The Relevance of the VIPER mission to NASA's Artemis human exploration of the Moon

Short title: VIPER Relevance to Artemis

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Abstract

NASA has ambitious plans to send astronaut crews to the south polar region of the Moon and explore this lunar terrain with humans for the first time through a series of Artemis missions. Artemis will provide economic benefits, drive technological advancement, and inspire the next generation of explorers. Simultaneously, Artemis presents a unique opportunity for humans to conduct high-priority planetary science in situ in the south polar region of the Moon. Prior to human exploration, landed robotic precursor investigations can provide valuable information to reduce risk and maximize discovery and productivity of subsequent crewed missions. NASA's Volatiles Investigating Polar Exploration Rover (VIPER) is a robotic mission designed to explore and characterize the lunar south polar region prior to crewed Artemis landed missions. VIPER is designed to explore multiple thermal regimes to characterize the lunar polar environment and regolith properties, and to explore for surface and subsurface ices. Each of these objectives are key for both scientific investigation and to detect and assess volatile deposits to support in situ resource utilization (ISRU) and a sustained human presence on the Moon. VIPER would also operate with a real-time mission operations architecture with relevance and feed-forward to Artemis crewed operations on the lunar surface. VIPER would provide key information regarding the lunar environment, scientific exploration, technologies, and real-time operations to optimize the valuable surface exploration time of Artemis crew members while simultaneously reducing risk to crew and increasing health and human safety on the lunar surface.

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1. INTRODUCTION

1.1 NASA's Artemis Missions

NASA's Artemis missions will lead humanity back to the Moon for the first time since the end of the Apollo program in 1972, in preparation for the next giant leap, the exploration of Mars. Artemis focuses on sending humans to the lunar surface through the Foundational Exploration (FE) set of missions while simultaneously working toward a Sustained Lunar Evolution (SLE) campaign segment to expand economic activities, increase utilization (including science), and enable higher levels of participation in activities on and around the Moon (NASA M2M 2024). To do so, NASA has planned a series of bold missions which will carry humans to the south polar region of the Moon with increasing capabilities. Through Artemis, NASA will provide economic benefits, drive technological advancement, and inspire the next generation of explorers. Simultaneously, Artemis presents a unique opportunity for humans to conduct high-priority planetary science and other activities in situ in the south polar region of the Moon.

Here we present the main characteristics of Artemis, including the early Artemis missions and the current vision for a sustained human presence on the Moon, demonstrating the relevance of the VIPER mission to NASA's plans for the human exploration of the Moon.

2. BACKGROUND

2.1 The Early Artemis Missions

2.1.1 Artemis I

The Artemis I mission was an uncrewed integrated test flight of the major components of NASA's Deep Space Exploration Systems, which includes the Orion capsule and the Space Launch System (SLS) rocket. Artemis I was launched from NASA Kennedy Space Center on 16 November 2022 with NASA's SLS rocket (Figure 1). Atop SLS was the Orion capsule developed by Lockheed Martin which will serve as the crew vehicle on subsequent Artemis missions. SLS is a super-heavy-lift rocket capable of launching Orion, crew, and cargo to the Moon in a single launch. The Orion capsule is designed to carry astronauts from Earth to space, provide abort capabilities in case of emergency, and provide re-entry capability for crew return to Earth. The Artemis I mission lasted 25 days, 10 hours, and 53 minutes and traveled 1.4 million miles with splashdown on 11 December 2022. The mission was successfully executed as planned, except for an unexpected char loss across the Orion capsule's heat shield. A NASA investigation discovered that gases generated inside the heat shield's ablative outer material (Avcoat) were unable to vent and dissipate as expected, which resulted in charred material breaking off in different locations. Nonetheless, flight data recorded acceptable temperatures within limits inside the Orion's crew cabin. With this increased understanding of the thermal protection system performance from the Artemis I test flight, NASA has concluded that crew will be safe using the current Artemis II heat shield with operational changes to entry (NASA 2024a).

Figure 1. Artemis I launch on 16 November 2022 from Launch Complex 39B at NASA's Kennedy Space Center in Florida. Photo credit: NASA/Joel Kowsky.

2.1.2 Artemis II

The Artemis II mission is a crewed mission planned for launch in 2026. Four astronauts have been named to the Artemis II crew (NASA astronauts Christina Koch, Victor Glover, Reid Wiseman, and Canadian Space Agency astronaut Jeremy Hansen) and will fly a 10-day mission around the Moon to test and demonstrate the capabilities required to embark on Artemis missions to the lunar surface. Artemis II will launch on the SLS and crew will fly in the Orion capsule for the first time to confirm that the spacecraft systems operate with crew within the deep space environment.

The Artemis II mission will fly a specific mission trajectory profile. After being launched by the SLS, the Orion capsule will perform several maneuvers to raise its orbit around Earth and ultimately place the crew on a lunar-free return trajectory where Earth's gravity will pull Orion back to Earth after flying by the Moon. During the flight, the crew will test and demonstrate multiple vehicle and spacecraft systems including, but not limited to, life support systems, communication and navigation, propulsion, and executing and evaluating Earth departure and return operations, emergency procedures, and radiation shelter testing. The crew will also have the opportunity to collect scientific observations of the lunar surface (including viewing certain regions of the lunar far side for the first time with humans) and contribute to planetary science investigations. Through this mission, the Artemis II crew will travel ~4,600 miles beyond the far side of the Moon, providing a unique vantage point of the Moon with the Earth 250,000 miles away.

2.1.3 Artemis III

Artemis III will be the first Artemis mission to send crew to the lunar surface. Artemis III will have four crewmembers. Two crew members will land in the south polar region of the Moon while the two other crew members will remain in lunar orbit. Artemis III will also launch on the SLS rocket, and the crew will lift off from Earth in the Orion capsule. Upon completion of the translunar injection maneuver, Orion will be set on a trajectory towards the Moon's gravitational field. Orion will then perform the required engine burns to place the vehicle in a lunar Near-Rectilinear Halo Orbit (NRHO). The NRHO has the benefits of being gravitationally balanced between the Earth and Moon and orbital stability can be achieved with minimal delta V, thus maximizing fuel efficiency. The NRHO has an elliptical orbit with a closest approach to the Moon at an altitude of 3,000 km and apogee of 70,000 km. The orbital plane is vertical to Earth, so this configuration also provides near-constant communication ability with Earth as terrestrial ground stations are always visible from the NRHO. In addition, the apolune point is towards the south, meaning that time is maximized for visibility with the lunar south pole and the location of the Artemis landings (Kikuchi et al. 2024).

Artemis III will deliver two crew members to the lunar surface via the SpaceX Starship lander, which serves as the Artemis III Human Landing System (HLS). Orion will dock with Starship in the NRHO and two crewmembers will transfer from Orion to Starship while the other two crewmembers will remain in Orion. Starship and Orion will undock and Starship will descend and land on the lunar surface (Figure 2). The Artemis III landed crewmembers will conduct extravehicular activities (EVAs) on the lunar surface with strategic science goals (Denevi et al. 2025) and complete surface operations within ~6.5 days (roughly the length of one orbit by Orion around the Moon in the NRHO). Upon completion of the surface phase of the mission, the crew will launch from the lunar surface in Starship to rendezvous with Orion, transfer back into the Orion capsule, and complete the return to Earth journey with Orion splashdown in the Pacific Ocean.

