Lunar Science Community Technology Development Priorities

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On behalf of the Lunar Exploration Analysis Group (LEAG) Executive Committee

LEAG https://www.lpi.usra.edu/leag/

LUNAR EXPLORATION ANALYSIS GROUP

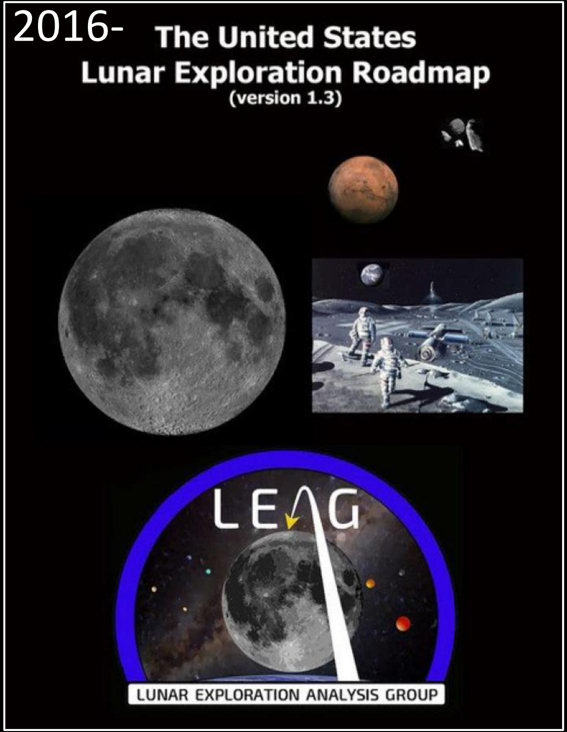
- Lunar Exploration Analysis Group (LEAG) was founded in 2004 to support NASA by analyzing scientific, technical, commercial, and operational issues relevant to lunar exploration: integrating science goals with exploration strategy.

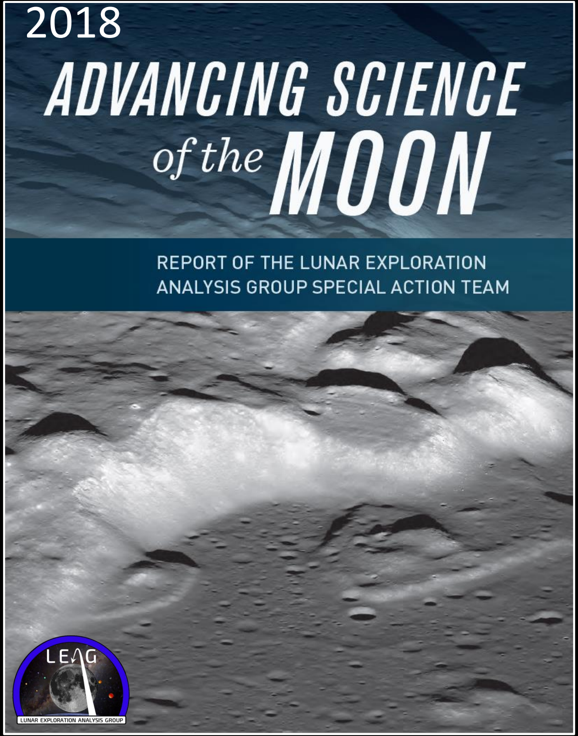
- LEAG supports the Human Exploration and Operations, Science, and Space Technology Mission Directorates.

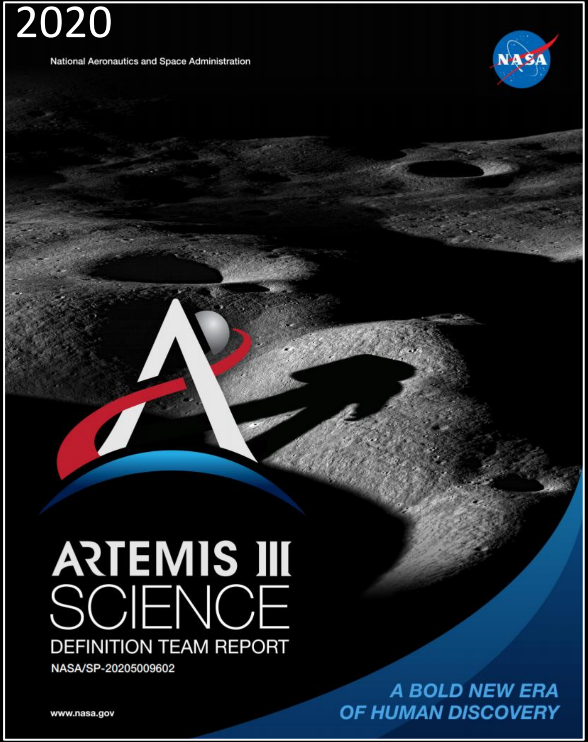
- LEAG is open to include the entire lunar science community, from a wide variety of backgrounds:
    - Academic, government, commercial (Commercial Advisory Board)
    - Science, engineering
    - Planetary science, astronomy, life sciences, physical sciences

- To further the exploration of the Moon, LEAG has generated numerous documents, including the findings of hosted/co-hosted conferences/meetings, the work of various Specific Action Teams, whitepapers for Decadal Surveys, scholarly publications, and the Lunar Exploration Roadmap.

Lunar Science Community Technology Priorities







Lunar Surface Innovation
CONSORTIUM

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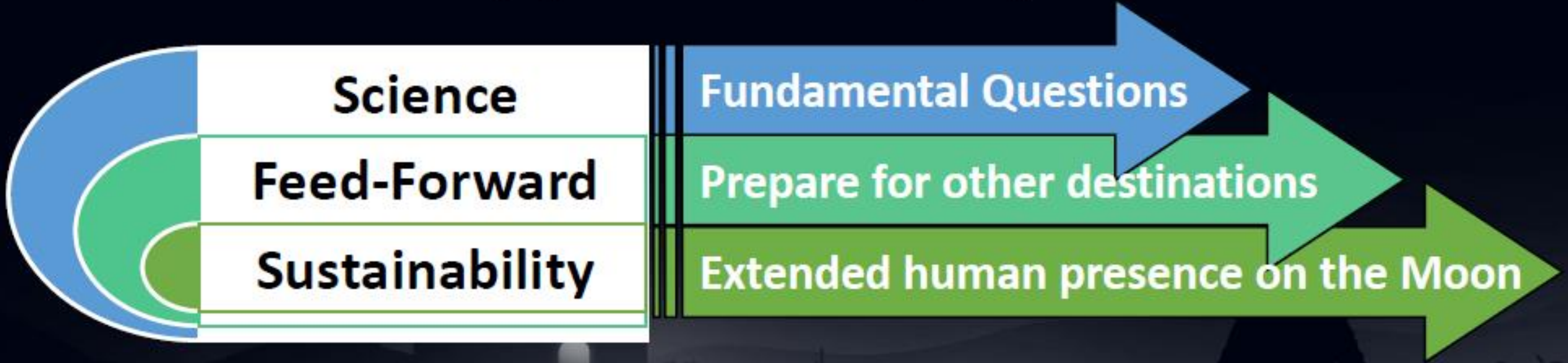
2020-

Lunar Exploration Roadmap (LER)

Purpose and Scope of the LER→ How do we get to the Moon to stay?

- Map science goals to objectives, observations, measurements;
- ID technological developments;
- Coordination with commercial and international partners;
- Feed-forward activities (explore Mars and beyond)

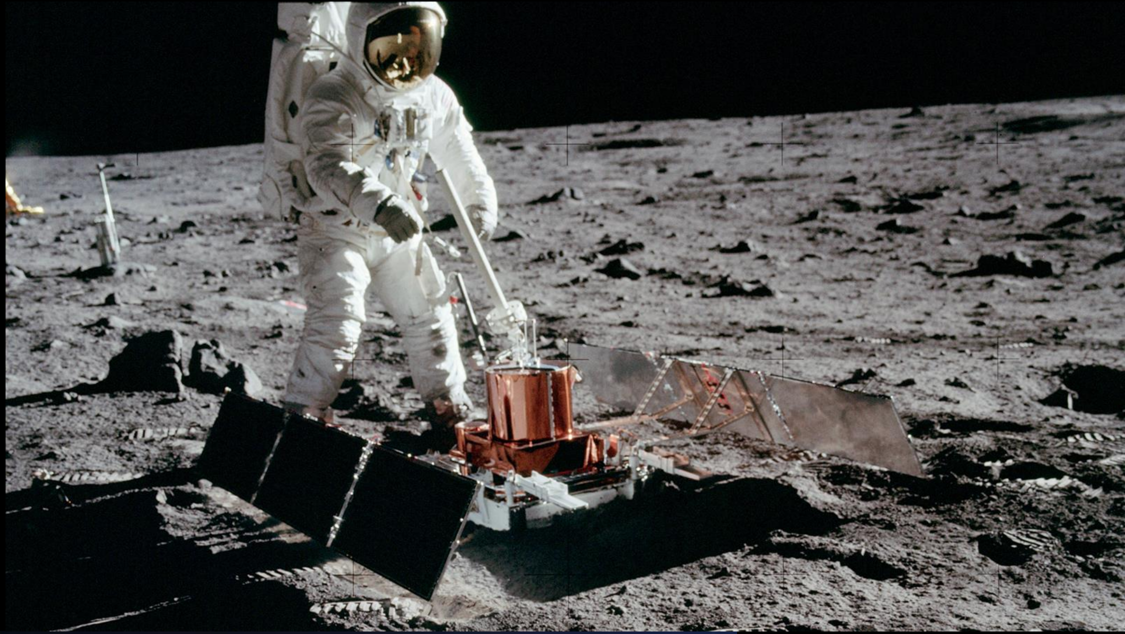


https://www.lpi.usra.edu/leag/roadmap/

Fagan et al., 2020, LSSW 1, #2241

LER: Science Theme

- Pursue scientific activities to address fundamental questions about the solar system, the universe, and our place in them:
  - Next generation planetary field tools, sampling gear (including cryogenic), portable instrumentation, *in-situ* analytical tools, and long-lived deployable instrument packages

