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Addressing the Environmental Challenges and Infrastructure Needs of the Lunar South Pole

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Abstract

NASA's Moon Base is establishing an enduring human presence at the lunar South Pole. The Moon Base will be a home for Artemis astronauts and a nexus of robotic activities. While the lunar South Pole is one of the most scientifically interesting and resource-abundant parts of the Moon, it also introduces a new environment with both opportunities and challenges to consider. These include a unique lighting environment, dramatic topography, varied terrain, and more. In addition to the natural environment, exploration creates an induced environment in which equipment, landing zones, and human factors create additional challenges. NASA's Moon Base strategy enables sustained exploration and a progressive buildup of capabilities in this harsh environment. Essential infrastructure for an ongoing human presence includes habitation, mobility, power, logistics, and more. These pieces must work together in a cohesive systems architecture to enable the United States' ambitious goals for lunar exploration. To realize these ambitions, NASA and its partners are building an evolutionary exploration architecture that achieves these capabilities. The architecture leverages industry and international partnerships to enable the breadth and demand of capabilities while ensuring exploration robustness. By demonstrating these systems and operations, the Moon Base will serve as proving ground for the technologies and operational capabilities needed to send the first humans to Mars and realize scientific and economic benefits here on Earth.

Keywords: Moon Base, human spaceflight, NASA, lunar South Pole, environment, infrastructure

Acronyms/Abbreviations

National Aeronautics and Space Administration (NASA)
Communications and positioning, navigation, and timing (C&PNT)
Plume-surface interaction (PSI)

1. Introduction

On March 24, 2026, NASA Administrator Jared Isaacman unveiled a series of transformative initiatives designed to advance American leadership in space and achieve national space policy.[1] During this Ignition [2] event, NASA introduced plans for developing humanity's first outpost on the lunar surface: the Moon Base.[3]

The Moon Base will comprise the surface infrastructure and systems needed to support visiting Artemis astronauts for progressively more ambitious missions. Its phased implementation plan will embrace industry and international partnerships to lay the foundation for an enduring human presence near the lunar South Pole.

NASA has selected the lunar South Pole region for human exploration for its unique scientific, economic, and operational opportunities.[4] This location is fundamentally different than the near-side equatorial sites visited by Apollo, offering new challenges that the agency must overcome.

Many of the factors that make exploring the lunar South Pole region challenging also make it attractive. Prolonged periods of sunlight (versus the approximately 14-day cycle of light and dark in the lunar equatorial regions) in certain areas create advantages for extended exploration operations in sunlit regions and provide favorable solar power generation and thermal environments.

The ancient terrain at the South Pole-Aitken basin offers a rich geologic record that is distinct from the regions explored by Apollo missions, enabling scientists to conduct new investigations both in-situ and using returned samples.[5] Additionally, permanently shadowed regions [6] could contain volatiles, such as water ice, that could prove both scientifically valuable and advantageous for future in-situ resource utilization. [7]

This paper explores the challenges and opportunities of the Moon Base, focusing on infrastructure considerations for the gradual buildup of Moon Base capabilities.

2. Moon Base Approach

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NASA's Moon Base approach comprises implementation over three phases guided by agency expertise in engineering and science. The Moon Base is a system of systems that must work together seamlessly to enable crewed and robotic exploration and utilization returns.

2.1 Phased implementation

The Moon Base follows a phased implementation approach to progressively develop the infrastructure needed to support an enduring human presence. As initial robotic missions prove out technologies, NASA and its partners will continue to develop and deliver additional infrastructure and services that can evolve over time. The Moon Base will not reside in a single location on the lunar surface but rather provide access to multiple exploration zones at areas of scientific interest in the lunar South Pole region.

2.1.1 Phase One

Robotic missions in Phase One will accelerate operational systems, such as landers and mobility systems, and further demonstrate initial capabilities (e.g., power) to survive extended periods of shadow. Scientific payloads will collect ground truth data about the lunar environment (see below for more information about these challenges) and prepare for human exploration. Concurrently, initial Artemis missions will return humans to the lunar surface for the first time since Apollo.



Fig. 1. Artist's rendering of conceptual Moon Base Phase 1 development activities near the lunar South Pole

2.1.2 Phase Two

Based on the data collected in Phase One, Phase Two will emplace increasingly capable power, mobility, and logistics systems in exploration rich areas. This deployment lays the groundwork for robotic system charging and hibernation, scientific and technology utilization and establishing early zones for habitation. Further, distributing systems in multiple zones increases architectural access to varied terrain and features and enables greater reconnaissance and data collection for lunar understanding.