Figure 2. Artist's concept of the Starship lander on the lunar surface. Image credit: SpaceX, NASA.

2.2 Artemis IV and Beyond

2.2.1 Artemis IV

NASA's Artemis campaign is planned to extend beyond the initial three missions. Additional Artemis flights will bring astronauts to the lunar surface for extended science and exploration activities, increased ability to survive and thrive off-planet, and ultimately to develop a sustained lunar presence. Artemis IV is currently planned to launch from Earth via SLS and Orion and will be the second Artemis crew to land on the Moon. The human landing architecture will be different than for Artemis III. On Artemis IV, a SpaceX Starship will dock with the lunar Gateway (a small multi-purpose space station in orbit around the Moon on the Near Rectilinear Halo Orbit, NRHO), allowing crew to transfer from the Orion capsule to HLS, which will then descend to the lunar surface. Upon completion of surface activities, the crew will launch from the Moon in the Starship, dock with the Gateway, transfer to the Orion capsule, and prepare for the return journey to Earth.

2.2.2 Artemis V

Artemis V will operate in a similar matter than Artemis IV and will and will include advanced capabilities such as the Lunar Terrain Vehicle (LTV). The LTV will be developed by the private sector under contract to NASA and will provide extended mobility for astronaut crews and the opportunity for teleoperation when crews are not present on the lunar surface. These concepts of operations will maximize the scientific and exploration productivity of the LTV asset on the Moon. Artemis V will also mark the first use of Blue Origin's Blue Moon lander to bring astronauts to the lunar surface. Subsequent missions will continue to build capabilities to support longer stays on the lunar surface, thereby leading to a phase of sustained exploration (SE).

2.3 Sustained Human Exploration

NASA's Moon to Mars Architecture outlines the exploration goals and roadmap to develop a campaign of Artemis missions to achieve more complex exploration objectives over time (NASA M2M 2024). Artemis is envisioned to begin with Foundational Exploration (FE) missions to test and demonstrate the fundamental technologies and capabilities needed to enable both robotic and crewed missions to the Moon and Mars. The FE phase of Artemis will be followed by the Sustained Lunar Evolution (SLE) phase. SLE will include increased scientific and exploration capabilities coupled with increased commercial activities at the Moon, which will allow NASA to look forward and focus on the next frontier(s) (NASA M2M 2024). The Moon to Mars architecture highlights the goal of "sustained human presence and exploration throughout the solar system" (NASA M2M 2024).

As a long-term goal of Artemis, sustained exploration is a key tenet that must be integrated into mission planning at the outset of Artemis campaign planning. The National Academies for Science, Engineering, and Medicine (NASEM) Decadal Survey report for Planetary Science and Astrobiology defines sustainable exploration as meaning "there are widely accepted reasons to continue human lunar exploration that justify the continued investment, commitment, and risk beyond a few missions" (NASEM 2022). Example reasons for a sustained lunar program are cited as continued scientific discoveries, investing in commercial development, technology development, educating the next generation of technical professionals and ensuring a scientifically literate public, and inspiring the public about these opportunities and future in space (NASEM 2022).

2.3.1. In Situ Resource Utilization (ISRU)

In Situ Resource Utilization (ISRU) near the sites of robotic and/or crewed missions may enable sustainable and affordable exploration of the Moon and Mars. NASA defines ISRU systems as the group of capabilities dealing with estimating resource reserves and harvesting these resources to generate products (e.g., consumables, feedstocks for manufacturing and construction) on other planetary bodies or environments. ISRU will further the goals of a project or mission while reducing the reliance on Earth-based resources and make space missions more sustainable and cost-effective (NASA M2M 2024).

For the Moon, the use of water ice to produce mission consumables has been identified as a critical capability to enable a sustained exploration program. However, our current understanding of the nature and extent of this water resource is not adequate for ISRU architecture planning and engineering design (Kleinhenz et al. 2020). To this point, water has been identified as a resource, but its use for ISRU requires characterizing a water reserve. Key to using space resources is knowing their location, quantity, distribution, and extractability. By adopting proven terrestrial methodologies for lunar resource exploration, the ability to detect and assess water ice deposits has been identified. Before lunar ISRU water and/or volatile mining hardware can be designed, built, or tested, ground truth information is required. Specific knowledge required includes water content as a function of depth and areal distribution (heterogeneity), form of sequestered water, physical and mineral characteristics of regolith at mineable depths, topography and rock size distributions at potential mining infrastructure locations, and PSR environmental conditions (Kleinhenz et al. 2020).

NASA’s Moon to Mars planning includes ISRU elements for both planetary bodies. The Moon to Mars sub-architecture element related to ISRU systems cites the objective to “extract resources in space or on the Moon or Mars to generate products" (NASA M2M 2024). In addition, plans for Mars call for infrastructure elements to “(d)evelop the power, communications, navigation, and resource utilization capabilities to support initial human Mars exploration” (NASA M2M 2024).

The NASA Architecture Definition Document (ADD, NASA M2M 2024) considers the objectives outlined in the Moon to Mars strategy (NASA M2M 2024) and breaks these down into functions and use cases to provide more detail on these topics and inform implementable programs and projects (NASA M2M 2024). Several gaps are identified in the ADD related to "In Situ Resource Identification, Characterization, and Mapping". Specifically, the ADD states that "(c)urrent knowledge of lunar and martian resources is insufficient to ensure the success of ISRU operations that will support human exploration" (NASA M2M 2024, page 440). The current state of the art capability to address this gap is identified by the ADD as "VIPER site selection tools and onboard instruments", highlighting the importance of VIPER for enabling future long-term human exploration (NASA M2M 2024, page 440). An additional gap titled "Water recovery from lunar regolith/ice" is identified in the ADD further supports that water is the primary demonstration target to enable a sustained lunar presence using ISRU (NASA M2M 2024, page 441).

2.3.2 Robotic precursor for human exploration

Robotic precursors are missions carried out prior to human missions to planetary destinations, including the Moon (Foing 2005). Precursors have the potential to significantly increase scientific and technical return from the subsequent planetary exploration missions conducted by humans as well as increase the safety of astronaut explorers by characterizing the off-world operational environment (Hodges and Schmitt 2011; Fong et al. 2013; Dobrea et al. 2025). Although orbital missions (e.g., Lunar Reconnaissance Orbiter, Mars Reconnaissance Orbiter, etc.) collect remote sensing data and produce a wide variety of high-quality maps and data products, this information is limited by remote sensing constraints pertaining to available orbital sensor types and resultant data resolution. Instead, instruments carried by robotic precursors (e.g., planetary rovers) can provide complementary observations of the surface and subsurface at resolutions and viewpoints not achievable from orbit. This surface level data can then be used to improve planning for subsequent human sorties and missions.

