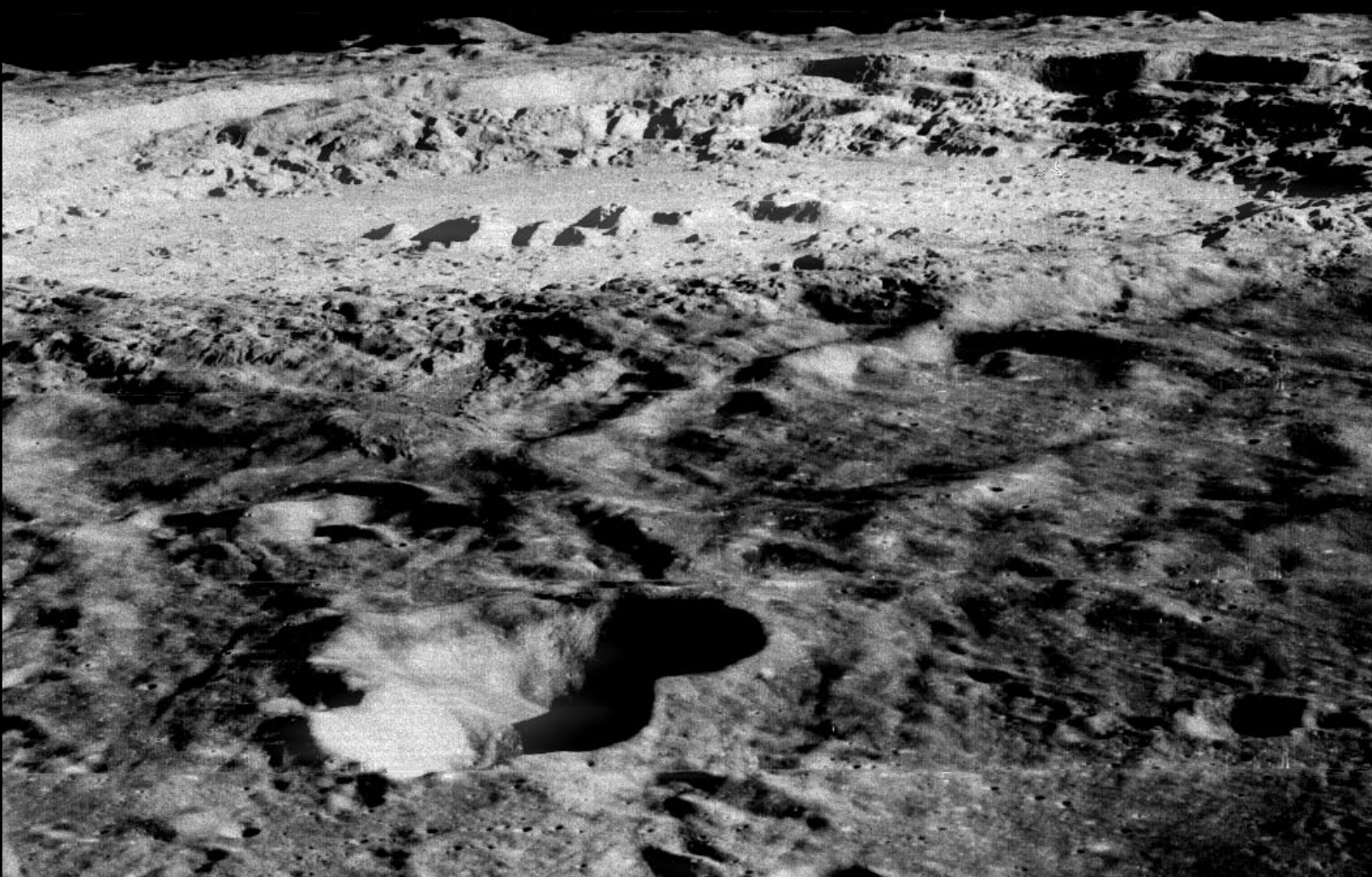


National Aeronautics and Space Administration



NASA's Lunar Robotic Architecture Study



Final Report

July 2006

Preface

This report documents the findings and analysis of a 60-day agency-wide Lunar Robotic Architecture Study (LRAS) conducted by the National Aeronautics and Space Administration (NASA). Work on this study began in January 2006. Its purpose was to:

- Define a lunar robotics architecture by addressing the following issues:
 - Do we need robotic missions at all? If so, why and under what conditions?
 - How would they be accomplished and at what cost? Are they within budget?
 - What are the minimum requirements? What is the minimum mission set?
- Integrate these elements together to show a viable robotic architecture.
- Establish a strategic framework for a lunar robotics program.

The LRAS Final Report presents analysis and recommendations concerning potential approaches related to NASA's implementation of the President's Vision for Space Exploration. Project and contract requirements will likely be derived in part from the LRAS analysis and recommendations contained herein, but these do not represent a set of project or contract requirements and are not binding on the U.S. Government unless and until they are formally and expressly adopted as such.

Details of any recommendations offered by the LRAS Final Report will be translated into implementation requirements. Moreover, the report represents the assessments and projects of the report's authors at the time it was prepared; it is anticipated that the concepts in this report will be analyzed further and refined. By the time some of the activities addressed in this report are implemented, certain assumptions on which the report's conclusions are based will likely evolve as a result of this analysis. Accordingly, NASA, and any entity under contract with NASA, should not use the information in this report for final project direction.

Since the conclusion of this study, there have been various changes to the Agency's current portfolio of lunar robotic precursor activities. First, the Robotic Lunar Exploration Program (RLEP) has been renamed the Lunar Precursor and Robotic Program (LPRP). On May 17, 2006, the Lunar Reconnaissance Orbiter (LRO) was confirmed to enter its implementation phase. Last, a new low-cost secondary payload known as the Lunar Crater Observation and Sensing Satellite (LCROSS) was co-manifested to launch with LRO in 2008. These changes are consistent with the conclusions and recommendations of this study, but came too late to be specifically reflected in this report.

The cover image of the Copernicus crater on the moon is seen from the Lunar Orbiter spacecraft, an Apollo lunar robotic precursor mission. Copernicus is 93 km wide and is located within the Mare Imbrium Basin, northern nearside of the moon (10 degrees N., 20 degrees W.). Image shows crater floor, floor mounds, rim, and rayed ejecta. Rays from the ejecta are superposed on all other surrounding terrains which places the crater in its namesake age group: the Copernican system, established as the youngest assemblage of rocks on the moon. Source: Shoemaker and Hackman, *The Moon* (London: Academic Press, 1962), pp. 289-300.

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1. Executive Summary

This report of the Lunar Robotic Architecture Study (LRAS) responds to a charter from the NASA Headquarters Office of Program Analysis and Evaluation (PA&E) on behalf of the NASA Administrator to recommend an architecture for lunar robotic precursors. PA&E chartered the Exploration Systems Architecture Study (ESAS) during the spring and summer of 2005 to provide an overall architecture for NASA's exploration mission. It then chartered LRAS to provide a flexible architecture for the robotic spacecraft that would be required on or near the Moon as precursors to each of the architectural elements that ESAS recommended.

The LRAS team was asked to address a basic set of questions:

- Do we need robotic missions at all? If so, why and under what conditions?
- How would they be accomplished and at what cost? Are they within budget?
- What are the minimum requirements? What is the minimum mission set?

The LRAS team concluded that there are compelling reasons to conduct robotic precursor missions. However, the extent of the requirements depends on the degree to which NASA will implement the ESAS architecture. The Agency still has many known decisions ahead of it and many additional decisions will present themselves as exploration of the moon proceeds. LRAS analyzed a set of scenarios, assembled a set of potential requirements.

The LRAS team makes two recommendations:

- 1. Adopt the set of requirements presented in Section 4 of this report.**
 - Establish a linkage between the risk reduction of the Constellation Program and individual requirements. As Constellation's risk strategy evolves, so may the precursor requirements.
- 2. Adopt the baseline architecture option through 2012 presented in Section 6 of this report.**
 - The Lunar Reconnaissance Orbiter (LRO) could be the first orbiter – it has passed confirmation review.
 - Decisions concerning ISRU and robotic missions starting beyond 2012 depend on results of earlier missions and therefore do not have to be made now.

In addition, the team recommends NASA pursue the future work identified in the "Future Work" section of this document (Section 6.6).

LRAS did not have a current set of robotic precursor requirements. Instead, the team drew upon the ESAS report, the outdated and early set of requirements of the Robotic Lunar Exploration Program (RLEP), and other recent analyses to lay out a linkage to Constellation needs. These linkages connect Constellation risks to discrete precursor requirements, and are flexible to evolve as the elements of the Constellation architecture are refined. Further, the robotic precursor missions support Constellation milestones and development. Schedule linkages were used to phase the requirements in time.

At first order, it appears the existing RLEP budget can accommodate all high-priority near-term (through 2012) requirements. Additional consideration was given to potential requirements, many of which might

still provide tremendous benefit. Within each category, the LRAS team examined a wide range of activities and determined whether “we would still send humans if we didn’t do them.” This provides a range of potential activities that scales with the available resources. The requirements form a minimum set, but with additional resources significant additional risk can be “bought down,” or reduced.

The requirements emphasize communication and navigation, high-fidelity mapping (visual, topographic, and resource), characterization of the environment (dust and radiation), preparation for in-situ resource utilization (ISRU) and the search for water. The primary uses of the results of these missions would be risk reduction for Constellation development, sortie site selection, sortie operations, and outpost development and site selection. The requirements are time-phased to match these needs. This means, for instance, that communications, mapping, and dust mitigation must be addressed before attempts to characterize any deposits of water in permanently shadowed craters.

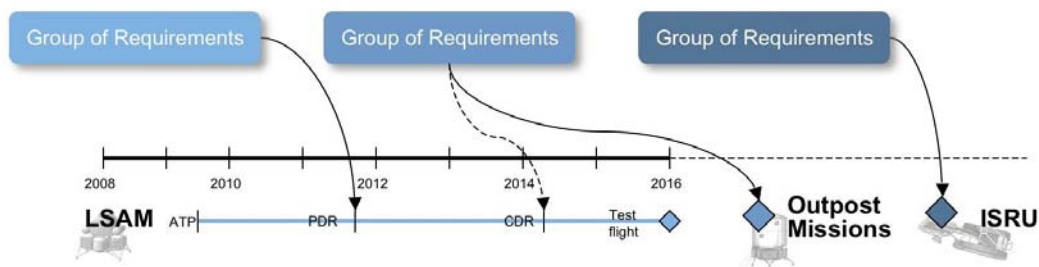


Figure 1-1. LRAS identified, grouped, and time-phased lunar robotic precursor requirements.

Opportunities exist for lunar science in conjunction with each element of the LRAS architecture. LRAS documented the competitive process by which these opportunities could be realized. The team identified no lunar science requirements for robotic precursor missions.

The LRAS baseline architecture is built upon a series of missions linked to their driving requirements:

- 2008 - Orbiter to provide visual, topographic, and resource mapping.
- 2011 - Fixed Lander to characterize the polar environment for Lunar Surface Access Module (LSAM) risk reduction.
- 2011 - Long-life Communications Relay to support all other robotic precursors.
- 2013 - Mobile Lander to investigate potential presence of water in cold-shadowed craters.
- 2015 - ISRU Rover to demonstrate resource production.

LRAS also analyzed a series of excursions from this baseline to evaluate de-scoped ESAS mission scenarios and other potential decisions. The excursions examined: decision options on a lunar orbiter; extensible communications; the number of landers; lander mobility; and ISRU. In particular, the minimum architecture – and one that is within the budget profile – assumes a deferral of both the Mobile Lander and the ISRU Rover. The decision on whether an outpost will need to take advantage of ISRU and if so, whether water is required, does not have to be made until the results of the initial orbiter mission have been analyzed. During the course of this study, the LRO project passed its confirmation review. The now-confirmed LRO meets all the requirements identified by LRAS for a lunar orbiter, exceeds some requirements, and accomplishes many of the highest value additional considerations.

Though LRO is not in the LRAS-recommended baseline, this report provides architecture excursions with LRO as the initial lunar orbiter missions

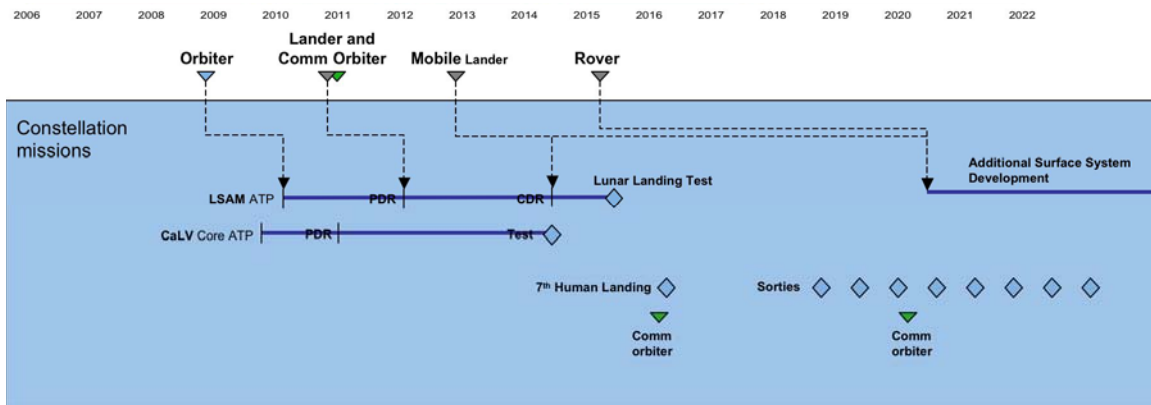


Figure 1-2. The LRAS Baseline Architecture and Linkages to the Elements of the ESAS Architecture

LRAS identified several promising opportunities that may increase efficiency and reduce budget demands; innovative low-cost missions, international partnerships, and selective NASA center assignments could all improve the LRAS baseline architecture and potentially reduce cost.

Current work on innovative, low-cost missions may produce tremendous benefits using novel approaches to further lunar exploration objectives. The recently announced secondary payload to accompany LRO is an early result of this promising work. The LRAS baseline resources ensure that the risk reduction requirements of Constellation are accomplished, but additional savings may be realized through implementation of lower-cost missions.

International partnerships may supplement the results of the baseline architecture. The baseline focuses on those things required to “buy down,” or decrease, Constellation risks. However, a number of activities – such as international lunar orbiter missions – were also identified that, while not absolutely required, would still produce tremendous benefit.

NASA may realize additional long-term efficiencies by the choice of center assignment. The LRAS baseline provides a number of opportunities for small- and mid-sized spacecraft development. Skills required to develop these spacecraft vary from communications and navigation to landers and mobility systems to search for water-ice in lunar craters. Implementing the LRAS baseline using NASA research and spaceflight center capabilities could provide opportunities to strengthen NASA’s space systems development and operations workforce and enhance center technical skills and capabilities for future exploration missions.

This report of the Lunar Robotic Architecture Study (LRAS) provides guidance and flexibility for decisions on lunar robotic precursor missions. The recommendations link to the results of the ESAS architecture and the needs of the Constellation Program. The analysis of various requirements and excursions is intended to provide the flexibility to evolve with the overall exploration architecture of the Agency. This LRAS report should serve as a valuable resource for NASA and others as we build the systems for exploring the Moon, Mars, and beyond.

2. Introduction

2.1. Background

The Vision for Space Exploration specifies a series of campaigns to return humans to the Moon, use it as a testbed, and then conduct human expeditions to Mars. Preparatory robotic exploration campaigns will precede the human campaigns to both the Moon and Mars.

Undertake lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system;

Starting no later than 2008, initiate a series of robotic missions to the Moon to prepare for and support future human exploration activities;

Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020; and

Use lunar exploration activities to further science, and to develop and test new approaches, technologies and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinations.

A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration, January 14, 2004

NASA established the Lunar Precursor and Robotic Program (LPRP) in mid-2004 to conduct the robotic lunar campaign, and established the Lunar Reconnaissance Orbiter as the first project within this program.



Figure 2.1-1. The three documents that guided the Lunar Robotic Architecture Study: A Renewed Spirit of Discovery, The Vision for Space Exploration, and NASA's Exploration Systems Architecture Study.

In the spring and summer of 2005, NASA conducted the Exploration Systems Architecture Study (ESAS). The ESAS study resulted in an overall candidate architecture for human lunar return: the launch

vehicles, propulsion elements, crew transport vehicles, and crew surface elements. During the development and testing of these architecture elements, a campaign of lunar robotic vehicles will conduct precursor lunar missions, scouting out potential landing sites, and laying the communications and navigational infrastructure upon which the human lunar missions will rely. ESAS framed the expected costs of such a robotic campaign based on the prior RLEP budget formulation work, but did not address the specifics of the robotics campaign architecture.

To complete the set of exploration architectures, a lunar robotics exploration architecture needed to be defined that fits within the environment established by the derived requirements of the human lunar exploration architecture. A robotics architecture should build on existing and planned communication and navigation assets that can be leveraged to support lunar missions, including the Deep Space Network and Tracking and Data Relay Satellite (TDRS) System. There are also existing and planned spacecraft from potential partners, including lunar missions by international space agencies. Precursor lunar science should complement the existing International Space Station research on space environmental effects and space science research on the solar system's evolution. Finally, as the architecture is being deployed, it may be itself leveraged to conduct priority science.

2.2. Study Charter and Scope

The NASA Headquarters Office of Program Analysis and Evaluation (PA&E) sponsored a study to develop a lunar robotics exploration architecture. The Lunar Robotics Architecture Study (LRAS) was chartered in January 2006 to provide recommendations and findings within 60 days and prepare a written report to document this analysis. A Terms of Reference (TOR) document for the study was signed to delineate its scope and deliverables. (See the appendices for the TOR.)

The LRAS team was chartered to define a lunar robotics architecture by addressing the following top-level issues:

- Do we need robotic missions at all? If so, why and under what conditions?
- How would they be accomplished and at what cost? Are they within budget?
- What are the minimum requirements? What is the minimum mission set?

The LRAS team integrated these elements together to develop a viable strategic framework for a lunar robotics program. The LRAS focused on robotic precursor missions having near-term benefit and requiring the most immediate decisions. As a basis for the lunar robotic architecture, the following definitions were employed:

- *Lunar* missions are activities that require or take advantage of the lunar environment, either on the lunar surface or in lunar orbit.
- *Robotic* missions are any that do not have humans aboard, including precursor missions, technology demonstrations, full-system demonstrations (e.g., LSAM demo), robotic infrastructure (e.g., communications relay), and robotic companion systems.
- An *Architecture* is the structure, relationships and principles governing the design and evolution of elements linked in accomplishing a purpose.
- *Architecting* means to identify the elements and the relationships among the elements, and establish the guidelines that govern development and evolution of the elements and interfaces, of a given purpose.

The LRAS team reviewed other robotic missions such as space weather sentinels that orbit closer to the sun, but did not include these missions in the lunar robotics architecture.

It is important to note that an architecture is not a robotics program, but merely a flexible framework on which a program could be devised. Program development was not within the scope of the LRAS activity; but rather is a crucial element and interface for follow-on activities.

2.3. Specific Questions

The LRAS team was tasked with finding the minimum set of lunar robotics requirements to enable human lunar exploration. The study assessed and compiled the top-level requirements derived from the Vision for Space Exploration, the ESAS human lunar return architecture and other sources, and then built architectures to satisfy the requirements within cost, schedule and risk constraints.

This involved answering the following series of more detailed questions regarding the requirements and a second series of architecture questions:

- What are the robotics architecture requirements for reducing the risks to human lunar return and how do these compare to other risks and mitigations?
- When does the specific site of the lunar base need to be established? How much surveying needs to be done, if any, to down-select to a site, and how much surveying needs to be done on the selected site?
- What are the precision navigation requirements that must be met with a robotic lunar infrastructure, and what navigational technologies must be tested on the lunar surface prior to human lunar return?
- What communication architecture needs to be deployed by the time of human lunar return and what benefits are there to deploying these elements earlier during the robotic campaign?
- What priority lunar science must be addressed prior to human return, e.g., biological sensitivity to dust, and how would these results be important inputs to future architecture decisions, e.g., lunar base location or in-situ resource utilization?
- What are the necessary precursors for demonstrating technologies for human surface activities, such as supplying power and conducting in-situ resource utilization demonstrations?
- How are the robotics requirements to be allocated among the existing programs and projects and across the set of potential robotics architectures?

The study provided a range of architectural options and a recommended option. For each option, the study answered the following:

- What are the costs of the architecture elements, including leveraged assets? Are these costs within the existing budgets or, if they go outside them, do they do no harm to higher priorities such as CEV acceleration?
- By what dates or milestones do the robotic elements need to be deployed, technologies validated, or scientific questions investigated prior to human lunar return?
- What technical requirements or critical needs does each element fulfill? How do these requirements or needs vary across architectural options?

- What are the highest cost, schedule, and performance risks that might affect the success of an individual element and overall campaign success?

The study further assessed the integration of the potential lunar science with NASA’s existing research strategy:

- What priority lunar science of the Moon could be enabled by robotic precursor missions meeting exploration requirements?
- What priority lunar science from the Moon is enabled by robotic precursor missions?

2.4. Schedule

The LRAS was chartered for a 60-day architecture study and analysis, with a mid-term and final review. After the final review, an additional 30 days was available to document the analysis in a written report. The study provided its midterm and final review as shown in the schedule below.

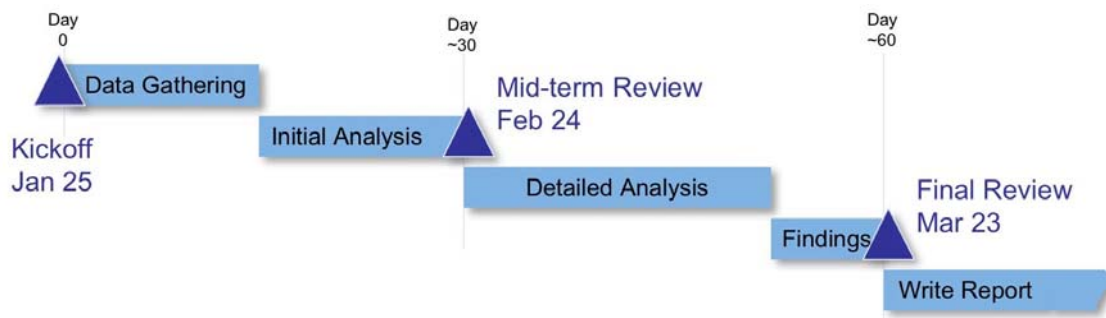


Figure 2.4-1. LRAS study schedule

During the data-gathering phase, the team received inputs from a comprehensive array of sources. (The full list of inputs is provided in Appendix C, “Inputs.”) During the initial analysis phase, the team identified the driving assumptions, constraints, and ESAS mission scenarios and assembled its draft list of requirements and additional considerations. After the mid-term briefing, the team finalized the list of requirements and additional considerations, and then used them to build architectural options. Team members then evaluated the cost, schedule, performance, and risk of each option. Finally, the team identified a recommended baseline and findings. Team members briefed each Mission Directorate and relevant Headquarters Mission Support office on the study results. The team made final presentations to PA&E and the NASA Administrator on March 23, 2006.

3. Approach

3.1. Assumptions and Constraints

Guiding principles

The LRAS team approached this study using the following guiding principles derived from the specific study questions listed in Section 2.3:

- Fulfillment of a clear need for lunar knowledge, risk reduction, or mission support in support of future crewed lunar missions.
- Identification of the requirements to enable successful crewed lunar missions.
- Prioritization of the requirements, yielding required and additional consideration sets of knowledge or activities.
- Provision of the maximum knowledge and risk reduction for minimum cost.
- Required traceability of the lunar robotic mission requirements to the Constellation Systems needs and schedule.

General Assumptions and Constraints

The top-level assumptions and constraints employed in this study were driven by the Vision for Space Exploration and the Exploration Systems Architecture Study. The top-level assumptions are as follows:

- The series of robotic missions to the moon will start no later than 2008.
- The lunar robotic architecture will fit within the context of the ESAS architecture, as modified by the Exploration Systems Mission Directorate, and be consistent with its baseline set of design reference missions (DRMs).
- Robotic architecture options include all uncrewed missions (across the Exploration Systems Mission Directorate, or ESMD) that support return to the moon.
- In all options, “Equatorial” represents NASA’s return to sites near the Apollo landings only (unless specified as “backside equatorial”). For any options to additional sites, refer to requirements for “Global.” (See below.)

Constraints derived from the ESAS are as follows: (see below)

- Return to the moon by 2020, with the goal of living and working there for increasingly extended periods, in preparation for human exploration of Mars and other destinations.
- Sortie mission durations are up to 7 days in length and begin no earlier than 2018 and no later than 2020. The lighting and thermal environments allow up to 14-day missions on most sites, with up to 30-day missions on continuously illuminated polar sites.
- The outpost will be established by first doing a series of sortie missions to a given location.
- Outpost mission durations are for 6 months, beginning no earlier than 2022 and no later than 2025.

Costs must be within the existing budgets or, if they exceed them, must do no harm to higher priorities such as CEV acceleration.

NASA FY07 Budget Estimates

ESAS Element	FY06	FY07	FY08	FY09	FY10	FY11
RLEP	134.3	272.7	366.9	411.3	421.0	414.5

Table 3.1-1. Budget for Elements of the Architecture (in millions of dollars)

A portion of the Exploration Communications Navigation Systems (ECANS) budget may apply to certain precursor communications spacecraft, especially long-life spacecraft that will operate well past the 2018 milestone for human lunar return. The amount of the Exploration Technology and LSAM budgets available for reducing the risks documented by LRAS is still to be determined.

Regions of the Moon

This study assumed that human sortie missions with a frequency of two per year would begin in 2018, with an outpost being established sometime after 2022. Robotic missions to define the required precursor information necessary to assure safe human missions to any location on the Moon would begin in 2008. The LRAS set of mission scenarios included: (1) a campaign of only short-term sortie missions, nominally a few days to a week at equatorial sites and up to 30 days at a highly illuminated polar site, (2) sorties at multiple sites followed by a permanent lunar outpost, and (3) sorties to a potential outpost site, followed by a permanent outpost. In addition, the study team considered two options for lunar in-situ resource utilization (ISRU): (1) a small-scale ISRU facility with a production capacity of about one to several metric tons/year, and alternately (2) a larger facility, nominally producing 50 to 100 metric tons/yr of O₂ from regolith or possibly O₂ and H₂ from water in a permanently shadowed crater. For the purposes of the study it was assumed that the second option would likely require a nuclear reactor power source, while the first option could likely be achieved with solar power.

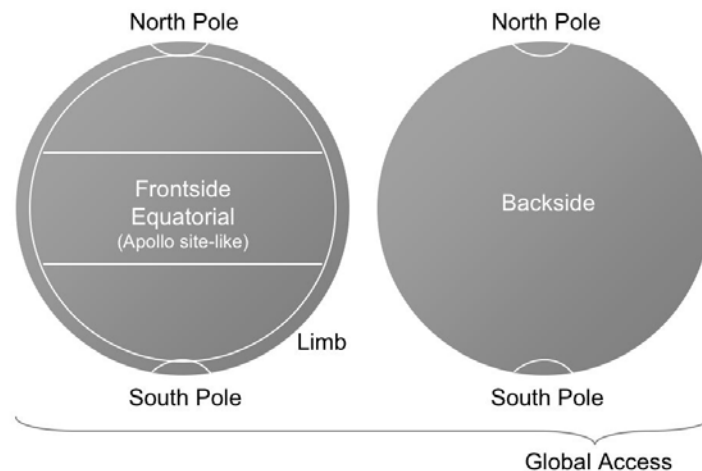


Figure 3.1-1. The regions of the moon as used by the ESAS and LRAS studies. Each region has its own challenges and benefits, such as thermal cycling, lighting, communication limitations, and available resources.

Mission scenarios were divided into three major landing site geographic groups: (1) front-side equatorial sites, including Apollo landing sites, (2) landing sites on the lunar limb including missions to either or both poles (global missions), and (3) back-side landing sites (global missions).