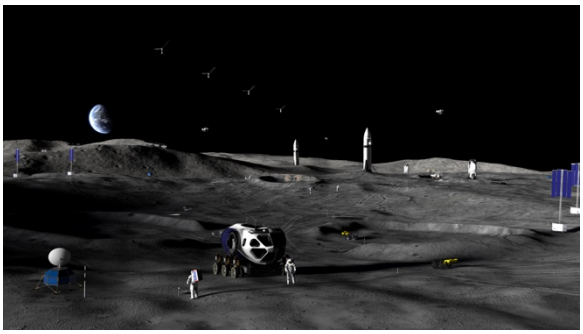


Fig. 2. Artist's rendering of conceptual Moon Base Phase 2 development activities near the lunar South Pole

2.1.3 Phase Three

Phase Three builds on the previous phases to deploy and aggregate large-scale systems that can support an enduring human presence. This will include initial habitation systems, a power grid (including initial nuclear power), and increasingly robust utilization systems. Crews will be able to access distributed zones using mobility systems. Newly deployed systems in this phase incorporate lessons learned from previous phases to increase reliability and robustness.



Fig. 3. Artist's rendering of conceptual Moon Base Phase 2 development activities near the lunar South Pole

2.1.4 Beyond Phase Three

The Moon Base does not end with Phase Three. These development phases merely represent the initial steps of a long-term exploration endeavor. The Moon Base and the human missions it enables will continue to grow and evolve, enabling increasingly ambitious exploration of our nearest cosmic neighbor while preparing NASA and its partners to journey to Mars and beyond.

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Fig. 4. Artist's rendering of conceptual Moon Base activities leading to an enduring human presence on the lunar surface

2.2 Strategic considerations

Phased implementation of the Moon Base will allow NASA and its partners to test revolutionary new technologies and quickly transition them to operational capabilities. A successful technology demonstration may become a critical piece of Moon Base infrastructure.

The Moon Base approach requires frequent and consistent access to the lunar South Pole region to empower exploration and science. It maximizes opportunities for lunar science and technology demonstrations with increasingly capable lunar landers from a wide variety of providers.

Industry innovations and international partner contributions to the architecture will accelerate the achievement of Moon Base phases. They will empower progressively more ambitious and lengthy crewed missions to the lunar South Pole region.

Ensuring the safety of astronauts at the Moon Base means embracing a robust architecture with dissimilar redundancy of component elements and the ability to maintain and repair them. Single points of failure stymie progress on the path toward an enduring human presence at the Moon Base.

Finally, science and inspiration are core to the Moon Base approach. Every mission must contribute to these aims, including ample opportunities for science investigations and public engagement. This means prioritizing payloads like high-definition cameras, which bring humanity along on the journey and offer new insights for lunar scientists.

3. Environmental Challenges

Achieving the Moon Base plan requires developing systems and operations that can overcome a wide range of environmental challenges. While NASA can draw on lessons from decades of human spaceflight, including Apollo and the International Space Station, the lunar South Pole presents unique conditions that NASA and its partners must address to pave the way for long-term exploration.

3.1 Lighting and shadow

The lighting environment in the lunar South Pole region is incredibly different than that of the equatorial maria and highlands visited by Apollo. The full lunar day/night cycle lasts about a month, with lunar day and night lasting about two Earth weeks each.[8]

Apollo astronauts would land near the beginning of the lunar day, meaning they had the advantage of full, bright sunlight for the duration of their missions. Since the Sun rose directly overhead, visibility was not an issue.[9] Additionally, they had plenty of solar energy available to them in the form of heat. (They also had ample solar electric generation opportunity available to them, though the Apollo mission architecture relied primarily on batteries and fuel cells.).[10]

In the lunar South Pole region, the Sun remains low on the horizon, casting dramatic shadows that impede visibility, hinder solar electricity generation, and subject systems to prolonged periods of extreme cold.[11] Moon Base systems, operational paradigms, and site plans must be robust to these challenges, generating enough power and heat to survive extended shadow. Additionally, site planners must consider shadows induced by visiting vehicles and emplaced infrastructure, which can obstruct solar visibility by nearby assets. Architectural considerations include significant power generation and storage infrastructure to augment or offload power required to survive the lunar night.[12]

3.2 Terrain

The lunar South Pole region is largely highlands, heavily cratered and mountainous terrain that covers most of the lunar surface. The highlands are significantly more rugged and challenging to navigate than the lunar maria, the flat plains formed by ancient lava flows filling massive craters.

