attempt, developed based on a traditional government contractor model with limited investment by private parties, has not enjoyed the same success to date.

The CCP model needs to be further tested as it is still unclear if it works broadly or if it only worked in one instance. There may be a greater potential for success in new space-oriented companies in the Model but aspects of the CCP, like Firm Fixed Price contracting, may need to be altered or adjusted to more effectively meet scheduling and development goals. While the model is tweaked to fix potential inefficiencies, the government will likely need to continue to act as anchor tenant to foster the long-term sustainability of the commercial market.

Ultimately, further efforts to infuse a CCP-like framework into the CLD program should be supported by the current CCP Program. Given the amount of time, energy, and resources that NASA, SpaceX, and Boeing have invested to finding the balance between commercial autonomy and Government oversight through the CCP, this historical experience would aid in avoiding some of the growing pains the CCP experienced in its early days, and would likely streamline some of the implementation challenges discussed above. Infusing the CLD Program with NASA personnel with experience working CCP would seem beneficial.

### ii. Applying A Proven Model to Commercial Space Stations

A multi-contract approach to the CLD framework allows for gradual steady growth of commercial trust in the CLD provider on behalf of both public and private sector customers. This is accomplished by drawing upon a long history of public-private space ventures. A tiered approach to the CLD framework through inception to implementation is evocative of the evolution of commercial space launch activities. Much like the CCP, the Development phase of a CLD demands a higher level of Government oversight. This ensures not only that Government customer needs are being addressed and lead to NASA successful qualification of the CLD provider's ability to provide service, but also that CLD operators can access the wealth of knowledge, technical expertise, and resources that NASA and other agencies may provide.

<sup>18</sup> Christopher J. Scolese, Charter of the Review of U.S. Human Space Flight Plans Committee, NASA (June 1, 2009), <https://www.nasa.gov/offices/hsf/about/charter.html> (last visited Oct. 17, 2024).

<sup>19</sup> National Aeronautics and Space Administration Authorization Act of 2010, Pub. L. No. 111-267 §§ 401(2)(7).

<sup>20</sup> Tariq Malik, President Obama Signs New Vision for U.S. Space Exploration Into Law, SPACE.COM (Oct. 11, 2010), <https://www.space.com/9305-president-obama-signs-vision-space-exploration-law.html> (last visited Oct. 17, 2024).

<sup>21</sup> What is Commercial Crew, NASA, <https://www.nasa.gov/humans-in-space/commercial-space/commercial-crew-program/commercial-crew-program-overview/> (last visited Oct. 17, 2024).

## IV. Recommendation: The Government should extend the FAA’s commercial liability regime to Commercial Space Stations

The CLD Working Group identified ongoing liability concerns relating to the implementation and operation of CLD as the second key impediment to the success of commercial space stations. Namely, the commercial sector lacks the ability to feasibly mitigate liability exposure both due to lack of avenues for insurance and indemnification. The CLD Working Group advocates that Congress consider using the Federal Aviation Administration’s (FAA) commercial liability regime, currently applied to space launches, as the blueprint to cover CLD.

At present, the CSLA is targeted toward launch and recovery and is not focused on on-orbit continuous operations. Given the identified need for CLDs, there is a pressing need for the expansion of the CSLA’s scope. Under the CSLA and its subsequent amendments, the FAA provides licensing for commercial space launch and reentry activities.<sup>22</sup> The CSLA defines the Department of Transportation granted regulatory supervision over commercial spaceflight, indemnifies companies against significant third-party damages, and shapes the regulatory framework for commercial human spaceflight. The CSLA specifies an insurance requirement, specifically that commercial launch operators are required to “obtain liability insurance or demonstrate financial responsibility” to cover third party injury, including property damage, physical injury, and death, as well as any damage to Government property, capped at \$500 million.<sup>23</sup> However, where a claim exceeds the required coverage amount, the Government agrees to indemnify up to “\$1,500,000,000 (plus additional amounts necessary to reflect inflation occurring after January 1, 1989)” for additional damages on a case-by-case basis, and subject to Congressional assent.<sup>24</sup>

There is currently no comparable liability regime for CLD akin to the CLSA. This places a significant business unknown and burdensome risk on the CLD developers and future operators. Without such a regime, CLD contractors and other commercial space facility companies face substantial financial exposure and insurability uncertainties.

## V. Recommendation: The Government should establish the LEO Accords as a normative mechanism for commercial space activity

Taking inspiration from the Artemis Accords which are a compilation of non-binding, multilateral agreements instituted by NASA and the US State Department in 2020, the CLD Working Group recommends the implementation of a set of LEO Accords. These LEO Accords are of particular importance given the commercial nature of the growing number and the global players entering in future earth orbiting space stations. All of these commercial stations will operate in legal contrast to the ISS, which was governed by Intergovernmental Agreement.<sup>25</sup> Thus, the LEO Accords would present a potential industry-level approach for norms setting to strive to achieve the establishment of non-binding–yet influential–principles promulgated at the Government level with ongoing Industry support and input. Such principles can act as a guide for creating an accepted set of international commercial standards.

### A. Proven Effectiveness of Norms-Setting

Perhaps the most salient evidence of the effectiveness of norms-setting is the ongoing success of the Artemis Accords. Recognizing this ongoing and growing need for commercial support, the Artemis Accords evolved as a set of non-binding “political commitments” on a set of principles that ought to govern human activity in outer space.<sup>26</sup> The Artemis program sets forth two primary objectives: returning humans to the Moon and eventually sending them to Mars. To accomplish these, the program highlights the essential role of private companies in the future of space exploration. Further, the subsequent Artemis Accords serve as a modern example of how commercial interests are being integrated into international legal frameworks. With 42 nations across six continents having signed the Accords, their widespread adoption reflects a global commitment to advancing commercial space activities.

In 2024, the Artemis Accords had several notable updates and developments. Namely, a significant list of countries joined the Artemis Accords, bringing the total to 46 additional signatories as of October 2024.<sup>27</sup> Secondly, transparency and safety were

<sup>22</sup> 51 U.S.C. 50901 - 50923.

<sup>23</sup> 51 U.S. Code § 50914.

<sup>24</sup> 51 U.S. Code § 50915 (Adjusted for inflation, approximately \$3.8B).

<sup>25</sup> Intergovernmental Agreement Among the Governments of Canada, the Federal Republic of Germany, Italy, Japan, the Russian Federation, the United Kingdom, and the United States on the International Space Station, Jan. 29, 1998.

<sup>26</sup> The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids, NASA (Oct. 13, 2020) [hereinafter Artemis Accords].

<sup>27</sup> Id.

emphasized at the International Astronautical Congress in Baku, Azerbaijan. Representatives from the signatories stressed the importance of disclosing information about mission plans, such as launch and landing dates, mission duration, and scientific activities. This effort aims to avoid interference and enhance the safety of lunar missions. Thirdly, the Artemis Accords continue to foster international collaboration, focusing on developing a sustainable and robust presence on the Moon. This includes sharing scientific data, ensuring the interoperability of systems, and providing emergency assistance, thereby creating a safe and cooperative environment for all participating nations. Lastly, regular workshops and meetings among signatories have been held to advance the principles of the Artemis Accords. These gatherings serve as platforms for discussing best practices, sharing progress, and addressing challenges related to lunar and space exploration.

The US space industry, both public and private, is at a pivotal moment where frameworks initiated domestically could influence the future of international law. By creating a regulatory and industry standards environment that supports businesses, the US not only helps its own companies advance new technologies but also makes its market more attractive to other countries seeking strategic partnerships. A Government-promulgated and commercially-supported set of LEO Accords would not only benefit both the Government and the commercial provider, but also provide clarity to the international community about the efficacy of CLD and encourage new and continued investment.

## VI. Conclusion & Summary of Recommendations

The transition from the ISS to commercially operated space stations represents a pivotal moment for space activities. To ensure the success of Commercial Space Stations, a multi-contract approach is recommended. This approach would allow for gradual government disengagement, ensuring CLDs meet both public and private needs. Government entities like NASA would act as anchor tenant in the early stages, fostering trust in the CLD providers. Moreover, extending the Federal Aviation Administration's (FAA) liability regime, which currently covers space launches, to on-orbit operations would mitigate liability risks for private space companies. Finally, establishing a set of "LEO Accords" for low-Earth orbit activities, similar to the Artemis Accords for lunar missions, could further support normative frameworks in the burgeoning commercial space sector. By fostering public-private partnerships, adjusting regulatory frameworks, and implementing new liability protections, the government can support the commercial sector's growth and help ensure the sustainability of human space activity beyond Earth.

### Summary of Recommendations:

1. **Adopt a multi-contract approach:** Commercial Space Station providers must balance public and private needs and interests to ensure efficacy and long-term sustainability.
2. **Extend the FAA's commercial liability regime:** The success of Commercial Space Stations hinges on the ability to mitigate liability exposure, which requires Government support and action to implement.
3. **Establish the LEO Accords:** As the Artemis Accords have shown, normative mechanisms provide a platform for identifying best practices and rules of the road for the future of commercial space activities.

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# From Surviving to Thriving

## Ensuring Long Term Human Viability in Space

*This paper is a product of the Reliability, Health, and Safety Working Group of the Beyond Earth Institute Leadership Council. While the paper represents a consensus of Working Group discussions, the views and recommendations do not necessarily represent those of the individual members or their respective organizations.*

By Ian Ching, Andrew Stephens, and Michael Halick (Contributing Editor)

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# Executive Summary

Safety and reliability are the cornerstones of the emerging space-based economic revolution. Reliability is the essential element of reducing the cost of space and increasing the attractiveness of profitable space ventures. These are the forces that will change the nature of space business and enhance our planet's economy. The future of commercial space settlements will be the product of human and robotic symbiosis. The increasingly capable digital assistance and the demonstrated use of semi-autonomous systems on the International Space Station (ISS) are a model for commercial ventures to follow.

This year, the Health, Safety, and Reliability Beyond Earth Institute (BE) Working Group (WG) has built on past investigations and discussions to craft this WG Report. Beyond Earth has held webinars on Human Spaceflight Safety, Artificial Gravity and authored reports covering those topics in 2022 & 2023.<sup>1</sup> From the collective discussions surrounding the topic, this WG has identified two crucial hurdles for a thriving and permanent human presence beyond Earth: artificial gravity and radiation protection. The WG explored the use of AG as a holistic approach to solving the root cause of deleterious effects of mid and long-term exposure to microgravity, and also investigated possible strategies to respond to the harmful effects of radiation, including protection, countermeasures, and operational architecture adjustments.

## I. An Overview of Space Flight Reliability, Health and Safety Regulation Outlooks

The rise of commercial spaceflight exhibits parallels similar to the transition from early aviation to widespread commercial air travel. This transition will change the character and nature of the space market and operating environment. In the initial stages of commercial air service, low customer volume and the high cost of owning and operating these businesses created high costs for adventure seekers and the first air passengers. This also kept the number of flights low. As competition was fostered, airlines expanded their customer base by offering lower ticket prices. This increase in the reliability and safety of flights was made possible by the development of new infrastructure, safety regulations, and even health standards. Similarly, as space exploration moves from a government-only endeavor to one that includes private enterprise (including space transportation, habitation, and potentially space real estate), there will be a critical need to establish comprehensively accepted industry standards and safety and health protocols to normalize the regularity of accessible commercial spaceflight.

Lessons learned from the development of commercial aviation can be leveraged for the benefit of space. For example, medical issues associated with early commercial air flights, such as fitness requirements, were paramount to early airlines. Higher altitude international flights, in-flight medical emergencies, and the close quarters concerns for spreading pathogens necessitated a roadmap for the airline industry's attention to appropriate health standards and safety protocols.<sup>2</sup>

### A. Research Options and Pathways Forward

The WG believes that as we move toward increased commercialization of the space economy, any guiding research roadmap addressing key health issues like artificial gravity (AG) and ionizing space radiation mitigation extends beyond traditional organizations and academic institutions previously involved. New perspectives and the assistance of agencies like the National Institutes of Health (NIH), the new Human Research Program Civilian (HRP-C), and emerging commercial providers are needed if such roadmap initiatives are to provide the information needed for operational, business, and design decisions.

Additionally, there is a crucial need for relevant commercial entities to evaluate NASA's Human Research Program (HRP) "Red Risks" to align with the unique challenges of commercial human spaceflight.<sup>3</sup> Such unique concerns for commercial space operators may include responses to microgravity-induced physiologic health issues such as muscle atrophy, bone density loss, and cardiovascular deconditioning, and how to handle medical emergencies such as stroke or cardiac arrest, which could be more pronounced for commercial space travelers who have not undergone the same rigorous training and fitness requirements as professional NASA astronauts and cosmonauts.

<sup>1</sup> Webinar: From Surviving in Space to Thriving In Space: Closing the Human Factors "Technology Gap," BEYOND EARTH (April 26, 2023), <https://www.youtube.com/watch?v=jLLtvz0cy8g>; Ian Ching, Achieving Safety And Reliability In Human Spaceflight: The Basic Requirements For A Human Existence Beyond Earth, Beyond Earth Working Group Report (2022), available at <https://beyondearth.org/wp-content/uploads/2023/01/Achieving-Safety-and-Reliability-Paper.pdf>; Thomas Ramirez-Pugh, Staying Safe in Space Policy Considerations and Recommendations on Reliability, Health, and Safety in Orbit and Beyond, Beyond Earth Working Group Report (2023), <https://beyondearth.org/wp-content/uploads/2023/10/Thomas-Article.pdf>.

<sup>2</sup> Danielle Silverman and Mark Gendreau, Medical issues associated with commercial flights, 2067, 2067 LANCET (2009).

<sup>3</sup> Zarana Patel et. al., Red risks for a journey to the red planet: The highest priority human health risks for a mission to Mars, NPJ MICROGRAVITY (2020).

## II. Artificial Gravity

### A. Artificial Gravity's Background

Humans, like all other creatures on Earth, evolved under the pull of gravity. From as early as the late 19th century, Russian rocket scientist Konstantin Tsiolkovsky proposed a spinning space station design to produce a gravity-like centripetal force acceleration. Since then, many concepts have emerged and been depicted in science fiction to produce an effect called artificial gravity.

AG results from the centrifugal forces generated by a rotating body. It is an approach for the design of spaceships that creates a gravity-like force through rotation of the spacecraft. By spinning the spacecraft, the crew feels the centrifugal force simulating gravity. It is believed that this gravity-like effect can reduce the detrimental effects of microgravity on the human body without the need for extensive exercise periods. Such a system is not without its engineering challenges. The minimal size for a spacecraft to rotate at a comfortable speed may not produce a profitable facility at current launch costs. There are also challenges related to vibrations, vehicle stability, and crew safety in an EVA (extra-vehicular activity) contingency.<sup>4</sup>

The factors that will determine the market success of an AG vessel are acceptable gravity levels, gravity gradients, and coriolis forces. The "gravity level" experienced by occupants is determined by the radius rotation and angular velocity of the system. A vessel with larger radii and slower rotation rates may provide more stability and uniform force, while a smaller radii will require faster rotations—which may cause initial discomfort and instability.

Gravity gradient refers to the difference in levels of gravity experienced by humans due to varying distances from the center of rotation. Assuming a crewmember stands with their feet on the inner "wheel" and head pointed to the center of rotation, their sensation of "gravity" will be different at the head vs. the feet. A study by Working Group member Angie Bukley (and others), notes that assuming a crew member's height was 2 meters, in a 100m rotating space station, the gravity gradient experienced would be a trivial 2%, whereas a 10m radius station would produce a 20-100% difference (dependent on the individual's posture).<sup>5</sup>

The Coriolis Force is the second force experienced in a rotating space system. The Coriolis Force is a: "... direct result of any linear movement within the rotating reference frame... (2.3)" that is not parallel to the direction of the angular velocity vector. In essence, an individual traveling "up" or "down" within the rotating wheel will feel a Coriolis force pushing from the sides, such that an object tossed "straight up" or a liquid poured into a container would land to the sides.



Pouring a liquid in a spinning space station  
Credit: Ramsy 1971

### i. NASA, Microgravity, and Artificial Gravity

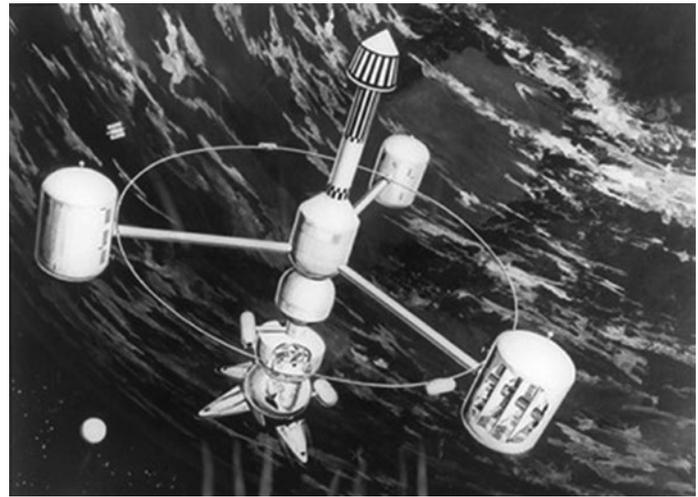
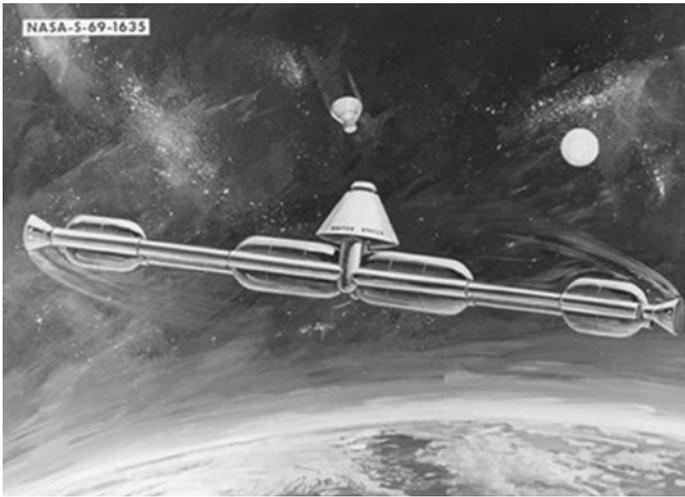
Over 60 years of spaceflight missions have produced a vast storehouse of data on the impacts of microgravity on human physiology. NASA investigations of AG approaches were initiated after astronauts returned from microgravity environments with weakened muscles because they had not been using them. For example, on Sept. 14, 1966, the Gemini 11 spacecraft was tethered to an Agena target vehicle. Command pilot Charles "Pete" Conrad and pilot Dick Gordon maneuvered their craft to keep the tether taut and, by firing their side thrusters slowly, rotated the combined spacecraft.<sup>6</sup> This produced a centrifugal artificial gravity force of about 0.00015 g. The astronauts onboard did not "feel" this low level of AG; however, they did report seeing objects "falling" during the rotation.

Later, in 1969, NASA actively investigated space station designs that would provide spin-induced artificial gravity. The AG space station designs were to be assembled on-orbit from spent Apollo program stages. A Statement Of Work solicited proposals to study a 12-crewmember Space Station to be launched in 1975. This station was to eventually serve as a building block, growing to a 100-crewmember Earth-orbital Space Base.

<sup>4</sup> Artificial Gravity, NASA, <https://www.nasa.gov/podcasts/houston-we-have-a-podcast/artificial-gravity/>, last visited Oct. 22, 2024.

<sup>5</sup> Angie Bukley et. al., Physics of Artificial Gravity, NASA, available at <https://ntrs.nasa.gov/api/citations/20070001008/downloads/20070001008.pdf>

<sup>6</sup> Sept. 14, 1966 - Gemini XI Artificial Gravity Experiment, NASA, <https://www.nasa.gov/image-article/sept-14-1966-gemini-xi-artificial-gravity-experiment>, last visited Oct. 22, 2024.



Artist concepts of two 1969 AG space stations proposed.

Like many NASA projects, growing budget demands for top-priority initiatives such as the space shuttle led to decisions that ended lower-priority and potentially costly efforts like the AG station. Since then, only a few human AG simulation experiments on Earth and in space have been undertaken. Most experiments have been conducted on the ground, in centrifuges and slow-rotation rooms. Space experiments included rotating chairs in Skylab experiment M131, which evaluated responses to rotational accelerations.<sup>7</sup> In 1998, NeuroLab flew on STS 90 and included an off-axis rotator neurological experiment.<sup>8</sup> Several small centrifuge space experiments on plants, animals, and insects have also been undertaken onboard the ISS.<sup>9</sup>

In addition, many companies, agency-led research (NASA's Human Research Program), and international organizations have provided a continuing stream of papers, ideas, and proposals for space AG facilities. This demonstrates that the idea for space facilities with AG capabilities has been in development for some time.<sup>10</sup>

## B. Adaptive Responses to Microgravity

The body's adaptive systems can be understood through a framework of short-range, middle-range, and long-range responses. The most immediate response is space motion sickness. Another short-range physiological response is body fluid shifts that occur within days to weeks. Middle-range responses, taking weeks to months, involve more complex hormonal changes, including the onset of Spaceflight-Associated Neuro-Ocular Syndrome (SANS) (a condition in which the shape of the eye changes thought to be due to fluid shifts in microgravity, causing vision impairment) and alterations in how

the brain and inner ear (vestibular system) respond to the lack of gravity.

It is important to note that there are currently no effective measures to counteract the reshaping of the eye in microgravity, which remains a major concern for long-duration missions. Long-range responses to exposure, which we are just beginning to understand, unfold over months to years, and may even involve genetic changes. Further, no experimental data exists on the impacts of periodic transitions between AG and microgravity or partial levels of lower AG. Understanding these long-term impacts of space travel and habitation environments will be essential for sustaining a permanent human presence beyond Earth.

### i. Delayed Change Onset Beyond Physiology due to Microgravity

There is a delayed onset of deleterious changes to the human body due to exposure to the microgravity space environment beyond the direct physiological impacts. These can be understood through the investigation of three categorized systems: short-range (neural)<sup>11</sup>, middle-range (neural and hormonal), and long-range (genetic).

These system responses are analogous to the body's response to altitude sickness. For example, in the short range, the nervous system reacts quickly to decreased oxygen levels by increasing breathing and heart rate. In the middle range, hormonal changes occur over a few days to weeks, leading to cellular adaptations to improve oxygen uptake. In the long-range, over months, the body produces new proteins and genetic structures to better cope with the reduced oxygen levels.

<sup>7</sup> J.S. Evans et. al., Skylab experiment M131: Rotating little chair, NTRS (1977).

<sup>8</sup> 25 Years Ago: The STS-90 NeuroLab Mission, NASA's Contribution to the Decade of the Brain, NASA, <https://www.nasa.gov/humans-in-space/25-years-ago-the-sts-90-neurolab-mission-nasas-contribution-to-the-decade-of-the-brain>, last visited Oct. 22, 2024.

<sup>9</sup> Donna Holpuch, Spinning in Space: Centrifuge on the International Space Station, HELMER SCI. (Feb. 28, 2018), <https://blog.helmerinc.com/spinning-in-space-centrifuge-on-iss>.

<sup>10</sup> The Beyond Earth Institute maintains a source reference artificial gravity data base.

<sup>11</sup> While some neural responses are short-term, others can take months to develop. For example, changes to brain structure have been documented in astronauts after months long stays aboard the ISS. Similar changes in brain structure were not seen after approximately 2 week long shuttle flights.

## ii. NASA Twins Study<sup>12</sup>

The NASA Twins Study provides critical insights into the biological and physiological effects of long-duration spaceflight, highlighting the various changes in gene expression, immune function, cardiovascular health, and cognitive performance that astronauts experience during extended missions in microgravity. Notably, the study identified both transient and persistent alterations, such as telomere lengthening, gene expression changes, and SANS.

These findings reinforce the potential role of artificial gravity as a countermeasure to combat the deleterious effects of microgravity on the human body. By simulating gravitational forces, artificial gravity could help mitigate fluid shifts, cardiovascular deconditioning, and musculoskeletal degradation, thus addressing several of the key issues observed in the Twins Study.

Similarly, the study's documentation of increased genomic instability and persistent DNA damage due to space radiation highlights the critical need for advanced radiation shielding technologies. These technologies could protect astronauts from the harmful effects of cosmic rays and solar particle events (SPEs), which the study suggests may contribute to long-term health risks, including cancer and cardiovascular disease.

## iii. Artificial Gravity as a Holistic Countermeasure

It is now well documented that the risks associated with prolonged microgravity include muscle atrophy, bone density loss, compromise to the immune system, and cardiovascular deconditioning, among other negative psychological impacts. As the human body in microgravity is not subject to normal gravitational forces over extended periods, the loss of bone density results in osteoporosis-like conditions, increasing the risk of fractures. Future space travelers on long-term missions lasting months to years for a trip to Mars will also experience cardiovascular declines, making a return to a planetary gravity environment challenging.

### C. Current State of Artificial Gravity

Experts in AG research state that “today’s approach to countering the deleterious effects of microgravity is piece-meal, whereas artificial gravity provides an integrated countermeasure affecting multiple physiologic systems.”<sup>13</sup> They also proffer that “artificial gravity has the potential to fully mitigate the physiological deconditioning that results from long-term exposure to weightlessness.”<sup>14</sup>

Yet a need for AG does not eliminate the need for ways to mitigate or reduce the impact of a crew member’s time in microgravity. This is because a key and unique attraction of space is the high value of the microgravity environment for high market-value industrial manufacturing, which creates promising new research that has important ramifications for people on Earth – as with Varda Space Industries’ HIV/AIDS medication ritonavir.<sup>15</sup> Thus, even with AG available on-board or at a co-orbiting facility, people will likely need to spend varying amounts of time in microgravity.

Further, due to microgravity’s deleterious impacts on the human body, NASA has devised treatments and regimens to counter these health issues, such as daily strength and cardio exercises for crew aboard the ISS (treadmill, recumbent bike, resistive exercise). Nevertheless, the NASA Johnson Space Center continues to develop exercise systems and technology to sustain crew health on extended missions. Among these new developments is the Miniature Exercise Device (MED), which is a compact motorized exercise device providing both resistive and aerobic exercise capability.<sup>16</sup> Other new technologies include the “Hopper,” “Force Shoes,” and “Portable Knee Dynamometer.” NASA hopes that such advancements will mitigate the long-term effects of microgravity and allow long-duration deep space missions.<sup>17</sup>

Yet, in the emerging marketplace of commercial space facilities, current ISS microgravity countermeasures may prove cumbersome and even problematic due to their mass and volume requirements, not to mention their demands on the crew’s productivity time. Current ISS approaches to countering the negative health effects of a microgravity environment include at least two hours per day of NASA mandated physical exercises. This does not include the required pre- and post-exercise requirements on crew time. Although this exercise activity helps reduce the problem of muscle loss to some extent, it does not address all health issues associated with a microgravity environment. It also creates a demand on valuable work and personal crew time. For this reason, long-term human habitation in space depends on finding a more encompassing/holistic response to the effects of microgravity. This may be a key reason why the emergence of private space stations is sparking renewed interest in harnessing centrifugal force to produce artificial gravity.<sup>18</sup>

<sup>12</sup> Francine Garrett-Bakelman et. al., The NASA Twins Study: A multidimensional analysis of a year-long human spaceflight, SCIENCE (2019).

<sup>13</sup> “ARTIFICIAL GRAVITY (GILLES CLEMENT & ANGIE BUKLEY EDS., 2007).

<sup>14</sup> Id.

<sup>15</sup> Stefanie Waldek, “Them space drugs cooked real good: Varda Space just made an HIV medicine in Earth orbit, SPACE (Mar. 29, 2024), <https://www.space.com/var-da-space-microgravity-pharmaceutical-production-success>, last visited Oct. 22, 2024.

<sup>16</sup> See Crew Exercise, NASA, available at <https://ntrs.nasa.gov/api/citations/20170011663/downloads/20170011663.pdf>.

<sup>17</sup> Id.

<sup>18</sup> Leonard David, Gravity of the Situation: Time for the “G-whiz” Factor?, (May 24, 2023), LEONARD DAVID <https://www.leonarddavid.com/gravity-of-the-situation-time-for-the-g-whiz-factor>, last accessed Oct. 22, 2024.

## i. International Roadmap for Artificial Gravity Research<sup>19</sup>

A 2017 paper by Gilles Clément summarized the research activities needed to implement artificial gravity onboard spacecraft.<sup>20</sup> However, while this roadmap laid out a strong foundation for AG research, progress since 2017 has been limited, and the vast majority of goals outlined in the roadmap have yet to be fully realized. Yet it stands as a potentially useful reference for future initiatives in AG research.

This International Artificial Gravity Roadmap outlines both ground-based and space-based research projects involving human subjects, animal models, and cell models, addressing the challenges of limited human subject availability and centrifuge access in space. It is translational across species and systems, integrating biological, physiological, behavioral, and human factors, and involves multidisciplinary collaboration among experts to incorporate AG technologies into spacecraft design. The roadmap aims to standardize study protocols and measurements to facilitate cross-study comparisons, identify research barriers, and ensure AG implementation within budget and on time for crewed space missions, with annual reviews by space agencies to adjust plans as needed.

## ii. AG BedRest Study (AGBRESA) Conclusion Assessment

The Artificial Gravity Bed Rest Study (AGBRESA)<sup>21</sup> concluded that for the two protocols studied—each consisting of 30 minutes of daily AG with 0.3Gz at the level of the inner ear—AG is not an effective countermeasure for long-term spaceflight. For this and other reasons, the NASA HRP has suspended further AG studies. However, many professionals in the field of Health and Human Spaceflight disagree with the conclusion. They argue that these studies were simulations, not based on actual tests in real orbital facilities, and tested only two protocols with exposure to AG for only 30 minutes per day. Still, others have argued that while AG may not be necessary for specific short-term missions, it remains crucial for sustaining human populations in orbit or on long-term missions beyond Earth.

WG discussions on AGBRESA noted the flaws in this study. Judging from the pictures, published by various studies, shows that the subject's heads were propped up on a pillow. As such, the head itself was not exposed to the continuous -6° head-down tilt. While the WG noted that corrections have been made in recent studies, we remain skeptical of the conclusions drawn from bed rest studies.

## D. Summary of Findings & Recommendations on Artificial Gravity

### Findings:

- The deleterious physiologic impacts to human systems of microgravity remain a major barrier to the health, safety, and reliable expansion of humankind into space.
- Large radius centripetal acceleration-induced AG capability in future space habitats has the potential to provide a holistic counter to a wide array of human health and physiologic deleterious effects caused by extended exposure to microgravity.
- Though providing valuable indicators, Earth-based simulators alone can not accurately produce the actual environments and conditions of an orbiting artificial gravity facility.
- To provide definitive evidence, research on the benefits, impacts, issues, and detriments of centripetal acceleration-induced AG is needed under actual space environmental conditions.
- A sufficiently large artificial gravity research facility has never been placed in orbit to conduct the necessary research on humans to gather the data and evidence to qualify or verify this capability.

### Recommendations:

- NASA co-hosted with the Beyond Earth Institute an exchange forum to discuss potential ways forward on AG research and experimentation that consider the current/projected exploration, market needs and interests.
- NASA should release a notice to industry of their anticipated future need for an orbital facility that can provide them services to conduct qualifying research and investigations on the value of large radius centripetal acceleration-induced AG.
- The administration, through a Space Council policy directive, should make the establishment of safe and reliable habitats for the healthy and extended stay of private citizens/humans in space a priority of the United States.
- To ensure more cohesive research & develop a set of AG investigations and recommended studies to guide the development of research facilities (Appendix A). These should include, but are not limited to:
  - Determination of the gravity threshold (gravity level and exposure times) required to reverse or prevent the detrimental effects of microgravity (e.g., an AG prescription.)

<sup>19</sup> Gilles Clément, International Roadmap for Artificial Gravity Research, NPJ MICROGRAVITY (2017).

<sup>20</sup> Id.

<sup>21</sup> Gilles Clément et al., Assessing the effects of artificial gravity in an analog of long-duration spaceflight: The protocol and implementation of the AGBRESA bed rest study, FRONTIERS IN PHYSIOLOGY (2022).

- The evaluation of centrifugation effects on different physiological functions as it is essential for informing potential design and operational responses.
- Assessment of physiologic, systematic, and psychologic effects on variable gravitation periods and acceleration exposure levels.
- Identify trends and the best countermeasures for the general public compared to highly trained astronauts.

### III. Radiation & Hazards to Human Space Flight

Radiation is one of the biggest hazards facing human health and safety in space. Earth's mass, magnetic field, and atmosphere provide significant protection from harmful radiation emanating from the Sun and other cosmic sources. The Earth's magnetic field generates a protective bubble around our planet called the magnetosphere.

The magnetosphere deflects many of the solar particles and much of the energy constantly streaming toward Earth. However, some solar wind breaks through and becomes trapped in the magnetosphere, producing plasma or charged gas. These trapped, energized particles travel along magnetic lines, which reduce altitude at higher latitudes, ultimately entering the atmosphere through funnel-shaped openings at the poles and resulting in spectacularly colorful auroras. The atmosphere also protects us as radiation particles collide with the air and lose their energy before reaching the ground. But, radiation exposure increases above the atmosphere in Low Earth Orbit (LEO), especially at orbits with higher inclinations.

Beyond the Earth's magnetic field, there is little protection against radiation with damaging energies. According to a recent NASA report, radiation exposure on a Mars mission with current technologies and systems would surpass the lifetime maximum acceptable dosage for humans.<sup>22</sup> The NASA Hybrid Electronic Radiation Assessor (HERA) experiment that flew on Artemis I also gathered deeper space radiation data indicating an average dose equivalent rate of 0.96–1.24 mSv/day.<sup>23</sup> This amount varied by the shielding location and vessel orientation. The total exposure for the Artemis I mission was between 26.7mSv and 35.4mSv. NASA standards for career dose limits are 600mSv. This is based on a 3% lifetime increased risk of radiation induced cancer (for a 35-year-old female astronaut). Considering that a Mars mission would be an 18 month round trip, plus time on Mars, those on such a trip can expect 518mSv - 670 mSv from flight time alone. Any Mars mission or long term stay on the

Moon will have to meet this NASA threshold or accept a higher lifetime risk of radiation induced illnesses. This mSv threshold is also an indicator for other radiation health dangers, including degenerative diseases. For long-term missions and habitats beyond LEO, space radiation protection is an essential health element for future Moon, Mars and spaceflight inhabitants.<sup>24</sup>

#### A. What is Space Ionizing Radiation?

Ionizing radiation consists of particles with enough energy to ionize atoms in the biological tissue it passes through. When these atoms are part of a DNA molecule, it can damage the biological tissue and possibly cause a mutation in the DNA.

There are five types of ionizing radiation—alpha particles, beta particles, positrons, gamma rays, and X-rays. The Spaceflight Radiation Health Program at Johnson Space Center outlines the three main sources of space radiation: trapped radiation, Galactic Cosmic Radiation (GCR), and energetic Solar Particle Events (SPE). GCR mainly consists of very high energy gamma and X-Rays but also contains nuclei of heavier atoms such as iron. Each source has varying degrees and types of particle types, energy levels, and intensity.

Trapped radiation, particularly in the South Atlantic Anomaly (SAA), contributes the most to radiation exposure for space stations in LEO including the ISS. The remainder of the damaging radiation is primarily due to GCR. GCR consists of highly penetrating particles and has sufficient penetrating energy that even a small amount of these particles can reach us here on Earth. SPEs, while short-lived, can be extremely intense.

#### B. Identified Radiation Countermeasure and Mitigation

##### i. Passive radiation shielding in LEO and beyond.

Passive shielding uses multiple layers of various materials. Depending on the habitat module type, the layer materials and shielding approaches will vary. In the near term, for space habitats residing in LEO and orbiting within the magnetosphere, it will be in the best interest of designers to optimize passive shielding to get the best radiation protection for their space modules and stations.

Even though LEO stations are often within the Earth's magnetosphere, intense solar events can release immense bursts of radiation. When this occurs, the astronauts aboard the ISS are notified to seek shelter in highly shielded compartments. More robust solar storm shelters will be needed if astronauts are beyond the geo-magnetosphere, such as on the Moon and in cis-lunar or Mars transit space.<sup>25</sup>

<sup>22</sup> S. Robin Elgart, "Space Radiation Environments and Research Directions," (conference presentation, American Society for Gravitational and Space Research International Conference, 2022, Houston TX)

<sup>23</sup> Space radiation measurements during the Artemis I lunar mission | Nature

<sup>24</sup> Why Space Radiation Matters, NASA (Apr. 23, 2017), <https://www.nasa.gov/analog/nsrl/why-space-radiation-matters>; Spaceflight Radiation Health Program at JSC, NASA, <https://srag.jsc.nasa.gov/Publications/TM104782/techmemo.htm>, last visited Oct. 22, 2024.