Front-side equatorial landing sites are characterized by continuous communications availability direct to Earth (DTE), with generally better-understood surface features and topography. A sortie mission to this region could be accomplished without any precursor robotic missions beyond that gathered during the Apollo missions. Locations on the lunar limb are characterized by limited DTE communications possibilities and less well-understood surface features; some localized polar landing sites may have the advantage of nearly continuous solar illumination. Back-side landing sites are characterized by poor to no knowledge of surface features and topography and no DTE communications, and require lunar relay satellites as the sole means of communications and tracking.

Polar landing sites may include the special case of missions to high latitudes above the nominal equatorial region but below the highly illuminated polar region. This special case is distinguished by the higher energy required to reach than the other two regions and not being close enough to a pole for near-continuous solar illumination. In all cases, the study assumed that for all human missions communication with earth would be assured either by direct line-of-sight or augmented by lunar orbiting relay satellites.

A sortie mission to the backside equatorial region would be somewhat riskier due the limited fidelity of gravitational and topographic maps, which could result in a few hundred meters in landing error.

The main attraction of a high polar region is the potential for a landing site with near-continuous solar illumination. This would eliminate the problems and risk imposed by a lunar night that, at the equator, is 334 hours long and as cold as -150°C . It would also provide continuous sunlight, enabling total dependence on photovoltaic power generation and relieving the potential requirement for a nuclear reactor power source. In addition, there is the possibility of substantial amounts of ancient cometary water embedded in parts of the walls or floor of a crater, such as Shackleton, that is permanently shadowed from the sun – and as cold as 40K (-233°C). This could potentially provide a practical source of lunar hydrogen, which when separated from oxygen enables lunar-produced rocket fuel. The only other source of hydrogen is the scarce amount from the solar wind, embedded in the lunar soil at about 50 parts per million (ppm). However, even if water exists on the Moon, the ability to conduct extensive mining operations under such harsh conditions represents a considerable technical challenge and risk. The economic value of producing H_2/O_2 fuel on the Moon has yet to be determined.

Nonetheless a permanently illuminated polar sight is the most attractive and the least risky for any mission lasting more than a few days, which includes all outpost missions. Potentially, an “eternally” illuminated site could be thermally benign and rich in solar energy and in-situ resources from regolith or ice. However, there is insufficient high-resolution data of the lunar surface to confidently identify a site of this type, though there is evidence that small islands of continuous illumination near a shadowed crater rim may exist. For the purpose of the LRAS, the team assumed a continuously illuminated site and the existence of reasonably accessible water in suitable quantities and concentration for practical in-situ resource utilization (ISRU) to exist at least at one of the poles, though neither is yet proven.

Elements of ESAS Architecture

The ESAS architecture lays out the elements required to return humans to the Moon, the relationship between the elements, and a set of design reference missions (DRMs) that would employ those elements. The elements break down into launch vehicles, human exploration vehicles, and infrastructure. The launch vehicles include a Crew Launch Vehicle (CLV) derived from a shuttle solid rocket booster (SRB), a Cargo Launch Vehicle (CaLV) derived from the shuttle SRBs and the external tank (ET), and an Earth Departure Stage (EDS) to carry a payload from Earth to the moon. The human exploration vehicles

include a Crew Exploration Vehicle (CEV) and its associated service module, a Lunar Surface Access Module (LSAM) with derivatives, and various outpost elements for use on the lunar surface. The architecture includes concepts for extending the capabilities of these elements to Mars exploration.

The LRAS team identified four places in which the architectural elements of ESAS and robotic precursors interconnect:

- LSAM design and landing site selection;
- Communications and navigation support to the CEV and LSAM;
- Outpost design and placement; and
- In situ resource utilization (ISRU) design and affordability.

ESAS defined the LSAM at a conceptual level, as shown in Table 3.1-2 at right. The LSAM is the first major element of the architecture to operate on the lunar surface, followed by the elements of an outpost.

ESAS defined a set of DRMs that included a series of human sortie missions to the lunar surface, followed by a slow buildup of an outpost. The location of the sorties and the outpost was left undefined, but regions of high interest were identified.

The DRMs include:

- Crew to and from the lunar surface
 - 7 day missions to anywhere on the surface
 - Crew rotation to lunar outpost
- Cargo to the lunar surface
 - One-way delivery of cargo to support longer duration missions
- Crew to and from Mars
 - 500 days on the surface
- International Space Station resupply capability – if commercial services are unavailable
 - Ferry crew up and down
 - Cargo up and down


Lunar Surface Access Module_(LSAM) Definition

4 crew to and from the surface
Seven days on the surface
Lunar outpost crew rotation
Global access capability
Anytime return to Earth
Capability to land 21 metric tons of dedicated cargo
Airlock for surface activities
Descent stage: Liquid oxygen / liquid hydrogen propulsion
Ascent stage: Liquid oxygen / liquid methane propulsion

Table 3.1-2. Lunar Surface Access Module Definition

Lunar architecture capabilities are driven, in part, by the duration, location and centralization of lunar surface activities. An initial strategy was chosen that begins with global-access, short-duration sortie missions, and transitions quickly to deployment of a permanent outpost. These trades also drive the required exploration support (power, communication, habitation, mobility, resource utilization, science).

While the specific lunar surface activities were left undefined, ESAS did identify the following classes of activities. The LRAS team used these items to infer the range of activities that would require precursor robotic missions:

- Initial demonstration of human exploration beyond Earth orbit.
- Learning how to operate away from Earth.
- Conducting scientific investigations.
- Using the Moon as a natural laboratory.
- Planetary formation/differentiation, impact cratering, volcanism.
- Understanding the integrated effects of gravity, radiation, and the planetary environment on the human body.
- Conducting ISRU demonstrations.
- Learning to “live off the land.”
- Excavation, transportation and processing of lunar resources.
- Beginning to establish an outpost – one mission at a time.
- Enabling longer-term stays.
- Testing of operational techniques and demonstration of technologies needed for Mars and beyond.

To see the full ESAS report, go to
http://www.nasa.gov/mission_pages/exploration/news/ESAS_report.html

3.2. Analysis Process

The LRAS team followed a traceable, unbiased, and open analysis process as follows:

1. Identify lunar robotics requirements from as many sources as available.
2. Categorize these requirements and determine applicability.
3. Rank these requirements by assessing their impact to Constellation through the use of the figures of merit similar to those used in ESAS.
4. Identify what type of platform would be needed to fulfill these requirements (i.e., lunar orbiter, surface penetrator, fixed lander, rover, hopper, etc.).
5. Group requirements that are on the same platform into sets that can be fulfilled by the same instrument, using existing instruments as a baseline.
6. Use the existing instrument mass and power levels to develop a baseline spacecraft mass, power level, and cost.

1. Identify requirements

The team gathered individual requirements from several documents:

- ESAS appendix 4 – assumptions about the RLEP architecture
- ESMD’s Cost Analysis Requirements Document (CARD)
- RLEP requirements document (draft)

Along with these documents, the team received several presentations focused on lunar science opportunities, the robotic architectures of the first two RLEP missions, the Space Communications Architecture Working Group results, and others.

2. Categorize requirements

The team then gathered and ranked the requirements from these documents and presentations. A structure for these requirements was created that sorted different requirements into possible future options for the lunar exploration program. These categories were based on increasing complexity of possible future human missions. Initially, an additional categorization was made into requirement “type,” and then arranged into a matrix as follows:

Four major categories for robotic requirements:

- 1) Communication and Navigation Support
 - Communication for critical event coverage (Lunar Orbit Insertion (LOI) burn on far side of the Moon)
 - Communication for high data rate relay
 - Navigation/tracking aid to meet 100m precision landing requirement
 - Communication and tracking support for elements with limited or no DTE communication access
- 2) Mapping and Environmental Measurements & Effects (including biological effects)
 - Lunar mapping
 - Landing site characterization such as soil density, debris, dust, radiation
 - Potential locations of water (only needed for polar landing)
 - Characterization of potential water sites (only needed for polar landing)
 - Illumination characterization
- 3) Preparation for Establishing an Outpost
 - Site selection
 - Autonomous assembly, cable laying, etc.
 - Regolith reconfiguration such as radiation protection
- 4) ISRU
 - Site selection
 - ISRU demonstrations and trials

Several mission scenarios for future exploration were considered that evolved from sortie-only missions to sorties leading to an outpost and finally sorties or outpost with various levels of ISRU:

- 1) Sorties only
 - a. Sorties to the equatorial region of the Moon
 - b. Sorties with global access
- 2) Sorties and an outpost (global access sorties)
 - a. Outpost constructed in one of the polar regions of the Moon
 - b. Outpost constructed in the mid-latitudes or near the equator
- 3) Sorties and ISRU (global access sorties)
 - a. ISRU plant constructed at one of the polar regions (extracting O₂ and H₂ from water if available and accessible or O₂ through regolith processing)
 - b. ISRU plant constructed in the mid-latitudes or near the equator (extracting O₂ only through regolith processing)
- 4) Sorties and the outpost incorporates ISRU (global access sorties)
 - a. Outpost and ISRU plant at polar region

b. Outpost and ISRU plant at equatorial or mid-latitude region

This leads to the following matrix of possibilities and the robotic support that would be useful and applicable:

	Sorties Only		Sorties and Outpost		Sorties and ISRU		Outpost Includes ISRU	
	Equatorial Only	Global Access	Polar Outpost	Equatorial Outpost	Polar Plant	Equatorial Plant	Polar Outpost	Equatorial Outpost
1) Comm & Nav Support	x	x	x	x	x	x	x	x
2) Recon for Landing sites		x	x	x	x	x	x	x
3) Outpost Setup Assistance			x	x	x	x	x	x
4) ISRU					x	x	x	x

Table 3.2-1. Possible Configurations of Sorties and Robotic Requirements

This framework was further expanded by listing all of the derived requirements and determining what missions would satisfy each requirement. As can be seen from this matrix, missions with ISRU drive the largest number and most demanding Robotic Lunar Exploration Program requirements.

The matrix demonstrates that the proposed requirements depend on what exploration missions are eventually selected. The team determined that 17 requirements need to be satisfied in preparing for a polar outpost, primarily due to the unknown nature of the lunar polar regions and the unknown environmental effects for long-duration stays on the moon. If ISRU is to be used, there are an additional 4 requirements that need to be fulfilled. The remaining requirements, if fulfilled, would reduce risk to the human missions but are not strictly necessary.

When this matrix was presented at the midterm review, the scope of the study was narrowed significantly. Most notably, large-scale ISRU dominated and greatly expanded robotics requirements to the point that it needed to be considered separately from other options. PA&E directed the team to look only at “sorties building to an outpost that would eventually use small-scale ISRU.” The team therefore focused the next phase of its analysis on requirements related to this mission category.

3. Assess the requirements and determine the platforms

The team used a priority ranking process to assess how important these requirements are to the Constellation mission. Without assuming a particular set of mission options, the team used a Quality Function Deployment ranking system to determine qualitatively the relative importance of each of these requirements.

Each requirement was scored on five (5) different figures of merit (FOMs). These FOMs were derived from the ESAS FOMs in order to maintain as much consistency as possible. The FOMs were:

1. Safety and Mission Success
 - a. Reducing risk to crew
 - b. Enhancing the probability of mission success

2. Effectiveness/Performance
 - a. Increasing surface accessibility
 - b. Increasing system availability
 - c. Increasing system operability
 - d. Increasing crew productivity
3. Extensibility/Flexibility
 - a. Increasing flexibility of the lunar mission
 - b. Extensibility to other destinations, especially Mars
 - c. Extensibility to commercial applications
 - d. Extensibility to national security
4. Programmatic risk
 - a. Reducing system development risk
 - b. Increasing architecture efficiency
 - c. Decreasing cost risk
 - d. Decreasing schedule risk
 - e. Increasing political viability
 - f.
5. Cost/risk
 - a. Reducing overall architecture cost
 - b. Increasing performance
 - c. Reducing overall architecture risk

The FOM scores formed the basis for selection of high-priority requirements and candidate missions to satisfy the requirements.

The team linked each requirement to specific exploration missions in Constellation's timeline, including when the program would need the data. For example, data gathered on lunar dust and long-term health hazards will be needed before extended-duration human missions to an outpost. This information is required before design of an outpost (notionally ~2016-2020); however, the effects of dust on the seals of an airlock is required to inform the design of the LSAM's airlock system, so this information is needed much sooner, approximately 2012.

The full list of requirements, including the platform that can perform the necessary measurements and the applicable part of the Constellation mission, is presented in section 5.3.

4. Determine how the requirements can be implemented

Once the requirement prioritization information was gathered, the team determined what platforms would be needed to fulfill the requirement. For instance, determining a safe landing site for a sortie may be done from an orbiting asset; however, characterizing the lunar dust requires a lunar lander.

The team considered four major types of lunar robotic missions:

- Orbiters
- Fixed landers
- Mobile landers, i.e., rovers or hoppers
- Other (non-robotic or robotic test flights of human equipment, such as the LSAM)

Some examples of requirements that can be fulfilled by orbiters are:

- High-resolution map of the surface of the Moon
- Image selected sites at landform scales
- Relay communications and tracking
- Orbital measurements of the thermal & radiation environments
- Characterization of lighting on the near-permanently lit areas of the poles
- Mapping and characterization of volatiles

Some examples of requirements that can be fulfilled by fixed landers are:

- Measure ground properties, radiation, dust and environmental conditions
- Demonstrate precision landing with hazard avoidance
- Prototype systems for measuring or mitigating environmental effects
- Characterize 1/6g fluid properties
- Determine effect of lunar dust on mechanical and biological systems
- Demonstrate small-scale ISRU

Some examples of requirements that can be fulfilled with mobile landers are:

- Search for water
- Demonstrate excavation for ISRU activities
- Demonstrate small-scale ISRU
- Demonstrate site surface preparation
- Demonstrate robotic habitat pre-emplacement and setup
- Demonstrate new mobility techniques
- Demonstrate of safe roving up to 30km

Some examples of requirements that can be fulfilled with other systems, such as LSAM, are:

- Over-the-horizon propagation of radio frequency (RF) – needed for the outpost extra-vehicular activities (EVAs) from base—this technology can be developed and tested on the first sortie missions
- Validating in-space operation of the LSAM engine is not an appropriate test for an RLEP mission. This engine should be tested as part of the LSAM development program.

5. Group requirements that can be met by classes of instruments

Some of the requirements can be preformed by the same instrument. For example, an orbiter in a low lunar polar orbit with a high-resolution camera could both map the moon’s surface and characterize the lighting on the near-permanently lit areas of the poles.

By utilizing data gathered from previous missions and from the RLEP program office, the team identified requirements that could be satisfied by several existing instrument designs. The results are presented in section 5.3.

6. Estimating mission mass and cost

Cost analysis was based on historic and estimated data. Data was mined from Integrated Cost and Schedule Analysis Tool (ICSAT), NASA / Air Force Cost Model (NAFCOM), Resource Data Storage and Retrieval (REDSTAR) library , Dr. Joe Hamaker’s Quickcost Cost Model, and the Independent

Program Assessment Office (IPAO) database. Additional data and engineering assistance was also provided by members from the JPL Advanced Design Team (Team X). Table 3.2-2 provides an overview of the data collected for the analysis of each major element.

Orbiter	Lander	Rover	Instruments
Lunar Orbiter	MER	Mars Pathfinder	Clementine
MRO	Phoenix	MSL	Phoenix
Cloudsat	MPL	MER	Mars Polar Lander
Grace	MSL		Lunar Orbiter
MGS			MRO
Mars Odyssey			Cloudsat
MCO			Grace
			MGS
			Mars Odyssey
			MCO

Table 3.2-2. Historic Data Used for Each Element of the Architecture

All cost estimating relationships (CERs) were based upon the selection of the most analogous historic and estimated data points. Generally, at least one specific independent variable (i.e. mass or power) must be selected to create a viable CER. The LRAS team used payload element mass as the basis for estimating cost. This was due to a lack of technical definition available for the cost team. Each element had a suite of instruments assigned to it to fulfill the requirements generated by the LRAS team. This information, along with the data set in Table 3.2-2, was utilized by the cost team to generate mass estimating relationships between instrument mass, element dry mass, and element wet mass. Mass derived from Mars Exploration Rovers (MER) was used as the independent variable for LRAS CERs.

3.3. Architecture Development and Integration

Establishing Precursor Baseline

The ESAS architecture was designed to provide flexible elements that can conduct a variety of human exploration mission scenarios. The architecture includes a number of design reference missions (DRMs) to illustrate the range of missions. It allows NASA to commit to elements incrementally through a series of demonstrations and future decisions. For example, the architecture provides the vehicle capability to land a crew anywhere on the lunar surface. Eventually, a specific series of landing sites will be selected based on information obtained from robotic precursor missions and each subsequent human sortie. As another example, NASA could develop an outpost but choose not to pursue in-situ resource utilization at that outpost.

This wide range of initial human exploration mission options resulted in an equally wide range of precursor robotic mission requirements. Subsequently, the study focused primarily on a human mission set based on several lunar sortie missions followed by a lunar outpost at a lunar pole with small-scale ISRU. The LRAS team developed a decision tree as shown below in Figure 3.3-1 that illustrates the

different mission scenarios that could result from different decision branches. For each mission scenario, there are a string of activities that would be needed ahead of time, possibly including precursor robotic activities. For example, to conduct ISRU operations, there are a series of ISRU developments and demonstrations that are needed, extending back prior to the first sortie mission. The total set of robotic precursor requirements is the combination of all the requirements for all mission scenarios.

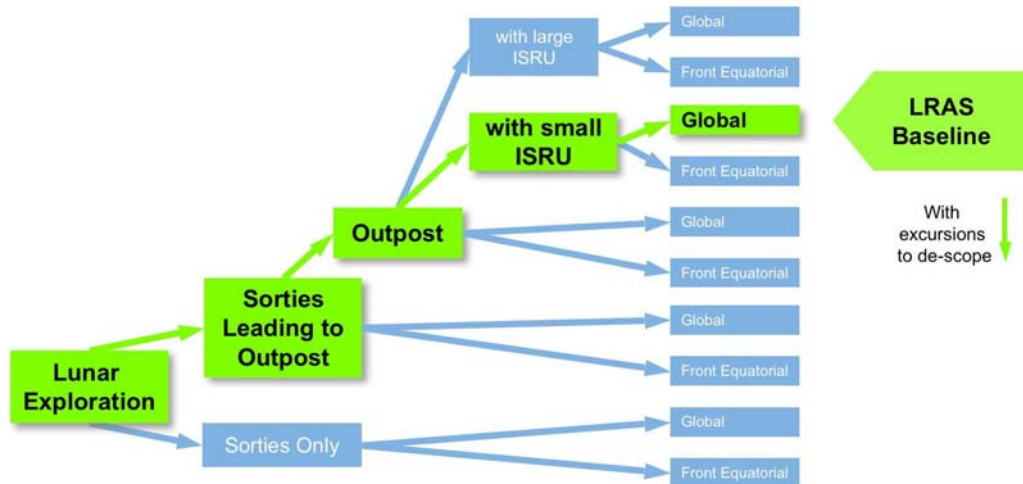


Figure 3.3-1. The LRAS focused on precursor requirements to support development of human polar outpost(s) and small ISRU, consistent with the Vision for Space Exploration. Global access was not precluded.

Because the human exploration mission scenarios largely build upon each other, LRAS chose as its own baseline the set of precursor requirements for the baseline ESAS mission scenario. This allowed the team to investigate nearly all the precursor requirements, with a simple, direct approach to de-scoping the precursors if a different branch is taken on the decision tree. The LRAS baseline architecture includes lunar robotic missions to meet all the requirements to first fly the human sorties, and then it adds missions to support polar outpost development with small ISRU. A series of excursions to this baseline explores alternative ways to fulfill these requirement, plus alternatives that only meet de-scoped requirements. The requirements for the supra-baseline case of large ISRU were examined, but no architecture excursions were analyzed.

Precursor Role in Integrated Architecture

The LRAS team examined how precursor missions were intended to integrate with the overall lunar exploration mission architecture. The ESAS architecture laid out an expectation for the role of lunar robotic precursor missions. There was a lunar robotic precursor campaign preceding the Apollo lunar landings that provided lessons on integration of robotic and human missions. Having looked at both the ESAS and Apollo expectations, the LRAS team felt that the lunar robotic precursors would be best deployed to buy down key Constellation risks, and that they must be done with sufficient lead time to allow for integration of the results into the Constellation designs.

Robotic missions to the Moon should be undertaken prior to human return to the Moon for several reasons. Robotic missions can collect strategic knowledge that permits safer and more productive human missions. Such data includes information on lunar topography, geodetic control, surface environment, and deposits of largely unknown

character, such as those of the polar regions. This information can be collected by a variety of spacecraft, including orbiters and soft landers.

In addition to collecting important precursor data, robotic missions can deliver important elements of the surface infrastructure to the eventual outpost site. Such deliveries include exploration equipment (i.e., rovers) and scientific instrumentation (i.e., telescopes). Additionally, since the extraction of resources will be an important activity of humans on the Moon, robotic precursors can deliver elements of the resource processing infrastructure, including digging, hauling, and extraction equipment. It is likely that NASA will want to experiment with various processing techniques and methods of extraction, and robotic missions can demonstrate process techniques at small scales in advance of the requirement to put large amounts of infrastructure on the lunar surface.

ESAS Final Report, section 4.3.10, November 2005

Overall, the ESAS architecture anticipates that lunar robotic precursors will provide early information for human missions to the moon, in particular key knowledge needed for human safety and mission success, and scientific results to guide human exploration. Robotic precursor missions may pre-deliver infrastructure elements for eventual human benefit and may themselves be evolvable to later human systems.

Most unknowns are associated with the north and south poles – likely destinations for a lunar outpost. The lunar robotic precursors are anticipated to improve our knowledge of these regions, including the thermal and lighting conditions, the terrain and surface properties, and the composition and physical nature of any deposits of water. Table 3.3-1 shows the preliminary analysis conducted by ESAS for four broad classes of potential lunar robotic precursor requirements. ESAS found that if an outpost were located at a polar site, all potential requirements would actually be needed to answer all the unknowns. For limb and low latitude equatorial sites, ESAS found that there are fewer unknowns and therefore fewer actual requirements for lunar robotic precursors.

Sites	Navigation, communication	Precision topography and local terrain	Surface deposit characterization	Site environment
Low latitude equatorial sites	No	Probably not	No	No
Limb sites	Yes	Yes	No	No
Polar sites	Yes	Yes	Yes	Yes

Table 3.3-1. ESAS classes of potential precursor requirements as a function of outpost site. The boxes indicate whether the classes would actually need to be required for each outpost site.

The Apollo Program was supported by a precursor robotic campaign from 1961 through 1967. Three major programs supported Apollo with lunar orbital and surface data:

- Ranger, a series of hard landing spacecraft flown between 1961 and 1965;
- Surveyor, a series of soft landing spacecraft flown between 1966 and 1968; and
- Lunar Orbiter, a series of orbiting spacecraft flown between 1966 and 1967.

Of the three programs, only Lunar Orbiter was begun after the decision to send Apollo to the Moon; consequently, it was necessary to adapt the Ranger and Surveyor spacecraft designs to support the Apollo spacecraft design. The data from the robotic programs served Apollo in two ways: as confirmatory data for evaluating designs and lunar surface models, and in the preparation of maps and topographic models of the lunar surface for use in simulation, crew training and mission operational planning and decision-making.

The experiments and photographic systems carried on Surveyor and Lunar Orbiter were more than adequate to supply the data about the lunar surface environment needed for Apollo designers and mission planners;

Data was not available in time for initial vehicle design; however, the data was available for mission operations planning and for design confirmation;

The best Lunar Orbiter resolution photographs had a detection resolution of approximately 4-5 meters for high resolution frames and 30-50 meter resolution for low resolution camera frames;

*Robotic Precursor in Support of Project Apollo:
Data Requirements, Program Review and Evaluation of Results
Dean Eppler, January 1991*

The LRAS team connected the lunar robotic precursors for the Constellation Program to the design reviews of the major Constellation elements. Further detail on this topic is available in Section 5.4.

Precursor Role in Risk Reduction

Key among the mission-level risks is the location of the landing site. Factors influencing the selection of the landing site include characterization of the regolith for composition and concentration of useful in-situ resources (including use of regolith as radiation protection); the risk from secondary, backscattered albedo radiation; and the thermal and insolation environment. While the fallback to an equatorial site is a lower-risk option, it is not the first choice.

The key operational risk is to assure human safety. Aside from radiation – both solar and cosmic – the highest risk identified by the team was likely from the lunar dust. The overall radiation risk is in two forms: (1) ubiquitous cosmic ray radiation, and (2) the continuous stream of particles in the solar wind. The former has very low particle fluence, but energies as high as several GeV/nucleon and a composition that spans the atomic spectrum. Hydrogen is the most abundant element, though iron is typically considered the most “dangerous” when its higher atomic weight is considered. Overall, cosmic rays are not acutely lethal but they are very difficult to mitigate, and over the long term represent a measurable health risk. The steady-state solar wind is far denser than cosmic rays but easier to mitigate. The primary solar risk is from large-scale coronal mass ejections that result in an intense flood of high-energy (MeV) protons and electrons. These events are infrequent, sometimes hard to predict, and can be lethal, though they typically last only a few days. Astronauts outside the earth’s protective magnetic field for an

extended period must be provided a safe haven from these “storms,” either as an integral part of the lander or created by a covering of lunar soil.

The risk from lunar dust is to both humans and mechanical systems. Lunar dust is very fine (grain size is mostly below 100 micron) and highly abrasive. Apollo astronauts found that after 3 days of EVA on the lunar surface, the joints of their suits were adversely affected and the suits could not have been used much longer without maintenance. They also found that dust permeated their living areas and was physically irritating. The overall temporary – and possibly long-term – effects of dust on human health remain an open issue, as do reduced operability and life-limiting effects on mechanical systems such as rovers, hatch seals and ISRU equipment.

A further surface-related risk is associated with ISRU, especially if useful amounts of water are found in a shadowed crater. While the elemental composition of the lunar regolith is similar to terrestrial soil – about 40% oxygen, with ample amounts of silicon, aluminum and iron – the mineralogical distribution is somewhat different. In principle, this should not be a fundamental problem for ISRU. However, from a practical standpoint not all processing methods are equally compatible with the lunar environment. Some are more sensitive to the specific composition of the feedstock and others tend to consume resources not readily replenished on the Moon (for example carbon electrodes). Thus, if ISRU is a high priority it could drive the location of an outpost away from an otherwise more desirable location. This is more so the case if lunar water is found in a quantity and state that can be readily extracted. If it exists at all it is only in a relatively few continuously shadowed regions. To date the evidence of water is indirect and based on abnormally high concentrations of hydrogen detected by the Clementine spacecraft in 1994. Subsequent radar imaging from the Arecibo observatory in Puerto Rico did not fully confirm this data. As noted, water could, in the long term, be a valuable lunar “natural resource.” However, even if there are ample amounts, it would have to be mined from the crater floor or walls in 40K thermal environment and transported to an outpost outside the shadowed region for processing. There is a possibility that water does not exist, is not in a useful concentration, or is too deeply imbedded beneath the surface for practical excavation.

A summary of these risk factors is presented in Table 3.3-2.

Constellation Risk Factors Considered	
<p>Mapping and characterization of the lunar surface:</p> <ul style="list-style-type: none"> • Enables precision landing and hazard avoidance • Enables more informed landing site selection (lighting, thermal, and volatiles) • Improved gravity mapping enables more accurate navigation for critical mission phases such as descent, rendezvous 	<p>Search for lunar volatile resources:</p> <ul style="list-style-type: none"> • Determine potential for mining water and other resources • Reduce operational risk for mobility systems • Provide data to support ISRU system design
<p>Provide communications for lander missions:</p> <ul style="list-style-type: none"> • Reduces hardware risks for future Constellation missions 	<p>ISRU demonstration/production:</p> <ul style="list-style-type: none"> • Reducing ISRU design and operations risk-
<p>Characterize lunar environment:</p> <ul style="list-style-type: none"> • Reduce risks due to dust: <ul style="list-style-type: none"> ○ Hardware Design ○ Operations ○ Define human exposure limits → informs hardware, EVA suits, mission operations, habitat... • Regolith characterization reduces hardware design risk • Ground truth lighting and thermal environment reduces hardware design risk • Direct measurement of the effect of the lunar environment may reduce hardware design risk for outpost 	<p>Mobility and Operations:</p> <ul style="list-style-type: none"> • Low gravity fluid dynamics will allow Environmental Control & Life Support System (ECLSS) risk reduction for outpost • Up to 30km roving further reduces operational risk for outpost EVA

Table 3.3-2. Risk Factors

4. Review of Candidate Requirements

4.1. Overview

The LRAS team reviewed a variety of materials to identify the complete set of requirements and additional considerations for lunar robotic precursors. As seen in Table 4.1-1 at right, this review intentionally included both official requirements documentation and unofficial preliminary material. The resulting set of items was of very uneven quality. The LRAS team consolidated the list into forty-six items, minimized the overlap between items, and documented the potential benefit of each item.

