Strategic Knowledge Gaps for the "Moon First" Human Exploration Scenario

Analysis and Findings of Lunar Exploration Analysis Group (LEAG) GAP-Specific Action Team (SAT)

SAT co-chairs: C.K. Shearer, C. Neal

Informing Exploration: Strategic Knowledge Gaps

- **To inform mission/system planning and design *and* near-term Agency investments**
  - Human Spaceflight Architecture Team (HAT) Destination Leads were asked to identify the data or information needed that would reduce risk, increase effectiveness, and aid in planning and design
  - The data can be obtained on Earth, in space, by analog, experimentation, or direct measurement
- **For some destinations, the needed knowledge is well identified**
  - Analysis Groups, such as LEAG and MEPAG, have identified pertinent measurements to gain the needed knowledge regarding the Moon and Mars
  - Significant advances in filling the knowledge gaps have been made (examples: LRO and MRO, and soon, MSL)
- **The Strategic Knowledge Gaps (SKGs) identified here will:**
  - Be provided to international space agencies in preparation for an upcoming ISECG Technical Interchange Meeting discussing robotic precursor missions
  - Form the basis for near-term Agency investments in robotic precursor missions through Announcements of Opportunity (AO), competed and secondary missions, etc. A few examples include:
    - New Frontiers 4 AO
    - Discovery 13 AO
    - NASA Lunar Science Institute Cooperative Agreement Notice
    - LASER (Lunar Advanced Science and Exploration Research) and SALMON (Stand Alone Missions of Opportunity Notice) calls
    - Development of early flight opportunities

LEAG GAP-SAT Charter

Charter

The Lunar Exploration Analysis Group (LEAG) has been tasked by the Human Exploration and Operations Mission Directorate (HEOMD) to establish a Specific Action Team (SAT) to evaluate and provide findings related to NASA's draft Strategic Knowledge Gaps (SKGs) identified by NASA's Human Spaceflight Architecture Team's destination leads. The SAT will focus on the SKGs in the context of implementing lunar mission scenarios. The Moon is one of the destinations being considered by NASA's Human Space Flight Architecture Team and the International Space Exploration Coordination Group's Global Exploration Roadmap (GER).

Based on the GER's "Moon first" scenario for human exploration beyond low Earth orbit (attached), as well as the broader context of NASA's Human Space Flight Architecture Team's (HAT) mission scenario development, the LEAG SAT **will identify, assess, and refine the basic knowledge / data sets that are required to safely, effectively, and efficiently implement human missions**. The group will **then identify the gaps in those knowledge / data sets that would need to be filled in order to implement the specific mission scenarios**. The missing knowledge could be either enabling (i.e., the absence of a particular knowledge / data set prevents the implementation of the architecture or significantly raises the technical / programmatic / schedule risk) or enhancing (i.e., that knowledge / data set significantly reduces the technical / programmatic / schedule risk). Such knowledge includes technology gaps; **the SAT should highlight any areas where investment in technology development would be enabling or game changing**.

LEAG GAP-SAT Charter

Charter

Of particular note is use of In Situ Resource Utilization (ISRU). The specific resource and its use will depend upon the specifics of the mission scenario and objectives. **For each mission scenario, the group will consider the knowledge / data gaps that exist in order to determine the viability of exploiting the resource in an effective manner.** Depending upon the mission scenario, a resource may include solar energy, various gases extracted from the regolith, or the extraction of other compounds (e.g. H_2O) and the possible production of daughter compounds (e.g., methane, CH_4).

Within the context of identifying strategic knowledge gaps, **the SAT will identify specific robotic precursor missions that could fill these gaps and thereby enable or enhance future human missions.** Potential links of this precursor missions to past National Academy studies (i.e., Planetary Science Division Decadal Survey) and the LEAG Roadmap should be explored.

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LEAG GAP-SAT Charter

Charter-Deliverables

1.List of required knowledge / data sets and their related trace to human exploration needs.

2. Gaps in that knowledge / data sets / technology relative to our current understand or subsequent to an extended Lunar Reconnaissance Orbiter mission or the successful implementation of the LADEE, GRAIL, and projected international robotic missions.

3. A timeline of when the missing knowledge must be acquired (or technology developed) in order to make architecture-specific decisions or in order to make subsequent measurement decisions. In the context of this timeline, the group should consider the typical amount of time between acquisition of the relevant information and the amount of time needed to define and implement a subsequent measurement.

4. Provide a list of existing and potential missions, experiments, modeling activities, technology, or any other activity that would fill the knowledge gaps. **Links of potential missions to past National Academy studies and the LEAG Roadmap should be explored.**

5. If additional measurements are required to fill knowledge gaps, identify the fidelity of the measurements needed, and if relevant, provide examples of existing instruments capable of making the measurements.

The group will assemble the information and findings into an appropriate set of power point charts and back up materials. It will also create a spreadsheet with the individual knowledge elements and whether that information is lacking, and if so how it could be filled.

