Lunar Exploration Analysis Group
Report of Analysis Results of the Exploration Specific Action Team (EXPO-SAT)

Introduction

The President's FY2011 NASA budge request directs the Exploration Systems Mission Directorate (ESMD) to develop a robotic precursor mission line that will lead to the development of a sustainable human solar system exploration program. Expo-SAT was organized to give a rapid response to a request from ESMD for a basis for this precursor program from the Lunar Exploration Analysis Group (LEAG) and its lunar community-based roadmap. The request was as follows:

ESMD requests the LEAG to form a Specific Action team (SAT) to give input to the robotic precursor mission line in the FY 2011 NASA budget. The SAT should examine exploration objectives in the "Early" stage of the existing Lunar Exploration Roadmap and extract key precursor investigations that enable future human exploration of the solar system. Such objectives include those that set the stage for human missions to the lunar surface and reduce both mission and astronaut risk. They also include resource identification, quantification, extraction, and utilization. This study will inform the definition of the exploration precursor robotic program. The analysis should identify key technology developments and demonstrations, as well as potential commercial on ramps. The report should also include a narrative on the benefits that such precursor investigations provide to enabling human exploration to the Moon as well as other solar system destinations. It is requested that the SAT report be delivered no later than April 9th, 2010.

Background:

The President's FY 2011 NASA budget directs ESMD to develop a robotic precursor mission line that would lead to the development of a sustainable human solar system exploration program. The requested SAT will leverage the existing Lunar Exploration Roadmap and use the results from this SAT to further revise the roadmap.

Procedures

Expo-SAT consisted of a core group of G. Jeffrey Taylor (University of Hawaii), Kurt Sacksteder (NASA Glenn Research Center), and Jeffrey Volosin (NASA Goddard Space Flight Center), with results reviewed by the entire Executive Committee of the Lunar Exploration Analysis Group. The core group is comprised of the Theme Leads for the Lunar Exploration Roadmap. As charged, the report focuses on near-term robotic mission investigations that would enable human exploration. The report is based almost entirely on previously developed LEAG SAT documents, with small modifications made on the basis of results from recent lunar orbital missions. These documents are the following:

Report of Analysis Results of the Geology-Geophysics Specific Action Team, (GEO-SAT)
http://www.lpi.usra.edu/leag/reports/geo_sat.pdf
LEAG Geological Science GEO-SAT Spreadsheet
http://www.lpi.usra.edu/leag/reports/geo_sat.xls
Report of Analysis Results of the Habitation Specific Action Team, (HAB-SAT)
http://www.lpi.usra.edu/leag/reports/hab_sat.pdf
LEAG Habitation HAB-SAT Spreadsheet
http://www.lpi.usra.edu/leag/reports/hab_sat.xls

DRAFT Lunar Exploration Roadmap
http://www.lpi.usra.edu/leag/ler_draft/draft_ler_v1.pdf

> These reports comprise input from the combined human exploration and multi-discipline science communities, including opportunities during their formulation to contribute content and comment via the Internet. Consensus priorities established by those analyses are unchanged in the present report. Only those objectives and investigations that were assigned as needing to be done early (robotic precursor missions or by the first, short-duration, human missions) are included in this analysis. As noted, the EXPO-SAT leverages the existing LEAG Roadmap. Results from this SAT represent a changing circumstance in terms of the role of the Moon in solar system exploration, so they will be used for further roadmap revision

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Paul Eckert – Boeing Corporation
Greg Schmidt – NASA Lunar Science Institute
Kurt Sacksteder – ISRU Rep., NASA Glenn Research Center
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Findings

The referenced source documents from which this report is drawn were the combined efforts of the exploration and science communities. Those previous findings provided prioritized objectives for lunar exploration and science missions that would be decades in their completion, lead to permanent habitation of the moon with both scientific and commercial activity, and provide strong development support for extending human exploration well beyond the moon. The blending of exploration and science objectives in these previous findings is possibly the most important contribution of the efforts that formed them. Early scientific objectives contribute to enabling human exploration in specific, practical ways; and subsequent human exploration and the accompanying technological capability tremendously expand the possibilities for scientific advancement. At the same time, the accumulation of scientifically enabled technological capability and operational experience for human exploration is not limited to fulfilling only scientific goals, but creates the opportunity for bringing first the Moon then other destinations into the Earth's economic sphere.

