Lunar Surface Innovation
CONSORTIUM

LSIC COMMUNITY REPORT

The Path to an Enduring Lunar Presence

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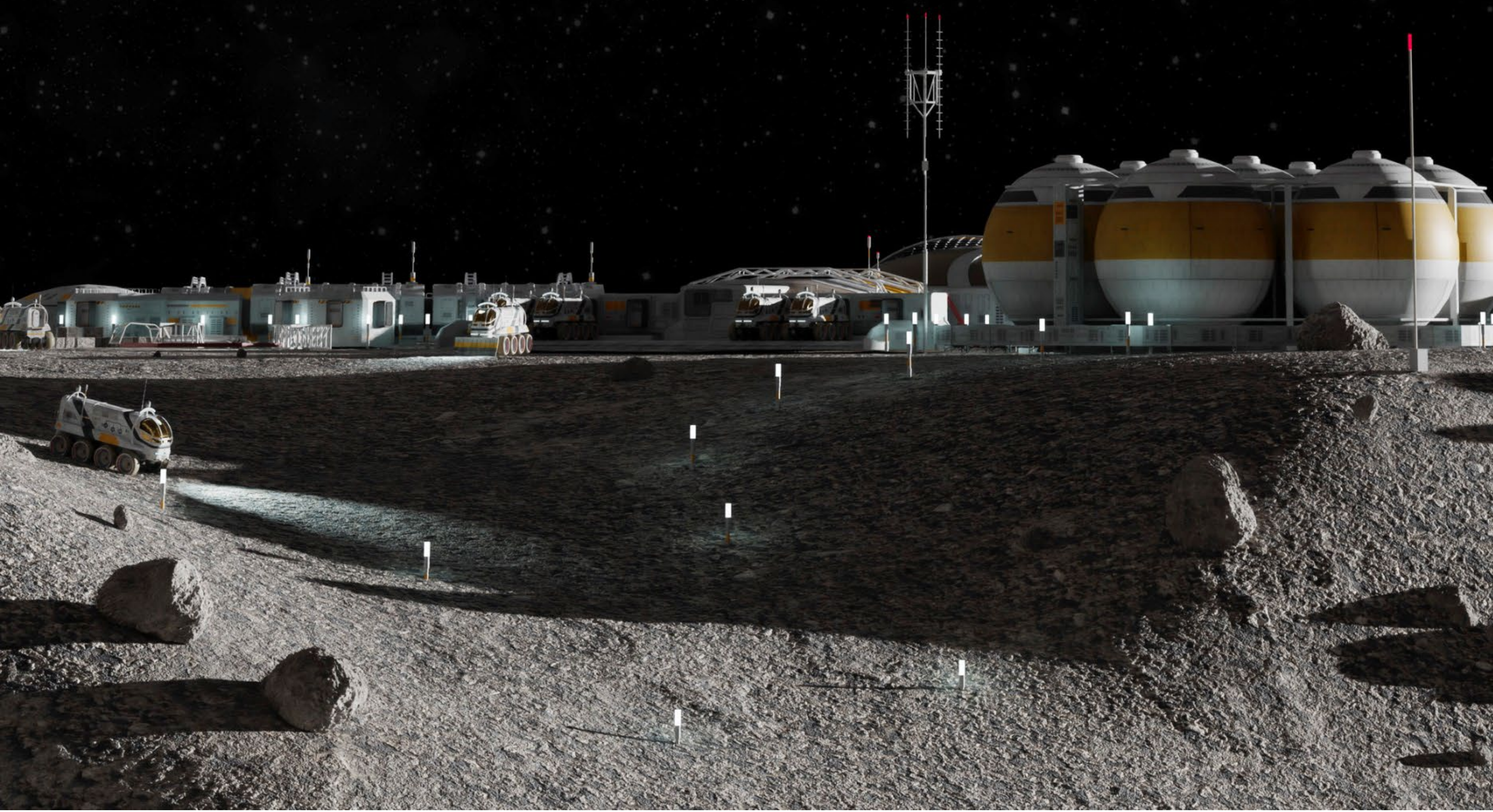

EXECUTIVE SUMMARY

The Lunar Surface Innovation Consortium (LSIC) is managed by JHUAPL for NASA to harness the creativity, energy, and resources of the nation to help NASA keep the United States at the forefront of lunar exploration. The LSIC operates in collaboration with the NASA Space Technology Mission Directorate under the Lunar Surface Innovation Initiative (LSII) and has more than 3000 participants across more than 45 countries. It fosters communications and collaborations among academia, industry, and Government through focus areas that have monthly meetings, small-group discussions, thematic workshops, and more.