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Modification to Deliverables
1.This initial phase of the LEAG GAP-SAT analysis focused on vetting the SKG identified by the Human Space Flight Architecture Team (HAT).
2. HAT SKG were modified and reorganized to provide detail and clarity.
3. A timeline of when the missing knowledge was established (or technology developed) in order to make architecture-specific decisions or in order to make subsequent measurement decisions.
4. The analysis identified links of potential missions to past National Academy studies and the LEAG Roadmap should be explored.
5. Philosophy and qualitative description of measurements were identified for knowledge gaps. Further SKGs were defined as enabling or enhancing. Specific quantitative measurements should be made by follow on analyses. The LEAG GAP-SAT analysis should be considered a first step in exploring SKG for lunar exploration. A second LEAG SAT (GAP-SAT II) will provide a quantitative description of measurements that are required to fill knowledge gaps, identify the fidelity of the measurements needed, and if relevant, provide examples of existing instruments capable of making the measurements.

LEAG GAP-SAT Charter

Schedule

December 15-16, 2011, GAP-SAT meets at Lunar and Planetary Institute.

An initial “draft” set of findings will be delivered to NASA on or about January 15, 2012.

A final set of finding will be delivered to NASA no later than March 1, 2012.

GAP-SAT Members

Membership
SAT Members: Chip Shearer, co-Chair: University of New Mexico Clive Neal, co-chair: University of Notre Dame William Farrell, NASA GSFC Sam Lawrence, Arizona State University Dean Eppler, NASA-JSC Paul Spudis, Lunar and Planetary Institute John Gruenner, NASA-JSC Leslie Gertsch, Missouri University of Science and Technology Larry Clark, Lockheed Martin Space Systems
Ex Officio Membership: Chris Culbert, Johnson Space Center John Connolly, Johnson Space Center Michael Wargo, NASA Headquarters

GAP-SAT analysis and restructuring of HAT "Moon First SKG"

The LEAG GAP-SAT analysis used as a starting point, the "Moon First SKGs" initially identified by the Human Space Flight Architecture Team (HAT) as a foundation . The LEAG analysis resulted in numerous changes to the HAT SKGs.

- **HAT-SKGs were reordered and characterized by themes and categories. For example: Themes: I. Understand the lunar resource potential, II. Understand the lunar environment and its effect on human life, and III. Understand how to work and live on the lunar surface.**

- **Although specific SKGs are dependent upon the architecture and goals of the "Moon First Scenario", we examined in detail SKGs tied to resource exploration and utilization (ISRU). This was prompted by ISRU being a "game changer" in how humans explore the Solar System by creating an infrastructure that enables a sustainable human presence.**

- **Several HAT-SKGs were subdivided for clarity**

- **Narratives to HAT-SKGs were expanded to clarify and rationalize the SKG.**

- **SKGs were defined as enabling or enhancing as defined in chart 12.**

- **Changes to the HAT-SKGs are summarized in chart 10.**

Strategic Knowledge Gaps

SKG Themes	SKG Categories	Examples of SKGs
I. Understand the lunar resource potential.	***A. Solar Resources*** ***B. Regolith Resources 1*** ***C. Regolith Resources 2*** ***D. Polar Resources*** ***E. Pyroclastic Deposit Resources*** ***F. Lunar ISRU production efficiency 1*** ***G. Lunar ISRU production efficiency 2***	**I-A** Solar illumination mapping **I-B** Regolith volatiles, Apollo samples **I-C** Regolith volatiles, in situ **I-D** Extent, magnitude and age of cold traps **I-E** Pyroclastic deposit volatiles, in situ **I-F** ISRU production efficiency, Earth testing **I-G** ISRU production efficiency, Moon testing
II. Understand the lunar environment and its effects on human life.	**A.** ***Solar Activity*** **B.** ***Radiation at the lunar surface*** **C.** ***Biological impact of dust*** **D.** ***Maintaining peak human health***	**II-A** Solar Event Prediction **II-B** Radiation shielding effect of lunar materials **II-C** Biological effects of lunar dust. Earth-based testing **II-D** Maintain peak human health and performance in dusty, high-radiation, partial gravity environments
III. Understand how to work and live on the lunar surface.	***A. Resource production*** ***B. Geodetic grid & navigation*** ***C. Surface trafficability*** ***D. Dust and Blast Ejecta*** ***E. Plasma environment and charging*** ***F. Energy production and storage*** ***G. Radiation shielding*** ***H. Micrometeorite shielding*** ***I. Lunar mass contribution and distribution*** ***J. Habatat, life support and mobility***	**III-A** Excavation of lunar resources **III-B** Lunar Geodetic Control **III-C** Trafficability: Modeling **III-D** Lunar Dust Remediation **III-E** Plasma Environment and charging **III-F** Propellant scavenging **III-G** Radiation shielding technology **III-H** Micrometeorite shielding technology **III-I** Lunar mass contribution **III-J** Semi-closed life support

Black text = SKG are identical or similar to those identified by HAT analysis.

Red text = SKG are added or significantly modified from HAT analysis.

Testing Relevancy Descriptions

Venue	Description
🔴	**Preferred Location**: Denotes a preferred testing venue or location for gaining required knowledge. Venue provides the best location to obtain knowledge, including actual or flight-like conditions, environments, or constraints for testing operational approaches and mission hardware.
●	**Highly Relevant**: Venue provides highly relevant location to obtain knowledge, including flight-like conditions, environments, or constraints for testing operational approaches and mission hardware. This venue can serve as a good testing location with less difficulty and/or cost than anticipated for the preferred location.
⊙	**Somewhat Relevant:** Venue can provide some relevant testing or knowledge gain (including basic analytical research and computational analysis). Conditions are expected to be not flight-like or of sufficient fidelity to derive adequate testing or operational performance data.
○	**Not Relevant:** Venue is not considered to be an adequate location for testing or knowledge gain.

