Office of Technology, Policy, and Strategy

Lunar Landing and Operations Policy Analysis

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This report would not have been possible without the extensive cooperation of experts across NASA. The work of NASA's Cross-Artemis Site Selection Analysis team has been particularly valuable, and we have relied on experts across mission directorates, centers, and within NASA Headquarters for every section of this report. This effort underscores the reality that creating a safe, sustainable, and predictable presence on the Moon and beyond is a task for the entire agency.

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Executive Summary

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Purpose of the Study

Just within the next four years, we expect to see at least 22 lunar surface missions. Half of these missions will occur in the Moon's south polar region. Due to this upcoming proliferation of actors and activities at or near the lunar south pole, and due to the potential close proximity of operations, NASA and other operators will face challenges never faced before.

NASA's Deputy Administrator and Associate Administrator of the Science Mission Directorate (SMD) tasked the Office of Technology, Policy, and Strategy (OTPS) with answering two questions related to the Artemis campaign: (1) what technical and policy considerations should NASA take into account in the selection of lunar landing and operations sites, and (2) what technical and policy considerations should NASA take into account when implementing tools such as safety zones in order to protect these operations and U.S. interests?

In addition to the challenges inherent in lunar operations, NASA subject-matter experts (SMEs) are concerned about certain challenges to NASA operations that may require policy solutions. The goal of this report is to provide options and recommendations to NASA leadership and program planners so that they can consider policy measures to respond to those challenges. This report also describes options for transparency, coordination, and implementation to increase the effectiveness of these measures.

Key Findings

SMEs expressed particular concerns relating to seven specific activities: landings, surface operations, surface travel, radio-frequency interference, human heritage, areas with special characteristics, and unexpected activities. Each of these challenges is amenable to one or more policy measures that can reduce the risk to NASA operations (see Table 1 below). Implementation of these policy measures would require that policy considerations be taken into account in spacecraft and mission design, a considered effort to make our policy choices known publicly, and coordination amongst space actors (see Table 2 below).

Not all challenges—and thus, not all policy responses to them—need be implemented immediately, simultaneously, or for every NASA activity. A gradual approach to implementing these measures is possible. NASA leadership will determine at which point, if ever, is a challenge significant enough to warrant action.

Question 1: What technical and policy considerations should NASA take into account in the selection of lunar landing and operations sites?

We identified seven major challenges to landing and operating at the lunar South Pole and provide the following policy tools (options and recommendations to address challenges) as additional points to consider for Artemis landing and operations sites.

Table 1. Key challenges to lunar landing and surface operations and corresponding policy tools to mitigate each challenge.

Challenge	Overview	Summarized Policy Tool
Challenges Posed by Landings	Landings will create plume-surface interactions (PSIs) that can damage assets—significant gaps in understanding their effects exist	Increase priority of obtaining PSI measurements; identify distances from landing sites that will reduce danger from particles to tolerable levels; develop "gold standards" for PSI predictions with partner space agencies; work with partners to develop landing and ascent infrastructure to mitigate dangers from particles
Threats to and From Surface Operations	Activities on the surface can cause damage to or interfere with surface assets and operations	Begin implementation of the concept of safety zones (envisioned in the Artemis Accords)—incorporate into mission planning and design on a mission-by-mission basis; take additional steps to reduce the need for safety zones (e.g., landing infrastructure); respect similar tools used by non-signatories to the Accords
Challenges to Moving Across the Lunar Surface	Technical constraints limit the ability to move between areas of interest—there is a need to ensure navigable pathways remain available for use	Ensure our understanding of navigable pathways between sites of interest is robust; if there continues to be a need to protect these pathways, identify them as "transit corridors" and ensure their protection; if fixed facilities must be placed on these corridors, make their locations known and ensure they do not block mobile assets
The Danger of Radio-Frequency Interference	Surface operations could be subject to radio-frequency interference	Continue to engage with the interagency and rely on the International Telecommunication Union (ITU)—specialized policy tools for lunar surface operations are not needed

Threats to Areas with Special Characteristics	Certain locations may warrant protection if operations may render them less useful	Ensure freedom of access to areas conducive to operations, such as the Connecting Ridge; work with Artemis partners to support United Nations space resource efforts for sustainable in-situ resource utilization (ISRU)
The Challenge of Unexpected Activities on the Surface	Security-related concerns could interfere with surface operations	Consider incorporating multi-purpose hardware (e.g., cameras, sensors) onto missions that can identify proximity operations from other actors
The Need for Human Heritage Protection	The U.S. may wish to preserve non-operational sites for their historic or cultural value	Continue to implement the 2011 Recommendations[1] for Apollo and Surveyor sites; apply them to any new heritage sites; use restraint in identifying any new heritage sites; determine if other nations request human heritage protection; look to terrestrial heritage protection to develop formal processes

Question 2: What technical and policy considerations should NASA take into account when implementing tools such as safety zones in order to protect these operations and U.S. interests?

When implementing tools to address challenges to landing and operating at the lunar South Pole, such as those mentioned in Table 1, we suggest the following as a means to increase their effectiveness, thus protecting operations and U.S. interests.

Table 2. Options for building transparency into next steps, coordinating when necessary, and implementing policy tools into mission planning.

	Purpose	**Summarized Options to Supplement Policy Tools**
Transparency	To address potential concerns and increase effectiveness of policy tools	Build on the transparency section of the Artemis Accords by 1) meeting with signatories to discuss policy tools for upcoming missions and, 2) developing a public relations strategy along with multilateral engagement to explain rationale for policy tools
Coordination	To actively involve the space community before implementing policy tools,	Work with the Department of State to ensure partners on joint missions share our views on responding to

[1] "NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts," July 2011: https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf.

	especially when related to cooperative missions	challenges; develop mechanisms for consultation and coordination to deconflict surface operations
Implementation	To put policy tools into practice by incorporating into mission plans	For missions over which NASA has operational control, build policy tools into mission planning; for missions operated as a service, work with contracting companies to implement relevant policy tools

Next Steps

Existing data is limited, and substantial lunar surface operations have yet to occur. Each mission and location on the lunar surface present unique physical characteristics. Discussion of the options and implementation of relevant policy tools will need to be tailored to each mission and should evolve as knowledge accrues.

Not all policy tools will need to be evaluated or adopted immediately; some may only become relevant as increasing numbers of missions go to the lunar South Pole. Likewise, increasing volumes of traffic to the lunar surface may require stricter implementation of certain tools; conversely, advances in technology and infrastructure could allow relaxation of those same measures. These policy tools should be revisited as necessary. As we gain experience, similar measures may be applied to missions to Mars and other celestial bodies.

Key next steps to address challenges to landing and surface operations include: 1) working desired policy tools from Table 1 into current and upcoming mission plans, 2) building options for transparency, coordination, and implementation from Table 2 into desired policy tools, and 3) revisiting these policy tools as needed, and especially as we learn more from early lunar surface missions.

Some of the options described in this report require technical information to be gathered and analyzed in light of the policy challenges identified here—that analytical and policy design work might be a useful early priority for NASA. As section 3.3 of this report describes, NASA may wish to begin developing technical criteria for landing standoff distances and safety zones now, for example, before they become operationally necessary, so that those measures are available when needed. Policymakers might consider beginning this sort of hybrid technical-policy design work now.

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Introduction

The Artemis campaign comprises a range of exploration and science missions. Artemis is not a traditional NASA "program" in the sense of having unified leadership and funding. Rather, it is a broad articulation of a unified purpose across missions, funding lines, directorates, and partnerships. Led by NASA with extensive commercial and international partnerships, the Artemis Program "will establish a sustainable presence on the Moon to prepare for missions to Mars."[2] The Artemis campaign will include crewed operations to lunar orbit and the lunar surface as well as uncrewed robotic operations in these areas. Major NASA-led programs that are part of the Artemis campaign include Gateway, Human Landing System (HLS), Orion, Space Launch System (SLS), Commercial Lunar Payload Services (CLPS), Extravehicular Activity (EVA) and Human Surface Mobility (HSM) program, and a lunar base. Each of these programs involves commercial and international contributions. International partner-led operations may include the European Large Logistics Lander (EL3), pressurized and unpressurized rovers, additional robotic surface missions, and contributions to surface habitats.[3,4,5,6] NASA and partners are also considering additional operations aimed at ensuring sustainability of operations, such as in-situ resource utilization (ISRU) and technical capabilities to support operations, including power, communications, and landing infrastructure. Taken together, these elements form the Artemis campaign—the most ambitious space exploration program ever undertaken by humanity.

In light of these plans for Artemis, the Science Mission Directorate (SMD) and the Deputy Administrator tasked the Office of Technology, Policy, and Strategy (OTPS) with answering two related questions: (1) what technical and policy considerations should NASA take into account in the selection of lunar landing and operations sites and (2) what technical and policy considerations should NASA take into account when implementing tools such as safety zones in order to protect these operations and U.S. interests? This report aims to answer those questions.[7]

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[2] "Artemis Program," NASA, last modified July 1, 2021, https://www.nasa.gov/artemisprogram.

[3] "Gateway International Partners," Gateway, NASA, last modified December 2, 2021, https://www.nasa.gov/gateway/international-partners.

[4] "N° 30–2022: From the Earth to the Moon and on to Mars – ESA and NASA take decisions and plan for the future," Press Release, European Space Agency, last modified June 15, 2022, https://www.esa.int/Newsroom/Press_Releases/From_the_Earth_to_the_Moon_and_on_to_Mars_ESA_and_NASA_take_decisions_and_plan_for_the_future.

[5] "NASA, Australia Sign Agreement to Add Rover to Future Moon Mission," Moon to Mars, NASA, last modified October 12, 2021, https://www.nasa.gov/feature/nasa-australia-sign-agreement-to-add-rover-to-future-moon-mission.

[6] "Joint Statement on Cooperation in Lunar Exploration," Press Release, Japan Aerospace Exploration Agency, last modified September 24, 2019, https://global.jaxa.jp/press/2019/09/20190924a.html.

[7] A list of all options and recommendations is excerpted in the Summary Chapter of this report.

As described in the Terms of Reference (TOR), this project gathered information in three phases.[8] First, OTPS conducted a series of meetings with NASA lunar program experts to develop a detailed baseline of what is possible and desirable from a programmatic perspective, as well as an understanding of what technical criteria should be used to implement policy tools. Those meetings are set out in Appendix B and the information gained is described in Part I of this report. Second, OTPS and the Office of International and Interagency Relations (OIIR) met with counterpart space agencies with whom NASA anticipates possible cooperation in lunar missions in order to seek their input on considerations relevant to the goals of the study; these conversations are also listed in Appendix B. After gathering this information, we created a set of draft options and recommendations and a draft report; we then shared this material with many of the internal experts we spoke to in Phase I to seek further comments. In the third and final phase, we shared the draft options and recommendations, and a draft report summary, with trusted outside experts (listed in Appendix B). The guidance provided by these experts has been considered in this document.

The goal of this report is to provide options and recommendations to NASA leadership and program planners so that they can implement specific policy and related tools in Artemis Program missions.

In Part 1 of the report, we set the scene, providing the context that gives rise to the need for policy options and recommendations. In Part 2, we describe the main challenges and hazards posed by landing and operating at the lunar South Pole. Each challenge has associated policy options and recommendations—this answers TOR Question 1. Part 3 describes the steps to take once policy tools move towards implementation—this answers TOR Question 2. Finally, Part 4 summarizes this study's key takeaways.

The options and recommendations contained in this report are intended to be flexible. As we discuss, not all options or recommendations need be considered or implemented immediately or for all operations, and implementation should adapt over time in light of new knowledge and should change in response to the realities of operations on the Moon. Because Artemis campaign missions have not yet begun, and because our knowledge of key technical and scientific factors is limited, these options and recommendations are inherently preliminary. Many of the operations described in this report as part of the Artemis campaign are in planning stages; this report attempts to describe considerations relevant to them all but draws heavily from current plans for early CLPS and initial HLS operations.

[8] Appendix A.

Part 1: Setting the Scene

As described above, Phase I of this project was intended to develop a baseline understanding of the goals of Artemis lunar operations as well as the technical constraints that shape our ability to meet those goals. Understanding those goals and constraints is critical to designing policy tools for lunar operations.

1.1 Goals of Artemis

The recently released "Moon to Mars Objectives" process identified numerous objectives for NASA's campaign to operate on the Moon and in cislunar space with an ultimate goal of human exploration of Mars.[9,10,11] An extensive internal and external comment process is ongoing to refine these objectives. The specific phrasing and organization of these objectives are not critical to this report; the draft objectives provide sufficient clarity to identify policy and operational issues that might result from lunar operations, particularly when combined with existing programs and architectures (as described below).

The first category of objectives relevant to lunar operations is science and exploration. Human and robotic exploration of the lunar surface aims to answer many questions about the nature of the Moon and the history of the solar system. Many of these objectives focus on investigating the nature of volatiles and other potential resources on the lunar surface.[12] These resources, particularly frozen volatiles, are most likely to be found in permanently shadowed regions (PSRs), which principally exist around the lunar poles.[13]

Lunar operations also have technology objectives. The Artemis campaign aims to develop, test, and deploy technologies that will allow expanded human and robotic exploration of the Moon and, ultimately, Mars. These technologies include power generation and transmission, communications networks, landing infrastructure, automated exploration capabilities, and pressurized habitats.[14]

Finally, an overarching objective of lunar operations is to develop a sustainable presence on the lunar surface. "Sustainability" is a broad concept: it encompasses the ability to operate an ongoing campaign of interrelated missions rather than a series of "one off" missions. Inherent in that

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[9] Cislunar space is generally considered to be the area defined by the orbit of the Moon around Earth, including lunar orbits and Earth-Moon Lagrange points.
[10] "Update: NASA Seeks Comments on Moon to Mars Objectives by June 3," Moon to Mars, NASA, last updated June 8, 2022, https://www.nasa.gov/press-release/update-nasa-seeks-comments-on-moon-to-mars-objectives-by-june-3.
[11] "Moon to Mars Objectives," NASA, accessed June 17, 2022, https://www.nasa.gov/sites/default/files/atoms/files/moon-to-mars-objectives-.pdf.
[12] See Moon to Mars Objectives: ES-5, LPS-2.
[13] J. Flahaut et al., "Regions of interest (ROI) for future exploration missions to the lunar South Pole," *Planetary and Space Science* 180 (Jan. 2020): https://doi.org/10.1016/j.pss.2019.104750.
[14] See Moon to Mars Objectives: L1-4.

concept is the idea of an evolving, increasing ability to engage in longer, more complex operations over time. Sustainability also implies the need to avoid taking actions that limit our ability to undertake operations in the future (e.g., by not blocking access to scientifically interesting locations with dead hardware), and to develop capabilities to reduce the financial and material cost of ongoing activities. This also relates to ethics and equity considerations, mentioned in Appendix D, which OTPS has ongoing work on.

Sustainability brings together the scientific and technology objectives of the Artemis program. For example, one step towards sustainable operations could be to couple newfound scientific knowledge about the presence of water ice with developments in automated robotic operations to enable ISRU. Sustainable operations then enable future scientific discoveries and technological advances, including by lowering costs, which in turn enable even more advances in sustainability. The aim is a virtuous cycle of increasing discovery and capabilities.

1.2 Anticipated Architecture

To pursue the objectives identified above, NASA and partners have developed a notional architecture for lunar operations. This notional architecture continues to evolve and contains many elements, most of which remain to be fully defined.[15]

Near-term missions are the most well-defined aspect of these plans. The CLPS initiative, operated by SMD, contracts with commercial companies to deliver science and technology payloads to the lunar surface. Currently consisting of fourteen vendors and seven awarded task orders,[16] CLPS will continue to add additional landings and increased capabilities (e.g., mobility, survive the night, sample return, etc.) as the initiative develops.[17] CLPS deliveries vary in size, cost, and destination, with approximately half of the currently planned deliveries targeting the south polar region. Although early CLPS deliveries and their payloads will for the most part only operate for a period of days or a few weeks on the Moon, they will provide scientific and other data necessary to enable future crewed and uncrewed missions.

Aside from CLPS, the most well-defined aspect of the Artemis architecture is the Human Landing System (HLS). As part of the NextSTEP public-private partnership model, NASA selected SpaceX's Starship to provide crewed landing in the vicinity of the lunar South Pole for the Artemis III mission.[18] Specific landing sites have yet to be determined. Some site down-selection may occur as the result of information gained from CLPS, an uncrewed demonstration prior to Artemis III, and

[15] We note that Gateway is a well-defined and critical component of the Artemis architecture. Because this report focuses primarily on policy issues relating to surface operations, we do not focus on Gateway.
[16] As of the time of drafting (July 2022). Please see Appendix C for more detail on CLPS missions.
[17] "Commercial Lunar Payload Services Overview," Commercial Lunar Payload Services, NASA, last updated July 21, 2022, https://www.nasa.gov/content/commercial-lunar-payload-services-overview.
[18] "NextSTEP H: Human Landing System," NextSTEP, NASA, accessed June 17, 2022, https://www.nasa.gov/nextstep/humanlander2.

other sources, but a final landing site decision will depend on the specific launch date. Artemis III is expected to spend approximately 6 days on the lunar surface.[19]

In March 2022, NASA requested SpaceX “to transform the company’s proposed human landing system into a spacecraft that meets the agency’s requirements for recurring services for a second demonstration mission.”

Plans for crewed landings on the Moon beyond Artemis III have not yet been finalized. In addition to Starship, Appendix P of the HLS program is currently in the process of selecting additional landing system providers for “Sustaining Lunar Development.” These providers will provide crewed transportation to the lunar surface after Artemis III (and a potential second demonstration mission). The spacecraft, timing, and destinations have not been decided, though the draft solicitation in Appendix P calls in part for “lunar surface landing near the South Pole, lunar surface extra-vehicular activity (EVA), [and] return of crew and materials from the surface and transfer from HLS.” Appendix P is intended to culminate in a crewed demonstration mission, with anticipated contract performance from 2023-2028.

Additional elements of the Artemis architecture remain in planning stages. For example, NASA is considering communications and power infrastructure to support sustained operations[20] and extensive planning has gone into developing “lunar base” concepts, though these ideas have not been finalized or otherwise approved.[21,22]

Finally, certain architecture elements exist only in study form. Safety features such as protection berms and waste disposal trenches, and structures such as prepared landing pads, remain key elements of architecture planning (and as will be discussed, of key importance to policy considerations), but have not yet made it from planning studies to programmatic documentation.

1.3 Technical Constraints

The lunar surface is not a hospitable environment. In addition to inherent difficulties of operating anywhere on the Moon (radiation, vacuum, dust), several technical constraints are particularly relevant to operations in the vicinity of the lunar South Pole. These constraints limit what operations are possible and where those possibilities exist.