<sup>25</sup> Id.

It has been suggested that multiple layers of low atomic number material shielding could help.<sup>26</sup> Lightweight materials like lithium hydride (a high density) Boron, polyethylene, and even water have good radiation protection properties because they contain a high amount of hydrogen.<sup>27</sup> However, large quantities of these materials are costly, difficult to incorporate in sufficient quantities, and expensive to launch because of the required mass. If there were a way to synthesize simple plastics like polyethylene in orbit in large quantities, then such shielding would make sense. Biosynthesis of methane from human waste in orbit may provide a possible means to manufacture such polyethylene shielding in orbit.<sup>28</sup>

One solution to radiation exposure is to use the mass of celestial bodies to shield future exploration efforts. This would include living inside a hollowed asteroid, under lunar regolith, or deep within speculated lunar lava tubes. Although the engineering and logistics of such approaches are complex, such radiation shielding countermeasures are a longer-term radiation mitigation solution.

## ii. Space Radiation Early Warning

The key to an ability to respond to solar radiation events is foreknowledge and quick warning of these impending radiation events. Current warning capabilities reside in the Space Weather Prediction Center at the National Oceanic and Atmospheric Administration. The primary sensor for detecting Coronal Mass Ejections (CME) predictions is the Solar Coronagraph, which measures the outflow of solar wind close to the sun. The Solar Ultraviolet Imager (SUVI) is responsible for measuring the magnetic fields within the CME, which are created by extreme ultraviolet light. These systems can provide advance notice of CMEs.<sup>29</sup>

Several satellites at the Earth-Sun Lagrange Point 1 location also provide measurements of the density, velocity, and magnetic field intensity of solar wind. As the Sun follows an 11-year activity cycle, these measurements provide information on solar wind activities, often giving Earth operations substantial warning. Long-term predictions can also be made by observing the sunspots' activities.

The current NOAA system provides a dashboard on solar and space weather predictions and advisories.<sup>30</sup> It requires the user to subscribe to their Solar Radiation Alerts. These alerts are issued when observed values at the NOAA GOES satellites exceed event thresholds. Alerts are issued for each NOAA Solar Radiation Storm Scale level, driven by the >10MeV proton flux. A single Alert is issued for the >100MeV proton flux.<sup>31</sup> NOAA's Space Weather Prediction Center (SWPC) provides a wide range of alerts, warnings, watches, and forecasts that can be received through email within moments of being issued. This current space weather prediction capability is limited and thus at risk of disruption.

## iii. Active Shielding Progress/Research

Active space radiation shielding uses electromagnetically generated fields to deflect charged particles. It has the potential to be a solution that can be used along with passive shielding to make deep-space travel safer. Active shielding is becoming more feasible thanks to advancements in superconducting materials and innovative designs. NASA's CREW HaT project, using a Halbach array of superconducting coils, creates efficient magnetic shielding. Though effective, it faces energy and mass challenges, leading to ongoing work to improve superconducting coils and cooling systems.<sup>32</sup>

Meanwhile, NASA's Active Shield Project, led by Dr. Daniel Fry and Dr. Stojan Madzunkov, focuses on electrostatic radiation shielding using their Active Shielding Particle Pusher (ASPP) simulation tool. Tests at Brookhaven National Laboratory have validated the accuracy of their models, and larger demonstrators are being considered. Despite this progress, critics highlight their complexity, cooling demands, and secondary radiation risks in solenoid designs.

It is important to note that the majority of magnetic shielding's mass comes from its cooling systems, and thus, the development of room-temperature superconductors would significantly reduce both the shielding's mass and complexity. Continued research into these areas is important if we move beyond LEO for extended stays and eventual settlement.

<sup>26</sup> Mark J. Miner, PhD, PE, Gravitics Inc.

<sup>27</sup> M.P. Loomis & J.O. Arnold, Thermal, radiation and impact protective shields (trips) for robotic and human space exploration missions, NASA (2007), available at 20070014633.pdf (nasa.gov)

<sup>28</sup> Kristina Rojdev & William Atwell, Hydrogen-and Methane-Loaded Shielding Materials for Mitigation of Galactic Cosmic Rays and Solar Particle Events, GRAVITATIONAL & SPACE R. (2015).

<sup>29</sup> Aurora Tutorial, NOAA, <https://www.swpc.noaa.gov/content/aurora-tutorial>, last visited Oct. 22, 2024.

<sup>30</sup> Products and Data, NOAA, <https://www.swpc.noaa.gov/products-and-data>, last visited Oct. 22, 2024.

<sup>31</sup> Subscription Services, NOAA, <https://www.swpc.noaa.gov/content/subscription-services>, last visited Oct. 22, 2024.

<sup>32</sup> Jacek Krywko, Shields up: New ideas might make active shielding viable, ARS TECHNICA (Mar. 11, 2024), <https://arstechnica.com/science/2024/03/shields-up-new-ideas-might-make-active-shielding-viable/>, last accessed Oct. 14, 2024.

#### iv. Bioremediation

Bioremediation includes medical and other physiologic means to repair or prevent damage by ionizing radiation. This is a new and emerging science that includes things like DNA damage repair stimulation, understanding changes of gene expression based on radiation and/or microgravity, and repair of biological macromolecules via tunable picosecond-pulsed transmission electrons, among others.<sup>33</sup>

### C. Summary of Findings & Recommendations on Radiation Protection

#### Findings:

- Methods for mitigating space radiation toward levels closer to radiation levels around the maximum yearly dose rates<sup>95</sup> are of critical importance for our future habitation in space.
- The radiation dose rate for long-term crewed activities beyond Low Earth Orbit will likely reach or exceed NASA standards for lifetime career exposure.
- Humanity's prospects of building long-term space habitations will require improvements in passive shielding approaches, techniques for bioremediation of damage, or active shielding technologies.
- It is currently difficult to conclusively assess the combined effects of prolonged radiation exposure and microgravity on the human body.

#### Recommendations:

- Space station/orbital habitat builders should consider placing inhabited space facilities in orbital inclinations closer to the Equator to avoid the South Atlantic [radiation] anomaly and to gain maximum protection from the thickest point of the Earth's magnetic field.
- To provide clear differentiation between the impacts of microgravity and ionizing radiation, clinical comparative radiation research should be conducted on large radius centripetal acceleration artificial gravity laboratory habitats.
- Commercial space habitat designers and builders should qualify and make radiation protection levels available to habitat customers for a given module.

- In the development of any industrial habitable space facility, radiation standards or regulatory discussions:
- As part of pre-mission counseling and informed consent, space passengers, astronauts, and workers should be informed of anticipated radiation exposures.
- As is the practice on Earth, in situations where personnel are potentially exposed to radiation, the monitoring and recording of radiation exposure during time in orbit for space passengers, astronauts, and workers should be recorded as part of passenger health records.
- Information should be made available in customer qualification information on the performance and need for a temporary radiation shelter on any given space station. This information should, at minimum, be based on considerations of its location, altitude, and inherent module radiation protection capabilities.
- Establish a more effective and accessible early solar radiation warning system to warn space inhabitants. This will allow space inhabitants to take any necessary sheltering or other mitigation actions. Whether this is an extension of the current U.S. government's system, a commercially provided data service, or an international monitoring and reporting system remains to be determined.
- Make access to the NASA archives on space radiation research, analysis, and findings available to qualified U.S. researchers and industry users. This will ensure frank and serious conversations on the viability, actions necessary, and technology needed for long-term human spacefaring are based on the best available data.

<sup>33</sup> Hyeokmin Choe et. al., Mitigation of radiation damage in biological macromolecules via tunable picosecond pulsed transmission electron microscopy, BIORX (2020); S.J. Kim & J.Y. Cho, Reproductive Challenges in Space: Understanding Microgravity Effects on Mammalian Reproduction, PROC. NAT'L ACAD. SCI., (2024); E.A. Blabber, Mechanical Unloading of Bone in Microgravity Reduces Mesenchymal and Hematopoietic Stem Cell-Mediated Tissue Regeneration, NPJ MICROGRAVITY (2017); C. Wang & J. Hu, Cardiovascular Health in Space Exploration: Challenges and Opportunities, FRONT CARDIOVASCULAR MED. (2024); W. Hui et al., Space Radiation Impacts on Human Neural Stem Cells: An Emerging Challenge for Deep Space Missions, NPJ MICROGRAVITY (2023); T.A. Johnson et. al., Spaceflight-Induced Muscle Atrophy and Its Potential Countermeasures, STEM CELL TRANSL. MED. (2020). <sup>95</sup> 10 CFR Part 20 ("Standards for Protection Against Radiation," establishes the dose limits for radiation workers. Although the limits vary, depending on the affected part of the body, the annual total effective dose equivalent (TEDE) for the whole body is 5,000 mrem (5 rem)...).

## IV. Unresolved Questions

### A. The Question of Oversight

This WG agreed that there has been much Government debate on Mission Authorization and how to manage Commercial Human Spaceflight from a standards and regulatory standpoint. The “Learning Period” from the original Commercial Space Launch Competitiveness Act (SPACE Act)<sup>34</sup> has been extended through January 2025. Yet, there appears to be much disagreement between the White House and Congress regarding the future of oversight authority, jurisdiction, and responsibility.

The question of which agencies should take the lead for human commercial space activities remains open. As the Department of Commerce (DOC) regulates novel space activities, many have proposed that the DOC serve as a single point for industry, acting as a guiding agent for companies in navigating the regulatory and licensing process. The book, “Red Moon Rising” by Greg Autry makes such a proposal. The U.S. Department of State also outlined a similar process in Circular 175.<sup>35</sup> The Beyond Earth Institute believes that this topic is vital for the future of Health, Safety, and Reliability. We will continue to monitor this topic for future assessment.

### B. Privacy in Health Data vs. Safety Research for Space Travellers

A major concern in health data collection for commercial space travel revolves around HIPAA compliance and data privacy. Programs like TRISH EXPAND and SOMA offer models balancing research with privacy, but concerns arise about whether commercial companies will also share health data, especially adverse outcomes during spaceflight. Furthermore, long-term funding for programs like TRISH is not guaranteed. There is an important dilemma regarding the appropriateness of sharing health data for research and “public safety.” Issues include determining the disclosure level and whether health data should be accessible to only healthcare providers, researchers, or industry professionals. The National Science Foundation (NSF) and DARPA have also expressed concerns about these data collection challenges, signaling the need for uniform guidelines. A major concern is the HIPAA aspect of patient data, which is necessary for research. A solution that balances privacy and data anonymity with future study needs may include waivers to use collected health data.

Concern has also been raised about whether commercial companies will even release their data on their passengers. In addition to legal HIPAA concerns, such data may be considered “Intellectual Property.” Our working group also pointed out that some companies may not share health data, which could cause embarrassment for fears of negative press or market impacts. The Working Group has tabled this question and looks forward to addressing and providing recommendations on this issue in the future.

<sup>34</sup> U.S. Space Law, SPACE FOUNDATION, [https://www.spacefoundation.org/space\\_brief/us-space-law/](https://www.spacefoundation.org/space_brief/us-space-law/), last visited Aug. 10, 2024.

<sup>35</sup> Treaty Procedures, US DEPT. OF STATE (Nov. 26, 2018), <https://www.state.gov/treaty-procedures/>, last visited Oct. 22, 2024.

## V. Conclusion

There are still many challenges to reliably ensuring the health and safety of inhabitants living and working in space for extended periods and perhaps the better part of their lives. Two of the most important challenges are finding a balance of countermeasures to the negative impacts of long-term exposure to microgravity and the danger of exposure to harsh space radiation.

This WG believes that what has come to be called artificial gravity holds the promise of a holistic countermeasure to the deleterious effects of microgravity. Although ground-based simulations provide indicative insights, the lack of a large-scale orbital spinning AG experimentation laboratory means critical answers remain unknown.

The WG has also found that a combination of orbit selection, habitat module-tailored passive shielding, and solar storm shelters (in combination with a reliable warning system) should allow initial LEO space stations an acceptable level of radiation protection. However, once beyond the protection offered by the Earth's magnetosphere, deep space radiation protection challenges become far more serious. Radiation protection and countermeasures in cislunar and deep space will require more aggressive attention. This includes the development of active radiation protection for space transports and orbiting habitats and exploiting features like lunar lava tubes and surface materials for shielding.

### Summary of Recommendations:

1. In coordination with academic, space organizations (such as BE), and commercial enterprises, NASA needs to identify the unknowns, develop experiment recommendations, and engineer the technologies that define the requirements for a near-term commercial low Earth orbit artificial gravity laboratory.
2. Methods for mitigating and countering damage caused by space radiation to long-term space inhabitants should strive to achieve levels closer to radiation levels around currently accepted industrial maximum yearly dose rates.<sup>36</sup>
3. Beyond Earth and its members should actively monitor and participate in the debates and development of health data collection methods that assure privacy while serving marketplace needs.
4. Beyond Earth and its members should actively monitor, participate in the debates, and present recommendations regarding regulatory oversight of space developments, facilities, and operations.

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<sup>36</sup> 10 CFR Part 20 ("Standards for Protection Against Radiation," establishes the dose limits for radiation workers. Although the limits vary, depending on the affected part of the body, the annual total effective dose equivalent (TEDE) for the whole body is 5,000 mrem (5 rem)...).

# APPENDIX A

**TABLE 1**

## Initial Recommendations for Ambulatory Artificial Gravity Space Laboratory Studies

Study	Comment
Map daily gravity use and develop minimum daily gravity exposures and levels requirements.	This includes the recommended exposure times within each gravitational acceleration. These should include general requirements but may also be on a case-by-case basis.
Determination of the effectiveness of intermittent centrifugation on test subject fitness and physiology	<p>This could include optimization of radius, rotation rate and gravity levels.</p> <p>Impacts on head orientation and distances from centrifugal axis.</p> <p>Subject movement, behavioral adjustments relative to position and angular acceleration.</p> <p>Visual environmental surroundings as they relate to motion sickness, work/task compatibility and recreation activities.</p> <p>Evaluation of circadian effects and influences between times of day including gravitational accelerations during sleep.</p> <p>Impact of artificial gravity on nutritional requirements.</p>
Compare the effectiveness of artificial gravity to microgravity Lower Body Negative Pressure and exercise.	
Conduct representative life support investigations similar to above on food crop plants and protein sources as well as environmental health, hygienic and micro biologics and viruses.	This could be accomplished on co-orbital free flying biosatellites.



# Exploring Frameworks for the Effective Development of the Cislunar Economy

## Findings & Recommendations

*This paper is a product of the Advanced Financing and Economics Working Group (WG) of the Beyond Earth Institute Leadership Council. While the paper represents a consensus of Working Group discussions, the views and recommendations do not necessarily represent those of the individual members or their respective organizations.*

By Joshua Osborne, Lauren Andrade, and Steve Hoeser

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# Executive Summary

The Beyond Earth Institute's Advanced Economics and Financing Working Group convened to address the challenges facing the establishment of economically viable and sustainable Cislunar business models. The discussions highlighted the importance of a robust legal framework, encompassing both international treaties and domestic laws, to support commercial activities in Cislunar space. The absence of an effective governing structure poses significant risks, including territorial conflicts and unsustainable resource exploitation, particularly in light of competitive pressures from state-sponsored initiatives like China's lunar ambitions. In response, the group examined the Lunar Development Cooperative (LDC) as a viable governance framework, emphasizing its potential to promote equitable resource distribution, foster private sector participation, and mitigate conflicts.

## I. Background

The Beyond Earth Institute's Advanced Economics and Financing Working Group (WG) met for its third annual cycle to address the challenges the space sector faces in attempting to establish economically viable and financially sustainable Cislunar business models. It was noted by the WG that one of the greatest foundational challenges to establishing these models is the lack of viable governance structure. The Working Group stressed that the creation and implementation of a framework of governance for Cislunar investment and business development is needed for the viability and sustainability of both business and non-business lunar efforts.

### A. Scope

The WG focused its discussions on identifying an effective means of developing the Cislunar economy. In pursuit of this goal, the WG focused on three key activities which have been identified as necessary to develop such an economy: (1) affordable, available—as well as safe and reliable—transportation; (2) actionable Lunar data; and (3) In situ resource utilization (ISRU).<sup>1</sup>

#### i. Transportation

To develop an autonomous Cislunar economy, you must first be able to reliably and consistently reach, operate within, and return from Cislunar space. Thus, a threshold issue for the development of the Cislunar economy will be developing low cost and predictable means of transporting both manned and unmanned spacecraft to and from the lunar surface or lunar orbit. Currently, many different types of actors are attempting to solve this

issue. These actors, or “end customers” can be institutional players (i.e. space agencies) or they can be private actors (i.e. space companies).<sup>2</sup> Regardless of which actor is discussed, all face the common challenges of lunar transportation. Some actors have addressed this issue through the development of their own private vehicles, while others outsource the needed transportation to private launch providers or institutional players.

While historically the public sector has predominantly provided transportation for space activities, this status quo is changing as governments dedicate greater resources to the development and sustainment of private space ecosystems.<sup>3</sup> For example, in the United States (US), companies such as Blue Origin and SpaceX have become major players, not only in the development of the Low Earth Orbit (LEO) Economy, but even in projects to the Moon through NASA's Artemis program.<sup>4</sup> However, this investment is not limited to the United States, in fact, it can be seen in nearly every major government involved in space activities (China, Japan, Europe, India, Russia, etc.).<sup>5</sup> Through investing in private space economies, governments can ensure that they are receiving the best technologies, at competitive pricing, while also fostering the growth of private space ecosystems.<sup>6</sup>

Ultimately, large-scale involvement of public actors in transportation to lunar-space will likely be balanced in the coming years with increased involvement from the private sector.<sup>7</sup> Moreover, this involvement is unlikely to be limited to only space-companies, as non-space companies will be incentivized to become more involved in the Cislunar economy.<sup>8</sup> Because of this the global lunar transportation market is expected to grow, increasing from \$9B USD between 2020-2025, to \$42B USD between 2036-2040.<sup>9</sup>

<sup>1</sup> See generally Lunar Market Assessment: Market Trends and Challenges in the Development of a Lunar Economy, PWC (Sept. 2021), <https://www.pwc.com/au/industry/space-industry/lunar-market-assessment-2021.pdf> (last visited Aug. 10, 2024).

<sup>2</sup> Id. at 4.

<sup>3</sup> Id. at 5.

<sup>4</sup> The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids, NASA (Oct. 13, 2020) [hereinafter Artemis Accords].

<sup>5</sup> PWC, supra note 1, at 6.

<sup>6</sup> Id.

<sup>7</sup> Id. at 10.

<sup>8</sup> Id.

<sup>9</sup> Id. at 12.

## ii. Lunar Data

Access to the Moon enables valuable data about the lunar environment to be gathered. Such data includes surface/subsurface environmental conditions and profiles, presence and amounts of water, prospecting data including geological composition of the regolith, mineral composition below the regolith, location and structure of lava tubes, etc.<sup>10</sup> This data is critical to determine the unique value of resources and to reap the benefits of a Cislunar economy.

Our ability and success in making decisions, selecting methods for successful expansion into this new ecosphere rests on an understanding of the layout, nature and resources of the lunar frontier. To properly locate and design facilities, habitats and equipment a clear picture of their operating environment is needed. Moreover, autonomous surface operations on the moon will require access to water. Thus, an understanding of the geological composition of the moon at varying depths enables an operator to find and develop strategies to mine valuable resources. This means there is a need and market for such data. This market can be categorized into three distinct subsets, each with its own applications and customer bases: (1) environment data; (2) telemetry data; and (3) entertainment data.<sup>11</sup>

Lunar environment data includes information about the lunar surface, its environments, particularly of import, and geologic data that includes lunar resource identification.<sup>12</sup> This data set is expected to be the largest of lunar data markets, with supply and demand coming from both public and private actors. Due to the expected importance of lunar resources to the development and value of the Cislunar economy, lunar environment data was, unsurprisingly, expected to consume the largest share of the lunar data market.<sup>13</sup>

Alternatively, telemetry data is derived from lunar instruments and vehicles, coming in two forms: (1) exploratory data; and (2) data with terrestrial applications ("spin-off data").<sup>14</sup> Both public and private actors can use this data in the development of space exploration technologies, while private actors can uniquely benefit from Spin-Off Data to develop terrestrial technologies for non-space related uses.<sup>15</sup> Again, as access to the Moon increases, the demand for such data will likely increase as well. Thus, the market for such data<sup>16</sup> and a supporting data communication network is also expected to grow.

Finally, entertainment data consists of images, videos, and recordings.<sup>17</sup> Currently, such data has largely been collected by public actors; however, in the near future, such data could be collected by private actors in the form of movies, TV shows, documentaries, etc. Nonetheless, this will likely remain the smallest percentage of the lunar data market, accounting for an estimated 0.2% of the overall lunar data market.<sup>18</sup>

Ultimately, the lunar data market is expected to grow substantially in the future. Such a market provides valuable business spin-offs and additional areas of revenue for organizations that plan to participate in the development of an autonomous lunar economy. As such, these markets will be essential to the development of the Cislunar economy.

## iii. Lunar In Situ Resource Utilization (ISRU)

Having a sustained manned or unmanned presence on the moon opens the path for local resource extraction and utilization. Moreover, such resource extraction and utilization is likely to be integral to the establishment of not only a Cislunar economy, but for future space missions beyond lunar space (i.e. Mars and deep space). Due to the expectation that ISRU will become vital to future space-based economies, many actors have begun developing technologies to engage in ISRU.<sup>19</sup>

Although the ISRU market remains largely uncertain, it is nonetheless expected to become a primary driver of Cislunar development. For this reason ISRU is expected to be essential to provide the base for numerous economic systems within the Cislunar economy. It is anticipated that the ISRU market will drive the development of life-support systems, as well as the development of propellant markets. Both of the aforementioned markets are expected to become fully autonomous and are integral not only to a sustained presence in Cislunar space, but also to future missions beyond Cislunar space. Ultimately, ISRU is expected to become the backbone of the Cislunar economy, with a gross profit expectation of over \$63B USD.<sup>20</sup>

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<sup>10</sup> Id. at 19.

<sup>11</sup> Id.

<sup>12</sup> Id. at 20, 23.

<sup>13</sup> Id. at 22.

<sup>14</sup> Id. at 20. Examples of exploratory data include monitoring propellant pressure or thruster temperature; while examples of Spin-Off Data include the application of automation technologies.

<sup>15</sup> Id.

<sup>16</sup> Id.

<sup>17</sup> Id. Such data comes in the form of recordings of astronauts on the lunar surface, the keystone example being "one small step for man."

<sup>18</sup> Id.

<sup>19</sup> Id.

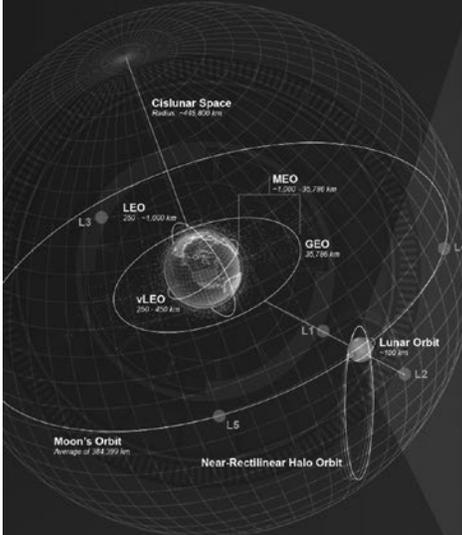
<sup>20</sup> Id.

# Emerging Industrial Base for Lunar Activities



Cislunar space is a volume of space beyond GEO mainly under the gravitational influence of the Earth. It includes Earth-Moon LLPs, trajectories within this region, and the Moon itself.

Companies with announced lunar business plans. Listing is not comprehensive.



**Services Companies**  
Example activities: transport of people and goods; provision of utilities; gathering and dissemination of data products; maintenance and servicing of hardware; medical and health services; security; entertainment and recreation; among many others

**Resources Companies**  
Example activities: extraction and processing of raw materials from the Moon, collection of solar energy, agriculture

**Manufacturing Companies**  
Example activities: transforming raw materials, construction, assembly of hardware

**Cargo and Human Transportation**

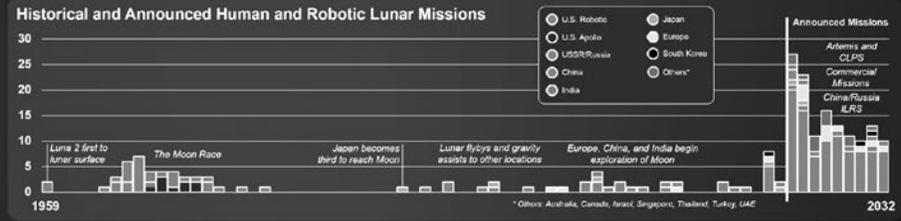
- Launch:** SpaceX, Blue Origin, ULA, Northrop Grumman, Firefly
- Landers+:** SpaceX, Blue Origin, III, Redwire, Quantum Space, InSpace, Firefly, Draper
- Lunar Rovers:** AVL, InSpace, Astrobotic, Anxion, Lockheed Martin, Sierra Space, Toyota, Sierra Space
- Spacesuits:** Axiom Space, Collins Aerospace, Voyager Space

**Utilities**

- Quantum Space, zeno, omnispace, Blue Origin, Airbus, Crescent, Blue Origin, Impulse Space Propulsion, Nokia, Advanced Space, Voyager Space, CosmoNexus, Aquarian Space, Proteinnovations

**Maintenance and Servicing**

- Redwire, OrbitFab, Quantum Space, Sierra Space, The Rocketeer, GIMA, Orbital, Morpheus Space, Firefly, Psionic



CLPS - Commercial Lunar Payload Services; GEO - Geosynchronous Orbit; ILRS - International Lunar Research Station; ISAM - In-space Servicing, Assembly, and Manufacturing; LEO - Low Earth Orbit; LLP - Lagrangian Libration Points; MEO - Medium Earth Orbit; vLEO - Very Low Earth Orbit

Image Source: Bryce Tech, <https://brycetechnology.com/reports/report-documents/emerging-industrial-base-lunar-2024/>

## B. Legal Framework

The legal framework within which a functioning Cislunar economy will develop features a mixture of international and domestic laws. From an international perspective, the Outer Space Treaty provides the overarching framework for international governance of space activities.<sup>21</sup> On a domestic level, laws which support the commercialization of space are integral to the analysis. For instance, the 2015 Commercial Space Launch Competitiveness Act, also commonly referred to as the Spurring Private Aerospace Competitiveness and Entrepreneurship Act (SPACE Act)<sup>22</sup>, and the Artemis Accords will both provide a domestic legal framework for the development of such an economy.<sup>23</sup>

## i. International Law

The 1967 Outer Space Treaty outlines the international legal framework for State activities in outer space. It is the most widely accepted of the space treaties with 115 States Party. Supported by the subsequent space law treaties,<sup>24</sup> the Outer Space Treaty provides the current foundation for what a State can and cannot do in outer space. It forbids States from laying claim to celestial bodies<sup>25</sup> while simultaneously recognizing the right of ownership of structures placed on said celestial bodies.<sup>26</sup> Notably, the Outer Space Treaty additionally calls for international cooperation,<sup>27</sup> and requires that States allow access to other States as well as take steps to prevent harmful interference, act with due regard in conducting space activities, and inform the international community of its space activities.<sup>28</sup> The Outer

<sup>21</sup> Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, Jan. 27, 1967, 18 U.S.T. 2410, 610 U.N.T.S. 205 (entered into force Oct. 10, 1967) [hereinafter Outer Space Treaty].

<sup>22</sup> US Commercial Space Launch Competitiveness Act, Pub. L. No. 114-90 [hereinafter SPACE Act].

<sup>23</sup> The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids, NASA (Oct. 13, 2020) [hereinafter Artemis Accords].

<sup>24</sup> See Agreement on the Rescue of Astronauts, the Return of Astronauts and the Return of Object Launched into Outer Space, Apr. 22, 1968, 19 U.S.T. 7570, 672 U.N.T.S. 119 (entered into force on Dec. 3, 1968); Convention on The International Liability for Damage Caused by Space Objects, Mar. 29, 1972, 24 U.S.T. 2389, 961 U.N.T.S. 187 (entered into force with respect to the United States on Oct. 9, 1973); Registration of Objects Launched into Outer Space, Jan. 14, 1975, 28 U.S.T. 695, 1023 U.N.T.S. 15 (entered into force on Sep. 15, 1976); Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, Dec. 18, 1979, 1363 U.N.T.S. 3 (entered into force on July 11, 1984).

<sup>25</sup> Outer Space Treaty, art. II.

<sup>26</sup> Id. at art. XIII.

<sup>27</sup> Id. at art. III.

<sup>28</sup> Id. at arts. IX, XI, XII.

Space Treaty also places responsibility on States to “authorize” and engage in “continuing supervision” of the activities of its nationals.<sup>29</sup> Further, regarding celestial bodies, including the Moon, the treaty mandates that they be used “exclusively for peaceful purposes.”<sup>30</sup>

In effect, the Outer Space Treaty lays the general framework for the later Rescue Agreement and Liability Convention, which further establish a right to rescue for astronauts in emergency situations and establish liability for the damage inflicted by space objects respectively.<sup>31</sup> The Registration Convention, “requires launching states to register their launched objects... [and] also calls upon states possessing space monitoring and tracking facilities to provide assistance in the identification of space objects which cause damage.”<sup>32</sup> Lastly, the Moon Agreement, which seeks to protect the moon and its resources, “requires states to establish an international regime to govern the exploitation of the moon’s natural resources.”<sup>33</sup> Notably, the Moon Agreement has only 17 States Party.

## ii. US Domestic Law

From a domestic perspective, the two major legal frameworks guiding the development of the Cislunar economy are: (1) the SPACE Act; and (2) the Artemis Accords. Each affects the development of the Cislunar economy in different, yet similar ways. The SPACE Act focuses on privatization of the space industry, whereas the Artemis Accords focus on supporting and harmonizing a return to the Moon by the United States and its allies.

The SPACE Act allows US industries to engage in the commercial exploration and exploitation of space resources and to encourage competitiveness in the launching of commercial spacecraft.<sup>34</sup> The law is an extension of the 1984 Commercial Space Launch Act (“CSLA”).<sup>35</sup> The CSLA granted the Department of Transportation (“DOT”) regulatory oversight over commercial spaceflight, and supports the commercial sector through regulatory and liability protections. The CSLA also provided for an extension for informed consent for commercial human spaceflight.

The 2015 SPACE Act expands upon the CSLA in several key ways. First, it postpones significant regulatory oversight of private spaceflight companies until 2024. Second, the SPACE Act extends the period during which the government indemnifies commercial spaceflight companies for third-party damages. Third, and perhaps most importantly, the SPACE Act grants private companies the right to own resources collected in space. Thus, the SPACE Act provides both protection from regulatory oversight and liability for private actors within the space economy broadly, while encouraging further commercialization of the space economies by granting ownership rights to resources collected from extraterrestrial sources. Notably, the US is not the only State with a robust legal framework for commercial space activities. Luxembourg, for example, has established itself as a leader in the regulation of private space activities, particularly with its focus on promoting commercial space exploration and resource utilization.<sup>36</sup> The Law of 20 July 2017 (Space Resources Law) provides a legal framework for private companies to engage in space resource activities, and recognizes the right of private operators to explore and use space resources, such as minerals from asteroids, under certain conditions.<sup>37</sup>

Following the SPACE Act, the development of the Artemis Accords in 2020 further outlined a multilateral vision for the future of lunar development. The Artemis Accords emerged as a set of non-binding multilateral agreements authored by the United States, which reiterate existing principles of international law and introduce new principles to be followed in outer space. The Artemis Accords tackle a variety of different issues including: (1) the registration of space objects;<sup>38</sup> (2) the release of scientific data;<sup>39</sup> (3) preserving outer space heritage;<sup>40</sup> (4) deconfliction of outer space;<sup>41</sup> and (5) orbital debris.<sup>42</sup> Particularly important for the development of a Cislunar economy, however, the Artemis Accords also addresses space resource extraction.<sup>43</sup> Specifically, Section 10 states that all resource extraction will be conducted in a manner that complies with the OST and that such extraction does not constitute appropriation under the OST.<sup>44</sup>

<sup>29</sup> Id. at art. VI.

<sup>30</sup> Id. at art. IV.

<sup>31</sup> Stephen Gorove, Sources and Principles of Space Law, in SPACE LAW: DEVELOPMENT AND SCOPE 45, 47 (Nandasiri Jasentuliyana ed., 1992).

<sup>32</sup> Id. at 48.

<sup>33</sup> Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, Dec. 18, 1979, 1363 U.N.T.S. 3 [hereinafter Moon Agreement] (entered into force on July 11, 1984).

<sup>34</sup> SPACE Act, *supra* note 23.

<sup>35</sup> 51 U.S.C. 50901 - 50923.

<sup>36</sup> See Arendt & Medernach, In review: space law, regulation and policy in Luxembourg, LEXOLOGY (Jan. 5, 2023), <https://www.lexology.com/library/detail.aspx?g=9a8432df-381b-4c70-be21-48a0fdb37c2> (last visited Oct. 17, 2024).

<sup>37</sup> Lux. Law of July 20, 2017, on the Exploration and Use of Space Resources.

<sup>38</sup> Artemis Accords at Section 7.

<sup>39</sup> Id. at Section 8.

<sup>40</sup> Id. at Section 9.

<sup>41</sup> Id. at Section 11.

<sup>42</sup> Id. at Section 12.

<sup>43</sup> Id. at Section 10.

<sup>44</sup> Id. at Section 10(2).

Thus, the Artemis Accords provides a normative framework not just for domestic actors within the United States to engage in extraterrestrial resource extraction, but for non-domestic signatories to the Accords.

Ultimately, the Artemis Accords and the SPACE Act jointly reinforce the conclusion that space resources can be mined and that such mining is legal under both domestic and international law. As discussed previously, the extraction of resources is expected to be a foundational aspect of the development of the Cislunar economy.<sup>45</sup> Thus, through both the SPACE Act and the Artemis Accords, a legal framework is established to develop a strong, and autonomous, Cislunar economy on a domestic level. However, while the Accords provide a shared set of principles among a group of willing collaborators, they do not provide an actual governing entity to coordinate development, enable the funding and sharing of infrastructure, and settle disputes.

### C. Challenges caused by the Lack of a Governing Framework for Cislunar Activities

The absence of a more robust governing framework for Cislunar development promotes major concerns for both space sustainability and security. The Moon, like all other areas of space, does not contain equal resources. Certain areas are more resource rich, while others are resource poor. As a result, resource rich areas are at risk of land-grabs. These land-grabs could, in turn, result in legal conflict between competing claims for said land up to open conflicts. To avoid the threat of land grabs and resulting conflict, a strong governing framework is necessary.

#### i. The First Mover Effect

The first mover effect is an advantage gained by an entity that is first to market.<sup>46</sup> Specifically, “A first mover in a particular market seeks to gain a benefit relative to competitors in a number of areas, such as having additional time to define the market, perfecting a product or service, building economies of scale, and erecting barriers to entry (for example, through the acquisition of scarce resources or the establishment of product stickiness).”<sup>47</sup>

The first mover effect presents long term challenges for the development of a sustainable Cislunar economy. Specifically, first movers have little incentive to preserve lunar land, or the resources contained therein, given that the lunar landscape is defined as a global commons, and thus, cannot be owned.<sup>48</sup>

The exponential effect imparted upon the first mover effect by a land’s classification as a global commons is known as the tragedy of global commons.<sup>49</sup> In 1968, Garrett Hardin suggested that the “tragedy” of any global commons is that it is inevitably over- or improperly used to the detriment of all humankind.<sup>50</sup> As a result, this may motivate the first lunar movers to get everything they can as quickly as they can, possibly to the detriment of future users. Moreover, such overutilization of the land may lead to conflict with potential competitors. Thus, abuse of the global commons is not merely an access issue, but also necessarily a space security issue as well.<sup>51</sup>

Ultimately, with an ineffective governing framework in place, the first mover effect could result in attempts in the monopolization of lunar resources by the first actor to reach them. In turn, this monopolization will lead to valuable resource depletion and thus severely damage the long-term sustainability of the lunar economy. Moreover, the need for the first mover to defend their claim to territories could lead to direct conflict over lunar territory. To prevent such issues, a strong governing framework is necessary to control territorial claims over lunar territory, regulate usage of lunar territory, and prevent conflict over lunar territory.

#### ii. The China Example

China understands the importance of being the first to develop the Cislunar economy. In June 2024, Chinese scientists proposed a three-phase plan for developing lunar infrastructure.<sup>52</sup> First, China aims to “establish satellites in elliptical frozen orbits.”<sup>53</sup> Second, it plans to place additional satellites and spacecraft at Earth-Moon LaGrange points and place a spacecraft in geostationary Cislunar orbit creating a “Cislunar space station.”<sup>54</sup> Third, it plans to add satellites into existing and new distant retrograde orbits to form near-Moon space and extended space constellations.<sup>55</sup> Through this aggressive plan, China demonstrates a concerted effort to not only take part in the Cislunar economy, but to shape it.