The reference documents, especially the Draft Lunar Exploration Roadmap, provide time-phased priorities, including activities that contribute the most benefit if accomplished early. The earliest of these activities and a description of their contribution to the resumption of human exploration of the moon are the core of the present findings. They are limited to those things that are achievable with near-term robotic missions to the moon, but in most cases these same objectives are quite adaptable to other destinations including Mars and small bodies.

The organizing objective of these early mission are natural resources - the identification, quantification, and mapping of natural resources, and subsequent demonstrations of capabilities to thoughtfully and efficiently use those resources to reduce the mass, cost and risk associated with human exploration. This premier priority is established in view of knowledge that there are other important technological advances needed for sustainable human space exploration including transportation and habitability capabilities. Natural resource-based exploration provides clear direction to human exploration, including site selection and the needed operational capabilities and objectives. Demonstrated ability to use quantified resources to reduce the mass, cost and risk of crewed missions is essential at the earliest stages of crewed mission planning so that those benefits are incorporated into the core of the relevant hardware engineering approach.

Similarly, a number of technology demonstrations could contribute to design optimization for future human and advanced robotic surface systems. These risk reduction demonstrations could reduce subsystem mass, volume, crew time and other resource requirements while improving reliability. The key will be to perform these demonstrations early enough in the development life cycle of future human surface systems to ensure that the results can be factored into designs.

A. Lunar Resources

These findings comprise objectives for robotic precursor missions derived from the reference documents that logically progress from resource prospecting to resource extraction and utilization demonstrations. The scope of the objectives begins modestly, then expands in duration and spatial reach with increasing experience in taming the difficult lunar environment.

1. Prospecting for Volatiles in Polar Regions

Sustained space-faring capability requires the use of extraterrestrial resources. An important first step in space resource utilization is to identify locations where specific resources exist in concentrations high enough to be useful for settlements and commerce. Results from previous missions, including detailed studies of samples returned by Apollo missions, have revealed a great deal about the resource potential of the Moon. This information includes the physical, chemical, and mineralogical make up of the regolith, solar wind contents, and concentrations and distribution of elements useful in construction (e.g., iron, aluminum). Additional prospecting missions may be needed at some point, but early robotic prospecting should concentrate on locations with potentially important resources that we know little about: permanently-shadowed regions at the poles.

Rationale

The Moon's spin axis is nearly normal to the ecliptic (88.5° inclination), resulting in locations of permanent darkness and quasi-permanent sunlight near the poles. The dark regions are extremely cold and any volatile material that gets into them cannot escape, becoming "trapped" for geological time spans. The possibility of trapped volatiles in the lunar polar regions is important as a resource to support human habitation and exploration of the Moon as well as the industrialization of cislunar space.

Determining the concentration, distribution, and composition of deposits in and near permanently-shadowed regions of the Moon is critical for making fundamental decisions about how human exploration and potential human settlement of the Moon is approached. Recent results from orbital and impactor missions indicate that significant deposits of water ice are available in polar regions. Such deposits would be extremely valuable for propellant and life support, and would be require less energy to extract (heating to 100°C versus at least 900°C for hydrogen reduction of non-polar regolith), assuming that H_2O is almost entirely in ice, not hydrous minerals. In the budget-constrained long-term political environment, strategic decisions should be made with all the pertinent data that can be assembled.