This white paper focuses on providing community perspective that helps answer the question, "in satisfying NASA's baseline Moon to Mars objectives, how can we ensure robust participation from industry and enable a transition away from NASA as a sole customer on the lunar surface?" This is often colloquially referred to as "NASA's handoff to industry," an idea which generates great interest across the LSIC, and is seen as the part of the path to an enduring lunar presence.

The first period of lunar development, led by NASA, should culminate in a base that resembles the first Mars base. This marks the Moon as a functional proving grounds for further space exploration. As NASA shifts its focus to Mars, there will still be a need for operations on the Moon, which may be met by commercial partners. By focusing on the minimum feature set for NASA's Moon to Mars lunar base, we are able to examine decisions impacting multi-decade goals. These concepts have been reviewed at LSIC meetings to solicit input; this document presents a distillation of the LSIC's perspectives.

In addition to spin-off technologies coming out of NASA, **translational technologies from industry, academia, and other governmental agencies offer opportunities for bringing the technical expertise of our Nation to bear** on the Lunar surface. By engaging in these efforts for the lunar surface, the US and other nations have demonstrated that they seek to **foster a new sector of the economy** that brings highly technical jobs, new economic markets, and the creativity and imagination of humanity. Early indicators of this future will be strongly tied to government investment, supplemented by cross-over to additional markets. The US Government's role in achieving a commercial lunar ecosystem includes stalwart support through the initial learning phases of Lunar presence. Early operations on the Moon will show us when we're ready to move on to Mars, and when we're ready for an expansion of commercial participation. It is essential to consider potential end states early in our execution in order to build in on-ramps for the futures we would like to achieve, and to act expeditiously to establish presence and associated normative behaviors that will set precedents for humanity's future.

STAKEHOLDERS

Coordination and communication will be crucial to define strategies, identify competence areas, and ensure value is delivered to all stakeholders[i]. Owing to the scale of the lunar endeavor, decision makers in Congress, NASA, and other governmental agencies need a clear understanding of the value of the lunar initiative in order to sustain funding. Continuity of intention and funding is essential to foster commercial investment: **an enduring presence on the lunar surface requires consistent intention and funding**. The LSIC community has repeatedly noted that NASA's transparency in their process and that the involvement of multiple stakeholders are key signals of stability that encourage industry involvement. In the absence of concrete scales for demand signals, a breadth of interest across stakeholders bolsters commercial confidence.

Many within the LSIC community attribute the success of the ISS to the involvement of international partners, and strongly support efforts to bring in the global lunar community. This includes **non-traditional players, many of whom are eager to earn the legitimacy of working with NASA on a large-scale endeavor**. Early coordination and communication are required to enable meaningful participation across domestic and international partners. In particular, attention to interoperability now will not only enable continual incremental innovation, but tractable avenues for international involvement. Government, industry, and international partners should be focused on developing systems that are inherently scalable and interconnected to enable global adoption and continual support across decades or more of demand on the lunar surface. Larger international players developing relevant technologies may offer substantial cost-savings on key technologies. **NASA's technology plans should work to explicitly and transparently include international participation.**