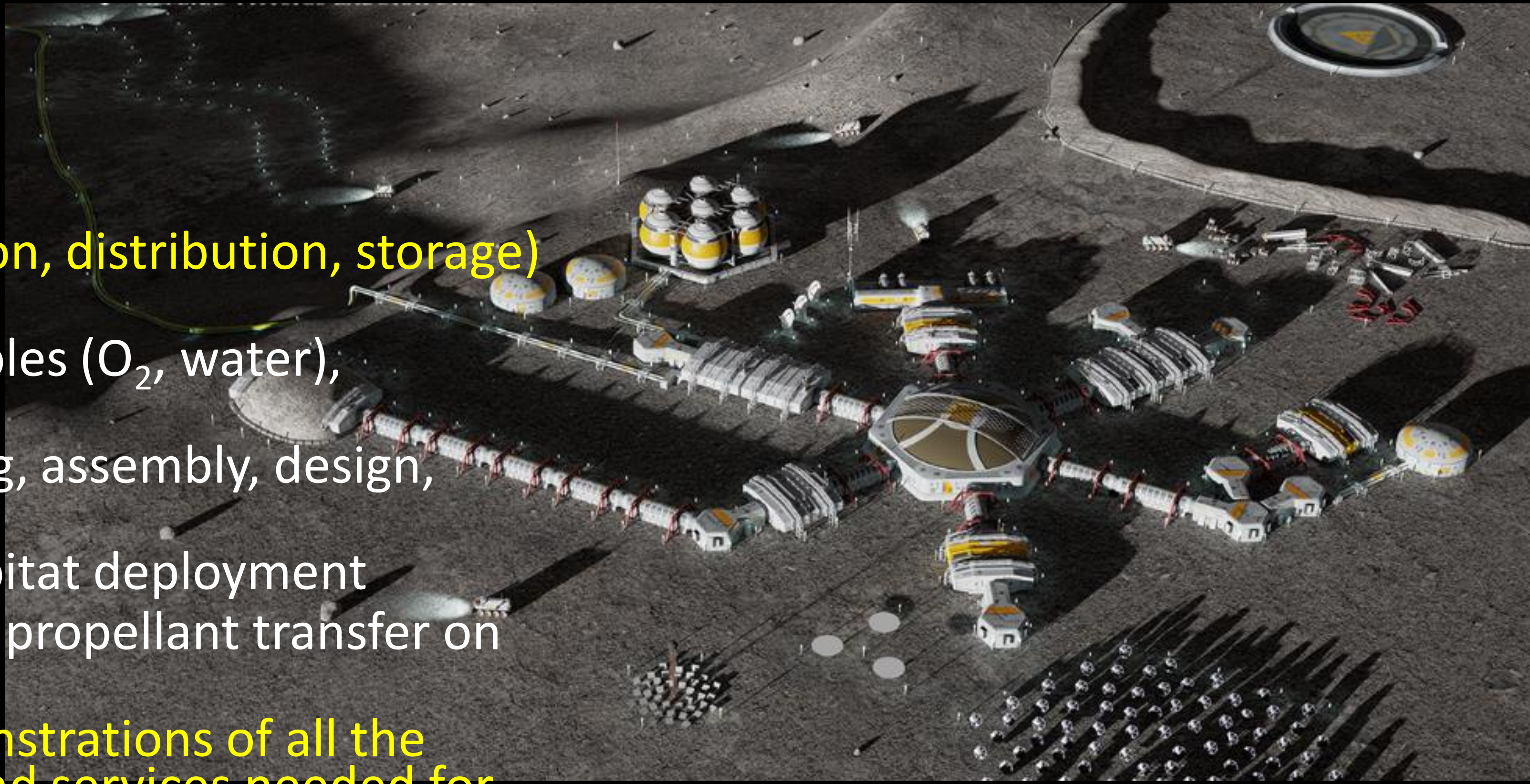


LER: Feed Forward Theme

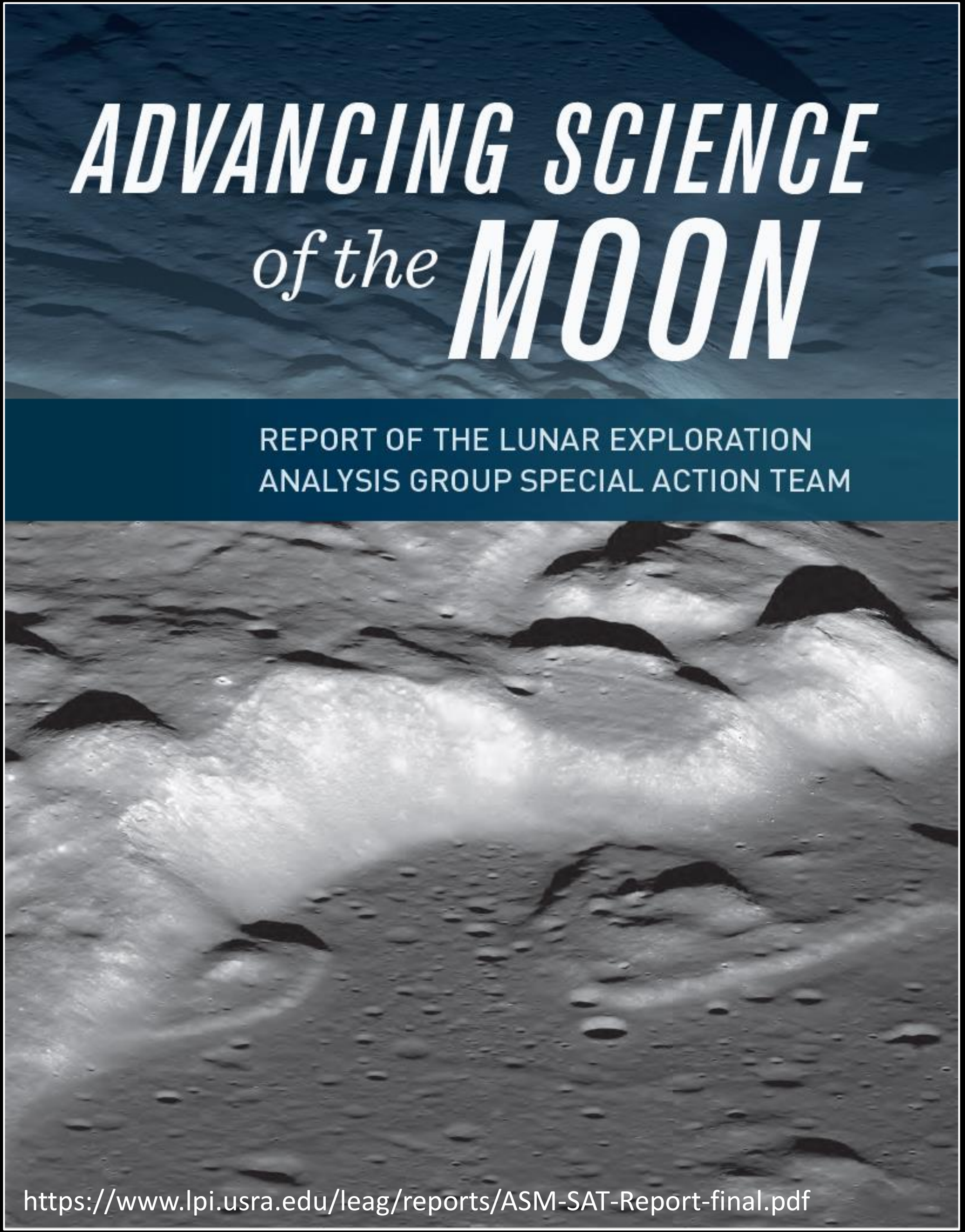
- Identify and test technologies on the Moon to enable robotic and human solar system science and exploration:
  - Autonomous hazard avoidance and precision landing
  - Life support systems for long-duration surface stays
  - Crew health systems for long-duration surface stays
  - Autonomous crew operations
  - Human-robot interaction
  - Sample collection and return (automated and human-tended)
  - Surface mobility
  - Navigation and communication
  - In-situ resource utilization (ISRU)
  - Surface power systems (generation, distribution, storage) – RTGs, solar, fission
  - Surface construction technologies and methods

LER: Sustainability Theme

- Extend sustained human presence to the Moon to enable eventual settlement:
  - Regenerative life support
  - Long-distance surface mobility
  - Navigation and communication
  - Surface power systems (generation, distribution, storage) – RTGs, solar, fission
  - ISRU: food production, consumables (O_2, water), reagents, propellants, materials
  - Repair, fabrication, manufacturing, assembly, design, testing capabilities
  - Excavation, construction, and habitat deployment
  - Cryogenic fluid management and propellant transfer on surface and in cis-lunar space
  - Small-scale and pilot-plant demonstrations of all the above and other infrastructure and services needed for science, exploration, and commerce

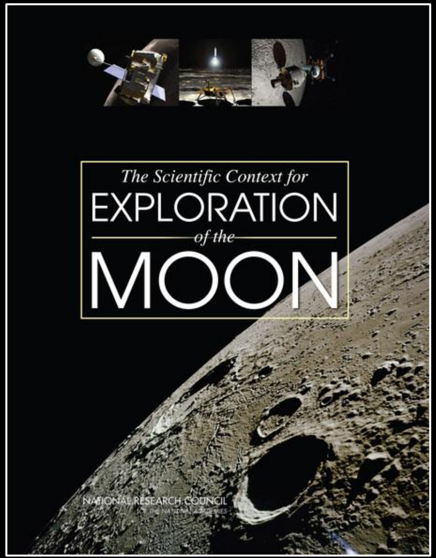


LSIC/JHUAPL



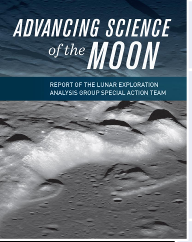
https://www.lpi.usra.edu/leag/reports/ASM-SAT-Report-final.pdf

- 2018 LEAG Specific Action Team (SAT) report that evaluates the progress made towards achieving the goals of the *Scientific Context for Exploration of the Moon* report (NRC, 2007).

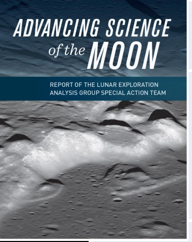


- Includes review of progress towards original 8 science concepts and added 3 new ones.

- Each science concept includes explicit and implicit technology needs.



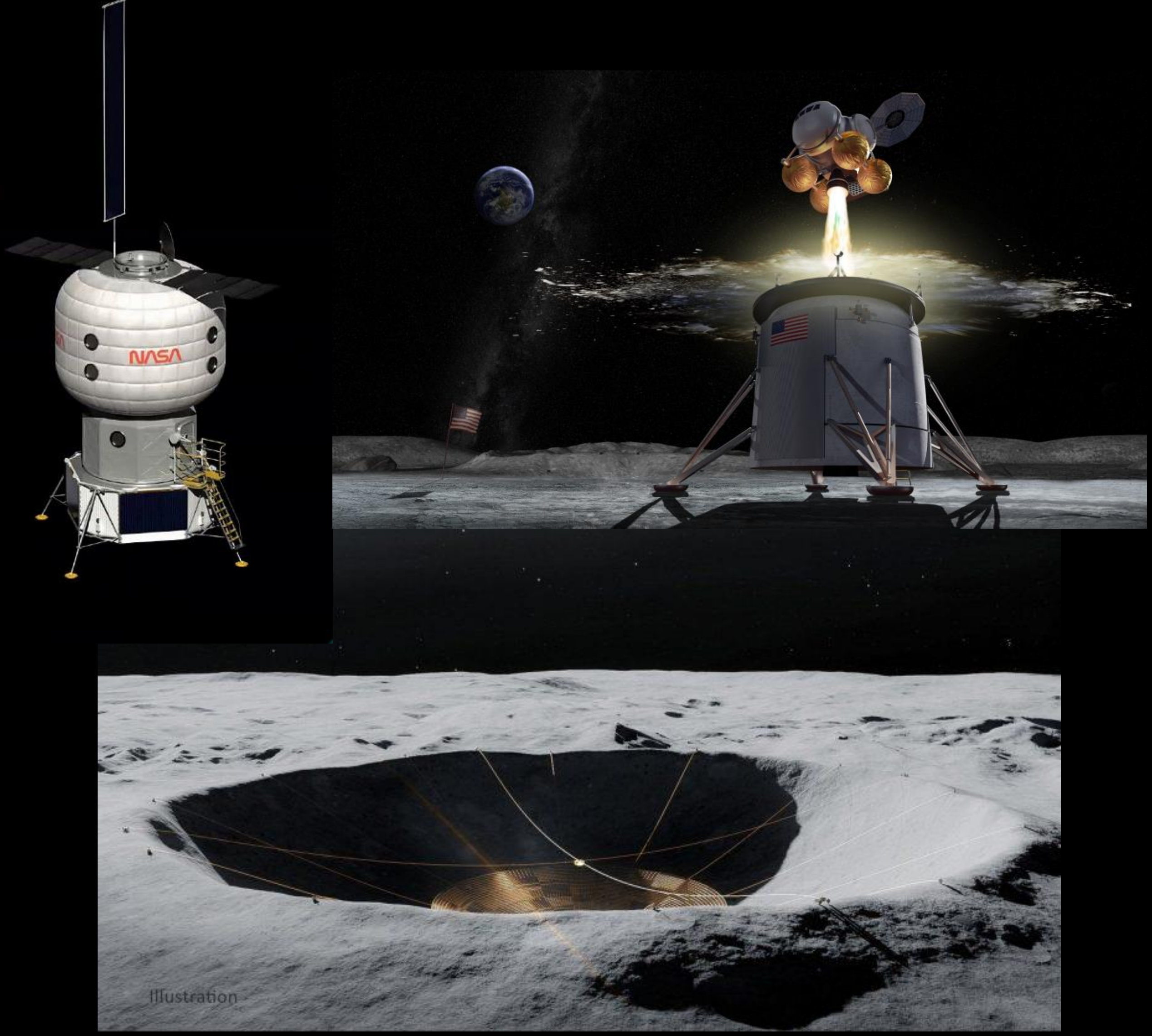
	Concept				
Technology	1: Bombardment history of the inner solar system is uniquely revealed on the Moon	2: The structure and composition of the lunar interior provide fundamental information on the evolution of a differentiated planetary body	3: Key planetary processes are manifested in the diversity of lunar crustal rocks	4: The lunar poles are special environments that may bear witness to the volatile flux over the latter part of Solar System history	5: Lunar volcanism provides a window into the thermal and compostional evolution of the Moon
In-situ dating/isotopic analysis	X	X	X	X	X
In-situ elemental/mineralogical analysis	X	X	X	X	X
In-situ geotechnical measurments				X	
Regional/global in-situ environmental monitoring (volatiles, dust)				X	
Regional/global geophysical network (seismic, heat flow, geodetic)		X	X		
Sample collection and return	X	X	X		X
Cryogenic sample collection and return				X	
Drilling			X	X	X
Subsurface sounding (GPR, electromag., seismic)			X	X	X
Precision landing to pre-determined study location	X			X	X
Surface mobility			X		
Access to extreme environment (poles, PSRs, underground)				X	X
Access to lunar far side (i.e. navigation, communications)	X		X		X
High-resolution orbital remote sensing	X	X	X	X	X