The discussion in the next sections provides the description, disposition, and rationale for each requirement and additional consideration. It is important to understand the requirements that were carried forward to form the basis for the baseline architecture, as well as the items that were considered important but were not carried forward. Many of the items that not carried forward have high benefit and, in fact, may be fulfilled by the actual missions NASA develops. The resulting set of requirements that LRAS identified differs from the current RLEP requirements set.

Some additional considerations are also presented because they are critical to the analysis of architectures but are not requirements. Opportunity science and nuclear surface power generation are clearly activities that may be conducted and will return specific benefits, but were not identified as the basis for lunar robotic missions.

The analytical methodology is discussed in section 3.2. Detailed data and analytical results for each item are provided in sections 5.2 and 5.3.

Source	Type	Status
Robotic Lunar Exploration Program (RLEP) Requirements ESMD-RQ-0014 Rev. A	Requirements Document	Outdated – Not Applicable
Constellation Architecture Requirements Document (CARD)	Requirements Document	Preliminary
LSAM Top Risks Discussion	Issues List	Preliminary
Exploration Systems Architecture Study (ESAS) Final Report	Architecture Description	High Level Document
Space Communications Architecture Working Group (SCAWG)	Architecture Description	Preliminary
Other working groups, including: LEAG, LADTAG, etc....	Issues Lists	Preliminary

Table 4.1-1. Status of Requirements Documents

4.2. Communications and Navigation

Constellation communications and navigation requirements are assumed not to be primary drivers for the baseline LRAS architecture. The robotic architecture is not required to pre-deploy beacons or other surface navigation aids for Constellation and is not required to demonstrate precision landing or hazard avoidance capabilities, or specific guidance, navigation, and control (GNC) sensors or systems. However, demonstrations of many of these capabilities through robotic precursor missions would be highly desirable, and in some cases may reduce risk and lower costs later in the program.

#	Requirements and Additional considerations	Type
1	Hazard Avoidance	Requirement
2	Precision Landing – 1km Unaided, 100m Aided	Requirement
3	Precision Landing – 10m	Requirement
4	Comm Relay (possibly including Backside)	Requirement
5	Improve Global Gravitational Map	Requirement
6	Over-the-Horizon Propagation of RF	Requirement

Table 4.2-1 Communications and Navigation Requirements

High-priority requirements for an orbiting robotic precursor mission with implications for navigation include providing high resolution topographical data to characterize landing sites (requirement #7), imaging landing sites at landform scales (requirement #8), and improving the lunar gravitational potential map (requirement #5).

There are several communication and navigation requirements that, while not drivers for the lunar robotic architecture, may provide significant risk mitigation or other benefits for the Constellation Program. Robotic landers provide opportunities to demonstrate precision landing capabilities that will eventually enable 100m (3-sigma) landing accuracy, and to demonstrate specific (navigation) software, sensors, and algorithms (requirement #40) used for descent and landing. Objectives that may be satisfied by either lander or orbiter spacecraft include demonstration of the routable, IP-based communication architecture as described in the Constellation C3I Interoperability Specification, obtaining additional experience with tracking and flight dynamics operations for spacecraft in the lunar environment, providing technology demonstrations of communication and tracking hardware, and providing residual communication and tracking assets for subsequent robotic and human missions.

Requirement #1: Hazard Avoidance

The robotic missions should demonstrate automated hazard avoidance sensors and systems in advance of the human missions. This capability has been demonstrated in many Earth applications, and with a high-resolution topographic lunar map can be adapted to robotic missions. Demonstration of this capability will reduce risk to the human landings.

Requirement #2: Precision Landing – 1km Unaided, 100m Aided

The robotic missions should test automated precision landing sensors and systems in advance of the human missions. This will reduce risk to the human landings and enable pre-emplacement of infrastructure equipment or consumables. Specific demonstrations that would provide risk reduction and operational experience for human missions include incorporation of onboard surface-relative sensors, and/or radiometric tracking data from a lunar relay or surface beacon into the navigation state during descent.

Requirement #3: Precision Landing – 10m

Although not a formal requirement in previous documents, objectives of robotic or human missions may require landing accuracies less than 100m. The robotic missions should attempt pinpoint landings in advance of the human missions. This will enable landing on or near (presumably very small) points of eternal light in the polar regions, or on the rim of a crater to support subsequent exploration within the crater. Landings in support of outpost missions may require similar landing accuracies to support precision emplacement of infrastructure.

Requirement #4: Communications Relay (Possibly Including Backside)

A robotic spacecraft targeted to land at a specific polar landing site is the primary driver for the requirement to deploy a lunar relay communication capability as part of the lunar robotic exploration program. NASA’s Space Communications Architecture Working Group has examined direct-to-Earth communication coverage for polar landing sites (see Figure 4.2-2). Even at the most advantageous polar landing sites, direct line-of-sight communication to Earth may be extremely limited, with average communication blackout periods ranging from 1 to 10 days per month. In worst-case locations, communication outages were as long as 18 days per month. Furthermore, direct-to-Earth communication would not be available for a mobile lander traversing into craters or behind local landscape features that obstruct a direct view of Earth. These facts drive the requirement for a lunar relay communication and tracking capability.

Region of Moon	C&N Characteristics
	Near Side 80°W-80°E <ul style="list-style-type: none"> • Continuous Coverage from Earth • Apollo style missions
	Near Side 80-85°E & W <ul style="list-style-type: none"> • Obstructed Coverage from Earth • May allow DTE with careful siting • Full site coverage requires orbital relay
	Limb & Far Side 85°W around back to 85°E <ul style="list-style-type: none"> • Low or No Coverage from Earth • Robotic missions require periodic relay • Humans require (near) continuous relay

Figure 4.2-1. Direct-to-Earth Communication Coverage Characterization

There are numerous secondary drivers for a lunar relay communications and tracking capability as part of the robotic program:

- Providing communication coverage for critical events on the lunar far-side;
- Providing a capability to perform gravity science by direct radiometric tracking of a another spacecraft in low lunar orbit (while orbiting the lunar far-side);
- Reducing the communication burden on vehicles operating in the lunar vicinity; and
- Providing an opportunity to pre-deploy infrastructure that may be utilized by Constellation.

Additionally, the lunar relay communication and tracking spacecraft enables important risk reduction for the Constellation Program in the area of communication, navigation, and flight operations. Specific technology demonstrations for Constellation could include:

- Demonstrate navigation software, sensors, and algorithms in a packet based communication system (requirement #40).

- Validate the Constellation C3I methodology (requirement #40).
- Validate IP at lunar distances (requirement #40).
- Demonstrate communication and tracking to users in low lunar orbit (LLO) or on the lunar surface through a relay.
- Obtain flight dynamics/operations experience with the lunar relay spacecraft.
- Use lunar relay tracking data during precision landing.

Relay satellites and corresponding ground infrastructure deployed to support robotic precursor missions may provide backup or augmented support for human lunar missions. Although the Constellation Program still will require the deployment of some dedicated relay communication and tracking assets, interoperable communication and tracking capabilities between robotic assets and Constellation assets will provide greater robustness and open up potential opportunities for risk reduction and lower costs. This includes actual relay communication assets as well as ground support infrastructure, communication protocols, frequencies, and specific hardware implemented on robotic orbiters and landers.

The following are some of the fundamental communications and navigation requirements for a lunar relay spacecraft supporting Constellation missions:

- Support the Constellation Command, Control, Communication, and Information Interoperability Specification, which specifies:
 - Frequencies
 - Data rates
 - Modulation
 - Protocols, including the use of IP
- Provide communication for landing sites with poor or non-existent line-of-sight communication with Earth.
- Provide communication and tracking for orbiting or surface assets when poor or non-existent Earth-based tracking is available.
- Provide two-way radiometric range and Doppler measurements for navigation of vehicles in the lunar vicinity.

The Constellation Design Reference Mission and Operations Concept specifies that Constellation missions, specifically lunar sortie missions, can be conducted to any location on the lunar surface. This implies a requirement for a lunar relay system providing global communications coverage to any location on the lunar surface; however, the current Constellation Bottoms-Up Review (BUR) guidance states that only South Pole coverage is required.

Requirement #5: Improve Global Gravitational Map

Robotic precursors shall improve the global gravitational map of the Moon by measuring the lunar-far side gravity. This requires tracking of a low-lunar orbiting spacecraft while it orbits over the lunar far-side (tracking through a lunar relay), or a mission involving two cooperative spacecraft in low lunar orbits performing inter-spacecraft ranging (e.g., GRACE).

An improved far-side gravity model will benefit all future lunar missions by reducing a primary navigation error source, will allow improved mission planning and delta-V budgets, and will allow robotic/imaging spacecraft to operate in much lower-altitude lunar orbits.

Benefits for human missions include reduced Deep Space Network (DSN) tracking, improved orbit accuracies and landed accuracies, and improved robustness in response to contingency situations (loss of communication/tracking).

Requirement #6: Over-the-Horizon Propagation of RF

A rover or astronaut on a surface EVA may not always have direct line-of-sight communications with either Earth or a fixed communications base station. Examples include EVAs in which astronauts are large distances from the outpost/lander, or in which a mobile lander is exploring a crater. Primary means of communications in these situations will be through an orbiting relay satellite, or through an intermediate surface asset (rover or other fixed base station). A technology demonstration can establish if proposed techniques using the dielectric effect of regolith to achieve over-the-horizon propagation of RF are viable. This may represent significant risk reduction for long-range astronaut surface sorties. Robotic missions shall demonstrate the different techniques for achieving communications between surface assets described above.

4.3. Mapping (Visual, Topographic, and Resources)

Mapping or characterization of lunar features, properties, and resources will assist Constellation’s mission in many ways; good maps early on will allow the entire mission to be more efficient and effective. There are three types of maps: visual, topographical, and resource. Visual maps will help to identify good landing sites and understand lighting and physical characteristics. Topographical maps will facilitate modeling of the surface. Resource maps will help locate bases where ISRU can more easily be performed. Additionally, improving lunar gravitational potential models was identified as a priority requirement in section 4.2.

#	Requirements and Additional considerations	Type
7	Topographical Map	Requirement
8	Visual Map – Landform Scales	Requirement
9	Orbital and Ground Truth Measurements of Thermal and Regolith Properties	Requirement
10	Characterization of Minerals and Volatiles in the Regolith	Requirement
11	Characterize the Lighting Near Permanently Lit Areas	Requirement
12	In-Situ Mapping of Water	Requirement

Table 4.3-1. Mapping Requirements

Requirement #7: Topographical Map

The robotic missions should create a center-of-mass referenced high-resolution topographical map with better than 1m relative accuracy. This will facilitate modeling of the surface, thus refining understanding of landing sites and lighting conditions throughout the year (through simulation models). Furthermore, the establishment of a high spatial resolution geodetic grid for the Moon was identified as a key measurement for the purpose of reducing the risk to human landings on the Moon.

Requirement #8: Visual Map – Landform Scales

The robotic missions should create a complete medium-resolution visual map of the entire surface of the Moon, including imaging of selected sites at landform scales as well as landing site scales relevant to hazards. Visual maps will help to identify good landing sites, as well as help characterize lighting and physical characteristics, and will reduce the risk to both robotic and human landings on the surface of the Moon.

Requirement #9: Orbital and Ground Truth Measurements of Thermal and Regolith Properties

This requirement specifically addresses detailed in-situ measurement of the thermal environment and the general physical characteristics of the regolith, including the distribution of grain size, density, compactness, and general radiation shielding properties. These data are of primary importance to an eventual outpost. While a sortie mission may choose to land in a relatively uncharacterized site – or even a site known to be environmentally hostile – a key aspect in the long-term viability of an outpost will be to choose a site that meets mission requirements and is as environmentally benign as possible. This will require a good knowledge of surface temperatures throughout a lunar cycle, as well as the reflectivity and emissivity of the soil and possibly the heat capacity of the soil if it is used as a protective covering. This may be more important near a shadowed crater, where the lunar surface temperatures can reach as low as 40K and may act as a very deep heat sink if “seen” by any part of a landed surface system. Regolith surface characterization is important to determine the tribological risk to mechanical systems. [Note this is differentiated from the issues with dust, the smallest of the regolith grains (nominally < 5 μm in size) covered in other requirements.] Also, regolith may be used as radiation shielding in place of shielding built into a lander. However, this may only be practical if its properties do not require excessive amounts to enable it to serve as a shield. Some estimates have been as high as 3m, depending on the ultimate biological shielding requirements for safe human habitation and the inherent shielding properties of the regolith at the landing site. While low-resolution measurement of temperature and surface composition can be made from orbit for initial screening, high-resolution measurements and physical characterization can only confidently be made in-situ.

Requirement #10: Characterization of Minerals and Volatiles in the Regolith

A key element of the overall human lunar mission strategy is to preserve the option to utilize in-situ lunar resource. The composition of lunar regolith resembles terrestrial soil (~40% oxygen plus major amounts of silicon, aluminum, calcium, and iron as well as small amounts of titanium), but the mineralogy of the soil is different from Earth and varies in different parts of the Moon. While there are no gasses present above the surface, there are relatively small amounts of hydrogen and helium (~50 ppm) and smaller trace amounts of other light elements (e.g., nitrogen) deposited by the solar wind. Characterizing the mineral and volatile composition at a potential landing site is very important since the suitability of a given process to extract specific material (in particular oxygen) from the regolith can be very dependent on the local mineralogy and inherent elemental concentration. Also, the absolute and relative abundances of solar wind implanted light elements will determine whether there is sufficient volatile material to warrant extraction efforts. Further, there is evidence of water ice in some permanently shadowed regions such as Shackleton crater. If there is water, it could eventually serve as an alternate source of O₂ or a unique source of H₂/O₂ rocket fuel. However, the evidence is only circumstantial based on much higher than normal concentrations of hydrogen registered by the Clementine spacecraft in 1994. It could be clumped or dispersed, near the surface or up to a few meters below. This same information – as well as a more complete compositional survey – is of importance to lunar science to understand better the evolutionary development of the Moon and the solar system. While orbital instruments can provide useful data on surface mineralogy, in-situ measurements are necessary for ground truth and, in particular, “sub-ground” truth at depths of a few meters (possibly down to 10m).

Requirement #11: Characterize the Lighting Near Permanently Lit Areas

A polar location with near-permanent solar illumination provides significant advantages for lunar outpost or sortie missions. This would eliminate the burden of surviving a lunar night, which at the equator can last 334 hours and be as cold as -150°C. As such, a sortie mission would not be limited to less than two weeks and an outpost would not have to go into “hibernation.” Further, permanent solar illumination can

enable an outpost to be fully solar powered, even possibly in the case of large-scale ISRU operations. This becomes more important if water is processed, since a site will have to be near the water source (e.g., a crater rim) and illuminated. While the Moon's axis of rotation does not have a significant inclination, it is tilted about 1 degree, so there is no location with assured continuous illumination. However, there is an indication of small, elevated patches near the poles that may be continuously illuminated, or nearly continuously illuminated. Whether it is full or near-continuous, the variation in the intensity (if it always illuminated but not uniformly), and the degree of reflectance from the surface are significant factors in determining the suitability of the site especially for a long-term outpost. Orbital measurements can identify with a high probability of continuous illumination, but the LRAS team concluded that site-specific, in-situ measurement of the actual insolation – both intensity and direction, and direct and reflected illumination – would be required to adequately reduce the risk to a long-term sortie mission or a permanent outpost.

Requirement #12: In-Situ Mapping of Water

A basic requirement of the LRAS study was to maintain the option to produce useful resources from in-situ lunar materials. While chemical, electrolytic, or thermal processing of regolith has been considered for four decades to produce principally oxygen – and byproducts such as metal and glass – relatively recent evidence suggests that ancient cometary water may still exist in permanently shadowed regions near the lunar poles, such as the Shackleton crater near the south lunar pole. If water exists it is currently considered at most to be 1.5% of the soil, based mainly on 1994 data from the Clementine spacecraft that first detected concentrations of hydrogen far above the typical background levels of about 50 ppm. One possibility for this anomaly is that the hydrogen is in the form of water, though experiments to confirm this have not yet been performed. If ample amounts of water exist and are readily accessible, this could directly serve the needs of human life support, either as a back-up to Earth-supplied water or as a relief from the requirements to fully recycle water. It could also be an alternate to regolith as a source of oxygen – but it would also produce hydrogen, providing a possible source of high performance rocket fuel on the Moon. The key questions other than its existence are: how water is deposited in micron-size crystals or lunar “ice cubes”; how it is distributed across the surface; and how deep, on a sub-meter scale; and where it is located relative to a viable outpost site. All of these questions need to be answered before water can be considered a practical lunar resource. While the distribution of water can be determined from orbit, physical characteristics of the deposits can only be determined in-situ. Further, the temperature in permanently shadowed areas where water may exist is as low as 40K (-233°C), eliminating the option for human “prospecting.” The LRAS team considered both locating possible sites for water “mining” and surface characterization of any found sites to be requirements for an extended lunar robotic architecture.

4.4. Environment (Dust and Radiation)

The Moon provides a harsh environment, with nearly non-existent atmosphere; intense ultraviolet (UV), galactic, and solar cosmic radiation; lack of liquid water; abrasive corrosive, potentially toxic dust; and large temperature extremes. In many ways, the environment of the Moon is even harsher than that of Mars, without the mitigating factors of an atmosphere to block radiation and an increased gravity environment. Assessment of lunar environmental effects on systems (human and physical) is an essential aspect of the development of innovative technologies, knowledge, capabilities, and infrastructures to support human and robotic lunar exploration. Apollo astronauts accepted a high level of risk for their short (3-4 day) stays on the Moon that will not be acceptable for longer sortie missions. Even more technical challenges must be overcome for longer duration stays on the lunar surface; based on Apollo experiences, dust and radiation may be limiting issues that will determine the extent of capabilities and mission durations that can be supported. Requirements related to the lunar environment include both better characterization of the environment, better understanding of its interactions with humans and machinery, and demonstrations of technologies for monitoring and mitigating environmental impacts.

Environmental characterization should occur as early as possible in the robotic lunar architecture in order to provide significant risk mitigation and other benefits for the Constellation Program by informing technology development and the design of vehicles, suits, life support, and other systems.

Requirement #13: Characterize Lunar Dust Environment

Lunar dust is a heterogeneous mix of broken particles (<50µm) of minerals and agglutinated glass that are the result of space weathering. Space weathering consists of the combined results of the lunar deep vacuum (~10-12 torr), micrometeorite impacts over billions of years, radiation (solar wind particles, galactic, cosmic), and temperature (+125°C to -240°C). Lunar dust is extremely abrasive with very large surface areas per mass and large numbers of nanophase iron particles in the glass. There are no terrestrial analogs for lunar dust, as all Earth minerals are exposed to the weathering of air and water. The closest

#	Requirements and Additional Considerations	Type
13	Characterize Lunar Dust Environment	Requirement
14	Determine the Effects of Lunar Dust on Systems	Requirement
15	Characterize 1/6 g Fluids/Two-phase System Characteristics	Requirement
16	Demonstrate Systems That May Be Affected by Partial Gravity	Non-RLEP Requirement
17	Measure Biologically Relevant Radiation Environments	Requirement
18	Investigate Potential Biological Impacts of Combined Lunar Environmental Factors (Radiation, Partial Gravity, Thermal, Micrometeorites, Dust)	Requirement
19	Conduct Correlated Experiments at Molecular, Cellular, and Whole-organismal Levels	Additional consideration
20	Prototype Systems for Monitoring Lunar Environmental Effects (Radiation, Dust, Gravity Transitions, Thermal Effects) on Humans	Non-RLEP Requirement
21	Prototype Systems for Mitigating Space Environment Effects on Humans (Radiation, Partial Gravity, Dust, Thermal Effects)	Requirement
22	Measure the Radiation Shielding Capabilities of In-Situ Materials at the Moon	Additional consideration
23	Validate Planetary Protection Strategies and Technologies	Additional consideration

Table 4.4-1. Environmental Requirements and Considerations

facsimile is industrially processed silicates, which are fine grained, have reactive surfaces, and have unusual morphologies that cause very serious and often lethal medical problems. Apollo astronauts found dust to be one of the most aggravating and restricting facets of lunar surface exploration, especially its adherence to all materials (including skin, suit material, and metal) and its restrictive friction-like action on everything.

All Apollo regolith samples returned to Earth were exposed to air, so reactivity measurements were not possible. To reduce the uncertainty associated with potential acute and chronic lunar dust toxicity to crewmembers conducting lunar exploration sortie and outpost missions, it is essential to understand the reactivity and particle size distribution of lunar soil. The uncertainty currently results in more conservative standards for astronaut dust exposure than may otherwise be required. Required measurements are the magnitude of reactive oxygen species (e.g., hydroxyls, superoxides, etc.) levels on the surface of lunar soil, the rate and degree of reactivity passivation upon exposure to oxygen, and the percentage of lunar dust/mass $<5 \mu\text{m}$ in size. The dust exposure standards have impacts on the lunar surface vehicle, airlock, and module systems design; thus more precise information about lunar regolith should be obtained robotically as early as possible in order to influence vehicle design and the development of measures to ensure astronaut health and safety.

Requirement #14: Determine the Effects of Lunar Dust on Systems

The abrasive nature and electrostatic charge of dust leads to major system and mission failure risks. The top two risks identified by multiple studies are 1) the risk of critical life-safety systems failing due to dust build-up on systems, and 2) the risk that adverse health effects will result if the crew inhales or ingests dust. Systems do not currently exist that can function in the lunar dust environment. Understanding how to shield filters, pumps, materials, seals, and other hardware is essential to driving the design of life support components that will be exposed to fine lunar dust. Dust contamination of the habitat and EVA systems, as well as the introduction of dust into the breathing volume, are viewed as significant issues. Both the extent and mechanisms of dust damage as well as the techniques to remove (e.g., magnetic brushes) or limit dust from breathing and mechanical systems (e.g., airlocks or electrostatic repellers) should be investigated on early lunar robotic missions in order to inform Constellation system design.

Requirement #15: Characterize 1/6 g Fluids/Two-Phase System Characteristics

Multi-phase flow in partial gravity needs to be understood to ensure that all components that utilize a liquid-vapor or liquid-gas system behave in a predictable manner in the lunar gravity environment. Validated engineering data currently do not exist to design these systems adequately. For example, gas-liquid packed-bed reactors are a critical operational component for many exploration life support unit operations (e.g., water recovery) and ISRU chemical processes. The most common mode of operation is “trickle flow,” where the liquid phase is gravity-driven and trickles downward over the solid packing. In the absence of gravity, the bed operates in a different flow regime (usually bubbly or pulse flow). It is important to ensure that the liquid phase is evenly distributed throughout the bed. Accurate prediction of the amount of liquid holdup is critical to successful operation. Also, if flooding occurs in the bed, the chemical or biological performance of the bed is greatly reduced. Understanding of flow boiling heat transfer and critical heat flux (CHF) at 1/6 g is needed for the design and safe and efficient operation of thermal and phase-change subsystems on the Moon. Short testing periods using aircraft have shown that nucleate flow boiling at low flow velocities greatly lowers the CHF in reduced gravity. Operating at CHF can lead to burnout in which metal walls can reach the melting point and fail. Exploration of the Moon requires enabling technologies for efficient and reliable energy generation (e.g., nuclear, chemical, solar sources), storage (e.g., rechargeable batteries, regenerative fuel cells, flywheels, latent heat phase change), and transfer (cabin temperature control, space suit temperature regulation). In order to improve energy-

to-mass ratios, present single-phase operations will need to be replaced with two-phase systems. Future design of important thermal subsystems in boilers, condensers, evaporators, heat exchangers, cryogenic fluid storage units, fuel cells, radiators and heat pipes involve complex multiphase fluid flow and transport challenges, which require measurement and testing of different active heat removal and intermittent forced-mixing behavior. The necessary information is g-dependent and not testable on Earth. Information obtained early in the lunar robotic program will contribute the most to decreasing design risk for the LSAM and subsequent Constellation modules.

Non-RLEP Requirement #16: Demonstrate Systems That May Be Affected by Partial Gravity

Multi-phase flow in partial gravity needs to be understood to ensure that all components that utilize a liquid-vapor or liquid-gas system behave in a predictable manner. The National Research Council report *Microgravity Research In Support of Technologies for the Human Exploration of Space and Planetary Bodies* (2000) identifies this as a high priority, because the validated engineering data currently do not exist to adequately design systems such that may be affected by partial gravity, including life support and advanced environmental monitoring and control components, ISRU, and in-situ fabrication and repair. As a general rule of thumb, subsystems, such as those for life support, should be fully validated six years prior to deployment of a system. Therefore, those Constellation subsystems that are affected by partial gravity will require demonstration robotically before human missions. However, the LRAS team felt that the LSAM robotic test missions were likely to be early enough to provide those demonstrations.

Requirement #17: Measure Biologically Relevant Radiation Environments

Galactic cosmic rays (GCR) have heavy nuclei and generate many secondary particles in the lunar soil that are hazardous to humans and sensitive electronic equipment. While the space radiation environment is reasonably well understood in general, characterization of the neutron albedo of the Moon (in particular energies in excess of 10 MeV, which are more damaging to humans) is a high priority in order to reduce uncertainty about the biologically relevant radiation environment that astronauts will be exposed to during lunar exploration measurement. In order to set dose limits, increased knowledge of both the biologically relevant radiation environment and biological responses to that environment is required. The characterization of the orbital and surface radiation environments will allow for proper mitigations to be developed to reduce risk for future missions to the Moon. Radiation monitoring instruments should be included as standard equipment on all lunar robotic orbital and lander missions.

Requirement #18: Investigate Potential Biological Impacts of Combined Lunar Environmental Factors (Radiation, Partial Gravity, Thermal, Micrometeorites, Dust)

Investigation of biological impacts of the lunar environment is necessary to reduce risk to crew safety during human missions to the Moon. Health risks from radiation include: carcinogenesis; acute and late central nervous system damage; tissue degeneration; fertility and sterility problems; and acute radiation syndromes. Most data on human responses to radiation come from studies of atomic bomb and nuclear accident survivors who suffered acute exposure to high-flux gamma rays, rather than chronic or fractionated exposure to the low-flux protons or heavy ions that astronauts are more likely to encounter. Currently, the effects of space radiation on humans must be extrapolated from data on humans exposed to other types of radiation or animals exposed to space-like radiation. The Moon affords an excellent opportunity to advance our understanding of radiation effects on humans and study the interactive effects of partial gravity, radiation, dust, and thermal extremes on humans and other organisms. Each of these environmental challenges has been studied singly to a lesser or great extent, but there has not been an opportunity to look at the potential synergistic impacts. For example, there is evidence that reduced gravity, radiation, thermal stress, and dust exposure all reduce the immune response of humans and other

organisms. However, no tests have been conducted yet to determine whether those impacts on the immune system are additive or have some other synergistic interaction when multiple challenges are present simultaneously. Especially in the case of partial gravity, these experiments are impossible to do on Earth, and the ISS provides a poor model for radiation or dust. Early lunar robotic studies on small organisms may provide knowledge critical for validation of risk models that will be used for projecting human health risks and performance degradation, and influence mission design requirements (e.g., shielding, operational mandates, and countermeasure development). This approach will result in significant risk mitigation for human exploration missions to the Moon and Mars. The capability to perform experiments in orbit or on the lunar surface should include remote autonomous experiments that provide statistically meaningful sample sizes.