EVOLUTION OF THE LUNAR SURFACE AND ESSENTIAL EARLY TECHNOLOGIES

Based on the Moon to Mars Blueprint Objectives and Planning Manifest[1], the lunar base will go through three phases. These phases have different technical and operational goals. Phase I focuses on technology and science on the Moon and establishing a minimum-viable base by approximately Artemis VIII. Phase II expands on this base to enable unprecedented science and prove out technologies that will be used on future Mars missions. During this period, operation of surface activities may transition from NASA to industry. If initial efforts are performed in consideration of industry needs, tendrils of an intrinsic lunar economy may emerge. Achieving this marks an open-ended Phase III, where commercial activities proliferate, with industry offering support and services to NASA. While in situ resource utilization (ISRU) may play a substantial role in Phase II and III, baseline Moon to Mars objectives for ISRU are to mature initial capabilities rather than deliver a system ready for an end user. The ultimate technologies for large-scale ISRU will benefit dramatically from the initial infrastructure and exploration that precedes it, especially resource evaluation, long-duration activities, and sub-scale efforts to demonstrate the viability of resource production. Further, the early development of Lunar infrastructure must support the eventual adoption of large-scale ISRU capability. Interoperability, rover development, power distribution, and scalable Lunar architecture are among the primary considerations.

There are four predominant areas that need to be addressed to achieve a successful lunar base representative of a Mars mission that does not preclude long-term utility.

- **Awareness:** Communications, position, navigation, and timing (PNT), and space-domain awareness (SDA) ensure safe transitioning to/from lunar orbit and operations while on the surface. Surface location beacons offer foundational PNT capability.
- **Excavation and Construction:** Providing routine access to emplaced infrastructure is an essential early objective. Features under consideration include landing pads, plume mitigation berms, roads, and regolith as a radiation shield.
- **Power:** The habitat needs crew-rated power sufficient to supply continuous 5-10kW per crewmember.[ii] (Colozza, 2020) A reliable power system is key foundational infrastructure. Power infrastructure considerations include interoperability and distribution.
- **Habitat:** The culmination of early infrastructure is a habitat that fully supports crew for two weeks to six months.

Communications and PNT

For both communications (comms) and PNT services, a successful transition to industry will require a large enough market that service providers can earn a profit. Owing to the critical need and cross-over application for these services across the cislunar domain, this is likely to be the first market to emerge and may be a harbinger for commercialization across other services. **Immediate attention is needed to ensure presently developing commercial efforts, proceeding without NASA funding, mature into a scalable and interoperable architecture that maintains the pristine far-side radio-quiet environment**. Lunar surface comms markets are much smaller and, while low-TRL, have a straightforward development path. A tech demo of 4G/LTE technology for the Moon is planned for late 2023 on a CLPS mission. A full GPS system for the Moon is cost-prohibitive in the near-term[iii], but surface navigation beacons could be widely integrated to offer a lower-cost alternative, and have demonstrated terrestrial value in mining and construction. Navigation may use a combination of inertial measurement units (IMUs), visual sensors, and position fixes from navigation beacons.

A notional timeline for transitioning communications to industry is below; earlier adoption of interoperable approaches may accelerate this timeline.

1. Nokia tech demo of 4G/LTE technology for lunar surface communications launches late 2023 on CLPS mission
2. ESA launches Lunar Pathfinder relay optimized for south pole users in 2025
3. Multiple companies and space agencies provide disparate (non-interoperable) communications relay satellite services to lunar surface users by 2030
4. Technologies to support 3GPP-based lunar surface communications, Delay-Tolerant Networking (DTN), and WiFi networking are available for purchase by 2030
5. Interoperable, DTN-compatible communications infrastructure for surface-to-surface communications at the lunar south pole, direct and satellite relay to Earth in the 2030's.

The following timeline shows three milestones for the PNT transition:

1. LuGRE GNSS receiver and Lunar Node 1 navigation beacon tech demos launch on CLPS missions in 2023
2. Lunar surface-capable GNSS receivers and navigation beacons are commercially available by early 2030s, along with lunar-capable IMUs and LIDARs for rovers
3. Surface navigation beacon infrastructure to support in-situ resource utilization and excavation and construction set up concurrently with power/communications towers available in limited geographic regions in mid 2030's.