While most Apollo missions visited lunar Maria, NASA does have crewed operational experience in the lunar highlands. Apollo 16 [13] landed in the highlands north of Descartes crater and explored the region over three EVAs.[14] The mission saw many of the terrain challenges that NASA will encounter while implementing the Moon Base, namely terrain types, slope, and elevation.

Scientists categorize the lunar highlands terrain from Apollo 16 into three types:

- Terrain type one comprises rolling hills with low slopes, subdued craters, and low block (boulder) abundances. This terrain was easily traversed by Apollo 16 astronauts and their Lunar Roving Vehicle.
- Terrain type two features more blocks and craters, as well as steeper slopes up to 20 degrees. This terrain was still moderately traversable by the Apollo 16 crew, though it

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required more caution and time to navigate than terrain type one.

- Terrain type three was hillier, with slopes of around 25 degrees more common. This terrain type tended to be located near younger, larger craters with significant block coverage. Terrain type three was challenging to traverse, but often included areas of greatest scientific interest.

The slopes and elevation changes NASA will encounter in the lunar South Pole region present challenges for mobility systems and site accessibility. As an example, Shackleton Crater — directly at the lunar South pole — is more than twice as deep as the Grand Canyon and could fit almost all of Washington, DC, within its crater walls. The average slope descending into the crater is 30 degrees, equivalent to an expert “black diamond” ski slope.

3.3 Regolith

Ubiquitous lunar regolith (dust) presents one of the most significant challenges of lunar exploration. Regolith is coarse, clings to equipment, and is potentially hazardous to human health. System designs must account for the potential negative effects of regolith, keeping it out of interfaces, habitable volumes, valves, and other sensitive areas.

Systems like rover wheels, space suits, and solar panels must account for regolith-related wear and tear. This creates the need for dust resistance, dust removal, regular replacements, or some combination of solutions. Dust-tolerant systems and connectors —which will be necessary throughout all lunar surface systems — are among NASA's highest-priority documented technology gaps.[15]

3.4 Temperature

The dramatic lighting conditions of the lunar South Pole region create extremes of temperature that Moon Base systems must accommodate. While the maximum temperature during sunlit periods is a manageable 54 degrees Celsius (327 Kelvin), areas in permanent or near-permanent shadow present a significant challenge for thermal systems design.[16]

In the permanently shadowed regions that the NASA hopes to explore for science and resource utilization, scientists have measured temperatures lower than -200 degrees Celsius (70 Kelvin).[17] Exploration systems in the lunar South Pole region will require innovative thermal systems and ample power augmentation to survive or operate at either temperature extreme.

3.5 Partial gravity

While NASA has extensive experience with microgravity operations from the International Space Station, its experience in partial-gravity operations is limited to only a few days' total time from the Apollo missions. Lunar gravity — approximately one-sixth of Earth's — presents significant complications for human operations and system design.

Logistics operations that are simple in microgravity — such as transferring heavy cargo through hatches — become far more complex in partial gravity; for example, an operation that would require one or two crew members in microgravity might require an entire multi-ton mobility and robotics system on the Moon. Additionally, NASA cannot simply adapt systems designed for use in microgravity for partial gravity (i.e., a space station habitation design is not suited for lunar surface applications without such extensive modification as to be impractical). NASA must design habitation, logistics, mobility, power, and other systems specifically for operations in the Moon's unique gravitational environment.

Many of the factors that make exploring the lunar South Pole region challenging also make it attractive. Prolonged periods of sunlight (versus the approximately 14-day cycle of light and dark in the lunar equatorial regions) in certain areas create advantages for solar power generation and extended sunlit operations. The ancient terrain at the South Pole-Aitken basin [18] offers a rich geologic record that is distinct from the regions explored by Apollo missions, enabling scientists to conduct new investigations both in-situ and using returned samples. Additionally, permanently shadowed regions could contain volatiles, such as water ice, that could prove both scientifically valuable and advantageous for future in-situ resource utilization.[19]

3.6 Radiation environment

Humans and spaceflight systems at the Moon cannot rely on the protection of Earth's magnetic field to reduce exposure to solar and cosmic radiation. The Moon Base must consider shielding and other countermeasures to protect against radiation's deleterious effects on both humans and electronics.