Robotic scouting (or robotic reconnaissance) can employ remotely operated planetary rovers to scout planned sorties prior to human extravehicular activity (Bualat et al. 2011; Hodges and Schmitt 2011). Scouting can be: (1) traverse-based (observations along a route); (2) site-based (observations within an area); (3) survey-based (systematic collection of data); and/or (4) "pure reconnaissance" (i.e., focused solely on information gathering). Robotic scouting for human missions differs from current practice with planetary rovers (e.g., Mars rover missions). In particular, rather than using robots as primary science instruments, robotic scouting focuses on using robots to collect "actionable" data to plan and coordinate subsequent human activity. Consequently, the concept of operations (conops), ground data systems, human-robot teamwork and task work, and mission operations must all be designed differently for scouting missions.

Numerous field studies have been conducted in planetary analog sites and have demonstrated that robotic scouting improves human missions in multiple ways (Bualat et al. 2011; Deans et al. 2009; Fong et al. 2010; Dobrea et al. 2025). First, robotic scouting results in increased scientific understanding such that more efficient and productive traverse plans can be produced and executed by the astronaut crews to optimize science and exploration return. Precursors also reduce operational risk by evaluating routes, terrain hazards, and site accessibility prior to human arrival. Precursor knowledge also improves crew productivity by facilitating situational awareness and understanding of site context. Ultimately, robotic precursor missions provide critical knowledge to inform architecture development and decision-making for human exploration missions (Korsmeyer et al. 2010).

We should note, however, that for robotic precursor missions to be effective, there must be good coordination between the work that robots perform and the subsequent work that humans will carry out afterwards (Deans et al. 2009). Specifically, the efficiency, productivity, and benefit of robotic operations are highly coupled to the robot's capabilities. Thus, human mission planning needs to involve consideration of not only what humans will do (e.g., in EVA) but also what precursor robotic missions can (and cannot) achieve, including activities that cannot be conducted by humans for a variety of reasons (risk, schedule, capability, etc). Moreover, it is important to understand that orbital remote sensing, robotic scouting, and human fieldwork are complementary and interdependent. Each of these provides different types of data, viewpoints, and resolution. Individually none of these exploration methods alone is sufficient to fully explore planetary surfaces. However, by using all three methods in combination, we can improve the coverage, completeness, and quality of observations and measurements.

3. VIPER Mission Overview

NASA's VIPER mission is the first step towards enabling sustainable human exploration of the Moon. VIPER will provide critical ground truth data and develop predictive capabilities to understand lunar volatile distributions, abundances, compositions, and key characteristics that are important for both science and enabling ISRU. VIPER includes a rover-mounted payload suite that

(1) can locate surface and shallow subsurface volatiles, (2) excavate and analyze samples of the volatile-bearing regolith, and (3) demonstrate the form, extractability and usefulness of the materials. VIPER's primary mission goal is to characterize the distribution of water and volatiles across a range of thermal environments (Colaprete et al. 2025a, this issue).

To achieve these objectives, VIPER will rove and provide in-situ measurements and data of lunar polar environments analogous to those that will be explored by Artemis astronauts on the lunar surface. Such precursor data is especially important since we have never explored the unique environments of the lunar polar regions before with humans. VIPER will provide human-scale information that is otherwise non-existent to inform Artemis hardware designs, operational procedures, and scientific investigations. For longer term Artemis mission planning, VIPER will provide critical information to detect and assess potential volatile resources to enable ISRU and a sustained human exploration of the Moon and beyond (Colaprete et al. 2025a, this issue).

3.1 VIPER Mission Elements

3.1.1 Science Goals

VIPER will address high-priority science questions while simultaneously providing critical information for exploration needs and to enable ISRU (Colaprete et al. 2025a, this issue). Science questions including the age, origin, and evolution of lunar polar volatiles have been identified within multiple guiding documents, including the National Academies Decadal Survey for Planetary Science and Astrobiology (NASEM 2022). NASA's Moon to Mars Objectives planning document identifies the Lunar and Planetary Science Goal to "(r)eveal inner solar system volatile origin and delivery processes by determining the age, origin, distribution, abundance, composition, transport, and sequestration of lunar and martian volatiles" (NASA M2M 2022). The NASA Artemis III Science Definition Team Report includes the objective of "Understanding the character and origin of lunar polar volatiles" (A3SDT 2020). Specific Artemis III goals regarding lunar polar volatiles science are shown in Table 1, all of which VIPER will contribute understanding. To address these science questions, VIPER will improve our understanding of the spatial distribution, physical state, and composition of surface and subsurface volatiles at meter and sub-meter scales unachievable from orbit, the relationship between the distribution and forms to environmental context (e.g., temperature, topography, geologic setting), and the type and interactions of volatile reservoirs, sources, and sinks.

A3SDT Objective 2 Understanding the Character and Origin of Lunar Polar Volatiles
Goal 2a: Determine the compositional state (elemental, isotopic, mineralogic) and compositional distribution (lateral and with depth) of the volatile component in lunar polar regions.
Goal 2b: Determine the source(s) for lunar polar volatile deposits.
Goal 2c: Understand the transport, retention, alteration, and loss processes that operate on volatile materials near and at permanently shaded lunar regions.
Goal 2d: Understand regolith modification processes (including space weathering), particularly deposition of volatile materials in the near-surface.
Goal 2e: Learn how water vapor and other volatiles are released from the lunar surface and migrate to the poles where they are adsorbed in polar cold traps.
Goal 2f: Understand the impact of exploration on the lunar volatile record across the surface.

Table 1. NASA Artemis III Science Definition Team (A3SDT) Report science objectives pertaining to lunar polar volatiles.

3.1.2 Mission Area

VIPER's landing site and mission area is located on Mons Mouton, a flat-topped topographic rise in the nearside south-circumpolar region, west of Nobile crater. The mission area is centered at 31.6218°E, 85.42088°S, and offers access to all relevant thermal environments and ice stability regions, while enabling Direct-to-Earth communication and benign terrain suitable for rover traverses (Figure 3; see also Shirley et al. 2025, this issue; Beyer et al. 2025a, this issue).