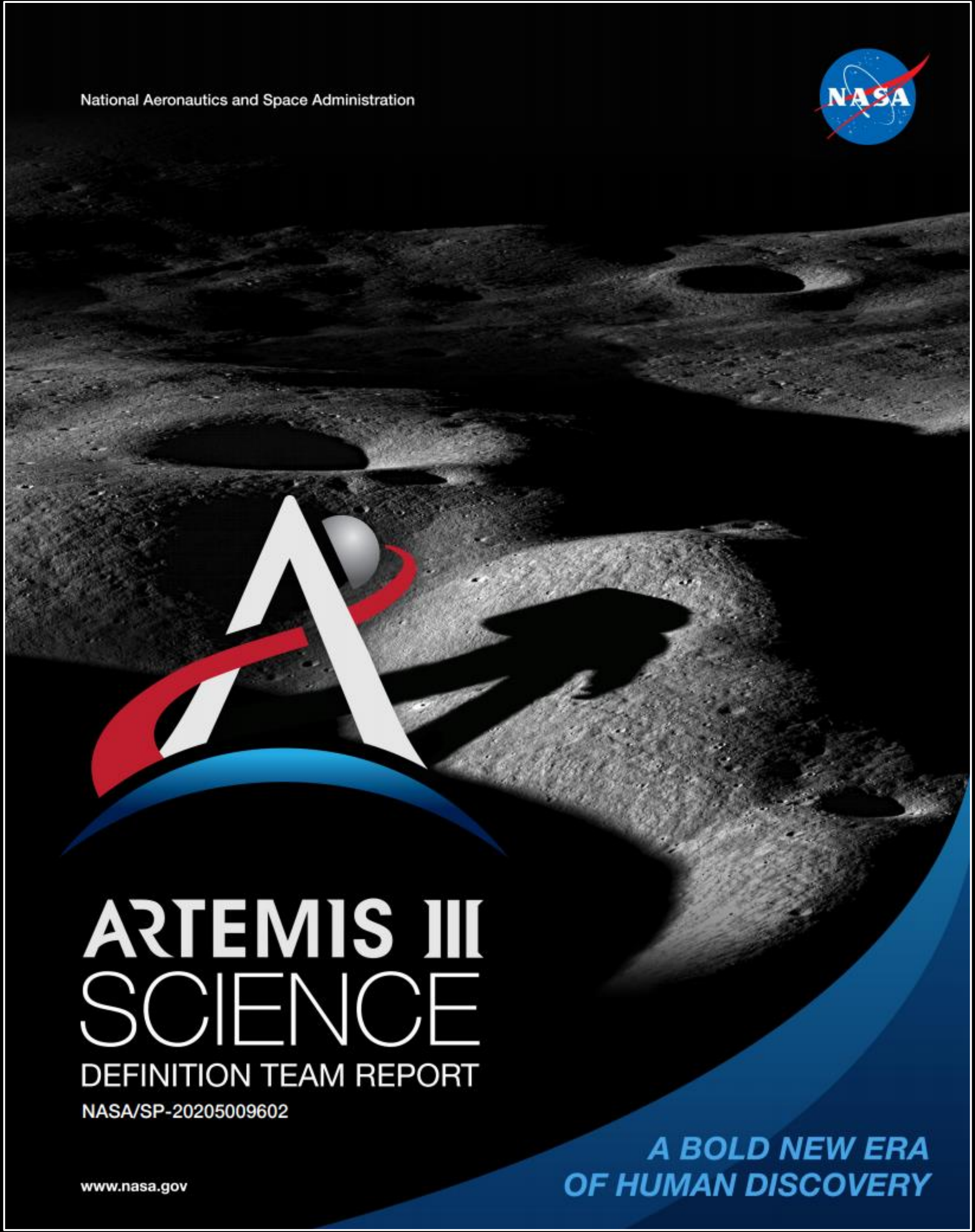


	Concept					
Technology	6: The Moon is an accessible laboratory for studying the impact process on planetary scales	7: The Moon is a natural laboratory for regolith processes and weathering on anhydrous airless bodies	8: Processes involved w/ atmosphere & dust environment of the Moon are accessible for scientific study while the environment remains pristine	9: The lunar volatile cycle	10: The origin of the Moon	11: Lunar tectonism and seismicity
In-situ dating/isotopic analysis		X	X	X	X	
In-situ elemental/mineralogical analysis		X	X	X	X	
In-situ geotechnical measurments		X		X		
Regional/global in-situ environmental monitoring (volatiles, dust)		X	X	X		
Regional/global geophysical network (seismic, heat flow, geodetic)	X				X	X
Sample collection and return	X	X	X		X	
Cryogenic sample collection and return		X	X	X		
Drilling		X		X		
Subsurface sounding (GPR, electromag., seismic)		X		X		
Precision landing to pre-determined study location	X	X		X		
Surface mobility						
Access to extreme environment (poles, PSRs, underground)				X		
Access to lunar far side (i.e. navigation, communications)	X		X		X	
High-resolution orbital remote sensing	X		X	X	X	X

LEAG Advancing Science of the Moon SAT

- Future lunar activities (science from the Moon; surface access):
  - Establish capabilities and infrastructure (landing, habitation, mobility, return) for regular and repeated access to the lunar surface.
  - Establish infrastructure (power, communications, navigation) for long-term deployment of instrumentation, experiments, and observatories on the lunar surface.
  - Human exploration capabilities for the Moon, Mars, and beyond.



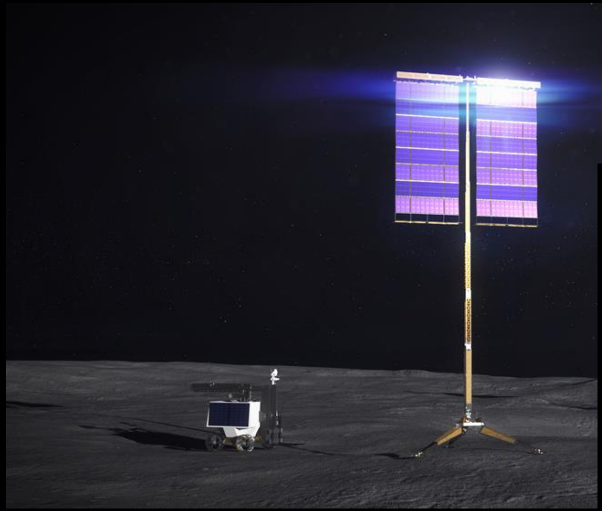


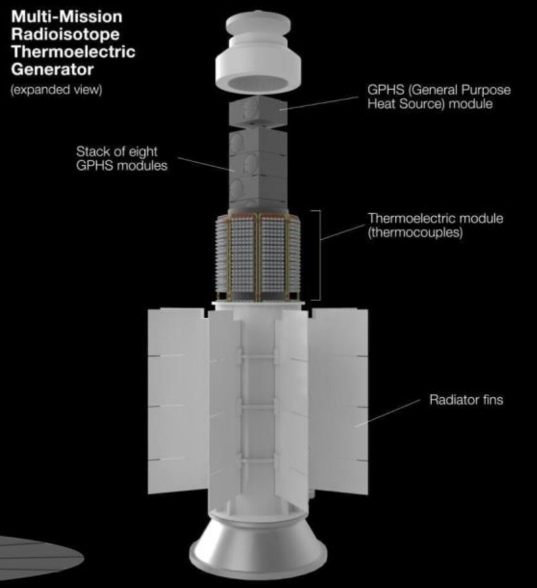
- The Science Definition Team (SDT) solicited community white papers focused on science objectives rather than instrument or technology development.
- Nevertheless, some technology priorities are explicitly highlighted by the 2020 SDT report findings and their recommendations:
  - Long-lived power systems
  - Communication/navigation infrastructure
  - Pre-deployment capability
  - Surface mobility
  - Cryogenic collection, storage, return and curation of samples
- Implicit throughout are also needs for development of next-generation orbital assets and surface instrumentation specifically designed for operation on the lunar surface (remote sensing, cameras, geologic tools, *in-situ* analysis instruments, geophysical instruments).

https://www.nasa.gov/sites/default/files/atoms/files/artemis-iii-science-definition-report-12042020c.pdf

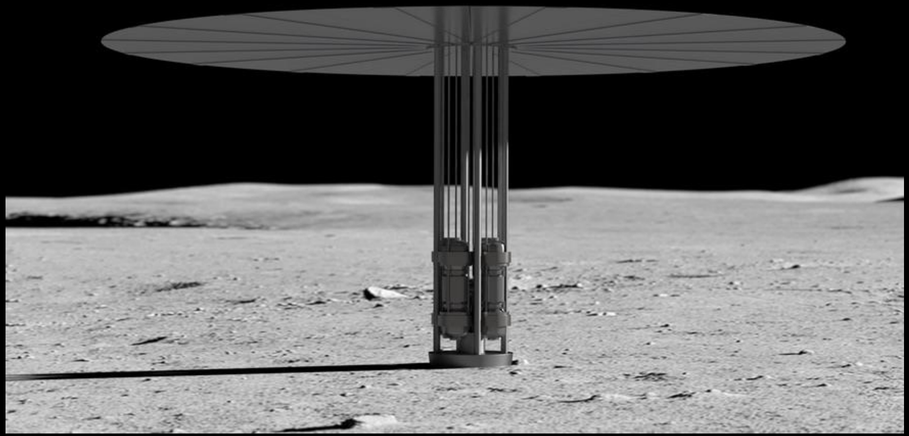
Artemis III Science Definition Team Report

- *Finding 7.1-1: Several of the investigations prioritized in this report would be maximally enabled by a long-lived power source and communications capability for deployed experiments.*
  - *Recommendation 7.1-1: NASA should pursue solutions for long-lived power and communications to enable networked operation of ALSEP-like packages at multiple landing sites, as needed to enable meaningful progress on many of the Goals described in Section 5, and feeding forward to future Artemis missions.*