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[19] “NASA‘s Lunar Exploration Program Overview,” Artemis Plan, NASA, last modified September 2020, https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf.
[20] “Moon to Mars Objectives,” NASA, accessed June 17, 2022, https://www.nasa.gov/sites/default/files/atoms/files/moon-to-mars-objectives-.pdf.
[21] “NASA‘s Lunar Exploration Program Overview,” Artemis Plan, NASA, last modified September 2020, https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf.
[22] “NASA’s Plan for Sustained Lunar Exploration and Development,” NASA, accessed June 17, 2020, https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf.

The first—and arguably most important—constraint is the availability of sunlight. Access to sunlight provides two benefits: power and thermal control. These benefits are interrelated: because of the extreme cold of the lunar night, heating systems will be needed for crewed and robotic operations if they are to survive periods of darkness. Early CLPS deliveries, for example, are expected to survive only one lunar day, permanently ending operations when they experience the extreme cold and loss of power of a lunar night.[23] Crewed operations are also planned to take place only during periods of sunlight.[24]

Because polar operations are, by definition, at high latitudes, sunlight approaches these areas from a shallow angle: shadows are long, and the sun never rises more than 1.5 degrees above the horizon.[25] At the same time, a handful of areas located on peaks and crater rims receive far more sunlight, on a yearly basis, than is available anywhere else on the Moon.[26,27,28] This low angle of insolation is also what gives rise to the PSRs described above.

The result of this solar environment is that the south polar region is one of large, constantly shifting shadows, interspersed with arcs, points, and a few regions of direct sunlight. These features change over the lunar day and year in a way that it is predictable indefinitely in advance. These always-moving sunlit areas are of critical importance to missions that rely on insolation for power and heating, as is the case for essentially all currently planned missions.

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[23] "Commercial Lunar Payload Services (CLPS) Technical Integration," NASA, last modified January 14, 2021, https://science.nasa.gov/science-pink/s3fs-public/atoms/files/CLPS-Technical-Integration-Schonfeld.pdf.

[24] "Artemis Lighting Considerations Overview," NASA-STD-3001 Technical Brief, NASA, last modified January 25, 2022, https://www.nasa.gov/sites/default/files/atoms/files/artemis_lighting_considerations_overview_technical_brief_ochmo.pdf.

[25] P. Glaser et al., "Illumination conditions at the lunar south pole using high resolution Digital Terrain Models from LOLA," *Icarus* 243 (Nov. 2014): https://doi.org/10.1016/j.icarus.2014.08.013.

[26] Despite popular belief, there are no "peaks of eternal light" on the Moon. Every site identified is in shadow at some portion of the lunar cycle. D. Ben J. Bussey, Paul D. Spudis, Mark S. Robinson, "Illumination conditions at the lunar south pole," *Geophysical Research Letters* 26, no. 9 (May 1999): https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/1999GL900213.

[27] P. Glaser et al., "Illumination conditions at the lunar poles: Implications for future exploration," *Planetary and Space Science* 162 (Nov. 2018): https://doi.org/10.1016/j.pss.2017.07.006.

[28] D. Ben J. Bussey, Paul D. Spudis, Mark S. Robinson, "Illumination conditions at the lunar south pole," *Geophysical Research Letters* 26, no. 9 (May 1999): https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/1999GL900213.

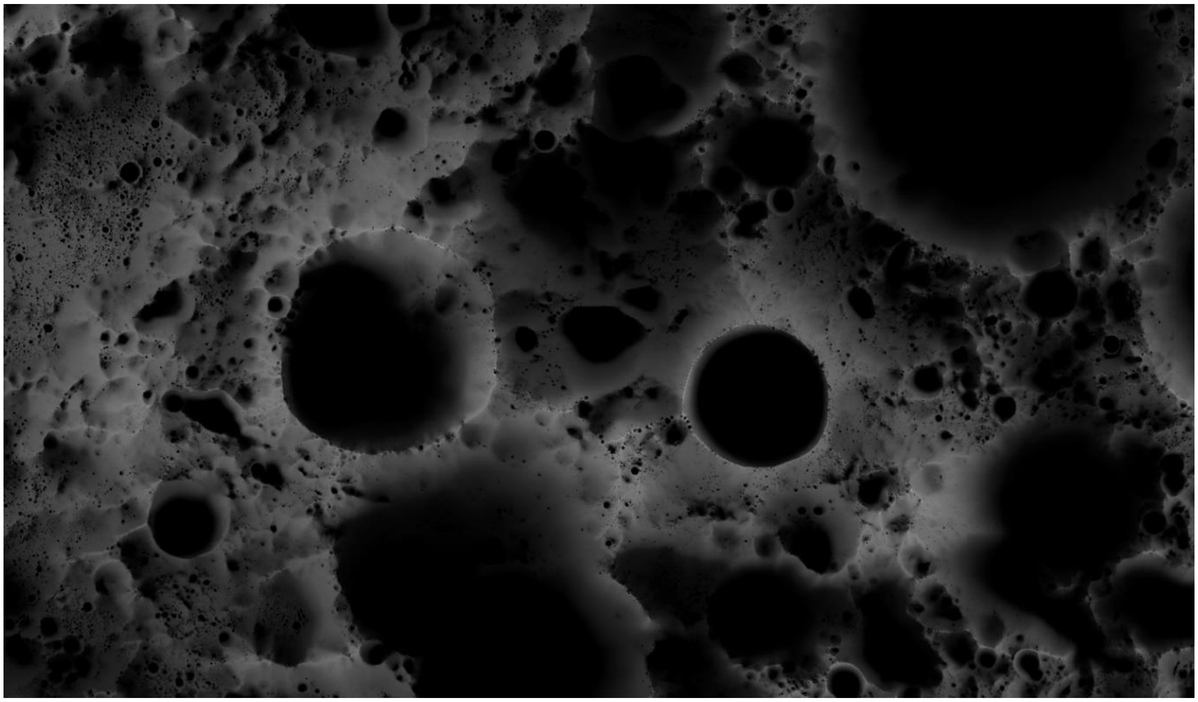

Figure 1. Average Illumination of the South Polar Region (Image Credit: CASSA)

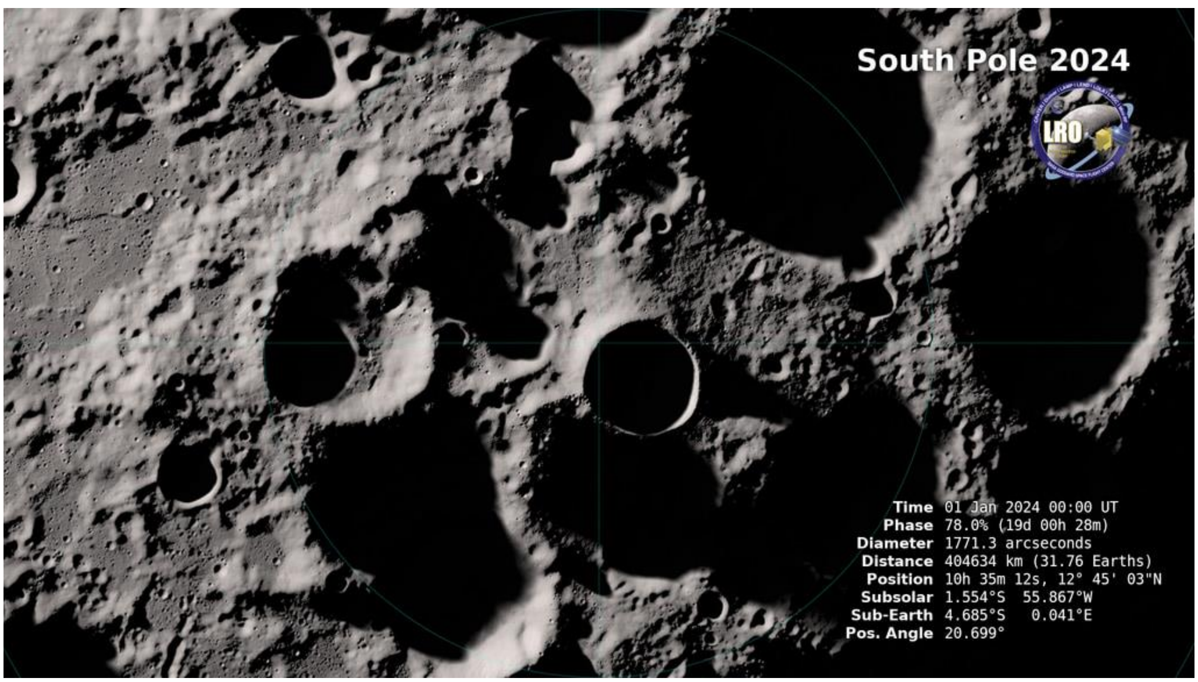

Figure 2. Representative Snapshot of Illumination at the South Pole (Image Credit: NASA's Scientific Visualization Studio)

Sunlight is not the only way to provide power and thermal control for lunar operations. Mission architectures that involve other power sources, such as fuel cells for short durations and nuclear power for longer durations, would reduce or eliminate the need for sunlight. Hybrid solutions might also be possible, such as fixed solar or nuclear-powered "charging stations." However, none of these alternative power sources have yet been incorporated into definite mission plans. The need for sunlight therefore remains a driving constraint for anticipated human and robotic lunar operations.

Another critical constraint is terrain. The lunar surface is diverse, but the south polar region is characterized by heavily disrupted terrain, with several large craters dominating the area. Peaks, valleys, boulders, and rocks of all sizes are common.[29,30,31] This dramatic landscape imposes technical challenges.

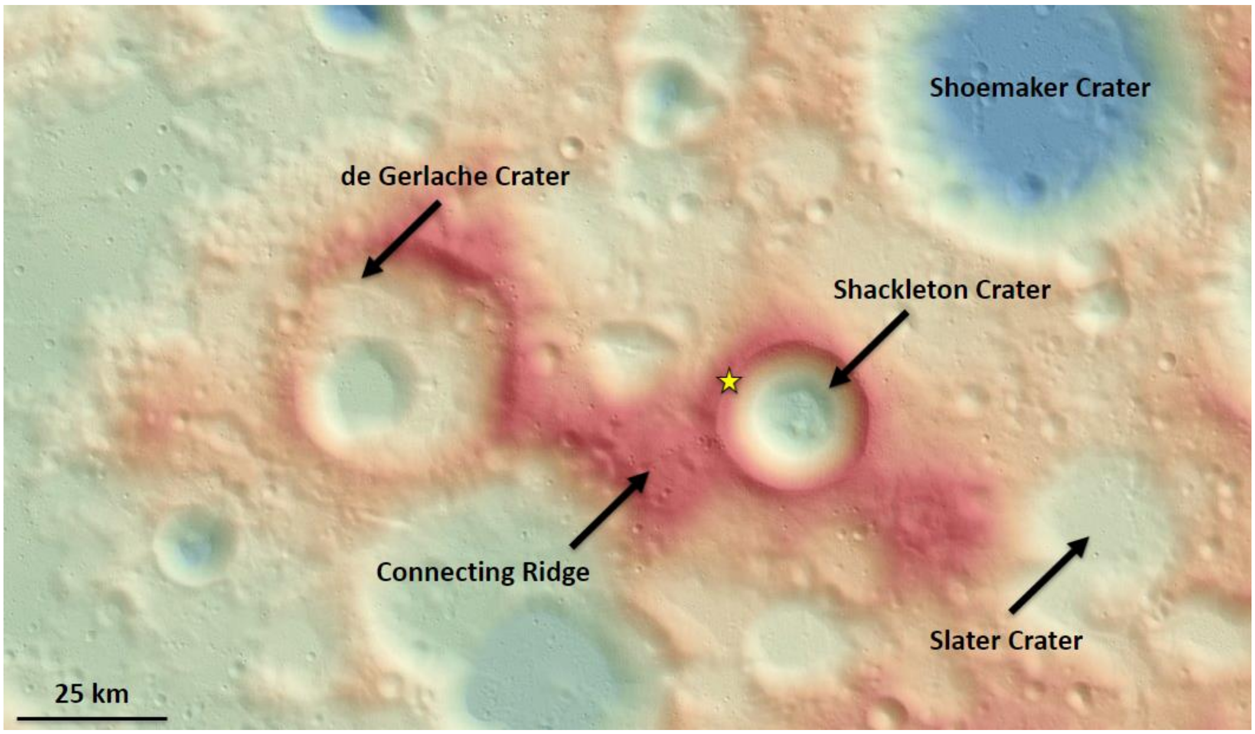

Figure 3. Topographic Relief of the Lunar South Pole and Areas of Interest (Image Credit: CASSA). 90°S is marked by the star at Shackleton Crater.

The first constraint imposed by the landscape is the need to identify relatively flat and uncluttered areas that can function as landing sites. CLPS contractual documentation requires those robotic craft to land within a landing ellipse 100m in diameter, while HLS contracts require a landing radius of 100m for HLS A and 50m for Option B and SLD.[32] There is a finite number of such locations in the

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[29] A.C. Cook et al., “Lunar polar topography derived from Clementine stereoimages,” *Journal of Geophysical Research* 105, no. E5 (May 2000): https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/1999JE001083.
[30] V.T. Bickel, D.A. Kring, “Lunar south pole boulders and boulder tracks: Implications for crew and rover traverses,” *Icarus* 348 (Sept. 2020): https://doi.org/10.1016/j.icarus.2020.113850.
[31] H. Araki, et al., “Lunar Global Shape and Polar Topography Derived from Kaguya-LALT Laser Altimetry,” *Science* 323 (Feb. 2009): https://doi.org/10.1126/science.1164146.
[32] G. Chavers, L. Watson-Morgan, M. Smith, N. Suzuki and T. Polsgrove, "NASA's Human Landing System: The Strategy for the 2024 Mission and Future Sustainability," *2020 IEEE Aerospace Conference* (2020): 10.1109/AERO47225.2020.9172599, and https://sam.gov/opp/2d5b3e1f38bd4035a06b64b4704e3455/view.

polar region that are free enough of obstructions to allow safe landings, though the specific number of those locations remains to be determined.

The second constraint imposed by the landscape involves moving from one location to another. Crewed and robotic craft will need to move, for example, from a landing site to an area of scientific interest, or between areas of interest. Although a few robotic craft may be able to "hop" between sites, most mobile assets will be rovers, and crewed activities will be similarly ground-bound. Transit between sites is not trivial: although the straight-line distances involved are not large, crewed and robotic rovers must avoid large obstructions, dangerous slopes, and similar hazards.

Finally, the nature of lunar terrain is directly linked to the availability of sunlight. Depending on their orientation, peaks, valleys, and other topologies experience more, or less, sunlight than other areas of the lunar surface.

As described in the Goals of Artemis section above, lunar volatiles—particularly water ice—are key to Artemis operations. Investigating the existence and composition of frozen volatiles is not only a science goal; accessing and using these resources to support future exploration through ISRU increases the sustainability and lowers the cost of operations. Frozen volatiles are most likely to exist in PSRs, which themselves are generally found in the bottom of deep craters located near the poles. Limited sorties may go elsewhere on the lunar surface, but this need for volatiles places an additional constraint on operations: the need to stay close to PSRs or other sources of accessible volatiles.

The final general constraint has to do with communications. Early mission plans require near-continuous radio communications with crewed activities.[33] At present, this is only possible with direct line-of-sight between Earth and certain locations at the lunar South Pole at certain times. These locations change throughout the Moon's sidereal month (27.3 days).[34] Orbital communication relays would resolve this constraint and are anticipated to be available after Artemis III. Until those assets are in place, the need to maintain direct line-of-sight with crewed operations remains.

Table 3. Summary of major technical constraints related to south polar operations.

Technical Constraint	Primary Benefit	South Polar Mission Impact
Availability of sunlight	Power, thermal control	Missions relying on solar energy (all currently planned missions)

[33] "NASA's Lunar Exploration Program Overview," Artemis Plan, NASA, last modified September 2020, https://www.nasa.gov/sites/default/files/atoms/files/artemis_plan-20200921.pdf.
[34] C. Immer, J. Lane, P. Metzger, S. Clements, "Apollo Video Photogrammetry Estimation of Plume Impingement Effects," *Earth and Space* 2008 (Apr. 2012): https://doi.org/10.1061/40988(323)1.

Terrain	Safe landings, transits between sites, access to volatiles	All missions
Direct line-of-sight with Earth	Communications with crewed operations	Artemis III

1.4 Implications of Goals and Constraints

Taken together, the goals and constraints relevant to lunar operations shape what is possible for mission planners. Each factor described in this section of our report has the effect of limiting where operations can take place, how long they can continue, and what mission objectives are realistically possible. The result is a series of filters, with each factor placing further limits on operations.

The net result of this filtering process is that near- and medium-term activities on the Moon will likely focus in a relatively small area. For example, only a small number of regions (centered around the lunar South Pole) contain PSRs that are likely to contain accessible volatiles. Within those regions, only a subset of sites has physical characteristics that are conducive to operations (e.g., by avoiding long periods of shadow and, for early missions, having direct radio line-of-sight to Earth). Access to these sites is a further constraint due to the need for relatively flat areas for landings and/or the need for sunlit corridors for surface travel.

The need for sunlight and for navigable terrain are highly interrelated. When these two constraints are combined, the result is very few "transit corridors" between areas of interest such as the rim of the Shackleton and de Gerlache craters. Some sections of these transit corridors are very narrow. If access to these particularly narrow sections were lost, it could create challenges for site accessibility.

NASA has developed an agency-wide process for taking these factors into account in mission planning. The Cross-Artemis Site Selection Analysis (CASSA) team brings together experts from NASA's Science Mission Directorate (SMD), Exploration Systems Development Mission Directorate (ESDMD), Space Technology Mission Directorate (STMD), and relevant centers to coordinate planning across human and robotic missions. The CASSA team also consists of an engagement strategy team and has started looking to external communities in for input on site selection for Artemis III.[35] Although CASSA's work is ongoing, current plans suggest that lunar surface missions will focus on fewer than ten sites in the south polar region, all in the vicinity of the Shackleton, de Gerlache, Shoemaker, and Slater craters. These craters are contained within an area about 35km wide by 70km long.

[35] "NASA Identifies Candidate Regions for Landing Next Americans on Moon," NASA, last modified August 19, 2022, https://www.nasa.gov/press-release/nasa-identifies-candidate-regions-for-landing-next-americans-on-moon.

Another key geographic feature is the “Connecting Ridge,” a high elevation area between the de Gerlache and Shackleton craters.[36]

Although some Artemis missions are planned for non-polar areas of the Moon (including the first and several other CLPS deliveries), the majority of human and robotic missions will target the areas identified in Figure 3. This density of operations located in a small area is the most significant factor driving the policy recommendations of this report.

1.5 Current Status of Planning

We recognize that mission planning is ongoing. Early missions—especially the first few CLPS deliveries and the first crewed surface landing of Artemis III—have relatively well-defined plans, targets, and architectures. Beyond this first group of missions, plans and architectures still need to be decided. Regardless of the reasons, policymakers should be aware that this lack of clarity makes it difficult to provide specific policy options and recommendations for these notional missions.[37] For example, NASA has publicly supported the development of a “base” at the lunar South Pole to support crewed operations, but the nature of this base—whether it will be fixed or mobile, its size, whether it has nuclear or solar power, etc.—remains undecided. The answers to those questions are of critical importance to developing policy options and recommendations. This report provides as much guidance as possible given existing levels of uncertainty, but policy recommendations will need to be refined and tailored as mission plans and architectures solidify.