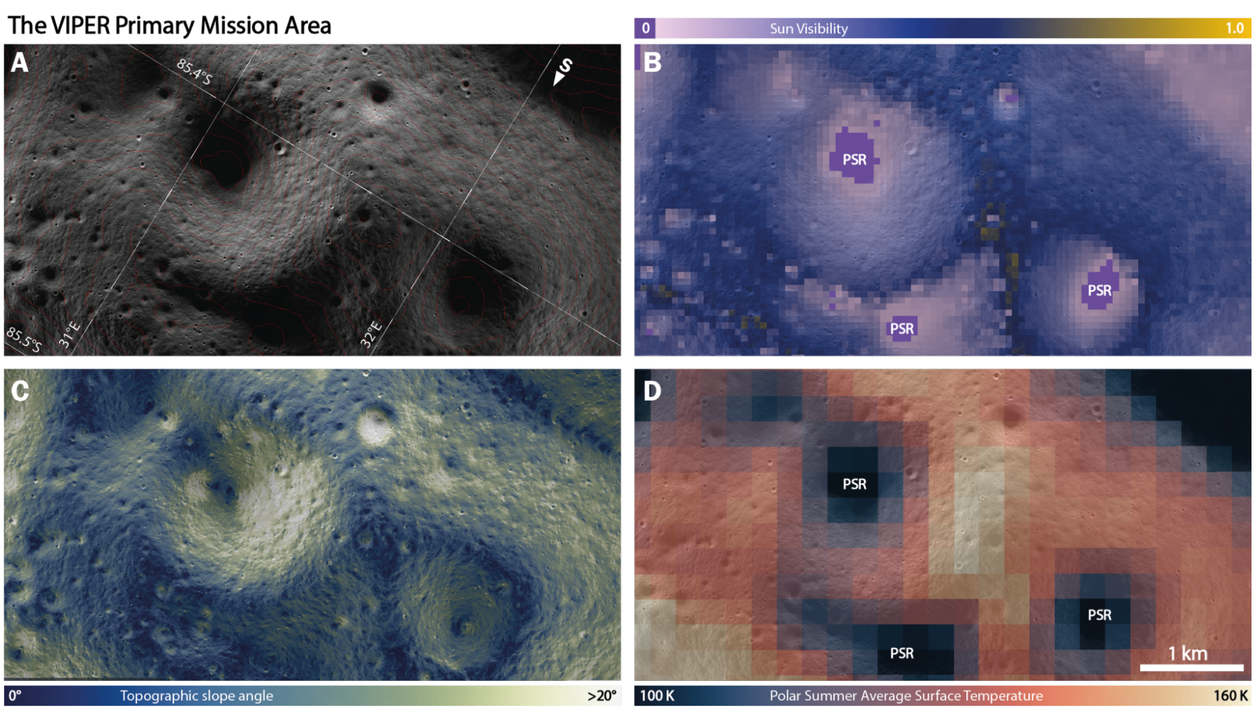

Figure 3. Overview of the VIPER Primary Mission Area (~5 × 4 km) in a Moon 2000 polar stereographic projection: A) LRO NAC mosaic, direction to south pole indicated by white arrow; B) Sun visibility, yellow colors denote regions with nearly constant illumination, light-violet colors denote regions with near-permanent shadow, dark-violet colors indicate permanently shadowed regions (PSRs); C) Topographic slope angle; and D) Diviner polar summer average surface temperature (pixel scale ~240 m). Please refer to Shirley et al. (2025, this issue) and Beyer et al. (2025a, this issue) for additional details about the VIPER landing site.

3.1.3 VIPER Payload

The rover payload is specifically tailored to measure volatiles, regolith, and environmental conditions. Specifically, the prospecting instrument suite, whose focus is on the identification of the form, character, abundance, and location of hydrogen-bearing and other volatiles, consists of a neutron spectrometer (NSS) (Elphic et al. 2025, this issue), a near infrared spectrometer and thermal radiometer (NIRVSS) (Colaprete et al. 2025b, this issue) and a mass spectrometer (MSolo) (Aguilar et al. 2025, this issue). These instruments operate continuously during rover driving operations. In addition, when the rover is stopped, a 1-meter drill (TRIDENT) (Zacny et al. 2025, this issue) can excavate the lunar subsurface in ten-centimeter "bites" for direct examination by NIRVSS and MSolo. Eight visible cameras (VIS) (Beyer et al. 2025b, this issue; Edwards et al. 2025, this issue) affixed to the rover body are not only used for rover driving and hazard avoidance, but also provide data on topography and rover-surface interactions (e.g., wheel tracks). Accelerometers within the rover's inertial mass unit (IMU) are used during driving to measure small changes in gravity to assess sub-surface content and as a seismometer during drilling with the drill as a direct source of seismic energy (Fernando et al. 2024). The rover's unique actuated suspension mobility system, primarily designed for improved slope climbing and passive obstacle traverse stability, can provide regolith geotechnical properties such as bearing capacity and shear strength (Rezich et al. 2025, this issue). Table 2 summarizes the key measurement capabilities for each instrument. Together, VIPER, including the rover and instruments suite, is a powerful payload for planetary science and exploration objectives.

			Volatiles			Regolith Properties			Environmental Conditions/ Context			
Instrument	**Measurement**	**Observations**	**Form/State**	**Abundance**	**Distribution**	**Bulk mechanical**	**Thermophysical**	**Composition**	**Geological Context/History**	**Lighting**	**Temperature**	**Dust**
MSolo	Mass spectra of gaseous species between 1-70 amu	Subliming surface volatiles along traverse and from drill cuttings pile; Key isotope ratios	X	X	X			X				
NIRVSS-AIM	Seven LED color imaging (2048x2048 pixel max resolution) over 348-940 nm	Context imaging below rover along traverse; surface morphology; high resolution imaging (<100 µm/pixel) at drill sites		X		X		X				X
NIRVSS -LCS	Thermal radiometry at 10, 14, 18 and 6-25 µm	Surface temperatures below rover <100 K				X	X				X	
NIRVSS-Spectrometer	Near infrared (NIR) reflectance spectra 1300-4000 nm	Surface composition (mineralogy, hydration, frosts) along traverse and from drill cuttings pile	X	X	X			X				X
NSS	Thermal & epithermal neutrons	Water Equivalent Hydrogen (WEH) and burial depth along traverse	X	X	X							
TRIDENT	Excavation subsurface material in 10 cm increments down to 100 cm; Subsurface temperatures at 2 depths (separated by 20 cm)	Regolith geomechanical properties, including discerning ice-rich from dry regolith; Subsurface temperatures and thermal conductivity	X	X	X	X	X				X	
VIS	Imaging at one color, with resolutions ~1 cm out to 10m; Stereo imaging	Surface morphology, rock & crater morphologies and distributions				X			X	X		X
Inertial Measurement Unit (IMU)	Gravimetry via 3-axis linear accelerometry while driving; Seismic observations while drilling	Subsurface temperatures and thermal conduction	X	X	X	X	X		X			
Rover Mobility Subsystem (RMS)	Mobility performance (drive, steering, suspension actuators; torque transducer)	Regolith geotechnical/mechanical properties along traverse; provides mobility for mapping				X						X

Table 2. Mapping of VIPER payload to science and exploration measurements.