Additional Consideration #19: Conduct Correlated Experiments at Molecular, Cellular, and Whole-Organismal Levels

As with early lunar robotic studies (see requirement #18), early applied robotic studies on small organisms can provide knowledge critical for the validation of risk models. In order to mitigate the risk to humans of exposure to the lunar environment, it is important and necessary to use a comparative approach to understand how biological organisms transduce, perceive, integrate, and respond to the impacts of reduced gravitational force and the integrated effects of radiation, dust and the reduced gravity environment. Human performance consequences, such as reductions in cognition, immune system function, wound healing, and other key functions, can be understood by utilizing correlated experiments with model biological systems and organisms to develop transfer standards that apply directly to determining human risk and developing countermeasures. Modern biomedical and pharmaceutical research and development relies heavily on the use of model systems, ranging from cells and microbes to larger organisms such as mice, rats, and pigs, for the bulk of research and the careful development of transfer standards of that research directly to human interventions, with final validation always through human trials. Research on Spacelab, Neurolab, and the Space Shuttle has already demonstrated the efficacy of utilizing model biological systems to elucidate and understand biological consequences of space flight and to inform the development of countermeasures to mitigate health and performance impacts. Lunar biological studies that begin with molecular, cellular, and microorganism responses can be carried out autonomously on lunar robotic missions and contribute to the development of technologies necessary for expanded studies with larger organisms. Biosentinel studies on robotic precursor missions to deep space can act as environmental monitors that inform many aspects of human risk by indicating bio-responses that correlate with human responses to that particular environmental challenge. More complex biological experiments carried out at lunar outposts offer unique opportunities to validate countermeasures and demonstrate and validate enabling bio-related technologies for Mars missions.

Non-RLEP Requirement #20: Prototype Systems for Monitoring Lunar Environmental Effects (Radiation, Dust, Gravity Transitions, Thermal Effects) on Humans

Missions of greater duration and distance require human support technologies that are more autonomous, efficient and reliable. Environmental monitoring technologies for the Moon are required to guarantee crew health and safety, and enable optimal performance throughout the mission. Reliable, validated environmental monitoring systems for radiation, dust, and temperature that function well in reduced gravity, remain functional without the possibility of support from Earth, and can be used repeatedly will significantly lower cost and risk. (The International Space Station, or ISS, is not an acceptable validation.) The prototyping of radiation monitors must be performed outside Earth's magnetosphere. For monitoring radiation, passive detector stacks to measure the accumulated dose of heavy ions should be designed to survive flight and be sensitive to the correct spectrum of particles. Lunar surface temperatures increase about 280K from just before lunar dawn to lunar noon, with the temperature at

lunar noon varying throughout the year. An accurate thermal monitoring system that can cover that range of temperatures in the partial gravity environment is required to enable the efficiency and effectiveness of the astronaut suits. Knowledge of the lunar dust environment gained from the initial lunar robotic lander(s) will inform the development of appropriate dust monitoring technologies. When astronauts adapt to the Moon's gravitational environment, balance, locomotion and eye-head coordination are transiently disrupted. In addition, during gravitational transitions such as entry descent and landing, head movements and/or vehicle maneuvering can cause spatial disorientation, perceptual illusions and/or vertigo. Monitoring of the gravity forces during transitions is critical to the mitigation of these effects.

Prototyping of environmental monitors could be done on either robotic orbiters or landers for radiation, but should be carried out on robotic lander missions for dust, gravity, and thermal monitoring. Validation should occur prior to human sorties, but could take place on LSAM test flights rather than as part of the Robotic Lunar Exploration Program.

Requirement #21: Prototype Systems for Mitigating Space Environment Effects on Humans (Radiation, Partial Gravity, Dust, Thermal Effects)

Technology maturation in preparation for human sorties is one of the key objectives of lunar robotic missions. As with lunar environmental effects (see requirement #20), reliable, validated systems for mitigating space environmental effects on humans – such as radiation and thermal shielding, exercise equipment to mitigate the deleterious health impacts of partial gravity, and dust removal mechanisms – will significantly lower cost and risk. Recommendations by the National Academy of Sciences, the National Council on Radiation Protection and Measurements, and the radiation protection community have remained constant since 1970, and include using new radiobiology knowledge and data to develop optimal shielding approaches. Measurements of the radiation shielding properties and performance of imported radiation materials must be performed and radiation transport models calibrated for each potential shielding option. Extended periods at the reduced lunar gravity of the Moon will likely result in the loss of both bone and muscle mass, potentially reducing human performance during lunar missions and posing risks upon return to Earth gravity. Exercise systems, together with other countermeasure protocols, will be critical to the mitigation of these effects.

Additional Consideration #22: Measure the Radiation Shielding Capabilities of In-Situ Materials at the Moon

Radiation shielding must be provided for any long-term human mission to the Moon. For sortie missions, adequate protection will have to be incorporated into the lander. However, an outpost will require a much higher level of shielding to protect astronauts from the long-term effects of high-energy, low-intensity cosmic rays and short-term but energetic and very intense solar mass ejections. It may not prove practical to build a habitat with adequate inherent shielding. If that is the case, in-situ materials can be used (i.e., regolith). Currently, it is not clear what level of shielding will be required or what amount of regolith shielding will be needed to meet that requirement. The uncertainty in the latter is related to the uncertainty in the measurement of basic, high-energy radiation transport to predict accurately the shielding properties in elementally diverse lunar soil. Ideally, the shielding material should have a low average atomic weight, which is not consistent with regolith. As such, shielding thickness can be reduced by “beneficiating” the soil (removing unwanted material and concentrating desired material), a possible common requirement for large-scale ISRU. The extent to which this helps will depend on the nature of soil at a landing site. Note that requirement #9 (“Orbital and Ground Truth Measurements of Thermal and Regolith Properties”) will address the bulk in-situ shielding properties. This will establish a baseline that can be compared with current knowledge of lunar soil from Apollo samples. However, validation of

modeling accuracy for well-characterized and compositionally well-separated samples at a potential outpost site is highly desirable for risk reduction.

The LRAS team felt that this was a valuable consideration, but that it would be premature to require it. The outpost requirements, concept of operations, design reference missions, and preliminary designs are notional at this time. The nature of the radiation to shield still remains to be tested in detail as per requirement #17. Further, this consideration could be accomplished during a sortie mission with astronauts available to conduct the necessary soil pre-processing and tests, or possibly to return samples to Earth for testing.

Additional Consideration #23: Validate Planetary Protection Strategies and Technologies

Planetary protection ensures that space exploration avoids forward biological contamination of planetary bodies by outbound spacecraft that could jeopardize the search for extraterrestrial life. In addition, the Earth and its biosphere must be protected from potentially harmful organisms that could be present in materials returned from extraterrestrial bodies. Under the current planetary protection policy for the Moon of the Committee on Space Research (COSPAR) of the International Council for Science, no decontamination procedures are required for outbound lunar spacecraft. However, chemical and microbiological studies of the impact of terrestrial contamination of the lunar surface by lunar spacecraft and Apollo astronauts could provide valuable data to help refine future Mars surface exploration plans, including planetary protection requirements for a human mission to Mars. Instruments that can detect minute levels of biologically derived organic compounds can also be used in studies to provide “ground truth” data for Mars sample return missions and help define planetary protection requirements for future Mars-bound spacecraft carrying life-detection equipment.

4.5. In-Situ Resource Utilization (ISRU)

The LRAS team assumed the use of in-situ lunar resources to support lunar surface operations – and potentially, in the long-term, broader exploration goals – to be an integral part of the overall exploration program. However, it was not considered a requirement for lunar sorties mission or an initial outpost. Further, the study considered two classes of ISRU: (1) a small-scale ISRU facility with a production capacity of about one to several metric tons/year (As a reference, the ESAS study determined that about 8 metric tons of O₂ would be needed to fuel two LSAM ascents per year and about 1 metric ton/yr as a “back-up” to closed-loop life support), and, alternately (2) a large facility nominally producing 50 to 100 metric tons/year of O₂ from regolith, or possibly O₂ and H₂ from water existing in a permanently shadowed crater.

#	Requirements and Additional considerations	Type
24	Demonstrate New Surface Mobility Technologies	Additional consideration
25	Demonstrate Excavation to Bury a Habitat or Stockpile Shielding	Additional consideration
26	Smoothing, Obstacle Removal, Emplacement of Registration Markers	Additional consideration
27	Demonstrate ISRU (O ₂) Production from Regolith	Requirement
28	Demonstrate O ₂ Production from Regolith Including Benefication and Storage	Requirement
29	Demonstrate H ₂ /O ₂ Production from Lunar Water	Requirement

Table 4.5-1. ISRU requirements

Additional Consideration #24: Demonstrate New Surface Mobility Technologies

The LRAS team had concerns regarding the long-term durability of mechanical systems (including seals) in a harsh lunar environment. Of particular concern is the abrasive effect of soil, including highly penetrating dust grains. This was a problem on the Apollo flights and there is no relevant experience to validate with confidence the multi-year durability of a lunar outpost. The specific concern over mobility systems is the risk of astronauts being stranded due to mechanical failure or the need to replace mobility systems much more frequently than planned. An indirect consequence is that the range of allowed astronaut mobility – and the mobility of robotic systems – may be restricted to the point where actual exploration or science is adversely affected. As such, the LRAS team considered in-situ validation of any new, untried mobility systems – such as rovers, hoppers or astronaut aids – to be highly desirable, but not required for an initial lunar robotic architecture. The specific systems at risk could just as well be demonstrated during a sortie mission. Note that this additional consideration complements requirement #32 “Demonstrate ‘Safe Roving’ and Return (to ~10 to 30 km),” which addresses validation of long-distance roving prior to initial mission use.

Additional Consideration #25: Demonstrate Excavation to Bury a Habitat or Stockpile Shielding

If adequate radiation protection requires a habitat to be excessively massive, it may prove more effective to use in-situ materials in construction. The two likely approaches are to cover the habitat with loose, bagged or, in some manner, consolidated regolith; and the other is to bury the habitat. Prior studies have indicated the required level of covering could be a few meters, requiring a substantial amount of material. This could become a problem if the time required to cover a habitat is more than a few days, since the astronauts would be using up their allowed surface exposure time. Thus, in-situ shielding would have to be applied relatively quickly in order for it to be a practical option. This may further require site preparation prior to landing, such as stockpiling soil near the habitat emplacement site. While the top 10 cm of the lunar soil are relatively loose and easily scooped, the soil below is highly compacted to a density as high as 85% of theoretical as a result of eons of micrometeorite impact. Thus, digging in the soil could prove to be very difficult. However, one study conducted during the period of the Space Exploration Initiative of the early 1990s indicated that explosive excavation may be done very precisely due to the absence of moisture in the soil. This may prove a better option than digging. Given the uncertainty in either option, the LRAS team concluded it is highly desirable to validate any in-situ shielding process and operational stress experienced by the required mechanical systems on the lunar surface prior to an actual mission application. The team also concluded that if this option is tested, it does not have to be done as part of a lunar robotic mission. While the actual site preparation could be done robotically from earth, the LRAS team believed this option could be better tested during a sortie mission to the outpost site since astronauts would be present to oversee the operations and best identify any limiting problems. Note that this additional consideration complements other site preparation risk reductions presented in additional consideration #26 (“Smoothing, Obstacle Removal, Emplacement of Registration Markers”).

Additional Consideration #26: Smoothing, Obstacle Removal, Emplacement of Registration Markers

If a lunar outpost is built, it will likely be highly desirable to perform some degree of general site preparation prior to emplacement, including removal of obstacles or flattening small undulations that may pose a risk to safe landing. It would be desirable to place positioning aids or beacons at specific locations to assist landing and to enable precise robotic placement of outpost systems. This would reduce risk and enable an optimum site to be selected and prepared for the habitat and other permanently placed systems. This can probably be done robotically from Earth with the necessary site preparation equipment in place.

It represents a potentially significant risk reduction operation, and should be part of outpost emplacement, rather than part of a lunar robotic architecture. Note that this additional consideration complements other site preparation risk reductions presented in additional consideration #25 (“Demonstrate Excavation to Bury a Habitat or Stockpile Shielding”).

Requirement #27: Demonstrate ISRU (O₂) Production from Regolith

A basic requirement of the LRAS study was to maintain the option to produce useful resources from in-situ lunar materials, specifically regolith. This requirement has been a strong consideration for all proposed human missions to the Moon. Most emphasis has been placed on extracting oxygen from lunar material, which constitutes about 40% of the lunar soil (similar to Earth) and could be used for life support and rocket fuel. The first processes for lunar O₂ production were proposed before the first Apollo landing, and though studied for over 40 years, no demonstration has ever been performed on the lunar surface. There are currently multiple processes that could potentially produce O₂ – ranging from a few kilograms to over 100 metric tons per year – from lunar soil. Each has its specific benefits and liabilities. Some are very tolerant of feedstock, but very energy demanding; others are more energy efficient but require a specific feedstock. In all cases, the critical issues are related to engineering feasibility, not basic physics or chemistry. Processes can be simulated on Earth to determine feasibility, and possibly tested on real lunar material. However, concerns over long-term stability, degradation of processing equipment, and start-up/shutdown in the lunar environment – particular in 1/6 gravity – cannot be confidently resolved on Earth. If lunar O₂ production is to be part of an architecture that supports a sustained human presence on the Moon, it must first be proven reliable, not just feasible. The LRAS team and NASA ISRU experts concluded that a lunar ISRU experimental demonstration was required for process validation and risk reduction, and that it could readily be carried and powered by a robotic lander. The emphasis of the experiment would be on basic process dynamics. If successful, a small pilot plant would likely be the next step prior to full implementation. This requirement is complementary to requirements #28 (“Demonstrate O₂ Production from Regolith Including Benefication and Storage”) and #29 (“Demonstrate H₂/O₂ Production from Lunar Water”).

Requirement #28: Demonstrate O₂ Production from Regolith Including Benefication and Storage

This requirement is closely coupled to requirement #35, which focuses on an in-situ experimental demonstration that validates the feasibility O₂ production from regolith. The experiment would focus on basic process dynamics. The next step, if justified, is to validate the process at a more integrated pilot plant level. NASA ISRU experts believe a pilot plant would weigh about 100 kg, consume only a few kilowatts of power, and could be deployed on a robotic lander. The plant would exercise the complete production process including long-term storage, and if necessary, benefication. (The latter refers to some processes being sensitive to the feedstock. In some cases the feedstock is a relatively small part of the lunar soil.) Using bulk regolith could result in processing an excessively large amount of material, most of which would be inert to the O₂ extraction. In other cases, the extraction process could produce byproducts that interfere with the O₂ process or damage processing hardware if bulk regolith is used. Both cases are fairly typical of many terrestrial processes, and there are standard benefication processes that may be useful on the Moon. However, the lunar constraints on mass, energy, and consumables present a very different engineering challenge than on Earth. As such, the LRAS team considered an end-to-end small pilot plant demonstration necessary for adequate risk reduction and appropriate for an extended lunar robotic architecture.

Requirement #29: Demonstrate H₂/O₂ Production from Lunar Water

If water exists it may directly serve the needs of life support (both as native water and a source of oxygen) and represent a unique source of rocket fuel on the Moon: H₂/O₂. Currently, the existence of water is still unproven and the economic value of producing rocket fuel depends on the nature and extent of future in-space exploration. In any case, the viability of using lunar water as a valuable in-situ resource is highly dependent on the difficulty of “mining” water-bearing soil in the shadowed regions and extracting the water from the soil. This includes determining the extent to which water would have to be – or even could be – separated (beneficiated) from the soil at the mining site or prior to electrolysis, and what unwanted byproducts may be produced along with O₂ and/or H₂. This assumes the thermal environment precludes human operations in a shadowed region, and that all “mining” activities would have to be done robotically. Assuming ample amounts of accessible water are found and processing is determined to be economically advantageous, a proof-of-concept, end-to-end validation demonstration should be conducted from mining to storage (if cryogenics are produced). The LRAS team recognized the speculative nature of lunar water but concluded a robotic demonstration could, and should, be part of an extended lunar robotic architecture. Further, the actual decision on whether to conduct such a demonstration could wait until the question of whether lunar water would be of any practical value was answered. This requirement complements requirement #12 (“In-Situ Mapping of Water”), which is focused on locating and characterizing possible deposits of lunar water in very cold (~40K) permanently shadowed regions such as Shackleton crater near the lunar south pole.

4.6. Other Risk Reduction for Development and Operations

There are a number of technologies that will need to be proven before a lunar outpost can be established. A number of other technologies might be beneficial, but are not required.

Requirement #32: Demonstrate “Safe Roving” and Return (to ~10 to 30 km)

While astronauts have operated a lunar rover for several kilometers on two separate Apollo missions, they did not rely on the rover for an extended period of time. Future lunar astronauts, whether serving on an extended sortie mission or a long-term outpost mission, will explore the region surrounding their landing site. For any distance over a few kilometers, a mobility system such as a rover will be required; this system must operate safely for the duration of the mission. For a permanent outpost, the useful life of the rover will likely be several years. Due to the potentially harsh thermal environment, lunar dust and inherently high abrasive nature of the regolith, the operational life of a rover – or any mechanical system – cannot be assured by terrestrial testing alone. In principle,

the thermal environment can be simulated, but the combined effect of temperature and physical/chemical effects involving actual soil can at best be approximated on Earth. As an example, the abrasive lunar soil, coupled with exposure bare metal surfaces in a cold, oxygen-free environment, may wear away protective or lubricating surfaces and result in a kind of welding known as galling. This is similar to the assumed problem with the Galileo spacecraft that prevented deployment of its primary antenna. Contrarily, there is evidence that lunar soil may passivate bare surfaces. The LRAS team considered in-situ risk reduction essential to assure the safety of astronauts for extensive lunar excursions. The range of ~10 to 30 kilometers was considered the limit for astronauts to travel and for “safe roving.” Apollo 15 completed three rover operations of 10.3 km (6 hr. 33 min.), 12.5 km (7 hr. 12 min.), and 5.1 km (4 hr. 50 min.), for a total of almost 28 km. Apollo 17 conducted similar roving operations for a total of almost 29 km.

A second issue is the ability of an unpowered rover to be driven into a 40K crater to extract water and return the “raw material” to a processing plant. If useful amounts of water exist in these regions, the greatest operational risk is the failure of mechanical systems in this environment, both repeatedly traversing long distances and digging into hard, extremely cold soil. While the thermal condition on the Moon can be duplicated on Earth, the physical conditions of the lunar terrain and soil cannot likely be duplicated to sufficiently reduce the risk of mining operations. A precursor rover mission into the crater could both search for water and determine the extent of the mobility system risk.

#	Requirements and Additional considerations	Type
32	Demonstrate “Safe Roving” and Return (to ~10 to 30 km)	Requirement
33	Validate In-Space Cycling of LSAM Engine	Non-RLEP Requirement
34	Demonstrate Telemedicine	Non-RLEP Requirement
35	Demonstration of Robotic Emplacement/Assembly Equipment	Additional consideration
36	Demonstrate Precise, Dexterous Assembly Operations	Additional consideration
37	Demonstrate Thermal Management Technologies	Additional consideration
38	Demonstrate Power Technologies	Additional consideration
39	Demonstrate New Propulsion Technologies	Additional consideration
40	Demonstrate New Software Technologies	Additional consideration
41	Demonstrate Hardware Structural Integrity	Additional consideration
42	Validate Cost Models	Additional consideration

Table 4.6-1. Other Risk Reduction Requirements

Non-RLEP Requirement #33: Validate In-Space Cycling of the LSAM Engine

Safe human landing on the surface of the Moon will require throttling the LSAM engine to about 10% of full thrust as well as in-space engine start and cutoff, based on current mission studies. Validation of this capability can generally be accomplished through ground-based testing. However, the LRAS team considered in-space validation a necessary risk reduction requirement to assure adequate safety for a human mission. Furthermore, considering sustained lunar exploration will involve a campaign of missions of about two per year, likely lasting over a decade, in-space validation seemed both prudent and affordable. The team did not believe that the LSAM engine validation should be part of a lunar robotic architecture. Validation should not be an integral part of LSAM development and does not need to be done in the vicinity of the Moon. In principle, the required engine cycling could be performed in LEO or anywhere outside Earth's atmosphere.

Non-RLEP Requirement #34: Demonstrate Telemedicine

Telemedicine is the use of telecommunications technology for medical diagnosis, patient care, and medical training – including pathology, radiology, and patient consultation – when the provider and client are separated by distance. Huge challenges include the integration of telecommunications, computer, and medical technologies and selecting the correct equipment in a field where technology may become obsolete before it is used. NASA has been actively monitoring the physiological and medical impact of space flight on astronauts since the beginning of the human space flight program, but venturing beyond low-Earth orbit will provide increased challenges as the possibility of return for medical treatment diminishes. The Moon provides an excellent platform for demonstrating advanced telemedicine technologies; those tests, however, can be best accomplished during human sorties rather than robotic lunar missions.

Additional Consideration #35: Demonstration of Robotic Emplacement/Assembly Equipment

It is likely that a significant amount of critical infrastructure, such as the power system and habitat, will be emplaced or assembled robotically prior to human occupation of a lunar outpost. This may be done remotely from Earth or in combination with sortie missions to the outpost site. This will likely require specialized equipment, such as a mobile transporter and a lifting device (e.g., crane). While these systems can be validated on Earth, their operation on the Moon will still not be proven. In particular, the combined effects of dust, 1/6 gravity on traction in the lunar soil, and in-situ lighting cannot be fully simulated on Earth. Considering the importance of safely and efficiently preparing an outpost for astronauts, the LRAS team believed a demonstration mission to assure eventual successful operation would be highly desirable to reduce risk but not required. This will be more important if extensive robotic setup activities are controlled from Earth. The team also concluded that such a demonstration should not be part of a lunar robotics architecture but integral to lunar surface systems development. Note that this consideration is complementary to consideration #36, which focuses on precise, dexterous assembly operations.

Additional Consideration #36: Demonstrate Precise, Dexterous Assembly Operations

In addition to emplacing or assembling major infrastructure components, such as a habitat prior to human occupation, lesser, more precise operations will likely be required. These may include operations such as connecting electrical cables, deploying solar arrays or radiators, deploying relatively delicate scientific instruments, or exercising latches and seals to assure integrity. Unlike major system emplacement, these operations could be performed by astronauts or robotically, and in the latter case either controlled from the surface of the Moon or from Earth. In either case, dexterous systems capable of precise movement

and force control are envisioned to perform the actual operations. While the systems themselves could likely be validated on Earth, the LRAS team believed a demonstration mission would be highly desirable to reduce risk but is not required. Such a mission could use actual operational robotic hardware and conduct simulated operations on test articles. The team also concluded that such a demonstration should not be part of a lunar robotics architecture, but integral to lunar surface systems development. Even if the experiments are done from Earth, it may be beneficial to conduct them during a sortie mission, with astronauts available to inspect the work to assure correctness. This additional consideration complements #35, which addresses validation of outpost emplacement/assembly equipment.

Additional Consideration #37: Demonstrate Thermal Management Technologies

This demonstration was labeled as an additional consideration because current thermal management technologies are adequate for a human flight to the Moon. However, little is understood about the problems associated with longer stays, such as: how does lunar dust affect a radiator? How well does a radiator work when it is receiving not just sunlight, but also reflected light from regolith?

Additional Consideration #38: Demonstrate Power Technologies

This demonstration was labeled as an additional consideration because current power systems such as solar panels are sufficient for a return to the Moon. If new power technologies are to be used, a robotic precursor could demonstrate them in the environment of the Moon; however, it is not anticipated that new technologies will be needed for sortie missions or longer-duration missions to the polar regions.

Additional consideration #39: Demonstrate New Propulsion Technologies

This demonstration was labeled as an additional consideration because any demonstration of a propulsion technology will have to be scaled to fit the smaller robotic precursor missions. It is assumed that a “test as you fly, and fly as you test” philosophy will be implemented by Constellation – if modifications are made to a piece of hardware after it is tested, that hardware should be retested before flight. Testing a scaled propulsion system on a robotic precursor by scaling its thrust down does not test the equipment in its intended flight use; therefore it has less benefit than a full-up test.

Additional consideration #40: Demonstrate New Software Technologies

This demonstration was labeled as an additional consideration because any software technologies that are demonstrated on a robotic precursor mission will most likely be updated and reconfigured to run on the final platform. Robotic precursor missions provide important opportunities for technology demonstration and/or risk mitigation for Constellation missions in the area of software and systems. Examples include: demonstrating navigation software used for descent and landing; autonomous navigation capabilities; software supporting contingency operations; and demonstrating software and algorithms used to implement a packet-based communication system per the Constellation C3I methodology.

Additional Consideration #41: Demonstrate Hardware Structural Integrity

This demonstration was labeled as an additional consideration because hardware structural integrity tests performed on a robotic precursor can generally be simulated in an Earth environment. Operating structures in a simulated lunar environment presents a design challenge that can be addressed without the need for a lunar robotic mission. Current design and analysis capability are sufficient to provide adequate margin for robotic and planned human exploration systems.

Additional Consideration #42: Validate Cost Models

This was labeled as an additional consideration because lunar robotic cost models are based on past experience with robotic systems and can be modified as the RLEP program evolves.

4.7. Additional Consideration: Nuclear power

The Lunar Robotics Architecture Study examined the requirements for nuclear power capability, both from the standpoint of what robotic activities are required to support eventual deployment of nuclear systems and what requirements robotic exploration of the Moon may have for nuclear systems.

Generally, nuclear systems are advantageous since they provide power though the lunar day and night cycle, obviating the need for energy storage to support nighttime operations when only solar power sources are used. Nuclear systems also have the advantage of naturally supplying energy in the form of heat for processes and maintaining a desired thermal environment. Note, however, that if large-scale ISRU becomes an integral element of a lunar outpost, nuclear power may be the only practical means to provide adequate levels of continuous power (about 50 to 100 kW).

#	Requirements and Additional considerations	Type
30	Nuclear Power for ISRU	Only Required for Heavy ISRU
31	Long Distance (2km) Cable Laying Equipment	Only Required for Heavy ISRU

Table 4.7-1. Nuclear Power Requirements

Additional Consideration #30: Nuclear Power for ISRU

The only current requirement identified for nuclear power to support robotic exploration was for several-hundred-watt-class radioisotope power to enable extended exploration of permanently shadowed regions, where a mobile lander would search for the form and characteristics of hydrogen. This requirement is a mission enhancement rather than a need, as the mission could be accomplished using energy storage with periodic trips to sunlight for recharging batteries.

Additional Consideration #31: Long Distance (2 km) Cable Laying Equipment

Nuclear reactor power sources will have to be located a distance from power loads due to the radiation generated by their operation, and to a lesser extent, due to the thermal environment around a nuclear reactor. Humans, electronics, and some structures must be shielded by mass or distance from radiation and high heat input. This necessitates cable, laid on the lunar surface, as the only practical means of distributing the electrical power. The distance trade, where greater distance reduces radiation shield mass while increasing cable mass and complexity, optimizes to around 2 km if the shield material is brought from Earth. (It optimizes to less than 200m if regolith is used as shielding.) Several issues are in need of investigation with distributing electric power through cable over long distances in vacuum and on the lunar surface, as well as with laying the cable. These issues include: cable size and mass; line losses; thermal environments; micro-meteoroid and orbital-debris protection; and the challenges of tele-robotic deployment of cable over the varied lunar surface. Lunar robotic missions will need to investigate these issues prior to deploying large-scale ISRU or any other system requiring the distribution of power over long distances. Radioisotope power sources do not have the same constraints on proximity for operations and other surface elements, because the active radiation generated is alpha particles and low-energy gammas (for Plutonium 238), which are much more benign.

4.8. Additional Consideration: Opportunity Science

The fundamental goal of the *President's Vision for Space Exploration* is “to advance U.S. scientific, security, and economic interests through a robust space exploration program.” NASA has clearly assigned the responsibilities and authorities to its Mission Directorates for achieving this. The Science Mission Directorate (SMD) has a vital role to represent the space and earth science interests of the U.S. scientific community. Science missions lay a vital foundation for exploration by providing the framework for the strategic knowledge that enables exploration. For example, SMD’s Heliophysics Research Program is undertaking the scientific study of the radiation environments beyond Earth’s magnetosphere where future space explorers will live and work. It is vital that to understand this environment in order to design missions and systems that can mitigate its effects. SMD’s Planetary Science research program will answer basic science questions about the Moon, Mars, and other solar system destinations, providing results that will inform the essential engineering decisions concerning the design and implementation of human exploration systems.