Enabling and Enhancing Moon First Scenario

	Definition
Enabling or Enhancing a Moon First Scenario	Following the completion of Lunar Reconnaissance Orbiter mission (LRO) there are no strategic knowledge gaps (SKG) that would inhibit the flight of a Apollo-style mission. However, in the context of a “Moon First Scenario” which develops assets and capabilities for human activity within the Earth-Moon system (EMS) and beyond EMS to NEA and Mars, there are numerous SKG that are required to be filled to enable and enhance more mature human exploration of the Moon and beyond. Enabling and Enhancing are used to fill these “Moon First Scenario” SKG.
Enabling	SKGs that prevent the possibility of carrying out a “Moon First Scenario” due to safety, reliability, operational, and resource utilization issues.
Enhancing	SKGs that inhibit the science-exploration value and effectiveness of the “Moon First Scenario”.

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Strategic Knowledge Gaps
I. Understand the lunar resource potential

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
A. Solar illumination mapping	● (red)	○	○	○	● (red)	Combined elevation-illumination models to map solar energy incidence over time. Data is in hand but R & A resources are required to reduce and leverage the data. LRO extended mission enables detailed multi-temporal mapping of lunar poles. **Detailed mapping enables polar exploration mission site selection.**
B. Regolith 1 Quality/ quantity/distribution/form of H species and other volatiles in mare and highlands regolith. Apollo heritage.	● (red)	●	○	○	○	Measure volatiles and organics returned in "pristine" Apollo samples (core vacuum sample containers 69001, 73001). Measure the extent of disruption of volatiles during handling and processing. **Enables prospecting for lunar resources and ISRU. Feeds forward to robotic and human analysis and sampling of lunar regolith and NEA-Mars. Relevant to Planetary Science Decadal survey.**
C. Regolith 2 Quality/ quantity/distribution/form of H species and other volatiles in mare and highlands regolith. Robotic missions.	⊙	○	○	○	● (red)	Robotic in situ measurements of volatiles and organics on the lunar surface and eventual sample return of "pristine" samples. **Enables prospecting for lunar resources and ISRU. Feeds forward to NEA-Mars. Relevant to Planetary Science Decadal survey.**

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Strategic Knowledge Gaps

I. Understand the lunar resource potential

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
D. Composition/quantity/distribution/form of water/H species and other volatiles associated with lunar cold traps.	●	●	○	○	●	Required "ground truth" in-situ measurement within permanently shadowed lunar craters or other sites identified using LRO data. Technology development required for operating in extreme environments. **Enables prospecting of lunar resources and ISRU. Relevant to Planetary Science Decadal survey.** ***More detail to follow on charts 16-18.***
E. Composition/volume/distribution/form of pyroclastic/dark mantle deposits and characteristics of associated volatiles.	●	●	○	○	●	Required robotic exploration of deposits and sample return. **Enables prospecting for lunar resources and ISRU. Relevant to Planetary Science Decadal survey.**

Strategic Knowledge Gaps

I. Understand the lunar resource potential

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
F. Lunar ISRU production efficiency 1	●	○	○	○	○	Determine the likely efficiency of ISRU processes using lunar simulants in relevant environments. Gap in understanding the yields of volatiles versus strongly-bound species **This is enhancing long duration activity on the Moon and potentially beyond LEO.**
G. Lunar ISRU production efficiency 2	⊙	○	○	○	●	Measure the actual efficiency of ISRU processes in the lunar environment. Highly dependent on location & and nature of the input material This could be tested in the following ways: (1) Produce and store small quantities of hydrogen and oxygen from lunar regolith by melting ice. (2) Demonstrate disposal of heated regolith after processing.(3) Process at high temperature to test techniques for extracting metals (e.g., Fe, Al) from regolith. **This is enhancing long duration activity on the Moon and potentially beyond LEO.**

Strategic Knowledge Gaps

Additional detail for SKG 1D

Map and characterize broadfeatures of polar cold traps

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Extent, magnitude and age of cold traps	●	○	○	○	○	DIVINER maps show temperature distributions, model stability and evolution of spin axis, mapping of old topographic lows.
Correlation of cold traps and permanent darkness (PSR)	●	○	○	○	○	Use LRO data to understand thermal environments of partly illuminated areas near poles
Geotechnical characteristics of cold traps	○	○	○	○	●	Landed missions to understand regolith densities with depth, cohesiveness, grain sizes, slopes, blockiness, association and effects of entrained volatiles
Physiography and accessibility of cold traps (robotic and human)	○	○	○	○	●	Landed missions to understand slopes, elevations, block fields, cohesiveness of soils, trafficability.
Charging and plasma environment within and near PSR	○	○	○	○	●	Landed missions to understand the charge reservoirs (plasma or ground) in the low conductivity environment. Limited plasma flow into PSRs may create poor electrical dissipation for tribocharging objects like drills, rovers, etc. The electrical 'ground' or reference point is not identified. Examine ion entry into PSRs as sputtering loss process.
Earth visibility timing and extent	●	○	○	○	○	Understand if Earth is sometimes visible from portions of PSR.