1.6 Prior Work

This report is not the first time NASA has considered the policy implications and operational needs of lunar missions. In 2011, NASA released “NASA’s Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts.”[38] The 2011 Recommendations were intended to provide guidance to commercial and other actors that might operate near historic NASA lunar sites: Apollo and Surveyor. This work considered some of the same considerations relevant to our current work, so we took the 2011 Recommendations into account in this report. Because the 2011 Recommendations are the only current, public, detailed

[36] CASSA began its work looking at approximately 230 sites; the plan is to down-select to 10 sites in 2023, then down-select to 3-5 sites by 2024.

[37] Policy-relevant decisions will be made at several levels of NASA: some are likely to be made at the directorate level, while others may fall to the A-Suite. This report is intended to provide guidance to all those levels of decision-making.

[38] Human Exploration and Operations Mission Directorate, Strategic Analysis and Integration Division, NASA HQ, “NASA’s Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts,” July 2011: https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf.

official recommendations from NASA relating to lunar operations, it is important to understand what they say and why before making our own recommendations.

The 2011 Recommendations are precisely what they say in the title: a set of technical recommendations for measures that actors could take to avoid damage to historic spacecraft sites, equipment, and artifacts such as footprints and flags.[39] The 2011 Recommendations are just that—recommendations—though the measures set out therein have been required to be included in NASA contracts and agreements since 2020.[40]

Because the 2011 Recommendations focus only on protecting heritage sites, they do not address all of the issues raised by Artemis campaign operations. However, the 2011 Recommendations did take into account concerns such as the impact of propulsive landings on the Moon to other hardware. Therefore, they provide a useful starting point for many of the recommendations and considerations below.

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[39] The 2011 Recommendations request space-faring entities to:
Refrain from landing or overflying (including the possibility of an instantaneous impact) within a "descent/landing boundary" of 2km around Apollo landers. This radius is based on analysis of Apollo footage, which suggests that the most dangerous particles ejected by plume-surface interactions (PSIs), between 1 and 10cm in diameter, could have traveled up to 1.5km.

- Refrain from landing or overflying (including the possibility of an instantaneous impact) within a descent/landing boundary of 0.5km around impact sites (e.g., Ranger, LCROSS, S-IVB). This radius is reduced from that accorded Apollo landers due to the lower scientific and cultural value of impact sites.
- Refrain from surfaces approaches to the Apollo 11 and 17 sites within 75m and 225m, respectively. These radii are sized to encompass all evidence of human activity.
- Refrain from surface approaches to the Apollo 12 and 14-16 sites within much smaller radii around each significant piece of equipment (e.g. 3m from descent stages, 1m from lunar rovers, etc.).
- Refrain from movement at a speed that could eject material forward when within 10m of laser ranging-retroreflectors, and from approaching the LRRRs within 1m.

Additional recommendations cover topics such as entry into Surveyor impact craters, avoidance of contamination, and disposal of new objects in heritage sites.

[40] See the discussion of heritage protection below.

Part 2: Challenges and Tools

TOR Question 1: What technical and policy considerations should NASA take into account in the selection of lunar landing and operations sites?

The background discussed above provides the basis to answer the first TOR question posed by SMD and the Office of the Administrator. After speaking with SMEs, we identified seven main challenges or hazards to landing and operating at the lunar South Pole. This portion of the report is organized by each challenge and contains policy options and recommendations that can be considered to address each of them. These options and recommendations are summarized in Table 4 below as "policy tools" and can also be found in the Summary chapter.

To exemplify how this section is broken out, many experts pointed out that propulsive landings on the surface of the Moon can pose hazards to other operations; we therefore have a set of policy tools (options and recommendations) on "Challenges Posed by Landings." SMEs also identified the need to protect surface operations from interference, to preserve the ability to move around the lunar surface, and to respond to security challenges posed by potentially hostile actors, along with other concerns. For each challenge or hazard, we provide one or more policy tools to mitigate that concern. Just as scientific instruments are tools to answer scientific questions, these are the policy tools in NASA's toolkit to respond to the challenges and hazards posed by lunar operations.

Although these tools are described separately, they could—and sometimes should—be deployed in conjunction or in sequence with each other for the same mission, depending on the nature of specific operations and the hazards they face or create.[41]

In addition to describing how these policy tools could be designed and implemented, this section of the report examines potential downsides and risks.

The following table summarizes the challenges and policy tools to follow.

Table 4. Key challenges and the corresponding policy tool to mitigate each challenge.

Challenge to Landings and Operations	Overview	Policy Tool (See Summary Chapter for Full List)
Challenges Posed by Landings	Landings will create plume-surface interactions (PSIs) that	Increase priority of obtaining PSI measurements; identify distances from landing sites that will reduce danger from

[41] For example, determining a safe distance from other actors to land a rover, then by implementing a safety zone around that rover while it is working, and then by creating a heritage protection area around that rover at end of life.

	can damage assets—significant gaps in understanding their effects exist	particles to tolerable levels; develop "gold standards" for PSI predictions with partner space agencies; work with partners to develop landing and ascent infrastructure to mitigate dangers from particles
Threats to and From Surface Operations	Activities on the surface can cause damage to or interfere with surface assets and operations	Begin implementation of the concept of safety zones (envisioned in the Artemis Accords)—incorporate into mission planning and design on a mission-by-mission basis; take additional steps to reduce the need for safety zones (e.g., landing infrastructure); respect similar tools used by non-signatories to the Accords
Challenges to Moving Across the Lunar Surface	Previously mentioned technical constraints limit the ability to move between areas of interest—there is a need to ensure navigable pathways remain available for use	Ensure our understanding of navigable pathways between sites of interest is robust; if there continues to be a need to protect these pathways, identify them as "transit corridors" and ensure their protection; if fixed facilities must be placed on these corridors, make their locations known and ensure they do not block mobile assets
The Danger of Radio-Frequency Interference	Surface operations could be subject to radio-frequency interference	Continue to engage with the interagency and rely on the International Telecommunication Union (ITU)—specialized policy tools for lunar surface operations are not needed
Threats to Areas with Special Characteristics	Certain locations may warrant protection if operations may render them less useful	Ensure freedom of access to areas conducive to operations, such as the Connecting Ridge; work with Artemis partners to support United Nations space resource efforts for sustainable ISRU
The Challenge of Unexpected Activities on the Surface	Security-related concerns could interfere with surface operations	Consider incorporating multi-purpose hardware (e.g., cameras, sensors) onto missions that can identify proximity operations from other actors

The Need for Human Heritage Protection	The U.S. may wish to preserve non-operational sites for their historic or cultural value	Continue to implement the 2011 Recommendations to Spacefaring Entities for Apollo and Surveyor sites; use restraint in identifying if any upcoming sites need protection; determine if other nations request human heritage protection; look to terrestrial heritage protection to apply learnings

2.1 Challenges Posed by Landings

Selection of landing sites is driven primarily by operational needs and mission goals. As described in Part I, planners for CLPS, HLS, and other missions will engage in a multi-factor analysis to determine appropriate landing sites, taking into account features such as the availability of sunlight, local terrain, access to other surface assets, proximity of scientifically interesting destinations, and other factors. However, SMEs have also made clear that decisions about where and how to land on the surface of the Moon can pose challenges and hazards to other activities; we discuss how to respond to those challenges here.

Landings on the Moon will create “plume-surface interactions” (PSIs): dust, rocks, and other surface material will be ejected from landing areas by the force of landers’ engines. This ejected material can pose a hazard to other objects in the vicinity of the landing zone. As a result, planners should take this danger into account when selecting landing sites. Landers themselves can also damage surface assets or resources by plume impingement coming directly from the lander. Characterizing this hazard may involve obtaining information from CLPS vendors. Since we will learn more about this as more missions occur, this report will focus on dangers caused by PSIs.

While much has been learned about the physics of PSIs over the last few decades, significant gaps in knowledge still exist and can only be filled by taking measurements during the landing of spacecraft. The only flight data currently available derives from analysis of footage from Apollo missions and basic analysis of the Chang’e-3 landing. As mentioned elsewhere in this report, those analyses suggests that in the case of Apollo, particles between 1 and 10cm in diameter ejected by PSIs could have traveled up to 1.5km from the landing sites.[42] Laboratory experiments, field experiments, remote sensing measurements, and computer models provide some insight into the PSIs that CLPS, HLS, and other Artemis operations might experience, but those predictions have not yet been

[42] Human Exploration and Operations Mission Directorate, Strategic Analysis and Integration Division, NASA HQ, “NASA’s Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts,” July 2011: https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf.

verified by experience. In the meantime, NASA investigators and leading SMEs continue to work to refine models.[43]

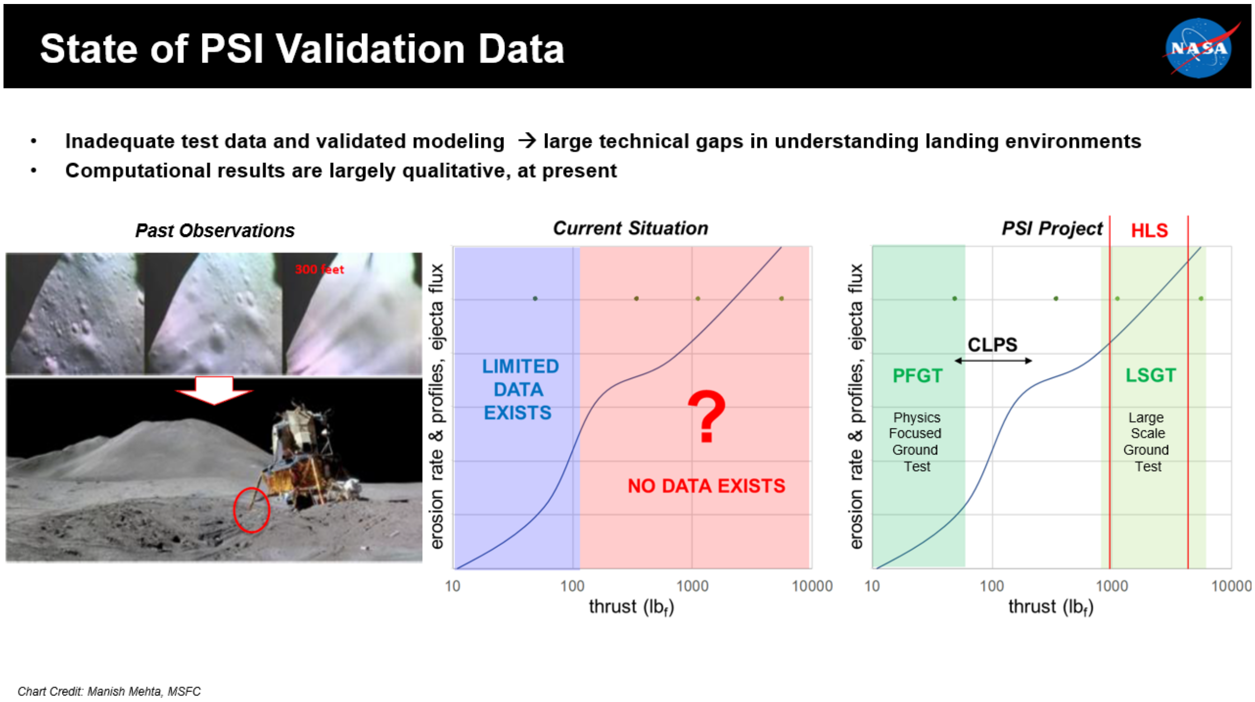

Figure 4. Current State of Knowledge Regarding PSIs[44]

Current predictions and Apollo data suggest that PSIs can eject surface debris at speeds up to 2km/s. Landings have the potential to transport material across the entire surface of the Moon and even into open space.[45] Substantial uncertainty exists, with different studies disagreeing about velocities of ejected particles by as much as 900m/s.[46] Fortunately, most debris—particularly more massive particles—are not likely to travel as far.[47] Larger rocket plumes, and ones from engines closer to the lunar surface, will eject more particles at higher velocities, so the design, configuration, and placement of engines all factor into the scale of PSI effects.

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[43] As does the UK Space Agency. Their Office of the Chief Engineer is funding two studies at British universities to conduct laboratory experiments and build computer models of PSIs.

[44] Michelle Munk, "Plume Surface Interaction: Surface Excavation and Construction Impacts," Surface Construction and Excavation Workshop, NASA, last modified August 20, 2021, https://ntrs.nasa.gov/api/citations/20210021530/downloads/LSIC_E%26C_Munk.pptx.pdf.

[45] M. M. Wittal, et al., "The Behavior of High-Velocity Dust Generated by Lander Plumes in the Lunar Environment," *AAS* 20-511 (June 2020): https://ntrs.nasa.gov/citations/20205003590.

[46] D. Fontes, J. Mantovani, P. Metzger, "Numerical estimations of lunar regolith trajectories and damage potential due to rocket plumes," *Acta Astronautica* 195 (June 2020): https://doi.org/10.1016/j.actaastro.2022.02.016.

[47] K. J. Berger, A. Anand, P. T. Metzger, C. M. Hrenya, "Role of collisions in erosion of regolith during a lunar landing," *Physics Rev. E.* 87 (Feb. 2013): https://link.aps.org/doi/10.1103/PhysRevE.87.022205.

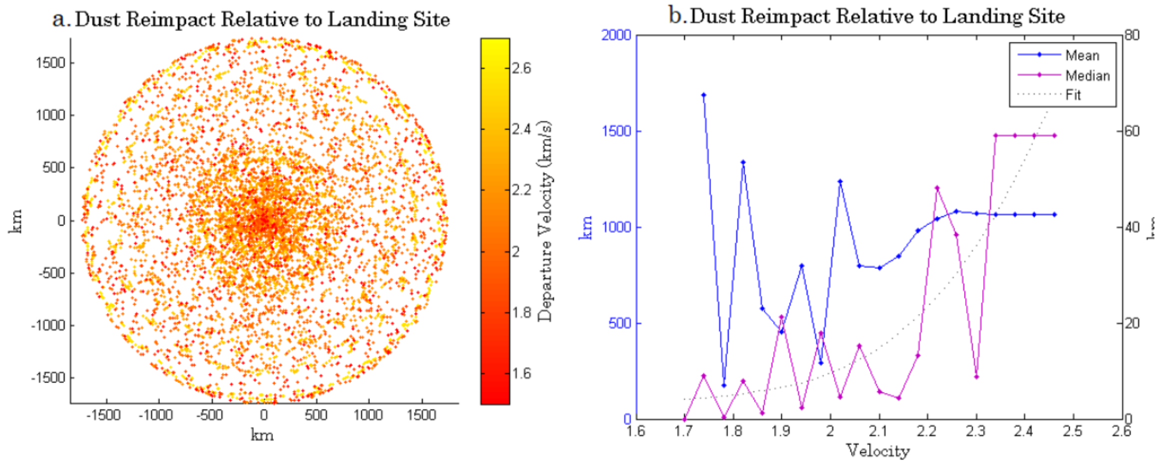

Figure 5. Plots displaying the "seemingly random" location and distribution of dust as a function of velocity relative to landing sites.[48]

The most direct way of obtaining PSI data is to have dedicated instrumentation, cameras, videos, or sensors for surface missions, providing quantifiable information in a variety of environments. Where missions, especially those in progress, cannot have dedicated hardware for PSI measurements, obtaining data indirectly may be possible. Indirect means can include data buys for lander, mission, or non-NASA payload data. Once lunar operations begin, additional data will become available for better understanding of PSIs in a variety of lunar terrains. A NASA PSI project plans to include the Stereo Cameras for Lunar Plume-Surface Studies (SCALPSS) instrument on two early CLPS landers; this instrument has been designed to gather the data needed to refine PSI models.[49] Another instrument that is funded through NASA's Lunar Surface Instruments and Technology Payloads (LSITP) program, Heimdall, will fly on a third CLPS delivery and take dedicated PSI measurements during descent, as well as image the surface after landing to understand physical changes in the regolith properties beneath the spacecraft.[50] Additional data should also become available by observing the effects of HLS landings. These types of imaging and descent data are imperative in helping close gaps in our current knowledge of PSI.

We recommend that missions increase the priority of obtaining PSI measurements when possible. Mission planners should look for opportunities for dedicated PSI measurements spanning more missions or obtain data by indirect means if that is not possible. Data regarding PSIs should be shared publicly, consistent with longstanding NASA practice. It should be noted that these two

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[48] M. M. Wittal, et al., "The Behavior of High-Velocity Dust Generated by Lander Plumes in the Lunar Environment," *AAS* 20-511 (June 2020): https://ntrs.nasa.gov/citations/20205003590.
[49] "Tiny NASA Cameras to Watch Commercial Lander form Craters on Moon," Moon to Mars, NASA, last updated May 19, 2021, https://www.nasa.gov/feature/langley/tiny-nasa-cameras-to-watch-commercial-lander-form-craters-on-moon.
[50] R. A. Yingst, et al., "THE HEIMDALL CAMERA SYSTEM: TURNING EYES ON THE MOON," *51st Lunar and Planetary Science Conference* (2020): https://www.hou.usra.edu/meetings/lpsc2020/pdf/1439.pdf.

recommendations are congruent with the key recommendation from SMEs on understanding and mitigating plume effects.[51] Adding capabilities of this sort would entail additional short-term cost compared to current plans, but would better inform how to protect hardware, especially in regions where many operations will occur; this could therefore reduce risks and, ultimately, costs.