For the Moon, SMD competitively selected through the Discovery program the Moon Mineralogy Mapper (M3) as a mission of opportunity. M3 will fly on the Indian Space Research Organization's (ISRO) *Chandraayan-1* Mission. SMD will issue by the end of the year a request for studies of innovative “suitcase science” instruments and packages to accompany future lunar astronauts. SMD will support the analysis of scientifically valuable results from ESMD missions. Science enabled by exploration activities will compete in the same prioritization process as the rest of the SMD science program. For example, if confirmed and implemented, the results of the Lunar Reconnaissance Orbiter will address priority science objectives identified by the National Research Council (NRC) in the 2002 decadal survey. As these data become available, SMD will support their scientific analysis by funding proposers selected through openly competed solicitations for SMD’s science research programs.

potential benefit to the program scenario. The requirements were then assigned a designation according to the particular scenario they supported.

The scenarios and associated requirements are shown in Table 5.2-1. Robotic lunar exploration program requirements are marked “RQ,” requirements that would be best fulfilled by other programs are marked “n-RQ,” and desires are labeled according to the benefit gained by fulfilling them. To emphasize the earliest scenario for which something is required, the boxes for all subsequent scenarios may not be filled in in the table. For instance, if it is required to conduct a measurement before a human sortie mission, then it is therefore automatically required to be conducted ahead of an outpost mission. This sets the stage for the next step in the analysis in section 5.3, where the LRAS team needed to focus in on the earliest scenario to identify the earliest date by which the requirement must be fulfilled.

Scenario Analysis												
#	Requirement	Sorties Only		Sorties Leading to Outpost		Outpost		Outpost with Small ISRU		Outpost with Large ISRU		LRAS Baseline
		Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	
Communications and Navigation												
1	Hazard Avoidance	n-RQ	RQ	RQ	RQ							RQ
2	Precision Landing – 1km unaided, 100m aided	Add'l Consid	RQ	RQ	RQ							RQ
3	Precision Landing – 10m				RQ							RQ
4	Comm Relay (possibly including Backside)		n-RQ		n-RQ							RQ
5	Improve Global Gravitational Map	Strong Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid					RQ
6	Over-the-Horizon Propagation of RF			Add'l Consid	Add'l Consid	n-RQ	n-RQ					RQ
Mapping (Visual, Topographic, and Resource)												
7	Topographical Map	Strong Consid	RQ	RQ	RQ							RQ
8	Visual Map – Landform Scales	Add'l Consid	RQ	Add'l Consid	RQ							RQ

Scenario Analysis												
#	Requirement	Sorties Only		Sorties Leading to Outpost		Outpost		Outpost with Small ISRU		Outpost with Large ISRU		LRAS Baseline
		Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	
9	Orbital and Ground Truth Measurements of Thermal and Regolith Properties	Add'l Consid	RQ	RQ	RQ							RQ
10	Characterization of Minerals and Volatiles in the Regolith	Add'l Consid	Add'l Consid	RQ	RQ	RQ	RQ					RQ
11	Characterize the Lighting Near Permanently Lit Areas		Add'l Consid		RQ							RQ
12	In-Situ Mapping of Water								RQ		n-RQ	RQ
Environment (Dust and Radiation)												
13	Characterization of Lunar Dust Environment	RQ	RQ	RQ	RQ							RQ
14	Determine Environmental Effects on Systems Including Dust (T70)	RQ	RQ	RQ	RQ							RQ
15	Characterize 1/6 g Fluids/Two-Phase Studies	Add'l Consid	Add'l Consid	RQ	RQ							RQ
16	Demonstrate Systems That May Be Affected by Partial Gravity (T80)	Add'l Consid	Add'l Consid	n-RQ	n-RQ	n-RQ	n-RQ					Non-RLEP Requirement
17	Measure Biologically Relevant Radiation Environments	Strong Consid	RQ	RQ	RQ	n-RQ	n-RQ					RQ
18	Investigate Potential Biological Impacts of Combined Lunar Environments (Radiation, Partial Gravity, Thermal, Micrometeorites, Dust)	Strong Consid	Strong Consid	RQ	RQ							RQ

Scenario Analysis												
#	Requirement	Sorties Only		Sorties Leading to Outpost		Outpost		Outpost with Small ISRU		Outpost with Large ISRU		LRAS Baseline
		Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	
19	Conduct Correlated Experiments at Molecular, Cellular, and Whole-Organismal Levels	Add'l Consid	Add'l Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid					Strong Consid
20	Prototype Systems for Monitoring Lunar Environmental Effects on Humans (Radiation, Partial Gravity, Dust, Thermal Effects)	n-RQ	n-RQ	RQ	RQ	n-RQ	n-RQ					Non-RLEP Requirement
21	Prototype Systems for Mitigating Space Environment Effects on Humans (Radiation, Partial Gravity, Dust, Thermal Effects)	Add'l Consid	Add'l Consid	RQ	RQ							RQ
22	Validate Radiation Transport Shielding Modeling	Strong Consid	Strong Consid	Strong Consid	Strong Consid							Strong Consid
23	Validate Planetary Protection Strategies, Technologies	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid					Add'l Consid
In-situ Resource Utilization (ISRU)												
24	Demonstrate New Surface Mobility Technologies	Add'l Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid					Strong Consid
25	Demonstrate Excavation to Bury a Habitat or Stockpile Shielding			Add'l Consid	Add'l Consid							Add'l Consid
26	Smoothing, Obstacle Removal, Emplacement of Registration Markers			Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid					Add'l Consid
27	Demonstrate ISRU (O2) Production from Regolith	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid			RQ	RQ	RQ	RQ	RQ
28	Demonstrate O2 Production from Regolith Including Beneficiation and Storage							RQ	RQ	n-RQ	n-RQ	RQ
29	Demonstrate H2/O2 Production from Lunar Water								RQ		n-RQ	RQ

Scenario Analysis												
#	Requirement	Sorties Only		Sorties Leading to Outpost		Outpost		Outpost with Small ISRU		Outpost with Large ISRU		LRAS Baseline
		Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	
30	Nuclear Power for ISRU									n-RQ	n-RQ	Only Required for Heavy ISRU
31	Long Distance (2km) Cable Laying Equipment									n-RQ	n-RQ	Only Required for Heavy ISRU
Other Risk Reduction for Development and Operations												
32	Demonstrate "Safe Roving" and Return (to ~10 to 30 km)			RQ	RQ							RQ
33	Validate In-Space Cycling of LSAM Engine	n-RQ	n-RQ	n-RQ	n-RQ							Non-RLEP Requirement
34	Demonstrate Telemedicine	Add'l Consid	Add'l Consid	n-RQ	n-RQ							Non-RLEP Requirement
35	Demonstration of Robotic Emplacement/Assembly Equipment			Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid	Strong Consid	Strong Consid	n-RQ	n-RQ	Strong Consid
36	Demonstrate Precise, Dexterous Assembly Operations			Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid
37	Demonstrate Thermal Management Technologies			Strong Consid	Strong Consid							Strong Consid
38	Demonstrate Power Technologies			Strong Consid	Strong Consid							Strong Consid
39	Demonstrate New Propulsion Technologies	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid							Add'l Consid

Scenario Analysis												
#	Requirement	Sorties Only		Sorties Leading to Outpost		Outpost		Outpost with Small ISRU		Outpost with Large ISRU		LRAS Baseline
		Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	Front Eq	Global	
40	Demonstrate New Software Technologies	Strong Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid	Strong Consid					Strong Consid
41	Demonstrate Hardware Structural Integrity	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid					Add'l Consid
42	Validate Cost Models	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid	Add'l Consid					Add'l Consid

Table 5.2-1. Scenario Analysis, Sorted by Requirements

5.3. Mission Implementation Analysis

The next step in the analysis was to determine how the requirements might be implemented. The linkages between Constellation missions and robotic requirements were identified. Some robotic requirements inform the design of the Lunar Surface Access Module (LSAM), while some requirements are for the lunar outpost phase of exploration.

In addition, the team assessed appropriate platforms for each requirement, such as an orbiter or lander. The appropriate platform identification and linkages Constellation needs supported the later time-phasing of requirements in the development of the schedule (described in section 5.4).

Potential payloads to fulfill each requirement were also identified. Potential instruments or existing payloads were assigned to each requirement, allowing for approximate mass, volume and power allocations to the platform types. Not every requirement required a specific instrument and additional considerations were not allocated to a spacecraft platform. Therefore, as seen in Table 5.3-1, instrument approximations were generated only as needed. This resulted in various mission options, which were grouped into architecture options.

Implementation Analysis									
#	Requirement	Earliest CX Mission Informed	Orbiter / Lander / Other	Instruments	Mass Range (kg)		Power Range (W)		
					L	H	L	H	
Communications and Navigation									
1	Hazard Avoidance	LSAM Design	Lander	LIDAR, Descent Imager, ,	5	22	1.5	8	
2	Precision Landing – 1km Unaided, 100m Aided	LSAM Design	Lander	LIDAR, Descent Imager, Radar Altimeter, IMU, Beacons	1	22	1.5	8	
3	Precision Landing – 10m	Outpost	Lander	LIDAR, Descent Imager, Radar Altimeter, IMU, Beacons	1	22	1.5	8	
4	Comm Relay (Possibly Including Backside)	All Flights	Orbiter	ECANS, Andrews, Ball, Boeing, Lockheed					
5	Improve Global Gravitational Map	LSAM Design	Orbiter	Orbital tracking via radio link using spacecraft, laser ranging					
6	Over-the-Horizon Propagation of RF	Outpost	Lander						
Mapping (Visual, Topographic, and Resource)									
7	Topographical Map	LSAM Design	Orbiter	Laser Altimeter, Visual Camera if useful at 50 X 50 m pixels	1	20	1.5	4.8	
8	Visual Map – Landform Scales	LSAM Design	Orbiter	Visual Camera	1	20	1.5	4.8	
9	Orbital and Ground Truth Measurements of Thermal and Regolith Properties	LSAM Design	Orbiter / Lander	Temp Sensor, Radiation Sensor, Radiation Telescope, Thermal Sensor, Thermal Spectrometer, Thermal Emission Imaging, Imaging IR Spectrometer,	2.1	11.2		14	
10	Characterization of Minerals and Volatiles in the Regolith	Outpost	Orbiter / Lander	DANS, X-ray spectrometer, Gamma Ray Spectrometer, Laser Induced Breakdown Spectrometer, Thermal Gas Analyzer, Volatile Sensor, Tunable Diode Laser, Neutron Detector, Radiometer, Alpha Detector, Infrared Spectrometer, Mineralogy Mapper, Low energy x-ray spectrometer, Radar Sounder, Spectrometer, Thermal Emission Spectrometer, IR Mineralogical Mapping Spectrometer, Radar Altimeter, Neutron Spectrometer, High Energy Neutron Sensor, Thermal Imager, Mass Spectrometer, X-ray diffractometer, Soil	2.1	30	5.7	32	

Implementation Analysis								
#	Requirement	Earliest CX Mission Informed	Orbiter / Lander / Other	Instruments	Mass Range (kg)		Power Range (W)	
					L	H	L	H
				Conductivity Experiment, Bearing strength				
11	Characterize the Lighting Near Permanently Lit Areas	Outpost	Orbiter / Lander	Cameras	.27 ea.			
12	In-Situ Mapping of Water	Outpost	Orbiter / Lander	Radar Sounder, CRISM, Neutron Spectrometer, HEND, Thermal Spectrometer, MVACS, Evolved Water Experiment	0.06	20	1.5	14
Environment (Dust and Radiation)								
13	Characterization of Lunar Dust Environment	LSAM Design	Lander	Magnet Arrays, Dust Counter, Atomic Force Microscope, Electron Spin Resonance,	0.73	+	3.8	30
14	Determine Environmental Effects on Systems Including Dust (T70)	LSAM Design	Lander	Magnet Arrays,	0.73	+	3.8	30
15	Characterize 1/6 g Fluids/Two-Phase Studies	Outpost	Lander					
16	Demonstrate Systems That May Be Affected by Partial Gravity (T80)	LSAM Design	Lander					
17	Measure Biologically Relevant Radiation Environments	Outpost	Orbiter / Lander	Small Bio Experiments, Radiation Sensor	5	10		
18	Investigate Potential Biological Impacts of Combined Lunar Environments (Radiation, Partial Gravity, Thermal, Micrometeorites, Dust)	LSAM Design	Lander	Small Thermal and Electrical Conductivity experiment, Small Bio Experiments, Radiation Sensor, Bio-reactor	5	10	7	+
19	Conduct Correlated Experiments at Molecular, Cellular, and Whole-Organismal Levels	Outpost	Lander	Cell growth and plant growth modules				
20	Prototype Systems for Monitoring Lunar Environmental Effects on Humans (Radiation, Partial Gravity, Dust, Thermal Effects)	LSAM Flight	Lander	personal dosimeters, others				
21	Prototype Systems for Mitigating Space Environment Effects on Humans (Radiation, Partial Gravity, Dust,	Outpost	Lander					

Implementation Analysis									
#	Requirement	Earliest CX Mission Informed	Orbiter / Lander / Other	Instruments	Mass Range (kg)		Power Range (W)		
					L	H	L	H	
	Thermal Effects)								
22	Validate Radiation Transport Shielding Modeling	LSAM Design	Lander						
23	Validate Planetary Protection Strategies, Technologies	Mars	Lander						
In-situ Resource Utilization (ISRU)									
24	Demonstrate New Surface Mobility Technologies	Outpost	Lander						
25	Demonstrate Excavation to Bury a Habitat or Stockpile Shielding	Outpost	Lander						
26	Smoothing, Obstacle Removal, Emplacement of Registration Markers	Outpost	Lander						
27	Demonstrate ISRU (O2) Production from Regolith	Outpost	Lander	Small extraction and processing plant	50	200			
28	Demonstrate O2 Production from Regolith Including Beneficiation and Storage	Outpost	Lander						
29	Demonstrate H2/O2 production from Lunar Water	Outpost	Lander						
30	Nuclear Power for ISRU	Outpost	Lander						
31	Long Distance (2km) Cable Laying Equipment	Outpost	Lander						
Other Risk Reduction for Development and Operations									
32	Demonstrate "Safe Roving" and Return (to ~10 to 30 km)	Outpost	Lander	Pathfinder/MER like hardware	10.5	185			
33	Validate In-Space Cycling of LSAM Engine	LSAM Design	Other (options include LEO testing)	Sensing and telemetry of engine operation					
34	Demonstrate Telemedicine	Outpost	Other (Options include ground and ISS testing)	Cameras, X-rays, monitors from Req 20, "Point-of-presence" testing					

Implementation Analysis								
#	Requirement	Earliest CX Mission Informed	Orbiter / Lander / Other	Instruments	Mass Range (kg)		Power Range (W)	
					L	H	L	H
35	Demonstration of Robotic Emplacement/Assembly Equipment	Outpost	Lander					
36	Demonstrate Precise, Dexterous Assembly Operations	Outpost	Lander					
37	Demonstrate Thermal Management Technologies	LSAM Design	Lander					
38	Demonstrate Power Technologies	LSAM Design	Lander	GRC Stirling cycle system				
39	Demonstrate New Propulsion Technologies	LSAM Design	Orbiter / Lander					
40	Demonstrate New Software Technologies	LSAM Design	Orbiter / Lander					
41	Demonstrate Hardware Structural Integrity	LSAM Design	Lander					
42	Validate Cost Models	LSAM Design	Orbiter / Lander					

Table 5.3-1. Implementation Analysis, Sorted by Requirements

The instrument data were used to estimate the total payload mass required to satisfy the requirements that each mission in the baseline. Instrument implementations were classified as orbiter- or lander-based instruments. Once those instrument types were chosen, representative masses were chosen from historical instruments. Once instrument groups were chosen, it was a fairly easy task to group them into theoretical missions:

Orbiter ~51kg

- Laser Altimeter and Camera: 21kg
- Temperature Sensor: 2.1kg
- Neutron Detector: 28kg

Fixed Lander ~51kg

- Imaging system 4kg
- Thermal Emission Spectrometer 2.1kg
- Wet Chemistry Lab, Microscopy, etc. 10kg
- Electron Proton Resonance 5kg

- Chemical Luminosity 3kg
- Reference Impedance Sensors 1kg
- Magnetic array, brushes 1kg
- Regolith characterization package 25kg

Mobile Lander ~40kg

- Radiometer & other inst. yeast canister 20kg
- Pancams and support structures 5kg
- Thermal Gas Analyzer 5kg
- Small robotic arm 10kg

Mobile Lander/Rover ~201kg

- ISRU demonstration plant 200kg
- Fluids testing equipment for 1/6g 1kg

5.4. Schedule Analysis

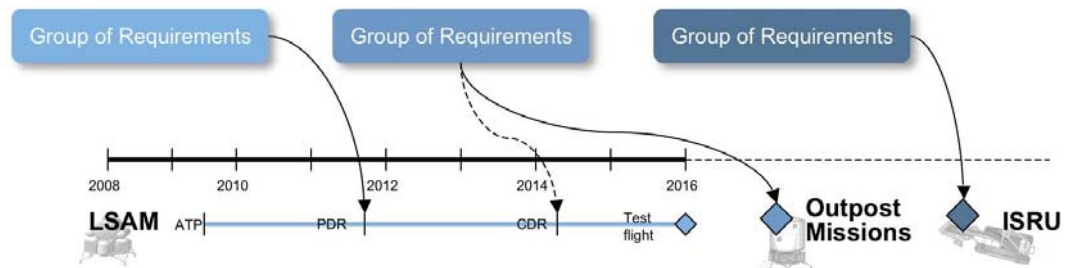


Figure 5.4-1. LRAS Analysis Process

As can be seen from the above chart, there are three groups of requirements keyed to various points in the Constellation timeline. These groups are linked to events in the timeline, not hard dates:

- 1) To reduce risk for the LSAM, the following requirements should be fulfilled *at least one year before* LSAM PDR:

- a. A visual map of the entire lunar surface should be constructed, with resolution at or better than 25m/pixel.
 - b. A topographical map of the polar regions should be constructed, with relative accuracy of 0.2m.
 - c. A resource map of the polar regions should be constructed, with resolution better than 10km/pixel.
 - d. Significantly improved lunar gravitational potential model should be developed through a dedicated gravity science investigation to measure far-side gravity.
 - e. A lander (or landers) should be sent to the polar region(s) of the Moon to get ground truth measurements of the polar environment, including lighting, terrain features, regolith characteristics, radiation and other environmental measurements.
 - f. This same lander should fully characterize lunar dust, and specific mitigation techniques should be tested to inform LSAM airlock design and human surface suit design. Specific characterization of the dust should include:
 - i. Determine the percent of dust <5 micrometers in size.
 - ii. Measure relative reactivity.
 - iii. Measure passivation characteristics.
- 2) Satisfying a second set of requirements will further reduce risk for the human lunar outpost. These requirements, if addressed and phased properly, could also inform the CDR of the LSAM—for instance, if something is significantly different about the Moon than initially believed *and* it affects the design of the LSAM, the information will be determined in time to inform system design. These requirements should be fulfilled in time to inform the design of outpost hardware, assumed here to receive Authority to Proceed (ATP) in 2018. Regardless of when ATP occurs, these robotic missions should complete their primary mission at approximately the same time.
- a. The answers to some ISRU questions will affect the initial design of the outpost and should be answered at this time: (1) Determine if useful resources can be extracted economically from lunar soil and (2) Determine if water-ice exists at the polar regions and whether it is in an extractable state, amount, and location.
 - b. The combined lunar environment might have some unknown synergistic biological effects; several biological experiments should be completed robotically to determine the long-term effects of the combined dust, radiation, and thermal environments.
 - c. Long-term operation in the lunar environment should be conducted to determine how mechanical systems will degrade over time.
 - d. Finally, the radiation shielding properties of the lunar regolith should be characterized to inform potential use as a shielding material.
- 3) A final set of requirements can inform habitat operations, roving capability and potential ISRU development and usage. These requirements will need to precede habitat development and the use of ISRU plants by at least the time required to design the habitat systems and develop the ISRU plants.
- a. An ISRU demonstration should be performed. This will be either extraction of hydrogen and oxygen from water-ice or extraction of oxygen from regolith.

- b. Characterize fluid and two-phase systems in lunar gravity. This requirement may be moved forward into section 2) or 1), but is thought to be essential for a chemical ISRU plant, while state-of-the-art knowledge is sufficient for the design of an outpost.
- c. Demonstrate up to 30km roving capability; the system will likely be designed after a thorough assessment of the effects of (2c) above.

5.5. Implementation Risk Analysis

It is important to note the risks to implementation of the architecture. Technical risks include: operation in the lunar environment, including lunar dust, thermal, and radiation; and, in particular, operations in the deep cold of permanently shadowed regions. The ability to perform landings in the near-permanently lit regions, and reliable mobility in the lunar environment (dust, thermal, power) also presents difficulties. In addition, if seeking to utilize in-situ hydrogen and/or water, it is important to understand the form and location in which the resource exists.

Additional implementation risks of the lunar robotic architecture involve: the appropriate phasing of lunar robotic requirements, such as environment characterization; development and demonstration of lunar resource utilization technologies; and technology development and demonstration for systems to directly support human presence on the Moon. The driving factor is selecting program content that realizes useful lunar data in a timely manner to inform future architecture or design decisions, guides further human exploration, and employs technology in compelling preparatory and assistive missions. An underlying emphasis on economy requires one to be judicious in tailoring the complexity of mission systems to meet the overall goals of exploration. In the earliest phases of the lunar robotic architecture, the emphasis is on data gathering and the expectation is that mission systems will emphasize re-utilization of technologies used for other planetary survey missions (e.g., instrument technology development costs should be minimal). With enhanced knowledge of the lunar environment in combination with better definition of manned-missions to the Moon, more complex mission systems can be defined that insert technology at the appropriate interval to support safe and robust human exploration. Definition of direct support of human missions via the lunar robotic architecture will by necessity be iterative as the Constellation Systems Program matures and program interfaces are developed.

Program budget is a driver in influencing how much can be done at a given time to meet the lunar robotic requirements. It is critical that the budget to support robotic missions be sustained. Due to the evolutionary nature of the knowledge gained, short-term decreases in budget will have a ripple effect on the entire architecture. Insufficient budget for the lunar robotic architecture early on causes higher levels of uncertainty and risk to be reflected in design standards (based on knowledge of the lunar environment) and thus in likely higher cost for follow-on human missions. It is equally important that attention be paid to achieve the maximum value within acceptable risk for the minimum possible cost and risk. Striking this balance is important to achieving an effective architecture within the program budget.

In addition, there is schedule risk associated with the development of both a lander and communications/navigation relay spacecraft in time for a 2011 or 2012 launch unless concept development for these spacecraft were to begin immediately. Moreover, it is recognized that a “new start” on a reduced-scope lunar orbiter to replace LRO would have a very low probability of meeting a 2008-2009 launch date.

Technology development to support the lunar robotic missions also poses some risk to implementation of the architectures presented. In particular, required long-lead technologies to support the missions were not included in the mission development schedules presented. To support the budget and timeline of this architecture, new technologies will require a level of development and bench testing to mature the technologies prior to consideration for the missions.

Commercial launch vehicle availability is also cause for concern. The availability (or lack) of the smaller-class launch vehicles may require NASA to utilize evolved expendable launch vehicles for robotic missions. Use of these larger-class vehicles for lower-cost robotic missions will require innovative approaches, such as co-manifested payloads with other science missions or those of other government agencies, or consideration of some alterations in the timeline presented here.

Additional risks are foreseen related to the level of maturity of several drivers. The Exploration Strategy with international and commercial stakeholders is under development. This activity will identify the collective needs, goals, and objectives for endeavors on the Moon and an associated architecture. The first workshop was held at the end of April and the activity is planned to provide a strategy by December 2006. These results should provide further clarity to the goals for the lunar robotic architecture. The Constellation Systems Program is in the process of developing requirements and competitive selection of some elements of the exploration systems architecture. These requirements, as well as potential cost and schedule growth, would affect the requirements for the lunar robotic architecture as well. In addition, the implementation risks of the Constellation Systems Program should provide input about knowledge needed from the lunar robotic missions.

It is also noted that if nuclear power sources are deemed necessary, there is some risk associated with review and approval of such technology and/or systems which typically has taken several years.

6. Architectures

6.1. Overview

Beyond simply identifying and prioritizing requirements for the lunar robotic architecture, the LRAS attempted to establish a link between the requirements and appropriate Constellation Program milestones. This approach allows the identification of a minimal mission set and timeline.

The LRAS team’s analytical results indicated that there are three groups of requirements, each linked to a Constellation Program milestone laid out in the ESAS Architecture. This led to the identification of three groups of LRAS architectural elements. The LRAS team tried to maintain traceability to Constellation’s needs throughout its process. To this end, the team categorized requirements based on which needs were addressed, and sequenced the architecture’s missions according to when those needs were realized. A sketch of the process is shown in Figure 6.1-1 below.

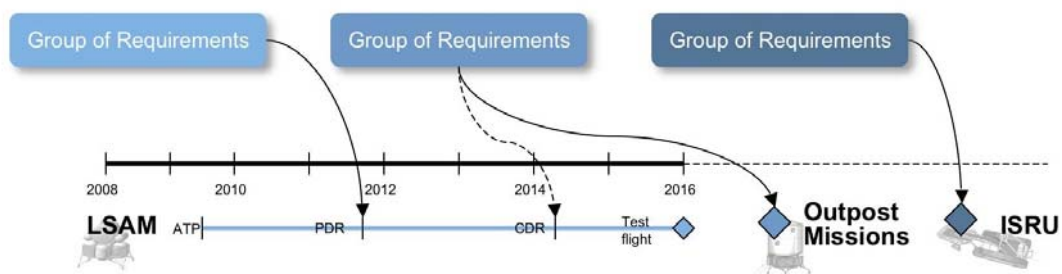


Figure 6.1-1. The architectures are constructed around specific groups of requirements.

As can be seen, there were three major groups of requirements that needed to be informed: LSAM Preliminary Design Review, outpost missions, and ISRU use. Accordingly, the team ordered the missions within each architecture to address these needs, including the highest-priority requirements on the first missions flown.

6.2. Baseline Architecture

Figure 6.2-1 shows the baseline architecture timeline:

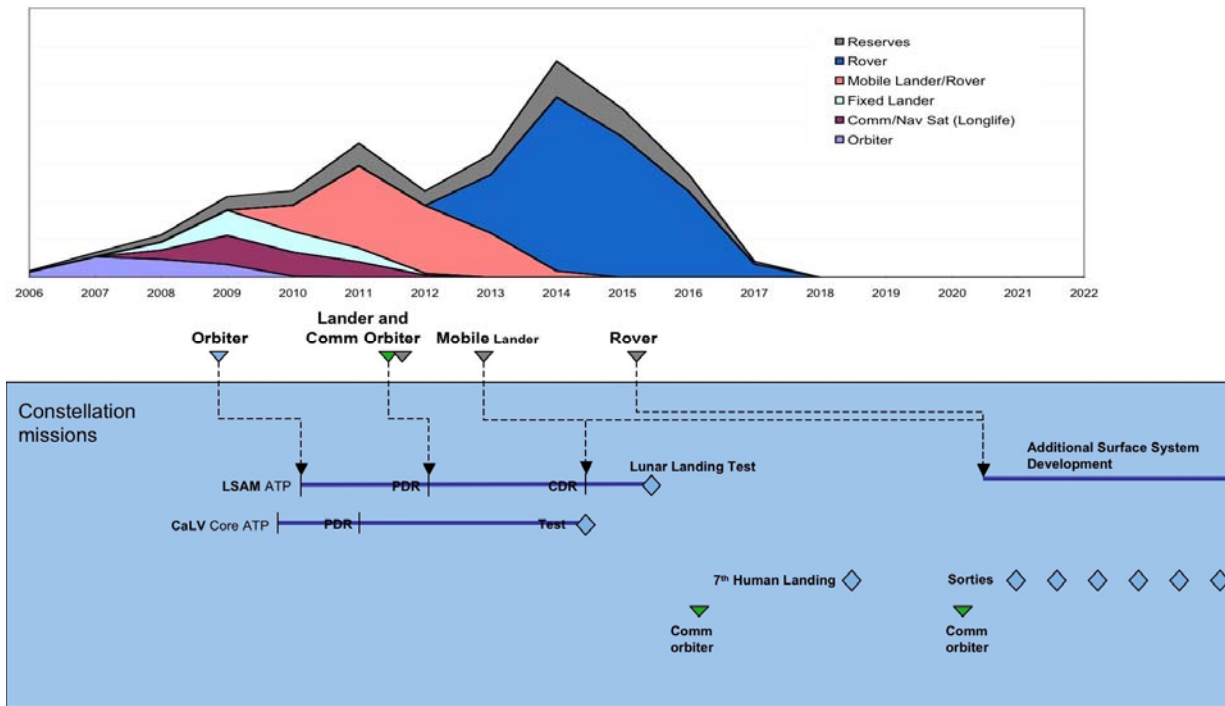


Figure 6.2-1. Baseline Architecture

The baseline architecture includes four separate launches occurring approximately every two years. The first mission is a lunar orbiter. The second mission is a fixed lander co-manifested with a communications relay satellite. The final two missions are mobile lander/rovers. The first two missions are scheduled on a timeline that allows the major results to inform the design of the LSAM (available prior to LSAM PDR).