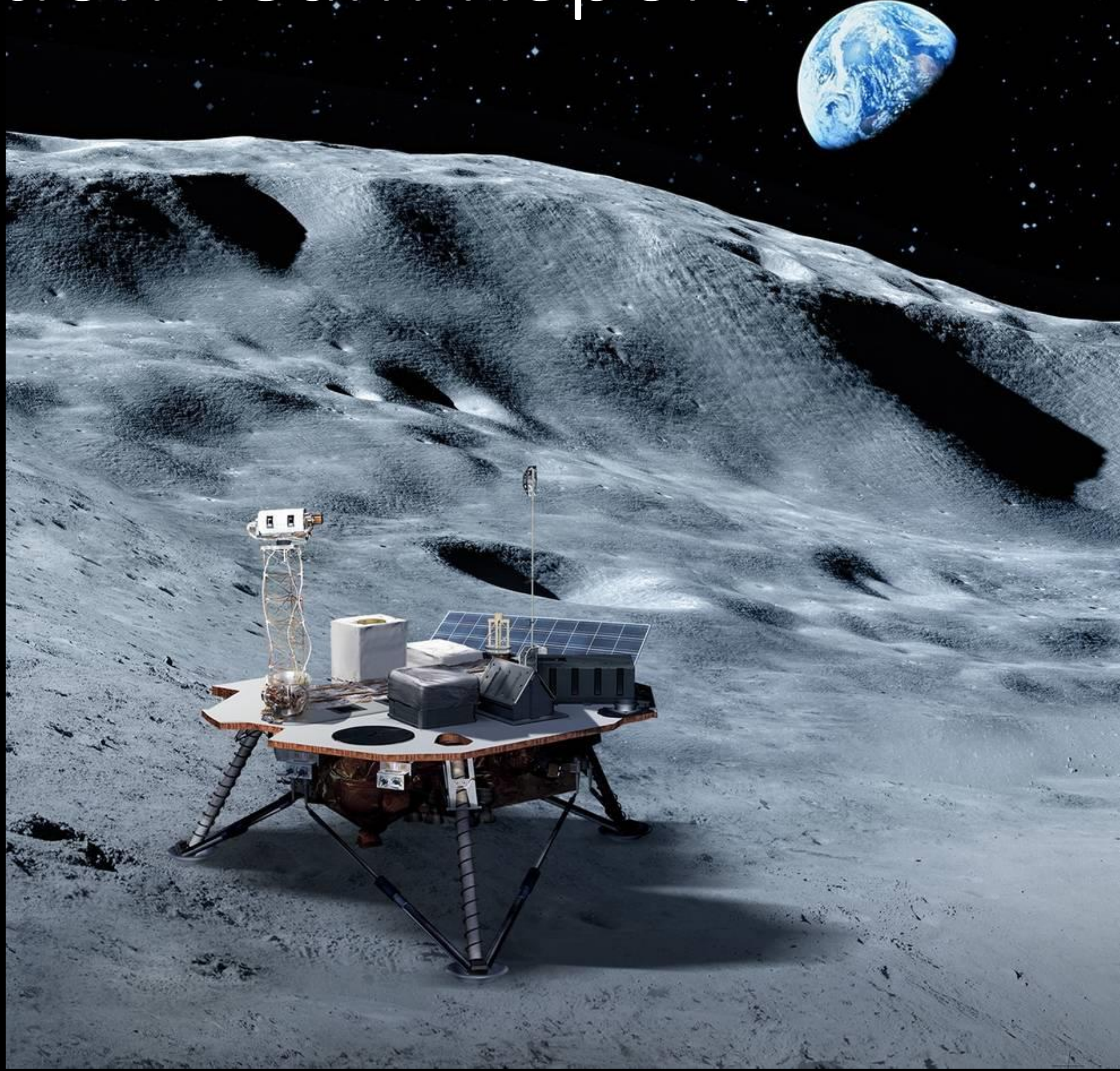
- Long-lived experiments on the Moon will require power sources that can survive and operate through the lunar night and/or in polar regions and permanently-shadowed regions (PSRs):
  - RTGs (and concomitant requirement to produce Pu fuel)
  - Solar arrays
  - Batteries and fuel cells
  - Fission power systems
- Surface operations (human, robotic, long-term experiments) will require communications (and navigation) infrastructure on the lunar surface.



Artemis III Science Definition Team Report

- *Finding 6.4-1: Existing mass allocations expected to be available on the HLS system for delivery of tools and payloads to the lunar surface are insufficient to achieve the full spectrum of science objectives outlined by the stakeholder community.*
    - *Recommendation 7.2-1: NASA should consider pre-positioning science assets in the vicinity of the Artemis III landing site. This could consist of an inert cache of tools/instruments to be accessed by crew upon arrival, and/or one or more instrumented landers or rovers for environmental monitoring.*

- Ability to pre-deploy science assets (instruments, tools) on the Moon would enable full spectrum of science activities to be achieved and would greatly increase science capability of human exploration as well as offer operational benefits:
    - Reconnaissance of human exploration areas
    - Deployment of consumables, spares, etc.
    - Precision/autonomous navigation technology
    - Monitoring of interactions between landing systems and lunar surface
    - Demonstrate surface rendezvous capabilities (feed-forward to Mars)



Artemis III Science Definition Team Report

- *Finding 7.3-1: Crew mobility on the lunar surface is a key factor for enhancing the scientific investigations outlined in this report.*
  - *Recommendation 7.3-1: NASA should include a rover or other mobility solution for crew use on the lunar surface starting as early in the Artemis program as possible, ideally for Artemis III.*

- Robust mobility systems are needed for short- and long-term exploration of a geologically and geographically complex planetary surface:
  - Allows access to a broader area for geologic characterization and sample collection.
  - Enables deployment of instrumentation over a broader area.
  - Unpressurized and pressurized (habitable) rovers will increase the time human crews can spend in the field doing science.

Artemis III Science Definition Team Report

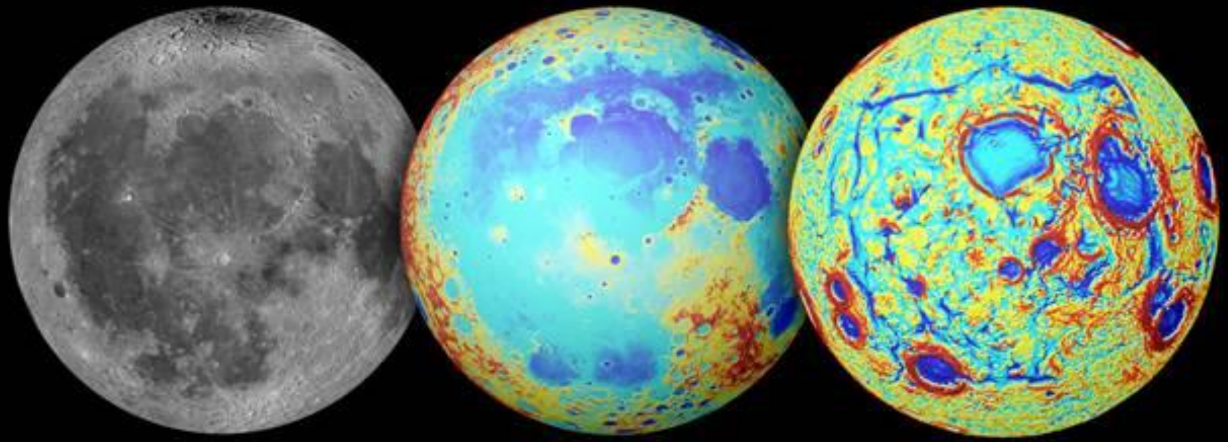
- *Finding 7.4-1: The ability to conduct cryogenic sample return from the Moon to Earth increases the scientific yield of samples containing icy and/or volatile components.*
  - *Recommendation 7.4-1: NASA should develop and implement the required hardware and operations to return a subset of the samples at temperatures low enough to preserve water ice and other low temperature volatiles of interest in the solid state throughout the entire journey from the lunar surface to Earth-based laboratories. Cryogenic sample return will increase the scientific fidelity of sample analyses of volatiles and ices. Minimizing the mass penalty for cryogenic sample return results in increased scientific yield of the mission since more mass can be allocated to the lunar samples instead of the sampling hardware.*

- Cryogenic storage and transport of samples that contain volatiles is critical for science investigation of those volatiles and their context.

Vehicle	Duration of Cryogenic Stowage Required	Key Challenge(s)
Human Landing System (HLS)	Up to 2 days	1. Minimal available space 2. Minimal available power
Gateway	Up to 5 days	1. Longevity of cryogenic system
Orion	Up to 6 days	1. Minimal available space 2. Minimal available power 3. Longevity of cryogenic system 4. Operation during re-entry

Artemis III Science Definition Team Report

- Cartographic and Data Considerations:
  - Update standard lunar reference frame.
  - Continue development of foundational data products (gravity model, topographic models e.g. GRAIL GRGM1200A, LDEM GDR, SLEDEM2015).
  - Tie the vast amount of orbital datasets and data products to the foundational data products.
  - Create new products (imagery, topography, geologic maps).
  - Make data sets readily and easily accessible to science and mission planning teams.



- Next-generation lunar orbiter.

Ongoing series of virtual workshops that engage the lunar science community on a wide range of topics germane to Artemis-era lunar exploration:

I: Tools and Instruments (May 28-29, 2020)
V: Science Enabled by Mobility (October 28, 2020)
VI: Foundational Data Products (November 19, 2020)
VIII: Real-Time Science Support of Artemis Crewed Operations (February 24-25, 2021)

LSSW I: Tools and Instruments

- Hardware, software/interface, integration, communications, data handling for instruments deployed as:
  - Handheld
  - Walking stick-mounted
  - Rover-mounted
  - Suit-mounted
  - Lander-mounted
  - Surface-deployable

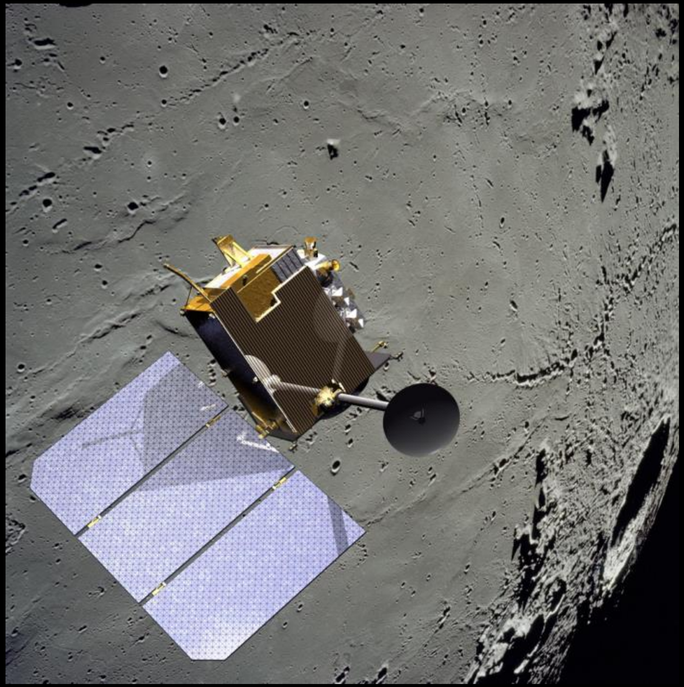
- Geologic tools and sampling gear
- Field-portable analytical instrumentation
- Geophysical and environmental monitoring instrumentation
- Imaging, geospatial data, close-range remote sensing

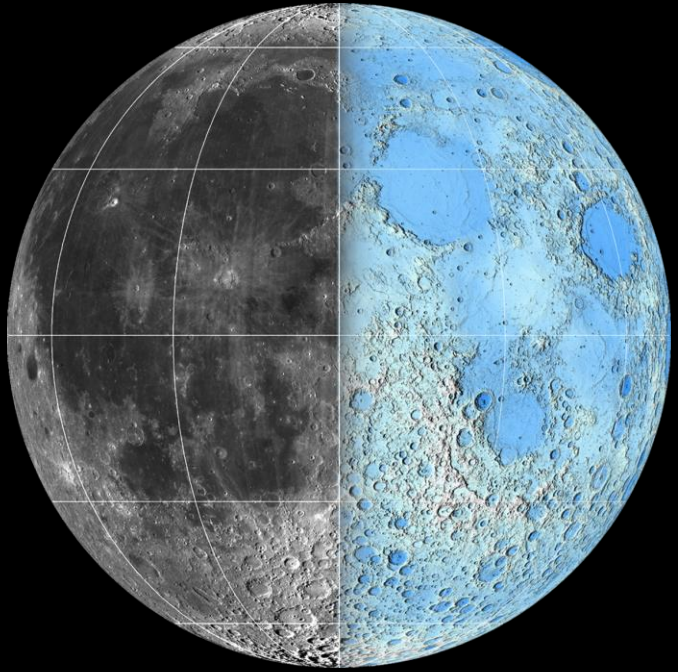
LSSW V: Science Enabled by Mobility

- Semi-autonomous mobility (without crew):
  - Access to inaccessible/dangerous areas
  - Systematic mapping and exploration
  - Mobile deployment/retrieval of instruments/samples
  - Systematic and repetitive tasks over wide area
  - Reconnaissance

- Human-capable mobility:
  - 100+ km range
  - Robotic arms
  - Integrated geophysical survey tools (GPR, neutron spectroscopy, etc.)
  - Dual use (with humans and autonomous/teleoperated when crew not present)
  - Deployment/retrieval of smaller, autonomous mobility systems
  - Communication and navigation infrastructure
  - Surface power infrastructure