Sources:
HAB-SAT objective mLRU1: Characterize and quantify the resource potential of the Moon.
LER: Objective Sci-A-3: Characterize the environment and processes in lunar polar regions and in the lunar exosphere.
LER: Objective Sci-A-1: Understand the environmental impacts of lunar exploration.
LER: Objective Sci-A-4: Understand the dynamical evolution and space weathering of the regolith

Feed Forward to Mars and Other Destinations:
LER Objective FF-A-4: Develop the capability to acquire and use local resources to sustain long-term exploration and habitation of planetary surfaces.
LER Investigation-FF-A-4A: Test resource identification/characterization procedures and technologies.

Initiative-A: Map and characterize the broad features of polar cold traps

In order to most effectively make use of the permanently shadowed regions on the lunar poles,, we must accomplish the following tasks before making detailed studies. Most of these measurements have been or are being accomplished or partially addressed by orbital missions such as LRO, Chandryaan-1, and Kaguya. However, further analysis and combination of data sets will be critical to determining the extent and physical properties of the cold traps. Therefore, in order to address this initiative, we must:

- Learn the extent, settings, physical properties, and locations of permanently dark cold traps near the lunar poles.
- Understand the thermal environment of these areas, including the effects of this thermal regime on lunar regolith and geotechnical properties.
- Understand the temporal history of lunar cold traps.
- Survey potential lunar polar landing sites for detailed study and subsequent resource extraction experiments.

Initiative-B: Detailed characterization of polar cold traps and nearby sunlit areas

Direct measurements of the type, form and distribution of subsurface volatiles within permanently shadowed craters will give us a detailed characterization of the potential resource as well as provide high-fidelity ground truth for remote sensing measurements. Partially to substantially illuminated areas are also worth examining as orbital reflectance data suggest enrichments in water in polar sunlit areas. It is important to assess how much could be present because sunlight may make operations easier. As emphasized in *Lunar Exploration Roadmap*, Goal Sci-A, Objective A-3, it is essential to make studies of the polar environment before human return to the Moon in order to understand these unique regions in their pristine state.

Specific measurements required:

Molecules and phases: H_2O is the primary target, including its phase state (crystal structure of ice, whether it is amorphous, amount adsorbed) as this may affect design of equipment to extract it efficiently. However, other volatiles may be present and could be useful resources, including CO, CO_2, CH_4, NH_3, and organic compounds derived from solar wind interactions with the lunar surface or from comet impacts. Fully assessing the resource potential hidden within the permanently shadowed regions (PSRs) requires determining the relative amounts of H_2O in ice deposits versus adsorbed onto surface grains.

Lateral and vertical distribution: Remote sensing measurements do not provide sufficiently high spatial resolution to allow us to determine the spatial resolution of water and other volatiles in permanently-shadowed regions. This is important to assessing the overall H_2O inventory and must be determined through direct sampling and *in situ* analysis. Detailed studies are needed to assess how many samples of a candidate landing site are needed to quantify the lateral and vertical distribution of H_2O. The scale of lateral investigations needs to be determined using orbital remote sensing data, but is probably larger than 100 m.

Environmental factors: Remote sensing measurements indicate extremely low temperatures in the darkest shadowed regions (25-50 K), but *in situ* measurements are needed to understand the details of the local environment. Specifically, surface temperatures need to be measured in areas receiving different fluxes of reflected sunlight. The temperature distribution with depth is important to measure for correlation with H_2O concentrations and to design extraction equipment.

Initiative-C: Characterize the geotechnical properties of the shadowed regolith

Once potential resources are identified, it will be crucial to determine the geotechnical properties of cold, polar regolith to design gear for resource extraction. Specific measurements needed are the physical and electrical properties, including shear strength, angle of repose, and electrical conductivity. All of these measurements need to be determined as functions of depth in the regolith in order to determine the extent and range of the physical properties in question. In addition, experiments designed to assess how machinery (scoops, drills, etc.) interact with the regolith are important to properly design extraction equipment. In addition, detailed (high spatial resolution) observations of topography in dark areas will help develop strategies for mining volatiles.