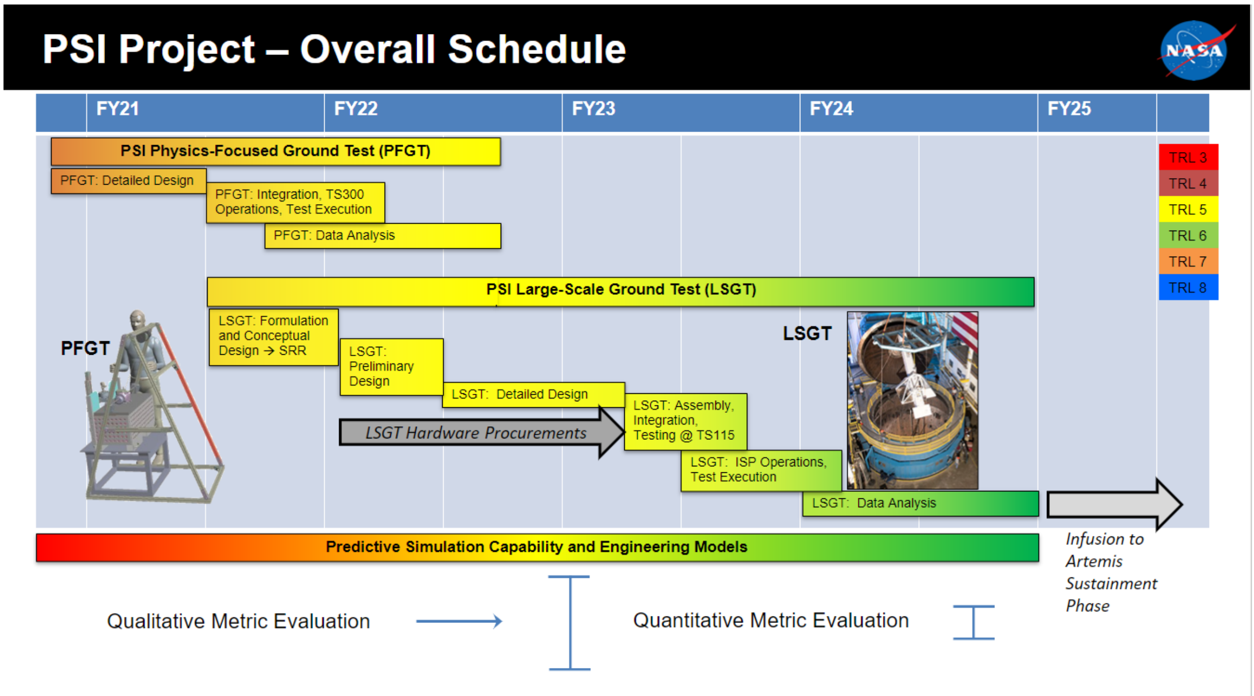

Figure 6. Anticipated Schedule of NASA's PSI Project[52]

Because of the substantial gaps in knowledge about PSIs, specific recommendations for lunar landings are difficult to provide. One fact appears certain: it is difficult to entirely eliminate the danger posed by plume-ejected debris to other activities that might be occurring on the lunar surface. "The hazard posed by that debris is a function of lander mass and distance from the landing site," but because debris can travel around the entire body of the Moon, there is no distance that can entirely avoid the possibility of any impacts.[53] Secondary impacts, and thus secondary ejecta, mean that even geographic features such as mountains, craters, and berms will not provide absolute protection. A paper by prominent experts summarizes the situation:

> Thus, for an exposed lunar base occupying 1 km2, the likelihood of sustaining an impact from a landing particle generated by 10 t lander may be described by the

[51] Ryan Watkins, et al., "Understanding and Mitigating Plume Effects During Powered Descents on the Moon and Mars," *Bulletin of the AAS* 53 (May 2021): https://doi.org/10.3847/25c2cfeb.f9243994.
[52] Michelle Munk, "Plume Surface Interaction: Surface Excavation and Construction Impacts," Surface Construction and Excavation Workshop, NASA, last modified August 20, 2021, https://ntrs.nasa.gov/api/citations/20210021530/downloads/LSIC_E%26C_Munk.pptx.pdf.
[53] D. Fontes, J. Mantovani, P. Metzger, "Numerical estimations of lunar regolith trajectories and damage potential due to rocket plumes," Acta Astronautica 195 (June 2020): https://doi.org/10.1016/j.actaastro.2022.02.016.

> equation… Such that at 1 km, an unprotected base might expect as many as 8 impacts per landing, each with a kinetic energy of~23.5 J. At 5 km, one would expect a 37 % chance of impact, at 10 km, that falls off to a 10 % chance of impact for base of the same size and so on. Thus, the question of risk turns to a question of durability and materials. It is not a question of if an impact will occur, but how many impacts and how the vehicle or space suit handles it.[54]

Once operations on the lunar surface begin—particularly when multiple operations are in a single region (e.g., the South Pole)—policymakers and mission planners will need to decide how far apart landings should be from ongoing operations, or how to protect surface assets from nearby landing spacecraft. This is a difficult question because of existing gaps in knowledge and the extreme distances traveled by ejected debris.

The drafters of the 2011 Recommendations were faced with a similar problem. They addressed this difficulty by estimating how far large particles (between 1 and 10cm) were likely to travel (1.5km), and therefore recommended that landings take place no closer than 2km from key Apollo sites.[55] By discounting the (nonzero) dangers posed by smaller particles and dust, they were able to constrain a protective zone around Apollo sites. A similar analysis could be useful now. According to leading experts in the field, the most useful measure of the danger posed by particles ejected by PSIs is energy flux: the total energy transmitted by ejected particles at various distances from a landing site, taking into account the mass, velocity, and number of particles striking an object at that distance from landing.[56] NASA could focus its investigations into this energy flux with the goal of identifying standoff distances from landing sites that will reduce the flux to tolerable levels. Mission planners could then refrain from landing craft within that distance from other operations taking place on the lunar surface. These distances will vary based on the size and engine configuration of landing craft, as well as the surface properties of the landing site. We recognize that landers will not target single points on the lunar surface: CLPS and HLS contracting documents require those landers to land within a certain radius of target locations, as described above. The landing target radius should be combined with the safety distance, such that a lander touching down on the edge of its target radius remains far enough away from other operations that existing operations on the surface are unlikely to experience high levels of energy flux. This focus has the advantage of ultimately developing technically based, publicly articulable justifications for our landing choices.

Instead of developing landing safety distances for each mission, some SMEs have recommended that NASA adopt simple, easily understood standard distances, at least until PSI models improve: i.e., "all CLPS missions should land x meters from currently-operating hardware" or similar.

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[54] M. M. Wittal, et al., "The Behavior of High-Velocity Dust Generated by Lander Plumes in the Lunar Environment," *AAS* 20-511 (June 2020): https://ntrs.nasa.gov/citations/20205003590.
[55] See discussion above, as well as in the Heritage section below.
[56] Dr. Philip Metzger, email to the authors, July 27, 2022.

Adopting such a measure would simplify mission planning, avoid limitations in current PSI models, and ease communication with the broader space community. However, adopting blanket measures—even in the short term—raises the risk of creating a perception that these measures are arbitrary and possibly attempts to displace other actors or otherwise “seize control” over certain areas.

Based on our conversations with partner space agencies, we understand that at least one of them is investigating the dangers of PSIs and considering how to reduce those dangers. As cooperative missions develop, it will be important to combine data as a first step towards developing joint PSI models and agreed safety measures. As the space community’s knowledge improves, it may be possible to develop broadly-agreed-to standards for how PSIs can be predicted, measured, and their dangers avoided. NASA SMEs could begin cooperative PSI prediction, measurement, and safety work with partner agencies and the private sector with the goal of developing “gold standards” for PSI predictions. Ultimately, shared models and common standards could create predictability and reduce disagreements between operators regarding landing safety. As a long-term goal, international standard-setting processes such as those managed by the International Organization for Standardization (ISO) could be adopted to unify operator treatment of PSI-related risks. After NASA SMEs begin cooperative work with partners to understand PSI risks, NASA could work with those partners to explore the possibility of formal standardization as a long-term goal.

There are limits to these recommendations. As described, focusing on avoiding particularly high energy flux will not eliminate the risk of impacts to other objects operating on the lunar surface. Impacts can and will occur, so shielding and other steps may be necessary. Additionally, in relatively small areas such as the Connecting Ridge, it may be difficult to find areas that are far enough away from ongoing operations to provide suitable landing sites, particularly taking into account the need to combine landing accuracy radii with safety margins as described above. Landing large distances away from places of interest (e.g., surface habitat or scientifically interesting locale) will also require long traverses, adding another level of complexity.

As the lunar surface becomes crowded in certain locations, these safety measures for landings will become simultaneously more important and more difficult to implement. We also note that landings are not the only time when PSIs and similar risks can occur; launching from the lunar surface could also pose risks to nearby operations. NASA and partners should consider placing a priority on the development of landing and ascent infrastructure, such as prepared landing and ascent surfaces, in areas that are likely to experience multiple operations in close proximity. Prepared surfaces could significantly reduce the danger of large ejecta, thus allowing landings and surface ascents to be closer to ongoing operations. Safety berms and similar naturally occurring features might also be useful in decreasing this safety distance.

In terms of timing, the hazards posed by landings to other ongoing operations will not materialize until multiple activities are occurring in proximity. NASA and the lunar community have a period of time to build on their knowledge of PSIs and other issues—and to develop shared metrics and mitigation steps—so that once landings begin to occur near each other, we will have more information upon which to determine specific safety distances.

Table 5. Challenges Posed by Landings: Summary of Policy Tools and Corresponding Rationale.

Landings will create PSIs that can damage assets—significant gaps in understanding their effects exist.

Policy Tool	Rationale
NASA could increase the priority of obtaining PSI measurements when possible. Mission planners could look for opportunities for dedicated PSI measurements spanning more missions or obtain data by indirect means if that is not possible. Data regarding PSIs should be shared publicly, consistent with longstanding NASA practice.	PSI prediction models require real-world data to validate simulations and inform safety measures. Absent accurate models, standoff distances will need to be larger than might be possible with accurate predictions.
NASA could focus its investigations into this energy flux [from ejected particles] with the goal of identifying standoff distances from landing sites that will reduce the flux to tolerable levels. We recommend that we refrain from landing craft within that distance from other operations taking place on the lunar surface.	Energy flux is the metric preferred by most SMEs in the academic and NASA community; it most closely predicts impacts on operators.
NASA SMEs could begin cooperative PSI prediction, measurement, and safety work with partner agencies and the private sector with the goal of developing "gold standards" for PSI predictions.	Cooperative PSI models can be more persuasive to the broader space community than would U.S.-centric models, and likely more accurate due to greater data availability.
After NASA SMEs begin cooperative work with partners to understand PSI risks, NASA could work with those partners to explore the possibility of formal standardization as a long-term goal.	PSI modeling is a technical safety measure; handling it through technical bodies could reduce potential for political influence, create predictability among operators, and standardize safety measures so as to avoid a "race to the bottom."

Policy Tool	Rationale
NASA and partners could place a priority on the development of landing and ascent infrastructure, such as prepared landing and ascent surfaces, in areas that are likely to experience multiple operations in close proximity.	Landing and ascent infrastructure can reduce the need for landing and ascent standoff distances and thus allow more operations in proximity.

2.2 Threats to and from Surface Operations

While landings on the Moon create the most dramatic risk to surface assets, surface operations also pose risks. These risks vary based on the nature of operations and hardware. Some operations may be at little risk of causing or suffering from harmful interference, while other operations may involve greater risk. Sometimes, these hazards are the result of nominal operations; other times, they would arise if equipment were damaged. For example, microwave and other transmitters can cause undesired thermal effects in other equipment, and ISRU processing might cause regolith to be ejected. Nuclear power sources, fuel depots, and even relatively small pressure vessels pose explosion, radiation, and other risks if damaged.

Artemis partners have coalesced around the idea of "safety zones" to manage these sorts of dangers. Defining safety zones, the Artemis Accords states:

> The area wherein this notification and coordination will be implemented to avoid harmful interference is referred to as a 'safety zone'. A safety zone should be the area in which nominal operations of a relevant activity or an anomalous event could reasonably cause harmful interference.

Phrased plainly, a safety zone is an area where one's own activities might cause interference to others if they came into the area or in which their presence might cause interference to one's own operations. Other actors are not required to stay out of safety zones; they are to notify the creator of the zone before entering and consult in advance to mitigate the interference.

The creation of safety zones on the Moon would be a significant operational, legal, and geopolitical step. As we discuss below, although safety zones derive from concepts in the Outer Space Treaty, they could be abused, and even reasonable safety zones could subject NASA and the United States to international criticism. It is therefore important to understand the legal, historical, and operational bases for this policy tool.

One slight precedent is the International Space Station (ISS). NASA has established a small "keep-out sphere" around the ISS, but this is a requirement for certification of commercial craft visiting the station, not a generally applicable rule for space actors. Because the details of this requirement are subject to International Traffic in Arms Regulations (ITAR), it is not discussed further here.[57] Regardless, this requirement is essentially a safety requirement for NASA's own contractors, so it is not a close analogy to the multi-actor safety zones envisioned by the Artemis Accords and needed on the Moon.

The 2011 Recommendations provide another example. As described in detail above, these recommendations request space actors to refrain from surface approaches to Apollo and Surveyor sites within certain distances, based on the characteristics and perceived value of those sites.

The ISS keep-out sphere and the 2011 Recommendations provide precedents from which policymakers can draw when designing safety zones on the Moon. However, the ISS and 2011 Recommendations were narrowly scoped and unilateral. To design and implement the concept of safety zones created by the Artemis Accords requires examination of the unique features of the Moon and Artemis campaign missions.

Before examining how safety zones could be implemented, it is important to understand what safety zones are. Section 11 of the Artemis Accords provides the most detailed, recent explanation of this policy tool. As a high-level commitment among international partners involved in the Artemis campaign, the Accords defines safety zones and describes how they are to be implemented for purposes of NASA operations on the Moon and, therefore, this report.[58]

The most critical element of safety zones is what they are not: they are not exclusion zones. Article I of the Outer Space Treaty declares that "there shall be free access to all areas of celestial bodies."[59] As a party to this treaty, the United States has no legal ability to exclude other actors from locations on the Moon. At the same time, other portions of the Outer Space Treaty provide building blocks from which safety zones can be constructed.

Article IX of the Outer Space Treaty requires states to give "due regard to the corresponding interests" of other states operating in space. Additionally, that article of the Treaty requires consultations prior to any activities that might create "harmful interference" in the activities of others in space, and Article VIII confirms that states retain ownership, jurisdiction, and control over their objects in outer space. One of the most useful achievements of the Artemis Accords is to combine these elements—due regard, consultations prior to interference, and the exercise of control over objects—into the tool that we call "safety zones."

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[57] NASA-authored references not subject to ITAR can be found at https://ntrs.nasa.gov/api/citations/20100014822/downloads/20100014822.pdf, https://ntrs.nasa.gov/citations/20150010757, and https://ntrs.nasa.gov/api/citations/20150010757/downloads/20150010757.pdf

[58] Additional discussion of the Artemis Accords and the Outer Space Treaty is contained in Appendix A.

[59] Because this provision is relevant to many of the policy tools described in this report, further discussion of the provision is provided elsewhere.

The Accords provides guidance regarding the design of safety zones, and commits signatories to the following principles:

> (a) The size and scope of the safety zone, as well as the notice and coordination, should reflect the nature of the operations being conducted and the environment that such operations are conducted in;
>
> (b) The size and scope of the safety zone should be determined in a reasonable manner leveraging commonly accepted scientific and engineering principles;
>
> (c) The nature and existence of safety zones is expected to change over time reflecting the status of the relevant operation. If the nature of an operation changes, the operating Signatory should alter the size and scope of the corresponding safety zone as appropriate. Safety zones will ultimately be temporary, ending when the relevant operation ceases; and
>
> (d) The Signatories should promptly notify each other as well as the Secretary-General of the United Nations of the establishment, alteration, or end of any safety zone, consistent with Article XI of the Outer Space Treaty.

The Accords further state that "The Signatory establishing, maintaining, or ending a safety zone should do so in a manner that protects public and private personnel, equipment, and operations from harmful interference."

Taken together, these criteria provide guidelines for our own establishment of safety zones around NASA's lunar operations. The criteria described in Section 11(7)(a-b) of the Accords are those relevant to the design of safety zones, and we examine them here.

To reiterate: "The size and scope of the safety zone, as well as the notice and coordination, should reflect the nature of the operations being conducted and the environment that such operations are conducted in…The size and scope of the safety zone should be determined in a reasonable manner leveraging commonly accepted scientific and engineering principles."

Because equipment will vary, detailed recommendations for safety zones are not possible at this time. We understand that a general rule—i.e., "safety zones should be 2km wide"—would be simple to implement, but there is no technical basis for such blanket determination and doing so would be inconsistent with the factors set out in the Accords. We are therefore unable to recommend a generalized design for safety zones. However, based on conversations with SMEs, we have been able to identify a minimum set of considerations that should be taken into account when considering dangers posed by surface operations. We recommend that for each mission, planners identify and quantify to the extent possible dangers posed by:

- Regolith ejected from the surface as the result of rover travel or other movement
- Pressure vessels during normal operations, at end of life, and in the event of failure

- Shadowing caused by tall structures
- Non-ionizing radiation from all sources
- Ionizing radiation from all sources
- Any chemicals released during normal operations or in the event of failure
- Any other hazards unique to specific hardware or operations (e.g., nuclear power systems)
- Special hazards posed by the nature of the location or terrain (e.g., significant slopes, boulders, dust, surface, or regolith characteristics)
- Damage to instrumentation (i.e., sensors, seismometers, or other instruments that may be damaged due to nearby landings and/or operations)
- Waste disposal

We have also worked with SMEs and used existing literature and knowledge to develop a system for designing and implementing safety zones. Policymakers could work with mission planners to (a) identify risks that each element of a mission could cause to others using the checklist above, (b) identify risks that other actors might cause to our own operations, and (c) identify a radius or other distance around each activity that can reasonably minimize (but likely not eliminate) those risks. These steps could become a standard element of mission planning, at least when multiple missions are operating in proximity. Safety zones could be tailored to the specific circumstances of our activities, but also take into account the geographical and other features of the target site (e.g., the presence or absence of ridges, boulders, etc. that could provide physical protection). Additional steps, such as the creation of protective berms, landing pads, and siting such objects inside craters, could be considered as part of mission planning to minimize the size and need for safety zones. The justifications for these safety zones should be clearly communicated to the space community.[60]

The issue of overflight deserves brief mention. In addition to applying to surface operations, safety zones also apply to activities that could accidentally become surface operations: that is, crashes. Respect for safety zones entails designing overflight paths and descent trajectories in such a way as to avoid instantaneous impacts inside safety zones.[61]

Once safety zones have been designed, implementation is relatively straightforward. Building on the transparency mechanisms discussed later in this report, the establishing actor (the U.S. Government / NASA, JAXA, etc.) needs to communicate the details of safety zones to the space community so that others can respect these zones. As promised by the Artemis Accords, we should be able to provide technical justifications for the design of each safety zone as described above. The Accords are clear that safety zones should be justified to the international community, but that the

[60] See the Transparency section below.
[61] This follows the precedent of the 2011 Recommendations, which request space-faring entities to avoid instantaneous impact possibilities within exclusion zones.

decision to implement them—and the design of them—rests with the actor engaged in the operations.

For signatories to the Artemis Accords, respect for safety zones means that signatories have promised to notify each other of safety zones, notify each other if a later actor wishes to enter an existing safety zone, and then to consult to mitigate any interference that might arise from that entry into the area.

Regarding non-signatories to the Accords, implementation is similar. Although non-signatories have not promised to respect safety zones as described in the Accords, all space-faring nations are parties to the Outer Space Treaty. As described above, that treaty requires them to give "due regard" to the interests of others, and to notify and consult in advance of any actions that might cause harmful interference. By publicly establishing safety zones around own operations, we have put the international community on notice that any entry into these areas could cause harmful interference, thus triggering the notice and consultation requirements of Article IX. The end result is therefore the same for signatories and non-signatories to the Accords: notice and consultation. Any disagreements regarding the application of the Outer Space Treaty should be resolved through diplomatic channels.