Strategic Knowledge Gaps
Additional detail for SKG 1D
Determine lateral and vertical distribution and extent of polar volatiles

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Concentration of water and other volatiles species with depth at 1-2 m scales	○	○	○	○	●	Polar cold traps likely less than ~2 Ga, so only upper 2-3 m of regolith are likely to be volatile-rich
Variability of water concentration on scales of 10's of meters	○	○	○	○	●	Volatiles are laterally variable, ranging from 0-100%. Need to know how it varies on scales of 10-100 m
Mineralogical, elemental, molecular, isotopic make up of volatiles	○	○	○	○	●	Water and other exotic volatile species are present; must know species and concentrations
Physical nature of volatile species (e.g., pure concentrations, intergranular, globular)	○		○	○	●	Range of occurrences of volatiles; pure deposits (radar), mixtures of ice/dirt (LCROSS), H_2-rich soils (neutron)

Strategic Knowledge Gaps

Additional detail for SKG 1D
Processes and history of water and other polar volatiles

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Spatial and temporal distribution of OH and H2O at high-latitudes	⦿	○	○	○	●	Survey surface-correlated OH at high latitudes with spectral mapping from orbit; correlate with exospheric measurements
Detect and measure exospheric water in association with surface-correlated deposits	○	○	○	○	●	Measure temporal and spatial distribution of water and other volatile species in exosphere
Monitor and model movement towards and retention in PSR	⦿	○	○	○	●	Measure gradient of concentration with latitude

Strategic Knowledge Gaps

II. Understand the lunar environment and its effects on human life

A. Solar Activity

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Solar event prediction	● (red)	○	⦿	⦿	●	Establish space weather modeling, forecasting and monitoring capabilities to warn transit/surface crews of potentially hazardous solar events. The goal of these systems should be to provide as early a warning as possible of dangers. Two time scales for consideration: alert on ~5- 10 days as active regions rotate s into moon-view (Sentinel monitor) and 10's of minutes to protect from an immediate release of an Earth-directed CME and associated SEPs **This is enabling for long duration human activity on the Moon and human exploration of NEA and Mars.**

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Strategic Knowledge Gaps

II. Understand the lunar environment and its effects on human life

B. Radiation at the lunar surface

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Radiation environment at lunar surface 1	●	○	○	○	○	Model primary and secondary radiation components; confirm secondary models by measuring the affect of appropriate, comprehensive radiation sources at terrestrial laboratories (e.g. Brookhaven) on detectors such as TPCCs and lunar soil/simulant. **Enabling technology for human safety**.
Radiation environment at lunar surface 2	⊙	○	○	○	●	Landed robotic missions needed to directly measurement primary and albedo/ secondary radiation on the lunar surface for Galactic Cosmic Rays and solar-derived radiation sources; GCRs and solar sources should be measured over a minimum of one solar cycle. **Enabling technology for human safety**.
Radiation shielding effect of lunar materials 1	●	○	○	○	○	Model and measure the radiation shielding properties of lunar soil samples and/or simulant. **Enabling technology for resource utilization.**
Radiation shielding effect of lunar materials 2	⊙	○	○	○	●	Landed robotic missions needed to directly measurement radiation shielding properties of lunar soil by covering detector arrays with variable depths and densities of regolith; detector arrays must have sufficient sensitivity and variation in particle energy to cover both the expected population of solar-derived radiation and Galactic Cosmic Rays. **Enabling technology for human safety**.

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Strategic Knowledge Gaps

II. Understand the lunar environment and its effects on human life.

C. Biological impact of dust

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Biological effects of lunar dust. Earth-based testing	●	●	○	○	○	Production of relevant lunar soil simulants. Measure reactivity of archived Apollo samples/lunar soil simulants. Measurements of the most pristine samples could yield the best data **This is enabling for a longer duration activity**
Biological effects of lunar dust. In situ testing	●	○	○	○	●	Test reactivity dust in the lunar environment. **This is enabling for a long duration activity.**

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Strategic Knowledge Gaps

II. Understand the lunar environment and its effects on human life.

D. Maintaining peak human health

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
How to maintain peak human health and performance in dusty, high-radiation, partial gravity environments	●	● (red)	●	⊙	○	Research the fundamental biological and physiological effects of the integrated lunar environment on biological systems In partial gravity environments, the effects of the mixed-type radiation spectrum, and the consequences of exposure to anhydrous lunar dust. **This is enabling the design and development of counter measures.**

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Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface

A. Resource Production

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Technology for excavation of lunar resources	⦿	●	○	○	● (red)	Create trenches, roads and collect raw material; enables ISRU and trafficability and plume mitigation**.** **Enabling for resource production on a large scale.**
Technologies for transporting lunar resources*	⦿	● (red)	●*	○	●	Load excavated regolith, transport, process, and dispose of regolith; enables ISRU, trafficability and plume mitigation. **Enabling for resource production on a large scale.**
Technologies for comminution of lunar resources	⦿	● (red)	○	○	●	Crush, grind; can greatly enhance ISRU efficiency; enables; understand effects of comminution. **Enabling for resource production on a large scale.**
Technologies for beneficiating lunar resources	⦿	● (red)	○	○	●	Sort by properties; some techniques are affected by gravity; can greatly enhance ISRU efficiency. **. Enabling for resource production on a large scale.**

* Technologies for transporting lunar resources: If refueling depots in cis-lunar space are part of the architecture, SKGs regarding transport of ISRU products could be closed using experiments developed for the ISS.