Additionally, improved space weather monitoring would provide significant advantages for Moon Base operations. The more warning mission planners have of incoming radiation events, the more opportunity they have to direct crew members to shelter in place or take other precautionary measures. This requires both better characterization of the local lunar radiation environment and monitoring sources of radiation, such as solar activity.

NASA's Artemis II mission tested equipment and operations associated with radiation, including observing solar activity [20] and measuring the effects of radiation using sensors inside the Orion spacecraft and innovative human "tissue chips."[21] Initial Moon Base missions

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can collect additional radiation data to inform future habitat design.

These factors make the South Pole both an exciting location for exploration and an ideal place for Moon Base infrastructure. However, system designs, described at a high level below, will need to account for the challenges detailed above.

4. Landers and Logistics

4.1 Landing site distribution

The numerous environmental factors described above affect landing site selection and distribution. Landers require sites that are sufficiently clear of debris, offer favorable illumination, and are accessible by mobility assets. Given the wide variety of terrain conditions in the lunar South Pole region, identifying these landing sites requires detailed reconnaissance and surface imaging.

With these sites identified, landers require precision landing capabilities: the ability to navigate to and touch down at the selected area, while avoiding hazards such as boulders and craters. Precision landing capabilities integrate positioning data, communications between landers and Earth-based ground control, and onboard remote sensing, including both cameras and ranging technologies like LiDAR, to navigate to the intended landing site and avoid hazards during final descent. Precision landing is essential for both crewed and uncrewed missions, though specific site needs and risk approaches will vary across missions.

Additionally, rocket exhaust plumes from lunar landings and ascents kick up dust and larger debris. The Moon Base will need to account for these plume-surface interactions (PSI) with a combination of additional data collection to further characterize the challenges; careful site selection to avoid damage to emplaced elements and infrastructure by vehicles arriving or departing; and potential regolith manipulation to build berms, landings pads, or other PSI mitigation features.

4.2 Logistics needs for crew support

Early Artemis missions will bring everything they need to the lunar surface with them. As Moon Base infrastructure grows to support longer mission durations, logistics deliveries in advance of crew arrival will become necessary. These deliveries would include consumables like food and water for the crew, gasses to support pressurized environments and EVAs, and spare parts and equipment needed to maintain Moon Base systems. These logistics needs place a significant burden on the architecture, requiring increasing downmass and astronaut time to facilitate logistics operations.

4.3 Decommissioning and disposal

In addition to landing site distribution constraints, landing site selection requires careful planning and coordination. If a lander is decommissioned in place, its landing site becomes unavailable for future use, unless the decommissioned lander can be relocated. Some landers, such as the Human Landing System, land and take off again, enabling the potential re-use of certain sites. Moon Base mission planning will require thorough analysis of available future landing sites to ensure that a near-term landing does not preclude future operations or otherwise make a more favorable sites permanently unavailable.

4.4 Offloading and manipulation

Landing cargo and payloads on the lunar surface is only the beginning of the logistical challenges for Moon Base. Once landed, cargo must move from point of delivery to point of use. This will require robotic capabilities to offload, manipulate, and transport cargo.

Some deliveries may arrive well in advance of Artemis missions and will require access to external power for conditioning. Without this power, the cargo may not survive in the harsh lunar environment until crew arrival.

While crew can manipulate cargo, time spent on logistics operations reduces the time available for astronauts to spend on science and inspiration. While initial missions may require extensive crew time for handling logistics, the architecture can evolve to add additional autonomous logistics systems, such as mated carriers, which enable intravehicular logistics transfer.

5. Communications and Positioning, Navigation, and Timing

Communications and Positioning, Navigation, and Timing (C&PNT) services are critical to the success of any space mission. As the Moon Base evolves, the number of cislunar C&PNT users and associated demands will quickly grow to exceed existing capacity. The lunar South Pole region includes portions of the Moon's far side, where direct-with-Earth C&PNT links are impossible.

5.1 Communications

Early lunar missions will rely on direct-with-Earth communications links as their primary communications pathway until lunar relay satellites become operational. Meanwhile, NASA and its partners will expand terrestrial ground station capabilities to support the growth in users and data throughput.