China’s comprehensive plan is significant because—should it succeed—it puts China strategically ahead of the game in developing the Cislunar economy, effectively making them the first mover. As stated by professor of space policy, Bledwyn Bowen, “[i]f China can sustain a long-term program for lunar exploration, it will give Beijing leverage in any future discussions and negotiations on the governance of the moon and in particular on the management and deconfliction of lunar operations.”<sup>56</sup>

<sup>45</sup> See discussion supra Section II(A)(iii) “ISRU.”

<sup>46</sup> First Mover Advantage, CFI, <https://corporatefinanceinstitute.com/resources/management/first-mover-advantage>, last visited Aug. 10, 2024.

<sup>47</sup> See Ken Isaacson et al., An Examination of the First Mover Advantage for a CBDC, FEDERAL RESERVE (Nov. 25, 2022), <https://www.federalreserve.gov/econres/notes/feds-notes/an-examination-of-first-mover-advantage-for-a-cbdc-20221125.html>, last visited Oct. 17, 2024.

<sup>48</sup> Outer Space Treaty, art. II.

<sup>49</sup> See generally Garrett Hardin, The Tragedy of the Commons, 162 SCIENCE 1243 (1968).

<sup>50</sup> Id.

<sup>51</sup> Id.

<sup>52</sup> See generally Mengfei Yang et al., Architecture and Development Envision of Cislunar Space Infrastructure (2024).

<sup>53</sup> Andrew Jones, Chinese Scientists Outline Major Cislunar Space Infrastructure Project, SPACENEWS (July 30, 2024), <https://spacenews.com/chinese-scientists-outline-major-cislunar-space-infrastructure-project/>, last visited Oct. 17, 2017.

<sup>54</sup> Id.

<sup>55</sup> Id.

<sup>56</sup> Id.

It is clear that the strategic significance of being the first to the Moon is not lost on China, nor is the strategic importance of Cislunar space in future deep space exploits.<sup>57</sup> To that end, China understands that controlling Cislunar space places them in a powerful position to influence future norm setting for international law relating to space, and will “promote international cooperation and development serving China’s ‘One Belt, One Road’ (BRI) initiative and providing services for the global development and utilization of Cislunar space...[and] leading to the formulation of relevant international rules and standards, while supporting the development and utilization of China’s Cislunar space and goals of global cooperation development.”<sup>58</sup>

Ultimately, China’s demonstrated rapid space activities and aggressive plans demonstrate the clear and present need for a counter responding and concrete free market based model for western Cislunar development. At present, such models are insufficient to compete with the Chinese plan. For a Western model to effectively compete with the Chinese model, western actors should lean into the systems that have made the west strong. Specifically, a Western model should focus on wielding international support to enable private sector participation and, thus, ensure free market access to the Cislunar economy.

## II. The Lunar Development Cooperative (LDC)

The Lunar Development Cooperative (LDC) concept was brought before the Working Group as a viable framework for Cislunar governance. The LDC would be a multi-national public-private partnership providing infrastructure, services, and a rules-based order for space users that opt-in to membership. The LDC’s contracts with its members would include binding legal requirements that fill in some of the governance gaps in space. As a for-profit social enterprise, the LDC’s governance and revenue structure would cause its decisions to be driven by the broader interests of the evolving lunar economy, society, and environment.<sup>59</sup>

The LDC provides solutions to many of the governance and development challenges discussed above, including the first-mover effect and China’s ambitions. Moreover, by ensuring the efficient creation of lunar infrastructure and responsible use of lunar sites,, the LDC reduces potential conflicts and protects lunar resources. This structure is also scalable and transferable to other outer space domains (e.g. Mars, asteroids, and orbital facilities). Most importantly, the LDC promotes private-sector and international participation, thereby enabling an open Cislunar market economy, while helping support the development of legal institutions that promote the sustainable and peaceful use of space.

<sup>57</sup> Mengfei Yang et al., *supra* note 53.

<sup>58</sup> Belt and Road Initiative, EUROPEAN BANK FOR RECONSTRUCTION AND DEVELOPMENT, <https://www.ebrd.com/what-we-do/belt-and-road/overview.htm>, last visited Oct. 17, 2024 (“China’s Belt and Road Initiative (BRI) (一带一路) is a strategy initiated by the People’s Republic of China that seeks to connect Asia with Africa and Europe via land and maritime networks with the aim of improving regional integration, increasing trade and stimulating economic growth.”)

<sup>59</sup> See Michael Castle-Miller et. al., *The Lunar Development Cooperative: A new idea for enabling lunar settlement*, SPACE REVIEW (Apr. 27, 2020), <https://www.thespacereview.com/article/3928/1>, last visited Oct. 17, 2024.

<sup>60</sup> *The Lunar Development Cooperative: A Framework for the Sustainable Development of Space*

### A. Findings

The Advanced Financing and Economics WG believes that the LDC is a viable potential solution to address many of the governance challenges and issues inherent in the creation and sustainment of future cislunar and the future space econosphere. The details and additional explanation of the LDC concept can be reviewed in detail in the associated Beyond Earth paper, *A Framework for the Sustainable Development of Cislunar Space and Beyond: The Lunar Development Cooperative*, authored by Advanced Financing and Economics WG member, Michael Castle-Miller.<sup>60</sup>

### B. Recommendation: The Advanced Financing and Economics WG recommends and supports further research and development of the LDC model as a viable governance structure for Cislunar activities and development of the space econosphere.

#### Specifically the WG recommends that:

1. The Beyond Earth Institute, in coordination with the newly established LDC Institute, should undertake extended investigation, debate, research and input to refine the LDC model. The LDC Institute will lead efforts conducting studies on the technical, economic, and legal feasibility of the LDC. The Beyond Earth Institute will focus on investigations of the international and policy implications. This WG believes that this additional research is necessary to draw on additional expertise to enhance and refine this concept and produce peer-reviewed studies of the LDC framework.
2. The Working Group further encourages that the Beyond Earth Institute along with its members and the LDC Institute engage with grant-making institutions and special donors to support these investigation initiatives to explore and refine the LDC as a viable solution for ensuring the sustainable development of a free and open space marketplace.

### III. Conclusion

The Advanced Economics and Financing WG recognizes the LDC as a promising framework for promoting a stable, sustainable, and inclusive Cislunar economy. Given the increasing competition in space, particularly from state-sponsored initiatives, the LDC presents a vital opportunity to foster collaboration among private and public stakeholders. By facilitating equitable and efficient access to space and encouraging participation from diverse actors, the LDC can mitigate the risks associated with the first-mover effect and potential territorial disputes.

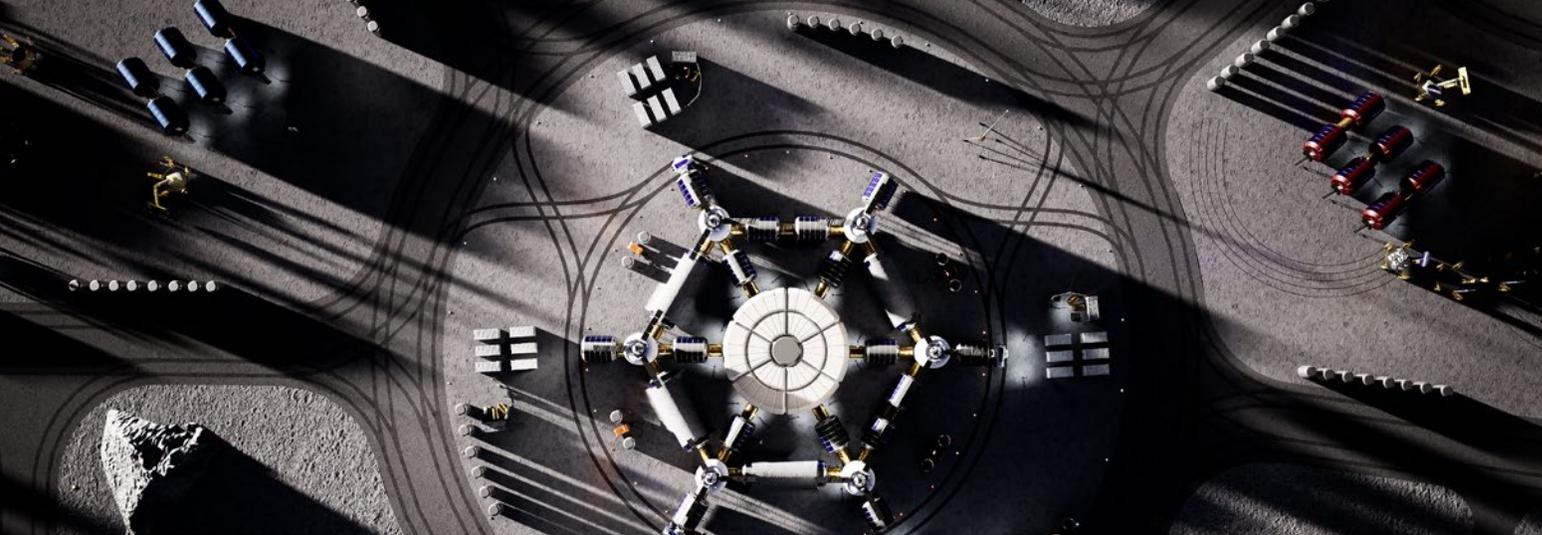
Ultimately, the LDC framework has the potential to transform Cislunar economic development into a collaborative and sustainable endeavor, positioning it as a cornerstone of future space governance. The WG looks forward to further exploration of this model and its implications for creating a robust, free market in space. Thus, the WG strongly recommends further investigation into the LDC model, emphasizing the need for rigorous research to refine its structure and implementation. Engaging with grant-making institutions for financial support will be crucial in advancing these efforts. The success of the LDC could set a precedent for governance in outer space, ensuring that the exploration and utilization of lunar resources benefit all of humanity while maintaining environmental integrity.

#### Summary of Recommendations:

1. The Advancing Economics and Financing Working Group has identified the LDC framework as a viable and strong candidate framework for space and Cislunar economic development, deserving aggressive investigation and refinement.
2. The WG further recommends, encourages and supports soliciting grant-making institutions for financial support of these initiatives thus ensuring rigorous exploration and refinement of the LDC as a viable solution for ensuring the sustainable development of a free and open space marketplace.
3. The WG will support further investigations of the LDC framework as a viable governance structure for Cislunar activities.

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# Enabling Large-Scale Habitation in Space

*This paper is a product of the Large-Scale Habitats Working Group of the Beyond Earth Institute Leadership Council. While the paper represents a consensus of Working Group discussions, the views and recommendations do not necessarily represent those of the individual members or their respective organizations.*

By Daniel Inocente, Jennifer Ludolph, and Steve Hoeser

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# Executive Summary

The Beyond Earth Institute believes that the establishment of humanity in space hinges on our ability to create large and thriving communities beyond Earth. Therefore, the Large Scale Habitats Working Group (WG) was established this year as a forum for members to solicit, identify and discuss the ways, means and methods necessary to enable significant scaling up of existing habitat occupancy limitations. The purpose of this WG is to conduct an overarching look at those aspects affecting, enabling and stimulating great attention on large scale habitat development.

This year's WG decided to focus on investigating the system engineering and technological capabilities that will be needed for sustainable surface habitats on the Moon, Mars, in orbiting facilities and other celestial bodies in our solar system. As part of this review, attention was given to those socio-economic factors which are vital stimulants to space settlement. An intended result was to identify key considerations to better enable the development and evolution to large scale habitats.

This WG report is written based on the work contained in the paper titled Human Habitation Systems for Large-Scale Surface Habitats by Large-Scale Habitats WG members Daniel Inocente and Jennifer Ludolph.<sup>1</sup>

## I. Background

When people envision space settlements, whether in movies or popular culture, they often imagine futuristic towns on alien planets, vast space stations, or cities carved into asteroids. However, these depictions rarely explore the intricate process of how such extraordinary feats of human engineering might actually come to be.

Large-scale habitation capabilities and future settlements are defined as those accommodating 20 or more individuals, moving beyond the size of small research outposts. Once the population reaches or exceeds 20, we envision a diverse mix of professional astronauts, commercial occupants, and civilian visitors. The logistical challenges of transporting, housing, and supplying this larger group, combined with the associated costs, signify the transition to large-scale habitation.

### A. Space Frontiers

This WG investigation was established to provide an overarching look across the spectrum of prerequisites for establishing large space habitats. The report represents the efforts of this WG in the context of a historically proven sequence in opening new frontiers for human settlement.<sup>2</sup> This sequence has three distinct phases each with distinct objectives. The first phase is exploration followed by an expansion phase culminating in permanent establishments of human activity.

Habitats in the exploration phase are for the most part self-contained. Like our early orbital space stations, they house few people for limited stays. They rely heavily on resupply missions from Earth and their primary purpose is research and investigation to collect data on the new frontier location to understand how to better live in this new environment and reduce risks.

Armed with information on the exploratory region, new larger habitats can be put in place in the expansion phase. These facilities will house a limited number (at most 10-20) of specialized and highly trained individuals. Like the International Space Station, these larger habitats will likely consist primarily of modules produced and shipped from Earth. By necessity, this allows for quality control and equipment assurances to verify these structures meet the harsh demands of the space environment. To better support this expansion, support infrastructure and logistic service capabilities are required to meet the growing demands of large habitations in a more cost effective manner.

Eventually, larger habitats will result in a more permanent human presence, ushering in the establishment phase. These larger habitats will become more specialized and diverse, including industrial, agricultural, laboratories and recreational facilities along with a host of service businesses. The degree of habitability will vary from short human visits to human tended and continuously inhabited structures. So too will the number of permanent human occupants ranging from a few tens to a hundred or more personnel. This phase requires supporting infrastructure, transportation and logistic networks capable of meeting the demands of the growing social and economic needs of the various space business, farming and resort parks. Depending on the motivating socio-economic factors and available local in-situ resources of the new location, local fabrication may begin to supplement earth built and shipped habitat modules.

<sup>1</sup> Daniel Inocente & Jennifer Ludolph, Human Habitation Systems for Large-Scale Surface Habitats, BEYOND EARTH INSTITUTE (2024).

<sup>2</sup> Steve Hooser, Getting back to the historic sequence of opening our space frontiers, SPACE REVIEW (Feb. 6, 2017), <https://www.thespacereview.com/article/3083/1>, last visited Oct. 17, 2024.

Within each of these phases, consideration of the factors that both allow and promote a successful transition to each successive habitation phase provides insights into their overall habitat selections, production and capability needs. These needed capabilities include:<sup>3</sup>

- Safe, reliable, and affordable transportation
- Dependable, affordable and available energy
- Information in the form of data and the ability to readily communicate locally and with other distant locations, safely navigate and a universal timing system.
- Industrialization that allows the creation of needed products and services that act as the basis for commerce.

Several of these foundational capabilities are key to establishing infrastructure necessary to support a growing number of larger scale habitats. Moreover, these infrastructure service capabilities must support the local, regional, and long-haul needs of surface habitats and surrounding business interests as well as orbiting space parks and transport systems. More in depth insight into these topics can be found in our associate Beyond Earth WG Reports. Many other groups and organizations are conducting extensive research into space security, so except for selected policy implications, investigations into this topic are noted but left to future efforts. A concept for cooperative governance can be found in the 2024 BE Advanced Economics & Financing WG report and supporting concept paper.<sup>4</sup>

## B. Focus and Scope

Realization of the establishment phase hinges on our ability to create large and thriving settlements. To support this will require our expansion requires gaining insights and perspectives into the enabling aspects foundational to our civilization's extension into space described above. Further, this year's WG investigated the needs of sustainable surface habitats on the Moon, Mars, orbiting facilities, and other celestial bodies in our solar system. This included reviews of the National Aeronautics and Space Administration's (NASA) current Moon to Mars Architecture, the Artemis Program, the impacts of habitat modularity, operations & control, and identified technology gaps. Also identified were topics and considerations which, though not covered this year, bear further investigation in the future.

## II. The Evolving Need for Infrastructure

Building and operating space development infrastructure requires industrial mastery of how to operate with acceptable safety and economy. This can only be accomplished with cooperation between participants to create common interfaces and accepted methods of governance. Of equal importance is a means to secure ongoing financing to manage and secure and operate capabilities.

Without the development of this industrial mastery, frontier opening stagnates in the exploration phase, state sponsored research sites or the rugged individual settler outpost phase. It does not progress to expansive economic growth characterized by resource extraction, local industrialization, services settlements, and interconnected economic and social development.<sup>5</sup> Toward this end, the Advanced Economics and Financing WG has identified and provided a detailed paper on an approach for financing the creation and operations of needed shared infrastructure services.<sup>6</sup>

### A. Space Transportation is a Key Enabler

It has been said about the impact of safe, reliable, and affordable transportation systems that "If you can't get there (where you want to go), you can't get there (achieve your goals at the desired end of trip location)." This will be true as humanity attempts to open and continue opening settlements ever deeper into the solar system.

To open space to humanity, humans will need to first establish socio-economic beachhead settlements at locations and regions that can be accessed with such transportation networks. The first is the nearest place in space that is now opening in low-earth-orbit. The transport system emerging that is driving this are new reusable low-cost predictable bulk cargo and passenger launchers. Leveraging the established LEO launchers the emplacement of an affordable, safe and reliable cislunar space transportation is critical to enable larger scale surface. Current chemical rocket capabilities will likely be sufficient to support the establishment of this cislunar transportation network. The propellant needs of these transports should also provide a market demand for lunar produced propellants.

<sup>3</sup> Steve Hoeser, Technology shocks are felt around the world, SPACE REVIEW (Oct. 16, 2017), <https://www.thespacereview.com/article/3083/1>, last visited Oct. 17, 2024.

<sup>4</sup> See Joshua Osborne et. al., Exploring Frameworks for the Effective Development of the Cislunar Economy: Findings & Recommendations, Beyond Earth Institute Working Group Report (2024).

<sup>5</sup> Mike Snead, quoted in Hoeser, supra note 1.

<sup>6</sup> Michael Castle-Miller, A Framework for the Sustainable Development of Cislunar Space and Beyond: The Lunar Development Cooperative, BEYOND EARTH INSTITUTE (2024).

Moving from the Moon toward Mars and beyond however, will require new faster more economic space transports to make large scale settlement practical. This will require development of more efficient thermal nuclear rockets<sup>7</sup> and an ultimate technologic objective of even greater capabilities and cost-efficiencies of fusion-driven rockets<sup>8</sup> being an ultimate goal for even faster deep space transport. Although for material and large bulk cargo may be emerge that exploiting slower but highly predictably scheduled and efficient ion-propulsion (already in use)<sup>9</sup> or small thrust fusion driven<sup>10</sup> Mars cyclers<sup>11</sup> becomes key to an overall effective deep space transport network.

### III. NASA's Space Settlement Plan

NASA's Moon to Mars Architecture<sup>12</sup> sets their comprehensive strategy for extending human presence beyond Earth by leveraging the Moon as a testbed for developing capabilities needed for Mars exploration. This framework integrates scientific, technological, and policy objectives to establish sustainable operations on the Moon through the Artemis Base Camp and related infrastructure. The architecture emphasizes an incremental approach, where lunar missions serve as a proving ground for testing and refining systems such as in-situ resource utilization (ISRU), life support, and power generation, which are critical for supporting long-duration Mars exploration missions.<sup>13</sup>

The NASA Moon to Mars Architecture White Paper paper also identifies critical technology gaps and evaluates technology readiness levels (TRLs) to inform the progressive development of capabilities that support Mars exploration.<sup>14</sup> Furthermore, it emphasizes the importance of fostering international collaboration and public-private partnerships, which are essential for sharing expertise, reducing costs, and promoting an interoperable exploration ecosystem.<sup>14</sup> It does not however appear to consider the import of including commercial representatives methods or approaches to providing needed services or capabilities.

This Report builds upon NASA's strategy by addressing the unique challenges of establishing large-scale surface habitats. The group, focusing on technology solutions, such as modular habitat designs and advanced life support systems, attempted to assess how these might be adapted and scaled for larger commercial settlements.

#### A. Impact of the Artemis Program

The Artemis Program represents NASA's cornerstone initiative to establish a sustainable human presence on the Moon for NASA personnel by the late 2020s.<sup>15</sup> The focus of the infrastructure proposed in the Artemis Program is targeted at achieving NASA's objectives outlined in the Moon to Mars Architecture.

The Artemis basecamp must have the support infrastructure and operational capabilities necessary to operate. It appears the intent is to design, develop and prove out the use of support systems in support of future missions to Mars and beyond.<sup>16</sup> However, to establish a truly sustainable mix of civilian and government human presence, such systems may be overly complex, costly and beyond the needs of lunar settlements. The following are key identified future permanent settlement capability enhancements needed:

1. Enhanced Power Generation Systems: A reliable power supply is essential for supporting lunar surface operations, especially during the two-week-long lunar night. To this end, advanced power generation systems, such as solar arrays combined with energy storage solutions and possibly compact nuclear reactors, will be needed. Developing hybrid energy systems that integrate these technologies should ensure continuous power availability. Such capability is crucial for maintaining habitat functions, scientific operations, and mobility systems during prolonged periods of darkness and extreme temperature fluctuations<sup>17</sup>.
2. Advanced Radiation Shielding: The Moon's lack of a protective atmosphere exposes habitats and crew to high levels of cosmic and solar radiation. Implementing advanced radiation shielding, such as multi-layer materials that incorporate hydrogen-rich compounds or water, is one method for providing essential for protecting astronauts and civilians during extended lunar stays. The use of local materials, like regolith, to create radiation barriers around habitats is another means that can further reduce radiation exposure and lower construction costs.<sup>18</sup> In addition, prospecting to determine if lunar lava tubes exist and can be used as ready-made radiation shelters has distinct cost, schedule and practical advantages. In the long run, active radiation protection systems should not be discounted, especially with availability of adequate power.

<sup>7</sup> Dr. Matthew Sambora, Demonstration Rocket for Agile Cislunar Operations, DARPA, <https://www.darpa.mil/program/demonstration-rocket-for-agile-cislunar-operations>, last visited Oct. 18, 2024.

<sup>8</sup> The Fusion Driven Rocket: Nuclear Propulsion through Direct Conversion of Fusion Energy, NASA, <https://www.nasa.gov/general/the-fusion-driven-rocket-nuclear-propulsion-through-direct-conversion-of-fusion-energy/>, last visited Oct. 22, 2024.

<sup>9</sup> Ion Propulsion, NASA, <https://science.nasa.gov/mission/dawn/technology/ion-propulsion/>, last visited Oct. 22, 2024; Debra Werner, Busek lauds on-orbit performance of OneWeb's Hall-effect thrusters, SPACENEWS (Aug. 8, 2023), <https://spacenews.com/busek-lauds-on-orbit-performance-of-onewebs-hall-effect-thrusters/>, last visited Oct. 22, 2024.

<sup>10</sup> Innovative fusion-enhanced propulsion and advanced DSP software, ROCKET STAR, <https://rocketstar.nyc/>, last visited Oct. 22, 2024.

<sup>11</sup> Aldrin Mars Cycler, BUZZ ALDRIN, [https://buzzaldrin.com/space-vision/rocket\\_science/aldrin-mars-cycler/](https://buzzaldrin.com/space-vision/rocket_science/aldrin-mars-cycler/), last visited Oct. 22, 2024.

<sup>12</sup> Moon to Mars Architecture, NASA, <https://www.nasa.gov/moontomarsarchitecture/>, last visited Oct. 17, 2024.

<sup>13</sup> Mars Exploration, NASA, <https://science.nasa.gov/planetary-science/programs/mars-exploration/>, last visited Oct. 17, 2017.

<sup>14</sup> Wright, M. (2019). Legal frameworks and international standards for space resource utilization.

<sup>15</sup> Artemis, NASA, <https://www.nasa.gov/feature/artemis/>, last visited Oct. 18, 2024.

<sup>16</sup> NASA Artemis Program Overview, NASA (2023), available at [ntrs.nasa.gov/api/citations/20230012221/downloads/Cohenartemispresentation.pdf](https://ntrs.nasa.gov/api/citations/20230012221/downloads/Cohenartemispresentation.pdf).

<sup>17</sup> Dunn, J., Parker, B., & Smith, T. (2019). Hybrid energy systems for powering lunar and Martian habitats.

<sup>18</sup> Guo, J., Zhang, S., & Liu, Y. (2020). Research on long-term radiation protection systems for space habitats.

3. **Modular Habitat Structures:** Modular habitats offer the flexibility to expand and adapt usable working & living space to changing mission requirements. Standardized, interconnectable modules can be configured for a variety of purposes, from living quarters to research laboratories, enabling the construction of a versatile and scalable base camp. Basic modular shell designs also simplify maintenance and upgrades and can take advantage of economies of scale thus ensuring that habitats can evolve as new technologies and capabilities are developed<sup>19</sup>.

An assessment is yet to be made regarding the suitability of the Artemis Program developed technologies and systems within commercial lunar applications. This should be done to avoid past overspecification and to provide the highest commercial transference potential. Further, NASA should consider using public-private approaches to obtain and acquire infrastructure services. This WG concluded this using similarity evidence seen in the move from government developed launch system capabilities to commercial ones. The availability and sharing of commercial infrastructure services also means potential relief from the burden of operations, and overhead cost to NASA.

#### **Recommendations:**

- **An independent commercial assessment should be made regarding the suitability of these developed technologies and systems within commercial lunar applications.** This assessment should include identification of the technology and system requirement needs for furthering expansion of lunar developments and expanded settlements.
- **NASA should consider and investigate the use of alternative commercial lunar infrastructure services.** The purpose of this is to see how the use of these elements could provide a means to enhance the capability, resilience and reduce the costs of Artemis operations. This should be done in conjunction with potential infrastructure providers and commercial users.

## **IV. The Value of Modular and Expandable Designs for Expanding Space Habitats**

This section explores the WG discussion on the advantages and associated value of building habitats in the near term with standardized, interconnectable modules to support the near term expansion of human activities in space.

### **A. The Value of Building with Standardized, Interconnectable Modules**

Modular designs involve constructing habitats using standardized, interconnectable components that can be configured and reconfigured as required. The harsh and unforgiving space environment demands the highest quality and assurance standards of each new habitat. This method by necessity has been adopted and used during early space station outposts like Skylab, during laboratory augmented space shuttle missions and the larger laboratory assembly of the ISS. The use of interconnectable space modules continues to be the favored space habitat fabrication and assembly approach used throughout the world.

This approach allows for the rapid assembly and immediate use of complex structures using a “building block” methodology, and also ensures the quality assurance of each unit module through pre-fabrication on Earth. The modular assembly approach supports in orbit and lunar surface and/or Martian surface initial outpost habitats to grow and new facilities for alternative purposes to become productive and operational.

The use of standardized connectors and interfaces ensures that different modules can be seamlessly integrated, allowing habitats to be adapted to diverse functions such as living quarters, laboratories, or storage areas. It is recommended that international industrial standards be developed for module connector types, power, data networks and life support interfaces to promote interoperability between different agencies and commercial entities. This will enable and foster collaborative development and the sharing of infrastructure<sup>20</sup>.

#### **Recommendations:**

- **Continue and extend the development of international industrial standards through organizations like the International Organization for Standardization (ISO).** Specific attention should be made to the development of common module connector types, power systems, data networks and life support interfaces. This will promote interoperability between different agencies and commercial entities. This will also enable and foster collaborative development and the sharing of infrastructure between global participants.
- **Incorporate modular maintenance protocols.** It is recommended that habitat developers share and incorporate modular maintenance protocols that allow for the rapid replacement of critical systems, such as environmental control and life support systems (ECLSS), power systems, and communication networks.<sup>21</sup> These maintenance protocols should enable the rapid replacement of critical systems, such as Environmental Control and Life Support Systems (ECLSS), power systems, and communication networks.

<sup>19</sup> Bishop, C., Richards, L., & Zhao, Y. (2018). Benefits of modular habitat design and space-based manufacturing.

<sup>20</sup> Zhang, Q., Lin, X., & Wu, S. (2019). Strategic positioning of space habitats for efficient transportation and operations.

<sup>21</sup> Jones, P., Clarke, D., & Peters, G. (2019). Implementation of closed-loop life support systems for lunar missions.

- **Facilitate collaborative development and sharing of infrastructure services.** Promote collaboration and shared infrastructure services by adhering to standardized interfaces, enabling the integration of habitat systems from multiple partners.

## B. Expandability: Adding New Sections Over Time

The ability to expand habitats over time as missions evolve, applications are added, and new technologies become available allows for adjustment of use and addition of capability. Modular habitats enable this with the addition of new sections based on changing needs, such as increased crew capacity, enhanced scientific capabilities, or the integration of new life support systems. This allows habitats to begin with core outpost modules for essential operations and be expanded with specialized tailor use modules to expand utility and habitable volume. Such incremental growth capability supports long-term planning and scaling efficiency with minimal disruption to ongoing activities.

### Recommendations:

- Design habitats for incremental expansion. Include pre-configured expansion points in initial habitat designs to allow for the seamless addition of new sections as mission needs evolve.
- Enable adaptable growth based on mission requirements. Design modular habitats to support incremental growth, such as adding new modules for increased crew capacity, scientific research, or manufacturing capabilities.
- Support long-term planning and efficient scaling. Adopt an incremental growth strategy that enables habitats to scale efficiently with minimal disruption to ongoing operations, ensuring adaptability and flexibility as new technologies and capabilities are developed.

## C. Easier Maintenance and Replacement of Individual Components

Modular habitats offer significant advantages for maintenance and the replacement of individual components. Standardized modules can be easily detached, replaced, or upgraded without affecting the rest of the habitat, reducing downtime and minimizing the impact on crew activities. This approach simplifies the management of spare parts, as common components can be used across multiple modules. Additionally, modular designs support the integration of new technologies as they become available, ensuring that habitats remain state-of-the-art and capable of meeting the demands of future missions. It is recommended that habitats incorporate modular maintenance protocols that allow for the rapid replacement of

critical systems, such as environmental control and life support systems (ECLSS), power systems, and communication networks.

### Recommendations:

- Simplify maintenance and component replacement. Design habitats with standardized modular components that can be easily detached, replaced, or upgraded, minimizing downtime and disruptions to crew activities.
- Establish modular maintenance protocols. Implement maintenance protocols that enable the rapid replacement of critical systems, such as Environmental Control and Life Support Systems (ECLSS), power systems, and communication networks.
- Standardize components across modules. Use common components across multiple modules to streamline spare part management and ensure compatibility, reducing complexity and storage needs.
- Enable technology integration and upgrades: Design modules to support the integration of new technologies, ensuring habitats remain up-to-date and adaptable to evolving mission requirements.

## D. Human Habitation Systems for Large-Scale Surface Habitats

Developing sustainable and adaptable long term large surface habitats on the Moon and Mars involves more than providing basic life support. Habitats must autonomously adapt to changing environmental conditions, integrate local resources, and support human performance in extreme environments over extended periods..

Advanced habitation systems are integral to ensuring that habitats can support long-duration missions in the challenging space environments of the Moon and Mars. By focusing on autonomous operations, resource utilization, and adaptive human systems, habitats can evolve with mission requirements and crew needs. Testing these systems on the Moon will provide critical data and operational experience to refine designs for Mars and other remote celestial locations, where operational constraints are more severe. The insights gained from this iterative habitat approach will be instrumental in bridging the gap between lunar and Martian habitats, to establish a sustainable permanent human space presence.

Creating controlled environments involves maintaining stable atmospheric conditions, mitigating radiation exposure, and managing temperature variations. Unlike smaller habitats, where manual interventions are feasible, larger systems require autonomous capabilities that can independently detect and correct life threatening anomalies.

## i. Dynamic Environmental Control and Life Support Systems (ECLSS)

ECLSS in both small and large habitats must balance recycling efficiency with cost of operations and resilience against potential failures. Existing systems, like those used on the ISS, have opted to use periodic procedures and manual adjustments for general maintenance. For future large scale surface habitats, ECLSS designs should integrate bio-regenerative components, such as algae or engineered bacteria, to support oxygen production and CO<sub>2</sub> removal, as well as AI-driven control systems that can simulate and anticipate fluctuations in the habitat's ecosystem. Distributing modular ECLSS units throughout the habitat can reduce systemic risks and allow isolated management of different habitat zones.<sup>22</sup>

Modularity in life support systems also supports habitat expansion and scalability for evolving mission needs.

### 1. Radiation Shielding:

The need for effective radiation shielding drives the exploration of hybrid structural designs that utilize both active and passive protection. Instead of traditional shielding methods that rely on mass-intensive materials, habitats can incorporate multifunctional structural elements that provide mechanical support and radiation protection simultaneously. For example, using double-walled habitat structures filled with regolith or water as shielding material could significantly reduce radiation exposure while enhancing structural stability. Additionally, advanced concepts such as superconducting magnets to generate localized magnetic fields could complement traditional shielding methods, enabling habitats to be designed with less reliance on transported materials.<sup>14</sup>

### 2. Thermal Management:

Maintaining thermal stability in habitats is complicated by the extreme temperature variations between lunar days and nights or Martian seasons. Advanced thermal control systems could employ phase-change materials (PCMs) embedded within the habitat's walls, which store thermal energy during the day and release it at night. Coupling PCMs with active heat exchange systems would allow habitats to maintain stable internal temperatures without excessive energy use. Developing PCMs that can withstand repeated temperature cycling without performance degradation is a critical area of research.<sup>23</sup>

### 3. Habitability and Comfort:

The internal design of habitats must provide functional spaces that adapt to mission phases and crew sizes. Utilizing reconfigurable modules that can serve as living quarters, laboratories, or recreation areas enables habitats to maintain

flexibility. Artificial lighting systems designed to replicate Earth's day-night cycle can help regulate circadian rhythms, reducing the risks of sleep disorders and fatigue. Employing materials and color schemes that promote a sense of openness and calmness can further enhance the psychological well-being of crew members, supporting long-duration missions.

## Recommendations:

- Integrate bio-regenerative components like algae or engineered bacteria into ECLSS for efficient oxygen production and CO<sub>2</sub> removal. Utilize AI-driven control systems to detect and correct anomalies autonomously, and distribute modular ECLSS units throughout the habitat to reduce systemic risks and support scalability.
- Incorporate hybrid structural designs that use multifunctional elements, such as double-walled structures filled with regolith or water, to provide both mechanical support and radiation protection. Explore advanced concepts like superconducting magnets to generate localized magnetic fields as a complementary shielding method.
- Employ phase-change materials (PCMs) within habitat walls to absorb and release thermal energy, maintaining stable internal temperatures. Pair PCMs with active heat exchange systems and develop PCMs that withstand repeated temperature cycling to enhance thermal management efficiency.
- Design internal spaces with reconfigurable modules to adapt to varying mission phases and crew sizes. Use artificial lighting to mimic Earth's day-night cycle and materials that promote a sense of openness and calmness, enhancing psychological well-being and supporting long-duration missions.

## ii. Ensuring Crew Health and Performance

Human systems in larger surface habitats and orbital settlements will need to address the complexities of maintaining crew health and performance over extended periods, ensuring resilience against both physiological and psychological stressors. It is now well known and established that there are a host of deleterious effects on humans when exposed to extended periods of microgravity. Even with the use of targeted countermeasures the total impact on the physiology and psychology of the human body remains a key impediment to larger scale extended human habitation in space. In addition there is only the exceeding limited data from longer Apollo astronaut moon missions on the extended effects of the partial gravity pull on the moon and mars.

<sup>22</sup> Smith, J., Williams, R., & Thomas, K. (2018). Evaluation of ISS life support systems for application in surface habitats.

<sup>23</sup> Johnson, D., Patel, S., & Miller, A. (2018). Thermal management strategies for lunar habitats.

The use of spin induced centripetal acceleration to produce artificial gravity in orbital space stations has been postulated as a holistic response to counter these negative impacts. This mitigation approach dates back to the late 19th century, with Russian rocket scientist Konstantin Tsiolkovsky. No data exists from the actual space environment testing or research on a large radius orbital artificial spin gravity laboratory. There is also no long term impact data on the effects of extended habitation on celestial bodies smaller than will expose settlers to gravity pulls that are lower than on earth. The question on impacts to daily changes in gravity acceleration experience going from one level to another is also absent.

Answering the question of how much gravity acceleration is needed in a given period of time for human health is of critical importance to humanity's ability to enable large scale permanent human habitats.

### 1. Integrated Health Monitoring and Predictive Analytics:

For extended missions, health monitoring systems must be capable of detecting subtle indicators of health deterioration. Wearable health monitors that track biochemical markers like hydration, bone density, and stress hormones could feed into an AI-driven analytics platform that generates health profiles for each crew member. Predictive models based on these profiles could provide early warnings and suggest interventions before critical health issues arise. This would allow for dynamic health management tailored to individual crew members and reduce the need for Earth-based support.