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Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface.

B. Geodetic Grid and Navigation

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Lunar Geodetic Control	● (red)	●	○	○	○	Combine Kaguya, ULCN2005, LRO LOLA, and LRO WAC GLD100 topographic products to produce a definitive lunar geodetic grid to facilitate future exploration planning**. This enhances current capabilities.**
Lunar Topography Data	●	○	○	○	● (red)	LRO data (LOLA and LROC WAC) has produced substantial improvements in lunar topography, providing two independent global topographic datasets with ~200 m/pixel resolution, which enables many exploration missions. An LRO extended mission of at least 5 years duration (i.e., to 2017) will enable collection of a definitive global DTM with 1-2 m/pixel resolution using the LROC Narrow Angle Cameras. This could be accomplished if HEOMD took over LRO once SMD accomplishes science goals. **This significantly enhances exploration planning and lowering the cost of future human lunar exploration.**
Autonomous surface navigation	●	○	○	○	● (red)	Ability to remotely traverse over long distances enables a)pre-positioning of assets and b) robust robotic precursor missions. Requires sliding autonomy and localized hazard avoidance technology (e.g., DARPA Grand Challenge). Significant development work can be performed on Earth prior to lunar surface deployment. **Enhances exploration by reducing cost and increasing the safety for human crews on over-the-horizon or long distance traverses. Enables lunar logistics.**

Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface

C. Surface trafficability

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Lunar surface trafficability: Modeling	● (red)	●	○	○	○	Production of relevant lunar soil simulants. Geo-technical testing (especially trafficability) of prototype or test hardware in high fidelity regolith simulants. Not required for Apollo-zone exploration but important for unexplored areas like Aristarchus-style regional pyroclastic deposits the lunar poles, and melt sheets of large impact craters. **Enables the characterization of a site for building-up asset for long duration activities. Enhances exploration of unexplored areas; required for large-scale ISRU.**
Lunar surface trafficability: in-situ measurements	●	○	○	○	● (red)	Characterization of geotechnical properties and hardware performance during regolith interactions on lunar surface. **Enables the characterization of a site for building-up asset for long duration activities. Enhances hardware performance in ongoing program.**

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Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface

D. Dust and Blast Ejecta

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Lunar Dust Remediation	●	●	○	○	● (red)	Test existing, well-defined mitigation strategies for hardware interactions with lunar fines, such as hardware encapsulation and microwave sintering of lunar regolith to reduce dust prevalence. **Dust remedition technology is enabling for human lunar exploration**.
Regolith adhesion to human systems and associated mechanical degradation	⊙	⊙	●	○	● (red)	In situ grain charging and attractive forces under appropriate plasma conditions to account for electrical dissipation . Analysis of wear on joints and bearings, especially on space suits **This is enabling for long duration activity on the Moon**.
Descent/ascent engine blast ejecta velocity, departure angle and entrainment mechanism	●	● (red)	○	○	○	Laboratory modeling with plume and entrained simulant. Measurements of the extent of high velocity sandblasting of *Surveyor 3.* **This is enabling for long duration activity on the Moon. Enhances robotic sample return to aid in resource characterization.**
Descent/ascent engine blast ejecta velocity, departure angle and entrainment mechanism	●	●	○	○	● (red)	Metric camera measurement of actual landing conditions and in-situ measurements of witness plates. **This is enabling for long duration activity on the Moon. Enhances robotic sample return to aid in resource characterization.**

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Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface.

E. Plasma environment and charging

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Determining near-surface plasma environment and nature of differential electrical charging at multiple lunar localities (includes PSRs)	⦿	○	○	○	●	The lunar near-surface electrical field and plasma environment is poorly known due to lack of direct, long term observations. Significant questions remain as to the degree of charging of hardware on the lunar surface, particularly night-side of the lunar terminator. Also, surface and surface-placed objects may undergo large changes in potentials during passages of solar storms. Direct observation is required in order to understand the variations of the electrical 'ground' defined by the plasma currents to an object placed on the surface. In PSRs, the lack of an obvious charge reservoir (i.e., low conductivity surface and obstructed plasma) suggests the possibility of poor electrical dissipation for tribocharging objects like drills, and rover tires. A surface mission would directly complement LADEE. **This is enabling surface operations and human safety.** .

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Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface

F. Energy Storage and Power Generation 1

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Energy Storage – non polar missions	⦿	●	○	○	⦿	Non-polar regions experience 14 days without solar power; needs for entire lunar night in the 100s to 1000s kW-hrs; batteries will be prohibitively heavy. **Enhancing robotic and human activity on the lunar surface. Enabling for long duration activity.**
Energy Storage – Polar missions	⦿	●	○	○	⦿	Polar missions may be positioned in areas with extended solar availability; blackouts may extend 3-5 days requiring 100s of kW-hours; batteries will be prohibitively expensive. **Enhancing robotic and human activity on the lunar surface. Enabling for long duration activity.**
Power Generation – Non-polar missions	⦿	●	○	○	⦿	Non-polar missions will require 10s of kiloWatts of deployable solar power; longer missions require 2-3 times mission power for stored energy. **Enhancing robotic and human activity on the lunar surface. Enabling for long duration activity.**
Power Generation – Polar missions	⦿	●	○	○	⦿	High grazing angle at poles requires rotational tracking preferably on high mast. **Enhancing robotic and human activity on the lunar surface. Enabling for long duration activity.**