There are potential downsides to the establishment of safety zones on the Moon. Although they are emphatically not "keep out" zones, some critics—notably the Russian government, but also academics—have attempted to portray the safety zone features of the Artemis Accords as an American attempt to claim portions of the Moon.[62,63] The actual establishment of safety zones could reignite those criticisms. Minimizing the size and number of safety zones, terminating them at the end of missions,[64] and providing reasonable scientific and technical justifications for zone design may mitigate geopolitical repercussions.

Another way to mitigate criticism of safety zones is to respect those of others. As a signatory of the Artemis Accords, we have already committed to respect the safety zones of other signatories. In addition to fulfilling that promise, we recommend that NASA and the U.S. Government respect safety zones or similar tools established by non-signatories as well, since the concept of safety zones is directly derived from the Outer Space Treaty. As long as non-signatories' safety zones are reasonable, they should be respected.

Of course, some actors may attempt to establish unreasonable safety zones or take similar attempts to "cordon off" large areas around their operations. If another actor were to do so, we

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[62] Walker A. Smith, "Using the Artemis Accords to Build Customary International Law: A Vision for a U.S.-Centric Good Governance Regime in Outer Space," *J. Air L. & Com.* 86 (2021): https://scholar.smu.edu/jalc/vol86/iss4/5.
[63] "Nasa proposals to allow establishment of lunar 'safety zones'," Science, The Guardian, last modified May 25, 2020, https://www.theguardian.com/science/2020/may/20/nasa-new-space-treaty-artemis-accords-moon-mission-lunar-safety-zones.
[64] Or, if residual danger exists (i.e., from remaining pressurized vessels), reducing the zone as much as possible.

should work with the State Department (if the other actor is international) or the space interagency (if the other actor is U.S. commercial) to respond. This response should keep in mind that safety zones are simply a mechanism for implementing existing obligations set out in the Outer Space Treaty: the obligations to give due regard and consult before interference. We could use our own technical knowledge to judge whether other actors' requests are premised on a realistic fear of interference; to the extent they are not, we could communicate that we do not recognize them as legitimate, but also explain what sort of safety zones or other measures we would consider justified. Ultimately, respect for safety zones—whether our own or others'—is an exercise in persuasion, applying mission and hardware-specific facts to existing legal obligations. This would be the case whether the Artemis Accords or the concept of safety zones existed; safety zones are simply a mechanism to regularize implementation of the Outer Space Treaty.

Respect for many actors' safety zones does have its own downsides. As lunar operations proliferate, the number of safety zones in place at any one time will increase. The need to provide notice, and then coordinate operations to minimize interference, may add complications to mission planning. In a rules-based system, this complication is largely unavoidable.

As a practical matter, safety zones will not be needed until operations begin occurring in overlapping locations on the Moon. However, arguments exist for implementing safety zones earlier, even when not operationally necessary; we discuss this in our Implementation section below.

Table 6. Threats to and from Surface Operations: Summary of Policy Tools and Corresponding Rationale.

Activities on the surface can cause damage to or interfere with surface assets and operations.

Policy Tool	Rationale
We recommend that for each mission, planners identify and quantify to the extent possible dangers posed by: • **Regolith ejected from the surface as the result of rover travel or other movement** • **Pressure vessels during normal operations, at end of life, and in the event of failure** • **Shadowing caused by tall structures** • **Non-ionizing radiation from all sources** • **Ionizing radiation from all sources** • **Any chemicals released during normal operations or in the event of failure**	Adopting a standard checklist of hazards to identify and use to construct a safety zone will simplify planning, standardize mission design, and enhance our ability to justify safety zones and other measures to other actors.

Policy Tool	Rationale
• Any other hazards unique to specific hardware or operations (e.g., nuclear power systems) • Special hazards posed by the nature of the location or terrain (e.g., significant slopes, boulders, dust, surface, or regolith characteristics) • Damage to instrumentation (i.e., sensors, seismometers, or other instruments that may be damaged due to nearby landings and/or operations) • Waste disposal	
Policymakers could work with mission planners to (a) identify risks that each element of a mission could cause to others using the checklist above, (b) identify risks that other actors might cause to our own operations, and (c) identify a radius or other distance around each activity that can reasonably minimize (but likely not eliminate) those risks.	This option implements the commitments set out in the Artemis Accords.
The design of safety zones could become a standard element of mission planning. Safety zones could be tailored to the specific circumstances of our activities, but also take into account the geographical and other features of the target site (e.g., the presence or absence of ridges, boulders, etc. that could provide physical protection).	This option implements the commitments set out in the Artemis Accords.
Additional steps, such as the creation of protective berms, landing pads, and siting such objects inside craters, could be considered as part of mission planning to minimize the size and need for safety zones.	Other safety measures can minimize the size and need for safety zones and similar measures, allowing more actors to operate in proximity.

2.3 Challenges to Moving Across the Lunar Surface

Through our work with NASA SMEs, we learned that a confluence of technical constraints may result in another challenge for lunar surface operations: the need to maintain our ability to travel on the surface of the Moon between landing sites and/or areas of interest. As described in Part I, solar-powered robotic and crewed vehicles will need to follow pre-planned pathways if they travel on the surface between locations in the south polar region. These pathways will be designed to maximize time spent in sunlight, minimize time spent in shadow, and follow terrain features that are traversable by anticipated vehicles. Computer modeling shows that in some cases, sections of these corridors are extremely narrow: as small as 20-40 meters wide.[65] This modeling includes technical assumptions about the rover such as a fixed solar panel height of two meters above the surface and maximum speed of one to three kilometers per hour for the rovers.[66]

Until lunar rover designs are selected, our knowledge of their technical constraints is based on assumptions such as these. As a result, models demonstrating the need for very narrow transit pathways may over- or underestimate the difficulty of identifying paths across the lunar surface. Nevertheless, if current assumptions are accurate and some transit pathways are so narrow and so potentially critical to NASA and other actors' operations, then it is important to ensure that they remain available for use.[67]

We recommend that mission planners optimize traversable pathways between landing sites and/or other sites of interest. Models can be revisited if and especially when more details on rover capabilities become known. Additionally, the agency could work with international partners whose missions may overlap with or benefit from the identification of these pathways. If rovers could be deployed that could survive, e.g., 200 hours of darkness, additional pathways might appear, and the paths identified to date might not be so restrictive. It is important to test the validity of assumptions underlying our current planning.

Current modeling is also based on an assumption that no supplemental power exists to support surface assets in transit between sites of interest. However, certain architectures, as well as ongoing talks with international partners, call for the deployment of solar, nuclear, or other power solutions that could provide supplemental power at key locations between areas of interest near

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[65] P. Glaser et al., "Illumination conditions at the lunar poles: Implications for future exploration," *Planetary and Space Science* 162 (Nov. 2018): https://doi.org/10.1016/j.pss.2017.07.006.

[66] These vehicles have not yet been selected, so their abilities are notional. NASA intends to release an RFP in late August of this year; the specific capabilities and limitation of lunar rovers will only be known once vehicle designs are finalized.

[67] Based on discussions with SMEs, we understand that secondary, tertiary, etc. pathways may also be identified, as well as utility corridors. The recommendations here focus on the most desirable, primary pathways, but additional corridors should be considered for protection if operationally necessary.

the lunar South Pole. If charging stations or similar assets became available, options for when and how to travel on the Moon would change.

Assuming that transit paths are truly rare and narrow and will remain so even as we deploy additional equipment to the lunar surface, policymakers could consider the creation and protection of "transit corridors" in the south polar region. Transit corridors are navigable pathways between potential areas of interest optimized to avoid darkness and terrain-related constraints. NASA could (1) identify these corridors, (2) make their locations publicly known, (3) refrain from placing or disposing of equipment or facilities in these corridors (with an exception described below), and (4) request other space actors to exhibit the same restraint, at least until our capabilities advance beyond the need to avoid long periods of darkness. Avoiding the placement of objects in these corridors can ensure that they remain available for future operations. The identification and protection of transit corridors is likely not possible until specific details of hardware have been finalized but should occur as soon as possible (assuming it is necessary at all) as a prophylactic measure.

The need to refrain from placing hardware in transit corridors is not absolute. As we discuss above, some architecture plans call for the establishment of stationary facilities at which mobile assets could recharge their batteries.[68,69,70] If these facilities are solar-powered, they would likely be situated on high-elevation points along areas where mobile assets are likely to travel—precisely the same sort of areas likely to be along the transit corridors we have identified. Likewise, some mission plans have called for radiation and other emergency equipment to be deployed in areas where crew plan to travel. If fixed facilities are deployed in areas where mobile assets are likely to operate, we recommend that they be provided with visual and radio beacons and their locations made publicly known. In all cases, these facilities should be situated so as not to block mobile vehicles, including large, crewed rovers, from transiting the area.

There are potential downsides to the protection of transit corridors. Refraining from placing or disposing of hardware in these areas may place operational limitations on missions. Just as with all restrictions, this could result in additional costs or reduced capabilities for specific missions. If scientifically useful sites were to be identified along transit corridors, we may be less able to investigate them with persistent platforms than we could in the absence of protected transit corridors.

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[68] "NASA's Plan for Sustained Lunar Exploration and Development," NASA, accessed June 17, 2020, https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf.
[69] "Fission System to Power Exploration on the Moon's Surface and Beyond," Space Tech, NASA, last modified November 19, 2021, https://www.nasa.gov/feature/glenn/2021/fission-system-to-power-exploration-on-the-moon-s-surface-and-beyond.
[70] "NASA, Industry to Mature Vertical Solar Array Technologies for Lunar Surface," Space Tech, NASA, last modified March 23, 2021, https://www.nasa.gov/feature/nasa-industry-to-mature-vertical-solar-array-technologies-for-lunar-surface.

More generally, transit corridors could raise similar concerns in the space community to those posed by safety zones: that NASA or the United States are unilaterally attempting to place certain areas off-limits, despite the Outer Space Treaty's provisions regarding free access to all areas of celestial bodies. These concerns could be mitigated by clearly stating that we are imposing the same restrictions on ourselves that we are asking the rest of the community to adopt, and by emphasizing that the goal is to maintain access to polar sites for all of humanity. Alternatively, NASA and the U.S. Government could work with other space agencies and the international community to develop some level of consensus about the need for transit corridors before calling for their protection. Finally, we could characterize transit corridors as temporary measures, needing protection only until additional rover or power capabilities exist.

Table 7. Challenges to Moving Across the Lunar Surface: Summary of Policy Tools and Corresponding Rationale.

Technical constraints limit the ability to move between areas of interest—there is a need to ensure navigable pathways remain available for use.

Policy Tool	Rationale
We recommend that mission planners optimize traversable pathways between landing sites and/or other sites of interest. Models can be revisited if and especially when more details on rover capabilities become known. Additionally, the agency could work with international partners whose missions may overlap with or benefit from the identification of these pathways.	It is critical to determine whether paths between areas of interest or landing and operations sites are rare and small, thus requiring protection.
The creation and protection of "transit corridors" in the south polar region could be considered.	If certain corridors are critical to surface operations, protecting our ability to continue to use them is also critical to those future operations.
NASA could (1) identify these corridors, (2) make their locations publicly known, (3) refrain from placing or disposing of equipment or facilities in these corridors (with an exception described in this report), and (4) request other space actors to exhibit the same restraint, at least until our capabilities advance beyond the need to avoid long periods of darkness.	These steps would ensure that critical transit corridors remain available for future missions by NASA and other actors, while still allowing their use in the meantime.

Policy Tool	Rationale
If fixed facilities are deployed in areas where mobile assets are likely to operate, we recommend that they be provided with visual and radio beacons and their locations made publicly known. In all cases, these facilities should be situated so as not to block mobile vehicles, including large, crewed rovers, from transiting the area.	Some fixed facilities may be required in corridors; these measures would minimize the impact of those facilities and allow operators to work around them (literally in some cases).

2.4 The Danger of Radio-Frequency Interference

SMEs also suggested that we consider challenges posed by radio-frequency interference (RFI) among lunar operations and examine whether specialized policy tools are appropriate.

Like those in orbit, lunar operations certainly could be subject to RFI. However, because this hazard is not unique to the lunar environment, we have identified no reason to diverge from the same solutions used to avoid RFI on Earth and in Earth orbit: international coordination through the ITU. The ITU already allocates frequencies for use by space objects, and it is set to place special emphasis on emerging space needs at the next World Radiocommunication Conference in 2023.[71] NASA already engages with the Federal Communications Commission (FCC), the National Telecommunications and Information Administration (NTIA), and the Department of State to prepare the U.S. Government's positions before the ITU and then implement frequency allocations, and uses internationally allocated frequencies for communications.[72] We recommend that NASA continue this engagement with the interagency and continue to rely on the ITU to avoid RFI in lunar operations. If additional international mechanisms ultimately prove to be needed (e.g., rules combining frequencies and locations such as those for geosynchronous orbit (GEO) satellites), NASA should work with the interagency to develop, promote, and implement those policies through the ITU.

Table 8. The Danger of Radio-Frequency Interference: Summary of Policy Tool and Corresponding Rationale.

Surface operations could be subject to radio-frequency interference.

[71] "Managing radio frequency spectrum amid a new space race," News, International Telecommunication Union, last modified November 12, 2021, https://www.itu.int/hub/2021/11/managing-radio-frequency-spectrum-amid-a-new-space-race/.
[72] For an explanation of the interagency process from the perspective of NASA, see *Spectrum 101*, 2016, at https://www.nasa.gov/sites/default/files/atoms/files/spectrum_101.pdf.

Policy Tool	Rationale
We recommend that NASA continue engagement with the interagency and continue to rely on the ITU to avoid radio-frequency interference in lunar operations.	The ITU appears to be engaged in a process to resolve issues relating to deep-space communications. The ITU has successfully resolved similar issues in other space regimes, so is best positioned to allocate frequencies for lunar operations as well.

2.5 Threats to Areas with Special Characteristics

In our conversations with SMEs, several noted that certain locations in the south polar region of the Moon warrant special consideration due to unique or rare characteristics. Lunar operations pose a risk of rendering these locations less useful, so special measures may be appropriate.

The first category of unique or rare sites are those with particularly high scientific value, especially PSRs located in large, old, relatively undisturbed craters. Locations with these characteristics are attractive to the scientific community as a potential "window" into the history of the solar system, and some experts have expressed a desire that they be protected from disturbance except for scientific investigation.[73] Volatile-rich PSRs are also areas that could be useful for ISRU operations, so there is a possibility of tension between scientific, exploration, and (perhaps) commercial activities at these locations.

Reserving locations for only scientific activities is possible but would require consensus among actors beyond NASA and the U.S. Government. No legal, policy, or diplomatic tools currently exist for this purpose; on the contrary, the Outer Space Treaty provides that "there shall be free access to all areas of celestial bodies."[74] NASA could make an internal decision to set aside certain PSRs (e.g., in the north polar region) for purely scientific activities with regard to its own missions, but ensuring that commercial and international actors exercise similar restraint would require securing consensus among them. If this is an effort NASA leadership wishes to pursue, SMD and other NASA leaders could engage with the scientific community to determine whether any locations exist that warrant being reserved for scientific purposes and, if so, collaborate with the Department of State and industry to secure the necessary broad consensus. We recognize that not all PSRs are equally valuable from scientific or other perspectives; small PSRs are likely to be common across the polar

[73] This idea is similar to how Antarctica is reserved for scientific purposes under the Antarctic Convention.
[74] In contrast to the Antarctic, where the Antarctic Treaty essentially reserves the entire continent for scientific purposes.

regions, and frozen volatiles may only exist in some subset of PSRs. If special protections are desired for scientific or other uses, the space community should work to articulate which locations are especially valuable and for what purposes. Limiting the number of protected locations would increase the probability of success, as would reiterating NASA's longstanding commitment to freely sharing the results of its scientific investigations. Because taking this step would mark a significant shift in national and international policy towards lunar exploration, we make no recommendation here as whether to pursue it.

Another location in the polar region deserves special consideration for a very different reason: the Connecting Ridge between the Shackleton and de Gerlache craters. Many SMEs have emphasized the unique importance of this geographic feature: not because it is scientifically interesting, but because it provides critical operational advantages. The Connecting Ridge is a relatively open area, well-suited to landings; it receives substantial amounts of sunlight; and it offers surface access to many of the most desirable locations in the polar region, including PSRs, sunlit peaks, and suspected volatile deposits. Because of these characteristics, the Connecting Ridge is a highly desirable location for operations for NASA and other actors.

Exclusive control over the Connecting Ridge is neither legally possible[75] nor practical; the ridge is approximately twenty-five by ten kilometers in size. Attempting to control such a strategic location could also cause substantial political and diplomatic objections and would interfere with operations for all other actors. For these reasons, we recommend efforts be made to ensure freedom of access for all space actors to this region of the Moon, such as by exercising restraint when hardware is disposed in the area and consolidating operations sites when possible while still meeting mission objectives.

Finally, a last location or series of locations, that may warrant specialized measures are sites where space resource extraction may occur on an ongoing basis. We note the importance of equity and ethics in Appendix D—specifically, how exploration can create tension between groups with differing values. Mining is one such example. Though long-term mining operations are largely out of scope for this analysis because they will not occur during the timescales covered by this report, we acknowledge the importance of near-term considerations to promote mining in an environmentally responsible way. Leveraging the strengths of international partners is one way to address this concern. Certain Artemis partners have extensive domestic histories of multi-stakeholder, environmentally responsible extractive industry work; they may be able to contribute to similar efforts for space resources. The Legal Subcommittee of the Committee on the Peaceful Uses of Outer Space (COPUOS) has formed a working group on space resources that may ultimately develop norms that could be incorporated into NASA's planning. NASA is already represented on the U.S. delegation to that working group, but may wish to play a more substantive role once organizational

[75] See the discussion of freedom of access in the Outer Space Treaty above.

questions about the group's mandate are resolved. We recommend that NASA work with Artemis partners to jointly support UN space resource efforts directed at practical, actionable norms and best practices that support ISRU efforts and sustainable operations.

Table 9. Threats to Areas with Special Characteristics: Summary of Policy Tools and Corresponding Rationale.

Certain locations may warrant protection if operations may render them less useful.

Policy Tool	Rationale
We recommend efforts be made to ensure freedom of access for all space actors to this region [the Connecting Ridge] of the Moon, such as by exercising restraint when hardware is disposed in the area and consolidating operations sites when possible while still meeting mission objectives.	The Connecting Ridge appears to be a potential area of landings and operations for multiple space actors, and central to NASA's ability to operate across the polar region. Ensuring access for all to the Ridge implements provisions of the Outer Space Treaty and protects NASA's equities.
We recommend that NASA work with Artemis partners to jointly support UN space resource efforts directed at practical, actionable norms and best practices that support ISRU efforts and sustainable operations.	ISRU efforts are some of the most controversial plans for our lunar programs and raise multiple policy issues. Engaging in multilateral fora is a way to minimize criticism and develop shared practices among multiple actors.

2.6 The Challenge of Unexpected Activities on the Surface

Throughout our conversations with SMEs, security-related concerns have been raised. For example, some individuals have expressed concerns that space actors hostile to U.S. Government programs could intentionally interfere with NASA's lunar operations. Some have also raised concerns regarding theft or inadvertent release of proprietary or export-controlled technology as a result of operations between actors from different countries or companies.