### 2. Physiological Countermeasures for Long-Term Missions:

Micro-gravity environments during long term missions present challenges such as muscle atrophy and bone density loss. Barring the incorporation of an artificial spin gravity system in such missions, exercise regimens will be needed. These countermeasures currently provide muscle resistance using advanced exercise equipment. Also considered have been tailored resistive robotic exoskeletons. Smaller integrating centrifuge-based exercise, off duty and sleeping facilities may also provide sufficient gravitational force exposure to counter the negative effects of microgravity.

### 3. Psychological Support Systems for Extended Missions:

Psychological well-being is critical for maintaining cognitive function, effective work performance and mental well being. Evidence from isolated nuclear submarines and past astronaut missions can provide a starting base for responsive measures.<sup>24</sup> Habitats could integrate adaptive VR systems that offer a range

of experiences, from virtual natural environments to interactive social settings that mimic Earth-based activities. These VR environments, combined with AI-driven conversational agents, could provide cognitive stimulation, emotional support, and a sense of connection, reducing feelings of isolation. Additionally, designing habitats with multi-use common areas that encourage social interaction, combined with private spaces that offer solitude, would help maintain psychological balance among crew members.

## Recommendations:

- **Continue to develop understanding of the unknowns of partial and artificial gravity.** Experiments and data collection on the impacts and long term effects of the use of artificial gravity and the long term effects of living on reduced gravity worlds like the moon and mars must be prioritized.. This includes investigations on new commercial large radius inhabited spinning “artificial gravity” laboratories capable of providing the needed answers to this question for orbital facilities. It is also noted that these facilities may also be able to provide early and supplementally valuable data to the data collected on the moon regarding impacts of fractional/partial gravity as well as early data on extended mars stays. This data would be collected using various rates of spin that will produce different levels of artificial gravity.
- **Integrated health monitoring and predictive analytics.** Implement wearable health monitors to track biochemical markers like hydration and bone density. Use AI-driven analytics to create personalized health profiles and predictive models for early detection of health issues and tailored interventions, reducing reliance on Earth-based support.
- **Implement physiological countermeasures.** Mitigate the effects of low gravity, such as muscle atrophy and bone density loss, through exercise regimens that include advanced equipment like flywheel-based devices and robotic exoskeletons. Consider incorporating centrifuge-based exercise facilities to simulate gravitational forces in a space-efficient manner.
- **Develop psychological support systems.** Utilize adaptive VR systems to provide virtual natural environments and interactive social experiences. Include AI-driven conversational agents for emotional support and cognitive stimulation. Design habitats with multi-use common areas for social interaction and private spaces for solitude to maintain crew psychological well-being.

<sup>24</sup> Charlotte Aufauvre-Poupon et. al., Subsurface Confinement: Evidence from Submariners of the Benefits of Mindfulness, 2218, 2218 MINDFULNESS (2021); Anna Russell, What Submarine Crews and Astronauts Can Teach Us About Isolation, NEW YORKER (Apr. 9, 2020), <https://www.newyorker.com/culture/culture-desk/what-submarine-crews-and-astronauts-can-teach-us-about-isolation>., last visited Oct. 22, 2024.

## V. Need for Advancement of Critical Habitation Technology

Surface habitat systems are the integrated technical enablers that ensure the safety, functionality, and sustainability of extraterrestrial habitats. In addition to items mentioned previously, these systems include ECLSS, internal power, thermal management, operations management & control and resource management. These systems form a habitat effective framework that allows humans to live and work beyond Earth. Their design must address not only the harsh environmental conditions but also the need for autonomy, adaptability, and resource efficiency. The importance of these systems lies in their ability to support long-term missions and enable future expansions. Detailed attention to advancing the cost efficiencies of these systems is paramount to expanding and establishing permanent space habitats, specifically in regard to:

- Environmental Control and Life Support Systems (ECLSS): Develop and demonstrate technologies for hybrid ECLSS. These include integrated bioregenerative elements, such as algae-based bioreactors, into mechanical life support systems. Such configurations enhance sustainability by reducing the need for Earth-based resupplies while maintaining a resilient environment for crew members.
- Habitat Power Systems: Investigate and develop standardized internal power grids capable of power pass-through while meeting local module electrical needs. Integrate waste heat management systems for efficient thermal control and flexibility in energy distribution.
- Thermal Management Systems: Investigate using phase-change materials (PCMs) and regolith-based composites to create passive and active thermal management solutions. These systems regulate internal habitat temperatures and offer additional protection against extreme external conditions.
- Operations Planning and Control Systems: Develop a distributed network of autonomous monitoring control nodes that can independently manage specific habitat modules. Integrate AI-driven diagnostics and predictive maintenance can reduce crew workload, provide networked alert monitoring and support autonomous more operations of expanding large scale habitat complexes.
- Mission Control Systems: Leverage autonomous mission control systems using cognitive computing and machine learning to handle high-level decision-making for routine habitat systems management. Utilize innovative interfaces such as haptic feedback and augmented reality to enhance crew interactions with habitat systems.

- Equipment for Surface Operations: Design multifunctional surface operation platforms with reconfigurable chassis and modular attachments to support habitat support tasks. These tasks include construction, maintenance, and resource extraction.
- Resource Management Systems: Develop advanced resource management systems that integrate ISRU technologies for water, oxygen, and construction material extraction. These systems will foster greater habitat autonomy from long logistics lines between distant locations in space. Exploiting modularity should allow for dynamic adjustment of resource production based on mission demands, creating a closed-loop system for sustainable habitat operations.

### A. Personnel, Support Crews and Habitat Systems

The seamless integration of personnel, support crews, and habitat systems is crucial to assure safety and effectiveness. As habitats become more sophisticated and mission durations extend, habitat systems must evolve to provide higher levels of autonomy, efficiency, and adaptability while ensuring that the owner and user objectives are met. The WG considered activities and factors affecting the interaction of crew, ground, and supporting systems that may be needed to optimize and develop advanced strategies for managing mission operations and emergency scenarios in the context of surface habitation.

#### Recommendations:

- **Employ semi-autonomous systems for emergency protocols.** Design habitats with semi-autonomous systems capable of executing predefined emergency protocols. This will ensure crew operational control in the absence of real-time ground support due to communication delays.
- **Structure habitats such that ground personnel shift from direct operational to supervisory and strategic roles.** Transition ground personnel roles from direct hand on operations to strategic decision-making, roles. This should be possible using AI-driven mission control software for situational awareness and decision support.
- **Establish reliable communication networks with redundancies.** Design communication infrastructure habitat links to provide robust, reliable and dependable communication capability.
- **Leverage AI systems to enhance data management:** Using AI systems in habitat complexes to filter and prioritize data should reduce cognitive load on both crew and ground controllers. This will help ensure efficient communication and understanding of critical information.

## B. Supporting Software Management Systems for Day to Day Operations

Supporting systems encompass mission planning software, logistics management platforms, and real-time monitoring tools that coordinate activities within and around the habitat. As missions become more complex, these systems must adapt to a variety of operational scenarios, including changes in crew size, resource availability, and mission timelines.

### Recommendations:

- **Leverage planning software to enable habitat personnel to make informed decisions when deviations from the standard operating procedures occur.**
- **Exploit AI-driven predictive models to help train habitat personnel to anticipate and address issues before they escalate.**
- **Employ real-time habitat monitoring systems to allow quick detection and resolution of anomalies to prevent cascading failures and safety risks.**
- **Design supporting systems for adaptability and operational flexibility to ensure continued functionality and safety under diverse conditions.**

## C. Robotic Systems and Automation in Habitat Operations

Robotic systems will be indispensable for habitat construction, maintenance, and logistic support operations. Ideally, these systems should function autonomously, with minimal human oversight. Until this threshold is reached, it is likely that a combination robotic/human (cobotic) relationship will provide an effective capability. This is a critical area of development that should allow and gain the cost efficiencies of operating robotic systems with humans in a shared workspace.<sup>25</sup>

### Recommendations:

- **Develop autonomous robotic systems.** Use a balance of robotic systems automation with minimal human oversight to help ensure efficient operations.
- **Create cobotic systems to enhance robot-human operations.** Establish human-robot interaction protocols to facilitate coordination between robotic systems and crew members, enabling seamless collaboration in shared workspaces.
- **Implement multi-robot coordination capabilities.** Develop algorithms that enable swarms of robotic units to perform collaborative tasks.
- **Exploit modular robotic platforms.** Equip robotic systems for use of interchangeable toolsets and mobile platforms to autonomously conduct repairs, transport resources, and assemble modules, enhancing adaptability and functionality in response to mission needs.

## D. Habitat Safety and Emergency Response Availability and Capability

As habitats move further from earth and each other the ability to provide responsive safety and Emergency services becomes more complex. Because of this, space habitats systems must be designed to handle a wide range of potential emergencies without external help. Given this isolation these systems must operate with a high degree of autonomy and provide the crew with the ability to manage emergencies without immediate external assistance.

Emergency response systems should be structured around a multi-layered approach that includes early detection, automated containment, and manual intervention protocols. For instance, in the event of a fire, integrated fire suppression systems can isolate affected modules and expel harmful gasses, while the habitat's life support system adjusts ventilation to prevent the spread of smoke or toxic substances. Simultaneously, pre-programmed emergency procedures could be automatically communicated to crew members and ground control, providing a clear action plan to address the situation.<sup>26</sup>

### Recommendations:

- **Design autonomous safety and emergency response systems.** Safety systems should be developed to operate autonomously and handle a wide range of emergencies to allow habitat complex personnel to manage anticipated emergency incidents without the need for immediate external support.
- **Implement a multi-layered emergency response strategy.** Structure safety systems around early detection, automated containment, and manual intervention protocols to effectively address environmental hazards, equipment malfunctions, and medical crises.
- **Incorporate integrated emergency suppression systems.** Equip habitats with fire suppression systems that can isolate affected modules, expel harmful gasses, and adjust ventilation to contain hazardous conditions.
- **Establish automated communication protocols.** Create pre-programmed emergency procedures that are automatically communicated to crew members and ground control, providing clear action plans for timely and coordinated responses.

<sup>25</sup> Harrison, T., Alvarado, J., & Lee, W. (2019). Study on ISRU scaling techniques for sustainable habitat development.

<sup>26</sup> Wright, M., The theory and economics of Mars and Moon colonization: Steps and policy advocacy. 239, 239 ESJ (2019).

## E. Integration of Habitat Operations Personnel and Robotic Systems

The successful integration of crew, ground personnel, and supporting systems is key to creating a cohesive operational ecosystem. By establishing clear protocols and utilizing advanced technology to bridge communication gaps, the habitat's operational effectiveness can be significantly enhanced. The implementation of AI-driven support systems that predict and adapt to changes in mission conditions, coupled with autonomous robotics, will reduce crew workload and increase overall mission efficiency. This holistic integration is necessary to support NASA's long-term vision for sustained human presence on the Moon and Mars, as it allows for scalable and resilient operations across diverse mission scenarios.

Ultimately, these systems must not only support the execution of planned activities but also provide the flexibility to adapt to new challenges and opportunities as human exploration pushes deeper into the solar system. Necessary systems include:

- **Internal Command Center:** Habitats can integrate an internal command center that serves as an extension of ground control, equipped with high-level decision support systems capable of simulating outcomes based on current mission parameters. This facility would provide the crew with more control over their immediate environment, enhancing autonomy while maintaining alignment with ground-based strategic objectives.
- **Centralized Operations Center:** A centralized operations center within the habitat can serve as the nerve center for all supporting systems, equipped with advanced visualization tools that provide a holistic view of all ongoing activities. This setup would allow crew members to monitor mission status, resource utilization, and system health, while also enabling them to coordinate surface activities such as EVA operations and robotic exploration.
- **Dedicated Robotic Work Zones:** Surface habitats should include dedicated robotic work zones where autonomous systems can operate independently of crewed areas, reducing interference and increasing safety. These zones could be equipped with docking stations for recharging, tool swapping, and data transfer, enabling continuous and efficient robotic operations.
- **Modular Safety Systems:** Habitat designs should incorporate modular safety systems that isolate compartments in case of a breach or hazard, preventing damage from spreading to critical areas. Emergency equipment, such as portable air supplies and medical kits, should be distributed strategically throughout the habitat to ensure accessibility regardless of the crew's location.

- **Co-botic Employment:** Investigate and identify co-botic employment opportunities that combine autonomous, AI enhanced, remotely operated and humans on-board robotic teaming capabilities to "force multiple" supporting habitat maintenance and construction.

## F. Systems for Operational Planning and Execution

Mission control facilities should provide comprehensive monitoring and control capabilities for all habitat systems and surface operations. These centers should be equipped with high-resolution displays, real-time data visualization tools, and decision support systems that align with the Moon to Mars Architecture's emphasis on robust situational awareness and mission adaptability. AI-driven predictive models could be used to simulate mission scenarios, providing insights on resource allocation and system performance under different conditions. A distributed control architecture could be used, with a primary mission control center located in the habitat and secondary nodes in surface vehicles and robotic units. This configuration would enable decentralized decision-making, reducing dependency on any single control point and enhancing resilience.

### Recommendations:

- **Establish comprehensive mission control centers.** Develop mission control facilities equipped with high-resolution displays, real-time data visualization tools, and AI-driven decision support systems to monitor and control all habitat systems and surface operations. Use a distributed control architecture with a primary mission control center in the habitat and secondary nodes in surface vehicles and robotic units to enable decentralized decision-making and enhance operational resilience.
- **Implement advanced logistics and resource management systems.** Create logistics systems that track supplies, manage inventory, and optimize resource use. Employ autonomous logistics drones or ground vehicles to transport materials between landing sites and habitats, reducing crew workload and increasing efficiency.
- **Develop centralized logistics hubs.** Establish a central logistics hub with automated inventory tracking and replenishment systems to streamline resource distribution. Integrate robotic systems with habitat modules via dedicated docking ports to enable direct loading and unloading of supplies without requiring human intervention.

## G. Service Systems for Crew and Habitat Support

Service systems are necessary must-have health capabilities. These include medical health and waste management services that require uninterrupted operations under varying conditions. In early habitats and habitable deep space transports hosting dedicated doctors and nurses will likely not be possible.

In space mission crews today, at least one astronaut usually has medical training. However, the development of remote virtual (for near earth habitats) and automated medical service capabilities (for more remote habitats) should be of high priority. Diagnostic, treatment, and telemedicine capabilities should be integrated into the habitat to support crew health. Additionally, waste processing systems are a vital part of all human habitats. Space waste systems have the added complexity because of the need to convert organic and inorganic waste into reusable resources to reduce resupply needs.

### Recommendations:

- **Provide integrated autonomous health services.** Implementation of autonomous medical systems with diagnostic, treatment, and telemedicine capabilities can not be overlooked to assure support crew health.
- **Incorporate advanced waste management and recycling systems.** Each habitat should include highly reliable waste processing systems to maintain health, enhance habitat self-sufficiency and reduce reliance on Earth-based resupplies.

## VI. Legal Framework for Space Habitation

Establishing large-scale habitats on celestial bodies like the Moon and Mars requires consideration of established international legal frameworks. These currently include the Outer Space Treaty (1967)<sup>27</sup> and the Moon Agreement (1984).<sup>28</sup> The international space law framework includes principles such as the peaceful use of space, the prohibition of territorial claims, and the responsibility of states for space activities, including those conducted by private companies. Overall, the framework aims to promote cooperation, ensure safety, and protect the interests of all nations in space exploration and use.

From a domestic law perspective, the two major legal frameworks guiding the development of the Cislunar economy are: (1) the Commercial Space Launch Competitiveness Act

(SPACE Act)<sup>29</sup>; and (2) the Artemis Accords.<sup>30</sup> Each affects the development of and operation of celestial based habitats. The SPACE Act focuses on privatization of the space industry, whereas the Artemis Accords focus on supporting and harmonizing a return to the Moon and later Mars by the United States and its allies. Perhaps the most important part for future celestial habitats is that the SPACE Act grants private companies the right to own resources collected in space. By implication this allows surface habitats to be emplaced, even if resource collection is not the primary intent.

For this paper, the WG focused on the Artemis Accords that were introduced in 2020 as a set of bilateral agreements between the United States and its space exploration partners. The Artemis Accords reaffirm the principles of the Outer Space Treaty, promoting transparency, interoperability, and the peaceful use of space. Its signatories agree to the concept of “safety zones.” These are designated areas around lunar or Martian habitats and installations that are intended to prevent harmful interference between activities conducted by different parties. While the Artemis Accords are not legally binding, they establish a normative framework for conducting space activities and offer a collaborative approach to space exploration.<sup>31</sup>

## A. Implications and Future Considerations of Legal and Policy Frameworks for Space Habitat Development

As human commercial activities on the Moon, Mars and other celestial bodies become a reality, the limitations and risks of the current legal frameworks become more apparent. To prevent this situation new policies, laws and agreements will be needed to address these issues. Future legal frameworks must incorporate will need to not only cover resource utilization but must establish clear guidelines for habitat ownership rights and laws governing their placement on celestial bodies.

One critical challenge is to develop a habitat governance model that balances the rights and responsibilities of state and private actors while promoting international cooperation. The legal frameworks should support sustainable exploration and resource management, prevent conflicts over resource claims, and ensure that space activities do not unduly impact the environment or violate the rights of other states. The development of such frameworks will likely require extensive international dialogue and collaboration, involving not only spacefaring nations but also emerging space actors and other stakeholders in the global space community.

<sup>27</sup> Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies, Jan. 27, 1967, 18 U.S.T. 2410, 610 U.N.T.S. 205 (entered into force Oct. 10, 1967) [hereinafter Outer Space Treaty].

<sup>28</sup> Agreement Governing the Activities of States on the Moon and Other Celestial Bodies, Dec. 18, 1979, 1363 U.N.T.S. 3 [hereinafter Moon Agreement] (entered into force on July 11, 1984).

<sup>29</sup> U.S. Commercial Space Launch Competitiveness Act, Pub. L. No. 114-90 [hereinafter SPACE Act].

<sup>30</sup> The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids, NASA (Oct. 13, 2020) [hereinafter Artemis Accords].

<sup>31</sup> Id.

## Recommendations:

- **Develop more comprehensive resource utilization guidelines.** Although the SPACE Act covers U.S. company space resource utilization, similar laws do not exist in other countries. For this reason the U.S. should lead in establishing international norms and agreements that define the rights and responsibilities of state and private actors regarding the extraction and use of space resources.
- **Define habitat placement and operational jurisdiction.** A means is needed that defines and allows for the placement of habitats and infrastructure on the surface of celestial bodies. Such a regime should also cover the extent of operational jurisdiction and ensure that entry and exit procedures for habitats provide for clear procedures for accessible to parties from different countries.
- **Establish safety and coordination protocols.** Define procedures and means to establish safety zones and coordination protocols. These surface habitat and facility protocols should be extended to include space traffic management frameworks to ensure the safety and sustainability of operations in cislunar space and beyond.
- **Promote international collaboration and transparency.** Foster international partnerships and encourage the sharing of data, technologies, and expertise to build a cohesive exploration ecosystem. Establishing transparent communication channels and collaborative research initiatives will ensure that all space activities align with international norms and contribute to the collective advancement of human space exploration.

## VII. Conclusion & Summary of Recommendations

The development of large-scale surface habitats in space represents a pivotal step toward establishing a sustainable human presence beyond Earth. This report addressed many of the multifaceted challenges associated with these endeavors. The WG offered strategies that integrate advanced potential technology solutions, international policy frameworks, and economic sustainability considerations.

Ultimately, commercial economic sustainability is critical for the long-term viability of lunar and Martian habitats. Although the U.S. and other governments will continue to be customers, commercial revenue-generating activities, such as tourism, resource extraction, or space-based manufacturing will be needed to cover costs of habitat construction and operation. Encouraging public-private partnerships and creating incentives for commercial investment are means to accelerate the development of these habitats. Competitive and cost cutting business strategies can lower the operating capital and investment required to create space habitats.

The value of modular and adaptable habitat designs, in conjunction with innovative life support systems, energy solutions, and radiation protection technologies are intended as guiding perspectives for future habitat development. By adopting a phased and iterative approach aligned with commercial needs NASA's Moon to Mars Architecture can better serve as a blueprint for mitigating risks and enhancing the technical and operational capabilities needed to support long-duration human missions. The establishment of sustainable surface habitats on the Moon and Mars requires a unified effort across technological, economic, and policy domains.

### Summary of Recommendations:

1. NASA and U.S. government investments should continue to support exploration as a precursor to commercial interest expansion and the ultimate establishment of large scale habitat based settlements.
2. In its development of technology and systems to support their exploration missions NASA should leverage the commercial space industry to help them better meet their commercial customer and NASA needs.
3. The insights and recommendations outlined in this report should be considered by NASA in support of its strategic goals and to promote the seamless integration of commercial lunar operations as a stepping stone for Martian exploration.

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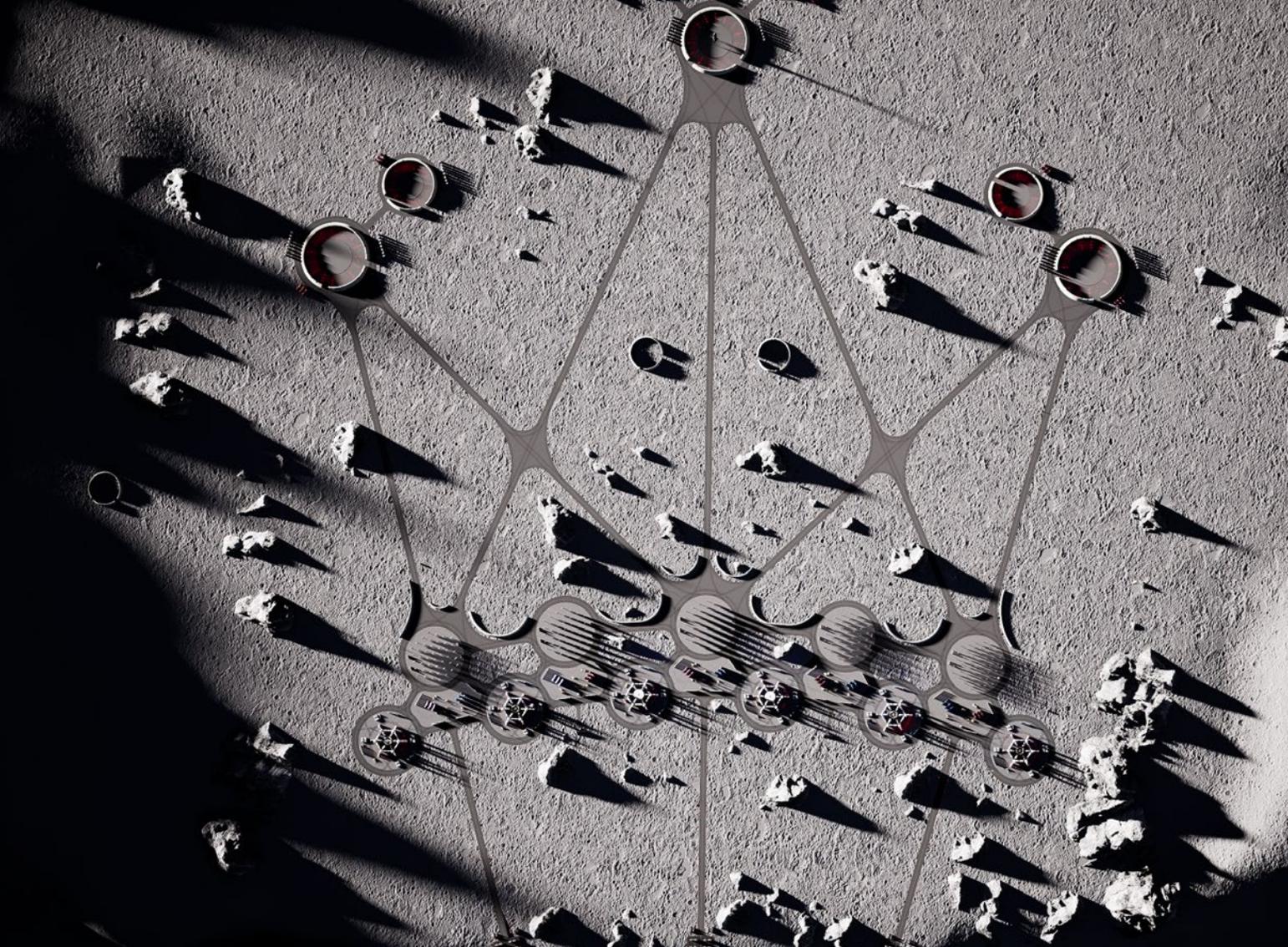
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Leadership Council**

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# **2024 Reports and Recommendations**

**Supplemental  
Papers**





# The Lunar Development Cooperative

## A Framework for the Sustainable Development of Space<sup>1</sup>

Michael Castle-Miller<sup>2</sup>

<sup>1</sup> This White Paper was made possible through the generous support of the Beyond Earth Institute, The Beyond Earth Institute is a 501(c)(3) non-profit corporation whose mission is to establish and sustain a policy and legal framework that enables economically vibrant communities beyond Earth. For their encouragement and in-depth technical review and input, special thanks goes to Steve Wolfe, Steve Hoeser, Lauren Andrade, Joshua Osborne, and the members of the 2024 Advanced Economics and Financing Working Group, especially Jack Gregg and Hoyt Davidson.

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# Executive Summary

## Background and Context

The industrialization of space will be critical to the health of our planet and the future of humanity. Unlocking the vast energy and material resources of our solar system will relieve our biosphere and fuel economic growth long into the future. However, gaps in the current space governance framework will keep us from achieving these goals in a way that ensures an open and sustainable space economy benefiting all.

Effective space governance must consist of (a) widely accepted rules of conduct and (b) organizations with the ability and incentive to administer those rules for a wide range of actors across many nations. While important steps have been made in recent years, the existing framework lacks these qualities. This absence increases the risk of exclusionary land grabs, resource overexploitation, and conflicts, particularly on the Moon, where mining will begin soon. Governments and international organizations are ill-equipped to resolve these issues in time to prevent these destructive outcomes.

## The Lunar Development Cooperative

### Introduction

The Lunar Development Cooperative (LDC) will help solve many of these problems. The LDC will be an infrastructure and public service provider for any company or government entity operating on the Moon that agrees to become an LDC member. As a condition for receiving LDC services, members will be contractually bound to abide by rules governing their activities. These rules will be consistent with international law and facilitate a sustainable free-market economy on the Moon.

### Structure

The LDC will be a for-profit, multinational, public private partnership. Shareholders will include as many nations and people as possible. Nations may purchase up to 49% of its shares, with individuals and private-sector investors owning the rest. Developing countries and indigenous groups will have special access to LDC shares, and its shares will be affordable and accessible for almost every human, making it humanity's holding company for the Moon.

Each individual, company, and nation will be subject to limits on its control of the LDC, preventing them from manipulating the LDC to benefit their own independent commercial, political, or military agendas at the expense of the LDC's purpose. The LDC will be subject to robust accountability mechanisms, and its income will be tied to the long-term economic, social, and environmental outcomes of the Moon.

### LDC Infrastructure and Services

The LDC will build and maintain infrastructure near high-value lunar sites where its members are likely to operate. The LDC's physical infrastructure will include landing pads, power stations, communications networks, water and oxygen storage, waste recycling networks, and other facilities. It will also provide a range of services to members, including risk insurance, emergency search and rescue, mineralogical data from resource-rich areas, diplomatic assistance, and regulatory streamlining. However, its most valuable service will be an enforceable rules-based framework that reduces risk and protects members' rights.

### LDC Registry and Membership Fees

The LDC will establish a registry in which members apply to record their planned uses of the lunar surface. Members' contracts with the LDC will obligate them to respect all uses recorded in the registry. Consistent with the Outer Space Treaty, the LDC registry will not in any way recognize ownership of lunar land. However, it will give members contractually enforceable rights to carry out activities they have recorded. As a result, it can serve as a building block for a space property rights system that will facilitate economic growth without land ownership.

An LDC member's membership fee will be based on the annual market value of the rights they have recorded in the registry. For example, a right to mine valuable minerals from a high-demand, permanently shadowed region directly adjacent to an LDC spaceport will have a high market value. The member holding this right will therefore pay a higher membership fee than a member mining resources in a less desirable remote location. This approach to pricing membership fees will prevent speculation and monopolization of lunar resources. It will also create a positive feedback loop in which the more the LDC creates a thriving and sustainable operating environment, the more its revenue will rise over the long run. It will use this revenue to re-invest in improved services and generate a return on investment.

## Enforcement and Accountability

The LDC's contracts with members will include binding rules governing a range of activities affecting the lunar economy, society, and environment. They will cover resource extraction techniques, dust mitigation, labor and human rights, harmful interference with other parties, environmental protection, minimum technical standards (such as for airlocks and life support systems), intellectual property, and anti-competitive practices.

The LDC's charter and member contracts will include clear guidelines and mechanisms for administering its rules. They will allow the LDC to require corrective action, impose fines or, in severe cases, revoke membership for violators. The LDC can seek enforcement, if needed, in international arbitration and courts of nations on Earth.

As a public-benefit company, the LDC will itself be governed by binding standards and accountability mechanisms included in its founding charter, shareholders agreement, and member contracts. The LDC will have a board of directors and professional management team carrying out day-to-day operations. It will also be overseen by an independent board of advisors and inspector general's office, which will conduct independent investigations, issue public reports, and support members and minority shareholders in filing suits against the LDC. Members will be able to challenge actions by the LDC in arbitration or designated courts.

The LDC's exclusive focus will be on providing public services benefiting the entire community and will be restricted from competing with its members by providing private goods, like lunar-mined resources. This will prevent it from using its control of infrastructure and rules to unfairly advantage its own products. The LDC will also use its rules and procurement practices to encourage competition in the lunar economy and lower barriers to entry.

## Supporting the Evolution of Space Institutions

The LDC will help support and influence the development of space law and align it with emerging commercial practices. Governments may eventually formally adopt the LDC's rules and its registry as law, much as they have historically adopted industry standards, informal rights, and codes of conduct developed by voluntary associations of merchants, sailors, miners, and fishermen. Much like trade associations on Earth, the LDC will also engage governments on behalf of members to help resolve conflicts and support the overall interests of the space economy.

The LDC can exist alongside other competing public service providers similar to the LDC. These emergent competitors will exert healthy pressure on the LDC to optimize its services, governance, and rules. However, the LDC's governance structure will give it a competitive advantage by creating a more trustworthy and efficient operating environment than either state-controlled or other private-sector entities. Ultimately, the LDC model can be replicated for other locations in space, including Mars, asteroids, and beyond, enabling humanity to develop and share the enormous potential of our solar system.

## Next Steps: The Lunar Development Institute

The Lunar Development Institute will help lay the groundwork for the LDC. It will engage international organizations, governments, the private sector, and other institutions to support the LDC's formation. It will help develop technical and financial plans for planned LDC infrastructure and missions. It will also collaborate with stakeholders to help craft the LDC's charter, rules, accountability mechanisms, and other core institutions. This work will be supported by donor contributions and research grants for a period of 5 years, when it will then establish the LDC, raise investment, and begin building infrastructure.

The urgency and impact of this work cannot be overstated. Precipitous drops in launch costs and geopolitical competition mean we may only have a few years before life on Earth begins its most significant expansion in history. The past tells us the institutions we create now to guide this expansion will have a profound impact on society for centuries into the future. If we act now, we can learn from our past failures and give countless generations almost unimaginable opportunities, prosperity, and hope.



Conceptual rendering of a lunar community enabled by LDC services. Courtesy of Daniel Inocente, Principal Architect & Founder, Daniel Inocente Architecture

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# I. The Need For Better Space Governance

## A. Reasons for Space Development

### i. The Benefits of Space

The development of space offers enormous benefits for humanity and Earth. Other books and articles offer in-depth descriptions of numerous reasons why humanity should settle and develop space, including technological advancement, international cooperation, and humanity's long-term survival. Two reasons that are particularly relevant to the economic development of space are:

1. Abundant natural resources - Our planet's resources are finite, and while we must continue improving at sustainability, they will become increasingly hard to obtain the more we grow. Our solar system, by contrast, offers enough clean energy and material resources to fuel our growth for thousands of years.<sup>3</sup>
2. Relieving the biosphere - Industrial activities increasingly strain Earth's climate and ecosystems. Many of these activities can be carried out in space, in areas devoid of life. For example, orbital processing and manufacturing plants can develop important products using raw materials from the Moon and asteroids, the sun's energy, and a zero gravity environment.

Beyond the already large satellite industry, industrial activities in space can produce both:

- High-value "export" products for Earth, such as crystals, advanced semiconductors, pharmaceuticals, rare metals and elements, data centers, tourism, and space solar power.
- Space-to-Space products, such as water (for transportation fuel and life support), metals, and building materials for habitats, facilities, and infrastructure.

Many people have legitimate concerns with the development of space.<sup>4</sup> As discussed in Section B, the current legal framework does not adequately reduce the risk of violent conflict, environmental destruction, and harmful economic and social conditions. As a result, some argue that space should be left entirely untouched, used purely for science, or only developed at a very slow pace.<sup>5</sup>

However, even if we accept these arguments, space will be developed soon regardless. Several major space faring nations and private companies are planning missions to the Moon slated for the next few years to prospect and mine natural resources, produce energy, and manufacture products. SpaceX's Starship, a

reusable, heavy-lift rocket, plans to deliver large payloads to the Moon at relatively low cost as soon as late 2026, making access to space much more affordable than ever before.

### ii. Why the Moon?

In the near term, most of the development in space will probably concentrate on the Moon. We have greater knowledge of and access to the Moon than any other space location with physical resources, including near-Earth asteroids and Mars.

Available data indicates the most valuable resources on the Moon may be concentrated in relatively few locations, some spanning only a few kilometers in size. For example, the Peaks of Eternal Light – areas at the poles almost perpetually exposed to the sun and ideal for energy generation – cover only about 1 sq.km.<sup>6</sup> The coldest of the cold traps, which offer rare volatiles as well as prized conditions for scientific experiments, are around 1 km total in diameter. The richest deposits of thorium and uranium cover only a few kilometers in total. Finally, probably only a handful of the roughly 200 lunar pits have overhangs or hollow lava tubes useful for settlements as natural radiation shielding and protection from temperature extremes.

As a result, the first companies and nations to occupy these sites could capture a majority of the Moon's economic value. After that point, these first movers will have enormous influence over the space economy, making it very difficult to build an effective framework that keeps their power in check.

## B. Problems with the Current Space Governance Framework

### i. What does "Governance Framework" Mean?

A thriving, open, and sustainable lunar economy depends on an effective governance framework. This paper views "governance framework" as encompassing two essential elements: (1) rules and (2) the effective administration of those rules.

1. "Rules" refers to the laws, regulations, industry standards, codes of conduct, and other formal and informal norms that govern behavior. For the space economy, these rules must be widely accepted and adhered to by a diverse range of actors spanning many nations, including commercial, governmental, and research organizations.
2. "Administration" refers to the implementation, enforcement, and adjudication of rules. Effective administration requires the existence of governmental and non-governmental organizations operating with both:

<sup>3</sup> O'Neill, G. K. (1977). *The high frontier: Human colonies in space*. William Morrow and Company.

<sup>4</sup> People encountering the idea of lunar development often have a few standard immediate concerns that should be mentioned. First, human activities will have no effect on tides, which are caused by the gravitational pull of the Moon on Earth, because nothing humans develop will make an appreciable difference on the total mass of the Moon. Secondly, it is very unlikely that humans will have a significant impact on the appearance of the Moon from Earth. The geological features of the Moon we can see with the naked eye are massive, and altering them would be an enormous, coordinated, and expensive undertaking. Activities affecting the brightness of the Moon are also unlikely and can be avoided with modest improvements in governance.

<sup>5</sup> Weinersmith, K., & Weinersmith, Z. (2023). *A city on Mars: Can we settle space, should we settle space, and have we really thought this through?* Penguin Press.

<sup>6</sup> Alanna Krolkowski, Martin Elvis, & Tony Milligan, *Crowding at Lunar Sites of Interest: Possible Ways Forward*, presented at the 2019 NSS International Space Development Conference.

- a. Ability – the organizations must have the political, legal, financial, and practical capacity to administer widely accepted rules.
- b. Aligned incentives – the success or failure of the organizations, and of the individual decision makers within them, must be tied to the long-term economic, social, and environmental outcomes of space development.

Without both the ability and incentive to administer effective rules, it is unlikely that any governing body will have a positive impact on the development of space.

Creating such a governance framework is essential to unlocking the full potential of the space economy. It must foster an open, competitive marketplace with low barriers to entry for new space startups and developing countries, sustainable resource use, international cooperation, and a fair and equitable society. This governance framework can begin with the Moon's key locations, and evolve, adapt, and replicate in other areas of the solar system, including asteroids and Mars.