LSSW VI: Foundational Data Products





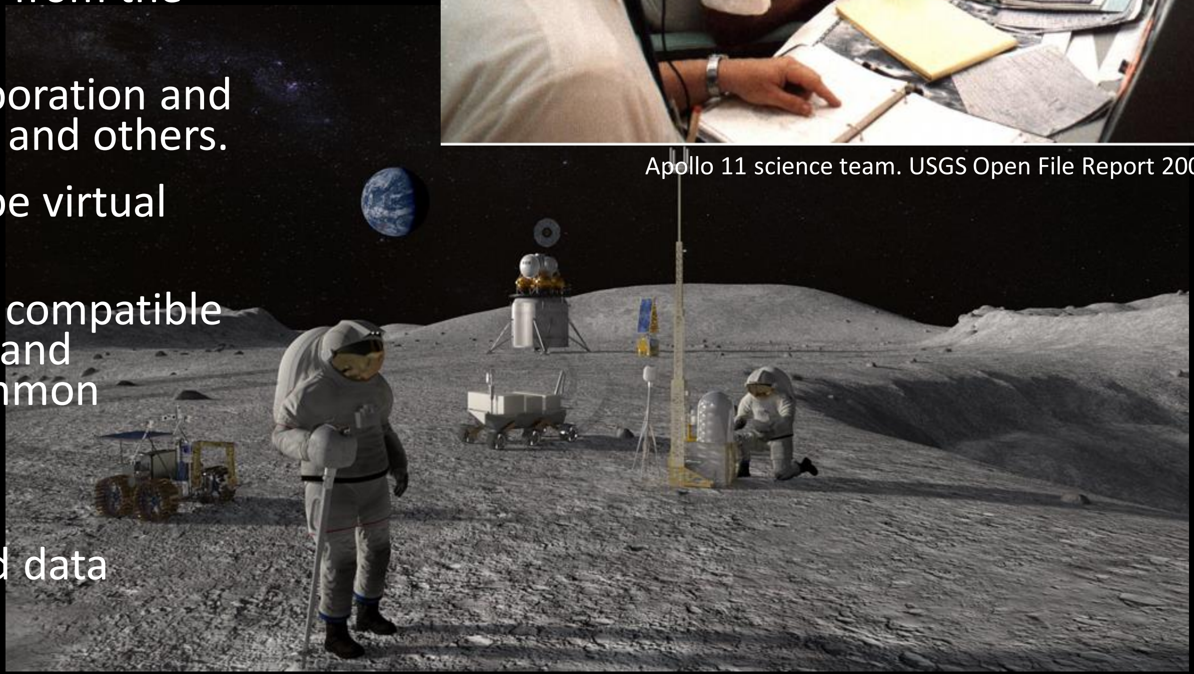
- New orbital platforms:
  - Next-generation LRO
  - Capability to monitor the dynamic environment created by surface exploration of Moon

- Navigation and communications infrastructure and cartographic base data to enable surface exploration.

LSSW VIII: Real-Time Science Support

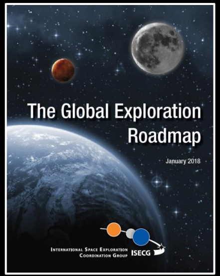
- IT infrastructure for transmitting, storing, processing, serving, and archiving mission data for all stakeholders (crew, science team, mission control, science community, public).
- Technology to enable both face-to-face and remote participation amongst science support personnel.
- Real-time transcription of mission audio that can be indexed and searchable.
- Real-time transmission/processing of high-definition imagery from the lunar surface to the science team.
- Virtual- and augmented-reality (VR/AR) tools to enable collaboration and data sharing amongst crew, science support, mission control, and others.
- VR/AR tools to enable science support team (and others) to be virtual explorers alongside crew.
- Cross-instrument data compatibility to ensure interoperable, compatible formats for all mission data (cross-referenced by time-stamp and location) housed in a central location and accessible by a common visualization and analysis system.
- Communication and navigation infrastructure on the Moon.
- Instrumentation and tools on the Moon to supply the needed data streams.

Apollo 11 science team. USGS Open File Report 2005-1190

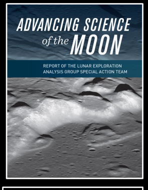


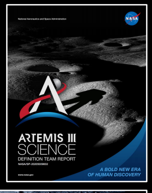
Lunar Science Community Technology Priorities: Overview and Common Themes

= *LSIC focus area topic*



Science Capabilities





- Continued remote sensing and orbital mapping
- Geology
  - Sampling tools (including cryogenic)
  - *In-situ* compositional and isotopic analysis
  - *In-situ* geotechnical analysis
  - Drilling
- Geophysics
  - Subsurface sounding
  - Deployable network of sensors
- Environmental monitoring
  - Field-portable
  - Deployable network of sensors
- Life science/biological monitoring, sample collection
- Astronomy (long-lived observatories)
- Tools to enable real-time science support of human (and robotic) missions: communications, collaboration, mission data handling, AR/VR visualization, cross-instrument data compatibility/interoperability

"Infrastructure" and Other Capabilities

- Autonomous, precision landing
- Power
- Communication
- Navigation
- Mobility
- Access to extreme environments
- ISRU
- Construction, excavation
- Life support, crew systems (habitats, etc.)
- Human-robot interaction

http://lsic.jhuapl.edu/

Lunar Surface Innovation CONSORTIUM

Administered by the Johns Hopkins Applied Physics Laboratory

LSIC Focus Areas:

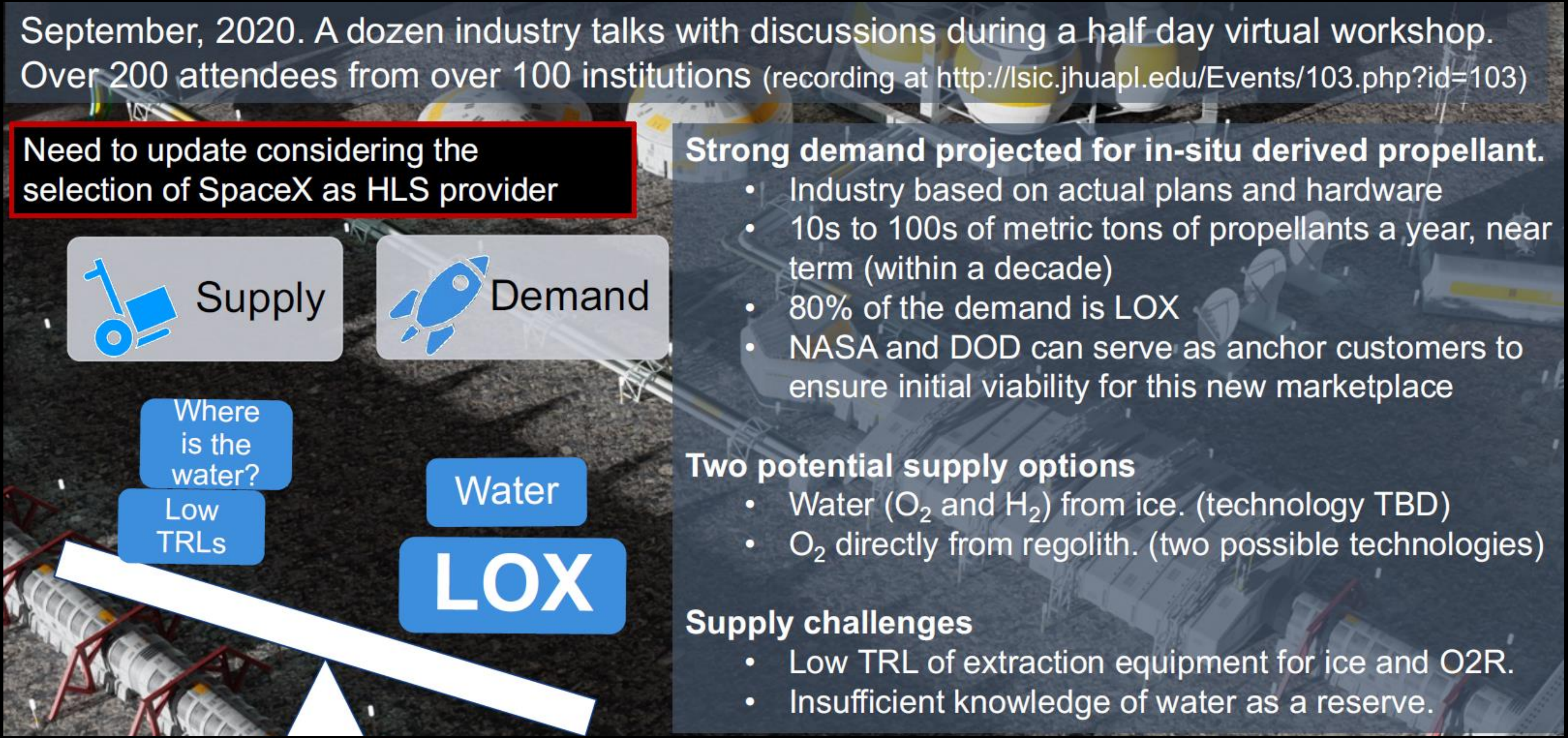
- In-Situ Resource Utilization (ISRU)
- Surface Power
- Extreme Environments
- Extreme Access
- Excavation and Construction
- Dust Mitigation

- Additional slides with Year 2 (2021-2022) vision and goal statements (highlighting technology development priorities) for each of the 6 LSIC focus areas.

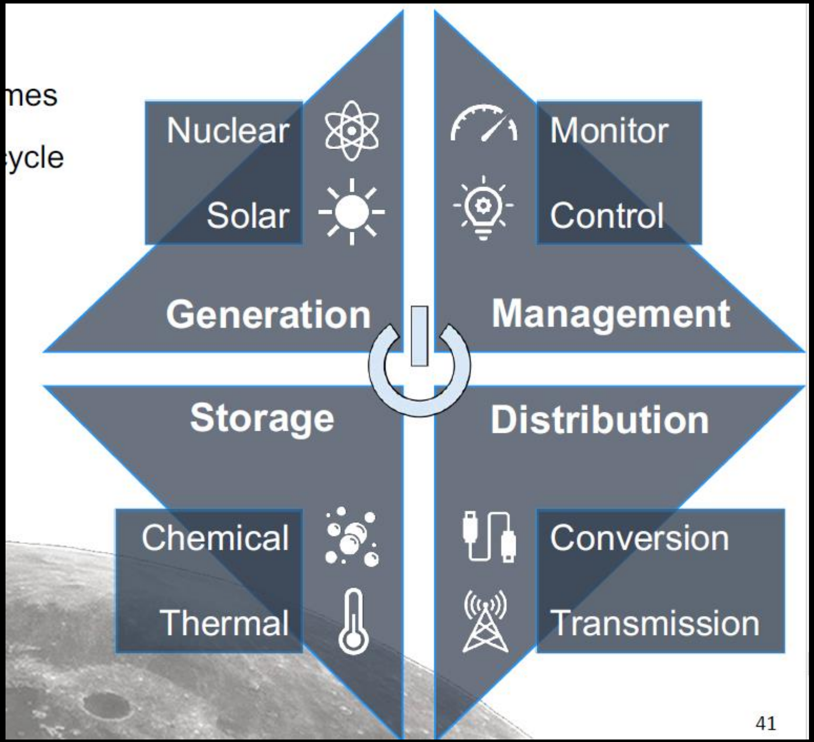
- Important and complementary intersections exist between the science-oriented priorities LEAG (and others) identify and the implementation-oriented priorities of LSIC with respect to technology.

- Slides taken from presentations made at LSIC 2021 Spring Meeting (virtual, May 11-12, 2001): http://lsic.jhuapl.edu/News-and-Events/Agenda/index.php?id=124

LSIC Focus Area: ISRU



LSIC Focus Area: Surface Power



Vision: NASA needs power systems which can survive the lunar night and enable exploration. The over-arching goal of the surface power focus group is to provide specific recommendations to NASA for rapidly achieving appropriate-scale power-related technologies needed to enable sustained presence and exploration.

To work towards this, we will first focus on connecting **power experts to their potential user base**, framed by the **economic and institutional drivers that set the scale of power demand**. This will enable us to identify near-term needs for immediate prioritization and long-term goals that impact early architectural decisions.