3.1.4 VIPER Concept of Operations

The VIPER concept of operations (conops) utilizes a real-time operations model where tactical operational decisions are made on short (minutes or less) timescales (Colaprete et al. 2025a, this issue). VIPER is intentionally designed to capitalize on data collected by the rover payload suite to inform subsequent rover operations including, but not limited to, rover traverse plans, observation and data collection opportunities, and drill sites (Lim et al. 2024). The VIPER Science Team (VST) plays a key operational role by analyzing and synthesizing rover data in real-time to provide recommendations during surface mission operations. The rapid speed of data synthesis and VST determinations of operational recommendations during the mission necessitate the ability to view and analyze rover data in real-time as well as track and maintain situational awareness of science findings and observations over the course of the mission. Specific tools, operational procedures, and communications protocols have been developed for VIPER to enable the rapid inputs from the VST to directly influence rover operations (Lim et al. 2025, this issue). The VST operational recommendations are critical for optimizing VIPER science and exploration return for enabling ISRU. The VST, located in the Mission Science Center (MSC), is responsive to the tactical operational cadence of the Mission Operations Center (MOC) with direct lines of communication between the MSC and MOC (Mirmalek et al. 2025, this issue). The coordination of the MSC and MOC necessitates pre-planned traverses and operational plans but must also include operational flexibility to be responsive to new discoveries and associated changes to the operational plan in real-time. In addition to the tactical operational inputs, the VST also provides strategic and Long-Term Planning (LTP) guidance to the mission (Lim et al. 2024).

4. VIPER’s Relevance as a robotic precursor to Artemis human missions

There is high value in collecting in situ knowledge of extraterrestrial environments and gaining operational experience in an off-world location prior to sending humans. Such robotic precursor missions serve to mitigate risks and provide critical data not otherwise obtainable to drive mission element designs and operations to reduce risk and maximize crew and vehicle safety. In addition to increasing the safety posture of the crewed mission, robotic precursors are valuable to inform surface operations and optimize scientific investigation by humans at the planetary destination. Prior to the Apollo crewed landings on the Moon, NASA developed and flew the Ranger and Surveyor robotic programs to the lunar surface to gain in situ knowledge of the lunar surface and ambient environment as well as gain operational flight experience on the lunar surface (Schurmeier et al. 1966; Kloman 1972; Hall 1977; Kring 2015). Since these missions targeted regions in the lunar equatorial regions, VIPER provides the opportunity to provide key data in the largely uncharacterized lunar polar regions which experience significantly different environmental conditions compared to the Ranger, Surveyor, and Apollo near-equatorial landing sites. Below we outline several key areas where VIPER's in situ measurements can provide important information for subsequent crewed Artemis missions. The following sections present VIPER's key contributions to the Artemis program.

4.1 Lunar Polar Volatiles

The lunar polar regions are unique on the Moon due to the expected presence of volatile species contained within polar cold traps. Due to the low angle between the Moon's rotational axis and the normal to the ecliptic plane combined with the low inclination of the Earth's orbit around the Sun and the lunar topography, permanently shadowed regions exist at both poles of the Moon and are among the coldest regions in the Solar System (Arnold 1979; Bussey et al. 2003; Feldman et al. 2001; Vasavada et al. 1999; Hayne et al. 2015; Sanin et al. 2017). The low temperatures of these PSRs, as well as within the shallow subsurface of transiently shadowed regions (TSRs), make these areas prime candidates for cold traps where volatile species can be stable against sublimation for billions of years (Vasavada et al. 1999; Siegler et al. 2016).

Temperature is a key criterion for determining which volatile species can be sequestered in a region. Figure 4 shows volatile species that are stable over geologic time as a function of temperature. Colder temperatures trap more species of volatiles, and hence the cold conditions in TSRs and PSRs in the lunar polar regions present the opportunity to trap these volatiles if and when they were delivered to or released on the Moon. VIPER will interrogate multiple Ice Stability Regions (ISRs) of varying temperatures and measure the distribution and abundances of these species (Colaprete et al. 2025a, this issue), not only providing in situ data regarding lunar polar volatiles, but also developing resource models with predictive capabilities to tie remote sensing data to VIPER ground truth (Coyan et al. 2025, this issue) and thereby more accurately understand and predict expected volatile deposits in regions not visited by VIPER, such as Artemis landing sites.

VIPER measurements of volatile compositions, abundances, and distributions will also be used to inform assessments and planning for astronaut crews in terms of human health and safety. The only confirmed occurrence of polar volatile compositions comes from NASA's LCROSS (Lunar Crater Observation and Sensing Satellite) mission, which identified small quantities of volatile species within the PSR of Cabeus Crater that may be of interest for human health and safety (Colaprete et al. 2010). The importance, or lack thereof, of these species in terms of human health should be better understood which is only possible with ground truth measurements. Measurements in regions more representative of the locations where Artemis astronauts will be exploring are also needed. The LCROSS site within Cabeus Crater represents a doubly-shadowed deep PSR region with among the highest levels of hydrogen (a proxy for volatile content) anywhere on the Moon (Colaprete et al. 2012). Indeed, the high levels and variety of trapped volatiles was a key reason this site was selected for LCROSS. In contrast, the candidate Artemis landing regions identified by NASA (NASA, 2024b) do not contain such large and cold PSRs. Instead, these regions have smaller and likely younger thermal environments that likely have not trapped the concentrations or variety of volatile species observed with LCROSS. Therefore, more relevant ground truth data is required, such as will be collected by VIPER, to robustly assess, mitigate, or reduce risk for human interaction with any volatile materials.

VIPER data will also inform safety concerns regarding volatile sampling and curation for Artemis missions. Artemis III will not utilize a freezer for sample return, and thus samples will warm to ambient temperatures upon return to Earth. Any volatiles or ices collected will degas within sample containers, and constraining the expected amounts of headspace gases produced and associated sample container pressures can help alleviate concerns over volatile leakage and crew exposure. Indeed, it is possible that the volatile contents of samples will be so low that the greater concern is cabin atmosphere leaking into the sample containers, thereby compromising the scientific integrity of the samples.

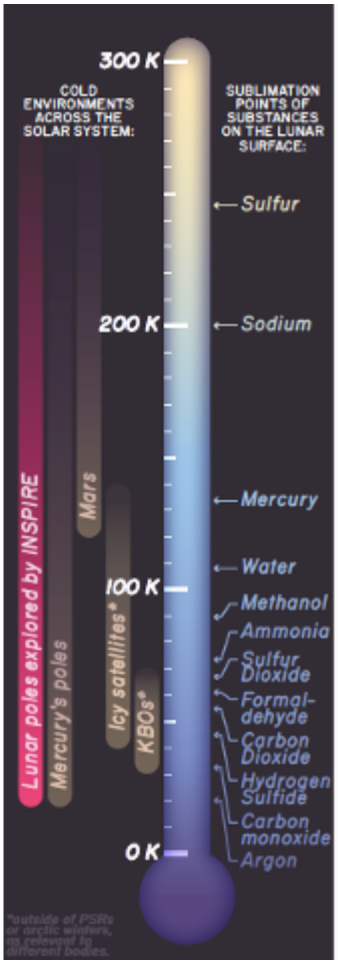

Figure 4. Thermometer shows the temperatures at which various volatile species are stable over geologic time defined as ices that would be lost to sublimation at a rate of less than 1 kg m^2 per billion years. To the left, the temperature ranges of various targets are noted, including the lunar poles, Mercury's poles, Mars, icy satellites, and KBOs. Graphic courtesy James T. Keane, NASEM Decadal Survey (2022).