## ii. Problems with Space Law

### Property Rights

The existing rules for space are not sufficient for the space economy. International space law provides high-level principles encouraging international cooperation and equitable access to space. However, these are not sufficiently detailed or enforceable to support space development.

Article 2 of the 1967 Outer Space Treaty has special relevance to the space economy for a few reasons. First, it prevents its member states from claiming territory in space, stating:

“Outer space, including the Moon and other celestial bodies, is not subject to national appropriation by claim of sovereignty, by means of use or occupation, or by any other means.”<sup>7</sup>

Secondly, Article 6 holds states responsible for the activities of non-governmental actors under their jurisdiction, including private companies. Many space law experts interpret these provisions to mean that neither private companies nor governments may claim permanent ownership of locations in space. This interpretation suggests that while companies can develop and use land, they may not have freehold ownership over it.<sup>8</sup>

National-level legislation is beginning to clarify property rights in space. Laws like the U.S. Commercial Space Launch Competitiveness Act<sup>9</sup> and the Luxembourg Space Resources Act<sup>10</sup> explicitly state that private entities can own resources they extract from space. Moreover, the Artemis Accords, which are a set of international principles guiding lunar exploration, assert that owning extracted resources does not constitute national appropriation under the Outer Space Treaty.<sup>11</sup>

Read together, these laws suggest that private companies and governments may own the structures they build and resources they extract from the Moon and elsewhere in space. However, according to dominant interpretations of the Outer Space Treaty, they cannot have permanent, freehold ownership of the land they develop.<sup>12</sup>

### Economic Development Without Land Ownership

Fortunately, it is possible to support a thriving economy without freehold land ownership. Land ownership provides a high degree of stability and flexibility, enabling owners to make large long-term investments and to alter or transact their property efficiently. However, other types of property rights regimes can also provide these benefits. The prosperous economies of Hong Kong and Singapore operate largely without private land ownership, for example. Indigenous communities, many of whom believe that land cannot be owned, have customary land tenure systems, in which the community stewards and enhances the value of land, including through development agreements with investors.

Many common-pool resources, like timber forests, grazing lands, and irrigation canals, have functioned very effectively without freehold ownership. In such cases, the users of the resource develop their own systems for allocating access rights and require holders of these rights to pay for infrastructure and services that enhance the value of the resource.<sup>13</sup> In many cases, these rights have been marketable, meaning they can be sold to other users and used as collateral for loans. These systems tend to be quite effective at preventing speculation, resource loss, and environmental damage.

### Needed Improvements

However, what is important for sustainable space development is a system where users can acquire secure rights to (a) operate and make long-term investments on the Moon; (b) keep the value those investments generate; and (c) flexibly change their investments in response to market conditions with low transaction costs.

<sup>7</sup> United Nations. (1967). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, Including the Moon and Other Celestial Bodies.

<sup>8</sup> Saletta, M., & Orrman-Rossiter, K. (2018). Can space mining benefit all of humanity?: The resource fund and citizen's dividend model of Alaska, the 'last frontier'. *Space Policy*, 43, 1-6.

<sup>9</sup> Government of the Grand Duchy of Luxembourg. (2017). Law of 20 July 2017 on the Exploration and Use of Space Resources.

<sup>10</sup> Government of the Grand Duchy of Luxembourg. (2017). Law of 20 July 2017 on the Exploration and Use of Space Resources.

<sup>11</sup> NASA. (2020). The Artemis Accords: Principles for Cooperation in the Civil Exploration and Use of the Moon, Mars, Comets, and Asteroids for Peaceful Purposes, Sec. 10(2).

<sup>12</sup> Notably, there are no reliable means of enforcing the Outer Space Treaty. Moreover, the treaty is not binding on any nations that have not ratified it or to companies under their exclusive jurisdiction. All current major space faring nations have ratified the Outer Space Treaty, however.

<sup>13</sup> Ostrom, E. (1990). *Governing the commons: The evolution of institutions for collective action*.

Unfortunately, no such system exists. Currently, a space company investing billions in developing a mine on the Moon might have a secure claim to the resources they extract, but potentially lack a legal right to stay at the site, keep others from interfering, or sell their investment if needed.

The good news is that it is possible to design one that does not involve national appropriation or private ownership of land, as Part II will show.

In addition to the property rights issue, there are many other regulatory gaps inhibiting the development of a sustainable and thriving space economy. These include labor and human rights; environmental and cultural heritage preservation; technical standards, such as for interoperability of airlocks, dust mitigation, and life support systems; and many more.

### iii. Problems with Space Administration

The gaps in the administration of space law are arguably as significant as the gaps in the legal framework. At the international level, several organizations are involved in regulating space activities, but their capacity to implement and enforce rules is limited. These include:

- The UN Committee on the Peaceful Uses of Outer Space (UN COPUOS) and the UN Office for Outer Space Affairs (UNOOSA) facilitate the negotiation and implementation of international space treaties.
- The International Telecommunication Union (ITU) allocates radio frequency spectrum and satellite orbits, ensuring that global communication networks operate without interference.
- The International Organization for Standardization (ISO) develops technical standards to help space systems function safely and consistently.

While these organizations contribute to the governance of space, they have little authority or capacity to enforce effective rules for space activities.

As a result, most space regulation is left to national regulatory agencies. These agencies, too, face significant challenges. They lack the authority to enforce their rules against space users from other nations and face hurdles when attempting to harmonize and coordinate their rules with other nations. Also, as private companies and nations expand their operations further away from Earth, their practical ability to monitor and enforce compliance will decline.

## Hypothetical Example: The Consequences of Existing Governance Gaps on Lunar Mining Operations

A private space company, LunarX, plans to launch a mission to mine water ice on the Moon, a resource critical for producing fuel and supporting human life. LunarX invests heavily, spending billions to land a robotic mining operation in a permanently shadowed crater, where water ice is believed to be abundant.

### Initial Success

LunarX successfully lands prospecting equipment, establishes a communication link with Earth, and begins gathering mineralogical data from the crater. They then find an extensive deposit and send a second mission to land mining equipment and return-launch vehicles. This mission begins excavation and transporting mined water to storage facilities in lunar orbit, where it will be used as fuel and life support for other space users. LunarX claims it needs a non-interference safety zone encompassing the entire crater to protect against damage from non-coordinated and unprotected competing operations.

### Competing Claims and Legal Uncertainty

A year into their operations, a rival company from another country, MoonCorp, arrives at the same crater and begins mining the same water ice deposit a short distance away. MoonCorp claims it has the legal right to operate in the area because it does not recognize LunarX's claim to the site under current space law.

The Outer Space Treaty prevents LunarX from owning the land it has developed, and there is no organization effectively managing access or mining rights. Each company now finds itself in a race to extract as much water ice as possible before the other depletes the resource.

### Diplomatic Efforts and Political Headwinds

Both LunarX and MoonCorp appeal to their respective governments for support. In response, their home countries engage in diplomatic efforts, seeking a bilateral solution and involving the United Nations in discussions. However, progress toward a resolution is slow. Both governments are preoccupied with other strategic concerns, and divisions arise within each country about how to handle the situation.

In both nations, "hardliners" insist their governments should refuse any compromise and protect their national interests at all costs. Meanwhile, others, skeptical of the companies' actions, argue that their governments should not intervene on the companies' behalf at all. Many citizens feel that there are far more pressing priorities at home than a lunar mining dispute, further slowing diplomatic progress.

### Environmental and Economic Damage

In the rush to extract resources fastest, both LunarX and MoonCorp operate inefficiently and dangerously. Each company spends a significant portion of their budget defending their equipment and operations against damage from the other. Additionally, the uncontrolled competition leads to excessive extraction, environmental damage, and the degradation of the water ice deposit. What could have been a long-term, sustainable resource is rapidly depleting, and the broader space economy suffers as a result.

### Private Settlement Amid Financial Collapse

As the conflict drags on, both LunarX and MoonCorp teeter on the brink of bankruptcy. Their operations have become increasingly costly due to interference and inefficiencies, and neither company can turn a profit. Desperate to avoid financial collapse, the two companies agree to a private settlement, mediated by a third-party arbitrator. The settlement allocates specific areas of the crater to each company, allowing them to continue their operations independently, but with a higher level of coordination.

### Worsening Conflict and the Onset of Chaos

However, by the time this private settlement is reached, the situation has grown more complicated. More companies from various nations have begun landing at other strategic lunar locations. Without a clear international framework to govern space resource extraction, these new entrants start mining the same locations as each other and engaging in similar conflicts as LunarX and MoonCorp. Incidents of interference, sabotage, resource depletion and violence multiply, and the threat of international conflict looms.

## iv. Implications

As illustrated in the above case study, problems with the space governance framework will rapidly increase risks and costs, compounding the already substantial expenses inherent in space activities and causing broader social impacts. The chances for a diverse, open, and competitive economy will dwindle.

Unless these gaps are addressed, space will be dominated by the few nations with the political capacity to spend vast public resources on space, and the private corporations with the highest risk tolerance. Only companies backed by powerful governments providing military and financial support will succeed. These entities will secure the most valuable lunar locations and defend them to prevent competition. Governments will rely on these companies to further their strategic interests, particularly in times of geopolitical or armed conflict.

Once these entities control the most valuable lunar locations, there is no guarantee they will use them efficiently. They will have little incentive to innovate efficient protective infrastructure so that many different parties can responsibly develop the same area. Instead, they will find it simpler to claim large exclusion

zones around their core sites as necessary to prevent conflict, interference, and resource protection.

With less healthy market competition, these entities will make less efficient use of lunar resources, letting them go to waste or intentionally limiting production to gain leverage in economic or political negotiations. They may also speculate on some of the sites, letting them go underused for years until demand rises significantly and then transferring them at a large profit.

Much of this activity might violate the Outer Space Treaty. However, without effective mechanisms for enforcing the treaty and with major nations backing the activities, little will be done to stop it.

### Lessons from History: The Formation of European “Company-States”

Finding relevant historical comparisons to the settlement of space is inherently challenging. When European powers colonized other continents from the 15th to the 18th Century, people there had already lived and cultivated thriving cultures, economies, and ecologies for thousands of years. For better analogies, we would need to look back to the settlement of truly uninhabited territory, such as the Pacific Islands by the intrepid Polynesian peoples 1,000 - 4,000 years ago, or to the settlement of the Americas (a land area roughly comparable to the Moon) many thousands of years prior.<sup>14</sup>

That being said, we can draw lessons from what we know of the more recent era of European colonization to understand and prepare for what is to come. During this period, European states lacked the political and financial resources to directly colonize other continents. As a result, they chartered the first corporations, owned in different cases by private investors or the state, to establish trade in Africa, Asia, and the Americas. Some of the most well known examples include the British East India Company, the Dutch East India Company, the Portuguese Estado da India, and the Hudson Bay Company.

These corporations became “company states.” Given the enormous capital requirements and risks, nations granted these companies monopolies over certain commodities, such as spices, metals, furs, or textiles. the power to govern the areas they occupied, including to pass laws, mint coin, establish courts, and wage war. As one might expect, they used their powers to serve their own interests, including to prevent competition by local entrepreneurs, impose heavy taxes, attack rival local nations and companies, and inflict abuses on workers with impunity.

European governments attempted to use these company states not only for enriching their nation's coffers, but to gain geopolitical dominance. In reality they had, at best, only partial control of their actions. Nations that had more control tended to drive the companies into

<sup>14</sup> These peoples were also, of course, settling lands filled with life – quite different from the Moon.

insolvency by forcing them to fight unprofitable wars and build economically unnecessary outposts. In many cases, however, states did not gain the practical ability to meaningfully regulate activities across such vast distances until the 19th Century. Both before and after this point, European colonization had a devastating impact on local populations.<sup>15</sup>

Similar events may unfold in space. As with the European states of this period, nations today may lack the budgetary or political resources to maintain substantial footholds in space, despite sensing a strong strategic interest in doing so. They may instead find it expedient to rely on large private-sector or state-owned corporations and, perhaps implicitly, empower them with similar monopoly privileges as earlier company-states. Given the remoteness of space, nations may find it impossible to regulate these companies' activities, even if they wanted to.

#### v. Limited Prospects for Change

Nations are unlikely to develop an effective governance framework for space on their own in time to avoid this future. This is due to the following factors:

1. **Difficulty Reaching Consensus on Rules -** Achieving agreement on detailed standards, rights, and obligations for space activities is unlikely in the near term. International negotiations are generally slow and uncertain, even in times of relative global cooperation and favorable domestic politics, and normally result in statements of broad principles rather than enforceable rules. Even if such rules are created, they will need to be updated regularly, as knowledge and conditions in space will evolve rapidly.
2. **Ensuring the Rules Support Economic Growth -** Even if nations can agree on enforceable rules, there is no guarantee the rules will promote economic growth. Many current proposals for addressing space governance problems would centralize power to regulate space activities in an intergovernmental body.<sup>16</sup> In practice, central-planning solutions like this tend to greatly slow economic development, are less responsive to local contexts, and are more susceptible to corruption.<sup>17</sup>
3. **Implementation and Enforcement Challenges -** Even if an agreement on rules conducive to economic activity is reached, nations are unlikely to have the political will to enforce it. Effective monitoring and enforcement in space requires significant investment and history suggests governments will choose to prioritize military advantage or financial interests over the formation of international market institutions that support a diverse, multinational space economy. If nations

did find the political will and resources to enforce such agreements, the bureaucracies created to administer these agreements will probably lack the efficiency, responsiveness, and innovation the space economy needs to thrive.

## II. The Lunar Development Cooperative

### A. Introduction

The Lunar Development Cooperative (LDC) will help solve many of the problems with space governance. The LDC will be a commercial entity providing infrastructure and other public services to any company or government entity operating on the Moon that agrees to become an LDC member. As a condition for receiving LDC services, members will be contractually bound to abide by rules governing their activities. These rules will help build a foundation for an open and sustainable market economy on the Moon.

The LDC's design will meet two key criteria for effective administration outlined in Section I.B:

1. **Ability:** As discussed in Section G, the LDC's physical presence in space, contractual relationships with members, and support from nations, will give it the legal and practical ability to implement and enforce binding rules governing its members' activities.
2. **Aligned Incentives:** As discussed in Sections F and H, the LDC will be subject to accountability mechanisms that keep it aligned with its social purpose, and its revenue will be tied to the long term value of the lunar economy, society, and environment.

The LDC concept aligns with the Outer Space Treaty, Artemis Accords, and other international norms. It can also be replicated for other valuable locations in space, such as for large asteroids and Mars.

### B. Formation and Organizational Structure

#### i. Organizational Form

The LDC will be a multinational, joint-venture public-private partnership and voluntary membership organization providing critical infrastructure and a rules-based order for space users. Created through combined capital investments from both private sector and government investors, it will serve private, governmental, and non-governmental members who opt-in and carry out operations on the Moon or in lunar orbit. Given its dual social and commercial purpose, it will be effectively a for-profit social enterprise, analogous to B-Corporations in the United States.

<sup>15</sup> Phillips, A., & Sharman, J. C. (2020). *Outsourcing empire: How company-states made the modern world*. Princeton University Press.

<sup>16</sup> For example, dominant space governance solutions, following the lead of the Moon Agreement (1979), have tended to propose solutions similar to the International Seabed Authority (ISA) and the Antarctic Treaty, both of which have served to limit development. The Moon lacks the biodiversity that the ISA aims to protect, and the social value of the Moon, which includes the sourcing of raw materials to support industrial activities, is considerably different from the role Antarctica plays. Therefore neither model is suitable for supporting the sustainable development of the Moon for the benefit of humanity.

<sup>17</sup> See, e.g., Ostrom, E. (1990); Acemoglu, D., & Robinson, J. A. (2012). *Why nations fail: The origins of power, prosperity, and poverty*. Random House; Scott, J. C. (1998). *Seeing like a state: How certain schemes to improve the human condition have failed*. Yale University Press; Ostrom, V. (1973). *The intellectual crisis in American public administration*. University of Alabama Press.

The LDC will be overseen by a board of directors and a management team, consisting of senior executives and a staff. Given its influential role, it will also be subject to strong oversight and accountability mechanisms implemented by an advisory board and inspector general described in Section H.

The Lunar Development Institute, described in Part III, will help lay the groundwork for the LDC. It will engage governments, the private sector, and other organizations to support the LDC's formation. It will also help develop technical and financial plans for the infrastructure and services the LDC will deliver after formation. Finally, the Institute will collaborate with a range of stakeholders to draft the founding charter, members contracts, and other legal instruments that will govern both the LDC and its members

## ii. Shareholding Structure

Any government or private-sector party from around the world will be able to purchase shares in the LDC. However, the shareholding structure will ensure its operations are driven by commercial objectives aligned with the broader interests of the space economy. Therefore two primary restrictions on LDC ownership will include:

1. Governments will be limited to owning 49% or less of the LDC, with the remaining 51% or more owned by individuals and private-sector organizations. Shareholding will include as many people and nations as possible.
2. No individual, entity, or nation will have so much control over the LDC that they can use it to serve their own independent interests at the expense of the LDC's purpose. For example, each private party and nation may be limited to owning no more than 10% of the LDC's total shares.<sup>18</sup> This rule will help prevent governments from controlling LDC decisions to advance independent political or military agendas, and private parties from stifling competition or establishing monopolies.

Governments will participate in the LDC through a variety of financial instruments. They can make direct capital contributions, such as investments from sovereign wealth funds, or provide loan guarantees and risk insurance, which will open up more funding from private investors. Governments may also enter into guaranteed purchase agreements, committing to buy a portion of the LDC's services or the products of LDC members. Importantly, these investments will differ from traditional space budget appropriations, as they are structured to deliver a profit, making them more justifiable to taxpayers.

On the private sector side, the LDC will begin with a small group of founding investors but will rapidly open its shareholding to as many entities and individuals as possible. It will set a low minimum investment threshold, such as \$1, and make shares available on a universally accessible trading platform. This approach will enable as much of humanity as possible to own the LDC, so that it serves as humanity's holding company for the Moon.

## iii. Developing Nation and Indigenous Group Participation

The LDC will enable developing nations and indigenous groups to participate more in the space economy. For instance, a developing country or indigenous group, even with a nascent or nonexistent space program, may make a relatively modest investment in the LDC and thus gain a stake in the emerging space economy. They may hold their stock in sovereign investment vehicles, which increase in value over time and enable them to invest in their own space programs.

Additionally, the LDC will create a stock option program for developing nations and indigenous groups, allowing them to buy shares at the initial, low offering price even after the shares have risen in value. The LDC's shareholding limits will also benefit developing nations, because wealthier nations will be limited in the amount of stock they can control, creating room for more diverse participation. Finally, developing nations and indigenous groups can participate in an independent advisory board that provides input and oversight over LDC decisions, as discussed in Section H.

## iv. Incorporation

The Lunar Development Institute will work with international stakeholders to incorporate the LDC. Instead of incorporating under the jurisdiction of a particular nation, the LDC will aim to incorporate under its own independent governance framework, similar to the way the World Bank, CERN, and other international organizations were incorporated. Alternatively, it may be incorporated in one of its founding-shareholder nations.

Nations may adopt their own domestic legislation governing their participation in the LDC. However, these laws would only determine their government's relationship to the LDC and would not be necessary to establish or govern the LDC.

## C. LDC Infrastructure and Services

After its formation, the LDC will develop the infrastructure and services most needed at that time to reduce barriers to participation in the lunar economy. These services will be available exclusively to LDC members, which will be any space user who forms a member contract agreeing to the LDC's rules for space activities and pays membership fees.

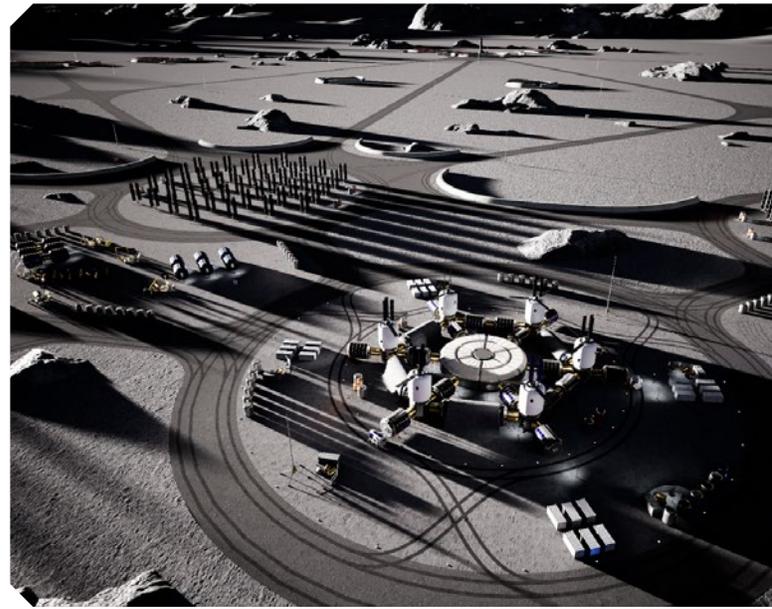
The LDC will finance these services through mechanisms used in other large-scale public-private partnership infrastructure projects. This will include a mix of debt and equity instruments, leveraging project finance vehicles and sovereign investments to lower risk and extend the return on investment (ROI) horizon.

The LDC's planned infrastructure and services will respond to the needs and circumstances of the time. The following hypothetical scenario outlines the types of services the LDC might offer over a 20 year period:

<sup>18</sup> This is a preliminary notional cap to illustrate the concept. The appropriate limits will be defined after further research. There may also be lower caps for voting shares than for non-voting shares.

### Years 1-3: Hypothetical Initial Off-Surface Infrastructure and Services

- Prospecting missions to gather data on the mineralogical composition of key locations on the Moon.
- Deploying orbital telecommunications relays and remote sensing infrastructure in lunar orbit.
- Streamlining regulatory processes with authorities in many nations to reduce approval times for launches, spectrum allocation, etc.
- Providing insurance to lower the financial risk for space operations.
- Developing data-sharing platforms where LDC members can access real-time data on lunar conditions, including topography, geology, and solar meteorological patterns.
- Launching an innovation fund and impact markets aimed at providing grants, prizes, or early-stage investment for innovative startups and research projects.



Aerial view of a conceptual LDC service hub. Courtesy of Daniel Inocente.



Conceptual master plan of LDC infrastructure. Courtesy of Daniel Inocente

### Years 3-7: Hypothetical Lunar Surface Infrastructure and Services

- Establishing an LDC registry to protect members from interference with registered activities.
- Building and operating landing pads with protective berms to mitigate lunar dust during landings.
- Developing lunar surface power generators and power beaming systems.
- Constructing surface telecommunications infrastructure for remote navigation and communication with lunar orbit and Earth.
- Building a harbor in lunar orbit or lagrange point 1 to facilitate cargo distribution to various locations on the surface.<sup>19</sup>
- Providing emergency search and rescue services.
- Establishing facilities with backup reserves of oxygen, water, food, and critical supplies.
- Mediating disputes between members to maintain a cooperative environment.
- Offering legal and diplomatic support to address interference from non-members.
- Instituting common technical standards for equipment and processes based on evolving best practices.
- Developing standardized contracts for use in commercial transactions.
- Developing cybersecurity measures to protect lunar operations and digital communications.

<sup>19</sup> Scholtes, K. (2024, April). Logistics and the design of a lunar harbor [PowerPoint slides]. Firefly Aerospace, presented at the Lunar Surface Innovation Consortium, available at [https://www.darpa.mil/attachments/DISTRO%20A%20-%20LunA-10%20LSIC%20Presentation\\_Firefly%20Space.pdf](https://www.darpa.mil/attachments/DISTRO%20A%20-%20LunA-10%20LSIC%20Presentation_Firefly%20Space.pdf)

## Years 7-20+: Advanced Infrastructure and Institutions

- Developing surface transportation networks, such as lunar roads and rail systems.
- Building and operating an electromagnetic railgun to propel material off the lunar surface.
- Building and managing a closed-loop biological waste processing recycling network, connecting members' habitats in a given region.
- Providing industrial waste management services, including processing and recycling systems.
- Assisting in the formation of a Strategic Space Commodities Reserve of key materials and resources at important locations.<sup>20</sup>
- Assisting in the formation of a Space Commodities Exchange for resource trading.<sup>21</sup>
- Offering IP protection services for technologies developed on the Moon, ensuring that companies retain their innovations and designs.
- Facilitating the creation of independent space dispute resolution systems, including arbitration and lunar courts.
- Supporting the development of a body of common law for the Moon, based on customs, best practices, arbitration decisions, and national legislation.
- Providing healthcare services for space workers and visitors.
- Developing a comprehensive disaster response framework to manage lunar emergencies, such as equipment failure, habitat breaches, or space weather events.
- Administering regulatory responsibilities delegated by governments.
- Developing a lunar space elevator for low-cost transportation of cargo and goods to and from the lunar surface.

The LDC will support the research and development of the underlying technology for these services where needed. It will use third party subcontractors to develop and deploy them, including existing space companies that are already developing these solutions. The LDC will establish guidelines and criteria for its investment decisions and procurement activities.

The LDC will aim to cluster its surface infrastructure around strategic locations that are already or expected to attract significant investor interest. This may include the lunar South and North Poles, permanently shadowed craters, areas of high-value mineral concentrations, and inhabitable lava tubes. The LDC will build spaceports in some of these areas so that its members will tend to locate their operations nearby, much as cities on Earth formed around important ports, harbors, and rivers.

The LDC will actively foster markets for the delivery of many of its services. It will aim to develop the capabilities of contracted service providers, provide members with a range of service delivery options to choose from, and simply monitor and fund the services. It may also transfer some services entirely over to the market. However, certain services, such as those involving the development and administration of rules and rights protection, will remain under the direct management of the LDC. The tools for enforcing and managing the transfer of LDC services are elaborated further in Section I.

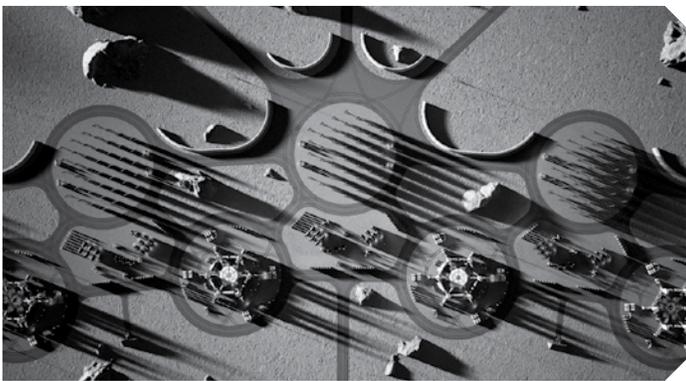
## D. LDC Registry

### i. Function

As discussed in Section I.B(1), the current status of property rights in space creates uncertainty for investors and poses environmental and social risks. The LDC will mitigate many of these problems with an LDC registry. The registry will not confer ownership of lunar land; rather it serves as a tool for managing uses of locations, providing greater security for investments, and reducing conflict.

LDC members seeking to use locations on the Moon will apply to have their proposed uses recorded in the LDC registry. LDC staff will review the application against clear and objective standards, including the size of the land area required, the anticipated quantity of resources to be extracted, the methods used, and the potential risks, waste, or environmental impact of the proposed activities. If the application satisfies the LDCs requirements, the LDC will approve it or, if not, require changes. Once approved, the member's planned use will be recorded in the LDC registry.

All LDC members will be obligated to avoid interference with the uses recorded in the LDC registry. A member who violates this obligation will be in breach of their membership contract with the LDC, resulting in fines, lawsuits, or, in serious cases, revocation of membership and denial of access to LDC services. The



Conceptual lunar habitat cluster enabled by LDC services. Courtesy of Daniel Innocente.

<sup>20</sup> National Space Council Users' Advisory Group. (2020, September 3). Assessing the utility of a U.S. strategic in-space propellant reserve: Economic development in low Earth orbit and cislunar space.

<sup>21</sup> Cahan, B.S., Pittman, R. B., Cooper, S., and Cumbers, J (2018) Space Commodities Futures Trading Exchange: Adapting Terrestrial Market Mechanisms to Grow a Sustainable Space Economy. New Space, September 1.

membership contract will also recognize other members harmed by the violation as third-party beneficiaries, allowing them to sue as well.

As a result, the LDC registry will confer contractually enforceable rights to members with uses recorded in it. A member's LDC membership fees will be priced based on the estimated market value of the rights they have recorded in the LDC registry, as discussed further in Section F.

As the lunar economy matures, the LDC will help establish markets for these rights in which members can buy, sell, lease, collateralize, or otherwise transfer rights recorded in the LDC registry to other members. This system will be similar to the way rights to carbon emissions, groundwater basins, irrigation canals, fisheries, and other common pool resources are established and transacted in many parts of the world.<sup>22</sup> It will provide many of the elements of an effective property rights system – including the ability to securely and flexibly make long-term investments, keep the value those investments generate, and transact with other parties – but without ownership of land.

### **Hypothetical LDC Registration 1: A Mining Company Operating in a Specific Location**

#### **Scenario:**

Lunar Resources Corp, a private company focused on mining lunar ice applies to the LDC to secure rights to a specific area near a permanently shadowed crater at the Moon's South Pole.

#### **Application Process:**

Lunar Resources Corp submits a proposal to the LDC detailing its intended extraction methods, the size of the area needed for mining operations, the estimated quantity of water ice to be extracted over time, and the expected impact on the surrounding environment. The LDC evaluates the application against its internal criteria and suggests a modification to the size of the land area to minimize overlap with a nearby planned research facility that could be affected by dust. The company agrees to the terms, and the LDC records its right to operate in the LDC Registry.

#### **Outcome:**

As a result, Lunar Resources Corp is protected from interference by other LDC members and can proceed with its mining operation. The company pays an annual membership fee based on the market value of the rights granted to it and is contractually obligated to respect the rights of neighboring users. If another company tries to mine in the same area, the LDC can intervene to enforce the terms of the registry, ensuring that the original claim is respected.

### **Hypothetical LDC Registration 2: A Resource Extraction Company Operating Over a Wide Area**

#### **Scenario:**

Lunar Minerals Inc., a private company specializing in the extraction of Helium-3, plans to harvest the resource from the Moon's surface. Helium-3 is scattered thinly over a large, wide area, so the company's operations will require access to an extensive region.

#### **Application Process:**

Lunar Minerals Inc. applies to the LDC to register its intended use and ensure its operations are protected from interference by other members. Its application specifies the exact boundaries of the large area required for its operations, the methods it will use to extract Helium-3, and its plans to minimize environmental impacts. The company emphasizes that its extraction techniques are non-invasive and will not disturb other potential resources in the area.

#### **Evaluation:**

The LDC evaluates the application carefully, considering how the extraction of Helium-3 could affect the broader environment and future uses of the area. The LDC verifies that the company's request meets LDC standards, utilizes sustainable extraction methods, and will not interfere with other valuable resources, such as nearby water ice deposits, or harm the potential for other future uses of the land. The LDC also ensures that Lunar Minerals Inc.'s operations will not hinder scientific research or future development projects in the region.

#### **Approval and Registration:**

The LDC grants Lunar Minerals Inc. the right to harvest Helium-3 over the specified area using the approved methods. The LDC registers these rights in the registry, ensuring that other members are aware of Lunar Minerals Inc.'s operations and cannot interfere with them. However, since the extraction method is non-invasive, the area remains available for other uses, allowing additional companies or researchers to conduct activities that do not conflict with the Helium-3 extraction.

<sup>22</sup> See, Ostrom, E. (1990).

## Hypothetical LDC Registration 3: A Space Tourism Company Making a Long-Term Investment at a Particular Site

### Scenario:

Lunar Getaways, a luxury tourism company, plans to build a high-end resort on the Moon for tourists and events. The resort is to be located in a scenic valley with breathtaking views of the lunar horizon, valley walls, and proximity to historic landing sites. Lunar Getaways intends to make a significant sunk-cost investment in constructing the resort and wants to ensure that the view remains unobstructed for at least 40 years, preserving the scenery for its guests and securing the value of its investment.

### Application Process:

Lunar Getaways submits an application to the LDC, detailing its plans to build the resort and requesting that the LDC protect the unobstructed view of the valley. The company specifies the boundaries of the location where it intends to build the resort structures and also defines the area where it seeks to maintain an unobstructed view. The request includes the right to prevent any development within that view corridor for the next 40 years.

### Evaluation:

The LDC evaluates the application by reviewing the proposed location and the surrounding area that would need to remain free of obstructions. It assesses whether there are other potential uses for the unobstructed view area and considers how restricting development in this zone might impact future projects or users.

### Approval and Registration:

The LDC grants approval to record in its registry Lunar Getaways's right to exclusive use of the site planned for the resort and a restriction on development in the view area for a period of 40 years. The record makes clear what activities are restricted for all other members within the specified view corridor during this time.

### Outcome:

Lunar Getaways proceeds with its massive investment, confident that the resort's site and views—one of its key attractions—are secured for the next four decades. The company pays an annual membership fee to the LDC based on the market value of the site and the protection of the unobstructed view. The LDC ensures that other users do not interfere with Lunar Getaways' rights, allowing the company to preserve the scenic beauty of the area for its guests.

## ii. Consistency with the Outer Space Treaty

The LDC's registry will be compliant with the Outer Space Treaty. Rights recorded in the LDC will not equate to appropriation by nations or private parties, because they will not confer permanent, or freehold, ownership of land. Rather, they will merely define the specific uses that the LDC chooses to recognize and protect against interference from other members through its contracts with them.

Importantly, the LDC will not act as a sovereign power. The LDC's authority to make and enforce rules, including for its registry, will be comparable to a voluntary trade association or union, which can enforce rules among its members but has no authority over non-members. This means that the LDC will only be able to restrict its members' access to land or resources, but not access by non-members who have opted out of LDC services.

Therefore, non-members will be theoretically free to carry out activities the LDC does not approve, even activities that interfere with the registered activities of LDC members. To the extent non-LDC members carry activities that lower the value of a member's recorded uses in the LDC registry, the member's membership fees will be reduced, since the market value of their rights will be lower.

## E. Managing Interference from Non-Members

The discussion above raises an important question: If the LDC will not have authority over the actions of non-members, how will it protect its members from interference by them? While the LDC will not be able to completely eliminate non-member interference, it will implement strategies that significantly reduce their likelihood and impact.

### i. Development Planning

First, the LDC will prioritize critical infrastructure and services that will be prohibitively difficult for individual space companies or nations to provide independently. The LDC, by pooling patient, reduced-risk investment from a diverse range of private and public sources, will build larger and higher-quality infrastructure than single companies or nations will be able to on their own. Moreover, because it will serve many members, the LDC will benefit from economies of scale, making its services far more cost-effective. For a company or nation to replicate such infrastructure on its own would require massive expenses that they could avoid by becoming LDC members.

Secondly, the LDC will pursue a strategy of clustering its services in high-demand areas likely to attract significant interest from space users, such as near rich mineral deposits, sites receiving near permanent sunlight, or lava tubes suitable for habitat construction. By concentrating its infrastructure and services around these strategic locations, the LDC will make it less likely that non-members will operate there.

Imagine how these two approaches will shape the rationale of a space user deciding on whether to become an LDC member. Without membership, such a company will need to independently source all the infrastructure to meet its operational needs. This scenario will be like a company opening a new factory on Earth without access to a power grid, water supply, roads, airports, etc., but instead will need to build it all itself. This will be especially challenging if the factory is in a town where all of this infrastructure exists around it but is not available to it. The company will need to find ways to work around the existing infrastructure and build its own. Given these challenges, if the company still wants to operate with independent infrastructure it will probably choose to operate in a remote area, where the risks of interference and conflict are minimal.

This means that space users that choose to go it alone will be more likely to operate in locations at some distance from the primary areas the LDC will serve. There, they will pose less risk to LDC members.

Based on this, LDC members who choose to locate in areas not well serviced by the LDC will face a greater risk of interference from non-members. However, these members will benefit from lower membership fees, as the rights granted through the LDC's registry, along with their access to LDC infrastructure, will have less value. This will be elaborated further in Section F.

Another possibility for non-members will be to seek services from alternative infrastructure providers, such as state-run entities or other private or public-private partnerships providing services for separate customer bases. However, as discussed in Section K, even if there will be enough market share for multiple providers, these alternative providers will likely be at a competitive disadvantage to the LDC unless they largely copy the LDC's approach.

Nevertheless, for purposes of the present discussion, the chances are low that these alternative infrastructure providers will invest in services at the same sites as LDC infrastructure. They will be more likely to prioritize areas with limited LDC service coverage. Consequently, it is unlikely that non-members will locate near the highest concentrations of LDC members, reducing the likelihood and severity of interference.