Connecting power experts to their potential user base
- Cross-cutting telecons
- Workshops
- Who's Who in Surface Power
- Power User Survey

Economic and institutional drivers that set the scale
- Discussion within telecons, invited speakers, etc.
- Follow-on work on supply and demand from ISRU
- Evaluation of NASA technology gap assessments

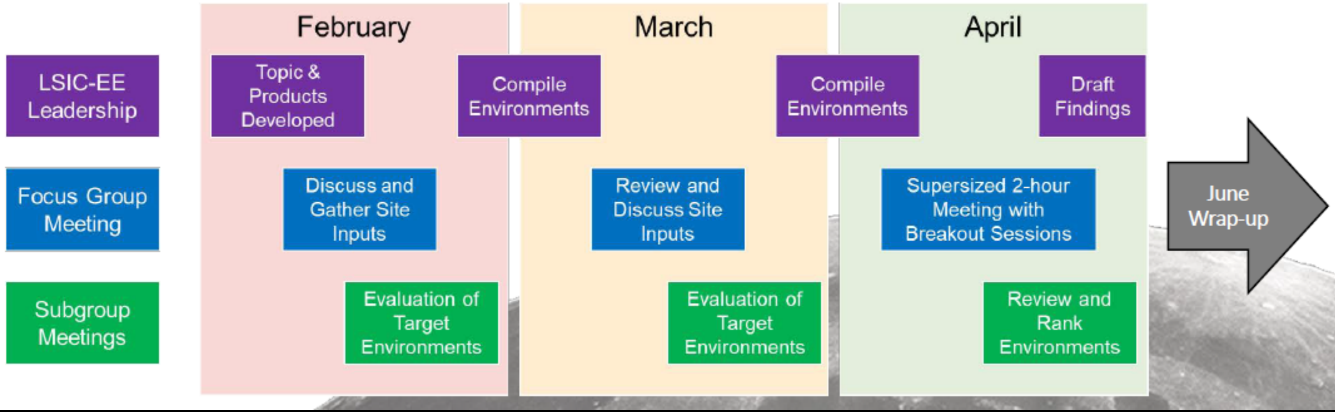
LSIC Focus Area: Extreme Environments

Identifying and Characterizing Specific Lunar Surface Environments

- "Breaking Down the Lunar Environment Monolith"
- How do different environments stress technologies in different ways
- How do specific lunar environment differ from descriptions of the general lunar environment?

LSIC-EE focus group and subgroups systematically addressed this topic over multiple meeting during winter and spring 2021

- Parts of 3 regular focus group meetings
- Parts of 20 regular subgroup meetings
- 2-hour working meeting in April 2021



Polar Environments	Non-Polar Environments
Permanently Shadowed Regions (PSRs)	Apollo-style Environments
Areas of High Illumination (>55% Illumination)	Topographic Margins
Mixed Polar Environments	Lunar Pits & Lava Tubes
	Surface Anomalies

Specific lunar environments included in this study cover all planned and anticipated landing site locations for both human and robotic missions

LSIC Focus Area: Extreme Access

High priority challenges and needs identified:

- Terrain Relative Navigation (TRN) systems need lunar maps with unique characteristics.
- Industrial partners and navigation engineers are not fully utilizing existing lunar data.
- Standard data sets and controlled maps would be beneficial for testing algorithms.
- Current flight processor capability may be insufficient for advanced TRN algorithms and map processing.
- Targeted new missions and instrumentation would fill gaps in data needed for TRN systems.
- Standardized rendering tools, data verification and validations metrics, and metadata are desired.

Vision: Build a community specializing in technology required to access, navigate, and explore surface and subsurface areas on the Moon. Identify areas of interest in technology development, evaluate readiness, and provide a resource for members to gain & share information, network, and discuss technology needs for lunar exploration.

Year 2 Goals:

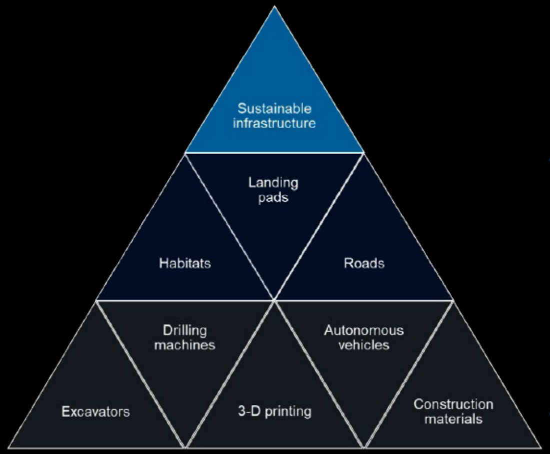
Identify mission/system elements needed to explore challenging lunar environments, including identifying specific technology needs and gaps, prioritizing development timelines, and providing a general roadmap and recommendations for needed technology, testing, and demonstrations.

- *Permanently Shadowed Regions (PSR) and lunar pits/lava tubes were chosen as high priority environments*
- *We will work with the EE group to identify environment requirements and challenges*
- *Conduct at least one targeted Technical Interchange Meeting (TIM)*

Build a community and develop collaborative relationships among members

- Inclusive monthly telecons with member technology spotlights and invited technical talks
- Provide networking opportunities at large LSIC meetings, mentoring through LSIC channels
- Community-led subgroups for in depth discussions and networking

LSIC Focus Area: Excavation & Construction



- **Infrastructure:**
  - Landing and Launch Pads
  - Habitats: in-situ and deployable
  - Roads, Berms, etc.
  - Space architecture – urban planning
- **Technology:**
  - Additive Construction
  - Autonomous Construction
  - High-fidelity excavation tools for lunar applications
  - Manufacturing technologies : sintering, regolith processing, additive manufacturing
- **In-situ Repair and Outfitting**
  - Maintaining the infrastructure
  - Spare parts : in-situ fabrication vs. sending
  - Outfitting requirements

Lunar Infrastructure Repair and Outfitting

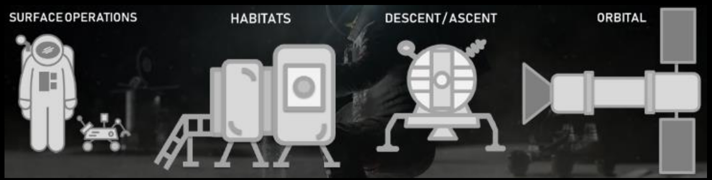
A lunar base will inevitably require capabilities in the areas of field repair, in-situ-fabrication of small parts and outfitting. We will initiate the development of a roadmap .

Areas of investigation:

- A base will need spare parts. What kind of spare parts are needed / maybe needed?
- What kind of parts are beneficial to be manufactured on lunar surface as opposed to sending from earth?
- What kind of outfitting inventory is needed for habitats and landing pad?
- Investigate the use of special purpose robots and their autonomous operation.
- What kind of in-situ fabrication and repair technologies are feasible and necessary?
- Create an industry-government eco-system in this area. A supply-chain framework?
- Propose CLPS activities.

Lunar Surface Innovation CONSORTIUM

Administered by the APL Johns Hopkins Applied Physics Laboratory



LSIC Focus Area: Dust Mitigation

- ***Optical Systems*** – Viewports, camera lenses, solar panels, space suit visors, mass spectrometers, other sensitive optical instruments
- ***Thermal Surfaces*** – Thermal radiators, thermal painted surfaces, thermal connections
- ***Fabrics*** – Space suit fabrics, soft wall habitats, mechanism covers
- ***Mechanisms*** – Linear actuators, bearings, rotary joints, hinges, quick disconnects, valves, linkages
- ***Seals and Soft Goods*** – Space suit interfaces, hatches, connectors, hoses
- ***Gaseous Filtration*** – Atmosphere revitalization, ISRU processes
- ***Lunar Surface Modification*** – Lunar landing pads, dust free zones and workspaces
- ***Isolation Technologies*** - Technologies that keep dust out

Vision: Build a broad and diverse community specializing in identifying and developing solutions that minimize the impact and hazard of lunar dust on robotic and human systems. Identify needs and gaps in dust mitigation, provide recommendations to foster development, and develop pathways for fielding that technology on future missions.

Objectives:

- Build a diverse community specializing in dust mitigation, including creation of subgroups focused on specific dust mitigation technology areas
- Evaluate specific dust mitigation technology areas for dust mitigation development, testing/maturation capabilities, and gaps
- Provide community recommendations and guides to NASA and broader community to encourage technology investments and how these technologies can be included in future missions

Dust Mitigation Subgroups:

- Participation from broad community is highly encouraged
- Contact: Facilitator_DustMitigation@jhuapl.edu

Dust Mitigation Subgroups

- Optical Systems
- Thermal Surfaces
- Fabrics
- Mechanisms
- Seals and Soft Goods
- Gaseous Filtration
- Lunar Surface Modification
- Isolation Technologies

High priority challenges and needs Identified:

- Establishing set of tolerances allowing systems to operate “dirty”
- Acquisition of ground truth dust properties and plume/ejecta data from precursor missions to validate modeling tools and designs
- Develop and standardize simulants and testing conditions to better capture real dust problems instead of approximations
- Pathways and mechanism for integrating dust tolerant/mitigation technologies into lunar systems and architecture
- Technology demonstrations on CLPS landers to test in real-world conditions

Technology gaps identified:

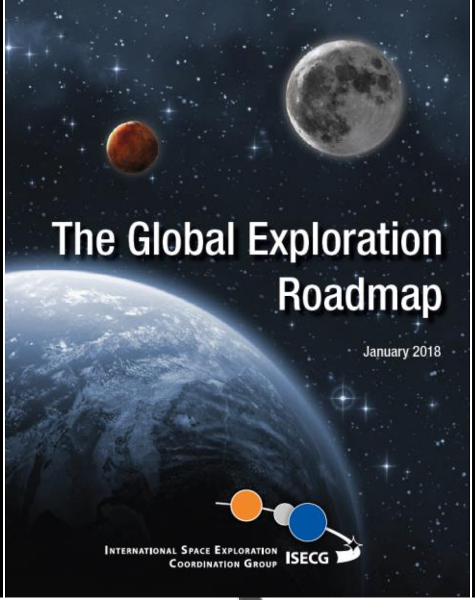
- Landing, launch, and surface transport dust ejecta/plume mitigation
- Passive/Active dust removal tools
- Dust tolerant space suits/fabrics
- Habitats and Vacuum/Filtration
- Dust tolerant mechanisms
- Dust tolerant joints, wheel bearings, and connectors
- Dust tolerant optical power systems
- Dust detection sensors
- Surface modification solutions

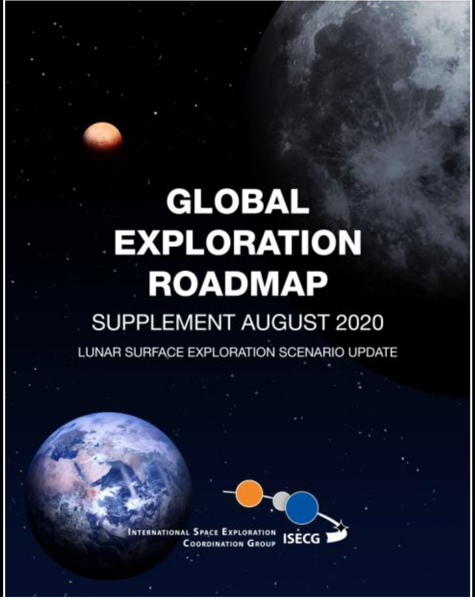
- Additional slides with summary tables from the *Global Exploration Roadmap* (GER; 2018 and 2020 supplement) and the companion white paper *Scientific Opportunities Enabled by Human Exploration Beyond Low-Earth Orbit* (2017).

- The science and technology priorities and vision in the GER are complementary to those in the LER and those expressed by the lunar science community through the other documents presented here.

- https://www.globalspaceexploration.org/

Global Exploration Roadmap





Lunar Science

The Moon preserves many of the geologic processes that occurred early in our Solar System and during the period when life formed. It preserves a record of the impact history over geologic time. Such records have been obliterated on planetary bodies that are active and have atmospheres. The Moon also preserves a record of the Sun's activity in its regolith and the early evolution of terrestrial planets. Volatile deposits at the lunar poles may contain a record of the volatiles transported to the inner Solar System. The radio-quiet lunar far side enables astrophysical investigations into the earliest stages of our universe through the deployment of radio telescopes. Human presence on the Moon would permit detailed geologic mapping, the collection of critical samples for analysis in Earth-based laboratories, and the emplacement of delicate instrumentation, including seismometers and other geophysical instrumentation.