VIPER will also provide critical information to enable ISRU on the Moon. VIPER will detect, assess, and characterize lunar polar volatile deposits to provide the key information required to plan ISRU activities, hardware, operations, and utilization. This methodology follows the blueprint developed by over a century of resource assessment and utilization on Earth. Best practices on the methodology for resource assessments state that "the assessments should be based on as comprehensive a set of geological and exploration history data as possible" (Charpentier and Klett 2005). VIPER is intentionally designed to "demonstrate the form, extractability and resource potential" of volatile deposits on the Moon (Colaprete et al. 2025a, this issue).

In addition, micro cold traps are ubiquitous within the lunar polar region and hence in all the candidate Artemis landing regions identified by NASA. Micro cold traps can range in size from ~10 cm to 100 m and are the most numerous cold traps on the Moon (Hayne et al. 2021). The distribution and sizes of micro cold traps are dictated by the small-scale lunar topography coupled with the inherent low sun angle at the lunar poles. The lack of direct sunlight creates these thermal regions that are cold enough to sequester volatile species (see Figure 4). Given the ubiquitous impact gardening that has created the small-scale topography of the Moon today (Cintala 1992; Sazlay et al. 2019; Costello et al. 2020), Artemis crew members are guaranteed to walk through numerous micro cold traps at their landing site within the polar region. However, these micro cold traps have never before been observed at the lunar poles. Therefore, an a priori understanding of the micro cold trap distributions, volatile contents, and temperatures would be beneficial for providing advanced understanding and targeting strategies of these small-scale regions.

4.2 Regolith properties

Understanding lunar polar regolith properties is important to Artemis missions to inform both crew and vehicle operations on the lunar surface. Crew will be conducting EVAs while on the lunar surface and therefore interacting with the lunar regolith through activities such as locomotion, instrument deployment, and sample collection, among others. Vehicles (such as the LTV) will also operate during and between later Artemis missions and will traverse across varied polar terrains. The goal of developing a sustained presence on the Moon presents the need for utilizing lunar resources and thus increased exploration and excavation activities as well as construction work to build lunar infrastructures, all of which benefit from improved knowledge of regolith geotechnical properties (Connoly and Carrier 2023). An increased landing cadence will also necessitate an improved understanding of surface-plume interactions from lander descents and ascents from the lunar surface. Knowing the geotechnical properties of the lunar polar regolith can be used to inform hardware designs and operational procedures for crew and other assets traversing and interacting with the lunar regolith.

VIPER will collect in situ data to characterize geotechnical properties within polar terrains. Measurements will be collected in sunlit areas, TSRs, and PSRs, where previous LCROSS data has suggested the porosity of regolith may be higher compared with areas that experience sunlight and thermal cycling (Schultz et al. 2010; Metzger et al. 2018). VIPER will also make geotechnical observations as a function of depth where previous Apollo data has indicated changes in the regolith properties (Lunar Sourcebook 1991). VIPER is designed to measure the following regolith properties: abrasion, adhesion strength, bearing capacity, cohesion, compaction or settlement, grain size and shape, internal friction angle (e.g., angle of repose), relative density, stiffness, bulk material strength, porosity, and shear strength (Colaprete et al. 2025a, this issue).

4.3 Lighting Conditions

The lunar polar regions have dramatically different lighting conditions compared with previous Apollo landing sites. Due to the low lunar obliquity of 1.5 degrees (Ward 1975) coupled with topographic effects, the sun remains low (<10 degrees) on the horizon throughout the year and creates complex illumination conditions which can vary over time. Near equatorial sites on the Moon experience a more regular day/night cycle of ~14 days of sunlight and ~14 days of darkness. In contrast, the polar regions of the Moon have regions of near-eternal sunlight (e.g., Shackleton Ridge remains lit for ~86% of the year), regions in topographic lows that remain complete shadow (PSRs) over geologic timescales, and regions with varying amounts of sunlight and shadow each year (TSRs) (Bussey et al. 2010). Lighting maps are generated by solar ray tracing over topographic data such as digital elevation models (DEMs). As a result, the resolution of illumination maps is limited by the resolution of topographic data. The highest resolution orbital topography data is from the Lunar Reconnaissance Orbiter (LRO) Lunar Orbiter Laser Altimeter (LOLA) instrument. At the poles, LOLA data is on the order of several meters resolution, and thus ground truth data is required to refine and validate illumination models at smaller (human) spatial scales. Through in situ measurements of illumination, VIPER will provide a dataset to develop tools and training for understanding the changing illumination conditions which will affect Artemis surface operations over the course of a landed crewed mission.

VIPER will also provide information regarding the three-dimensional nature of shadows on the Moon, particularly in proximity to PSRs. Upon approach to a PSR, the shadowed region changes both laterally and vertically, e.g., different heights above the ground will experience the transition from shadow to light as a function of location. This shadowing phenomenon is similar to a “beach effect” where the shadow becomes ‘deeper’ as entry to a PSR progresses. Figure 5 shows a model depicting varying heights of shadow and partial Sun exposure based on realistic lunar surface topography. Here the definition of the depth depends on a Sun fraction parameter. For example, in three-dimensional space there would be a set of planes (roughly, depending on horizon distance) above the surface representing 100% Sun, 90%, 80% and so on down to 0% (full shadow). The surface would undulate under these planes. Figure 5 shows that for this PSR the shadow slowly increases as one moves further into the PSR. For much of the PSR activity, the VIPER rover will be in partial sun and hence in a power generating mode while within an extreme thermal environment. Understanding the variation in shadow as a function of height and location is important to Artemis astronauts (and assets such as the LTV) for if/when either enter a PSR. For example, in this PSR an astronaut would have their head in Sun (assuming a 2-meter tall astronaut) while traversing for ~10s of meters within the PSR.