Figure 6.2-1 shows an orbiter flying in late 2008. This orbiter is considered to be a new mission, designed to meet the minimum lunar mapping requirements, *not* the current Lunar Reconnaissance Orbiter (LRO). The information gathered from this orbiter's experiments would inform LSAM Authority To Proceed. The major concerns addressed by this mission are: mapping the Moon, with measurement in visible light; measuring lunar topography; and areas of potential water deposits. The information gathered would include:

- A high-resolution visual map, including information on the near permanently lit regions of both poles. The polar regions and other sites of interest would be measured at approximately 1m/pixel, the rest of the Moon at approximately 50-100m/pixel.
- A high-resolution topographical map of the Moon. Absolute altitude would be gained at approximately 25m error limit, with relative error less than approximately 0.5m.
- A map of hydrogen deposits >100ppm on the Moon <10km/pixel.
- A measure of the space radiation environment near the Moon.

Additional objectives for the first orbiter mission include developing an improved lunar gravitational potential map, and demonstration of a secondary communications relay payload.

Based on the assumption that the initial sorties leading to the outpost will land at polar locations (consistent with the ESAS reference outpost site), the LRAS team concluded that a mission smaller than

LRO and focused on mapping the poles would be sufficient to meet requirements. Preliminary cost estimates, based upon parametric methods, indicate that this mission would cost less than our current understanding of the cost to complete the LRO. Any final Agency decision to pursue this architecture should factor in: the greater uncertainty of this cost estimate compared to the relatively mature estimates for LRO; the decreased architectural flexibility to implement early sortie missions to locations other than polar sites or those mapped during Apollo; and the time required to develop a new mission that could delay its launch beyond 2008. NASA confirmed the LRO mission late in the preparation of this final report.

The major concerns addressed by the fixed lander are: ground truth measurements of lighting, soil composition, thermal environment and characterization of lunar dust to inform mechanical designs and biological concerns. The fixed lander would perform the following measurements:

- Demonstrate precision landing (<100m error eclipse)
- Characterize the lunar dust
 - Measure percent of dust < 5um
 - Relative reactivity
 - Passivation characteristics
- Characterize regolith thickness and composition
- Ground truth lighting and thermal environment of landing site

Robotic landers provide opportunities to demonstrate precision landing capabilities that will eventually enable 100 m (3-sigma) landing accuracy, and to demonstrate specific (navigation) software, sensors, and algorithms (LRAS-34) used for descent and landing.

A relay communication orbiter would be co-manifested with the fixed lander in 2011, taking advantage of excess payload capacity available with the second launch. The communications orbiter is to be deployed into a frozen elliptical orbit, providing partial communications coverage to the south polar region. It will serve as a relay for the information gathered by the lander and the following two missions, and is therefore designed as a long-life orbiter (5-6 year life).

There are several communications and navigation requirements that, while not drivers for the lunar robotic architecture, may provide significant risk mitigation or other benefits for the Constellation Program. Objectives that may be satisfied by either lander or orbiter spacecraft include: demonstrating the routable, IP-based communications architecture as described in the Constellation C3I Interoperability Specification; obtaining additional experience with tracking and flight dynamics operations for spacecraft in the lunar environment; providing technology demonstrations of communications and tracking hardware, including secondary communications/tracking payloads; and providing residual communications and tracking assets for subsequent robotic and human missions.

The third mission in the baseline series is a mobile lander. It was not determined what sort of mobility this lander would have, as the team did not wish to stifle innovative architecture possibilities or creative thinking. The primary goals of this mission are to determine if there is water on the Moon in a sufficiently accessible form and location, and in sufficient quantities to make it worthwhile to attempt to mine it for in-situ resource utilization. This mission primarily informs the eventual construction of an outpost, and its measurements would include:

- Checking for water-ice in at least 20 sites in a shadowed crater. It was noted that hydrogen deposited by the solar wind is ubiquitous but only in a concentration of 50-100 ppm; consequently mining H₂ is not practical. The large number of sites is necessary to employ a scientific process to determine with confidence, that if there is water available in the selected crater, it has not been missed.

- Measure the radiation shielding effects of regolith. (This experiment could be moved up to as early as the fixed lander mission if necessary.)
- Through a yeast or similar biological experiment, measure the combined lunar environmental effects on life. (This experiment could be moved up to as early as the fixed lander mission if necessary.)
- Prove that mechanical systems can survive and operate for ~1 year in this lunar environment.

The final mission in the recommended architecture is a rover. This mission's primary goal is to demonstrate ISRU of one sort or another on the Moon. If the third mission determines the presence of accessible water-ice in sufficient quantity that is deemed worthwhile of mining, the final mission will attempt to demonstrate mining and processing of water-ice. If not, then oxygen can be extracted from the regolith anywhere on the Moon through chemical processes. This mission will inform the eventual use of ISRU at a lunar outpost. In all, three different experiments are intended for this mission:

- ISRU production of oxygen or oxygen and hydrogen of up to 1,000kg.
- Characterize fluid and two-phase systems in 1/6 gravity. (This experiment could be moved up to as early as the fixed lander mission if necessary.)
- Roving up to 30km as a precursor to human rovers for the outpost.

6.3 Excursions to the Baseline Architecture

Several excursions to the baseline architecture were considered. These excursions were meant to highlight possible de-scopes or expanded opportunities that could be leveraged in implementing the exploration objectives.

Excursion 1 – Baseline with LRO as the orbiter

The first of these excursions is the deployment of the Lunar Reconnaissance Orbiter (LRO) instead of the notional orbiter listed here in the baseline architecture. LRO is already underway, and there may be good reason to allow this mission to complete its development. LRO meets the LRAS mapping requirements, has already completed concept development, and is in the preliminary design phase. Moreover, even if a significant savings could be realized by reducing the scope of the first orbiter, a “new start” on an alternative orbiter at this late time would have a very low probability of meeting the 2008 date set as a goal of the Vision for Space Exploration. Second, once a mission has been started initial design costs are incurred that would not be recovered if the mission were cancelled. Finally, it is sufficient in its information gathering. In fact, it performs more measurements than are actually needed to reduce the risk to Constellation. The notional cost profile and timeline is shown below in 6.3-1.

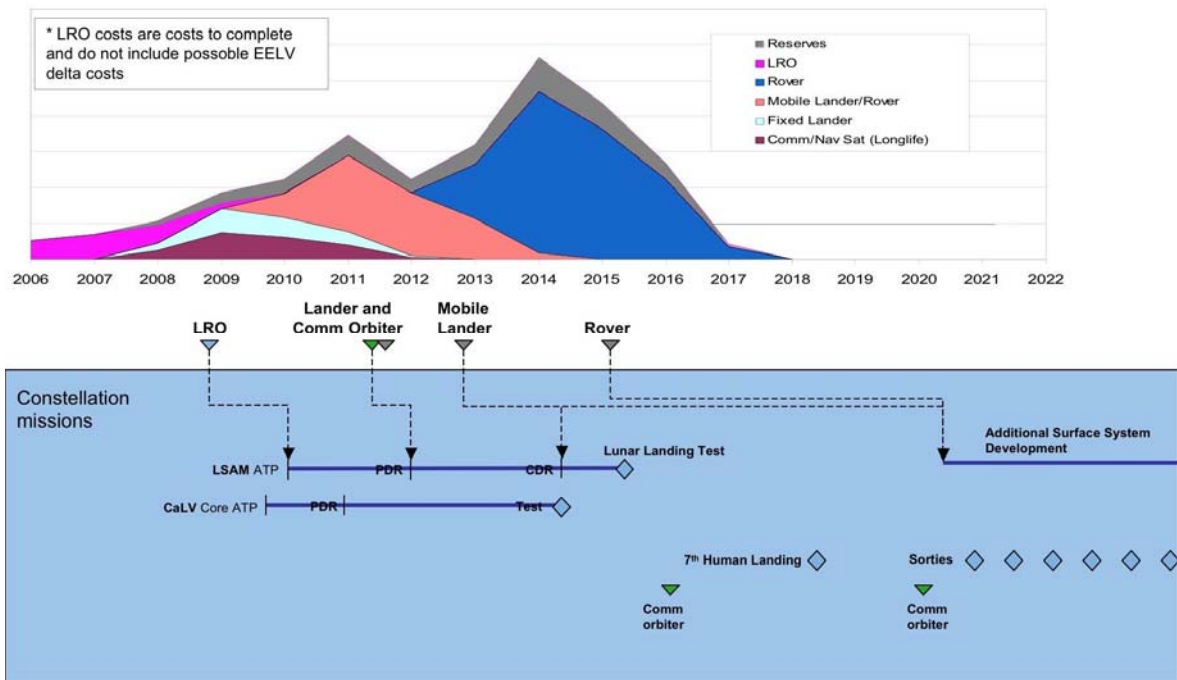


Figure 6.3-1. Excursion 1 -- Baseline with LRO as the Orbiter

The changes to this architecture consist solely of replacing the initial mapping orbiter with LRO. As the diagram shows, there would be an increased initial cost incurred in the first two years. A decreased schedule risk would likely be a benefit of this excursion.

With the exception of providing a dedicated gravity science investigation or including a secondary communications/tracking payload, LRO meets all of the LRAS objectives for orbiter #1. Note that NASA confirmed the LRO mission late in the preparation of this report.

Excursion 2 – Baseline with an additional fixed lander to the north pole

Excursion 2 is an opportunity for NASA. For a nominal increase in cost of approximately \$100M, NASA could send two fixed landers, one to the north lunar pole, and one to the south. There is good reason to do this, as the northern pole may have points that are even more exposed to continuous light than does the south pole. Figure 6.3-2 shows the changes in the budget profile that would occur as a result.

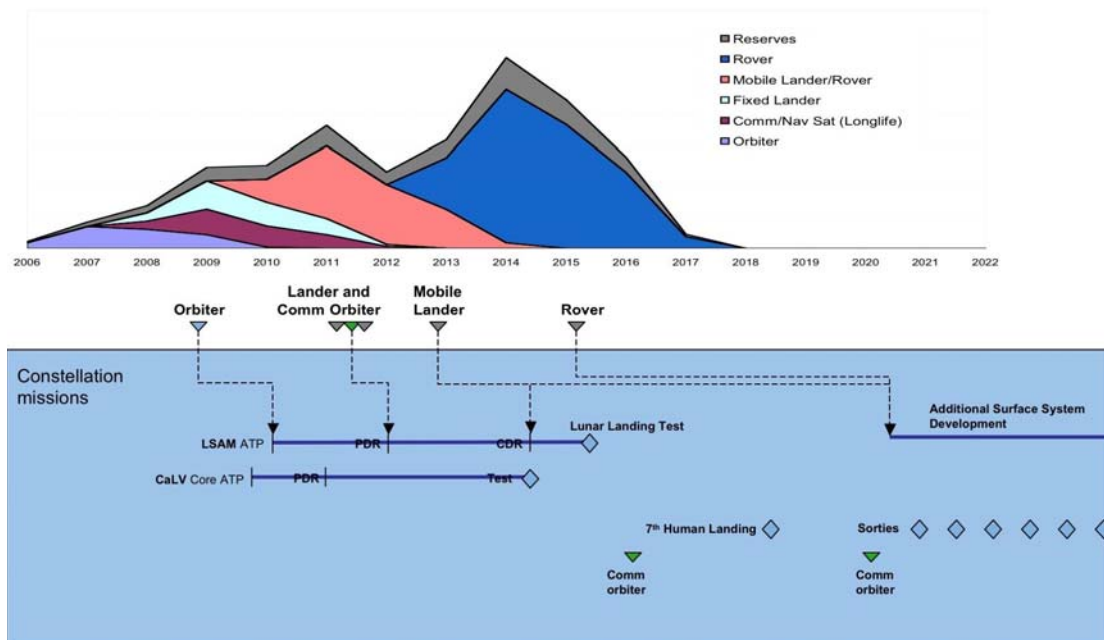


Figure 6.3-2. Excursion 2 -- An Additional Fixed Lander to the North Pole

As can be seen in Figure 6.3-2, there is a very slight increase in the year-to-year cost estimate in years 2010-2013. Approximately 40% of the increase is due to the triple manifesting of two landers and an orbiter onto an EELV instead of a Delta-II class vehicle; the other 60% is in the recurring engineering cost of constructing a second fixed lander.

Note that the communications relay satellite from the baseline architecture provides partial communications and tracking coverage to a region near the south pole. A second lander at the opposite pole would have very limited coverage from this relay satellite, and thus would require a landing site with some DTE communications availability.

There are several other possibilities for providing coverage to multiple locations on the lunar surface, including: different lunar relay orbit selection, a lunar relay orbiter at the Earth-Moon L2 point, or deploying additional lunar relay assets. Examining these trades, however, was beyond the scope of the LRAS study. The LRAS study relied upon the results of the Space Communication Architecture Working Group in recommending the polar relay satellite approach.

Excursion 3 – Baseline with combined fixed lander and first mobile lander to “touch the water early,” no ISRU demonstration

Excursion 3 highlights the large costs associated with an immediate need to determine the potential for water in craters on the Moon. By developing and flying a communications orbiter, a mapping orbiter, and an “all-in-one” rover (one meant to fulfill the functions of the fixed lander and the first mobile lander) simultaneously, the unknowns about presence and accessibility of water on the Moon could be resolved. This excursion exceeds the current budget guideline in the near-term. This is shown below in Figure 6.3-3.

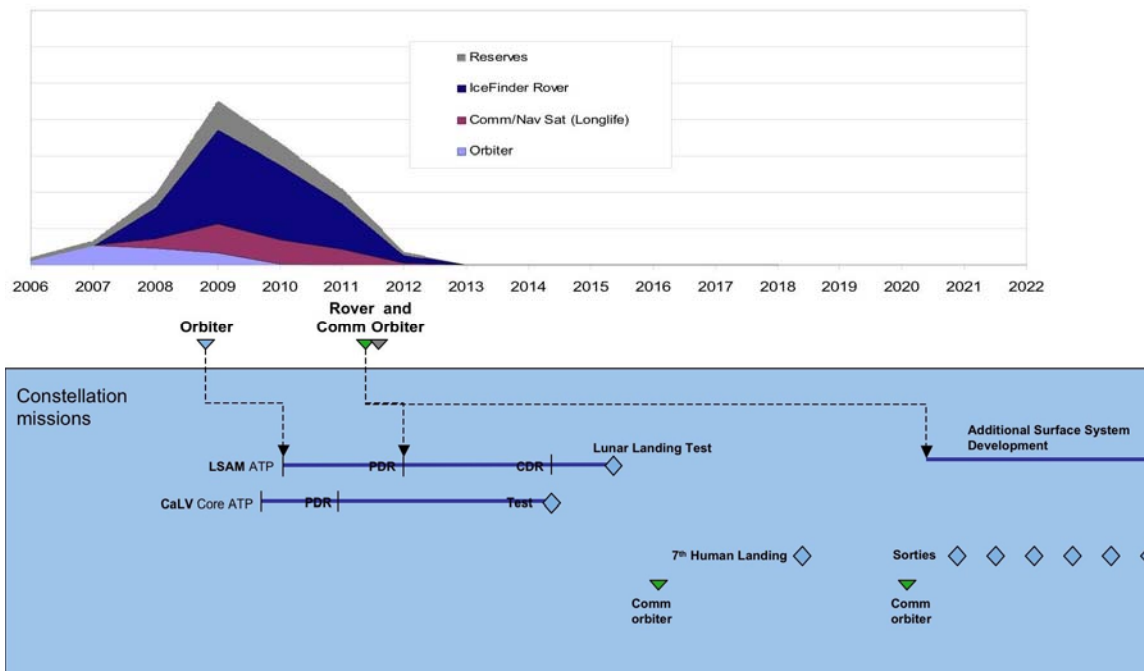


Figure 6.3-3. Excursion 3 – Combining the Fixed Lander with the Rover to “Touch the Later Early” and Conduct No ISRU Demonstration

As 6.3-3 shows, the planned launch date of the rover has not been moved, and occurs in late 2011. This timeframe could shift if the timeline for the LSAM shifts, as it is linked to the LSAM PDR. Shifting it to the right (a later date) would allow it to fit more closely to the planned RLEP budget, but the total estimated cost would increase due to inflation as well as a longer timeline. Such a change in the normal development cycle might also increase the cost risk of the mission.

Another possible negative in addition to the high cost is the technical risk associated with this scenario. It has been suggested that relatively frequent launches are beneficial for distributing risk, developing exploration technology, and maintaining public interest and support of NASA’s return to the Moon. This scenario includes only two launches, one in 2008 and one in 2011, and no subsequent launches prior to LSAM.

Excursion 4 – Baseline with combined fixed lander and first mobile lander to “touch the water early” followed by ISRU demonstration

Figure 6.3-4 below shows the estimates for a full-up mission to “touch the water early,” followed by the ISRU rover. The time-phasing of this architecture is calculated to inform the outpost early enough to develop the ISRU technologies in time for the first occupation of the outpost.

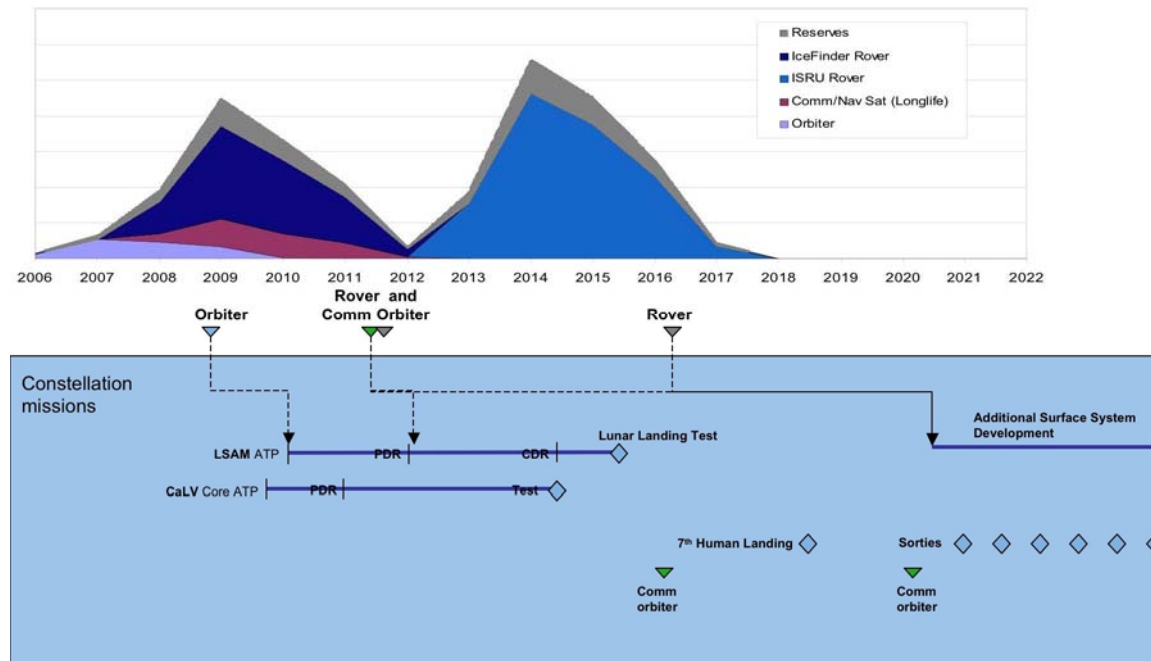


Figure 6.3-4. Excursion 4 -- “Touch the Water Early” (as in Excursion 3) but with Added ISRU Demonstration

This is a logical follow-on to the previous excursion. If water-ice is found, it would be possible to send a mission to mine such resources. Again, the timing of both of these missions is linked to the Constellation timeline, and so the second rover is flown later in the program cycle. It would be possible to smooth the cost curves by stretching the development cycle out with the likely increase in cost risk; another possible extension might occur if there is a delay in the LSAM development cycle. This excursion also exceeds the budget guideline.

Excursion 5 – Baseline with both mobile landers deferred, no ISRU demonstration

Since it is not critical to the Constellation timeline to determine if there is accessible water early in the lunar exploration, it is feasible to defer the mobile landers. The fixed lander and the communications orbiter could be sent together. The communications orbiter and the mapping orbiter could be combined for a truly minimum-cost (and minimum-activity) scenario but the spacecraft would have to be designed for other considerations, including significantly more delta- V (net velocity change to the vehicle) to maneuver to a higher orbit and better reliability of parts for longer lifetimes. It should be noted that in this case, since there is only one mission to the surface, the communication satellite does not need to be long-lived. This is shown in Figure 6.3-5.

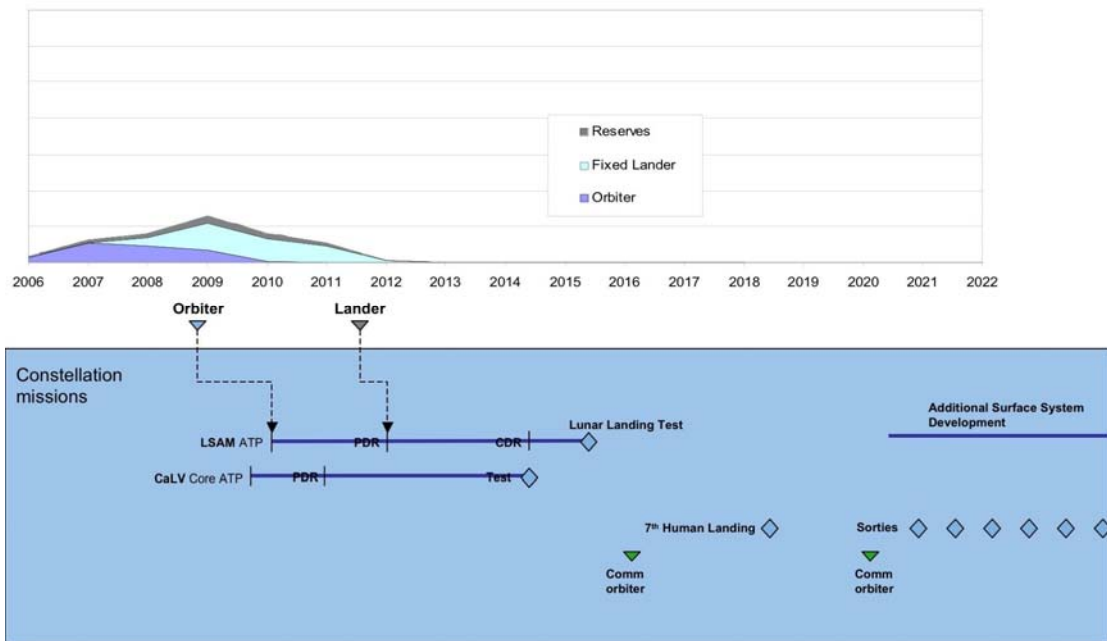


Figure 6.3-5. Excursion 5 – Baseline with Both Mobile Landers Deferred

Note that in this scenario, all ISRU activities are postponed until human exploration begins. It would be possible to move up the regolith characterization to the fixed lander to determine how much oxygen was in the regolith at the chosen site. It would also be possible to manifest another lander to the north pole, as in excursion #2, for an additional \$100M.

This excursion foregoes an opportunity for bolstering public support. Frequent launches are beneficial for increasing public interest and support of the exploration program. This excursion can be accommodated within the budget guideline.

Excursion 6 – Baseline with both mobile landers deferred and with LRO as the first orbiter, no ISRU demonstration

If LRO is selected to be the orbiter, there are two impacts: 1) LRO has a higher cost than the orbiter in the baseline architecture, and 2) LRO is not designed to be a communications orbiter, so a separate communications satellite would need to be sent. Note that NASA confirmed the LRO mission late in the preparation of this report. Figure 6.3-6 shows the expected impact to the budget of enacting this excursion:

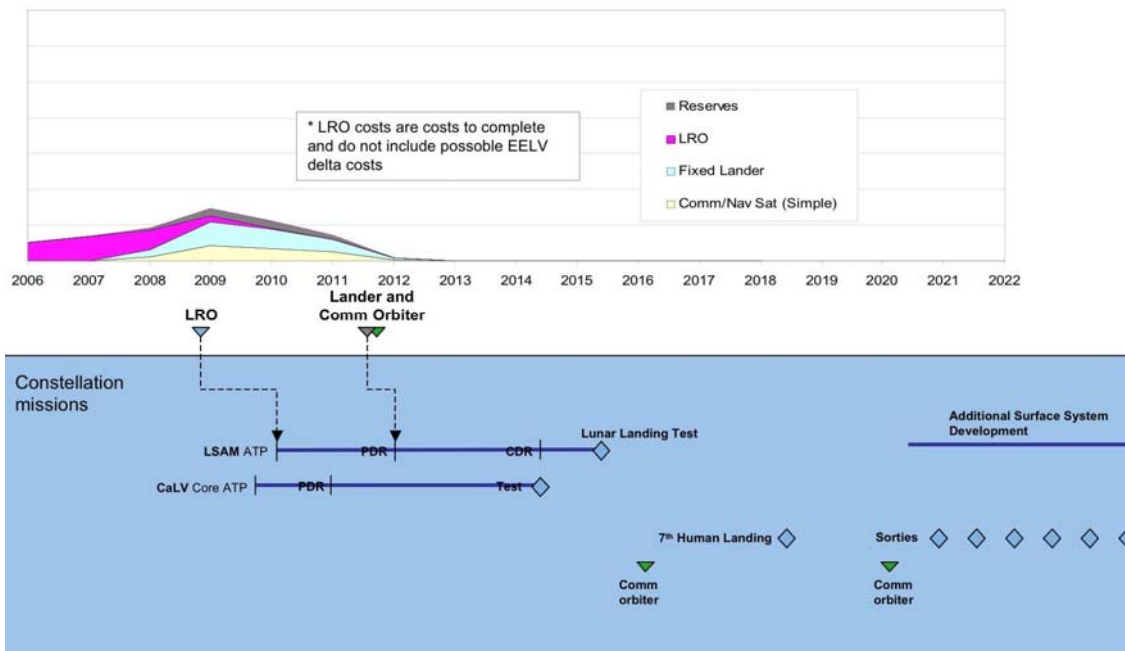


Figure 6.3-6. Excursion 6 – Baseline with Both Mobile Landers Deferred and LRO as the Orbiter

Again, this excursion contains only two launches, one in 2008 and one in 2011. This excursion can be accommodated within the budget guideline.

Excursion 7 – MER-class rover and robust communication

In excursion 7, the lander is given minor mobility hardware, similar to the Mars Rovers Spirit and Opportunity. Additionally, several extra comm/nav satellites are added, allowing the build-up of a constellation of satellites by the beginning of human missions.