Our investigation has revealed no way to judge the likelihood of these risks, but they are at least physically possible. The creation of safety zones, described above, could serve to mitigate some of these risks, particularly the risk of inadvertent release of technology.

However, a space actor willing to engage in intellectual (or physical) property theft, or to intentionally interfere with NASA operations, is unlikely to be deterred by a safety zone. For that reason, mission planners could consider including hardware that would allow them to identify and record any unexpected activities in their vicinity. This hardware need not be focused on only this one task: engineering cameras or other equipment could serve multiple purposes, so long as it is capable of recognizing and responding to proximity operations by other actors. Although adding cameras or other sensors could increase the mass, power requirements, and bandwidth required by lunar operations, this equipment could also be used for other purposes, such as navigation and public engagement. Power and bandwidth-preserving steps could also be taken, such as only transmitting data if nearby movement is detected—along the lines of a home doorbell camera. Including these capabilities on our missions could serve to deter threats and seek accountability if they materialize. If adding these capabilities is overly burdensome to apply to all lunar missions, we should consider whether specific missions warrant this level of protection due to the nature of equipment or operations involved.

Table 10. The Challenge of Unexpected Activities on the Surface: Summary of Policy Tool and Corresponding Rationale.

Security-related concerns could interfere with surface operations.

Policy Tool	Rationale
Mission planners could consider including hardware that would allow them to identify and record any unexpected activities in their vicinity.	Recording equipment can help NASA respond to unexpected proximity operations, hazards, or other concerns as well as perform additional outreach and science tasks.

2.7 The Need for Human Heritage Protection

Another challenge—or at least a consideration—for lunar operations is the need to protect human heritage sites. SMEs, Congress, and civil society organizations have all emphasized their desire for NASA to include heritage protections in its operations. Doing so will require a combination of technical knowledge, historic insight, and diplomacy.

As we mentioned above, this is not the first time the agency has examined this issue. In 2011, NASA published "Recommendations to Space-Faring Entities" regarding "how to protect and preserve the historic and scientific value of U.S. Government lunar artifacts."[76] These recommendations (also

[76] Human Exploration and Operations Mission Directorate, Strategic Analysis and Integration Division, NASA HQ, "NASA's Recommendations to Space-Faring Entities: How to Protect and Preserve the Historic and Scientific Value of U.S. Government Lunar Artifacts," July 2011: https://www.nasa.gov/pdf/617743main_NASA-USG_LUNAR_HISTORIC_SITES_RevA-508.pdf.

discussed in the Safety Zones and Prior Work sections) focus on the Apollo and Surveyor sites, and provide detailed, non-binding suggestions to "help preserve and protect lunar historic artifacts and potential science opportunities for future missions." To reiterate, the 2011 Recommendations specify details such as "exclusion zones," "collision avoidance windows," "artifact boundaries," avoidance of overflight, and surface mobility boundaries. These recommendations differ for different Apollo sites based on (1) the perceived heritage value of the site (e.g., Apollo 11) and (2) whether the sites contain elements of ongoing scientific interest (e.g., laser ranging retro-reflectors). Because the specific guidelines are set out above, we do not restate them here.

In 2020, the Artemis Accords included a section on human heritage, ensuring that this is a shared goal among Artemis partners. Section 9 of the Accords states:

> The Signatories intend to preserve outer space heritage, which they consider to comprise historically significant human or robotic landing sites, artifacts, spacecraft, and other evidence of activity on celestial bodies in accordance with mutually developed standards and practices.[77]
>
> The Signatories intend to use their experience under the Accords to contribute to multilateral efforts to further develop international practices and rules applicable to preserving outer space heritage.

Also in 2020, the One Small Step to Protect Human Heritage in Space Act was adopted by Congress.[78] This legislation requires NASA to "add the [2011 Recommendations and any subsequent similar recommendations] as a condition or requirement to contracts, grants, agreements, partnerships or other arrangements pertaining to lunar activities carried out by, for, or in partnership with [NASA]."[79]

We are therefore faced with a situation where we have detailed internal NASA guidelines for protecting the Apollo and Surveyor sites that we must also apply to commercial and international partnerships. No specific guidelines or legal requirements for other potential heritage sites exist, other than the general commitment in the Artemis Accords to "preserve outer space heritage."

Protection of lunar heritage requires at least a two-step process: (1) identification of the sites to be protected and (2) development of measures that will protect those sites. For Apollo and Surveyor sites, both criteria are already met. We therefore recommend that the 2011 Recommendations be

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[77] The Accords consider heritage to include "sites" as well as "artifacts" and "other evidence of activity." When referring to heritage or heritage sites in this report, we adopt this broad definition.

[78] Public Law 116-275, Dec. 31, 2020. Available at https://www.congress.gov/116/plaws/publ275/PLAW-116publ275.pdf.

[79] The law also provides for a waiver if the Administrator finds that carrying out this obligation in particular instances "would be unduly prohibitive to an activity or activities of legitimate and significant historical, archaeological, anthropological, scientific, or engineering value."

continued and implemented for Apollo and Surveyor sites, and that their recommendations be implemented in commercial and international partnerships as required by law.

Regarding future sites, the first step is identification. There is no formal international or domestic process through which these sites could be identified. During the negotiation of the Artemis Accords, drafting countries considered whether they should include heritage criteria in the Accords' text. These countries decided that because heritage protections are of value to the entire international community—and because they could be abused (see below)—these criteria should be developed through multilateral diplomatic efforts.[80] This has not yet occurred.

Until a widely accepted method to identify heritage sites is developed by the international community, each spacefaring nation will need to determine which of their own sites deserve heritage protections and convince other actors to respect those decisions. For now, we recommend that NASA work with the Department of State and other relevant U.S. agencies and departments to identify which, if any, additional U.S. robotic or human sites warrant heritage protection. Because these sites will be indefinitely protected—and thus generally off-limits for operations—we recommend that NASA exercise extreme restraint in seeking heritage protection for future sites, particularly those in potentially crowded areas such as the south polar region. Heritage protection is also only appropriate after operations have ceased; while operations are ongoing, other policy tools, such as safety zones, are more well-tailored to protecting those activities.

In order to identify other actors' sites that might warrant heritage protection, we recommend that NASA work with the Department of State to determine whether other nations request heritage protection. Any dispute about the appropriateness of such a designation should be handled through diplomatic channels; if an internationally agreed upon process ultimately develops to identify heritage sites, that process should supplant this informal, diplomatic process.

An internationally agreed upon process to identify heritage sites would provide many benefits. Terrestrially, processes such as those for United Nations Educational, Scientific and Cultural Organization (UNESCO) World Heritage Site designation and underwater archaeological sites have provided a level of neutrality, consensus, and certainty that is not possible under current space law, which does not explicitly provide for heritage protections. NASA could work with interagency experts on terrestrial heritage protections and the Department of State to (1) learn best practices for heritage site identification and (2) begin raising this issue in appropriate international fora such as COPUOS and potentially UNESCO itself.

Once U.S. and international heritage sites have been identified, either through national processes (for now) or internationally agreed upon procedures (eventually), appropriate measures should be put in place to protect them.

[80] Personal knowledge of the authors.

What it means to protect space heritage has not been decided by the international community. NASA is committed to implementing the 2011 Recommendations, but no protection measures have received broad acceptance for space. However, certain terrestrial analogues do exist; the closest is probably protections for maritime archaeology sites.

One aspect of protection appears clear: heritage protections are intended to preserve cultural and historical value, not to enable development. Heritage protections would not be appropriate for locations in which we are engaged in ongoing operations.

Until the international community develops more specific heritage protection measures for outer space, we recommend applying the recommendations set out in 2011 to heritage sites that are identified anywhere on the Moon, including in the polar region. Providing other actors' sites—and our own future historic site(s)—the same protection as Apollo and Surveyor simplifies planning, minimizes the potential for claims of preferential treatment and creates consistency until an international standard is developed.

There are potential downsides to heritage protection. Heritage protections raise many of the same concerns as do safety zones: some could claim that they are de facto "appropriation" of lunar territory, and/or that the United States and NASA should not speak on behalf of other actors when determining what sites beyond U.S. borders deserve protection. This risk is increased by the indefinite duration of heritage protections, but these risks are mitigated by the fact that heritage protections restrict our own activities as much as they do those of others, and by the fact that we are willing to apply these same protections to heritage sites from other countries. We could also draw from terrestrial heritage protections, such as maritime archaeological protections, when those precedents are useful. We recommend exercising restraint in identifying new heritage sites to minimize criticism and increase the likelihood that other actors will adopt similar protective measures.

Any heritage sites should be identified and communicated to the space community as soon as possible to ensure protection, so we should consider whether NASA sites (such as the first Artemis crewed landing) warrant protection before those operations are complete.

Table 11. The Need for Human Heritage Protection: Summary of Policy Tools and Corresponding Rationale.

The U.S. may wish to preserve non-operational sites for their historic or cultural value.

Policy Tool	Rationale
We recommend that the 2011 Recommendations be continued and implemented for Apollo and Surveyor sites, and that their recommendations be	This ensures consistency in rules between what is required for our commercial actors and our own operations.

Policy Tool	Rationale
implemented in commercial and international partnerships as required by law.	
We recommend that NASA work with the Department of State and other relevant U.S. agencies and departments to identify which, if any, additional U.S. robotic or human sites warrant heritage protection. Because these sites will be indefinitely protected—and thus generally off-limits for operations—we recommend that NASA exercise extreme restraint in seeking heritage protection for future sites, particularly those in potentially crowded areas such as the south polar region.	Balancing the need to protect legitimate heritage with the danger of creating backlash requires caution and an effort at persuading the community.
We recommend that NASA work with the Department of State to determine whether other nations request heritage protection. Any dispute about the appropriateness of such a designation should be handled through diplomatic channels; if an internationally agreed upon process ultimately develops to identify heritage sites, that process should supplant this informal, diplomatic process.	If we request protection for our own sites, we must be willing to protect those of others as well.
NASA could work with interagency experts on terrestrial heritage protections and the Department of State to (1) learn best practices for heritage site identification and (2) begin raising this issue in appropriate international fora such as COPUOS and potentially UNESCO.	Developing a formal, multilateral process is the only durable way to ensure indefinite heritage protections.
We recommend applying the recommendations set out in 2011 to heritage sites that are identified anywhere on the Moon, including in the polar region.	This builds consistency in rules between Apollo, Surveyor, and Artemis sites.
We recommend exercising restraint in identifying new heritage sites to minimize criticism and increase the	Balancing the need to protect legitimate heritage with the danger of creating backlash requires caution

Policy Tool	Rationale
likelihood that other actors will adopt similar protective measures.	and an effort at persuading the community.

Part 3: Transparency, Coordination, and Implementation

TOR Question 2: What technical and policy considerations should NASA take into account when implementing tools such as safety zones in order to protect these operations and U.S. interests?

When implementing any of the policy tools described in Part 2, we recommend the following as a means to increase their effectiveness, thus protecting operations and U.S. interests. Note that this includes tools such as safety zones but applies to all of the policy tools.

The first step in responding to the challenges posed by lunar operations is deciding how NASA wants to respond; the tools for doing so are described in Part 2. However, making our own decisions about how we wish to proceed is only the first step. For these decisions to be effective, we must also communicate those decisions to other actors, coordinate when necessary, and build our decisions into mission planning. This part of our report provides a set of options for doing so and is summarized in the following table.

Table 12. Summarized Options to Supplement Policy Tools.

	Purpose	**Options to Supplement Policy Tools (See Summary Chapter for Full List)**
Transparency	To address potential concerns and increase effectiveness of policy tools	Build on the transparency section of the Artemis Accords by 1) meeting with signatories to discuss policy tools for upcoming missions and, 2) developing a public relations strategy along with multilateral engagement to explain rationale for policy tools
Coordination	To actively involve the space community before implementing policy tools, especially when related to cooperative missions	Work with the Department of State to ensure partners on joint missions share our views on responding to challenges; develop mechanisms for consultation and coordination to deconflict surface operations
Implementation	To put policy tools into practice by incorporating into mission plans	For missions over which NASA has operational control, build policy tools into mission planning; for missions operated as a service, work with contracting companies to implement relevant policy tools

It is also worth keeping in mind that not all of the challenges discussed in Part II will be immediately important to our lunar operations. Some challenges—such as those posed by landings in proximity to ongoing operations—will only become a serious concern once traffic to the Moon increases. Other challenges may subside in importance as we develop additional lunar capabilities, such as through adoption of nuclear power, enabling travel through shadows. Policy and similar measures may not need to be adopted until challenges become imminent, but policymakers should also be aware that there may be benefits to deploying policy tools in relatively benign circumstances before testing them with "hard cases." For example, as we discuss above, although safety zones may not become a practical necessity for a few years, we could nevertheless create safety zones for short-term missions located far from any other actors, such as for early CLPS missions, as a way to establish precedent without imposing any difficulties on other actors.

3.1 Transparency

Most of the policy tools discussed in this report have never been used in outer space. In addition, some of these tools—particularly safety zones and heritage sites—could be abused, or be perceived to be abused, to (functionally if not legally) claim territory and displace other actors. Some commentators and national actors have already expressed concerns about safety zones along these lines.[81,82] Much of this criticism has been about process, with countries such as China and Germany arguing that these issues should be discussed through traditional United Nations mechanisms. To blunt these concerns, it will be important to involve these fora whenever possible. In terms of substance, we will need to engage in a concerted effort to describe what we are doing and justify those actions to prevent negative political repercussions, maintain public and international support for our programs, and shape future behavior.

Transparency can also serve practical goals. For policy tools to be effective, other actors must know that they exist so that they can respect them.

The U.S. Government has already made a commitment to transparency in lunar operations in the Artemis Accords. Section 4 of the Accords is entitled "Transparency" and states that "the Signatories are committed to transparency in the broad dissemination of information regarding their national space policies and space exploration plans in accordance with their national rules and regulations." In addition, the Accords contains additional transparency measures for specific issues: Section 8 commits signatories to "open sharing of scientific data" and Section 10 commits them to "informing the Secretary-General of the United Nations as well as the public and the international scientific community of their space resource extraction activities in accordance with the Outer

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[81] Jack Wright Nelson, "Safety Zones: A Near-Term Legal Issue on the Moon," *Journal of Space Law* 44, no. 2 (2020): https://ssrn.com/abstract=3849238.
[82] L. Mallowan, L. Rapp, M. Topka, "Reinventing treaty compliant ''safety zones'' in the context of space sustainability," *Journal of Space Safety Engineering* 8 (June 2021): https://doi.org/10.1016/j.jsse.2021.05.001.

Space Treaty." The greatest level of detail is provided in Section 11 regarding safety zones and deconfliction of space activities. Here, commitments include:

To provide each other with necessary information regarding the location and nature of space-based activities under these Accords if a Signatory has reason to believe that the other Signatories' activities may result in harmful interference with or pose a safety hazard to its space-based activities;

> To provide notification of their activities and commit to coordinating with any relevant actor to avoid harmful interference;
>
> The Signatory maintaining a safety zone commits, upon request, to provide any Signatory with the basis for the area in accordance with the national rules and regulations applicable to each Signatory; and
>
> The Signatories should, as appropriate, make relevant information regarding such safety zones, including the extent and general nature of operations taking place within them, available to the public as soon as practicable and feasible, while taking into account appropriate protections for proprietary and export-controlled information.[83]

Finally, our commitment to transparency can keep us honest with ourselves. By ensuring that we are able to publicly articulate the justifications for our actions, we can help ensure that we are not overstepping or abusing our position as a dominant civil space actor. Some public reactions to NASA's lunar operations will almost certainly be ethical in nature, as they were with Apollo.[84,85] By adopting a clear commitment to transparency not only for our mission plans but also our policy tools, we can force ourselves to grapple with the social and ethical implications of our activities.

For these reasons, implementing policy tools in our own missions is only the first step. We must also share this fact with the world and convince key actors that what we are doing is appropriate. If we do not believe that we can achieve that level of acceptance, we may wish to reconsider our choices.

Fulfilling this need for transparency could come in many forms. As described, the Artemis Accords already contains some commitments: a general commitment to public sharing of policies and plans, open sharing of scientific information, providing the United Nations Secretary-General and scientific community information about space resource activities, and informing fellow Accords signatories of

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[83] Artemis Accords, Section 11, excerpts. Intervening language omitted to focus on transparency obligations.
[84] Mark Williamson, "Space ethics and protection of the space environment," *Space Policy* 19 (2003): http://www.chriscunnings.com/uploads/2/0/7/7/20773630/space_environment.pdf.
[85] "The Apollo 11 Mission and the Challenge of Solving the Plight of the Poor," Blog, accessed June 17, 2022, https://launiusr.wordpress.com/2014/06/06/the-apollo-11-mission-and-the-challenge-of-solving-the-plight-of-the-poor/.

safety zones. To meet these commitments as well as realize the full benefits of transparency, we recommend that NASA leadership consider several transparency measures.

Most immediately, transparency requires communication with our commercial and international partners. As a first step, we recommend working with the Department of State to convene a meeting of Artemis Accords signatories—or a subset of them actively involved in lunar operations—to discuss with them policy and related measures that we anticipate using for upcoming lunar missions.

More public steps also have value, including formal United Nations processes. The United States is already obligated to provide basic space-object registration data to the United Nations pursuant to the Outer Space Treaty and Registration Convention. Furthermore, Article XI of the Outer Space Treaty commits Parties to "inform the Secretary-General of the United Nations as well as the public and the international scientific community, to the greatest extent feasible and practicable, of the nature, conduct, locations and results of [activities in outer space]." We could build on our longstanding registration practice and combine it with our Article XI obligations to provide formal notice to the international community of lunar operations, as well as associated measures such as safety zones.

Notably, the civil society effort "The Article XI Project" is creating a draft template that states could use to provide the United Nations with precisely this sort of information.[86,87] Working with the Department of State (which is responsible for our international registration filings), we could use this mechanism to provide not only registration data to the United Nations, but also data necessary for other actors to avoid conflicts with our operations.

Public statements in the form of speeches and interviews by principals (the NASA Administrator and Deputy Administrator, the Vice President, and the Executive Secretary of the National Space Council) should also be used. Although not a useful vehicle to provide detailed operational data, these mechanisms are invaluable in explaining why we choose to take certain measures, and for describing what we are—and are not—doing. We could also discuss our lunar plans at the United Nations Committee on the Peaceful Uses of Outer Space (UNCOPUOS).

Finally, we could continue to share information about exploration plans and missions on public-facing assets such as NASA-controlled websites. In addition to the general information and scientific data typically provided, it may be useful to consider providing sufficient detail such that other actors could successfully deconflict their operations with our own. Barring that, we could provide contact information through which that sort of information could be shared.