### **Hypothetical Example: A Non-Member Mining Company's Potential for Interference with LDC Members**

Ironclad Minerals Corp., a mining company from a repressive nation seeks to begin mining operations for water-ice, thorium, uranium, and aluminum on the Moon. After conducting surveys, the company identifies a few areas with rich deposits of these minerals. However, the top two sites have already seen significant development by the LDC and its members.

#### **LDC's Offerings**

At these prime locations, the LDC has built small spaceports, offering launch and landing services for its members. One of the sites also features a peak of eternal light, a highly coveted location that receives near-constant sunlight, where the LDC has established a solar power plant and power beaming infrastructure, providing abundant and low-cost energy to members. Additionally, both sites are equipped with LDC telecommunications towers linked to orbital relays, offering reliable communication with Earth. The LDC provides emergency shelters, search and rescue services, and backup life support in these areas, along with a closed-loop biological waste recycling network that efficiently processes human and plant waste, distributing the resulting useful by-product resources to support gardens at members' habitats. This waste recycling network, though currently serving around 10-12 members at each site, is expected to grow in value as more members join, enhancing its resilience and ability to ensure ecological balance among habitats.

Furthermore, Ironclad Minerals Corp. learns that the LDC has plans to construct a space station at Lagrange Point 1, which will prioritize cargo shipments for LDC members, making it easier for them to transport resources to and from different locations on the lunar surface and Earth orbit.

## Ironclad's Practices

However, several aspects of the LDC's membership and operational requirements present challenges for Ironclad Minerals. The company plans to use cheap, low-skill mining techniques that, while cost-effective, will result in significant resource wastage and environmental degradation—practices that violate the LDC's sustainability standards. Additionally, the company intends to rely heavily on forced labor, drawn from its home country's prisons and political dissidents. It plans to provide only the bare minimum in working conditions, ensuring workers survive long enough to be productive for a few years before being replaced by new conscripts. The company also intends to maintain strict control over labor by violently suppressing any strikes or protests. These practices directly contradict the contractual obligations of LDC members, which protect workers' rights and environmental standards. Joining the LDC without significantly changing their plans would make the company vulnerable to fines and legal action through international arbitration.

## Decision Dilemma

Ironclad Minerals faces a difficult decision. It has three main options:

1. **Locating at one of the top two sites where the LDC is already present.** This would mean building its own infrastructure, including launch facilities, power supply, and telecommunications, despite the existence of higher-quality infrastructure provided by the LDC. The company would likely face constant disputes with LDC and the individually affected LDC members over shared resources and surface operations and would have to allocate additional resources to defend its operations.

2. **Locating at the third-best site where the LDC has no presence.** While the mineral deposits here are not as abundant, the company would avoid conflicts with LDC members and could operate independently, albeit with the significant cost of building its own infrastructure from scratch.
3. **Agreeing to change its practices** to comply with the LDC's labor, environmental, and operational standards and become an LDC member. This would allow the company to benefit from the LDC's superior infrastructure.

## Final Decision

Ironclad Minerals ultimately chooses option (2): to relocate to one of the less resource-rich areas where the LDC has no presence. This decision allows the company to avoid the costs of complying with LDC standards, particularly since it has an abundant, replenishable supply of forced labor from its home country. Additionally, the company's home government, which is hostile toward any cooperation with the LDC, offers financial support to cover some of the infrastructure costs.

As a result, Ironclad Minerals begins operations in a remote area, far from the LDC's hubs. Since they have rejected LDC membership, the LDC is unable to directly prevent Ironclad from violating its workers' rights or harming the environment where they operate.

However, the LDC has had a positive influence. It protected its members from interference at its core hubs, allowing them to operate in a more peaceful, just, and prosperous environment. It has also made Ironclad's decision more difficult and costly and made it more likely that other similar parties will see it is in their economic best interest to choose the LDC system.

## ii. Diplomacy

The LDC will also protect its members from interference by leveraging its bargaining strength to influence policymakers from supportive countries on Earth. The LDC will encourage these governments to apply diplomatic pressure on behalf of its members to reduce interference, much like the role trade associations play on Earth.

Additionally, over time, nations may grant formal or informal recognition to the LDC's rules and the rights recorded in its registry. This will give the LDC members' claims regarding interference greater authority in domestic and international law.

## F. LDC Revenue

The LDC will have two sources of operational revenue: membership fees and usage fees. Over the long run, revenue from membership fees will far surpass usage fees and become the primary means for both delivering a return on investment and aligning the LDC's incentives with the overall growth of the space economy. Usage fees, which include charges for the use of power, utilities, landing pad, and other services, will have far less revenue-generating potential. Moreover, keeping usage fees low will help reduce barriers to accessing space and be an attractive advantage of LDC membership.

### i. The Pricing of Membership Fees

Membership fees will be calculated based on the estimated annual market value of the rights the member has secured from LDC membership. This "market value" will represent the highest amount a party is willing to pay each for the rights recorded in the LDC registry. This value will be driven by both demand and supply factors.

#### Demand Factors:

Factors affecting the level of demand for rights recorded in the LDC registry include:

- Natural characteristics of the location: Rights recorded for activities in areas rich in resources or with unique attributes (e.g., permanent sunlight) will naturally attract higher demand and therefore be more valuable.
- Proximity to LDC infrastructure: Rights recorded for activities close to landing pads, power grids, and communication networks will be more in demand and therefore more valuable.
- Quality of LDC services: The level of service the LDC provides will affect demand and therefore increase the value of rights.
- Security of the rights in practice: How effectively the LDC can protect a member's rights from interference by other members or non-members will affect their value.
- The LDC's governance and enforcement: The LDC's ability to create and enforce rules that foster a thriving lunar economy, society, and environment will increase demand for LDC membership and enhance the value of recorded rights.

#### Supply Factors:

The supply side of the value equation will be determined by the level of exclusivity the member requires. Here, the LDC will evaluate how many other rights it could grant for the same site, either for simultaneous or future use. A member who requires exclusive use of a specific area for a long period, including access to all surface and subsurface minerals, will pay a higher membership fee than a member seeking less exclusive use of the same area.

The hypotheticals below help unpack this pricing approach by extending upon the previous scenarios described in Section D.

## Hypothetical Membership Pricing Example 1: Lunar Resource Corp. – Mining Rights to a Specific Location

### Scenario:

Lunar Resource Corp. seeks to mine a specific quantity of water ice from a particular deposit in a crater near the Moon's south pole.

### Demand Factors:

- Natural Characteristics: The crater is an optimal location, with permanently shadowed regions and areas that receive near-constant sunlight. It is known to have an abundant supply of valuable minerals.
- Quality and Proximity of LDC Services: The LDC has built high-quality infrastructure adjacent to the site, including a landing pad and a reliable power supply.
- Protection: The LDC's enforcement of contracts is robust, and there is a low risk of interference from other members. Non-members are also unlikely to operate in the area due to the strong LDC presence.
- Governance: The LDC's rules and administration are well regarded, creating an efficient, fair, and predictable operating environment while protecting the long-term value of the lunar environment.

### Supply Factors:

Lunar Resource Corp. plans to mine at most 25% of the deposit, leaving room for other companies to also mine there. As such, they are requesting non-exclusive rights to a quarter of the deposit.

### Result:

The value of the mining rights is high due to the site's natural advantages and proximity to LDC infrastructure. However, since the rights are non-exclusive and shared with three other companies, Lunar Resource Corp.'s membership fee will be set at no more than 25% of the total estimated annual value of the mining rights in the area.

## Hypothetical Membership Pricing Example 2: Lunar Minerals Inc. – Resource Extraction Over a Wide Area

### Scenario:

Lunar Minerals Inc. intends to harvest Helium-3 over a broad area, while minimizing disruption to other potential uses of the land.

### Demand Factors:

- **Natural Characteristics:** The area has few natural advantages and no significant concentrations of other valuable minerals.
- **Quality and Proximity to LDC Services:** The site is far from the nearest LDC spaceport, requiring the company to cover long distances for transport and provide its own power.
- **Protection:** Due to the remote location, there is a moderate risk of non-LDC members attempting to also extract Helium-3 from part of the same area before Lunar Minerals Inc reaches it.

### Supply Factors:

The company plans to run its equipment over the area once in a two-year period. The land will be available for other uses both during and after this time. However, there is a risk that the harvesting process could destroy resources that might become valuable in the future, which might reduce the value of rights the LDC would record for the area in the future.

### Result:

The value of the requested rights, and thus the membership fee, is relatively low. This is because the area is not in high demand, being far from LDC services and its ability to protect against interference from non-members. Also, the non-exclusive nature of the request allows the LDC to grant rights to other parties. However, the fee will be increased somewhat to account for the risk of damaging future resources.

## Hypothetical Membership Pricing Example 3: Lunar Getaways – Long-Term Investment at a Particular Site

### Scenario:

Lunar Getaways wants to build a resort in a scenic valley assuring unobstructed views of the surrounding walls and horizon for at least 40 years.

### Demand Factors:

- **Natural Characteristics:** The site offers stunning views, especially during “Earthrises,” which have been popularized in recent photographs. However, the location lacks significant natural resources.
- **Quality and Proximity to LDC Services:** The resort would benefit from close proximity to the LDC’s best spaceport, a stable power supply, emergency response services, and high-quality transportation options.
- **Protection:** While the LDC infrastructure protects against non-member interference, there is an issue with a nearby LDC member, a mining company, whose operations sometimes generate dust that affects the valley. The LDC is actively addressing the issue through fines and legal action and has promised to step up enforcement if the resort is built.

### Supply Factors:

Lunar Getaways is requesting exclusive rights to the area for 40 years, with a prohibition on any other development in the vicinity.

### Result:

The market value of these rights is high due to strong demand for the location and the long exclusivity period. The membership fee will be somewhat reduced, however, by the ongoing enforcement challenge with the neighboring mining company.

## ii. Benefits of the LDC’s Revenue Model

The LDC’s approach of pricing membership fees based on the annual market value of the rights recorded in the LDC registry will have significant social benefits.

### Finances Space Infrastructure without Taxes

The revenue generated from membership fees will be large enough to repay the cost of the LDC’s infrastructure and services. This means LDC expenses will pay for themselves without taxing people on Earth or in space.

The more the LDC makes efficient investments in infrastructure, adopts and enforces good rules, and generally manages and serves its members well, the more space users will become LDC members and carry out activities near LDC infrastructure. These members will want to protect their investments by acquiring rights from the LDC registry. As demand for these rights rises, so will their market value, which will translate into a corresponding increase in revenue from membership fees. The LDC will recycle this revenue into further infrastructure and service investments and to repay the previous investments.

Economic theory and actual practice on Earth bear this model out. Investments in infrastructure and good governance have historically increased demand for scarce resources, raising the value of access to these resources to match the costs of investment. For instance, major infrastructure projects during the 19th century, such as the transcontinental railroads and Erie Canal, as well as new systems for allocating rights to natural resources, like mining, fishing, timber, and oil, had an enormous impact on values in the American Midwest and West.

As a result, it should be unnecessary for governments to raise taxes to finance space infrastructure. Instead, they can make investments in the LDC that generate a profit for taxpayers.

### **Prevents Speculation and Ensures Efficient Use**

By tying membership fees to the value of rights in the LDC registry, the LDC will ensure that locations are put to their highest and best use. Members will be less likely to leave valuable sites underutilized because they will be paying a membership fee based on the market value of their rights to use the site. Members will therefore have no incentive to speculate on lunar sites. Because they must pay annually for the value of the rights they hold, they will seek to develop and generate revenue from the rights, or, if they cannot, to sell them to another member who will.

#### **Hypothetical Example of Membership Fees Preventing Speculation**

Lunar Resource Corp., having secured valuable rights to mine water ice from a crater, encounters financial trouble. Several investors pull out, leaving the company without the capital necessary to carry out its mining project.

Without the obligation to pay annual membership fees, Lunar Resource Corp. might be tempted to sit on its rights and speculate on the site. Given the rising demand for mining rights at this crater, the company could hold onto its claim for several years and later sell it at a substantial profit.

However, since the LDC's membership fees are based on the annual market value of the mining rights, holding the rights without generating revenue from the site would only lead to mounting expenses, further worsening its financial difficulties.

As a result, Lunar Resource Corp. transfers its rights to another LDC member who is ready to begin developing the site. The LDC's membership fees pricing mechanism effectively avoided speculation and ensured the site was used more efficiently.

### **Aligns the LDC's Incentives with the Common Good**

This revenue model will also align the LDC's incentives with long-term economic, social, and environmental benefits. The more the LDC:

- Develops and provides critical services;
- Fosters open, competitive, and inclusive economies;
- Promotes thriving environments for workers, visitors, and residents; and
- Preserves and enhances the lunar environment,

...the more demand will rise from space users to become members and record rights in the LDC registry. Higher demand will translate directly into higher revenue from membership fees, reinforcing the LDC's motivation to sustain a healthy and vibrant lunar ecosystem over the long run.

In contrast, if the LDC prioritizes short-term returns at the expense of long-term sustainability—such as by allowing influential members to harm other members or degrade the environment—it will risk losing trust and membership will drop. As trust diminishes, there will be less demand for registrations and, consequently, a decline in revenue.

LDC investors will be also encouraged to prioritize long-term value creation over short-term returns through financing tools, such as sustainability-linked bonds, to attracting patient capital.

## **G. Enforcement of LDC Rules**

The LDC will be uniquely positioned to address enforcement challenges in space on behalf of national governments. In many cases, it will have superior monitoring capabilities, greater ability to hold members legally accountable, and a stronger incentive to protect the long-term value of the lunar economy than governments on Earth.

### **i. Monitoring Capabilities**

The LDC's physical presence in space, owing to its role in maintaining critical infrastructure and facilities, will provide it with the ability to monitor members' activities. This on-the-ground oversight will allow the LDC to track compliance in real time, a task that will be difficult for Earth-based governments without a significant direct presence in space.

<sup>23</sup> See, e.g., Arnott, R. J., & Stiglitz, J. E. (1979). Aggregate Land Rents, Expenditure on Public Goods, and Optimal City Size. *The Quarterly Journal of Economics*, 93(4), 471–500 (describing the Henry George Theorem). Many cities finance infrastructure based on this principle. OECD/Lincoln Institute of Land Policy, PKU-Lincoln Institute Center (2022), *Global Compendium of Land Value Capture Policies*, OECD Regional Development Studies, OECD Publishing.

<sup>24</sup> Libecap, G. D. (1989). *Contracting for property rights*. Cambridge University Press.

## ii. Contract Enforcement

The LDC will hold its members accountable through its contracts with them. Members' contracts will cover a variety of issues, such as interference with rights recorded on the LDC registry, minimum technical standards, intellectual property protection, waste management, environmental protection, human rights and labor practices, resource extraction techniques, and anti-competitive or monopolistic behavior. The LDC will base these standards on existing international instruments and best practices, drawing from the ISO, U.N. Declaration of Human Rights, International Labor Organization Conventions, and other broadly accepted documents.

The contracts will specify what actions the LDC will take in response to breaches of these rules. For minor violations, the LDC may merely issue warnings or require verifiable corrective action. In more serious cases, it will impose fines. If a member fails to pay fines or refuses to comply with corrective actions, they may lose rights to certain LDC services.<sup>25</sup>

Similar to most international business contracts today, member contracts will outline dispute resolution mechanisms, which will include choice of law and choice of forum clauses. These clauses will specify arbitration options or designate the courts of particular nations where disputes may be brought. To enforce arbitral awards against a member, the LDC may leverage the New York Convention, which enables the enforcement of arbitral awards through court judgments in nearly any country on Earth.<sup>26</sup> This will enable the LDC to seize a members' assets held in any of these nations to recover its award.

## iii. Independent Arbitration and Courts

As space development progresses, the LDC will play a key role in facilitating the creation of independent arbitration and judicial institutions in space. These institutions will become increasingly specialized in addressing the unique legal and operational challenges of space activities.

Over time, the LDC will collect and publicize decisions from these bodies and foster the development of commercial and technical standards based on widespread practices among space users. By assembling these rulings and standards into public databases, the LDC will help shape an evolving body of lunar law and norms, providing greater clarity and predictability for space users and judges.

Crucially, the LDC will be obligated to respect the independence of these courts and arbitration centers, recognizing that independent judicial systems are essential for the sustainability of a thriving lunar economy and society.

## H. Legal Safeguards and Accountability

While linking the LDC's revenue model will help align its incentives, it will not be enough to ensure the LDC prioritizes long-run economic, social, and environmental conditions. Given its scope and influence, the LDC will need to be subject to binding legal requirements and accountability mechanisms.

### i. Shareholder Restrictions

To prevent any single party from dominating the LDC, strict limits will be placed on the percentage of shares that any private entity or government can own, such as 10%. Lower limits may be placed on voting shares than on non-voting shares. This will ensure that no entity can steer the LDC toward its own goals at the expense of the cooperative's broader mission.

For example, government members will not be able to acquire enough control to influence the LDC's decisions for geopolitical or military purposes. Instead, their investment will serve two objectives: to help develop a sustainable lunar economy for the benefit of all and to generate a financial return on investment.

Similarly, private companies will be prevented from using their shares to advance commercial interests that conflict with the overall goals of the lunar economy. For instance, they will be prevented from manipulating LDC rules or enforcement practices to stifle competition or benefit their own operations at the expense of others.

Enforcing these restrictions will require tracing ownership through complex corporate structures to prevent parties from acquiring excessive shares via shell companies or indirect ownership. To accomplish this, investors will be subject to independently verified reporting requirements that enable LDC oversight bodies to trace beneficial ownership. Emerging decentralized digital identity technology will help aid this effort.

### Hypothetical Example: What the LDC Could Become without Limits on Shareholding

Maxime Aldrich, the world's first trillionaire, has already established a portfolio of Fortune 500 companies, including an artificial intelligence company and AstraLift, a leading space transportation provider. Now, he sets his sights on space as the next frontier for his empire, planning to launch a series of ventures including lunar mining, mineral processing, fuel production, and habitat construction companies. To support these ventures, Aldrich proposes the creation of the Lunar Development Cooperative (LDC) as a public-private partnership, offering services not only to his companies but to the wider space industry.

<sup>25</sup> In such cases, the LDC will be legally bound to make accommodations necessary for avoiding serious risk to human life.

<sup>26</sup> United Nations. (1958). Convention on the recognition and enforcement of foreign arbitral awards.

### Shareholding under Aldrich's control

However, unlike our proposal, Aldrich structures the LDC so that 49% of the shares are sold to governments, while he retains a controlling 51% stake for himself, without any limits on individual shareholding stakes.

Aldrich's home country agrees to purchase 40% of the LDC, while allied nations acquire the remaining 9%. At first, Aldrich pledges that the LDC will function as a neutral, public service entity dedicated to fostering an open and competitive space ecosystem. In the early years, the LDC delivers on this promise, building critical infrastructure that serves a broad range of space enterprises—including some that directly compete with Aldrich's companies.

### The LDC Begins to Turn From Its Core Purpose

As time passes, Aldrich begins to use his majority control to steer LDC policies in his favor. The LDC introduces new rules requiring members to disclose sensitive proprietary information under the pretext of improving oversight. Soon, innovations from competing firms mysteriously begin to show up in Aldrich's ventures. The LDC also starts favoring companies that collaborate with Aldrich's enterprises, while competitors face stricter enforcement of rules and less favorable access to services. LDC members soon realize that doing business with Aldrich offers distinct advantages over competing with him.

Meanwhile, Aldrich's government starts exerting influence on LDC operations. Political leaders push for unnecessary pet projects, and government agencies demand involvement in member approvals, adding costly and time-consuming regulatory hurdles. Their defense ministry asks the LDC to divert resources toward military capabilities to counter the rising threat of a rival spacefaring nation.

Aldrich recognizes that these demands would impose unsustainable costs on the LDC, but knowing that his country is a major investor and a key customer for his separate private ventures, he compromises. While he tempers some of the more extreme proposals, inefficient infrastructure projects begin draining LDC resources, and the value of the LDC's services to its members declines.

Eventually, Aldrich uses his majority control to enact policies that force all LDC members to use AstraLift for Earth-Moon transport and prohibit them from selling to or buying from companies outside Aldrich's conglomerate. He then lowers the prices his ventures pay for goods and services, ensuring that suppliers can barely remain profitable.

Frustrated by these actions, LDC members file lawsuits and appeal to regulators in Aldrich's home country for an antitrust investigation. If these mechanisms are unsuccessful, LDC members have no viable alternatives. Creating a competing infrastructure provider is virtually impossible, given the enormous cost of building space infrastructure, combined with the fact that the LDC's policies, under Aldrich and his nation's control, have limited growth in the market.

### Inability to Reign Aldrich in

While these disputes are ongoing, tensions between his country and its rival escalate when the rival establishes a lunar base with military capabilities. In response, policymakers in Aldrich's home country pressure the LDC to dramatically increase its defense spending to prepare for potential conflict and to commit to attacking the rival's assets on the Moon if ordered. Aldrich, realizing this could further destabilize the LDC, initially resists. However, the promise of lucrative defense contracts for his other companies—and a tacit agreement from his country leaders to overlook his monopolistic practices—convinces him to support the plan.

As a result, the LDC increasingly redirects its resources away from core infrastructure services and regulation, prioritizing military development and geopolitical interests. With Aldrich's monopolies firmly entrenched and the quality of LDC infrastructure declining, members struggle to operate profitably. The general public, once filled with hope about an open and competitive space economy, watches as the vision for a thriving space ecosystem collapses under the weight of monopolistic control and heightened risk.

### How This Could Have Been Avoided

If the LDC had shareholding limits, neither Aldrich nor his government would have exerted so much control over the LDC. Aldrich's voting shares and overall ownership would have been brought to a level that prevented him from using the LDC to benefit his separate ventures at the expense of the overall lunar society. His government's shares would similarly have been insufficient to cause the LDC to divert resources to unprofitable projects serving political and military interests unrelated to the LDC's purpose. The LDC's governance and accountability mechanisms would also have been more effective and empowered LDC members and minority shareholders to force it to maintain a more open, competitive, and peaceful economy.

## ii. Contracts with Members

LDC contracts will not only create obligations for members, but give them rights and means of holding the LDC accountable. These contracts will obligate the LDC to adhere to standards ensuring fair treatment and high-quality services. If the LDC fails to meet these obligations, members will be able to turn to independent accountability mechanisms, such as the inspector general, or to independent courts to seek remedies.

## iii. Founding Legal Agreements

The LDC will also be bound by the commitments laid out in its founding legal documents, including its Shareholders' Agreement and Charter. These agreements will impose legal obligations on the LDC to uphold its mission of promoting long-term economic, social, and environmental conditions on the Moon. Key elements will include:

- **Adherence to International Norms:** The LDC will be obligated to promote international law and best practices, including international space law, labor standards, human rights protections, and environmental safeguards.
- **Respect for Indigenous Groups:** The LDC will need to respect the cultural or spiritual connections that indigenous peoples have to space, ensuring their interests will be considered in decision processes.
- **Minority Shareholder Rights:** Minority shareholders will have the ability to file lawsuits if the LDC acts in ways inconsistent with its mission. This will safeguard against larger shareholders working in tandem to overly influence operations for their personal gain.
- **Broad Distribution of Benefits:** The LDC will ensure equitable distribution of the value it generates in space, ensuring that shares are purchasable and tradable by as many people on Earth as possible. The LDC will serve as humanity's holding company for the Moon.

## iv. Governance and Accountability

The LDC will be controlled by a board of directors comprising representatives of key shareholders and shareholder groups, as well as a number of independent directors selected for their expertise. The LDC's day-to-day operations will be handled by a professional management team, including a chief executive officer appointed by the board of directors.

To ensure impartial oversight, the LDC will be subject to independent accountability mechanisms, overseen by an independent advisory board. The advisory board will consist of representatives of selected stakeholder groups, including minority shareholders, civil society non-governmental organizations (NGOs), developing nations, and indigenous groups. It will be generally responsible for ensuring the LDC's decisions remain aligned with its purpose and for providing recommendations to the LDC board of directors and management team.

The advisory board will also create and oversee an independent Inspector General's office. This independent body will have a staff of professionals that are empowered to:

- Investigate allegations of wrongdoing within the LDC.
- Issue public reports, including independent audits and the results of investigations.
- Initiate legal action either on behalf of specific injured parties or in the public interest.
- Provide support to independent private lawsuits or criminal investigations involving the LDC or its subcontractors.

The Inspector General's office will operate independently from the LDC's control, providing essential oversight to ensure that the organization's power is used responsibly and transparently.

## I. Preventing Monopolies in Space

### i. Preventing the LDC from Competing in Ordinary Goods and Services Markets

#### In Principle

To promote an open and competitive space economy, it will be essential to prohibit the LDC from competing with its members. The LDC's exclusive focus will be on providing infrastructure and other public services, not on providing private goods and services, such as lunar-mined resources and processing lunar materials.

If the LDC were to compete in these markets, it would create conflicts of interest with its members. As Adam Smith outlined in *The Wealth of Nations*, entities that create and enforce marketplace rules must remain distinct from participants in those markets.<sup>27</sup> Otherwise, the rules will inevitably be manipulated to create monopolies and stifle innovation and competition.

Two examples demonstrate the dangers of combining rule-making authority with commercial participation:

1. **Tech Monopolies:** Some tech companies today have been accused of performing a dual role as both an infrastructure provider and a competitor in the marketplace their infrastructure creates. This arrangement encourages the companies to control access to the infrastructure in ways that benefit their own separate products. In space, where regulatory oversight will be weaker than on Earth, this risk would be much greater.
2. **Company States of the 17th and 18th Centuries:** Entities like the British and Dutch East India Companies controlled both trade and lawmaking in their respective colonies. These companies used their dual authority to impose monopolistic practices. In India, for instance, local textile producers were prohibited from selling to anyone but the British East India Company, which contributed to severe economic exploitation and mass starvation. We must avoid replicating this dynamic in space.

<sup>27</sup> Smith, A. (1776). *An inquiry into the nature and causes of the wealth of nations*. W. Strahan and T. Cadell.

<sup>28</sup> Phillips and Sharman (2020).

<sup>29</sup> Dalrymple, W. (2019). *The anarchy: The relentless rise of the East India Company*. Bloomsbury Publishing.

## Nurturing Competitive Markets

The LDC will also be structured to foster competitive markets for some of its services. In the early stages of lunar development, the LDC may need to provide certain services where no other alternative providers exist. However, as the market matures, the LDC will transfer some of these services. This could involve:

- **Subcontracting to Multiple Providers:** The LDC will subcontract some of its services to private providers, ensuring competition among these subcontractors while maintaining its focus on public services and governance.
- **Impact Markets and Incentive Programs:** The LDC may create competitive markets for its objectives by agreeing to purchase positive outputs or award prizes for attaining important public goals, similar to the Ansari X Prize. By stepping into the role of a funder and overseer, rather than direct service provider the LDC will stimulate private sector innovation and efficiency.

Historical examples of this approach in the space sector include:

- **INTELSAT:** Initially established as an intergovernmental satellite telecommunications provider, INTELSAT served as a crucial infrastructure provider before transitioning to a more competitive market where private satellite companies operate independently.
- **NASA's COTS and Commercial Crew Programs:** NASA's Commercial Orbital Transportation Services (COTS) program involves contracting with private companies to develop cargo transport capabilities to the International Space Station. NASA provides partial funding and oversight while allowing private companies to handle design, manufacturing, test and operations, resulting in a thriving commercial space industry.

## Accountability to These Obligations

The LDC's governance and accountability mechanisms will help ensure the LDC remains committed to these priorities. For instance:



Conceptual rendering of lunar-surface services. Courtesy of Daniel Inocente.

- The LDC's founding charter and governance documents will include binding standards preventing it from competing in certain markets and transferring some functions over to market participants when feasible.
- The Inspector General will conduct independent annual audits to ensure that the LDC is not encroaching on commercial markets and remains focused on providing infrastructure and other public services.
- The Inspector General will publish annual reports detailing the LDC's progress at divesting from markets where private providers emerge.
- Members will have the right to lodge disputes with the LDC if they believe it has improperly entered a commercial market. These disputes will be resolved by independent arbitration or courts.

### ii. Preventing Anti-Competitive Behavior Generally in Space

The LDC's structure will incentivize it to prevent the formation of cartels or other anti-competitive practices in space. Because the LDC will derive its revenue from the overall increase in the value of the lunar economy, it will benefit from fostering a diverse and dynamic economy where competition thrives, including from small startups.

Therefore, the LDC will seek to identify and prevent practices like price fixing, market division, and exclusionary tactics that early movers could use to lock in advantages. This might occur, if, for instance, a group of companies attempted to monopolize the mining of water ice on the Moon by colluding to control all access to key resource sites. Under LDC rules, this behavior would be deemed anti-competitive and in violation of its rules for members. These companies would either need to reform their practices to comply with LDC standards or face penalties, including the possibility of being expelled from LDC membership.

## J. LDC's Relationship with International Space Law and National Governments

### i. The LDC as a Catalyst for the Development of Space Law

The LDC's multinational structure will position it well to develop a responsive and broadly accepted legal framework for space activities. For instance, the LDC registry may evolve into a formal property rights registry for space, recognized and adopted by national governments.

There are numerous historical precedents for this. For instance, gold miners in the American West developed informal "mining camp rules" in the 19th century to allocate rights relatively fairly and efficiently around a deposit. These rules were eventually adopted as law by state and federal government agencies.<sup>30</sup> Similarly, local fishermen's associations in many countries have developed rules for inshore fisheries that were later recognized by official legislation.<sup>31</sup> These examples illustrate how informal systems developed by voluntary associations, like the LDC, can lay the groundwork for formal rights.

<sup>30</sup> Libecap, G.D. (1989).

<sup>31</sup> Ostrom, E. (1990).

Similarly, the LDC's rules for members—such as those covering dust mitigation, environmental protections, life support systems, and building codes—could eventually be adopted by governments as official regulations. This would parallel the development of the *lex mercatoria* (merchant law) during the Middle Ages, which began as an informal set of transnational commercial rules created by merchants and eventually became the foundation for modern commercial law.<sup>32</sup> Similarly, maritime law emerged from the customary practices of sailors and ship owners, evolving into an internationally recognized legal framework.<sup>33</sup> As the LDC's rules gain traction, they too could contribute to the evolution of customary international law for space.

## ii. Delegated Responsibility for Regulation

In the future, governments and international bodies could delegate regulatory responsibilities to the LDC. For instance, organizations like the ITU could delegate the management of spectrum allocation to the LDC. In this capacity, the LDC could allocate spectrum as tradable rights, charging users based on the annual market value of the allocated spectrum. This approach would ensure that spectrum is used efficiently, maximizing its value for space operations.

National government regulators might also collaborate with the LDC. For instance, the LDC could help process various license and permit applications in order to streamline and harmonize procedures. Nations might also rely on it to help manage space traffic and control debris.

## iii. Diplomacy and Conflict Resolution

The LDC will also play a diplomatic and stakeholder-engagement role. In cases where non-LDC members interfere with the activities or rights of LDC members, the LDC will engage Earth-based governments to apply diplomatic pressure or pursue legal remedies to resolve conflicts.

Additionally, the LDC will collaborate with policymakers in multiple countries to reduce regulatory barriers and encourage a more open space economy. Since the LDC's revenue will be tied to the long-term interests of space, it will have a strong financial incentive to promote a well-regulated and competitive space environment.

## iv. Sovereignty and Taxation

Although the LDC will carry out some of the responsibilities typically provided by governments, it will not be a state or possess sovereign powers. Therefore, it will not have the power to force parties' behavior, except insofar as those parties have voluntarily granted the LDC these powers in a member contract. LDC members will also be free to withdraw from membership.

Similarly, the LDC will not impose taxes. Instead, the LDC's revenue will be derived from membership fees, which will be based on the market value of the rights recorded in its registry.

These fees will recover the value created by the LDC, rather than taxing what members produce.

While Earth-based governments could tax the companies in their jurisdictions that operate in space, such taxation would be separate from the LDC's membership fees. The LDC's financial model will ensure that members retain the benefits of their productive activities.

## K. The LDC's Relationship with Other Similar Entities

There will be no legal barriers preventing the emergence of other infrastructure providers that compete with the LDC in its core service areas. The LDC will not have the authority to stop either individual space users from building their own infrastructure or other service providers similar to the LDC from serving a pool of customers.

### i. Likelihood of Multiple Providers

It may be unlikely that there will be multiple competitors to the LDC on the Moon. The infrastructure the LDC builds will come at an enormous cost. As mentioned in Section E, it will be impractical for a single space company to replicate this infrastructure solely for its own operations. It may even be impractical for another provider to serve multiple customers.

For there to be another entity like the LDC on the Moon, there would need to be a very large market of customers for them both to serve for each to justify their costs. The market may not become that large, at least for several decades.

If the market does grow large enough for the LDC to have competitors, this will not undermine the LDC's role. Competition in public service provision will benefit the space economy and, ultimately, the LDC by driving it to increase efficiency and service quality. If competing providers impose their own rules governing their users' activities, the LDC will need to ensure that its rules foster a more attractive and thriving ecosystem for its members.

In this scenario, the LDC's governance structure will give it a competitive advantage. It will provide space users with a more trustworthy and efficient operating environment than competing models, such as those created by state-controlled providers or other private-sector-controlled providers.

### ii. Competitiveness with State-Controlled Infrastructure Providers

State-controlled infrastructure providers will be prone to greater inefficiency. Historically, such entities tend to be driven more by political or bureaucratic interests that are not well-aligned with the needs of infrastructure users or, in some cases, even long-term economic, social, and environmental concerns. Space users

<sup>32</sup> Michaels, R. (2007). The true *lex mercatoria*: law beyond the state. *Ind. J. Global Legal Stud.*, 14, 447.

<sup>33</sup> Cordes, A. (2017). *Lex maritima?: Local, regional and universal maritime law in the Middle Ages*. In *The Routledge Handbook of Maritime Trade around Europe 1300-1600* (pp. 69-85). Routledge.

relying on such providers probably will find weaker infrastructure and service quality, less responsiveness, and more cumbersome procedures than under the LDC.

Additionally, users will lack confidence in the long-term commitment of the government to the project. The budget devoted to state-owned space infrastructure will likely shift with changing politics on Earth, creating risks over the long run for the entities that depend on it.

Wealthier authoritarian states may marshal impressive political and financial resources for space infrastructure development. However, they will be plagued by the inefficiencies of central planning, combined with a lack of transparency and accountability. Members will reasonably fear that unless they are closely connected to political leaders, they may not receive fair or reliable treatment.

### iii. Competitiveness with Other Privately Controlled Infrastructure Providers

Members of a private-sector-controlled infrastructure provider without the LDC's governance mechanisms will face the risk of unfair or predatory treatment. The controlling shareholders of these providers will be tempted to adopt rules or regulate access to benefit their independent commercial interests at the expense of competitors. This risk is discussed in Section I(i) in relation to the LDC, but it applies equally to its competitors.

The hypothetical example in Section H, which describes what the LDC would be like without shareholder restrictions, provides an indication of the environment other private sector or state-controlled providers might create for their members. It is likely that, given the choice, these providers' members will defect to the LDC.

### iv. LDC Copycats

Other infrastructure providers adopting governance structures similar to the LDC may emerge. These would, for instance, adopt shareholder restrictions and accountability mechanisms that ensure a focus on enhancing value for the overall space economy rather than on the independent interests of major investors.

However, this would be a positive development. If these providers govern more effectively and offer better services than the LDC, they will greatly benefit the future of space. And if the LDC loses market share or fails because it cannot compete with them, this will ultimately serve the greater good.

Ultimately, the LDC will encourage its model to be copied. For instance, it will support development cooperatives in other locations, such as on Mars, asteroids, and throughout the solar system.

## III. Next Steps

### A. Rationale and Urgency for the Lunar Development Institute

We do not have the luxury of time to slowly build the governance framework for space. Ongoing competition between the U.S. and China for space dominance and precipitous drops in the delivery of payload to space will mean that companies and governments will soon begin mining and building on the lunar surface. The LDC will support and steer this activity when it happens to ensure an open and sustainable lunar economy. However, if the LDC arrives too late, it will be impossible to prevent first-movers from monopolizing the Moon's key resource deposits.

Unfortunately, we cannot establish the LDC immediately, for a few reasons:

1. **Investor Expectations and Timelines:** As a for-profit company, the LDC will need to present a credible path to delivering a near-term return on investment before it can raise capital from private and government investors. This will not happen until there are potential LDC members who will, within 1-2 years, carry out ongoing operations on the Moon using LDC infrastructure. Until then, there will not be a sufficient market for core LDC services.
2. **Relationship Building with Space Regulators:** The LDC will aim to both build space infrastructure itself efficiently and streamline regulatory approvals for space activities conducted by its members. To accomplish these goals, we will need to build strong support and collaboration from government entities for the concept in advance. This will take time.
3. **Getting the Governance Framework Right:** The LDC will not be an ordinary space company but a governance and public service provider. The rules it adopts will have a lasting impact as humanity settles the vast new landscape of space. We must get these rules right and ensure they are embraced widely by the private and public sector across many nations.