As the Moon Base progresses to later phases, central communications stations on the lunar surface will provide local communications users and aggregate downlinks direct with Earth or through relays. This will enable higher throughput and reduce the number of concurrent links with Earth.[22] Additionally, later phases may see optical communications capabilities to address the limitations of radio frequency

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communications, including: bandwidth, spectrum and overall size of frequency packages and power used.[23]

5.2 Positioning, navigation, and timing

Initial Moon Base users and missions will largely rely on terrestrial sources and onboard sources for Positioning, Navigation, and Timing (PNT) data. As Moon Base implementation progresses, lunar relays will provide signals similar to those of Global Navigation Satellite System Constellations like GPS and Galileo. Users requiring higher fidelity navigation (i.e., greater than within 10 meters) would supplement these signals with additional sensors.[24]

6. Mobility Considerations

6.1 Crewed mobility

Crewed mobility expands the human exploration footprint, enabling astronauts to reach increasingly distant sites of interest. Unpressurized systems enable EVA-suited astronauts to make shorter, local traverses and expand utilization opportunities. Pressurized rovers enable longer traverse distances and also provide a place for astronauts to live and work for longer durations.

6.2 Cargo mobility

Cargo mobility is an essential component of Moon Base operations. Robotic assets will deliver and emplace logistics, set up infrastructure (e.g., power and habitation systems), and conduct utilization activities (e.g., science and technology demonstrations) during and between human missions. These activities include operations that must occur in preparation for crew arrival, such as moving logistics to where they will need to either be picked up and brought into a habitat or docked with a receiving module. The use of autonomous systems significantly reduces the demand upon crew time, and also enables the Moon Base to emplace infrastructure that would be too large for crew members to handle, such as a habitat.

6.3 Relation to terrain, slope, elevation

Crewed or uncrewed, mobility systems will need to contend with the rugged lunar South Pole environment. This includes crossing various types of lunar terrain, from fine regolith highlands to very rocky areas, and contending with steep slopes. Mobility of this type is difficult on Earth, but the lunar regolith described above complicates traction and maneuvering further. Any mobility system design will need to account for these factors, with the challenges shifting as vehicle size and mass scale up.

7. Power Infrastructure

To realize the Moon Base, NASA is developing a power strategy that meets the demands of the lunar South Pole region. That strategy includes a gradual buildup of power infrastructure across Moon Base phases to meet the growing power needs of Moon Base assets.[25] It also considers the long-term needs of lunar exploration, including minimizing delivered mass, balancing complexity and risk, and assuring extensibility to future phases.

Early Moon Base missions and systems will be largely power self-sufficient (i.e., they do not require power augmentation.) As the architecture progresses, Moon Base elements can rely on emplaced power infrastructure to meet their needs. Offloading the burden of power generation and storage onto shared systems will increase architecture efficiency and thus make more downmass available for science, utilization, cargo, and technology demonstrations.

The power trade space includes variety of power generation, energy storage, and power transfer systems and capabilities. Each has benefits and drawbacks that must be weighed against one another and analyzed in the broader context of the Moon Base systems architecture.

7.1 Power generation

NASA is considering two main power generation technologies for its crewed surface exploration architectures: nuclear and solar power. Both power technologies introduce architecture dependencies, such as the need for offloading, emplacement, setup, and connection to a lunar power grid, and a potential, longer-term need for maintenance.

Solar power systems benefit from extensive flight heritage; the technology is reliable and well-understood (though NASA has yet to demonstrate the deployable, vertical systems that would be most beneficial in the lunar South Pole region.) Using solar power systems to support a lunar power grid could leverage prior experience with space-based systems, potentially creating cost and schedule savings.

While the variability in availability of sunlight in the lunar South Pole region could present challenges for solar power generation, creative engineering techniques can maximize availability. Regardless, an architecture that relies solely on solar power would need complementary energy storage systems to manage prolonged periods of extreme dark and cold.

Nuclear power system advantages include the production of continuous, predictable power regardless of access to sunlight. Nuclear power generation technologies include small-scale power or thermal generation through radioisotope thermoelectric generators and/or radioisotope heater units and large-scale power generation through nuclear fission power systems like Lunar Reactor-1.