TABLE 3

Lunar Surface Exploration Scenario Objectives

Expand Human Presence into the Solar System | Understand Our Place in the Universe | Engage the Public | Stimulate Economic Prosperity | Foster International Cooperation

OBJECTIVE	RATIONALE	ISECG GOAL	PERFORMANCE MEASURE TARGET*
Demonstrate human landing/ascent capability to and from the lunar surface.	To mitigate the risk for future human Mars exploration and for future government activities and commercial markets on the lunar surface. Number of crew should be as many as possible considering the nature of international programme, but within the realistic constraints of crew transportation capability planned by governments and envisioned commercial missions.	Expand Human Presence into the Solar System; Stimulate Economic Prosperity; Foster International Cooperation	4 crew
Demonstrate a range of cargo delivery capabilities on the lunar surface for large surface elements and logistics.	To mitigate the risk for future human Mars exploration and for future government activities and commercial markets on lunar surface. As much cargo capability as possible is desired. Cargo capacity performance measure range is driven by: 1) Mass of crew consumables necessary for sortie mission will be around 1-2 tons; and 2) current human ascent module is estimated to be 9 tons.	Expand Human Presence into the Solar System; Stimulate Economic Prosperity; Foster International Cooperation	>9 t for large surface elements, >1 t for logistics, x cubic meters of cargo delivered.
Demonstrate Extra Vehicular Activity (EVA) capabilities on the lunar surface.	To mitigate the risk for future human Mars missions and sustainable lunar exploration and for commercial activities on the lunar surface.	Expand Human Presence into the Solar System; Stimulate Economic Prosperity; Foster International Cooperation	Reusable EVA systems with reasonably minimal maintenance including onsite dust management/mitigation and science sampling/ curation techniques.
Demonstrate human long-range traversing capability on the lunar surface.	To mitigate the risk for future human Mars exploration and for future government activities and commercial markets on the lunar surface. Mobility capability design life of 10,000 km is the total round-trip distance to explore and traverse the five crew sites indicated in the 2018 GER.	Expand Human Presence into the Solar System; Stimulate Economic Prosperity; Foster International Cooperation	10,000 km (cumulative)
Demonstrate reliability of human long-duration habitation capability and operational procedures on the lunar surface.	To mitigate the risk for future human Mars exploration and for future government activities and commercial markets on the lunar surface. Systems need to be capable of environmental extremes (e.g., temperature, radiation, pressure). Demonstration of human long-duration habitation and reliability can be achieved over a series of crewed and uncrewed missions, yielding the confidence for long-duration missions on the Moon and Mars. Astronaut operations need to be implemented and checked in different operative scenarios.	Expand Human Presence into the Solar System; Stimulate Economic Prosperity; Foster International Cooperation	500 days (cumulative)
Demonstrate crew health and performance sustainability to live and work on the lunar surface for a sufficient duration to validate Mars surface missions.	To understand the human health effects of low gravity and deep space environment for long-duration missions on the Moon and notional Mars crewed surface mission. A number of medium-duration missions are expected to address the ability to understand how crew health and performance are affected by long duration exposure in the deep space environment.	Expand Human Presence into the Solar System; Understand Our Place in the Universe	TBD days (continuative) Comprehensive evaluation needed to determine the minimum duration and number of missions.
Demonstrate in-situ resource production and utilisation capability sufficient for crew transportation between lunar surface and Gateway and lunar surface utilisation needs.	To expedite sustainability for future human Moon and Mars exploration and to identify future commercial markets on the lunar surface.	Expand Human Presence into the Solar System; Stimulate Economic Prosperity; Foster International Cooperation	Produce 50 tons of propellant per year.
Conduct effective global human/robotic cooperative science exploration to perform groundbreaking science.	To accomplish lunar objectives specified in the ISECG Science White Paper, "Scientific Opportunities Enabled By Human Exploration Beyond Low-Earth Orbit" as well as lunar objectives identified by ISECG agencies.	Understand Our Place in the Universe	Comprehensive evaluation needed to determine value of science.
Develop infrastructure (e.g., power and communication systems) necessary to achieve the objectives for sustained exploration.	To demonstrate and establish infrastructure capabilities including a certain level of power and communication systems for achieving objectives such as long-duration habitation, ISRU, diverse science and public engagement. Commercial activities rely on infrastructure to stimulate economic growth.	Stimulate Economic Prosperity	300 kW of power generation and 1 Gbps for data rates, availability of TBD systems.
Engage the public in general and the youth in particular with human/robotic lunar surface exploration by bringing the action to large audiences, making full use of the state-of-the-art technology and through new ways of communication.	To inspire new generations, increase awareness of the relevance of space, and recognise the importance of different perspectives and domains of knowledge present in different scientific endeavours. Also, public participation is necessary in the long run to ensure sustainability of such plans (civic engagement/empowerment). If space exploration is a topic of interest to the public, the public has increased its potential to participate in policy making or at least influence it. Show the relevance of STEM and inspire young people to follow in those footsteps.	Engage the Public; Stimulate Economic Prosperity	On national level as feasible, measuring positive public attitude towards lunar surface exploration (e.g., > 30% agreement) through surveys, website hits, social media impact, etc.
Implement new commercial arrangements that stimulate economic prosperity and foster commercial opportunities.	To achieve commercially led sustainable (i.e., market-driven economy with diminishing reliance on governments) economic activities on the Moon, new commercial arrangements are essential.	Expand Human Presence into the Solar System; Stimulate Economic Prosperity	Increasing number of commercial partners or stakeholders providing critical lunar services year after year.
Provide a large number of collaboration opportunities for international partners to contribute to the lunar surface scenario.	To encourage global participation in the lunar surface scenario, inclusive of a range of contributions from science to hardware.	Foster International Cooperation	More than 100 nations' participation to lunar surface scenario.

*Performance measure targets reflect long-term objectives and can be achieved in a single mission or over a series of missions across several decades.

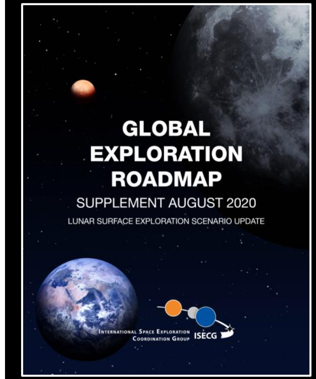
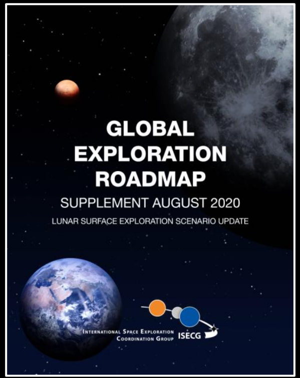
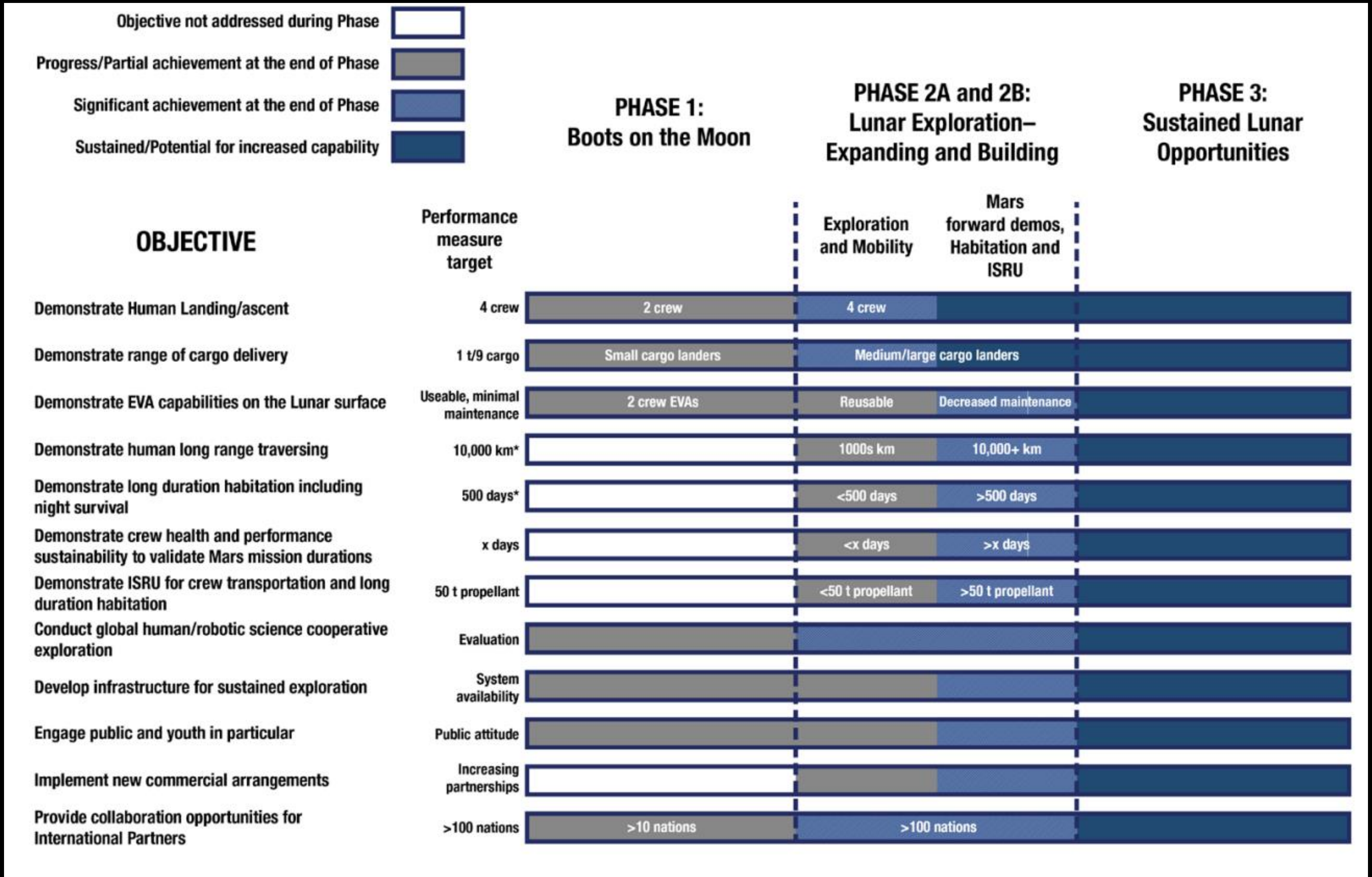


TABLE 4

Key Elements of Lunar Surface Exploration Scenario

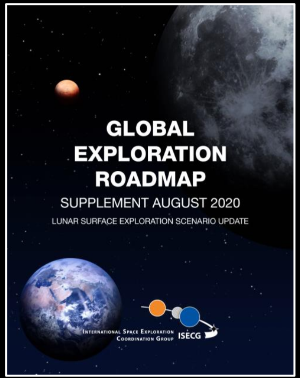
PHASE	ELEMENT	FUNCTION
1	Crew Vehicle	Vehicle provides transportation for a crew of four between Earth and the lunar vicinity, including sustainment of the crew during space travel and providing safe reentry from deep space. As an example, NASA's Orion spacecraft has a four-crew, 21-day capability.
	Unpressurised Rover	Provides transportation on the lunar surface for two extra-vehicular activity (EVA)-suited crew with payload. The range of the unpressurised rover is targeted to be greater than 2 km for each excursion. The rover may be used during uncrewed periods through tele-operations.
	Human Lander	Initial capability will provide transportation for two crew between the lunar vicinity and the lunar surface, with an evolutionary goal of four crew, for up to an 8-day mission.
	EVA Suits	Dedicated suit system for use in deep space in microgravity locations or on the lunar surface to allow crewmembers to perform extra-vehicular activities (EVA) for up to 8 hours. EVA suits are planned to be used through a conventional airlock system and evolve to support suitport capability.
	Small Landers / Robotic Precursors	Delivery of cargo to the lunar surface. Target range of cargo is 10s-100s of kg. Robotic precursors for science, utilisation and potential pathfinder for technology demonstrations.
2A	Small Pressurised Rover	Provides mobility of up to 600 km per mission and habitation for two crew on the lunar surface for up to 42 days. Assumed reuse over multiple crew missions and ability to locate to new landing sites between crew missions.
	Logistics Capability	Delivery of logistics and cargo to the lunar vicinity. Depending on launch vehicle, a range of cargo between ~2000 to 3400 kg can be accommodated to Gateway.
	Medium-Class Cargo Landers	Delivery of cargo to the lunar surface. Target range of cargo is ~1000-2000 kg. Cargo can include science payloads, logistics and equipment.
	Communications Relay	Uplink and downlink of data between lunar surface and Gateway or Earth. Communication bands under consideration include S-band, X-band, Ka-band and optical comm. Gateway elements can fill this need.
	Power	Provides supplemental power generation and storage to localized assets (such as ISRU demonstrations, rover recharge, habitat) on the lunar surface. Target of ~17 kW to support Phase 2A operations.
	Utility Rovers	Provides mobility options to support science and ISRU. Payload accommodations of 25-250 kg. Capable of traveling up to 2000 km.
	ISRU Pilot Plant	Subscale version of the Phase 3 operational plant that demonstrates ~1/100 of the oxygen needed from the Phase 3 operational plant. Will prove safety of operations and reliability needed for the operational plant.
2B	Long-Duration Habitation	Lunar surface habitation to support four crew for up to 60 days. Assumes provisions are delivered separately or with the crew and sufficient volume is available, which may be provided by several pressurised surface elements.
	Reusable Human Lander	Provides crew transportation between lunar vicinity and the lunar surface. Reusable ascent element for a crew of four for a multiple stage lunar lander. Propellant for ascent element can be supplied on orbit or on the surface.
	Nuclear Power	Modular power system sized to provide ~10 kW for the lunar day or night. Multiple units can provide power to meet infrastructure demands.
	ISRU Plant	Operational ISRU plant capable of producing ~50 tonnes of propellant per year. Electrolysis is used to create hydrogen and oxygen for propellant for a reusable lander. Excavation, collection and storage would be part of the plant system.
3	Crewed Hopper	Provides unpressurised two-way crew transportation within a 1000 km range of the landing site for a crew of four EVA-suited astronauts. Hopper is assumed to be refueled on the lunar surface between uses.