Strategic Knowledge Gaps
III. Understand how to work and live on the lunar surface
F. Energy Storage and Power Generation 2

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Lander propellant scavenging	⦿	○	○	○	●	Determine the efficiency of extracting residual oxygen from tanks in lunar landers. Variables include propellant settling in 1/6g, and LOX-He separation. **Enhances exploration by increasing the efficiency of using available resources.**

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Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface

G. Radiation Shielding

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Test radiation shielding technologies	●	● (red)	⊙	○	●	In addition to Earth-based testing, could be further accomplished during robotic missions. **Enabling for protecting astronauts on the lunar surface from galactic cosmic rays (GCR) and solar energetic particle (SEP) events.**

Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface

H. Micrometeorite Protection

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Test micrometeorite protection technologies	●	●	⦿	○	●	Need to develop experimental data for the range of micrometeorite impactors and impact energies expected in the lunar environment. Data to be used for the development of improved hydrodynamic codes for impact shielding, which can in turn be tested in terrestrial gun facilities. Enabling for the developing all surface equipment, including rovers, EVA system hardware, landers experiments and orbiting hardware. Testing these technologies could be done during robotic sample return. **Enhances safety on the lunar surface.**

Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface

I. Lunar Mass Concentrations and Distributions

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Lunar Mass Concentrations and Distributions (i.e. Gravitational anomalies)	⊙	○	○	○	●	Understanding of the lunar gravity field affects the accuracy of navigation predictions, the ability to do precision landing and the stability of spacecraft left in orbit for long periods w/o active orbit maintenance (e.g, the stability of the Apollo 15 ejected sub-satellite (months) to similar hardware on Apollo 16 (2 weeks). The Kaguya and LRO missions have significantly improved our experience with stable orbits; GRAIL will provide very detailed knowledge of the lunar gravity field. **Enhancing knowledge of orbital dynamics and resource prospecting.**

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Strategic Knowledge Gaps

III. Understand how to work and live on the lunar surface

J. Habitat, life support, and mobility

Strategic Knowledge Gap	Research and Analysis	Earth-based Testing	ISS / ISTAR	LEO	Robotic Lunar Missions	Narrative
Fixed Habitat	⦿	●	○	○	○	
Mobile Habitat	⦿	●	○	○	○	
Semi-closed life support	⦿	●	○	○	○	
Human Mobility System	⦿	●	○	○	⦿	

Strategic Knowledge Gaps

Linkages to Planetary Science Decadal Survey and LEAG Lunar Exploration Roadmap

Strategic Knowledge Gap	Enabling or fulfilling science identified in Planetary Science Decadal Survey	Sequence in LEAG Lunar Exploration Roadmap P= prior to precursor missions E = robotic precursor missions M=robotic precursor missions & short duration human missions L=long duration human missions
I-A. Solar Resources	●	P
I-B Regolith Resources	●	P
I-C Regolith Resources	●	E
I-D Polar Resources	●	E
I-E Pyroclastic Deposit Resources	●	E
I-F Lunar ISRU production efficiency		P
I-G Lunar ISRU production efficiency		E
II-A Solar Activity	●	E
II-B Radiation at the lunar surface	●	E
II-C Biological impact of dust		M-L
II-D Maintaining peak human health		M-L

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Strategic Knowledge Gaps

Linkages to Planetary Science Decadal Survey and LEAG Lunar Exploration Roadmap

Strategic Knowledge Gap	Planetary Science Decadal Survey	Sequence in LEAG Lunar Exploration Roadmap P= prior to precursor missions E = robotic precursor missions M=robotic precursor missions & short duration human missions L=long duration human missions
III-A Resource production		L
III-B Geodetic grid & navigation	●	P-E
III-C. Surface trafficability		M
III-D. Dust & Blast Ejecta		P-M
III-E. Plasma environment & charging	●	E-M
III-F. Energy production and storage		L
III-G. Radiation shielding		L
III-H. Micrometeorite shielding		L
III-I. Lunar mass concentrations and distribution	●	P
III-J Habatat, life support and mobility		M-L

Strategic Knowledge Gaps

Linkage to LEAG Robotic Precursor Campaign

<u>Pre-Phase I.</u> **Building upon the results of the Kaguya, GRAIL, LRO/LCROSS, Chandrayaan-1, Lunar Prospector, and Clementine, as well as samples returned from the Apollo Program. Technology development of in-situ resource utilization should occur during this phase.**

<u>Phase I: Lunar Resource Prospecting.</u> **In this phase, mobile explorers are required to explore polar regions (volatiles) and non-polar regions (e.g., mature Ti-rich soil for solar wind implanted H, pyroclastic deposits for indigenous volatiles, etc.). These prospectors will incrementally fill strategic knowledge gaps by:**