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[86] Italian Space Agency, discussion with the authors, June 6, 2022, and Antonino Salmeri, discussion with the authors, May 2022.
[87] "THE ARTICLE XI PROJECT," Academics, Cleveland State University, accessed June 17, 2022, https://www.law.csuohio.edu/academics/globalspacelaw/projectXI.

To summarize, we recommend a full public relations strategy, as well as multiple streams of multilateral engagement, to articulate our justifications for policy measures in order to forestall negative reactions and solidify our behavior as a precedent to be followed rather than a threat to the space community.

Table 13. Transparency: Summary of Options and Rationale.

Options to Supplement Policy Tools	Rationale
We recommend working with the Department of State to convene a meeting of Artemis Accords signatories—or a subset of them actively involved in lunar operations—to discuss with them policy and related measures that we anticipate using for upcoming lunar missions.	Cooperative missions will require adoption of shared policy measures and achieving consensus among those measures will reduce criticism that they are illegitimate.
We recommend a full public relations strategy, as well as multiple streams of multilateral engagement, to articulate our justifications for policy measures in order to forestall negative reactions and solidify our behavior as a precedent to be followed rather than a threat to the space community.	Adoption of the recommendations set out in this report will only be successful if these measures are understood and implemented by other actors.

3.2 Coordination

Transparency is a critical first, step but implementing our decisions will require further involvement with the space community: active coordination. The need for coordination when engaged in cooperative missions is obvious, but more general coordination will be required when multiple actors are operating in proximity on the Moon.

Regarding cooperative missions, we recommend working with the Department of State during joint mission planning to ensure that our partners share our views regarding the steps necessary to respond to the challenges and threats described in this report.

More general coordination will likely also become necessary, particularly when more than two space actors operate in proximity. In conversations with partner space agencies, one major partner expressed the view that some level of centralized coordination among actors may become necessary as lunar operations increase in number. Notice, coordination, and deconfliction measures are relatively straightforward for two actors, but once three or more actors are involved, the difficulty of, for example, establishing overlapping safety zones, will compound. This partner asked whether a single country or space agency should serve as a sort of convenor among parties involved in lunar operations, facilitating (but not deciding) solutions to common problems.

Having any country serve as a centralized facilitator for lunar cooperation entails some risk. Other actors could perceive that role as a power-grab and it could also place the facilitator in an awkward position when mediating situations that involve its own agency's or country's operations. Nevertheless, it may become practically necessary to create formal coordination mechanisms. We recommend that policymakers work with the Department of State, industry, international partners, and ultimately the broader space community to develop mechanisms for consultation and coordination to deconflict operations on the Moon. To design these mechanisms, we could build on existing groups of partners and fora, such as Artemis Accords signatories and the International Space Exploration Coordination Group (ISECG).

Finally, as we discuss above, there are certain issues—such as the danger posed by PSIs—that could benefit from standardization across the space community. For those issues, ad hoc coordination on a mission-by-mission basis may be sufficient in the short and medium-term, but the adoption of standardized measures could ultimately reduce the need to engage in detailed coordination because each actor would already know what safety measures they could expect to be followed by other operators.

Table 14. Coordination: Summary of Options and Rationale.

Options to Supplement Policy Tools	Rationale
We recommend working with the Department of State during joint mission planning to ensure that our partners share our views regarding the steps necessary to respond to the challenges and threats described in this report.	Cooperative missions will require adoption of shared policy measures and achieving consensus among those measures will reduce criticism that they are illegitimate.
We recommend that policymakers work with the Department of State, industry, international partners, and ultimately the broader space community to develop mechanisms for consultation and coordination to deconflict operations on the Moon.	Deconfliction mechanisms require agreed processes across the space community.

3.3 Implementation

In addition to informing partners and the space community of our plans, we also need to put those plans into practice through mission planning.

For example, CLPS missions could be designed to respect safety zones for each other and for HLS, and vice versa. Likewise, all NASA-affiliated missions could refrain from stationing or abandoning objects in critical transit corridors, or from interfering with heritage sites. Implementation in this sense is simply a question of mission planning—ensuring that the choices we have made to respond to lunar challenges are incorporated into operational plans.

For missions over which NASA has operational control (e.g., HLS), operational implementation is relatively straightforward. Policy decisions should be communicated to relevant directorates, offices, and programs within the agency, and processes should be developed to ensure that these actors understand and build the appropriate policy decisions into their plans.

For CLPS missions, and other missions operated as a service—where the contracting company, not NASA, has operational control—implementation may require additional effort. Because we do not directly control mission plans for these activities, NASA should consider working with relevant contracting companies to ensure that they build NASA-determined policy tools into their mission plans. The Office of the General Counsel and relevant program offices will need to be consulted to determine specifics for each mission, program, or contract.

Not all policy measures described in this report would require such a level of control over our contractors. When policy measures would require our contractors to do or not do certain things—such as avoiding heritage sites, including certain instruments on landers, or refraining from disposing of equipment in certain areas—we would likely need to work with contractors to include those requirements in contracting or other documents. However, for policy measures that entail requesting other actors to do or not do certain things, NASA and other departments/agencies may be able to implement them without a need to include those measures in contracting documents. For example: if we decided to establish a safety zone around a CLPS mission, we would not need to include any requirements in the contracting documents for that CLPS provider (other than possibly obtaining technical data in advance to help us design the safety zone). NASA, the Department of State, and the U.S. Government generally could design, publicize, and attempt to persuade other nations to respect that safety zone in their own operations.

In addition to using contracting and similar mechanisms to implement policy measures for our commercial partners, U.S. Government regulators could choose to include these measures in their licensing requirements. It is currently unclear whether regulators have the legal ability to do so at present; the National Space Council-led regulatory reform process should clarify that question by the end of 2022 and may pursue regulatory reforms that would enhance regulators' abilities to include requirements such as these in their licenses and authorizations. If regulators prove able and willing to do so, building these measures into the U.S. regulatory system would have the advantage of applying these measures to purely commercial activities—which NASA cannot directly control—and of reducing the need for NASA to serve as a de-facto "regulator" of our commercial partners.

There may be financial and other costs to implementing the measures recommended in this report. Some place restraints on our own freedom of action, others would require certain technologies to be included in missions, and others would have impacts for our contractors. All of this entails costs: monetary costs but also opportunity costs by restricting our own behavior. OTPS does not have sufficient data to calculate the magnitude of those costs at this time. However, these measures are designed to further U.S. interests—including for safety of our own operations—with the ultimate goal of reducing risk and maintaining freedom of action for NASA and its partners. When considering whether to implement the recommendations contained in this report, all costs and benefits should be considered.

We also recognize that implementing these measures would entail some level of administrative burden within NASA. For example, measures such as landing standoff distances and safety zones would require collection of technical data regarding specific craft and landing and operations sites and engaging in analysis to determine appropriate standoff and safety distances. Likewise, building these measures into mission planning would require taking policy considerations into account in a way that NASA does not routinely do, particularly for science and exploration missions.

Nevertheless, whether or not NASA adopts the recommendations contained in this report or some similar measures, we will ultimately have to address the underlying concerns that motivated these recommendations in the first place. For example, even if we did not implement safety zones as set out in the Artemis Accords and this report, we would still need to respond to safety-of-operations issues posed by proximity operations once multiple actors are operating on the lunar South Pole. If the space community does return to the Moon with overlapping missions, engaging in the kinds of analyses we describe in this report will become a matter of operational necessity. The recommendations in this report are an attempt to regularize this work, ultimately leading to more predictable and safe operations.

It is critical to recognize that these recommendations need not be implemented all at once, or for each mission or activity. It remains unclear how many U.S. and other activities will actually take place on the Moon close in time and space. Early missions, such as the first CLPS missions and Artemis III, are unlikely to be near any other actors and are not planned to go near any existing heritage sites (Apollo and Surveyor). We could choose not to implement these measures unless and until overlapping operations are likely or certain, or to implement these measures piecemeal, adopting only those recommendations that provide substantial benefits or address substantial risks for specific missions and operations.

Certain policy implications of lunar operations will only become pressing when the number of actors and activities in an area increases. For example, early missions will likely be able to proceed without using prepared landing pads, but an increased cadence of landings in vicinity to each other may require a prepared surface to mitigate plume and debris impingement. Likewise, disposal and potential salvage of defunct equipment may be possible on an ad hoc basis for some time, but overarching policies could become beneficial with increasing numbers of missions. Several SMEs have expressed concerns over the "debris field" that will accumulate over time. Inactive assets, especially if in an area of interest, could unintentionally create challenges to overcome. This includes not just surface assets, but also orbital elements that could intentionally impact the surface. Even short-term ad hoc efforts could create negative precedents, so early adoption of policy tools should be considered. Regardless, these tools will have to evolve in step with the evolution of lunar operations.

There may be benefits to implementing some of these measures earlier than a purely technical perspective would deem necessary. For example, the first CLPS mission, planned for later this year, is an Astrobotic contract that would transport the Peregrine One lander to Lacus Mortis, a mid-latitude location far from any other surface operations. Because this lander will be far from any other actors and is in an area we do not anticipate will become crowded over time, we could choose not to implement any of the recommendations contained in this report for this mission. A similar decision could justifiably be made for many other planned missions. However, these same facts mean that policy measures such as safety zones would not actually impose any limitations on other actors should we choose to implement them. Just as we use missions such as this to test technologies for more challenging destinations such as the lunar South Pole, we could also use Peregrine One or similar missions to practice the design and implementation of policy measures such as safety zones in a situation that is relatively low stakes in terms of how we impact other actors.

Ultimately, the decision about whether and how to adopt these recommendations is a policy choice. As a signatory to the Artemis Accords, the United States has committed to using and respecting safety zones and to protecting heritage sites. However, what those commitments mean in practice remains to be determined, and the other recommendations contained in this report are not commitments the United States has ever made publicly. Each of the recommendations contained in this report derives directly from concerns raises by NASA SMEs and respond to specific, technical- and science-based challenges. However, these recommendations do present both pros and cons, and we are not recommending that every measure be taken for every mission. This report is intended to support decisions by policymakers and mission planners, not to dictate those decisions.

Table 15. Implementation: Summary of Options and Rationale.

Options to Supplement Policy Tools	Rationale
For missions over which NASA has operational control, **policy decisions should be communicated to relevant directorates, offices, and programs within the agency,**	Implementation of policy tools varies by NASA's level of operational control—NASA can incorporate

Options to Supplement Policy Tools	Rationale
and processes should be developed to ensure that these actors understand and build the appropriate policy decisions into their plans.	policy tools as needed for missions it more directly controls
For CLPS missions, and other missions operated as a service, NASA should consider working with relevant contracting companies to ensure that they build NASA-determined policy tools into their mission plans.	Implementation of policy tools varies by NASA's level of operational control—NASA may have to consider policy tools on a case-by-case basis to implement desired policy tools into contracts for missions where NASA has less operational control

Part 4: Summary, Conclusions, and Next Steps

The Artemis campaign has already begun with the launch of the CAPSTONE lunar orbiter in June of this year and the imminent launch of SLS. Robotic surface missions will begin in a matter of months, ushering in years of high-cadence, increasingly complex missions to the lunar surface by NASA and commercial and international actors.[88] In addition to the challenges inherent in lunar exploration, this new era raises a number of challenges that require a mix of policy and technical solutions.

4.1 Summary of Findings, Options, and Recommendations

Through our conversations with SMEs, we identified seven categories of challenges to lunar landings and operations. Each set of challenges can be mitigated by policy measures; this report provides (1) policy tools (options and recommendations) to do so, and (2) options to supplement policy tools to increase their effectiveness. These are summarized below.

The measures discussed in this report need not all be implemented simultaneously or for each lunar mission. A practical, evidence-based approach to implementation—focusing on what challenges particular missions face and what policy tools can best mitigate those challenges—is called for as the Artemis campaign continues.

Policy Tools to Address Challenges to South Polar Landing and Operations

Landings

NASA could increase the priority of obtaining PSI measurements when possible. Mission planners should look for opportunities for dedicated PSI measurements spanning more missions or obtain data by indirect means if that is not possible. Data regarding PSIs should be shared publicly, consistent with longstanding NASA practice.

NASA could focus its investigations into this energy flux [from ejected particles] with the goal of identifying standoff distances from landing sites that will reduce the flux to tolerable levels. Mission planners could then refrain from landing craft within that distance from other operations taking place on the lunar surface.

NASA SMEs should consider beginning cooperative PSI prediction, measurement, and safety work with partner agencies and the private sector with the goal of developing “gold standards” for PSI predictions.

After NASA SMEs begin cooperative work with partners to understand PSI risks, NASA could work with those partners to explore the possibility of formal standardization as a long-term goal.

[88] Appendix C

NASA and partners should consider placing a priority on the development of landing and ascent infrastructure, such as prepared landing and ascent surfaces, in areas that are likely to experience multiple operations in close proximity.

Surface Operations

We recommend that for each mission, planners identify and quantify to the extent possible dangers posed by:

- Regolith ejected from the surface as the result of rover travel or other movement
- Pressure vessels during normal operations, at end of life, and in the event of failure
- Shadowing caused by tall structures
- Non-ionizing radiation from all sources
- Ionizing radiation from all sources
- Any chemicals released during normal operations or in the event of failure
- Any other hazards unique to specific hardware or operations (e.g., nuclear power systems)
- Special hazards posed by the nature of the location or terrain (e.g., significant slopes, boulders, dust, surface, or regolith characteristics)
- Damage to instrumentation (i.e., sensors, seismometers, or other instruments that may be damaged due to nearby landings and/or operations)
- Waste disposal

Policymakers could work with mission planners to (a) identify risks that each element of a mission could cause to others using the checklist above, (b) identify risks that other actors might cause to our own operations, and (c) identify a radius or other distance around each activity that can reasonably minimize (but likely not eliminate) those risks.

The design of safety zones could become a standard element of mission planning. Safety zones should be tailored to the specific circumstances of our activities, but also take into account the geographical and other features of the target site (e.g., the presence or absence of ridges, boulders, etc. that could provide physical protection).

Additional steps, such as the creation of protective berms, landing pads, and siting such objects inside craters, could be considered as part of mission planning to minimize the size and need for safety zones.

We recommend that NASA and the U.S. Government respect safety zones or similar tools established by non-signatories.

Moving Across the Lunar Surface

We recommend that mission planners optimize traversable pathways between landing sites and/or other sites of interest. Models can be revisited if and especially when more details on rover capabilities become known. Additionally, the agency could work with international partners whose missions may overlap with or benefit from the identification of these pathways.

The creation and protection of "transit corridors" in the south polar region could be considered.

NASA could (1) identify these corridors, (2) make their locations publicly known, (3) refrain from placing or disposing of equipment or facilities in these corridors (with an exception described in this report), and (4) request other space actors to exhibit the same restraint, at least until our capabilities advance beyond the need to avoid long periods of darkness.

If fixed facilities are deployed in areas where mobile assets are likely to operate, we recommend that they be provided with visual and radio beacons and their locations made publicly known. In all cases, these facilities should be situated so as not to block mobile vehicles, including large, crewed rovers, from transiting the area.

Radio-Frequency Coordination

We recommend that NASA continue engagement with the interagency and continue to rely on the ITU to avoid radio-frequency interference in lunar operations.

Areas with Special Characteristics

We recommend efforts be made to ensure freedom of access for all space actors to this region [the Connecting Ridge] of the Moon, such as by exercising restraint when hardware is disposed in the area and consolidating operations sites when possible while still meeting mission objectives.

We recommend that NASA work with Artemis partners to jointly support UN space resource efforts directed at practical, actionable norms and best practices that support ISRU efforts and sustainable operations.

Unexpected Activities on the Surface

Mission planners could consider including hardware that would allow them to identify and record any unexpected activities in their vicinity.

Human Heritage Protection

We recommend that the 2011 Recommendations be continued and implemented for Apollo and Surveyor sites, and that their recommendations be implemented in commercial and international partnerships as required by law.

We recommend that NASA work with the Department of State and other relevant U.S. agencies and departments to identify which, if any, additional U.S. robotic or human sites warrant heritage protection. Because these sites will be indefinitely protected—and thus generally off-limits for operations—we recommend that NASA exercise extreme restraint in seeking heritage protection for future sites, particularly those in potentially crowded areas such as the south polar region.

We recommend that NASA work with the Department of State to determine whether other nations request heritage protection. Any dispute about the appropriateness of such a designation should be handled through diplomatic channels; if an internationally agreed upon process ultimately develops to identify heritage sites, that process should supplant this informal, diplomatic process.

NASA could work with interagency experts on terrestrial heritage protections and the Department of State to (1) learn best practices for heritage site identification and (2) begin raising this issue in appropriate international fora such as COPUOS and potentially UNESCO.

We recommend applying the recommendations set out in 2011 to heritage sites that are identified anywhere on the Moon, including in the polar region.

We recommend exercising restraint in identifying new heritage sites to minimize criticism and increase the likelihood that other actors will adopt similar protective measures.

Options to Supplement Policy Tools

Transparency

We recommend working with the Department of State to convene a meeting of Artemis Accords signatories—or a subset of them actively involved in lunar operations—to discuss with them policy and related measures that we anticipate using for upcoming lunar missions.

We recommend a full public relations strategy, as well as multiple streams of multilateral engagement, to articulate our justifications for policy measures in order to forestall negative reactions and solidify our behavior as a precedent to be followed rather than a threat to the space community.

Coordination

We recommend working with the Department of State during joint mission planning to ensure that our partners share our views regarding the steps necessary to respond to the challenges and threats described in this report.

We recommend that policymakers work with the Department of State, industry, international partners, and ultimately the broader space community to develop mechanisms for consultation and coordination to deconflict operations on the Moon.

Implementation

For missions over which NASA has operational control, policy decisions should be communicated to relevant directorates, offices, and programs within the agency, and processes should be developed to ensure that these actors understand and build the appropriate policy decisions into their plans.

For CLPS missions, and other missions operated as a service, NASA should consider working with relevant contracting companies to ensure that they build NASA-determined policy tools into their mission plans.

4.2 Known Unknowns

This report is being written before any detailed, on-the-ground exploration of the lunar South Pole has taken place. As missions proceed (particularly VIPER and crewed operations), we expect to fill major gaps in our knowledge. As we answer these questions, policy tools should be adjusted to fit the facts.

One critical question is whether particularly valuable resource deposits exist in certain locations on the lunar surface. Modelling and remote sensing suggest large water ice deposits in certain PSRs, but those projections remain untested; even if remote sensing data is accurate, we are unlikely to learn which deposits can most easily be accessed and used until we have robotic and/or human presence to verify those facts. Early missions may identify particularly valuable or accessible resources; if that occurs, policy tools should be tailored to the characteristics of those resources, building on the criteria and considerations we have discussed in this report.

Other questions depend on human behavior. Although numerous lunar missions are planned by commercial and international actors, it remains to be seen which of those will occur.[89] Of those that do occur, we are unaware whether those responsible will consider their missions to be deserving of scientific or heritage protection, or, conversely, whether other actors will seek heritage protections for their own sites or view certain locations as deserving of special protection that we have not considered.