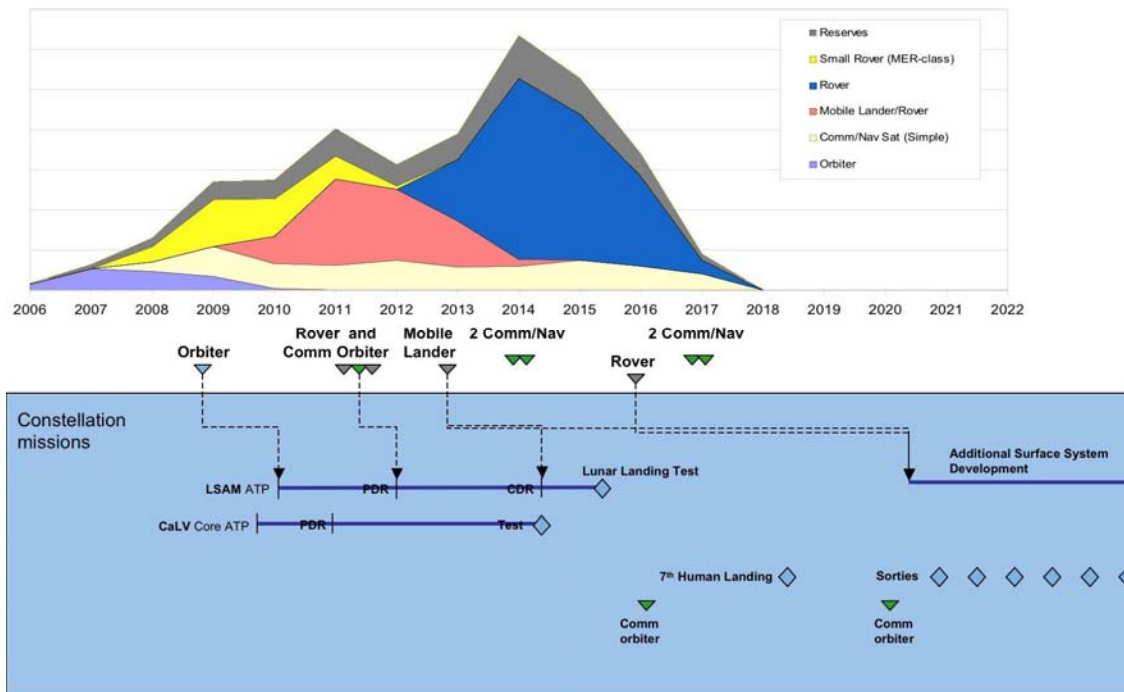


Figure 6.3-7. Excursion 7 – Baseline with MER-like Rover and a Robust Communication Infrastructure

Excursion 8 – Two MER-class rovers and robust communication

In Excursion 8, two landers are given minor mobility hardware, similar to the Mars Rovers Spirit and Opportunity. It is thought that these rovers would explore both north and south polar regions. Additionally, several extra communications and navigation (comm/nav) satellites are added, allowing the build-up of a constellation of satellites by the beginning of human missions. These multiple satellites also mitigate the risk of covering both poles with a single satellite. Excursion 7 and Excursion 8 are nearly identical. It is thought that an additional rover would cost on approximately 20% over the original cost, and that cost is spread through 6 years, so the graphs appear almost identical.

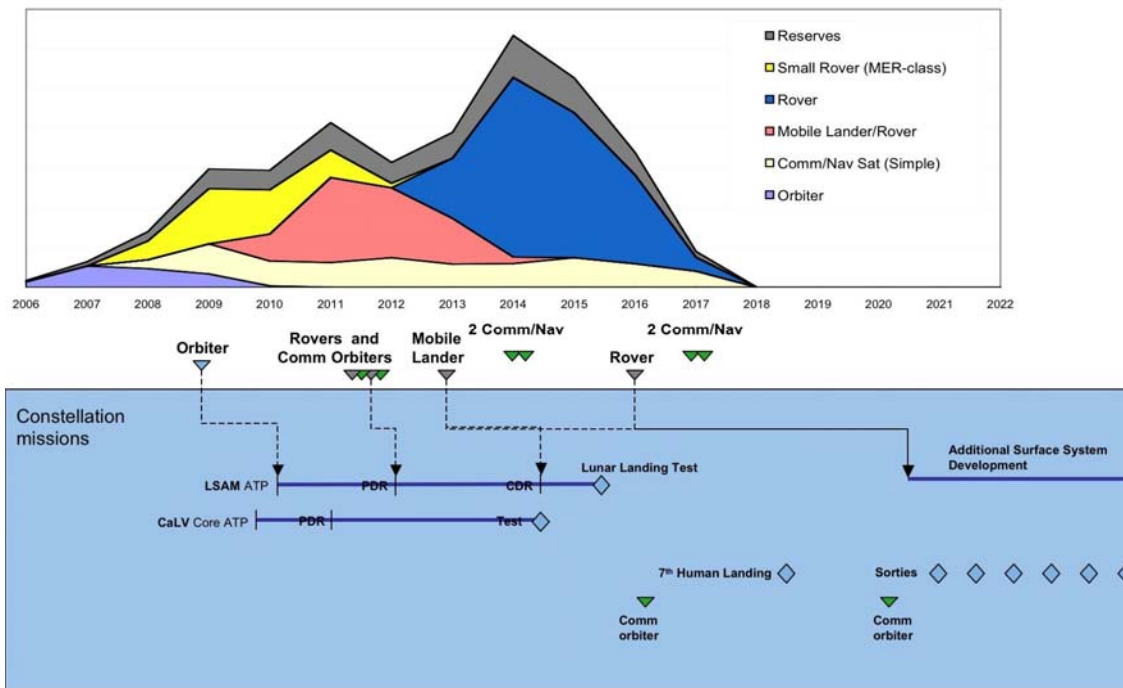


Figure 6.3-8. Excursion 8 – Baseline with Two MER-like Rovers and a Robust Communication Infrastructure

Excursion 9 – MER-class rover, ISRU demonstration, and robust communication

In this excursion, the lander is given minor mobility hardware, similar to the Mars Rovers Spirit and Opportunity, and is also given a small In-Situ Resource Utilization (ISRU) package. This package is meant only to demonstrate the technology’s feasibility, not to produce any substantial amount of usable resources. Additionally, several extra comm/nav satellites are added, allowing the build-up of a constellation of satellites by the beginning of human missions.

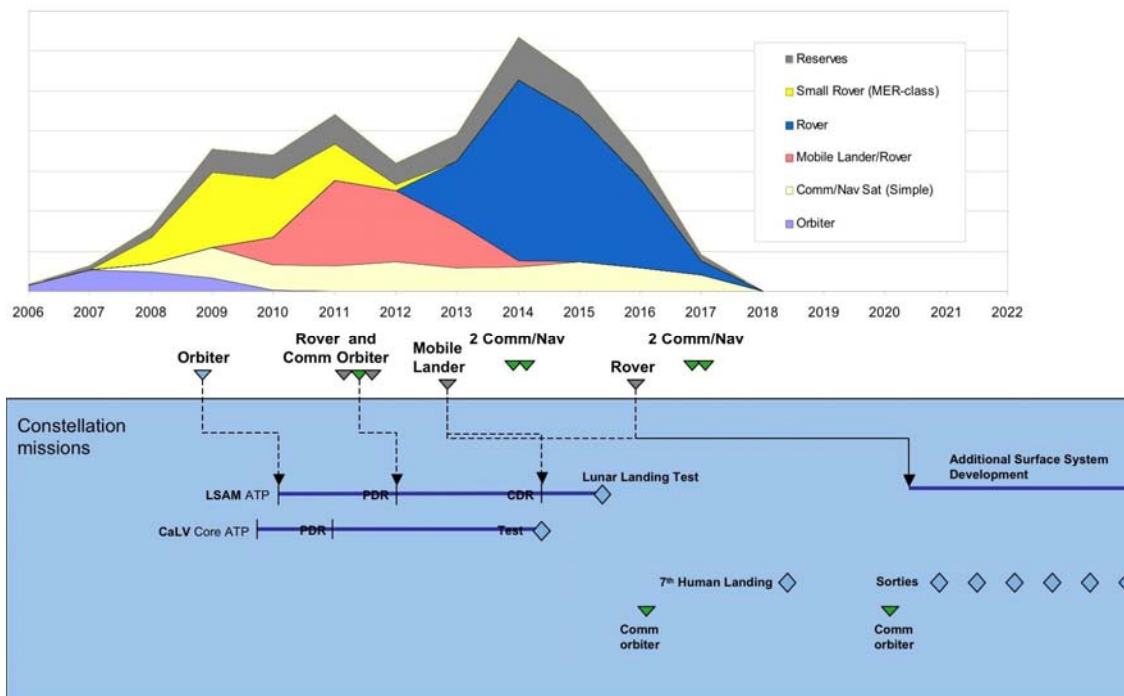


Figure 6.3-9. Excursion 9 – MER-like Rover, ISRU Demonstration, and a Robust Communication Infrastructure

Excursion 10 – 2 MER-class rovers, robust communication, ISRU demonstration, followed by search for water, followed by ISRU rover

In Excursion 10, the landers are given minor mobility hardware, similar to the Mars Rovers Spirit and Opportunity, and are also given small In-Situ Resource Utilization (ISRU) packages. This package is meant only to demonstrate the technology’s feasibility, not to produce any substantial amount of usable resources. Additionally, several extra comm/nav satellites are added, allowing the build-up of a constellation of satellites by the beginning of human missions. This is followed by the deep-cold crater-ice searching rover, and finally by the ISRU rover mission. Excursion 9 and Excursion 10 are nearly identical. It is thought that an additional rover would cost on approximately 20% over the original cost, and that cost is spread through 6 years, so the graphs appear almost identical.

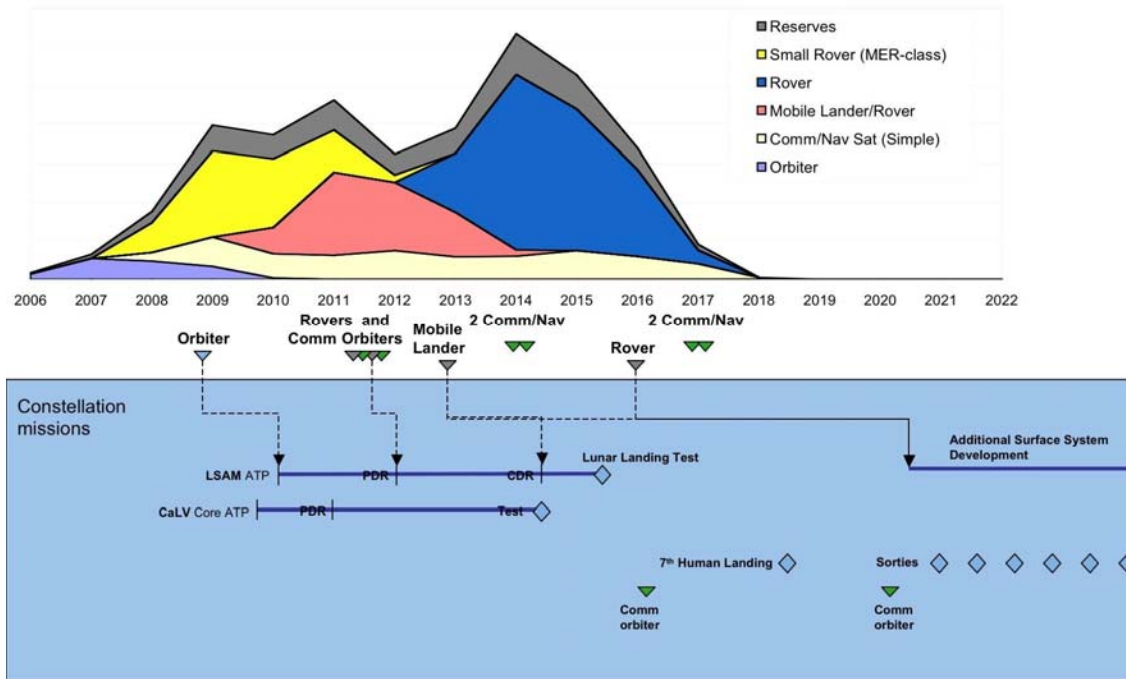


Figure 6.3-10. Excursion 10 – Baseline with MER-like Rover and a Robust Communication Infrastructure

Excursion 11 – MER-class rover, robust communication, and ISRU deferred

In Excursion 11, the lander is given minor mobility hardware, similar to the Mars Rovers Spirit and Opportunity. Additionally, several extra comm/nav satellites are added, allowing the build-up of a constellation of satellites by the beginning of human missions. All ISRU work is deferred to a later date. This excursion can be accommodated within the budget guideline.

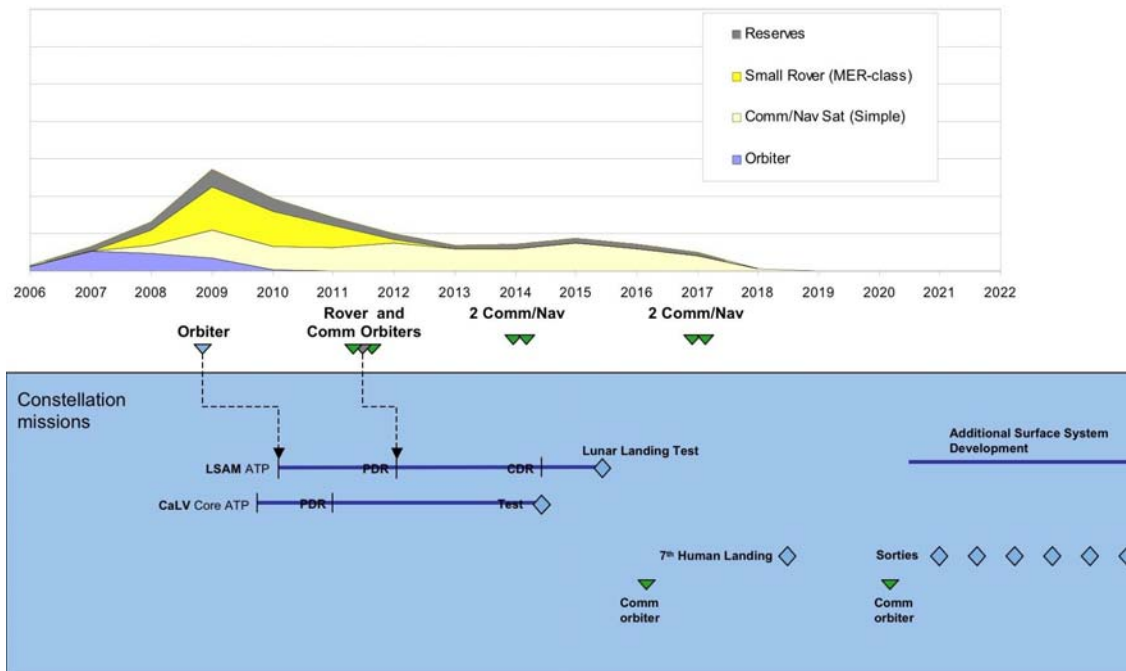


Figure 6.3-11. Excursion 11— MER-like Rover, a Robust Communication Infrastructure, and Deferred ISRU

Excursion 12 – 2 MER-class rovers and robust communication

In Excursion 12, two landers are given minor mobility hardware, similar to the Mars Rovers Spirit and Opportunity, and are also given small In-Situ Resource Utilization (ISRU) packages. This package is meant only to demonstrate the technology’s feasibility, not to produce any substantial amount of usable resources. Additionally, several extra comm/nav satellites are added, allowing the build-up of a constellation of satellites by the beginning of human missions. All large ISRU work is deferred to a later date. This excursion can be accommodated with an adjustment of funding in the budget guideline.

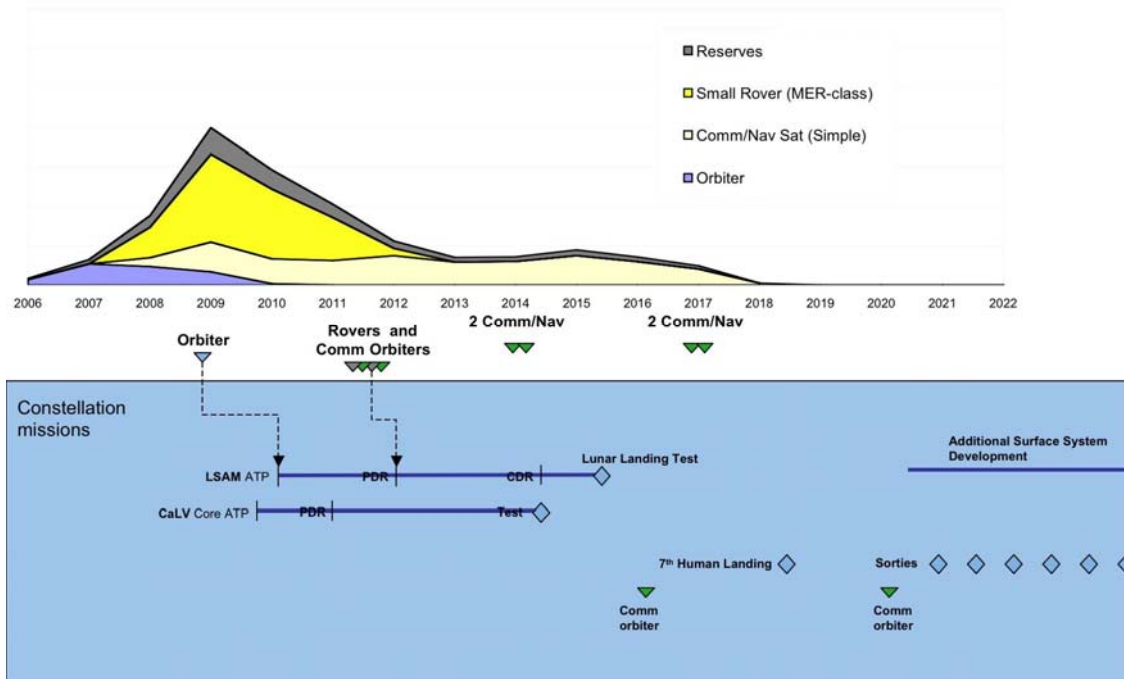


Figure 6.3-12. Excursion 12 – Two MER-like Rovers, a Robust Communication Infrastructure, and ISRU Demonstration

6.4 Cost / Benefit Analysis

The costs and benefits of the baseline architecture and its excursions were computed based on the cost models and experience from previous orbiter and planetary lander missions. The total real-year costs were tabulated and then normalized so that the baseline architecture equaled 100. A table summarizing the results is presented below.

Architecture	Normalized Real-year Costs	Benefits
Baseline Mission (Orbiter, Fixed Lander, Comm Satellites, Two Mobile Landers with ISRU Demo)	100	Covers identified major needs for Constellation
Baseline with LRO as the Orbiter	102	Covers identified major needs for Constellation – Leaving LRO as the first orbiter
Baseline with Additional Fixed Lander to North Pole	102	2 fixed landers, one to each pole—helps characterize points of eternal light at both poles; possible comm. limitations
Baseline with Combined Fixed Lander and First Mobile Lander to “Touch the Water Early”, No ISRU Demo	46	Covers identified major needs for Constellation and identifies water early on; not supported by near-term budget
Baseline with Combined Fixed Lander and First Mobile Lander to “Touch the Water Early”, with ISRU Demo	98	Covers identified major needs for Constellation and identifies water early on; not supported by near-term budget
Baseline with Both Mobile Landers Deferred, No ISRU	14	Covers identified major needs for LSAM, but does not cover mobile lander functions or ISRU
Baseline with Both Mobile Landers Deferred w/ LRO as the Orbiter, No ISRU	20	Covers identified major needs for LSAM, leaving LRO in place, and does not cover mobile lander functions or ISRU

Table 6.4-1. Summary of Normalized Costs and Benefits of the Baseline Architecture and Its Excursions

6.5 Architecture Flexibility

An overarching assumption of the LRAS study is that the final decision on the human lunar mission architecture would not be decided for several years, and that any proposed lunar robotic architecture must have a high degree of flexibility. A specific requirement given to the study team was to assume global lunar access and use of in-situ resources. Initially the study considered a wide range of sortie and outpost options to determine robotic requirements. It allowed for just sortie missions and sortie missions followed by an outpost. This was the same basic scope assumed by the ESAS team.

Based largely on lunar geography and environmental factors, the missions divided into three main groups: (1) equatorial missions, (2) polar missions and (3) high-latitude, sub-polar missions. The first group was characterized positively by commonality with Apollo missions on the front side. These represented the easiest landing sides, with the backside considered somewhat more difficult. The major detraction from equatorial missions is the very long (334 hr), cold (~ -150°C) lunar night. This limited sorties to about 10 days and set limitations on a possible outpost. One serious limitation would be the almost-certain

requirement for a nuclear power source for any needs over 50 kW, such as large-scale ISRU. The polar regions offer the possibility of sites with continuous, or near-continuous, solar illumination. Such a site would potentially be very benign thermally – no long, frigid lunar night – allowing for sorties of unrestricted duration, as well as the possibility of relying totally on solar power. Another potential advantage is the possible existence of ancient cometary water in permanently shadowed areas such as the Shackleton crater near the south pole. Also, a polar landing is only slightly more demanding in terms of energy than an equatorial mission. Missions between the equatorial and polar regions offer no particular advantage and are the most demanding energy-wise. They also do not impose any significant robotic challenges beyond those of equatorial and polar missions.

The LRAS team also separated missions into large-scale and small-scale ISRU missions. In all cases when large-scale ISRU (e.g. 50-100 mt/yr O₂) was considered, the issues associated with resource mapping, mining, beneficiation, processing, power and storage dominated the robotic architecture. As such, the team considered this a special case and subsequently only considered small-scale ISRU (e.g. 1-10 mt/yr O₂). Other than that, the LRAS study considered all human mission scenarios possible and developed a basic architecture that could accommodate the full range of options. However, to define a baseline the team focused on a series of sortie missions followed by a polar outpost with small-scale ISRU. This provided a robust set of requirements that met the needs of most other mission scenarios.

The most significant variation from the baseline may be in assuring continuous communication with Earth. A single lunar relay satellite can provide partial communications to a single lunar region (i.e., the south pole). Two relay satellites in a frozen elliptical orbit can provide continuous communications to a single region. A polar mission (or a mission to another lunar limb location) may have some limited DTE communications. A backside mission would require a minimum of one relay satellites, and more likely two in order to provide redundant communications capability. Continuous communication over the entire lunar surface could be met by a constellation of 5-6 satellites. The latter was beyond the scope of the LRAS study. However, the LRAS team determined that additional small relay satellites could be part of each LRAS and human sortie mission as secondary payloads if needed.

While the team determined that lunar resource mapping was, in general, a key early robotic requirement, the commitment to ISRU could wait if there was no early economic advantage to using water for rocket fuel. If O₂ and its primary byproducts (metals and glass) are the principle benefits of ISRU, then regolith can serve as a ubiquitous and practical source of raw material. This puts no hard restriction on sortie or outpost siting, and a decision of whether to exploit ISRU is not critical. NASA ISRU experts estimate that a small regolith ISRU experiment could be developed in five years, and the capability for operational small-scale ISRU in ten years. However, if rocket fuel is a high priority, a polar outpost is required and the existence of large amounts of accessible water is crucial to achieving this objective. Furthermore, the feasibility of conducting “mining” operations in a 40K environment would need to be demonstrated relatively early, likely prior to the first human landing. If a good polar site is selected for thermal and illumination reasons, then validation of water processing can wait, as long as there is a source nearby. This latter case makes the issue of “finding the water” critical; it does not address whether it can or will be used. Currently, the search for water is part of the extended baseline lunar robotic architecture with the validation of mining maintained as an option.

Overall, the LRAS architecture includes an orbiter and lander to meet the initial core common requirements and later rovers (or other mobility systems, such as hoppers) to address the “human mission-specific” issues such as “mining” water-ice. Characterization of the elemental and mineralogical composition of the lunar soil, both on the surface and up to several meters below, will contribute to answering scientific questions about the Moon and about the formation of the Earth and solar system. This includes looking for water and other volatiles, one of the National Research Council decadal

survey's scientific priorities. As such, there is significant opportunity for lunar orbiters, landers and rovers to serve both exploration and science.

Beyond the synergies of meeting exploration requirements and addressing key science questions, there is the opportunity to co-manifest science missions with exploration missions. The conceptual missions comprising the current baseline architecture for the six primary excursions have a launch vehicle mass margin of at least 20% to 25% on top of conservative estimates for mission hardware (e.g., spacecraft bus, lander, reference instruments, etc.). Further, many assume use of an EELV, for which the Air Force has developed a special secondary payload adapter ring capable of accommodating multiple payloads. This makes the design and integration for one or more secondary exploration or science payloads comparatively easy, greatly enhancing the flexibility of the lunar architecture.

6.6 Future Work

Results of this study will be provided to the NASA Administrator, the Office of Program Analysis and Evaluation, and the Exploration Systems Mission Directorate (ESMD), the Space Operations Mission Directorate (SOMD) and the Science Mission Directorate (SMD) for consideration and implementation. There are several areas that the LRAS team would like to recommend for future study in developing a final lunar robotic architecture.

Improved Definition of Human Lunar Mission Requirements and Risks

For this study the LRAS team developed and now recommends adoption of a set of requirements drawn from the ESAS report, the outdated/early set of requirements of the Robotic Lunar Exploration Program (RLEP), and other recent analyses. As the elements of the Constellation lunar architecture are refined, all aspects of these requirements should be updated in order to: preserve linkage to the intent; improve the clarity of the requirement; allocate more accurately and quantify the performance and other parameters required; improve the assessment of risk; clarify the interdependencies among requirements; and improve the understanding of the time-phasing of the need dates.

Ultimately, all human lunar mission risks must be identified and quantified, and a process must be implemented to allocate the reduction of those risks among technology programs, robotic precursor missions, and any other available means. For those risks identified as being most appropriately handled via robotic mission (data collection, experiments, technology demonstrations, or deployment of infrastructure), the cost of conducting the experiments and/or demonstrations must also be quantified, along with the risks of failing to conduct those experiments or demonstrations. With both the benefits (human mission risk/cost reduction) and the costs (precursor mission experiment/demonstration cost) understood, managers can make accurate assessments of the robotic experiments and demonstrations, missions, or mission sets that provide the greatest amount of human mission benefit for the least cost and risk.

It is also important to align the architecture with the Constellation Systems Program schedule, which was undergoing significant changes during the execution of this study. To ensure alignment, it is recommended that the robotic architecture be revisited after an initial baseline Constellation Systems schedule has been established.

In-Situ Resource Utilization and Surface Power Option Analysis

Since in-situ resources utilization is a key factor in lunar exploration, it is also recommended that a more detailed ISRU trade study be performed that examines the costs and benefits associated with options such as the level of ISRU employed, the resources selected, and the approach selected. One trade that has been

frequently discussed is the selection of obtaining oxygen directly from heating of the lunar regolith or from potential water ice in permanently shadowed regions. It is important to understand the costs and benefits within the larger exploration architecture context, including factors such as launch mass, comparable lifecycle cost reduction, infrastructure cost, and risk. It is also important to understand the cost and benefit of potential precursor missions to demonstrate feasibility and operations of ISRU systems.

Surface power in support of the lunar outpost phase is also an area that merits further study. The performance, cost, and risk of nuclear and solar power options should be well understood early. Robotic missions may also provide emplacement of the systems needed for future crewed use.

International Cooperation

International cooperative opportunities should also be considered. In order to achieve the cost savings to the U.S. that this study sought, it may be critical to employ international cooperation to achieve some of the more ambitious goals in the architecture. Cooperation through the lunar robotic program may also provide pathfinder opportunities for a larger cooperation in the lunar outpost phase and toward the establishment of a permanent human presence on the Moon.

Technology Development

The LRAS team also recommends further work in understanding the technology development needs to achieve the lunar robotic architecture. This study did not include the time or funding necessary for significant technology development; for its purposes, an assumption of four years from project start to launch was employed. It is critical to have an understanding of the underlying technology development needs to execute the requirements provided, and the costs associated with those needs. For the robotic precursor missions supporting the initial human return to the Moon, the schedule does not allow for any significant technology development. This is not true for later robotic missions, such as the companion robotic systems that will support, complement and supplement human activities on the Moon. The LRAS team recommends near-term investment in systems analysis studies to identify long-lead, high-payoff technologies for the robotic systems that will accompany and support human explorers.

Communications, Navigation, and the Lunar Gravity Model

Though specific requirements for communications and navigation are still to be refined by the programs, the robotic communications/navigation relay is envisioned to be a small- to mid-sized spacecraft that co-manifest with the second robotic mission (lander) in 2011. It is recommended that a set of guidelines be developed regarding the advantageous use of secondary communications and navigation payloads on robotic precursor missions as well as Constellation residual assets.