- **Defining the composition, form, and extent of the resource;**
- **Characterizing the environment in which the resources are found;**
- **Defining the accessibility/extractability of the resources;**
- **Quantifying the geotechnical properties of the lunar regolith in the areas where resources are found;**
- **Being able to traverse several kilometers and sample and determine lateral and vertical distribution on meter scales;**
- **Identifying resource-rich sites for targeting future missions.**
- **Achieving these objectives requires the ability to traverse several kilometers, sample and determine lateral and vertical distribution on meter scales, and operate (for the polar regions) in a low-temperature permanently dark environment.**
- **Although the focus of these missions are on resources, other knowledge gaps such as plasma environment and charging, geodetic grid, dust-blast ejecta, surface trafficability, solar activity, radiation at the surface can be addressed.**

Strategic Knowledge Gaps

Linkage to LEAG Robotic Precursor Campaign

Phase II: Lunar Resource Mining (LRM). Based on the Phase I results, an end-to-end resource miner feasibility demonstration would be deployed to the area with the most abundant and extractable resources. During this phase the following need to be demonstrated:

- **Feedstock acquisition and handling;**
- **Resource extraction, refinement, transport, and storage;**
- **Usability of resources (e.g., fuel cell, small engine test; propellant depot test);**
- **Regolith handling and size sorting technologies (only for mineral-based resources);**
- **Operable life to give information on the longevity of systems and materials in the lunar environment;**
- **Dust mitigation strategies.**

Phase III: Lunar Resource Production. Based upon the results of Phase II, a larger-scale (i.e., more appropriate scale) continuous processing capability would be deployed to the most appropriate site. Greater quantities of resources will be produced and be used to undertake more extensive demonstrations such as life support, mobility technologies, and fuel for a robotic sample return.

- **An automated full-scale production capability would be established prior to the first extended human stay on the lunar surface.**

Strategic Knowledge Gaps

Linkages to LEAG Robotic Precursor Campaign

Strategic Knowledge Gap	Pre-Phase I	Phase I. Lunar Resource Prospecting	Phase II: Lunar Resource Mining	Phase III: Lunar Resource Production
I-A. Solar Resources	●			
I-B Regolith Resources	●			
I-C Regolith Resources		●		
I-D Polar Resources		●		
I-E Pyroclastic Deposit Resources		●		
I-F Lunar ISRU production efficiency	●			
I-G Lunar ISRU production efficiency		●		
II-A Solar Activity	●	●		
II-B Radiation at the lunar surface		●	●	●
II-C Biological impact of dust				●
II-D Maintaining peak human health	●	●	●	●

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Strategic Knowledge Gaps

Linkages to LEAG Robotic Precursor Campaign

Strategic Knowledge Gap	Pre-Phase I	Phase I. Lunar Resource Prospecting	Phase II: Lunar Resource Mining	Phase III: Lunar Resource Production
III-A Resource production			●	●
III-B Geodetic grid & navigation	●			
III-C. Surface trafficability		●	●	●
III-D. Dust & Blast Ejecta	●	●	●	●
III-E. Plasma environment and charging		●	●*	
III-F. Energy production and storage				●
III-G. Radiation shielding		●		
III-H. Micrometeorite shielding		●		
III-I. Lunar mass concentrations and distribution	●			
III-J Habatat, life support and mobility			●	●

*** Phase I or II could include flying a space weather package to address both radiation and surface charging issues.**

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Evolutionary strategy for filling SKG

2011 2020 2030 2034

On-going and developing missions

LRO Grail LADEE

Small-scale, Human-scale, Human enabled

Opportunities for commercial or international lunar missions

I-A. Solar Resources
I-B Regolith Resources
I-F Lunar ISRU production efficiency
II-A Solar activity
II-D Maintaining peak human health
III-B Geodetic grid & navigation
III-D. Dust & Blast Ejecta
III-I. Lunar mass concentrations

I-C,D,E. Resources exploration
I-G Lunar ISRU production efficiency
II-A Solar activity
II-B Radiation at the lunar surface
II-D Maintaining peak human health
III-C. Surface trafficability
III-D. Dust & Blast Ejecta
III-E. Plasma environment & charging
III-G. Radiation shielding
III-H. Micrometeorite shielding

II-B Radiation at the lunar surface
II-D Maintaining peak human health
III-A Resource production
III-C. Surface trafficability
III-D. Dust & Blast Ejecta
III-E. Plasma environment & charging
III-J Habatat, life support and mobility

II-B Radiation at the lunar surface
II-C Biological impact of dust
II-D Maintaining peak human health
III-A Resource production
III-C. Surface trafficability
III-D. Dust & Blast Ejecta
III-F. Energy production and storage
III-J Habatat, life support and mobility

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Example: Filling SKG within HAT “Moon First” Scenarios #3⇒#5⇒#43)

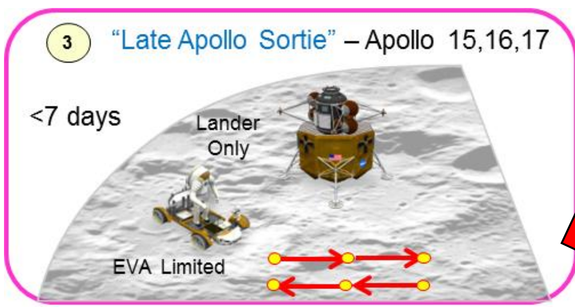
Building Blocks for Enabling and Enhancing Scenario Sequence #3 ⇒#5 ⇒#43