More generally, the volume of traffic to the Moon and the polar region remains unclear. NASA mission planning continues to evolve, as does that of other actors. Policy measures may need to become more restrictive if traffic becomes heavy; conversely, technical innovations and additional data may allow relaxation of certain restrictions. As we describe in the Implementation section, many of these policy measures may not be operationally necessary until multiple actors are operating in proximity to each other.

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[89] Appendix C

4.3 Revisiting the Recommendations

The options described in this report—and the issue of policy implications of lunar operations generally—should be revisited on an ongoing basis. Additional knowledge will allow better-informed tools and increasing operations will require different measures than will early, intermittent operations. Although many of the options described in this report implement certain legal and political commitments, none of these measures are required to be implemented precisely as described in this report. NASA, the U.S. Government, and commercial and international partners should engage in an ongoing, iterative process of developing and modifying policy tools just as we do technologies.

4.4 Conclusion

This report should not be the end of this conversation. As the Artemis campaign continues, NASA, our partners, and other space actors will gain additional knowledge that should be used to inform further development of these and other policy tools. Likewise, the precise nature, scope, and cadence of lunar missions remains to be seen; policy measures will likely need to be adapted to respond to however crowded the Moon turns out to be, particularly in the south polar region. Identification of particularly valuable sites, such as large deposits of volatiles and/or areas of unique interest should also shape implementation of these tools. Policymakers, mission planners, the scientific community, and the broader international and commercial community should engage on these issues in an ongoing, iterative way to see what works, what doesn't, and what measures are most supportive of sustainable operations.

Appendix A: Terms of Reference

Background

Technical and scientific criteria provide constraints on the availability of landing and operations sites on the surface of the Moon—particularly in the vicinity of the lunar South Pole. In the short term (one to five years), NASA plans to launch numerous missions to the lunar South Pole, as do multiple other commercial and international actors. With multiple operations occurring simultaneously, these activities could interfere with each other and/or create limitations on the ability of others to operate.

In addition to scientific and technical considerations, the choice of landing and operations sites near the lunar South Pole raise a range of other considerations. Because of the relatively small number of useful landing sites that meet particular mission objectives (i.e., those meeting desired technical and scientific criteria), polar sites are a limited resource. Space actors that occupy and utilize these sites could, at least to some extent, displace other actors from those same sites.

NASA may wish to take technical and policy considerations into account in the selection of landing and operations sites in order to, e.g. (1) protect the safety of U.S. Government operations, (2) secure freedom of action for U.S. interests, (3) minimize negative political, international, and public perception repercussions of site choices, and (4) establish and promote international standards. The choice of landing and operations sites, as well our publicly articulated views surrounding those choices, could create a precedent that guides future human exploration of the Moon and other celestial bodies, including Mars and asteroids.

Scientific and technical criteria significantly limit the areas of the lunar surface that could serve as landing and operation sites for U.S. robotic and crewed activities, especially in the vicinity of the South Pole. Particularly important criteria include: persistent line-of-sight to Earth, the nearby presence of permanently shadowed regions (PSRs) that might contain water ice deposits, and the availability of sunlight throughout mission durations. With regard to south polar destinations, ninety-three potential landing sites were identified by NASA directorates and shown to meet these criteria, spread across seven polar regions. Of these, only a very small number are reachable at each mission availability date. Other space actors, such as foreign and commercial actors, are likely to be faced with similar constraints, and therefore likely to focus on many of the same potential sites as NASA. The United States and these other actors may choose to establish safety zones and utilize other policy mechanisms to protect operations in these areas.

Existing international law and norms of behavior provide some guidance. The 1967 Outer Space Treaty provides for freedom of access to all areas of celestial bodies. The Treaty also requires states to give “due regard to the corresponding interests” of other states operating in space. Finally, the

Treaty requires consultations prior to any activities that might create "harmful interference" in the activities of others in space.

The United States and partner nations have built on our Outer Space Treaty obligations with the Artemis Accords, which contain more detailed commitments relating to civil exploration activities. Section 11 of the Accords sets out detailed rules for deconflicting operations amongst space actors. The United States has publicly committed to implementing these rules in our exploration plans. Most importantly, we have committed to (1) refrain from creating harmful interference in the activities of other Signatories and (2) publicly establish "safety zones" around our operations. These zones must be based on publicly articulable needs and must change or terminate as our operations evolve. The Accords state: "The size and scope of [a] safety zone...should reflect the nature of the operations being conducted and the environment that such operations are conducted in; The size and scope of [a] safety zone should be determined in a reasonable manner leveraging commonly accepted scientific and engineering principles." Although we cannot lawfully exclude other actors from areas of the surface, the Accords provide for consultations before any other signatory enters a declared safety zone. With regard to non-signatories of the Accords, the U.S. Government takes the position that the Outer Space Treaty nevertheless requires some form of coordination prior to operating in the vicinity of previous arrivals to a celestial body.

Legal, policy, and technical issues relating to the protection of human heritage in outer space also provide useful guidance, particularly with regard to the issue of safety zones. This project will draw from internal NASA guidance relating to the protection of Apollo sites, the recent One Small Step Act, and international efforts to identify and protect heritage in space.

Goals and Study Questions

This study aims to answer two related questions: (1) what technical and policy considerations should NASA take into account in the selection of lunar landing and operations sites and (2) what technical and policy considerations should NASA take into account when implementing tools such as safety zones in order to protect these operations and U.S. interests?

Although this project will consider a wide range of technical and policy considerations, two issues will receive particular focus: the selection of landing and operations sites and the establishment of safety zones around these locations. Put another way, the core of this project is to help answer the questions: where should NASA operate, and how can we protect those operations?

Scope of Work and Proposed Approach

The scope of this project is limited to recommendations regarding NASA and NASA-sponsored crewed and robotic activities on or around the lunar South Pole, and is limited to relatively early-stage operations, up to the establishment of a persistent human presence.2 The Commercial Lunar Payload Services (CLPS) initiative, Human Landing System (HLS) program, and as-yet-finalized missions will be covered by this scope, so long as they are by, or for, NASA. Activities by purely private sector actors will not be the subject of these recommendations.

Although this project will place special emphasis on operations in the vicinity of the lunar South Pole because scarcity and interference issues are likely to first arise there, the considerations relevant to this inquiry, and the guidance and recommendations that will be developed, will also be helpful in shaping NASA operations in other locations. Although physical differences in celestial bodies will necessarily result in operational differences, the interests, goals, risks, benefits identified, and the recommendations developed here will pave the way to answering these same questions on Mars, in the asteroid belt, and elsewhere.

This project will be conducted in such a way as to develop guidance and recommendations that will lead to publicly defensible operational choices, such as the selection of specific sites on the surface of the Moon and the establishment of safety zones to protect them. The project will begin with a series of meetings with NASA lunar program experts in order to develop a detailed baseline of what is possible and desirable from a programmatic perspective, as well as an understanding of what technical criteria should be used to implement tools such as safety zones. The second phase of the project will be meetings with counterpart space agencies with whom NASA anticipates possible cooperation in lunar missions in order to seek expert-level input on considerations relevant to the goals of the study. OTPS will then develop initial draft guidance and recommendations.

Phase three of the project will be to share the core elements of the guidance and recommendations with outside reviewers, representing a wide range of backgrounds, in order to receive their individual views regarding any problems or omissions with that guidance. Outside experts are expected to include: academic space law and policy experts from Japan, the Netherlands, and the United Kingdom; industry representatives from companies with plans for lunar activities; an academic from the United States focusing on lunar surface operations; members of the intelligence community with expertise in space; and representatives of civil society organizations.

Ultimately, guidance and recommendations that survive scrutiny will be compiled into a report by OTPS. This report will include specific case studies, drawn from currently planned and anticipated operations, in order to demonstrate how guidance and recommendations could be implemented.

Intended Outcomes

Answering these overarching questions will provide guidance to NASA when faced with specific questions such as how many polar sites to operate simultaneously, whether they should give greater priority to geographically strategic sites, whether and when they should defer to other space actors in accessing certain locations, and when and how to implement safety zones.

The project team will work discreetly with international partner space agencies, and international and interdisciplinary experts to provide specific, actionable guidance and recommendations to lunar program managers and NASA leadership.

Deliverables

This study will deliver a brief paper with policy options, their pros and cons, rationale for recommendation, and effects of implementing the guidance and recommendations.

Intended Distribution and Access

The final report is intended to be accessed by OTPS, the Office of the Deputy Administrator, and other stakeholder offices or programs as identified by OTPS and the Office of the Deputy Administrator.

Pending final review by relevant directorates, NASA leadership, and the interagency, a summary of the guidance and recommendations, or decisions that derive from it, could be made available publicly. Decisions about public release and communications strategies should be made only after project completion.

Appendix B: List of Those Consulted

Phase I: Internal Discussions (NASA Lunar Program Leads/Points of Contact and SMEs)

- CASSA - overview
- CASSA - lighting conditions
- CASSA - mission availability
- CASSA - site planning and governance
- CASSA - engagement strategy
- CASSA - hazards and mitigations list review
- Agency-level architecture
- HLS perspective
- CLPS perspective
- VIPER and instrument perspective
- Entry, Descent, and Landing (plume-surface interactions)
- PSI modeling and environments
- OIIR - International Programs

Phase II: External Discussions (Space Agencies)

- United Kingdom Space Agency (UKSA)
- European Space Agency (ESA)
- German Aerospace Center (DLR)
- Luxembourg Space Agency (LSA)
- Italian Space Agency (ASI)
- Japan Aerospace Exploration Agency (JAXA)
- Australian Space Agency (ASA)

Phase III: External Reviews (Cross-Disciplinary Experts)

- China Aerospace Studies Institute
- For All Moonkind
- International Institute of Air & Space Law, Leiden Law School, The Netherlands
- Open University
- Secure World Foundation
- University of Central Florida

Appendix C: List of Near-Term Lunar Missions

Anticipated Lunar Surface Missions in the Near-Term (2022-2026)

*South Pole/South Polar Region landing and/or operations

Note that launch dates may change and additional missions may arise within this timeframe.

Country	Organization	Mission	Launch
U.S.	NASA	CLPS Task Order 2 (Intuitive Machines)†	2022
U.S.	NASA	CLPS Task Order 2 (Astrobotic) †	2022
Japan	JAXA	Smart Lander for Investigating the Moon (SLIM)[90]	2022
Japan	ispace	Hakuto-R Mission 1[91]	2022
India	ISRO	Chandrayaan-3[92]	2022
Russia	Roscosmos	Luna-25[93]	2022*
U.S.	NASA	CLPS Task Order PRIME-1 (Intuitive Machines) †	2023*
U.S.	NASA	CLPS Task Order 19C (Masten Space Systems) †	2023*
India	ISRO	Lunar Polar Exploration (LUPEX), joint JAXA mission, ISRO lander[94],[95]	2023*
U.S.	NASA	CLPS Task Order 19D (Firefly Aerospace) †	2024
U.S.	NASA	CLPS Task Order 20A VIPER (Astrobotic) †	2024*

90 "International Space Exploration," JAXA, accessed June 17, 2022, https://www.exploration.jaxa.jp/e/program/#lunar.

91 "Project," ispace, accessed June 17, 2022, https://ispace-inc.com/project/.

92 "India targets August launch for Chandrayaan-3 lunar lander," SpaceNews, last modified February 3, 2022, https://spacenews.com/india-targets-august-launch-for-chandrayaan-3-lunar-lander/.

93 "Russia aims to rekindle moon program with lunar lander launch this July," Science and Astronomy, Space, last modified February 11, 2022, https://www.space.com/russia-rekindle-moon-program-luna-25-launch.

94 "Global Exploration Roadmap," International Space Exploration Coordination Group, last updated August 2020, https://www.exploration.jaxa.jp/e/program/#lunar

95 "International Space Exploration," JAXA, accessed June 17, 2022, https://www.exploration.jaxa.jp/e/program/#lunar.

Country	Organization	Mission	Launch
U.S.	NASA	CLPS Task Order CP-11 (Intuitive Machines) †	2024
U.S.	NASA	NextSTEP-2 App. H Option A: Uncrewed Demo (SpaceX)[96]	2024*
Japan	ispace	Hakuto-R Mission 2[97]	2024
China	CNSA	Chang'e 6[98]	2024*
China	CNSA	Chang'e 7[99]	2024*
Israel	SpaceIL	Beresheet2[100],[101]	2024
U.S.	NASA	CLPS Task Order CP-12 (RFP in progress) †	2025
U.S.	NASA	NextSTEP-2 App. H Option A: Artemis III Crewed Demo (SpaceX)[102]	2025*[103]
Russia	Roscosmos	Luna-27[104]	2025*
U.S.	NASA	CLPS Task Order CP-21 (Announced) †	2026
U.S.	NASA	CLPS Task Order CP-22 (Announced) †	2026*

[96] "Report regarding NASA Human Landing System Program," Explanatory Statement accompanying FY 2022 Consolidated Appropriations Act (P.L. 117-103), NASA, last modified April 2022, https://www.nasa.gov/sites/default/files/atoms/files/hls_30_day_report_final_041922.pdf.
[97] "Project," ispace, accessed June 17, 2022, https://ispace-inc.com/project/.
[98] "Future Chinese Lunar Missions," Goddard Space Flight Center, NASA, last modified September 3, 2021, https://nssdc.gsfc.nasa.gov/planetary/lunar/cnsa_moon_future.html.
[99] "Future Chinese Lunar Missions," Goddard Space Flight Center, NASA, last modified September 3, 2021, https://nssdc.gsfc.nasa.gov/planetary/lunar/cnsa_moon_future.html.
[100] "Moon Lander," Science and Research, Israel Aerospace Industries, accessed June 17, 2022, https://www.iai.co.il/p/moon-lander.
[101] Israel, UAE to collaborate on Beresheet 2 moon mission," Middle East, The Jerusalem Post, last modified April 30, 2022, https://www.jpost.com/middle-east/article-705511.
[102] "As Artemis Moves Forward, NASA Picks SpaceX to Land Next Americans on Moon," Moon to Mars, NASA, last modified April 22, 2021, https://www.nasa.gov/press-release/as-artemis-moves-forward-nasa-picks-spacex-to-land-next-americans-on-moon.
[103] "NASA Provides Update to Astronaut Moon Lander Plans Under Artemis," Moon to Mars, NASA, last modified March 23, 2022, https://www.nasa.gov/press-release/nasa-provides-update-to-astronaut-moon-lander-plans-under-artemis.
[104] Luna 27," Wikipedia, accessed June 17, 2022, https://en.wikipedia.org/wiki/Luna_27.

†CLPS mission status presented at the Lunar and Planetary Science Conference in March 2022. (Note that PRIME-1, Task Order 19D, Task Order 20A, Task Order CP-12, Task Order CP-21, and Task Order CP-22 have been updated to reflect changes from March 2022 to July 2022.)[105]

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[105] P. B. Niles, "SUMMARY OF THE CONTRACTED DELIVERIES OF NASA PAYLOADS TO THE MOON VIA COMMERCIAL LUNAR PAYLOAD SERVICES (CLPS)," *53rd Lunar and Planetary Science Conference* (2022): https://www.hou.usra.edu/meetings/lpsc2022/pdf/2791.pdf.

Appendix D: Beyond this Project

A Note Regarding Mars

This report focuses on lunar operations because those portions of the Artemis campaign are most well-defined and soonest in time. However, operations on other celestial bodies, such as Mars, raise the same policy challenges as do those on the Moon. The physical characteristics of the Moon and Mars are different in ways that can—and should—affect the details of policy solutions to Mars operations. For example, the presence of an atmosphere on Mars limits travel of debris ejected by landing operations, as does Mars' higher gravity, but that same atmosphere increases the likelihood of cratering by PSIs. Furthermore, Mars is subject to far stricter planetary protection protocols than is the Moon, and those requirements will need to be incorporated into Martian mission planning. Nevertheless, the policy tools described here are suitable for application on Mars, with modifications to suit the characteristics of that planet. As mission plans for Martian operations evolve, questions of policy should be included at each stage of planning and implementation.

Equity and Ethics

Exploration of the Moon and the solar system raises more issues than can be addressed in this report. This report attempts to answer those questions posed by SMD and the Office of the Administrator; those questions are largely technical, scientific, and operational. However, exploration of the Moon—particularly when it involves commercial activities and the possibility of human habitation—also raises issues of ethics and equity. As with any new endeavor, there is a chance that our exploration will interact in complicated ways with human concerns, such as unequal access to resources, geopolitical power dynamics, cultural values, and more. Some of the recommendations contained in this report may have implications for these questions as well.[106] These issues deserve focused attention, and we note that OTPS has ongoing work on social and ethical considerations in other projects, namely, how NASA should operationally consider long-term societal and ethical implications of Artemis. This work can ultimate help support NASA's vision for sustainable and responsible exploration, as robust and transparent ethical dialog helps enable long-term shared visions and public benefit.

[106] None of the recommendations in this report are exclusive to NASA missions. Although this report is intended to guide NASA planning, NASA and the U.S. Government should be willing to respect the same or similar measures taken by other space actors. In that sense, these recommendations are "neutral," but even facially neutral measures can have the effect of amplifying existing inequalities or other features of the status quo.

Appendix E: Acronyms

Acronym	Definition
ASA	Australian Space Agency
ASI	Italian Space Agency
CASSA	Cross-Artemis Site Selection Analysis
CLPS	Commercial Lunar Payload Services
CNSA	China National Space Administration
COPUOS	Committee on the Peaceful Uses of Outer Space
DLR	German Aerospace Center
EL3	European Large Logistics Lander
ESA	European Space Agency
ESDMD	Exploration Systems Development Mission Directorate
EVA	Extravehicular Activity
FCC	Federal Communications Commission
GEO	geosynchronous orbit
HLS	Human Landing System
HSM	Human Surface Mobility
ISECG	International Space Exploration Coordination Group
ISO	International Organization for Standardization
ISRO	Indian Space Research Organization
ISRU	in-situ resource utilization

Acronym	Definition
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
ITU	International Telecommunication Union
JAXA	Japan Aerospace Exploration Agency
LSA	Luxembourg Space Agency
LSITP	Lunar Surface Instruments and Technology Payloads
LUPEX	Lunar Polar Exploration
NASA	National Aeronautics and Space Administration
NTIA	National Telecommunications and Information Administration
OIIR	Office of International and Interagency Relations
OTPS	Office of Technology, Policy, and Strategy
PSI	plume-surface interaction
PSR	permanently shadowed region
RFI	radio-frequency interference
RFP	request for proposals
SCALPSS	Stereo Cameras for Lunar Plume-Surface Studies
SLIM	Smart Lander for Investigating the Moon
SLS	Space Launch System
SMD	Science Mission Directorate
SME	subject matter expert
STMD	Space Technology Mission Directorate

Acronym	Definition
TOR	Terms of Reference
UKSA	United Kingdom Space Agency
UN	United Nations
UNCOPUOS	United Nations Committee on the Peaceful Uses of Outer Space
UNESCO	United Nations Educational, Scientific and Cultural Organization
VIPER	Volatiles Investigating Polar Exploration Rover