2. Extracting Resources

Rationale

Once usable amounts of a resource (e.g., water ice) are identified, it will be essential to develop the technology to extract it. We must know how to excavate, manipulate, transport, sieve, and transport regolith, and then process it to produce the desired products (e.g., hydrogen and oxygen gases) and to store them. Technology development needs to begin early in any exploration program to allow sufficient time for technology maturation to flight level, and is central to learning how to live and work in space.

Sources:
HAB-SAT objective mLRU5: Perform lunar resource excavation.
HAB-SAT objective mLRU6: Develop and validate tools, technologies and systems to extract and process resources on the Moon, with extension to other exploration destinations.

Feed Forward to Mars and Other Destinations:
LER Objective FF-A-4: Develop the capability to acquire and use local resources to sustain long-term exploration and habitation of planetary surfaces.
LER Investigation-FF-A-4D: Test phase separation technologies for handling solids, liquids, and gases.

Initiative-D: Excavate lunar resources

It is essential to determine the viability of technology to do *in-situ* resource utilization, possibly including the capability for excavation of large masses of raw material in harsh lunar environments. Development of equipment that will work reliably in a range of lunar environments reduces technological, economic, schedule, and political risks associated with activities that extract and use lunar resources. This development also increases mission planner confidence, including that for Mars applications and supports commercial investment in establishing lunar infrastructure. Related to this is development of drilling technology, which may be uniquely valuable to prospecting, production, and scientific exploration. Examples of specific types of experiments and technology development include the following:

- Test excavation techniques to create trenches 1 meter deep.
- Load excavated regolith onto a conveyor belt to test effectiveness at transporting regolith and longevity against abrasion, dust clogging, and other problems.
- Load excavated materials into resource extraction apparatus, or demonstrate that such transfer can be made.
- Crush rock fragments larger than processing equipment can handle.
- Sieve regolith materials into size fractions more suitable for resource extraction.

Initiative-E: Resource processing

This initiative includes a variety of engineering science and technology activities that range from fundamental investigations of lunar resource properties to experimentally validating tools, software, components and systems that perform various engineering unit operations associated with processing lunar resources. It stems from HAB-SAT objective mLRU6. Early robotic tests could include the following:

- Produce and store small quantities of hydrogen and oxygen from lunar regolith by melting ice.
- Demonstrate disposal of heated regolith after processing.

- Process at high temperature to test techniques for extracting metals (e.g., Fe, Al) from regolith.

B. Technology Demonstrations Leading to Sustainable Exploration

The utilization of resources is essential to sustainable human exploration of the Moon and other destinations in the solar system. Modest technological capability for efficiently and reliably collecting and processing resources into mission critical products should be demonstrated in the earliest robotic precursor missions setting into motion a chain of more extensive and ambitious technology demonstrations to prepare for the return of humans to the Moon and beyond. Subsequent technology demonstrations should expand the scope of resource prospecting and extraction to demonstrate long-duration operational survivability and reliability and broader geographical diversity. Expanding the scope of resource utilization should be accompanied by related technology demonstrations including thermal survivability, dust tolerance and mobility capabilities, etc. that enable the expanded resource scope and other key aspects of human exploration. Thus, in addition to in-situ resource identification, characterization and processing, there is a second category of technology and process demonstrations that can be performed on lunar robotic missions. These robotic investigations can serve as risk reduction for future human planetary surface systems for the Moon and other destinations.

Rationale

Achieving the initial objectives for resource characterization and mapping, and resource extraction and processing is unprecedented away from Earth, but also the basis for each of the succeeding steps in restarting human lunar exploration. In part because budgets are likely to be constrained and in part because much will ride on success, the objectives of the earliest surface missions should minimize risks stemming from the challenging the lunar environment, especially temperature extremes and difficult terrain. This approach may result in missions to locations where the resource concentrations are lower than might be located in permanently shadowed craters but under sunlit working conditions with more moderate temperatures and solar-based power. Even a modest but successful resource prospecting and utilization demonstration will forever change how human space travel is pursued.