Power

No single method of power generation under development for the lunar surface is sufficient to meet the demand of 100 kW to support an ISS-scale lunar station. Instead, the power architecture by the 2030's will be comprised of heterogeneous generation, storage, and distribution across km+ distances. Extensibility and interoperability of this architecture is critical for a commercial future. Power systems in advance of an interconnected FSP system (possible by 2030) will require particular attention to survival through the lunar night. Placement and CONOPS will have dramatic impact on energy storage demands, readily outstripping battery capabilities to require regenerative fuel cells (RFCs) or long-range distribution (cables or beamed) if even modest activity is expected during periods of darkness. RFCs may also be useful for other early elements that require large-scale energy storage.

There is considerable promise for industry investment in advanced terrestrial reactors to complement NASA's and OGA investments in FSP, but the community is wary of the program's political sensitivities, cost, and time delays. The lessons learned by the space nuclear community are hard-felt and should be carefully considered. Near-term application is limited primarily by funding, test facility infrastructure, and regulatory support and collaboration between institutional stakeholders (mainly NASA, DOE, NRC, DoD). In particular, there is an opportunity to leverage synergistic development of space nuclear and terrestrial microreactor technology maturation, which has resulted in improved fuel forms, advanced moderator and reflector materials, heat transfer technologies, power conversion and rad hardened electronics.

With its systems-based development process that emphasizes practicality and infusion, the Vertical Solar Array Technologies (VSAT) program could be a pathfinder for technology infusion from industry. A CLPS-mission that emplaces a VSAT which is integrated into the Artemis architecture would be seen as an achievement for industry, while making substantial progress towards the M2M LI-1 objective. Illumination will be critical to Phase I, but our predictive power is limited by the resolution of current digital elevation maps. Furthermore, difficulties in deployment of very large arrays, extended periods of very limited illumination during lunar winter, and a desire for proving Mars-forward FSP technology implies multi-modal generation.

The following milestones summarize how power generation technologies are expected to advance to achieve the NASA's overall objectives for 2030:

1) Mid-2020's: First VSAT at the 10 kW scale arrives on the Moon in the mid-2020's.
2) Mid-Late 2020's: another VSAT and preliminary grid elements deployed and tested.
3) Mid-Late 2020's: Terrestrial FSP demonstration.
4) Late 2020's: First FSP, operational and ready to integrate into grid at the 40kW scale.
5) Early 2030: Fully connected power grid, including several VSATs and potentially one or more FSPs. **Achieving this marks the beginning of reliable power as a service and unlocks potential for commercialization.**

Excavation & Construction

The process of transforming the bare regolith surface into an infrastructure capable of a sustained lunar presence will require tremendous resources as well as advancements in excavation and construction (E&C). **Reusable landing pads, plume protection berms and roads to get from landing pad to lunar base station are milestones in the transition into an enduring presence.** Additional improvements will include structural elements for deployment of power generation elements or ISRU equipment, trenches for power grid lines, and rover 'garages'. Rovers will need to move, level, and pave regolith. Early demonstration of these capabilities supports longer-term infrastructure and builds operational knowledge.

Once reusable assets are permanently landed on the Lunar surface, subsequent landings must ensure safety from debris ejected by the landing of the descent vehicle (dust, regolith, and rocks), which has the potential for inducing catastrophic and system failures. An architecture decision needs to be made early to fix the optimal plume mitigation strategy. The decision space ranges from landing close to the habitat with the need for a landing pad and berm to landing far from the habitat with roadways that allow the passage of heavy and outsize cargo. This consideration must be brought into play very early in the mission design process, since supporting E&C technologies may need maturation much earlier than has been anticipated.

Prior to Phase III, a demonstration will be needed to support advanced manufacturing and autonomous construction capabilities. In order to acquire the regolith, robotic excavation technologies will be necessary and these excavators will be very different from terrestrial ones due to the harsh environment on the Moon and the severe mass and volume limitations that are imposed by the space transportation launch vehicles[iv].