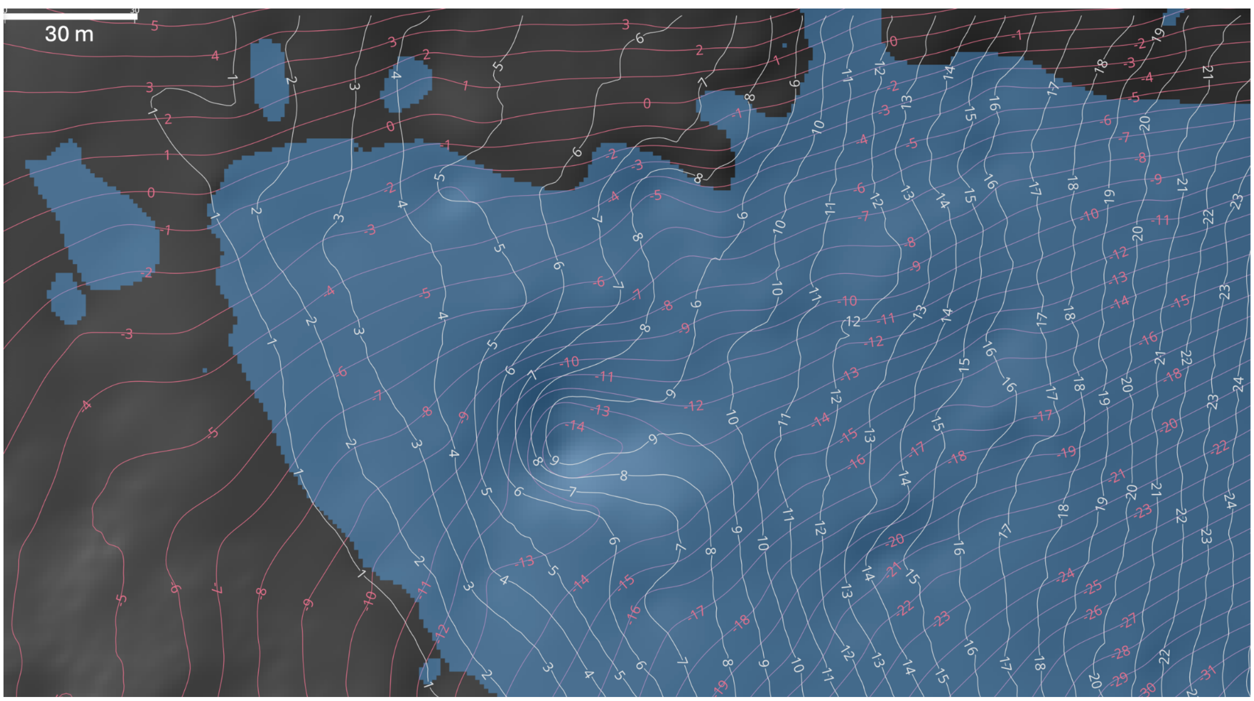

Figure 5. Model of shadow amounts and heights as a function of location. This example of a shadow depth product is at a proposed location (30.9923E, 85.4102S) for entering permanent shadow during a reference VIPER traverse. Blue is permanent shadow. The white lines are elevation contour lines at 1 m spacing. The orange lines are shadow depth at 1 m spacing. The outer shadow depth line is at 1 m (i.e., there is no 0 m line). The time is partway through the prospecting entry. The Sun is coming from the northwest at azimuth 319 deg with an elevation of 5 deg. The surface slope is 6.5 deg in the area of the traverse, hence the slowly increasing shadow depth. Note it is possible to have permanent shadow at the surface but have rover solar arrays and cameras in sunlight above the surface.

This lighting is important to understand in multiple Artemis scenarios involving both crew and uncrewed surface assets. An astronaut entering a PSR will have to visually cope with the brightness and contrast differences at the transitions between dark and light which influences operations, safety, and science. For example, astronauts must also be aware of these conditions for scientific sample collection. A crew member may collect regolith and/or volatile samples within the PSR in shadow on the PSR floor, but if the astronaut lifts that sample above the PSR floor before fully sealing the sample container, the sample can be exposed to sunlight and trigger volatile loss, thereby compromising the sample integrity. Shadow height as a function of location will also be important for robotic vehicles (e.g., LTV or other) which rely on solar panels for power. Understanding the shadowing as a function of height over space and time is paramount to ensuring adequate power is supplied to the vehicle for operations. The threshold tolerance for operations will depend on context and operational use cases. For example, any camera operations will be highly sensitive to light exposure levels as any appreciable fraction of the Sun's disk can saturate camera pixels. For cases of solar panel charging on robotic vehicles (including VIPER), partial levels of sunlight can still yield commensurate amounts of power, and the height of the solar panel array (top/bottom) are highly relevant and must be considered.

4.4 Validation of Polar Highlands Site Characterization Derived from Orbital Imagery

The candidate Artemis landing sites are located within the lunar south polar region with terrain characterized as lunar highlands. The highlands are composed primarily of anorthosite (rocks containing >90 wt.% plagioclase) and likely represent the remnants of an ancient Lunar Magma Ocean (LMO) where the crust and mantle of the Moon were molten and lighter minerals (such as plagioclase) rose to the surface while denser minerals (such as olivine and pyroxene) sank deeper into the lunar interior (Pieters 1986; Elardo et al. 2011; Elkins Tanton et al. 2011; Maurice et al. 2020; Xu et al. 2020; Gross and Joy 2023). The Apollo missions landed in the lunar highlands in the equatorial regions, however no human missions have been conducted in south polar highland terrains.

Landing site characterization, including boulder identification, for the Artemis candidate landing regions is primarily based on panchromatic images acquired by the Lunar Reconnaissance Orbiter Camera (LROC) with highest resolutions of sub-m per pixel and the ability to resolve objects of multiple meters in size (Robinson et al. 2010). VIPER surface imagery from the VIS system and navigation and hazard cameras (Beyer et al., 2025b, this issue; Edwards et al. 2025, this issue) will provide detailed knowledge of human-scale hazards (e.g., rocks and craters <2 m in size) to ground truth the candidate Artemis landing regions. A detailed understanding of candidate landing regions is important for selecting landing sites, enabling safe landings, planning EVA traverses, and ensuring the safety of crew members on the lunar surface.

Multispectral or hyperspectral orbital observations provide information on the composition of the south polar highland terrains, including within the candidate Artemis regions, at the tens of meters to kilometer scale. The interpretation of Kaguya Spectral Profiler (SP) data at a spatial resolution of 1 km per pixel suggests that the south polar region is characterized by relatively homogeneous FeO (~5–10 wt%) and plagioclase (~80–90 wt%), with the lowest FeO values (~5–7 wt.%) found in the 89°–90°S region near Shackleton crater, between Shoemaker and Faustini craters, as well as on the central peak of Amundsen crater (Lemelin et al. 2022). Exposures of pure anorthosites (≥98 wt.% plagioclase) were observed by Yamamoto et al. (2012) and Lemelin et al. (2017) on the rim of Shackleton crater. Data from the Chandrayaan-1 Moon Mineralogy Mapper (M3) and the Kaguya Multiband Imager (MI) at 62-140 meters per pixel suggest that the VIPER landing region contains low- to high-Ca pyroxene, high plagioclase abundances (likely anorthosite), and potentially hematite (Beyer et al., 2025b, this issue). In situ observations from NIRVSS onboard VIPER are critical to better understand the composition of the lunar soil at finer scales more relevant for human exploration and to interpret orbital observations.

4.5 Real-time Mission Operations

VIPER utilizes a unique real-time operations model to utilize VIPER data to inform science and operations during the mission (Colaprete et al. 2025a, this issue). This mode of real-time operations allows VIPER to capitalize on new knowledge gained from the in-situ measurements to inform both strategic and tactical mission operations while rapidly responding to the dynamic lighting and communications environment. The VIPER mission operations architecture is intentionally designed to incorporate new scientific discoveries during the mission and includes the flexibility to adapt mission plans and operations accordingly (Lim et al., this issue, 2025; Mirmalek et al. 2025). Specific tools and operational procedures have been developed (Mirmalek et al., this issue, 2025) and will be tested through VIPER to enable the real-time operational cadence. Lessons learned from VIPER flight operations can be extended to Artemis operations. Tactical and strategic planning based on real-time mission data can maximize safety and productivity, and VIPER provides a proof-of-concept of this methodology for this concept of operations and will demonstrate the benefits of this mode of operations. Process lessons and science-focused data systems built for VIPER science operations are extensible to Artemis operations. Tactical and strategic planning based on real-time mission data can optimize science return, safety and productivity. VIPER provides a proof-of-concept of this methodology for this concept of operations and will demonstrate the benefits of this mode of operations.