Note: Assumes reuse of capabilities into following phases
**** Cumulative over one to several missions***

Figure 5. Objectives Progression across Phases.



Conclusion

Scientific investigations on the Moon will be vital preparation for human visits to more distant solar system destinations. In addition, the investigations will improve our understanding of the origin and evolution of the Earth-Moon system and terrestrial planets in general. The Moon has experienced many of the geologic processes that shape the diverse terrestrial planets in the Solar System: Mercury, Venus, Earth, and Mars. These phenomena (i.e. impact cratering, volcanism, and tectonics) can be studied on the lunar surface to provide insights on the earliest history of the Solar System including the formation and evolution of the terrestrial planets.

The geological complexity of the Moon necessitates careful selection of samples for return to Earth in order to address the plethora of scientific questions related to the lunar surface. Sample return is a significant scientific benefit of human exploration, and lessons learned from the Apollo program include the use of geologically trained explorers for selecting the best samples for analysis.

An example of scientific study that can be advanced by the analysis of new lunar material is the dating of impact events, which will shed light on the impact flux for the Earth-Moon system over geologic time. This will advance scientific knowledge of all planetary bodies as they are dated based on the lunar chronologic record, in addition to various astrobiological ramifications, e.g. meteorite impacts implicated in extinction events on Earth.

Humans will also facilitate the placement of delicate surface instrumentation on planetary surfaces. The far side of the Moon is "radio quiet", offering the unique opportunity for sensitive measurements of the earliest moments of the Universe.

Several life sciences questions pursued by human exploration of the lunar surface will inform and facilitate progress beyond the Earth-Moon system. Long-duration human exposure to the fractional gravity of the Moon may provide insight on a range of health issues such as osteoporosis. It will also guide the protection of astronauts during travel to Mars and extended stays on its surface. Similarly, efficient plant growth in hostile (gravity/radiation) environments is important for sustained human exploration.

To become a truly space-faring-species, humans must use local resources instead of launching all support materials from Earth. The Moon is an ideal location to learn how to "live off the land", and polar ice deposits present opportunities for synergistic science and exploration investigations.

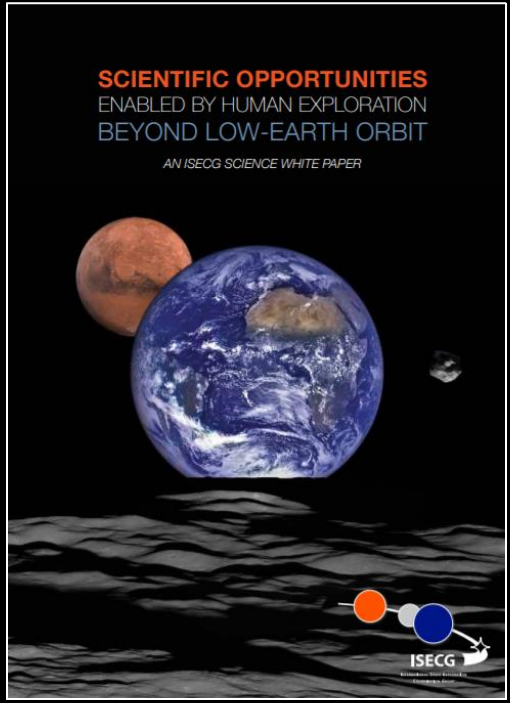
Finally, serendipitous discoveries make human surface exploration such an exciting prospect because so much will be learned that cannot be predicted. The Apollo expeditions show numerous examples of unplanned scientific discoveries occurring due to the sharp eye of a geologically trained astronaut.

Sample collection

Instrumentation

Crew health/ECLSS

ISRU



Global Exploration Roadmap Critical Technologies

(Summary Table)

	Today ISS & Spaceflight Heritage	Near-Future Moon Vicinity/Surface	Future Mars Vicinity/Surface
Propulsion, Landing, Return			
In-Space Cryogenic Acquisition & Propellant Storage	Spacecraft: CPST/eCryo demo	u-G vapor free liquid tank to propulsion transfer, Efficient low-power LOx & H_2 storage >1 Yr (Mars)	
Liquid Oxygen/Methane Cryogenic Propulsion		Throttleable Regen Cooled Engine for Landing (Lunar Scale)	Throttleable Regen Cooled Engine for Landing (Mars Scale)
Mars Entry, Descent, and Landing (EDL)	Spacecraft: MSL class (~900 kg)	Demonstration of advanced technology in deep space environment	Large Robotics >1000 kg; Human ~40,000 kg
Precision Landing & Hazard Avoidance	Spacecraft: Lunar & Mars Landers State-of-the-Art	~100 m accuracy, 10's cm hazard recognition, Support all lighting conditions	
Robust Ablative Heat Shield Thermal Protection	Spacecraft: Orion Heatshield test flight (EFT-1)	~1000 W/cm2 under 1.0 atmospheric pressure	~2,500 W/cm2 under 0.8 atmospheric pressure
Electric Propulsion & Power Processing	Spacecraft: 2.5 kW thruster (Dawn)	~10 kW per thruster, High Isp (2000 s) (for some mission options)	~30-50 kW per thruster (for some mission options)
Mid & High Class Solar Arrays	ISS: 7.5 kW/Panel	High Strength/Stiffness Deployable, 10-100 kW Class (for some mission options)	Autonomously Deployable, 300+kW Class (for some mission options)
Autonomous Systems			
Autonomous Vehicle System Management	ISS: Limited On-Board Mgmt functions, < 5 s comm delay	On-Board Systems Mgmt functions (handles > 5 s comm delay)	On-Board Systems Mgmt functions (handles > 40 min comm delay)
AR&D, Proximity Operations, Target Relative Navigation	ISS: Autonomous docking	High-reliability, All-lighting conditions, Loiter w/ zero relative velocity	
Beyond-LEO Crew Autonomy	ISS: Limited Autonomy	Automate 90% of nominal ops Tools for crew real-time off-nom decisions	
Life Support			
Enhanced Reliability Life Support	ISS: MTBF <10 E-6, Monitored/operated by GC	More robust & reliable components (eliminate dependence on Earth supply logistics) Increased systems autonomy, failure detection capabilities, and in-flight repairability	
Closed-Loop Life Support	ISS: 42% O_2 Recovery from CO_2, 90% H_2O Recovery	Demonstration of advanced technology in deep space environment	O_2/CO_2 Loop closure; H_2O Recovery further closure; Solid Waste, reduce volume/storage
In-Flight Environmental Monitoring	ISS: Samples to Earth	On-Board Analysis for Air, Water, Contaminants	

Global Exploration Roadmap Critical Technologies (Summary Table)	Today ISS & Spaceflight Heritage	Near-Future Moon Vicinity/Surface	Future Mars Vicinity/Surface
Crew Health & Performance			
Long-Duration Spaceflight Medical Care	ISS: First Aid+, return home	Demonstration of advanced technology in deep space environment	Training (pre & in-flight) for medical aspects Continuous monitoring & decision support
Long-Duration Behavioral Health & Performance	ISS: Monitoring by Ground	Demonstration of advanced technology in deep space environment	Cognitive performance monitoring Behavioral health indicators & sensory stim.
Microgravity Counter-Measures	ISS: Large treadmills, other exercise equipment	Demonstration of advanced technology in deep space environment	Compact devices to assess/limit disorders Reduced weight/vol. aerobic & resistive eqpt.
Deep Space Mission Human Factors & Habitability	ISS: Large crew volume, food & consumables regular resupply	Demonstration of advanced technology in deep space environment	Assess human cognitive load, fatigue, health Optimized human systems factors/interfaces
Space Radiation Protection (GCR & SPE)	ISS: Partially protected by Earth Apollo: (accepted risk)	Advanced detection & shielding New biomedical countermeasures	

Global Exploration Roadmap Critical Technologies
(Summary Table)

Infrastructure & Support Systems

Technology	Today ISS & Spaceflight Heritage	Near-Future Moon Vicinity/Surface	Future Mars Vicinity/Surface
High Data Rate (Forward & Return Links)	Ground (DSN): 256 kbs Forward, 10 Mbs Return Link	Demonstration of advanced technology in deep space environment	Forward: 10's Mbps; Return: Optical > 1Gb/s
Adaptive, Internetworked Proximity Communications	ISS: Limited capabilities	Demonstration of advanced technology in deep space environment	>10's of Mbps simultaneously between users Multiple Modes; Store, Forward & Relay
In-Space Timing & Navigation	ISS: Limited to GPS range Spacecraft: DSN Ranging	Demonstration of advanced technology in deep space environment	Provide high-spec Absolute & Relative pos'n Space-Qualified clocks 10x-100x beyond SOA
Low Temperature & Long-Life Batteries	ISS: Lithium-ion (-156 C short duration), ~167 Wh/Kg	Lunar night temperatures and duration	
Comprehensive Dust Mitigation	Apollo: limited 3 day crew ops Rovers: limited mitigation	Multiple Active & Passive technologies required Significant advances in Life cycle	
Low-Temperature Mechatronics	ISS: +121 to -157 C	Operations to -230 C (cryo compatible); multi-year life	
ISRU: Mars In-Situ Resources		Potential Test-Bed for Mars Forward, and enhance lunar missions	O_2/CH_4 generation from atmosphere LOX/LH_2 generation from soil
Fission Power (Surface Missions)		Potential Test-Bed for Mars Forward, and enhance lunar missions	Fission Reactor (10's of kWe)

Global Exploration Roadmap Critical Technologies (Summary Table)	Today ISS & Spaceflight Heritage	Near-Future Moon Vicinity/Surface	Future Mars Vicinity/Surface
EVA/Mobility/Robotic			
Deep-Space Suit	ISS: EVA Ops at 0.3 Bar (4.3 Psid)	EVA Ops at 0.55 Bar (~8 Psid), extended EVA lifecycle On-Back regen CO_2 & humidity control, High Specific-Energy Batteries	
Surface Suit (Moon & Mars)	Apollo: 3 day max (Lunar)	30 day min duration, improved lower torso mobility, dust tolerant	1 year+ duration, thermal insulation (CO_2 atmosphere)
Next Generation Surface Mobility	Spacecraft: Lunar and Mars Rovers State-of-the-Art	Autonomous & Crewed capability, less Ground Control Extended range, speed, payload; navigate soft/steep varying soils	
Tele-robotic Control of Robotic Systems with Time Delay	ISS: <1-10 Sec delay for GC Ops Spacecraft: Lunar/Mars Rovers	Few seconds to 10's of seconds Dynamic environments w/variable delays & LOC	Up to 40 Minutes
Robots working side-by-side w/ crew	ISS: Limited (Robotic support to EVA)	EVA control robots w/ no reliance on Ground Control International standard & protocols	