Architectural considerations for nuclear power systems include ensuring appropriate distance from habitation or crewed exploration sites. Establishing these keep out zones and autonomous systems to operate

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within them will ensure crew safety from radiation exposure or system mishaps.

7.2 Power storage

Adding energy storage capacity (paired with solar generation), in the form of batteries or regenerative fuel cells, to the Moon Base power grid could reduce the required mass of individual exploration assets and increase the flexibility of NASA's lunar architecture. NASA quantifies the amount of energy that must be stored to supply power during a lunar night period as effective energy storage duration. This number reflects the performance required to maintain power delivery during night operations at a specific location.

Effective energy storage duration varies greatly across the lunar South Pole region. As such, NASA's integrated Moon Base power strategy is considering site selection as a key design factor in assessing power system options. Planning for high power intensive activities to occur during solar insulated periods can be effectively paired with reduced power operations during shadow to keep alive and maintenance.

7.3 Power distribution

For external power augmentation to provide maximum architectural benefit to Moon Base, NASA must address the technologies for power transfer between power generation, storage, and users. Separation distances could range from several meters between co-located assets at a single site to several kilometers between remote exploration zones.

NASA is analyzing two primary approaches for power transfer: cabling and power beaming. While cabling is ubiquitous on Earth, the lunar environment presents unique design challenges. Cabling and associated electronics, (e.g., converters, connectors, etc.), must be robust to the lunar environment, accounting for extreme temperatures, dust, vacuum, and lower gravity; however, has a much higher energy transfer efficiency. Power beaming is a relatively new technology that wirelessly transfers power to exploration assets. This capability would offer flexibility in the Moon Base power architecture and may have applications particularly supporting systems needing to be deployed in challenging locations or at significant distances from primary power systems. These technologies need further development and demonstration before operational use and consideration of the significant energy loses in the overall system efficiency.

8. Demands of Long-Term Habitation

As the Moon Base grows and evolves, demand for habitation space will increase. This includes the space that astronauts need to sleep, eat, exercise, perform hygiene activities, conduct intravehicular science, and prepare for and conduct EVAs. At first, crewed missions to the lunar surface can rely on landing vehicles for living space, but as more astronauts spend more time on the Moon, they will require more habitable volume.

Habitable space is a function of both total volume and floor space, both of which grow as the number of crew to support increases. This sizing creates mass and volume constraints, to the point where it may not be feasible to launch an individual module that can accommodate crew needs. Instead, NASA and its partners can use an aggregation strategy to progressively grow habitation capabilities.

The Moon Base can start with an initial habitation module, then connect additional modules to increase the total pressurized living space, much like the construction of the International Space Station. These additional modules could include new specializations or unique capabilities, such as space and interfaces for utilization payloads or larger airlock facilities to accommodate more crew members and enable more — and larger — EVAs.

With these added habitation capabilities come additional needs. More crew members means more need for logistics (including the delivery, mobility, and conditioning systems described above. More habitation modules also require more power, driving the need for external augmentation from an integrated lunar power grid. While an initial habitation module could provide its own solar power to support shorter missions and smaller crew complements, a growing habitation cluster will need to draw on additional power produced separately to enable longer mission durations and survival through prolonged periods of shadow.

9. Conclusion

NASA's Moon Base will be humanity's first outpost on another world, enabling an enduring presence in the lunar South Pole region. The Moon Base approach allows NASA and its partners to learn as we build, spurring innovation, economic output, and scientific discovery.

Maximizing science and exploration returns means emplacing infrastructure to provide shared services like power, mobility, and communications. It also means using every landing as an opportunity to learn more about the Moon and inspire the public to dream of our future there.

As NASA progresses through Phase One of Moon Base implementation, the agency is leveraging decades of lunar observation data and collecting ground truth data about the lunar South Pole region. This science advances human exploration; characterizing the environment aids in strategic development to better engineer subsequent systems and support analysis as the agency identifies the characteristics of areas to emplace critical infrastructure.

The agency is actively seeking commercial and international partnerships to enable all phases of Moon Base development. Interested parties seeking to engage with the Moon Base effort should consider the functional

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gaps defined to accomplish Moon Base capabilities and the architecture-driven technology [26] & data [27] gaps published in the agency's Architecture Definition Document.[28] They communicate a demand signal for the types of systems, investigations, research, and technology development efforts that will be most beneficial to the Moon Base architecture.

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