Therefore, as a first step, the Lunar Development Institute, a non-profit research organization, will be formed to lay the groundwork for the LDC. It will collaborate with governments, space companies, international organizations, and other stakeholders to test, refine, and build support for the LDC model.

## B. Anticipated Timeline, Objectives, and Key Activities in the Development of the LDC

**Years: -5 – 0 (“Institute Phase”, approx. 2025-2030):**

**Objective 1:** Raise funding and build the core Lunar Development Institute team

### Key Activities:

- Fundraising: Outreach to major donors, grant-making institutions, and the general public.
- Organizational formation: Incorporate the Institute and acquire tax exempt status.
- Team Building: Retain and hire specialists in economics, law, engineering, marketing, international relations, and business.

**Objective 2:** Achieve broad-based understanding and support from major space-faring nations, private space companies, and NGOs.

### Key Activities:

- Public outreach: Attend and host conferences, workshops, and other events to engage stakeholders.
- Educational materials development: Publishing reports, explainer videos, and models articulating the concept.
- Public education and awareness campaign: Coordinated outreach supported by materials to engage the public in support of lunar development objectives.
- Virtual simulation: An online multiplayer game in which players can establish operations in a simulated lunar environment under the LDC framework.

**Objective 3:** Obtain letters of intent from prospective LDC members (space companies and government agencies intending to use LDC infrastructure once developed)

### Key Activities:

- Develop the business case: Brief outlining the detailed approach to LDC membership, how it would reduce costs and mitigates risks for space users.
- Stakeholder outreach: Meetings with space entrepreneurs and government agencies aiming to carry out operations on the Moon.
- Public relations: Regular announcements (press releases and engagement with media) sharing progress of LDC membership commitments.

**Objective 4:** Develop detailed technical and financial plans and prototypes for the development of core LDC infrastructure and services

### Key Activities:

- LDC Member Needs Analyses: Conduct interviews with key potential LDC members to better understand their needs for shared lunar infrastructure and services in terms of types, magnitudes, timing and priorities.
- Feasibility studies: Conduct economic and market studies for the lunar economy, analyze locations, evaluate engineering designs, model revenue and expenses, and evaluate competitiveness with other potential public service providers.
- Prototyping: Testing and refining LDC services through virtual simulations and physical prototypes.
- Financial Architecture: Design the financial structures needed to lengthen ROI timelines and de-risk investment in LDC infrastructure.
- Scenario Planning: Use the online multiplayer simulation game to analyze LDC incentives and likely outcomes under various scenarios in the development of the space economy over the rest of the century.

**Objective 5:** Detail the key documents that will govern the LDC and its members, including:

1. “Constitutional” / Primary Instruments: LDC charter, shareholders agreement, and member contracts; and
2. Secondary Instruments: Detailed procedures and standards for key LDC regulatory activities and rules of conduct.

### Key Activities:

- Technical standards development: Studies and collaboration with industry and regulatory representatives to define technical requirements and standards necessary for standard operations on the Moon, including dust mitigation, life support systems, airlock operation, etc.
- LDC governance: Collaborate with stakeholders and experts to detail the organizational structure of the LDC, the inspector general, and other accountability institutions and to define the requirements and mechanisms to be included in the LDC charter, shareholders agreement, members contracts, and other founding legal instruments.
- Rules of conduct: Engage international legal and policy experts to study and develop rules covering environmental protection, labor, human rights, resource conservation, interference, anti-competitive behavior, and other issues, ensuring alignment with international and domestic law and norms.
- Procedure development: Develop procedures for LDC administrative responsibilities, such as LDC registry approval, monitoring and enforcement of members’ activities, and oversight and accountability of the LDC itself.

## Year 0 (LDC Launch, approx 2030)

Having established detailed technical plans and support for the concept, the Institute will then spearhead the formation of the LDC. This will involve calling in investment commitments from major sovereign and private investors that the LDC has attracted interest from, hiring staff, forming contracts with third-party service providers, and beginning development of the initial infrastructure and services outlined in Section II.C., above.

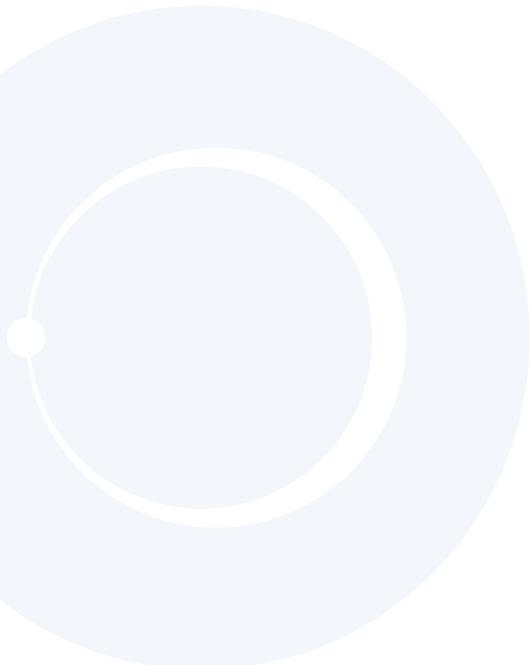
The timing of this transition will depend on external factors, such as:

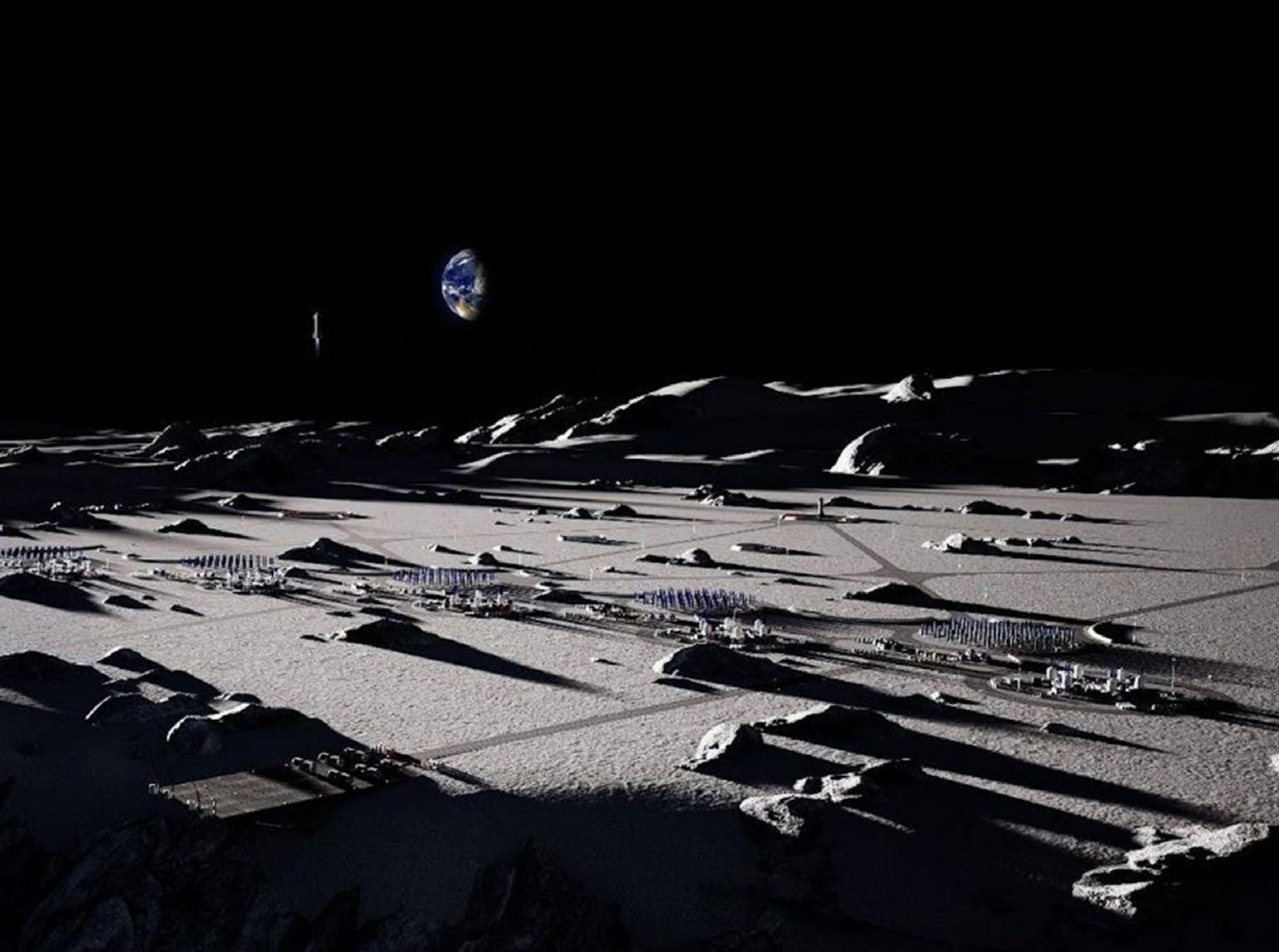
- Technological development - Technological readiness level of the most valuable LDC infrastructure planned in phases 1 and 2.
- Transportation costs - Operation of low-cost, heavy lift reusable rockets that significantly reduce the cost of getting payload to lunar orbit.
- National commitment - Significant progress by major spacefaring nations toward developing a sustained presence on the Moon.
- Stakeholder acceptance - Support from nations, companies, and other stakeholders for the LDC concept.

## IV. Conclusion

There has never been an event in human history comparable to the development of the Moon. The closest comparison we have may be the first humans to arrive in the Americas approximately 15,000 years ago. But humanity has never settled areas entirely devoid of life.

We can predict the first ones to occupy the Moon's key resource locations will wield considerable influence, shaping the rules of the market for all who come after. If we create effective space institutions now, we will be able to guide these events and enhance their benefits. The LDC will provide such institutions, having the ability and incentive to support the development of the Moon. In this way, we will ensure an open, sustainable, and peaceful lunar economy and society for all.





# Strategic Capabilities for Large-Scale Habitation

## Technologies, Systems and Infrastructure

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By Daniel Inocente & Jennifer Ludolph

Image Credit:  
Resource Site Lunar Base Concept, Daniel Inocente Architecture

# Executive Summary

Abstract: Developing sustainable and adaptable long term large surface habitats on the Moon and Mars involves advancing both the ways and means in which these facilities are designed, built and operated. Large scale Habitats will require the ability to autonomously adapt to changing environmental conditions, integrate local resources, and to support human performance in extreme environments over extended periods. This paper explores the key technical elements and proposes advanced design concepts to enhance the scalability and functionality of these systems, aligning with NASA's Moon to Mars objectives.

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# I. Introduction

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NASA's Moon to Mars Architecture sets a comprehensive strategy for extending human presence beyond Earth by leveraging the Moon as a testbed for developing capabilities needed for Mars exploration. This framework integrates scientific, technological, and policy objectives to establish sustainable operations on the Moon through the Artemis Base Camp and related infrastructure. The architecture emphasizes an incremental approach, where lunar missions serve as a proving ground for testing and refining systems such as in-situ resource utilization (ISRU), life support, and power generation, which are critical for supporting long-duration Mars missions (NASA, 2024).

This paper builds upon NASA's strategy by addressing the unique challenges of establishing larger-scale surface habitats, focusing on how technology solutions, such as modular habitat designs and advanced life support systems, can be adapted and scaled for Mars. The paper also identifies critical technology gaps and evaluates technology readiness levels (TRLs) to inform the progressive development of capabilities that support Mars exploration (Guo et al., 2020). It also touches on the importance of fostering international collaboration and public-private partnerships, which are essential for sharing expertise, reducing costs, and promoting an interoperable exploration ecosystem (Wright, 2019). By aligning with the Moon to Mars strategy, this paper contributes to the vision of establishing a sustainable human presence on the Moon as a stepping stone for future Mars missions, ultimately enabling a cohesive exploration framework that advances NASA's long-term goals of exploring deeper into the solar system.



Image Credit: Artemis Basecamp Concept, NASA

## II. The Value of Modular and Expandable Design for Lunar and Martian Habitats

A key element for ensuring the scalability and long-term sustainability of surface habitats on the Moon and Mars is adopting a modular and expandable design philosophy. Modular habitats offer numerous benefits, including the ability to grow and adapt as mission needs evolve, facilitate easier maintenance, and enable compatibility with new technologies. This section explores the advantages and recommendations for building habitats with standardized, interconnectable modules that support the expansion of human activities in space.

Building with Standardized, Interconnectable Module designs involve constructing habitats using standardized, interconnectable components that can be configured and reconfigured as required. This approach allows for the rapid assembly of complex structures using a “building block” methodology, where modules can be pre-fabricated on Earth, launched, and assembled on the lunar or Martian surface. The use of standardized connectors and interfaces ensures that different modules can be seamlessly integrated, allowing habitats to be adapted to diverse functions such as living quarters, laboratories, or storage areas. It is recommended that international standards be developed for module dimensions, connector types, and life support interfaces to promote interoperability between different agencies and commercial entities, thereby enabling collaborative development and the sharing of infrastructure (Zhang et al., 2019).

The ability to expand habitats over time is crucial as missions evolve and new technologies become available. Modular habitats enable the addition of new sections based on changing needs, such as increased crew capacity, enhanced scientific capabilities, or the integration of new life support systems. For example, a habitat might begin with core modules for essential operations and be expanded with specialized modules for laboratories or manufacturing facilities as the mission matures. This incremental growth strategy supports long-term planning and allows habitats to scale efficiently with minimal disruption to ongoing activities. It is recommended that initial habitat designs include pre-configured expansion points to facilitate the attachment of new modules and enable the efficient scaling of habitat capabilities (Bishop et al., 2018).

## III. Ease of Maintenance and Component Replacement in Modules

Modular habitats offer significant advantages for maintenance and the replacement of individual components. Standardized modules can be easily detached, replaced, or upgraded

without affecting the rest of the habitat, reducing downtime and minimizing the impact on crew activities. This approach simplifies the management of spare parts, as common components can be used across multiple modules. Additionally, modular designs support the integration of new technologies as they become available, ensuring that habitats remain state-of-the-art and capable of meeting the demands of future missions. It is recommended that habitats incorporate modular maintenance protocols that allow for the rapid replacement of critical systems, such as environmental control and life support systems (ECLSS), power systems, and communication networks (Jones et al., 2019).

## IV. Controlled Habitation Environments for Long-Duration Stays Missions

Creating controlled environments involves maintaining stable healthy atmospheric conditions, mitigating radiation exposure, and managing temperature variations. Unlike smaller habitats, where manual interventions are feasible, larger systems will require greater autonomous capabilities. This capability will be extremely important to rapidly and that can independently detect and correct life threatening anomalies.

### 1. Dynamic Environmental Control and Life Support Systems (ECLSS):

ECLSS in both small and large surface habitats must balance high recycling efficiency with cost of operations and resilience against potential failures. Existing systems, like those used on the ISS, have opted to depend on periodic procedures maintenance and manual adjustments for general maintenance. For future large scale surface habitats, future ECLSS designs should integrate bio-regenerative components, such as algae or engineered bacteria, to support oxygen production and CO<sub>2</sub> removal, as well as AI-driven control systems that can simulate and anticipate fluctuations in the habitat’s ecosystem. Distributing modular ECLSS units throughout the habitat can reduce systemic risks and allow isolated management of different habitat zones (Smith et al., 2018). Modularity in life support systems also supports habitat expansion and scalability for evolving mission needs.

### 2. Radiation Shielding:

The need for effective radiation shielding drives the exploration of hybrid structural designs that utilize both active and passive protection. Instead of traditional shielding methods that rely on mass-intensive materials, habitats can incorporate multifunctional structural elements that provide mechanical support and radiation protection simultaneously. For example, using double-walled habitat structures filled with regolith or water as shielding material could significantly reduce radiation exposure while enhancing structural stability. Additionally,

advanced concepts such as superconducting magnets to generate localized magnetic fields could complement traditional shielding methods, enabling habitats to be designed with less reliance on transported materials (Guo et al., 2020).

### 3. Thermal Management:

Maintaining thermal stability in habitats is complicated by the extreme temperature variations between lunar days and nights or Martian seasons. Advanced thermal control systems could employ phase-change materials (PCMs) embedded within the habitat's walls, which store thermal energy during the day and release it at night. Coupling PCMs with active heat exchange systems would allow habitats to maintain stable internal temperatures without excessive energy use. Developing PCMs that can withstand repeated temperature cycling without performance degradation is a critical area of research (Johnson et al., 2018).

### 4. Habitability and Comfort:

The internal design of habitats must provide functional spaces that adapt to mission phases and crew sizes. Utilizing reconfigurable modules that can serve as living quarters, laboratories, or recreation areas enables habitats to maintain flexibility. Artificial lighting systems designed to replicate Earth's day-night cycle can help regulate circadian rhythms, reducing the risks of sleep disorders and fatigue. Employing materials and color schemes that promote a sense of openness and calmness can further enhance the psychological well-being of crew members, supporting long-duration missions (Kim et al., 2021).

## Recommendations:

- **Dynamic Environmental Control and Life Support Systems (ECLSS):** Integrate bio-regenerative components like algae or engineered bacteria into ECLSS for efficient oxygen production and CO<sub>2</sub> removal. Utilize AI-driven control systems to detect and correct anomalies autonomously, and distribute modular ECLSS units throughout the habitat to reduce systemic risks and support scalability.
- **Radiation Shielding:** Incorporate hybrid structural designs that use multifunctional elements, such as double-walled structures filled with regolith or water, to provide both mechanical support and passive radiation protection. Explore advanced concepts like superconducting magnets to generate localized magnetic fields as a complementary and augmentative active shielding methods.
- **Thermal Management:** Employ phase-change materials (PCMs) within habitat walls to absorb and release thermal energy, maintaining stable internal temperatures. Pair PCMs with active heat exchange systems and develop PCMs that withstand repeated temperature cycling to enhance thermal management efficiency.

- **Habitability and Comfort:** Design internal spaces with reconfigurable modules to adapt to varying mission phases and crew sizes. Use artificial lighting to mimic Earth's day-night cycle and materials that promote a sense of openness and calmness, enhancing psychological well-being and supporting long-duration missions.

## A. Human Systems: Ensuring Crew Health and Performance

Human systems in larger surface habitats and orbital settlements will need to address the complexities of maintaining crew health and performance over extended periods, ensuring resilience against both physiological and psychological stressors.

### 1. Integrated Health Monitoring and Predictive Analytics:

For extended missions, health monitoring systems must be capable of detecting subtle indicators of health deterioration. Wearable health monitors that track biochemical markers like hydration, bone density, and stress hormones could feed into an AI-driven analytics platform that generates health profiles for each crew member. Predictive models based on these profiles could provide early warnings and suggest interventions before critical health issues arise. This would allow for dynamic health management tailored to individual crew members and reduce the need for Earth-based support (Guo et al., 2020).

### 2. Physiological Countermeasures for Long-Term Missions:

Low-gravity environments present challenges such as muscle atrophy and bone density loss. Exercise regimens that simulate resistance training using advanced equipment, such as flywheel-based devices or robotic exoskeletons, could be incorporated within habitats to support physical health. Integrating centrifuge-based exercise facilities could further simulate gravitational forces, providing a more comprehensive countermeasure for the negative effects of reduced gravity. These solutions would need to be space-efficient and adaptable, minimizing impact on habitat layout while allowing crew members to incorporate exercise into their daily routines (Zhang et al., 2019).

### 3. Psychological Support Systems for Extended Missions:

Psychological well-being is critical for maintaining cognitive function and mission performance. Habitats could integrate adaptive VR systems that offer a range of experiences, from virtual natural environments to interactive social settings that mimic Earth-based activities. These VR environments, combined with AI-driven conversational agents, could provide cognitive stimulation, emotional support, and a sense of connection, reducing feelings of isolation. Additionally, designing habitats with multi-use common areas that encourage social interaction, combined with private spaces that offer solitude, would help maintain psychological balance among crew members (Anderson et al., 2018).

## Recommendations:

- **Integrated Health Monitoring and Predictive Analytics:** Implement wearable health monitors to track biochemical markers like hydration and bone density. Use AI-driven analytics to create personalized health profiles and predictive models for early detection of health issues and tailored interventions, reducing reliance on Earth-based support.
- **Physiological Countermeasures:** Mitigate the effects of low gravity, such as muscle atrophy and bone density loss, through exercise regimens that include advanced equipment like flywheel-based devices and robotic exoskeletons. Consider incorporating centrifuge-based exercise facilities to simulate gravitational forces in a space-efficient manner.
- **Psychological Support Systems:** Utilize adaptive VR systems to provide virtual natural environments and interactive social experiences. Include AI-driven conversational agents for emotional support and cognitive stimulation. Design habitats with multi-use common areas for social interaction and private spaces for solitude to maintain crew psychological well-being.

### B. EVA Systems and Surface Mobility for Enhancing Habitat Capabilities

Extravehicular activities (EVAs) are essential for habitat maintenance, resource extraction, and surface exploration. The design of advanced EVA systems should enhance mobility, efficiency, and safety for astronauts operating in extreme environments.

#### 1. Spacesuits with Modular EVA Tool Attachments:

Future spacesuit designs could incorporate modular attachment points that enable astronauts to easily connect various tools or equipment directly to their suits. This would allow for rapid reconfiguration of toolsets during EVA operations, minimizing the need to return to the habitat for tool changes. Adding self-sealing materials to spacesuit layers would mitigate risks from micrometeorite impacts, enhancing astronaut safety during prolonged surface operations (Smith et al., 2018).

#### 2. Surface Mobility Platforms for Habitat Construction and Maintenance:

Rovers and robotic assistants equipped with modular toolsets could play a crucial role in constructing, maintaining, and expanding habitats. Autonomous bulldozers or excavators could prepare construction sites, while robotic cranes could handle heavy lifting tasks, such as assembling large habitat modules or deploying ISRU systems. The ability to swap out toolsets or add new modules would make these platforms highly versatile, capable of adapting to different tasks as habitat needs evolve (Harrison et al., 2019).

## Recommendations:

- **Spacesuits with Modular Tool Attachments:** Design future spacesuits with modular attachment points for connecting various tools and equipment directly to the suit. This will enable astronauts to rapidly reconfigure toolsets during EVAs, minimizing the need for returning to the habitat and improving efficiency. Incorporate self-sealing materials in the suit layers to protect against micrometeorite impacts and enhance safety.
- **Surface Mobility Platforms:** Develop versatile surface mobility platforms, such as rovers and robotic assistants, with interchangeable toolsets for a wide range of tasks, including construction, maintenance, and resource extraction. Equip platforms like autonomous bulldozers, excavators, and robotic cranes with modular tools to increase adaptability for evolving habitat needs.
- **Automation for Habitat Construction and Maintenance:** Utilize autonomous surface mobility systems for site preparation and habitat expansion. Implement robotic systems for heavy lifting and ISRU deployment, enhancing operational capabilities and reducing the need for manual interventions.

## Implications for Surface Habitat Development

These advanced habitation systems are integral to ensuring that habitats can support long-duration missions in the challenging environments of the Moon and Mars. By focusing on autonomous operations, resource utilization, and adaptive human systems, habitats can evolve with mission requirements and crew needs. Testing these systems on the Moon will provide critical data and operational experience to refine designs for Mars, where operational constraints are more severe. The insights gained from this iterative approach will be instrumental in bridging the gap between lunar and Martian habitats, ultimately enabling NASA to achieve its Moon to Mars objectives and establish a sustainable human presence on both celestial bodies.

## V. Critical Habitation Technology

Surface habitat systems are the integrated technical enablers that ensure the safety, functionality, and sustainability of extraterrestrial habitats. These systems—spanning Environmental Control and Life Support Systems (ECLSS), power, thermal management, and operations control—form the essential framework that allows humans to live and work beyond Earth. Their design must address not only the harsh environmental conditions but also the need for autonomy, adaptability, and resource efficiency. The importance of these systems lies in their ability to support long-term missions and enable future expansions, making them a cornerstone of sustainable space exploration. This chapter explores novel approaches to these systems and proposes innovative design strategies for creating more resilient and adaptable surface habitats.

## Environmental Control and Life Support Systems (ECLSS)

The ECLSS is the lifeline of any extraterrestrial habitat, responsible for maintaining breathable air, potable water, and a safe environment by regulating temperature, humidity, and pressure. In traditional designs, ECLSS components are primarily mechanical, relying on pumps, filters, and chemical reactions. However, hybrid systems that integrate bioregenerative elements, such as algae-based bioreactors, offer a new paradigm for creating a more sustainable life support system. These bioreactors can be incorporated into the habitat's structural shell, forming part of the outer insulation while also purifying air and providing nutritional supplements. The system could be designed to function in tandem with mechanical scrubbers, ensuring redundancy and resilience. This configuration would not only enhance air quality but also serve as a visual connection to Earth's natural environments, improving crew mental health and well-being. Such hybrid systems reduce logistical burdens by minimizing the need for Earth-based resupply and support a more autonomous operational model.

### A. Power Systems

Power systems are the backbone of habitat operations, providing the necessary energy to run life support, lighting, communications, and other critical systems. A novel approach to power generation and distribution involves creating a distributed power grid within the habitat environment. This grid could use mobile power nodes—small, portable energy units that can be positioned as needed. Such nodes, equipped with solar arrays or small-scale nuclear reactors, would provide a versatile energy infrastructure capable of adapting to changes in habitat layout and mission needs. For example, mobile photovoltaic units mounted on automated rovers could travel to optimal locations for solar harvesting during the day and return to the habitat to provide energy during the night. This distributed system allows for gradual expansion of the power network as the habitat grows and ensures energy resilience by decentralizing power sources and distribution points. Additionally, the integration of waste heat recovery systems into the power infrastructure would enable the efficient reuse of excess thermal energy for secondary functions, such as water heating or thermal management.

### B. Thermal Management Systems

Thermal management systems must balance the internal habitat environment with the extreme external temperatures of the Moon and Mars. An innovative design strategy is to incorporate phase-change materials (PCMs) into habitat walls and flooring, which can absorb and release heat to regulate internal temperatures naturally. This passive thermal management approach reduces the energy required for active heating and cooling, allowing the habitat to maintain stable conditions even during periods of fluctuating external temperatures. PCMs, combined with multi-layered insulation panels, can create a self-regulating

thermal barrier that responds dynamically to changes in external conditions. To further optimize thermal management, regolith—a readily available resource on both the Moon and Mars—could be used as a construction material for creating external shielding. Regolith combined with aerogels or advanced composites forms a lightweight yet highly effective insulator, offering protection against extreme cold and radiation. This approach not only enhances thermal performance but also reduces the need for Earth-supplied materials, aligning with the principles of in-situ resource utilization (ISRU).

### C. Operations Planning and Control, Equipment

Operations planning and control systems ensure that surface habitats can function independently, without constant oversight from Earth. A key design innovation for such systems is the integration of autonomous control nodes distributed throughout the habitat. Each node could manage a specific module or subsystem, allowing for localized control and decision-making. This distributed architecture would enable the habitat to operate autonomously, with each node capable of self-reconfiguration and task allocation based on real-time mission demands. For instance, a node embedded in the habitat's greenhouse module could independently adjust environmental conditions for optimal crop growth while coordinating with other nodes managing life support and power systems. These autonomous nodes would communicate through a shared protocol, enabling seamless integration of new equipment or reconfiguration of habitat layout without the need for extensive system redesigns. The use of AI-driven diagnostics and predictive maintenance algorithms would further reduce the workload on crew members, allowing them to focus on critical mission tasks.

### D. Mission Control Systems

Mission control systems must be capable of autonomous operation due to the inherent communication delays between Earth and distant space habitats. Cognitive computing and machine learning can be employed to create a mission control system that performs high-level decision-making independently, allowing it to respond to emergencies without real-time intervention from Earth. An innovative interface design for these systems could incorporate haptic feedback and gesture-based controls, providing intuitive interactions for crew members. By integrating these interfaces within the habitat's structural elements—such as smart walls or interactive panels—crew members can access critical data and control habitat systems without the need for dedicated consoles or terminals. Augmented reality (AR) overlays can be used to provide real-time data visualization, highlighting system statuses or environmental conditions directly within the crew's field of view. This immersive experience would enhance situational awareness and enable crew members to perform complex tasks more efficiently.

## E. Equipment for Surface Operations

Surface operations equipment must be adaptable to handle a variety of tasks under diverse environmental conditions. A multifunctional equipment platform that features a reconfigurable chassis could support multiple attachments, enabling it to switch roles based on mission needs. For instance, a base unit could serve as a transport rover, while additional modules could transform it into a construction vehicle or a scientific survey unit. Such platforms would be designed with a universal attachment system, allowing tools such as excavators, manipulators, or scientific instruments to be quickly swapped or combined. This modular approach would reduce the number of specialized vehicles needed and streamline logistics. Furthermore, autonomous construction units equipped with robotic arms and 3D printing capabilities could deploy and assemble habitat modules on-site, using local resources to fabricate building materials. This would enable habitats to expand incrementally, reducing the need for pre-fabricated components from Earth and supporting sustainable habitat development.

## F. Resource Management

Effective resource management is essential for maintaining sustainability in long-term missions. An advanced resource management system would integrate ISRU technologies directly into the habitat infrastructure, creating a closed-loop system that continuously extracts, refines, and utilizes local resources. For example, water extraction units could be embedded within habitat walls, capturing moisture from the air or processing water from external sources. This water could be purified and stored within the walls themselves, serving as both a consumable resource and an additional layer of radiation protection. Similarly, oxygen and hydrogen generated through electrolysis of water could be stored in modular tanks that connect to the habitat's ECLSS, providing life support and potential fuel for surface vehicles. By designing these systems with modularity in mind, habitats can dynamically adjust resource production and allocation based on changing mission conditions, ensuring that critical supplies are always available while minimizing waste.

### Recommendations:

- **Environmental Control and Life Support Systems (ECLSS):** Develop hybrid ECLSS that integrate bioregenerative elements, such as algae-based bioreactors, into mechanical life support systems. This configuration enhances sustainability by reducing the need for Earth-based resupplies while maintaining a resilient environment for crew members.
- **Power Systems:** Implement a distributed power grid with mobile power nodes equipped with solar arrays or small-scale nuclear reactors to support dynamic energy needs. Integrate waste heat recovery systems for efficient thermal management and flexibility in energy distribution.

- **Thermal Management Systems:** Utilize phase-change materials (PCMs) and regolith-based composites to create passive and active thermal management solutions. These systems regulate internal habitat temperatures and offer additional protection against extreme external conditions, aligning with in-situ resource utilization (ISRU) principles.
- **Operations Planning and Control Systems:** Develop a distributed network of autonomous control nodes that can independently manage specific habitat modules. Integrate AI-driven diagnostics and predictive maintenance to reduce crew workload and support autonomous operations.
- **Mission Control Systems:** Create autonomous mission control systems using cognitive computing and machine learning to handle high-level decision-making. Utilize innovative interfaces such as haptic feedback and augmented reality to enhance crew interactions with habitat systems.
- **Equipment for Surface Operations:** Design multifunctional surface operation platforms with reconfigurable chassis and modular attachments to support various tasks, including construction, maintenance, and resource extraction. Employ autonomous construction units with robotic arms and 3D printing capabilities to build and expand habitats on-site.
- **Resource Management Systems:** Implement advanced resource management systems that integrate ISRU technologies for water, oxygen, and construction material extraction. Design these systems with modularity to dynamically adjust resource production based on mission demands, creating a closed-loop system for sustainable habitat operations.

## VI. Crew, Ground, Personnel, and Supporting Systems

The seamless integration of crew, ground personnel, and supporting systems is crucial for the success of complex surface missions on the Moon and Mars. As habitats become more sophisticated and mission durations extend, these systems must evolve to provide high levels of autonomy, efficiency, and adaptability while ensuring that mission objectives are met safely and reliably. This chapter discusses how the interaction of crew, ground, and supporting systems can be optimized and explores advanced strategies for managing mission operations and emergency scenarios in the context of surface habitation.

### A. Crew and Ground Personnel Coordination

Coordination between crew and ground personnel involves more than standard communication—it requires the establishment of a dynamic operational framework that enables both entities to respond effectively to unforeseen circumstances. In the context of lunar or Martian operations, the communication

delay becomes a significant factor. Mars, for instance, has a communication delay of up to 24 minutes one way, making real-time responses impractical for critical decision-making. To address this, habitats must incorporate semi-autonomous systems that can execute predefined protocols during emergencies, providing the crew with an additional layer of operational control in the absence of immediate ground support. Ground personnel will need to shift from direct operational roles to supervisory and strategic decision-making roles, relying on AI-driven mission control software to provide situational awareness and decision support. This transition necessitates reliable communication networks with built-in redundancies, such as optical laser links, to minimize data loss. Additionally, utilizing AI systems to filter and prioritize data can reduce the cognitive load on both ground controllers and crew members, ensuring that critical information is communicated without overwhelming the decision-making process (Jones et al., 2018).

### Recommendations:

- **Implement Semi-Autonomous Systems for Emergency Protocols:** Design habitats with semi-autonomous systems capable of executing predefined emergency protocols, ensuring crew operational control in the absence of real-time ground support due to communication delays.
- **Shift Ground Personnel to Supervisory and Strategic Roles:** Transition ground personnel roles from direct operations to strategic decision-making, using AI-driven mission control software for situational awareness and decision support.
- **Establish Reliable Communication Networks with Redundancies:** Develop robust communication networks, such as optical laser links, to minimize data loss and maintain effective communication between crew and ground personnel.
- **Leverage AI Systems for Data Management:** Use AI systems to filter and prioritize data, reducing cognitive load on both crew and ground controllers and ensuring efficient communication of critical information.

## B. Supporting Systems for Mission Execution

Supporting systems encompass mission planning software, logistics management platforms, and real-time monitoring tools that coordinate activities within and around the habitat. As missions become more complex, these systems must adapt to a variety of operational scenarios, including changes in crew size, resource availability, and mission timelines.

Advanced planning tools must be able to simulate a wide range of scenarios, from resource allocation and equipment maintenance to crew health monitoring and surface operations. AI-based predictive models can generate potential mission outcomes based on historical data and real-time inputs, enabling crews to make informed decisions when deviations from the

nominal mission profile occur. Real-time monitoring tools should provide comprehensive visibility of habitat systems and surface assets, ensuring that any anomaly can be quickly detected and addressed. This is especially important in scenarios where a delay in response time could lead to cascading failures or safety risks.

### Recommendations:

- **Utilize Advanced Mission Planning Tools:** Implement planning software that can simulate various operational scenarios, including resource allocation, equipment maintenance, crew health monitoring, and surface operations. This capability will enable crews to make informed decisions when deviations from the mission profile occur.
- **Integrate AI-Based Predictive Models:** Use AI-driven models to predict potential mission outcomes based on historical data and real-time inputs, helping crews anticipate and address issues before they escalate.
- **Employ Real-Time Monitoring Tools:** Develop comprehensive monitoring systems that provide visibility of all habitat systems and surface assets, allowing quick detection and resolution of anomalies to prevent cascading failures and safety risks.
- **Adapt Systems for Operational Flexibility:** Design supporting systems to be adaptable, accommodating changes in crew size, resource availability, and mission timelines, ensuring continued functionality and safety under diverse conditions.

## C. Robotic Systems and Automation

Robotic systems are indispensable for surface operations, including habitat construction, maintenance, and scientific exploration. These systems must function autonomously, with minimal human oversight, and possess the capability to coordinate with human activities. For example, robotic arms or mobile platforms equipped with interchangeable toolsets could autonomously conduct habitat repairs, transport resources, or assemble new modules based on mission demands.

A critical area of development is the integration of robotic systems with human operations in a shared workspace. This involves the creation of human-robot interaction protocols that define how robots respond to crew inputs, prioritize tasks, and manage resources. Multi-robot coordination algorithms, which enable swarms of robotic units to perform collaborative tasks, will be essential for scaling up operations, such as constructing additional habitat modules or establishing resource extraction sites (Harrison et al., 2019).

## Recommendations:

- **Develop Autonomous Robotic Systems for Surface Operations:** Create robotic systems capable of performing habitat construction, maintenance, and scientific exploration tasks with minimal human oversight, ensuring efficient autonomous operations.
- **Integrate Robotic Systems with Human Operations:** Establish human-robot interaction protocols to facilitate coordination between robotic systems and crew members, enabling seamless collaboration in shared workspaces.
- **Implement Multi-Robot Coordination Algorithms:** Develop algorithms that enable swarms of robotic units to perform collaborative tasks, such as habitat construction and resource extraction, supporting scalable and efficient surface operations.
- **Design Modular Robotic Platforms:** Equip robotic systems with interchangeable toolsets and mobile platforms to autonomously conduct repairs, transport resources, and assemble modules, enhancing adaptability and functionality in response to mission needs.