Once initial demonstrations are successful, the return on the investment made in robotic precursor missions can be substantially improved if the landed prospecting, extraction and processing capabilities become capable of extended duration operations, lasting months to years and surviving temperature extremes that may be experienced even outside the permanently shadowed craters. Additionally, extending the duration of resource-based missions will entail surviving repeated exposures to abrasive regolith during excavation, handling and processing. Introducing a robust mobility capability once the initial resource demonstrations are successful will enable comparative evaluation of resource extraction and processing at sites that are geologically varied and more challenged by terrain.

These investigations focus on low TRL areas where partial gravity or other lunar environment characteristics can be valuable in evaluating performance prior to applying these technologies/process to subsystem design. Robotic investigations can include notional human spaceflight subsystem requirements to ensure that the flight experiment results can be scaled to apply as direct as possible to human surface subsystem designs. Priority should be given to those areas where technology/process maturation could lead to design optimization that significantly reduces human surface subsystem resource requirements (power, mass, crew time, etc.) over current designs. The timing of these investigations must be early enough so that the results can be analyzed and factored into subsystem designs at an early stage in the process.

1. Enabling Extended Duration Missions

Initiative-F: Demonstrate surface power and energy storage systems

This initiative specifies the demonstration of capability to enable the thermal survival of robotic precursor systems through significant durations of darkness that might be encountered in resource prospecting ground truthing operations and in resource extraction activities. Thermal survival of smaller robotic assets may be enabled by use of radioisotope power sources, but utilization of modified regolith or boulders as thermal energy reservoirs may offload thermal management related mass, both energy sources and insulation, from rovers and improve their useful payload complement. Surviving the thermal environment of the polar resource reservoirs is the highest priority for sustainable exploration capability in both robotic precursor activity and later human exploration operations.

In addition, investigations on long-life, lightweight, rechargeable power systems that can provide energy for mobile and stationary surface subsystems could have application to future human and robotic exploration of the Moon and other destinations.

Sources:
LER: Objective Sust-B-3: Development of Surface Power and Energy Storage Systems; Initiative F: Develop large-scale stationary and small-scale distributed (Thermal Wadi) thermal energy storage systems.
LER: Objective Sust-B-5: Deployment of Robotic Facilities for Science and Exploration Operations; Initiative E: Develop standardized infrastructure on the lunar surface for support of robotic operations including power, communications, navigation and other systems.

Feed Forward to Mars and Other Destinations:
LER Objective FF-A-5: Develop the capability to produce adequate levels of power on planetary surfaces to allow human crews to work and live productively

Initiative-G: Develop the capability for human crews to operate safely on planetary surfaces, protected from the extreme environment and hazards**.**
Recent studies have begun to show that not only do lunar dust grains act as an inhalation hazard and skin irritant as indicated from Apollo missions, but hydroxyl radicals and super oxides on the grain surfaces present reactive toxicity hazards to the health of human crews. To this end, further characterization of pristine lunar regolith/dust grains from both a bulk chemical composition and chemical reactivity needs to be completed. Mitigation of both the physical and chemical effects of lunar dust on biological systems should be resolved before long-term duration missions are embarked upon. Additionally, the radiation environment on the lunar surface should be completely characterized in order to engineer appropriate habitats for long duration stays.

Sources:

LER Investigation-FF-A-9C: Test dust mitigation technologies to prevent dust from interfering with mechanical systems and causing health problems for astronaut crews (high priority – second phase)

Feed Forward to Mars and Other Destinations:
LER Investigation-FF-A-9C: Test dust mitigation technologies to prevent dust from interfering with mechanical systems and causing health problems for astronaut crews (high priority – second phase)
LER Investigation FF-A-9A: Test radiation shielding technologies - essential for protecting astronauts on the lunar surface from galactic cosmic rays (GCR) and solar energetic particle (SEP) events.
LER Investigation FF-A-9B: Test micrometeorite protection technologies - to prevent damage caused by micrometeorite impacts.