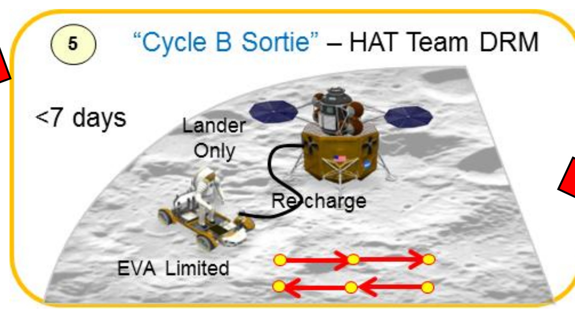
PRE-Phase 1
- I-A. Solar Resources
- I-B Regolith Resources
- I-F Lunar ISRU production efficiency
- II-A Solar activity
- II-D Maintaining peak human health
- III-B Geodetic grid & navigation
- III-D. Dust & Blast Ejecta
- III-I. Lunar mass concentrations

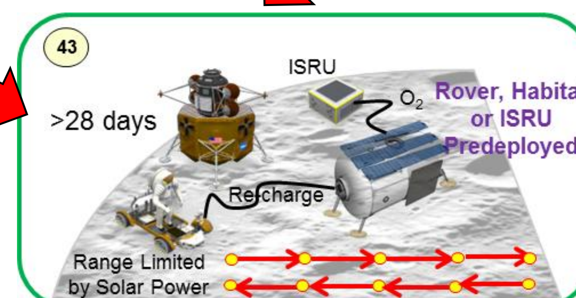
Phase 1
- I-C,D,E. Resources exploration
- I-G Lunar ISRU production efficiency
- II-A Solar activity
- II-B Radiation at the lunar surface
- II-D Maintaining peak human health
- III-C. Surface trafficability
- III-D. Dust & Blast Ejecta
- III-E. Plasma environment & charging
- III-G. Radiation shielding
- III-H. Micrometeorite shielding

Phase 2
- II-B Radiation at the lunar surface
- II-D Maintaining peak human health
- III-A Resource production
- III-C. Surface trafficability
- III-D. Dust & Blast Ejecta
- III-E. Plasma environment & charging
- III-J Habatat, life support and mobility

Phase 3
- II-B Radiation at the lunar surface
- II-C Biological impact of dust
- II-D Maintaining peak human health
- III-A Resource production
- III-C. Surface trafficability
- III-D. Dust & Blast Ejecta
- III-F. Energy production and storage
- III-J Habatat, life support and mobility







Strategic Knowledge Gaps (SKG)
Findings I

- **Finding 1. Following the completion of Lunar Reconnaissance Orbiter mission (LRO) there are no SKGs that would inhibit the flight of a Apollo-style mission.**

- **Finding 2. However, in the context of a "Moon First Scenario" which develops assets and capabilities for human activity within the Earth-Moon system (EMS) and beyond EMS to NEA and Mars, there are numerous SKGs that enable and enhance a more mature human exploration of the Moon.**

- **Finding 3. Although specific SKGs are dependent upon the architecture of the "Moon First Scenario", resource exploration and utilization (ISRU) is a "game changer" in how humans explore the Solar System by creating an infrastructure that enables a sustainable human presence.**

Strategic Knowledge Gaps
Findings II

- **Finding 4. Prior to robotic missions, SKGs can be filled with on-going missions, ISS, Earth-based technology development, and lunar samples studies. SKG that can be addressed in this manner include: I-A. Solar Resources, I-B Regolith Resources, I-F Lunar ISRU production efficiency, II-A Solar activity, III-B Geodetic grid & navigation, II-D Maintaining peak human health, III-D. Dust & Blast Ejecta, and III-I. Lunar mass concentrations and distribution.**

- **Finding 5. A systematic robotic precursor campaign can be used to fill additional SKGs to enable and enhance a "Moon First Scenario" as noted in Finding 2. Although these robotic mission emphasize SKGs tied to investigating unexplored lunar terrains, prospecting for potential resources, and resource utilization, they are apt for filling SKGs relevant to plasma environment and electrical charging, radiation on the lunar surface, effect of dust on technology and biology, surface trafficability, and propulsion-induced ejecta.**

- **Finding 6. In addition to filling SKGs, robotic and early human missions both enable and enhance important lunar and solar system science that has been identified in the NRC Planetary Science Decadal Survey, other NRC studies, and LEAG Exploration Roadmap.**

Strategic Knowledge Gaps
Findings III

- **Finding 7. The LEAG GAP-SAT analysis should be considered a first step in exploring SKG for lunar exploration. A second LEAG SAT (GAP-SAT II) will provide a quantitative description of measurements that are required to fill knowledge gaps, identify the fidelity of the measurements needed, and if relevant, provide examples of existing instruments capable of making the measurements.**

- **Finding 8. SKGs tied to the "Moon First" Scenario cross-cut other destinations.**
  - The three R's for enabling human missions: Radiation, Regolith, Reliability
  - Geotechnical properties
  - Volatiles (i.e., for science, resources, and safety)
  - Propulsion-induced ejecta (Moon, NEAs, Mars)
  - In-Situ Resource Utilization (ISRU)/Prospecting (Moon, NEAs, Mars)
  - Operations/Operability (all destinations, including transit)
  - Plasma environment and charging (Moon, NEAs)
  - Human health and performance (all destinations, including transit)