The following are the key milestones for E&C:

1) Subscale Landing Pad Construction Demonstration. Partial completion may help protect essential infrastructure such as VSAT
2) Subscale Berm Construction Demonstration
3) Subscale Road Construction Demonstration
4) ISRU Pilot Excavator demonstration

Habitats

Habitat considerations are well-established, with numerous NASA-sponsored studies and assessments in this area[v] and extensive effort on EHP elements. To achieve an enduring presence, additional attention is needed on the implied demands for other technology domains and on the standardized functionality that can support larger architecture objectives. In particular, where possible, early elements should be prioritized for modular, bidirectional power handling with standardized connectivity, to support and take advantage of the incremental construction of an electrical power grid. For communications and PNT, all surface habitats should have full-duplex RF systems that can facilitate formation of an integrated communications system on the surface. Transmit-only RF beacons in all landed elements can help instantiate a PNT network for the lunar surface. Far-side operations need careful attention to spectrum management owing to the scientific value of the uniquely pristine nature of its radio environment.

CROSS-CUTTING THRUSTS: DUST, INTEROPERABILITY, AND DOMAIN AWARENESS

Lunar dust impacts all aspects of activity on the Moon and the lifetime of assets amidst pervasive lunar dust must be taken into account to achieve a sustained lunar presence. **By investing in dust mitigation technologies, NASA can demonstrate a commitment to continued use of the lunar surface.** Dust can be addressed by technologies, CONOPS (including maintenance/repair), and risk tolerance. Landings and activities produce ballistic dust and regolith while architecture and CONOPS will impact mitigation strategies. Although some standards currently exist that pertain to system testing[vi] as well as human health and performance[vii], there remains need for selection and handling of lunar dust simulant, development of multi-system dust mitigation stations, and an increase in industry focus on dust mitigation.

The LSIC interoperability working group has called for a systematic approach to the coordination of technology developers, identification of critical interfaces, and development of interoperability profiles or requirements. Major primes might benefit from sole-sourcing of lunar technologies and thus have a conflict of interest in endorsing interoperability, however, several developers across market scales within the LSIC have supported this movement. Industry recognes **interoperability as an indicator of a long-term commitment to lunar surface activity**. This is also supported by the Moon to Mars recurring tenet RT-7. Efforts towards interoperability are expected pay off in later stages of the lunar endeavor, it may also facilitate isolated elements within the Artemis era to more deeply integrate within the lunar infrastructure.

Domain awareness on the lunar surface and within the orbitally-complex cislunar environment is often neglected in discussions, but is an essential component of safety. While navigation beacons can support positional awareness on the lunar surface, a more concerted effort towards domain awareness encompassing space weather, autonomous element activity, accessible elements, etc. will provide the necessary confidence required for all who operate on the lunar surface.

KEY INFRASTRUCTURE DECISIONS

The development of incremental capability on the Moon to support Moon to Mars objectives has been analyzed with a focus on enabling a commercial lunar ecosystem. A minimum feature set was determined to bound the discussion and produce pragmatic recommendations on early infrastructure. Three major decisions will improve the effectiveness of technology investments towards achieving the fundamental architecture of the lunar base.

Infrastructure Decision 1: Lunar landing events produce hazardous ejecta. An infrastructure decision should be made by 2027 between landing close to emplaced infrastructure and landing farther away to prevent ejecta-induced damage. This decision fundamentally impacts supporting technology requirements. Landing near the habitat requires a functional capability to build a "flat and hard" landing pad along with a berm to contain small ejecta particles. Landing far requires traverse from landing site to habitat, which could be as simple as a "dirt road" requiring clearance of boulders along planned paths.

Infrastructure Decision 2: Power and communication decisions should be made in the same timeframe to enable 1) the "lunar electrical power grid" (M2M LI-1) and 2) "Moon to Earth RF comms" (M2M LI-2). These two decisions drive the development of interfaces, grids, communications, and modularity. Ideally every system landed on the Lunar surface would have similar interface capability to allow expansion and interoperability. Comms and PNT interdependencies require advanced planning and coordination, especially in the context of potentially multiple independent architectures.

Infrastructure Decision 3: Prior to 2031 determine functionality and equipment needed for "environmental monitoring and situational awareness" (M2M LI-9). This capability is necessary to protect astronauts living in the Surface Habitat on a long term basis. The schedule for this detailed development should be back-planned in the context of longer-duration habitats.

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