LER Investigation FF-A-9E: 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.

2. Enabling Extended Range Missions

Initiative-H: Demonstrate Small Scale Robotic Mobility

Surface mobility systems with the following attributes need to be tested:
RANGE: traverse distances of at least several 100s km away from a landing or outpost site,
DURATION: surface exploration sorties lasting up to several weeks
TERRAIN: Capability to access both steep (defined by slopes of >XX degree) and rough terrain
TIME: Use time on the surface as efficiently as possible, so as to maximize the fraction used for science exploration. Optimize Autonomy.

Sources:
LER Objective FF-A-3: Develop surface mobility capabilities that allow human crews to efficiently and safely explore the surface of Mars (3 Investigations);

C. Human Health

Keeping humans healthy and at peak performance during extended stays on the Moon will require an understanding of how features of the lunar environment affect human health, starting from fundamental biological and physical processes. This knowledge will provide data toward understanding the risk present in the system, aiding the design of mitigation strategies. Studies can provide data points for understanding the effects of gravity levels between 1/6 and 1g, the effects of the mixed-type radiation spectrum, and the consequences of exposure to anhydrous lunar dust, none of which can be simulated on Earth, enabling the design and development of countermeasures. Reduced gravity studies may also inform the design of possible future artificial gravity space vehicles. Some fundamental breakthroughs in lunar biological/physiological science and technology are likely to drive advances in terrestrial medicine and may also lead to new commercial products and therapies. These studies can begin on early robotic missions using appropriate biological test materials.

Sources:

HAB-SAT Objective mHH1: Study the fundamental biological and physiological effects of the integrated lunar environment on human health and the fundamental biological processes and subsystems upon which health depends.

LER: Objective Sci-D-11: Study and assess effects on materials of long-duration exposure to the lunar environment

LER: Objectives Sci-D-12 through Sci-D-22: Effects of space environment on biological systems and remediation of said effects.

Feed Forward to Mars and Other Destinations:

LER Objective FF-A-9: Develop the capability for human crews to operate safely on planetary surfaces, protected from the extreme environment and hazards.

Initiative-I: Study the fundamental biological and physiological effects of the integrated lunar environment on biological systems

Conduct fundamental research to understand the physiological, biological, and mental effects of the lunar environment on humans. The effects of fractional gravity, radiation bombardment, and dust on biological systems can be investigated through cell and small indicator organism research experiments carried by early robotic missions.

D. Commercial Opportunities

Robotic missions offer enticing opportunities for collaboration between government and the private sector that could lead to substantial commercial opportunities in the future. Two complementary approaches can be considered.

Initiative J: Provide space and power on NASA lunar robotic missions

In this case a private company would build and operate a payload, such as a prototype hydrogen and/or oxygen storage facility, that would be carried on a NASA mission to the lunar surface. The company would receive free transportation to the Moon, but would be investing in technology that could prove useful in human exploration.

Initiative K: NASA-provided payloads on commercial lunar robotic missions

Private entities are already considering sending their own spacecraft to the Moon and requesting ideas for payloads. Establishing a competitive program for exploration payloads that would address the technology issues outlined in this report (perhaps modeled after the SALMON program created by SMD) would be an effective use of NASA funding, potentially resulting in more frequent and lower-cost access to the Moon, particularly for small payloads.

E. ESMD-SMD Synergies

Given the broad community that LEAG represents, we note that the initiatives listed above could potentially facilitate cooperation between ESMD and SMD. One avenue of cooperation that could also be explored is for ESMD and SMD to partner in the next call for proposals for the NASA Lunar Science Institute. For example, a node that focused on in-situ resource utilization would have a significant impact on both exploration and science. Therefore, the LEAG strongly encourages a dialogue with SMD on this and other potentially synergistic initiatives