4.6 Shadow Operations and Sampling

VIPER mission requirements dictate that the rover shall enter and operate in multiple shadowed regions on the lunar surface. VIPER is required to investigate and collect measurements within multiple ISRs defined as dry (no water ice is thermally stable within the upper meter of the surface), shallow (ice is stable in the upper 20 cm of subsurface), and deep (ice is stable between 20-85 cm) as predicted from thermal modeling (Colaprete et al. 2025a, this issue). VIPER will interrogate regions in sunlight and will also drive into PSRs, TSRs, and micro cold traps, collecting surface measurements of these terrains for the first time. Through this work, VIPER will characterize shadowed environments, conduct rover operations (including drilling and sample measurements from drill cuttings), and provide valuable information regarding environmental conditions and operations in polar shadow. As example data that will be provided by VIPER, the camera systems will quantify the level of 'darkness' in PSRs and shadow (Beyer et al., this issue, 2025b; Edwards et al. 2025, this issue). Outside of doubly shadowed regions, scattered sunlight from crater walls and/or topographic highs provide low levels of sunlight even in PSRs. Initial analyses of the PSR within Shackleton Crater using ShadowCam data suggests that secondary lighting in PSRs is non-homogeneous, dynamic, and complex (Mahanti et al. 2023). VIPER will quantify the light levels in shadow which is important to understand when planning and predicting light levels expected for ultimately executing crew activity in shadowed terrains.

VIPER will also characterize geotechnical properties in shadowed regions for the first time. LCROSS data and theory predict that the porosity within PSRs may be higher compared with sunlit regions due to the lack of thermal cycling (Schultz et al. 2010; Metzger et al. 2018). NASA's LCROSS (Lunar Crater

Observation and Sensing Satellite) mission impacted into the PSR of Cabeus Crater in the lunar south polar region and showed a delayed near-infrared impact flash which may be attributable to a higher porosity regolith structure (Schultz et al. 2010). VIPER will measure the regolith and constrain geotechnical properties within both sunlit and shadowed regions in the polar region. Examples of VIPER observations to constrain geotechnical properties include, but are not limited to, rover wheel slippage and/or sink, compaction and definition of wheel tracks in regolith, IMU measurements of gravity, wheel-regolith interactions and drill activities, thermophysical measurements (surface and subsurface) of temperature, thermal inertia, and thermal conductivities, small-scale surface morphologies (e.g., rocks, porosity), and derived drill data such as regolith bearing strength and the tailings pile angle of repose. Constraining geotechnical properties within both shadowed and sunlit terrain will thereby inform Artemis hardware design and mitigate risks associated with operational interaction with regolith.

Electrical potential may also be increased within PSRs which is important to understand for rover and crew operations and suit design for Artemis. In regions of lunar shadow, the photoelectric and solar wind plasma sheets are reduced compared with the lunar dayside. As a result, it may be more difficult to remove accumulated electric charge from human systems charged by contact electrification with the regolith (Farrell et al. 2008). In addition, topographic features such as crater walls that create shadowed regions can block the solar wind and create plasma miniwakes which are subject to well-known plasma ambipolar expansion processes that define the electric potential structure at the surface of leeward mountain faces and within polar shadowed craters (Farrell et al. 2010). These conditions in the shadowed polar regions have no pathway for accumulated charge to “leak away” or dissipate, thereby potentially creating an electrostatic hazard (Farrell et al. 2008). VIPER operations in these environments and rover performance will constrain the electrostatic conditions within both sunlit and shadowed polar terrains.

VIPER will constrain PSR temperatures (including subsurface temperatures through the drilling activities and embedded temperature sensor), providing important constraints on the temperatures expected to be encountered by Artemis astronauts when conducting science and exploration activities. The TRIDENT drill has the capability to measure subsurface temperatures within the borehole while NIRVSS can measure temperatures at the surface (Zacny et al., 2025, this issue; Colaprete et al. 2025b, this issue). In addition, VIPER will characterize the behavior of volatiles under changing thermal conditions, i.e., how volatiles respond and degas when removed from the in-situ environment during extraction and sampling activities. MSolo and NIRVSS will measure the drill cuttings pile on the lunar surface and monitor the changes and release of volatile species once the drilled sample is removed from the subsurface and deposited on the lunar surface by TRIDENT (Colaprete et al. 2025b, this issue). Through these observations, VIPER will also provide critical compositional data of potentially hazardous volatile compounds and their concentrations. For example, LCROSS showed mercury may be present within PSRs (Gladstone et al. 2010), consistent with theoretical predictions and measurements of lunar samples and lunar meteorites (Reed et al. 1971; Jovanovic and Reed 1990). VIPER will provide critical information regarding the abundance, distribution, and concentration of various volatile species, providing knowledge to inform human exploration and develop appropriate mitigation strategies, or to retire the risk if hazardous materials are not found in appreciable quantities.

5.Conclusions

VIPER represents a first step towards enabling ISRU and the long-term human exploration of the Moon and beyond. The value of robotic precursor activities in advance of human exploration has been demonstrated through the Apollo program, and decades of research has demonstrated the utility of precursor missions in advance of human exploration (Hodges and Schmitt 2011). VIPER is the first off-world resource mapping mission and will operate in the south polar region of the Moon to characterize potential resources and inform subsequent ISRU architectures for sustained human exploration. NASA has identified candidate landing regions for Artemis, all located in the lunar south polar region. The lunar south polar region is an optimal locale that will enable a long-term human presence on the Moon based on the anticipated deposits of volatiles that may serve as resources for ISRU as well as regions of extended sunlight for operations and power. By conducting VIPER as a robotic precursor mission prior to crewed Artemis missions, VIPER will provide in situ data regarding regions to be visited by the Artemis astronauts. This information is key to reducing risk to human health and safety and optimizing Artemis mission activities. VIPER will pioneer real-time mission operations with feed-forward to Artemis human missions which will also need to be responsive to data collected in real-time on the lunar surface from astronauts, Artemis deployed instruments, etc. VIPER serves as a pathfinder for human exploration, providing in-situ data regarding varying thermal environments and ice stability regions to address immediate Artemis human mission planning needs. VIPER measurements can mitigate risks associated with human operations on the lunar surface and will also provide key in-situ environmental data that can inform Artemis hardware and operations, ultimately serving to reduce risk and increase the safety, performance, and productivity of the Artemis missions. Likewise, a similar rationale applies to Mars where a robotic precursor mission to detect and assess ice-rich martian resources prior to human activity can inform the subsequent human mission planning and architecture to ensure a sustainable human presence on the Red Planet.

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