## D. Safety and Emergency Response Systems

Safety systems must be designed to handle a wide range of potential emergencies, including environmental hazards, equipment malfunctions, and medical crises. Given the isolated nature of lunar and Martian habitats, these systems must operate with a high degree of autonomy and provide the crew with the ability to manage emergencies without immediate external assistance.

Emergency response systems should be structured around a multi-layered approach that includes early detection, automated containment, and manual intervention protocols. For instance, in the event of a fire, integrated fire suppression systems can isolate affected modules and expel harmful gases, while the habitat's life support system adjusts ventilation to prevent the spread of smoke or toxic substances. Simultaneously, pre-programmed emergency procedures could be automatically communicated to crew members and ground control, providing a clear action plan to address the situation (Wright et al., 2020).

## Recommendations:

- **Design Autonomous Safety and Emergency Response Systems:** Develop safety systems that can operate autonomously and handle a wide range of emergencies, allowing crew members to manage incidents without immediate external support.
- **Implement a Multi-Layered Emergency Response Strategy:** Structure safety systems around early detection, automated containment, and manual intervention protocols to effectively address environmental hazards, equipment malfunctions, and medical crises.

- **Incorporate Integrated Emergency Suppression Systems:** Equip habitats with fire suppression systems that can isolate affected modules, expel harmful gases, and adjust ventilation to contain hazardous conditions.
- **Establish Automated Communication Protocols:** Create pre-programmed emergency procedures that are automatically communicated to crew members and ground control, providing clear action plans for timely and coordinated responses.

## E. Integration of Crew, Ground, and Robotic Systems

The successful integration of crew, ground personnel, and supporting systems is key to creating a cohesive operational ecosystem. By establishing clear protocols and utilizing advanced technology to bridge communication gaps, the habitat's operational effectiveness can be significantly enhanced. The implementation of AI-driven support systems that predict and adapt to changes in mission conditions, coupled with autonomous robotics, will reduce crew workload and increase overall mission efficiency. This holistic integration is necessary to support NASA's long-term vision for sustained human presence on the Moon and Mars, as it allows for scalable and resilient operations across diverse mission scenarios.

Ultimately, these systems must not only support the execution of planned activities but also provide the flexibility to adapt to new challenges and opportunities as human exploration pushes deeper into the solar system.

Recommendations:

- **Internal Command Center:** Habitats can integrate an internal command center that serves as an extension of ground control, equipped with high-level decision support systems capable of simulating outcomes based on current mission parameters. This facility would provide the crew with more control over their immediate environment, enhancing autonomy while maintaining alignment with ground-based strategic objectives.
- **Centralized Operations Center:** A centralized operations center within the habitat can serve as the nerve center for all supporting systems, equipped with advanced visualization tools that provide a holistic view of all ongoing activities. This setup would allow crew members to monitor mission status, resource utilization, and system health, while also enabling them to coordinate surface activities such as EVA operations and robotic exploration.
- **Dedicated robotic work zones:** Surface habitats should include dedicated robotic work zones where autonomous systems can operate independently of crewed areas, reducing interference and increasing safety. These zones could be equipped with docking stations for recharging, tool swapping, and data transfer, enabling continuous and efficient robotic operations.

- Modular safety systems: Habitat designs should incorporate modular safety systems that isolate compartments in case of a breach or hazard, preventing damage from spreading to critical areas. Emergency equipment, such as portable air supplies and medical kits, should be distributed strategically throughout the habitat to ensure accessibility regardless of the crew's location.

## VII. Infrastructure Support for Large-Scale Surface Habitats

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The development of sustainable surface habitats on the Moon and Mars, as outlined in NASA's Moon to Mars Architecture Definition Document, necessitates a multi-faceted approach to infrastructure support, integrating a variety of facilities, systems, and operational strategies that ensure scalability, adaptability, and resilience in extreme environments. This chapter focuses on how these infrastructure elements can be designed and enhanced to support long-term human habitation and scientific research, aligning with NASA's phased development strategy for building a permanent human presence on the Moon and Mars.

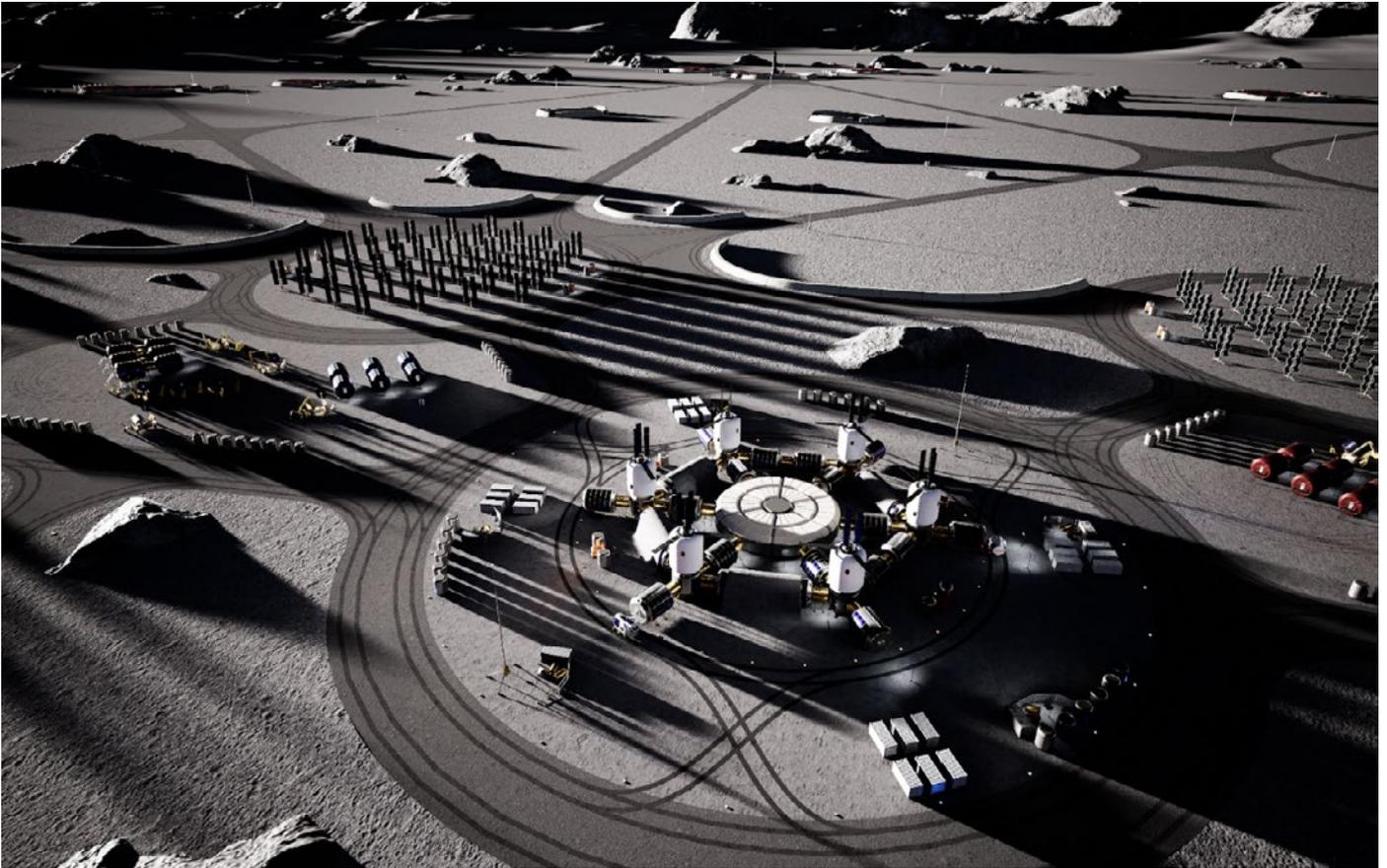


Image Credit: Lunar Base Development & Power Infrastructure Concept, Daniel Inocente Architecture

## A. Facilities for Surface Operations

Facilities form the foundational layer of any surface habitat, providing essential shelter and functional spaces for crew activities, scientific research, and logistical operations. The document emphasizes that facilities should be modular, flexible, and designed to withstand the environmental challenges of each celestial body. For the Moon, this means ensuring resistance to extreme temperature fluctuations and abrasive lunar dust, while for Mars, habitats must also address atmospheric pressure differences and the challenges associated with regolith-based construction.

### 1. Primary Habitat Structures:

Habitat structures on the Moon and Mars must incorporate modularity as a core design principle to enable phased deployment and future scalability. This approach aligns with the Moon to Mars Architecture's directive for establishing expandable habitats that can grow with mission needs. One potential design strategy involves using a radial configuration with interconnected modules that serve different functions, such as living quarters, research labs, and storage facilities. Each module could be constructed using a combination of inflatable and rigid structures, offering flexibility during transportation and deployment. Additionally, integrating ISRU-based materials, such as regolith bricks, into the habitat's external shell could provide both structural support and radiation shielding, reducing reliance on Earth-based materials [(Mason et al., 2020)]. An example configuration could include a central core module for command and control, surrounded by dedicated modules for sleeping quarters, laboratories, and workshops. This layout facilitates efficient power distribution, thermal regulation, and operational oversight. Further, placing common areas and social spaces centrally can reduce isolation and enhance crew interaction, contributing to long-term psychological well-being.

### 2. Landing and Launch Platforms:

As described in the Moon to Mars Architecture, the establishment of landing and launch platforms is crucial for logistical support and interplanetary transit. These platforms should be co-located with surface habitats to minimize transit times and maximize efficiency during supply and crew transfer operations. On the Moon, regolith dust presents a significant hazard during takeoff and landing. Advanced dust mitigation techniques, such as electrostatic repulsion or regolith stabilization using sintered surfaces, could be implemented to prevent damage to habitat systems and equipment [(Jones et al., 2018)]. Landing pads could be equipped with regolith-reinforced blast walls and automated surface-cleaning systems to control dust dispersion. Integrating electromagnetic or plasma-based dust repellents around the platform's perimeter can further minimize contamination and improve visibility during descent and ascent operations.

### 3. Energy Generation and Storage Facilities:

The need for continuous energy availability, especially during extended lunar nights and Martian winters, requires a diversified energy strategy. The document suggests a combination of solar power, nuclear reactors, and energy storage systems to ensure redundancy and adaptability. Solar arrays positioned on elevated platforms or crater rims can maximize sunlight exposure, while small modular nuclear reactors can provide baseline power during periods of limited solar availability [(Dunn et al., 2019)]. Energy storage systems, such as advanced batteries and regenerative fuel cells, should be co-located with power generation facilities and integrated with habitat systems through a microgrid architecture. This setup allows for real-time energy management and redistribution based on operational needs. For example, excess energy generated during the day could be stored in thermal batteries that release heat at night to maintain stable habitat temperatures.

### 4. Surface Mobility and Maintenance Facilities:

Surface mobility systems, including rovers and autonomous vehicles, are essential for habitat construction, maintenance, and exploration. Dedicated maintenance facilities equipped with robotic repair arms, 3D printers, and spare parts storage can support the refurbishment of mobility systems and reduce the need for Earth-based resupply [(Harrison et al., 2019)]. Establishing a multi-level maintenance facility with segregated zones for light and heavy repairs would streamline operations and minimize cross-contamination between critical systems. Integrating automated diagnostic systems that can assess the health of surface vehicles and robotic units upon entry would further enhance efficiency and safety.

### Recommendations:

- **Modular and Scalable Habitat Structures:** Design primary habitat structures using modular components that allow phased deployment and future scalability. Utilize a radial configuration with interconnected modules for different functions (e.g., living quarters, research labs) and consider integrating in-situ resource utilization (ISRU) materials, such as regolith bricks, for structural support and radiation shielding.
- **Efficient Landing and Launch Platforms:** Co-locate landing and launch platforms with habitats to minimize transit times for crew and supplies. Implement advanced dust mitigation techniques, such as regolith-reinforced blast walls and automated surface-cleaning systems, to protect habitat systems and equipment.
- **Diverse Energy Generation and Storage Facilities:** Establish a diversified energy strategy combining solar power, small modular nuclear reactors, and advanced energy storage systems to ensure continuous power availability. Integrate energy storage systems with habitat power infrastructure to manage and distribute energy efficiently based on operational needs.

- **Surface Mobility and Maintenance Facilities:** Develop dedicated maintenance facilities equipped with robotic repair arms, 3D printers, and diagnostic systems to support the maintenance and refurbishment of surface mobility systems. Establish multi-level maintenance facilities with segregated zones to streamline operations and reduce cross-contamination between critical systems.

## B. Systems for Operational Planning and Execution

### 1. Mission Control and Operations Centers:

Mission control facilities should provide comprehensive monitoring and control capabilities for all habitat systems and surface operations. These centers should be equipped with high-resolution displays, real-time data visualization tools, and decision support systems that align with the Moon to Mars Architecture's emphasis on robust situational awareness and mission adaptability. AI-driven predictive models could be used to simulate mission scenarios, providing insights on resource allocation and system performance under different conditions [(NASA, 2024)]. A distributed control architecture could be used, with a primary mission control center located in the habitat and secondary nodes in surface vehicles and robotic units. This configuration would enable decentralized decision-making, reducing dependency on any single control point and enhancing resilience.

### 2. Logistics and Resource Management Systems:

The document highlights the importance of logistics systems that track supplies, manage inventory, and optimize resource utilization. Autonomous logistics drones or ground vehicles could be used to transport materials between landing sites and habitats, minimizing crew workload and enhancing operational efficiency. Implementing a central logistics hub equipped with automated inventory tracking and replenishment systems would streamline resource distribution. Robotic systems could be integrated with habitat modules through dedicated docking ports, allowing for direct loading and unloading of supplies without human intervention.

#### Recommendations:

- **Establish Comprehensive Mission Control Centers:** Develop mission control facilities equipped with high-resolution displays, real-time data visualization tools, and AI-driven decision support systems to monitor and control all habitat systems and surface operations. Use a distributed control architecture with a primary mission control center in the habitat and secondary nodes in surface vehicles and robotic units to enable decentralized decision-making and enhance operational resilience.
- **Implement Advanced Logistics and Resource Management Systems:** Create logistics systems that track supplies, manage inventory, and optimize resource use. Employ autonomous logistics drones or ground vehicles to transport materials between landing sites and habitats, reducing crew workload and increasing efficiency.
- **Develop Centralized Logistics Hubs:** Establish a central logistics hub with automated inventory tracking and replenishment systems to streamline resource distribution. Integrate robotic systems with habitat modules via dedicated docking ports to enable direct loading and unloading of supplies without requiring human intervention.

## C. Integration of In-Situ Resource Utilization (ISRU)

ISRU is central to reducing the logistical burden of transporting materials from Earth. The Moon's regolith and Mars' atmosphere offer potential sources of oxygen, water, and building materials that can be used to sustain long-duration missions. The Moon to Mars Architecture encourages the development of scalable ISRU technologies that can support not only initial mission needs but also future habitat expansion. A dedicated ISRU facility, equipped with regolith processing units and electrochemical reactors, could be constructed adjacent to the habitat. The facility would extract oxygen and water from local resources and produce construction materials, such as regolith bricks or polymer composites. An integrated pipeline network could then transport these materials to the habitat's construction zones or storage areas, enabling continuous habitat growth and maintenance.

#### Recommendations:

- **Develop Scalable ISRU Technologies:** Focus on scalable in-situ resource utilization (ISRU) systems that can support both initial mission requirements and future habitat expansion by utilizing local resources such as the Moon's regolith and Mars' atmosphere.
- **Establish Dedicated ISRU Facilities:** Construct dedicated ISRU facilities adjacent to habitats to process local materials and extract vital resources like oxygen and water. These facilities can also produce building materials, such as regolith bricks or polymer composites, to support habitat construction and maintenance.
- **Implement Integrated Pipeline Networks:** Design an integrated pipeline network to transport extracted resources and processed materials from the ISRU facility to habitat construction zones or storage areas, enabling continuous habitat growth and reducing reliance on Earth-based resupply.

## D. Service Systems for Crew and Habitat Support

Service systems include health services, waste management, and emergency response capabilities. These systems must be designed to function autonomously, ensuring uninterrupted operations under varying conditions.

1. **Health Services:** Autonomous medical systems with diagnostic, treatment, and telemedicine capabilities should be integrated into the habitat to support crew health. AI-driven health monitoring can detect early signs of illness and suggest preventive measures based on crew health trends.
2. **Waste Management and Recycling:** Advanced waste processing systems that convert organic and inorganic waste into usable resources, such as fertilizer or construction materials, can enhance self-sufficiency and reduce resupply needs.
3. **Emergency Response Systems:** Modular safety systems that isolate affected areas in case of a breach or hazard can protect critical habitat functions. Automated safety protocols, combined with decentralized control nodes, allow for rapid response to emergencies, minimizing damage and ensuring crew safety [(Wright et al., 2020)].

### Recommendations:

- **Integrate Autonomous Health Services:** Implement autonomous medical systems with diagnostic, treatment, and telemedicine capabilities to support crew health. Utilize AI-driven health monitoring to detect early signs of illness and provide preventive care based on health trends.
- **Develop Advanced Waste Management and Recycling Systems:** Establish waste processing systems that convert organic and inorganic waste into usable resources, such as fertilizer or construction materials, to enhance habitat self-sufficiency and reduce reliance on Earth-based resupplies.
- **Incorporate Modular Emergency Response Systems:** Design modular safety systems that can isolate affected areas in the event of a breach or hazard. Combine automated safety protocols with decentralized control nodes to enable rapid emergency responses, minimizing damage and ensuring crew safety.

Integrating these infrastructure elements with a focus on environmental resilience, resource utilization, and modularity supports NASA's objectives for sustainable surface habitation as detailed in the Moon to Mars Architecture Definition Document. The proposed designs and enhancements aim to improve the adaptability and scalability of habitats, ensuring that they can support evolving mission requirements and contribute to long-term human presence on the Moon and Mars. By building on the principles of modularity and ISRU, future habitats can reduce dependency on Earth-based resources and achieve a higher degree of autonomy, ultimately paving the way for deep-space exploration and settlement.

## VIII. Technology Gaps for Large-Scale Surface Habitats on the Moon and Mars

The establishment of large-scale surface habitats on the Moon and Mars is essential for achieving a sustainable human presence in extraterrestrial environments. However, this goal presents a series of complex technical challenges that demand innovative solutions and the development of advanced technologies. As highlighted in NASA's ranking of civil space challenges, significant gaps remain in critical areas such as radiation protection, closed-loop life support systems, in-situ resource utilization (ISRU), energy production, and thermal management [(NASA Civil Space Shortfall Ranking)]. These challenges are pivotal to ensuring long-term survivability, structural integrity, and sustainability in space. In addition, legal frameworks and economic sustainability also play vital roles in shaping the future of human habitation beyond Earth. This chapter addresses these critical gaps, offering advanced design insights and potential technological innovations required to overcome them, ensuring that human exploration of the Moon and Mars progresses in a safe, viable, and forward-thinking manner.

### A. Long-Term Radiation Protection

Protection against harmful cosmic and solar radiation is one of the most pressing challenges for long-term habitation on the Moon and Mars due to the absence of a protective atmosphere and magnetic field. Current passive shielding technologies, which primarily rely on dense materials like regolith or water, provide effective radiation protection but add significant weight to the habitat structure. An advanced approach could involve utilizing locally sourced materials such as compacted regolith or creating composite shielding materials that incorporate lightweight aerogels, reducing mass while maintaining protective capacity. Hybrid shielding designs that integrate passive and active systems, such as localized magnetic or electrostatic fields, can offer an additional layer of protection by deflecting charged particles. These active systems are still in early development stages but, when combined with modular passive elements, can create adaptive shielding configurations that respond to changing radiation levels. Addressing these gaps will require iterative testing of passive shielding materials alongside further research into compact, high-efficiency active shielding technologies.

## B. Closed-Loop Life Support Systems

Closed-loop life support systems are essential for minimizing dependency on Earth-based resupplies and ensuring long-term sustainability in lunar and Martian habitats. While current Environmental Control and Life Support Systems (ECLSS) can recycle water and regenerate oxygen with a high degree of efficiency, they rely heavily on mechanical systems that require regular maintenance and resupply. Integrating bioregenerative systems, such as algae-based photobioreactors, can enhance air and water recycling while reducing the mechanical complexity of the system. Algae bioreactors can be incorporated into habitat walls, serving both as air purifiers and supplemental food sources, thus adding a multifunctional aspect to the habitat's internal environment. By combining biological and mechanical processes, these hybrid ECLSS configurations can increase resilience against component failure and create a more robust life support system. However, additional research is needed to address the technology gaps related to maintaining and controlling biological systems in a low-gravity environment, as well as integrating them with existing mechanical ECLSS components.

## C. Large-Scale In-Situ Resource Utilization (ISRU)

ISRU is pivotal for achieving self-sufficiency by utilizing local resources to produce water, oxygen, and building materials. Current ISRU technologies, such as small-scale water extraction and oxygen production from regolith, are at low Technology Readiness Levels (TRLs) and are not yet capable of supporting large-scale habitat construction or long-duration missions. A key design concept for scaling ISRU involves modular extraction and processing units that can be deployed in phases. These units can initially support basic resource extraction, such as water harvesting and oxygen production, before being expanded to handle more complex tasks like metal refining and regolith-based construction material production. Integrating these modular ISRU units into the habitat architecture will enable continuous, scalable resource production as mission needs evolve. However, there are significant technology gaps in the efficiency of these processes and the reliability of systems operating in the extreme environments of the Moon and Mars.

## D. Energy Production and Storage

Reliable energy production and storage are critical for sustaining habitat operations on the Moon and Mars. Solar power is a proven technology for energy generation but is limited by the fluctuating availability of sunlight—such as during the long lunar night or Martian dust storms. To overcome these limitations, hybrid energy systems that combine solar power with compact nuclear fission reactors can ensure continuous power availability.

For instance, solar arrays equipped with advanced tracking mechanisms can maximize energy capture during the day, while Kilopower reactors can provide a steady power supply when solar energy is unavailable. Additionally, incorporating regenerative fuel cells and thermal energy storage systems can help balance power supply and demand. These solutions, however, need further development and testing to address the gaps in their reliability and efficiency under extraterrestrial conditions, where extreme temperatures and radiation can affect performance.

## E. Thermal Management

The Moon and Mars experience extreme temperature variations that place significant demands on thermal management systems. Traditional passive insulation methods, such as multi-layer insulation panels, are effective but may not provide sufficient protection against the rapid temperature swings experienced on the lunar surface or during Martian dust storms. Incorporating advanced thermal control materials, such as phase-change materials (PCMs), into the habitat structure can help stabilize internal temperatures by absorbing and releasing heat as needed. These materials could be integrated into the habitat's structural shell to create a self-regulating thermal barrier. Active thermal management systems, such as heat pumps and radiators, are also necessary for precise temperature control in critical areas of the habitat. However, developing these systems to operate efficiently in the thin atmospheres and low gravities of the Moon and Mars remains a major technical challenge.

## F. Structural Integrity

The reduced gravity and extreme environmental conditions on the Moon and Mars pose unique challenges to the structural integrity of habitats. Traditional building materials and construction methods used on Earth may not perform well under these conditions, where reduced gravity alters material behavior and the lack of atmospheric pressure can cause rapid thermal expansion and contraction. Developing new materials, such as regolith-based composites or basalt fiber-reinforced polymers, can enhance structural stability while reducing the need for Earth-supplied materials. Additionally, incorporating flexible connectors and expansion joints into the habitat design can accommodate thermal stress, preventing material fatigue and structural failure over time. Hybrid structural systems that combine rigid and flexible components could also provide greater resilience against seismic activity or micrometeorite impacts.

## Recommendations:

- Long-Term Radiation Protection: Develop hybrid shielding systems that utilize locally sourced materials (e.g., compacted regolith, aerogels) combined with active protection methods like magnetic fields to reduce mass and enhance protection against cosmic and solar radiation.
- Closed-Loop Life Support Systems: Integrate bioregenerative components, such as algae-based photobioreactors, into mechanical Environmental Control and Life Support Systems (ECLSS) to enhance recycling of air and water while minimizing maintenance and dependency on Earth-based resupplies.
- Scalable In-Situ Resource Utilization (ISRU): Design modular ISRU units that can be deployed in phases to support basic resource extraction (e.g., water and oxygen) and scale up to more complex tasks like refining metals and producing construction materials. Address technology gaps in efficiency and system reliability to ensure long-term functionality.
- Hybrid Energy Production and Storage: Implement hybrid energy systems that combine solar power with compact nuclear reactors, such as Kilopower, to provide continuous energy. Incorporate regenerative fuel cells and thermal storage to balance energy supply and demand during periods of limited solar availability.
- Advanced Thermal Management Systems: Utilize advanced materials like phase-change materials (PCMs) for passive thermal management and integrate active systems, such as heat pumps and radiators, to maintain stable internal temperatures. Optimize these systems for low gravity and extreme temperature variations on the Moon and Mars.
- Enhanced Structural Integrity: Develop new building materials, such as regolith-based composites and basalt fiber-reinforced polymers, to improve structural stability. Include flexible connectors and expansion joints in habitat designs to accommodate thermal stresses and provide resilience against seismic activity or micrometeorite impacts.

## IX. Existing Legal Framework for Space Habitation

Establishing large-scale habitats on the Moon and Mars requires adherence to established international legal frameworks, such as the Outer Space Treaty (1967) and the Moon Agreement (1984). The Outer Space Treaty, often referred to as the “constitution of space law,” provides the foundation for international space activities by declaring that space and celestial bodies are not subject to national appropriation, ensuring that all activities in space must be conducted for the benefit of all humankind and must be peaceful in nature (United Nations Office for Outer Space Affairs, 2020). This treaty has been ratified by most spacefaring nations, making it a cornerstone for regulating state

and private activities in outer space. However, the treaty is broad and leaves open to competing legal interpretations.

Expanding beyond the treaty, there are potential conflicts between the principles of the Artemis Program and China’s International Lunar Research Station (ILRS) Program. This lack of consensus highlights the need for updated legal frameworks to govern resource utilization and habitat establishment on celestial bodies.

For this paper, we are focusing on the Artemis Accords that were introduced in 2020 as a set of bilateral agreements between the United States and its space exploration partners. The Artemis Accords reaffirm the principles of the Outer Space Treaty, promoting transparency, interoperability, and the peaceful use of space. One of the key contributions of the Accords is the concept of “safety zones,” which are designated areas around lunar or Martian installations that are intended to prevent harmful interference between activities conducted by different parties. While the Artemis Accords are not legally binding, they establish a normative framework for conducting space activities and offer a collaborative approach to space exploration (NASA Artemis Accords, 2020).

### Implications and Future Considerations for Habitat Development

As human activities on the Moon and Mars expand, the limitations of the current legal frameworks become more apparent, necessitating the development of new policies and agreements to address emerging issues. For example, the existing treaties do not provide clear guidance on the ownership of resources extracted from celestial bodies, nor do they address the potential for private ownership of habitats and infrastructure. As a result, future legal frameworks must incorporate regulations for resource utilization and establish clear guidelines for habitat ownership, ensuring that all activities comply with the principles of non-appropriation and international cooperation.

One critical challenge is to develop a governance model that balances the rights and responsibilities of state and private actors while promoting international cooperation. The legal frameworks should support sustainable exploration and resource management, prevent conflicts over resource claims, and ensure that space activities do not harm the environment or violate the rights of other states. The development of such frameworks will require extensive international dialogue and collaboration, involving not only spacefaring nations but also emerging space actors and other stakeholders in the global space community (Wright, 2019).

## Recommendations:

- Develop Comprehensive Resource Utilization Guidelines: Establish international agreements that define the rights and responsibilities of state and private actors regarding the extraction and use of space resources. These agreements should outline mechanisms for equitable benefit-sharing and ensure that resource utilization does not lead to conflicts or environmental degradation.

- Define Habitat Ownership and Operational Jurisdiction: Create a regulatory regime that allows for the establishment of habitats and infrastructure by state and private entities, while maintaining compliance with non-appropriation principles. This regime should specify the extent of operational jurisdiction and ensure that habitats are accessible to all countries for peaceful purposes.
- Establish Safety and Coordination Protocols: Implement safety zones and coordination protocols to prevent harmful interference between activities conducted by different actors on the Moon and Mars. These protocols should be incorporated into broader space traffic management frameworks to ensure the safety and sustainability of operations in cislunar space and beyond.
- Promote International Collaboration and Transparency: Foster international partnerships and encourage the sharing of data, technologies, and expertise to build a cohesive exploration ecosystem. Establishing transparent communication channels and collaborative research initiatives will ensure that all space activities align with international norms and contribute to the collective advancement of human space exploration.

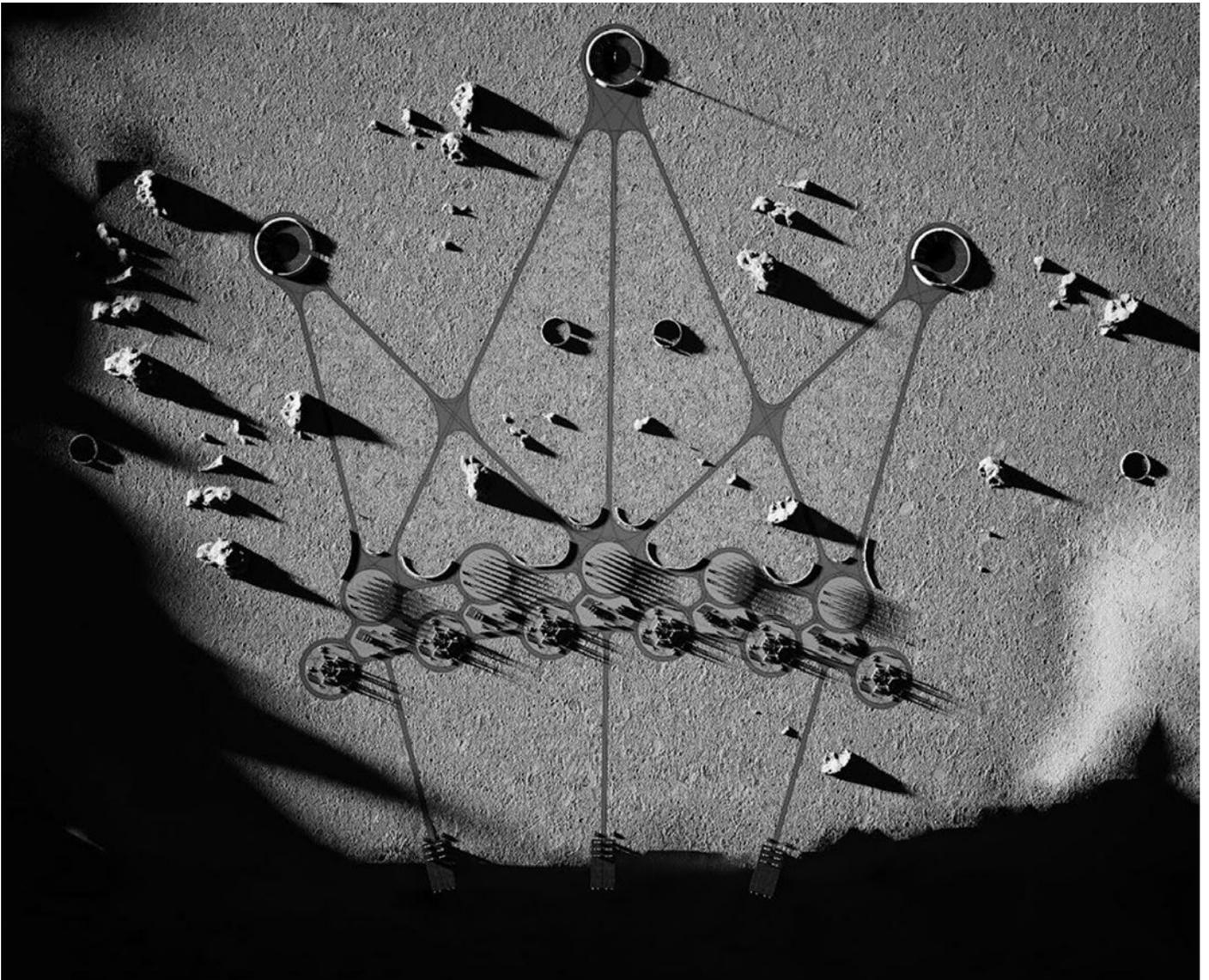


Image Credit: Lunar Masterplan Concept, Daniel Inocente Architecture

# X. Policy Frameworks for Large-Scale Surface Habitats on the Moon and Mars

To support the sustainable development and operation of large-scale surface habitats on the Moon and Mars, comprehensive policy frameworks must be established. These frameworks should promote international cooperation, technological interoperability, and a phased approach to scaling up infrastructure. The following policy recommendations focus on ensuring that these habitats are developed in a manner that facilitates collaboration, optimizes funding strategies, and supports long-term sustainability.

## A. Interoperability and Standards

Interoperability and standardization are critical for ensuring that surface habitats and their associated systems can operate seamlessly across international and commercial partners. Establishing common technical standards for habitat modules, connectors, life support systems, and communication protocols will enable different entities to contribute to a unified infrastructure. This standardization reduces development costs, simplifies integration, and ensures that habitats can evolve with new technologies. It is recommended that an international body, such as the International Space Exploration Coordination Group (ISECG), be responsible for defining these standards and coordinating their implementation across participating space agencies and commercial partners (Wright, 2019). By adhering to these standards, partners can develop compatible systems and share infrastructure, making it easier to establish a cohesive human presence on the Moon and Mars.

## B. Incremental Scaling

Incremental scaling is essential for gradually building up the infrastructure needed to support large-scale surface habitats. This approach allows for a phased development plan that addresses immediate mission needs while laying the groundwork for future expansion.

**Phased Development Plan:** A phased development plan involves starting with core modules that provide essential life support and operations capabilities and then adding new modules and systems as needs evolve. Initial phases should focus on establishing basic infrastructure, such as power generation, communication networks, and small-scale ISRU capabilities. Subsequent phases would expand habitat capacity, add specialized research and manufacturing facilities, and increase self-sufficiency. By following a phased approach, the risk and cost of initial investments are reduced, while providing flexibility to adapt to new discoveries and technological advancements (Bishop et al., 2018).

**Funding Mechanisms:** Securing funding for large-scale surface habitats requires a mix of public and private investment. Public funding from governmental space agencies will be necessary for initial phases of development, particularly for establishing core infrastructure and conducting critical research. However, private sector involvement should be encouraged through grants, tax incentives, and public-private partnerships that share the risks and rewards of space exploration. Establishing a lunar or Martian economic zone with favorable policies could attract commercial ventures and generate additional funding streams, such as resource mining, tourism, and space-based manufacturing (Lopez et al., 2018). These mechanisms will enable steady financial support for ongoing development and ensure that habitats can expand over time as new revenue opportunities are realized.

## C. Economic Sustainability

Though not covered in this paper, economic sustainability is critical for the long-term viability of lunar and Martian habitats. Identifying revenue-generating activities, such as tourism, resource extraction, or space-based manufacturing, can offset the high costs of habitat construction and operation. Encouraging public-private partnerships and creating incentives for commercial investment can accelerate the development of these activities. Cost reduction strategies, such as using ISRU-based construction techniques and modular habitat designs, can lower the initial investment required and increase scalability, making large-scale habitats more economically feasible.

Future considerations in this space could begin with encouraging public-private partnerships and developing ISRU-based construction techniques to reduce costs and increase scalability. Establish a regulatory framework that supports commercial activities and promotes economic growth in space habitats.

## XI. Conclusion

The development of large-scale surface habitats on the Moon and Mars represents a pivotal step toward establishing a sustainable human presence beyond Earth. This paper addresses the multifaceted challenges associated with these endeavors, offering strategies that integrate advanced technology solutions, international policy frameworks, and economic sustainability considerations. The proposed modular and adaptable habitat designs, in conjunction with innovative life support systems, energy solutions, and radiation protection technologies, lay the foundation for a robust and scalable infrastructure that can evolve to meet the changing needs of future missions.

Key recommendations, such as the utilization of in-situ resource utilization (ISRU) for building materials and energy production, the implementation of modular habitat systems, and the fostering of international partnerships, are essential to achieving a cohesive architectural framework that bridges lunar and Martian operations. By adopting a phased and iterative approach, NASA's Moon to Mars Architecture can serve as a blueprint for mitigating risks and enhancing the technical and operational capabilities needed to support long-duration human missions.

The establishment of sustainable surface habitats on the Moon and Mars requires a unified effort across technological, economic, and policy domains. The insights and recommendations outlined in this paper aim to support NASA's strategic goals, promoting the seamless integration of lunar operations as a stepping stone for Martian exploration. Through continuous innovation and collaboration, these habitats will not only enable scientific advancement and exploration but also pave the way for the long-term settlement and development of extraterrestrial environments.



Image Credit:  
Large-Scale Hybrid Lunar Habitat Concept Daniel Inocente Architecture

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