Improvements to the lunar gravitation model will be important for executing precision landings and providing robustness in the face of contingency situations for human missions to the Moon. In the implementation of the lunar robotic architecture, consideration should be given as to how a lunar gravity science investigation might be conducted in the most cost-efficient manner.

Launch of a relay satellite as a co-manifest with a fixed lander in 2011 or 2012 already represents a short design cycle. Pre-phase A activities should be initiated immediately to begin the processes of: forming a team; defining and maturing requirements; vetting the spacecraft lifetime and deployment strategy against the evolving robotic and constellation mission set; maturing the architectural views for the robotic lunar

relay; developing an operations concept; and identifying technology demonstrations that may be included as secondary payloads.

The “Communications and Navigation” section of the appendix (Appendix D) to this report includes a more detailed discussion based upon the work of the Space Communications Architecture Working Group (SCAWG), including sections on “LRAS Relay Future Plans” and “Summary and Recommended Next Steps.”

Definition of an Exploration Space Weather System

As discussed in the “Space Radiation and Space Weather” section of the appendix (Appendix J), the scope of the LRAS did not include implications for the non-lunar robotic space weather architecture. The LRAS team recommends that the NASA Exploration Systems, Space Operations, and Science Mission Directorates (ESMD, SOMD, and SMD) jointly study and understand the requirements for space weather robotic systems needed to safeguard human voyages to the Moon, Mars, and other destinations. The appendix provides additional recommendations for this effort.

Examination of Lower-Cost Mission Options

It is also important to note that several lower cost mission concepts were presented to the team during the course of this study. The team recommends some effort to fully understand the benefits and risks of utilizing such lower-cost approaches to fulfilling the requirements for a lunar robotic architecture. It is possible that such approaches will provide for more frequent, lower-cost mission opportunities.

7. Conclusions and Recommendations

This report of the Lunar Robotic Architecture Study (LRAS) responds to a charter from the NASA Headquarters Office of Program Analysis and Evaluation (PA&E) on behalf of the NASA Administrator to recommend an architecture for lunar robotic precursors. PA&E chartered the Exploration Systems Architecture Study (ESAS) during the spring and summer of 2005 to provide an overall architecture for NASA's exploration mission. It then chartered LRAS to provide a flexible architecture for the robotic spacecraft that would be required on or near the Moon as precursors to each of the architectural elements that ESAS recommended.

The LRAS team was asked to address a basic set of questions:

- Do we need robotic missions at all? If so, why and under what conditions?
- How would they be accomplished and at what cost? Are they within budget?
- What are the minimum requirements? What is the minimum mission set?

The LRAS team concluded that there are compelling reasons to conduct robotic precursor missions. However, the extent of the requirements depends on the degree to which NASA will implement the ESAS architecture. The Agency still has many decisions to make. Many additional decisions will present themselves as exploration of the Moon proceeds. LRAS analyzed a set of scenarios, and assembled a set of potential requirements.

LRAS makes two recommendations:

1. Adopt the set of requirements presented in Section 4 of this report.

- a. Establish a linkage between the risk reduction of the Constellation Program and individual requirements. As Constellation's risk strategy evolves, so may the precursor requirements.

2. Adopt the baseline architecture option through 2012 presented in Section 6 of this report.

- b. The Lunar Reconnaissance Orbiter (LRO) could be the first orbiter – it has passed confirmation review.
- c. Decisions concerning ISRU and robotic missions starting beyond 2012 depend on results of earlier missions and therefore do not have to be made now.

In addition, the LRAS team recommends NASA pursue the future work identified in the "Future Work" section of this document (Section 6.6).

LRAS did not have a current set of robotic precursor requirements. Instead, the team drew upon the ESAS report, the outdated and early set of requirements of the Robotic Lunar Exploration Program (RLEP), and other recent analyses to lay out a linkage to Constellation needs. These linkages connect Constellation risks to discrete precursor requirements, and are flexible to evolve as the elements of the Constellation architecture are refined. Further, the robotic precursor missions support Constellation milestones and development. Schedule linkages were used to phase the requirements in time.

At first order, it appears the existing RLEP budget can accommodate all high-priority near-term (through 2012) requirements. Additional consideration was given to potential requirements, many of which might still provide tremendous benefit. Within each category, the LRAS team examined a wide range of activities and determined whether “we would still send humans if we didn’t do them.” This provided a range of potential activities scalable with the available resources. The requirements comprise a minimum set; significant risk can be “bought down,” or reduced, with additional resources.

The robotic precursor requirements emphasize communication and navigation, high-fidelity mapping (visual, topographic, and resource), characterizing the environment (dust and radiation), preparing for in-situ resource utilization (ISRU), and searching for water. The primary uses of the results of these missions would be risk reduction for Constellation development, sortie site selection, sortie operations, and outpost development and site selection. The requirements are time-phased to match these needs. This means, for instance, that communications, mapping, and dust mitigation must be addressed before attempts can be made to characterize any deposits of water in permanently shadowed craters.

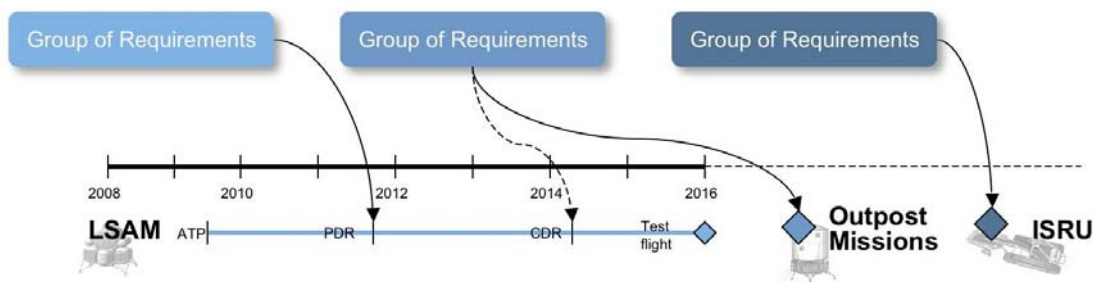


Figure 7.1-1. LRAS identified, grouped, and time-phased lunar robotic precursor requirements.

Opportunities exist for lunar science in conjunction with each element of the LRAS architecture. LRAS documented the competitive process by which these opportunities could be realized. The team identified no lunar science requirements for precursor missions.

The LRAS baseline architecture consists of a series of missions, linked back to their driving requirements:

- 2008 - Orbiter to provide visual, topographic, and resource mapping
- 2011 - Fixed Lander to characterize the polar environment for Lunar Surface Access Module (LSAM) risk reduction
- 2011 - Long-Life Communications Relay to support all other robotic precursors
- 2013 - Mobile Lander to investigate potential presence of water in cold shadowed craters
- 2015 - ISRU Rover to demonstrate resource production

LRAS also analyzed a series of excursions from this baseline to evaluate de-scoped ESAS mission scenarios and other potential decisions. The excursions examined decision options on a lunar orbiter, extensible communications, the number of landers, lander mobility, and ISRU. In particular, the minimum architecture – one that is within the budget profile – assumes a deferral of both the Mobile Lander and the ISRU Rover. The decision on whether an outpost will need to take advantage of ISRU and if so, whether water is required, does not have to be made until the results of the initial orbiter mission have been analyzed.

During the course of this study, the LRO project passed its confirmation review. The LRO meets all the requirements identified by LRAS for a lunar orbiter, exceeds some requirements, and accomplishes many of the additional considerations of highest value. Though LRO is not in the baseline, this report provides architecture excursions that support the LRO as the initial lunar orbiter missions

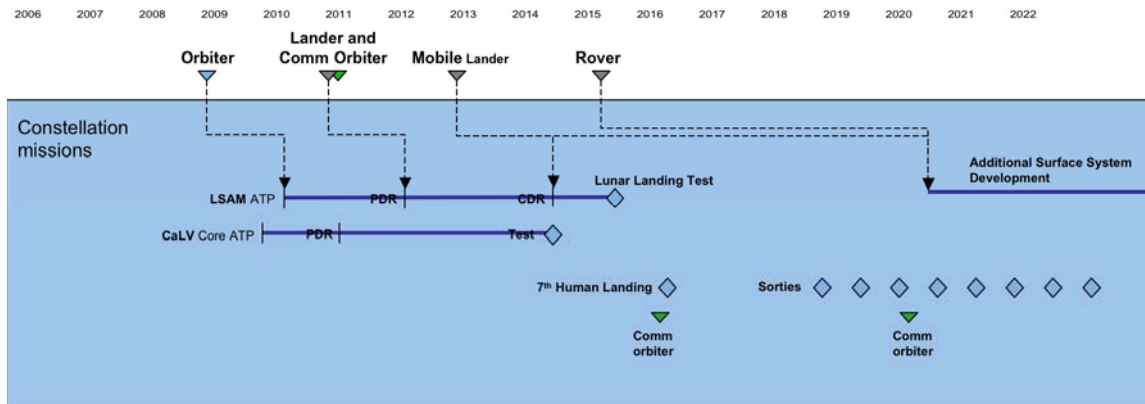


Figure 7.1-2. LRAS Baseline Architecture and Linkages to the Elements of the ESAS Architecture

LRAS identified promising opportunities that may increase efficiency and reduce budget demands. Innovative, low-cost missions; international partnerships; and selective NASA center assignments could improve the LRAS baseline architecture and potentially reduce cost.

Current work on innovative, low-cost missions may produce tremendous benefits using novel approaches to further lunar exploration objectives. The recently announced secondary payload to accompany LRO is an early result of this promising work. The LRAS baseline resources ensure that the risk reduction requirements of Constellation are accomplished, but additional savings may be realized through implementation of lower-cost missions.

International partnerships may supplement the results of the baseline architecture. The baseline focuses on those things required to buy down Constellation risks. However, a number of activities – such as international lunar orbiter missions – were also identified that, while not absolutely required, would still produce tremendous benefit.

Additional long-term efficiencies may accrue to NASA by the choice of center assignment. The LRAS baseline provides a number of opportunities for small- and mid-sized spacecraft development. The skills required to develop these spacecraft vary from communications and navigation to landers and mobility systems to search for water-ice in lunar craters. Implementing the LRAS baseline using NASA research and spaceflight center capabilities could provide opportunities to strengthen NASA’s space systems development and operations workforce and enhance center technical skills and capabilities for future exploration missions.

This report of the Lunar Robotic Architecture Study (LRAS) provides guidance and flexibility for decisions on lunar robotic precursor missions. The recommendations link to the results of the ESAS architecture and the needs of the Constellation Program. The analysis of various requirements and excursions is intended to provide the flexibility to evolve with the overall exploration architecture of the Agency. This LRAS report should serve as a valuable resource for NASA and others as we build the systems for exploring the Moon, Mars, and beyond.

Appendices

Appendix A. Terms of Reference (TOR)

***Terms of Reference (TOR)
Review Plan for NASA's***

Lunar Robotic Architecture Study

February 14, 2006

Submitted by:

Original signed by

Dr. Daniel R. Mulville

Office of Program Analysis and Evaluation
NASA Headquarters

Approved by:

Mr. William Claybaugh

Studies and Analysis Division Director
Office of Program Analysis and Evaluation
NASA Headquarters

Dr. Scott Pace

Associate Administrator,
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CHANGE LOG

Date	Event	Change	Studies and Analysis Signature	Program Analysis and Evaluation Signature
1/26/2006	Initial Draft	n/a	n/a	n/a
2/2/2006	Draft incorporating all initial comments	Clarified Purpose and expanded Resources and Deliverables sections	n/a	n/a
2/14/2006	Baseline	n/a	Approved by Bill Claybaugh	Approved by Scott Pace

Background

The Vision for Space Exploration (VSE) specifies a series of campaigns to return humans to the Moon, use it as a testbed, then conduct human expeditions to Mars. Preceding the human campaigns to both the Moon and Mars are preparatory robotic exploration campaigns.

- *Undertake lunar exploration activities to enable sustained human and robotic exploration of Mars and more distant destinations in the solar system;*
- *Starting no later than 2008, initiate a series of robotic missions to the Moon to prepare for and support future human exploration activities;*
- *Conduct the first extended human expedition to the lunar surface as early as 2015, but no later than the year 2020; and*
- *Use lunar exploration activities to further science, and to develop and test new approaches, technologies and systems, including use of lunar and other space resources, to support sustained human space exploration to Mars and other destinations.*

A Renewed Spirit of Discovery: The President's Vision for U.S. Space Exploration, January 14, 2004

NASA established the Robotic Lunar Exploration Program (RLEP) in mid-2004 to conduct the robotic lunar campaign, and established the Lunar Reconnaissance Orbiter as the first Project within this Program.

In the spring and summer of 2005, NASA conducted the Exploration Systems Architecture Study (ESAS). The ESAS study produced an overall architecture for human lunar return, in particular laying out the launch vehicles, propulsion elements, crew transport vehicles, and crew surface elements. During the development and testing of these architecture elements, a campaign of lunar robotic vehicles will be conducting precursor lunar science, scouting out potential landing sites, and laying the communication and navigational infrastructure upon which the human lunar missions will rely. ESAS framed out the expected costs of such a robotic campaign, based on the prior RLEP budget formulation work, but did not address the specifics of the campaign architecture.

To complete the set of exploration architectures, a lunar robotics exploration architecture must be defined. It must fit within the environment established by the derived requirements of the human lunar exploration architecture. There are also existing and planned communication and navigation assets that can be leveraged, including the Deep Space Network and TDRS System. There are also existing and planned spacecraft from potential partners, including international partners. The precursor lunar science must fit into the existing environment of International Space Station research on space environmental effects and space science research on the solar system's evolution. Finally, as the architecture is being deployed, it may be itself leveraged to conduct priority science.

Purpose

The study shall assess and compile the top level requirements derived from the Vision for Space Exploration and the ESAS human lunar return architecture:

- What are the robotics architecture requirements for reducing the risks to human lunar return and how do these compare to other risks and mitigations?
- When does the specific site of the lunar base need to be established? How much surveying needs to be done, if any, to down-select to a site and how much surveying needs to be done on the selected site?
- What are the precision navigation requirements that must be met with a robotic lunar infrastructure and what navigational technologies must be tested on the lunar surface prior to human lunar return?
- What communication architecture needs to be deployed by the time of human lunar return and what benefits are there to deploying these elements earlier during the robotic campaign?
- What priority science on or from the moon must be addressed prior to human lunar return, i.e. biological science, and what scientific results would be important inputs to future architecture decisions, i.e. lunar base location or in-situ resource utilization?
- What are the necessary precursors for demonstrating technologies for human surface activities, including supplying power and conducting in-situ resource utilization?
- How are the requirements best distributed among the existing Programs and Projects across the set of potential robotics architectures?

The study shall provide a range of architectural options and a recommended option. For each option, the study shall answer the following:

- What are the costs of the architecture elements, including leveraged assets? Are these costs within the existing budgets or, if they go outside them, do they do no harm to higher priorities such as CEV acceleration?
- By what dates or milestones do the robotic elements need to be deployed, technologies validated, or scientific questions investigated prior to human lunar return?
- What technical requirements or critical needs does each element fulfill? How do these requirements or needs vary across architectural options?
- What are the highest cost, schedule, and performance risks that might impact the success of an individual element and overall campaign success?

The study shall assess the integration of the potential lunar science with NASA's existing research strategy:

- What priority science of the moon could be enabled by robotic precursor missions meeting exploration requirements?
- What priority science on or from the moon is enabled by robotic precursor missions?

Duration

The study shall provide the NASA Administrator a baseline architecture recommendation by Friday, March 31, 2006. Additional study may be commissioned beyond that date. The final full report, with all background analysis shall be provided by Friday, April 28, 2006 to the Office of PA&E.

Scope of Work

Requirements scope: the full set of science and exploration precursor requirements relevant to the Moon. This includes all lunar science requirements (including prioritization), requirements from the CEV, LSAM, and other human architecture elements, and communication requirements.

Architecture scope: the architectures required to meet all science and exploration precursor requirements relevant to the Moon. This includes elements of multiple Programs in multiple mission directorates. In particular, the entire RLEP Program, the Constellation ECANS Project, the SOMD Space Network communication infrastructure, and the SMD Deep Space Network communication infrastructure.

Consideration should also be given to how other non-NASA partners – including international partners – might contribute data and services as well as implied hardware elements to the architecture. The expectation is that the U.S. will lead lunar exploration with options for international partners to contribute.

Study Approach

The study will use the following baseline work breakdown structure to conduct its analysis:

- Gather, integrate, and synthesize prior work
 - Including products from ESAS, RLEP, the Lunar Exploration Analysis Group (LEAG), ESMD Requirements Division, and the Advanced Planning and Integration Office (APIO) strategic roadmaps
- Synthesize and document derived requirements and constraints
 - Develop metrics based on the requirements for assessing architecture options
- Develop architectural options
 - Assess the options against the metrics
- Validate requirements, metrics, and options at a mid-term brief
- Conduct final options assessment
- Develop recommendations
- Conduct “Red Team” review
- Write report

- In parallel, work with other analysis activities:
 - LEAG (SMD/ESMD), Communication architecture study (SOMD), RLEP planning (ESMD), RLEP readiness reviews (PA&E)

Resources

The study team shall consist of approximately fifteen core members drawn from the NASA civil service and from outside of NASA as needed. The core team membership must include representatives from the major existing programs affected by the scope of the study, including the RLEP Program and the lunar science community. In addition, the core team should have among its members a familiarity with developing architectures and technology and research portfolios within given constraints. Finally, additional support to the core team members shall be used as needed for tasks such as cost estimation and for providing background on previous architecture work.

Deliverables

The goal is to provide a technical report as a companion document to the ESAS architectures. Additional presentation materials will be provided for interim review of the technical work prior to the final report. Deliverables include:

Mid-term Presentation

- Summary of derived requirements
- Preliminary architecture options

Final Presentation

- Architecture options
- Recommendations

Final Report

- Summary of derived requirements and critical needs, and their traceability
- Options plus analysis, measures, etc...
- Assessment of how requirements and options vary over different assumptions
- Assessment of how risk is bought down over time and how the strategy can adapt as conditions change and discoveries are made
- Recommendations

Appendix B. Team

The core team consisted of the following members:

Dan Mulville	PA&E, Study Team Lead
Garth Henning	PA&E, Study XO
Terri Lomax	PA&E / Human Safety and Life Support
Jason Derleth	PA&E / ESAS Study
Len Dudzinski	PA&E / Nuclear Study
Tom Morgan	SMD Representative / Lunar Science
Gordon Johnston	SMD Representative
Mark Borkowski	ESMD Representative / RLEP
Michele Gates	SOMD Representative
John Rush	SOMD / Comm Study
Mike Moreau	ESMD / Navigation
Murray Hirschbein	ARMD
Jim French	JRF Engineering Services

Additional support provided by:

Tom Coonce	PA&E / Cost Analysis
Charles Hunt	PA&E / Cost Analysis
Butler Hine	ESMD / RLEP
Sylvia Cox	ESMD / RLEP

Appendix C. Inputs

During the course of the 60-days LRAS work, the study team received inputs from a variety of sources. These inputs were intended to provide the team with all the relevant data needed to conduct the analysis.

Detailed Architectural Analysis

- ESAS (week 1, Stanley)
- ESMD/DIO (pre and post ESAS) (week 2, Craig, Timm)
- RLEP Program (week 2, Hine)

Detailed Programmatic Briefings

- RLEP (week 1, Borkowski)
 - LRO (week 4, Chin)
 - RLEP-2 (week 3, Lavoie)
- Constellation (week 3, Woodward)
 - Draft CARD (week 2, Volosin)
 - LSAM (week 3, Sayied)
 - ECANS (week 2, Vrotsos)
- HSRT (week 3, Lomax)

Status Reports

- Science (Decadal Survey, LEAG) (week 1, Morgan)
- FY07 Budget Request Rollout (week 3, Leshner)
- LRO PDR (week 4, Tooley)
- Nuclear Study (week 1, Dudzinski)
- Communication Architecture Study (week 1, Rush)
- NAC/NRC (week 3, visited NAC)

Additional Briefings

- ISRU
- Dust
- LRO Co-manifest payloads
- Updates from LEAG, Comm, Nuclear
- MIT/Crawley Commonality Study

Appendix D. Communication and Navigation

Constellation Communication and Navigation Requirements

One of the high-level “Needs, Goals, and Objectives” stated for the Constellation Program implies a capability to land at any location on the Moon, including polar and backside landing sites for which direct-to-Earth communication would be difficult or impossible:

Provide the capability for the Constellation system to allow global access to any site on the moon with anytime return. [Constellation P-033]

In order to enable global access, a lunar relay communication and tracking capability will be required. Some existing requirements with direct implications for the lunar relay include:

- Landed accuracy (1km unaided, 100m aided)
- Support the Constellation Command, Control, Communication, and Information Interoperability Specification:
 - Frequencies
 - Data rates
 - Modulation
 - Protocols, including the use of IP
 - Other key parameters
- Provide communication for landing sites with poor or non-existent line-of-sight communication with Earth
- Provide communication and tracking for orbiting or surface assets when poor or non-existent Earth-based tracking is available
- Provide 2-way radiometric range and Doppler measurements for navigation of vehicles in lunar vicinity

Other significant drivers for the eventual lunar relay that have not been specified include:

- Will there be a requirement for communication coverage of critical events (maneuvers) performed on the lunar far side (out of view of Earth)?
- The Constellation Design Reference Mission and Operations Concept specifies that Constellation missions, specifically Lunar Sortie missions, can be conducted at any location on the lunar surface. Assuming that communication is required to at “any location,” a Lunar Relay system has to be deployed. However, the current Constellation budget guidance states that only south pole coverage is required. The actual need date for “global” communication and tracking capability will have a significant effect on deployment, lifetime, and sustainability decisions.

Assumed RLEP Communication and Navigation Requirements

RLEP2 preliminary design activities conducted in early 2006 provided some definition of notional communication and navigation requirements for robotic precursor missions:

- Communication coverage of mission surface elements = 90% (note: this is a major driving requirement that will effect the number or size of relays, depending on implementation)
- Mobile Solution (MS) navigation via two-way range and range-rate
- Assumed command rates: 4 Kbps for Lander; 10 Kbps for Mobile Solution
- Assumed data rates: 300 Kbps for Lander; 100 Kbps for Mobile Solution
- Landing accuracy 100 m, 3-sigma, unaided

- Improved lunar gravitation potential model (to achieve precision landing and to enable operation of lunar orbiters at very low altitudes).

The RLEP2 study also provided an opportunity to examine notional data-rate requirements on a lunar relay spacecraft to support robotic precursor missions. The backhaul communication includes the direct-from-Earth (DFE) link and the direct-to-Earth (DTE) link; the notional data rates are 12 kbps and 1800 kbps respectively. To ensure compatibility with the Constellation frequencies and protocols, it is assumed that S-band communication will be employed for proximity communication, and S-band (contingency) and Ka-band (nominal) for backhaul communication.

Communication and Navigation Elements of LRAS

The LRAS developed a set of missions with the objective to satisfy the highest-priority Constellation requirements. Overall, most of the communication and navigation requirements identified through the LRAS study were not deemed to be significant drivers for the baseline or excursion architectures presented in this report.

The highest-priority navigation requirements were incorporated into the first robotic precursor mission (orbiter) in the LRAS baseline. These included providing high-resolution topographical data to characterize landing sites [LRAS-7], imaging landing sites at landform scales [LRAS-8], and improving the lunar gravitational potential map [LRAS-5]. The gravity science investigation is the only one of these key requirements not satisfied by the excursions with LRO as the first orbiter.

Robotic landers provide opportunities to demonstrate precision landing and hazard avoidance capabilities that will eventually enable 100 m (3-sigma) landing accuracy, as well as specific (navigation) software, sensors, and algorithms [LRAS-41] used for descent and landing. Objectives that may be satisfied by either lander or orbiter spacecraft include: demonstrating the routable, IP-based communication architecture as described in the Constellation C3I Interoperability Specification; obtaining additional experience with tracking and flight dynamics operations for spacecraft in the lunar environment; providing technology demonstrations of communication and tracking hardware; and providing residual communication and tracking assets for subsequent robotic and human missions.

The robotic architecture is not required to pre-deploy beacons or other surface navigation aids for Constellation, nor is it required to demonstrate precision landing or hazard avoidance capabilities in advance of the actual LSAM test flight (unmanned landing), or specific navigation/GNC sensors or systems. However, demonstrations of many of these capabilities through robotic precursor missions would be highly desirable and in some cases may reduce risk and lower costs later in the program.

LRAS Lunar Relay Implementation and Alternatives Considered

The decision to send robotic spacecraft to specific polar landing sites is the primary driver for the requirement to deploy a lunar relay communication capability as part of the lunar robotic exploration program. NASA's Space Communication Architecture Working Group has examined direct-to-Earth communication coverage for polar landing sites (Figure 1). Even at the most advantageous polar landing sites, direct line-of-sight communication to Earth may be extremely limited, with average communication blackout periods ranging from 1 to 10 days per month. In worst-case locations, communication outages were as long as 18 days per month. Furthermore, direct-to-Earth communication would not be available for a mobile lander traversing into craters or behind local landscape features that obstruct a direct view to the Earth. These facts drive the requirement for a lunar relay communication and tracking capability.

Region of Moon	C&N Characteristics
	Near Side 80°W-80°E
	<ul style="list-style-type: none"> • Continuous Coverage from Earth • Apollo style missions
	Near Side 80-85°E & W
<ul style="list-style-type: none"> • Obstructed Coverage from Earth • May allow DTE with careful siting • Full site coverage requires orbital relay 	
Limb & Far Side 85°W around back to 85°E	
<ul style="list-style-type: none"> • Low or No Coverage from Earth • Robotic missions require periodic relay • Humans require (near) continuous relay 	

Figure D-1. Direct-to-Earth Communication Coverage Characterization

The baseline Lunar Robotic Architecture includes a single communication and navigation relay satellite launched as co-manifest with a fixed lander in 2011. This spacecraft is assumed to have a lifetime of 5-6 years which would provide relay communication for three robotic lander missions flown between 2011 and 2017. The manifest with the first (fixed) lander was chosen because of excess launch vehicle capacity available with this launch.

Several requirements are implicit in the assumption that a single lunar relay satellite will meet the needs of all of the subsequent robotic missions. Analysis performed by the Space Communication Architecture Working Group (SCAWG) and Exploration Communication Navigation Systems (ECANS) has shown that activities focused in a specific region of the Moon (i.e., its south pole) can be supported by a specialized elliptical orbit with two assets providing continuous coverage. Polar or backside landing sites could be supported by single relay satellite in elliptical orbit providing partial coverage. Truly global coverage – maintaining the flexibility to visit any lunar landing site at any time – would require more satellites. The SCAWG has presented several concepts for full lunar coverage starting with a minimum of five lunar relay satellites. The landers in the LRAS baseline are assumed to be deployed to the south polar region of moon, to landing sites in which reliable direct-to-Earth communication will not be possible. The lunar relay satellite is assumed to be deployed into a frozen elliptical orbit, providing partial communication coverage of the south polar region.

The spacecraft is assumed to provide moderate data rates that can be met through an S-band communication link. Furthermore, the spacecraft is designed with sufficient redundancy of critical systems and with sufficient orbit maintenance capabilities to ensure a lifetime of 5-6 years.

Based in part on the results of a recent JPL Team X study conducted by the LCNS Project, it was assumed that these capabilities could be met by a spacecraft with a (wet) mass of between 350 and 600 kg and costing approximately \$360 million. The Team X study assumed a long-life, fully redundant lunar relay spacecraft suited for human spaceflight operations and communication data rates and burdens meeting the current Constellation communication requirements.

In recognition that the design trade space for the lunar relay capability is very much open, the LRAS considered several other lunar relay implementation options. Figure D-2 illustrates the LRAS communication and navigation relay baseline, and some alternative implementations considered. Alternative #1 represents an approach considered for some of the RLEP 2 lander concepts, in which each missions brings along a dedicated, short-duration communication relay to support specific landed operations for that mission. Alternative #2 represents an accelerated deployment of the Constellation lunar relay satellites to support later robotic precursors, with the possible augmentation by a dedicated relay satellite to support earlier missions.

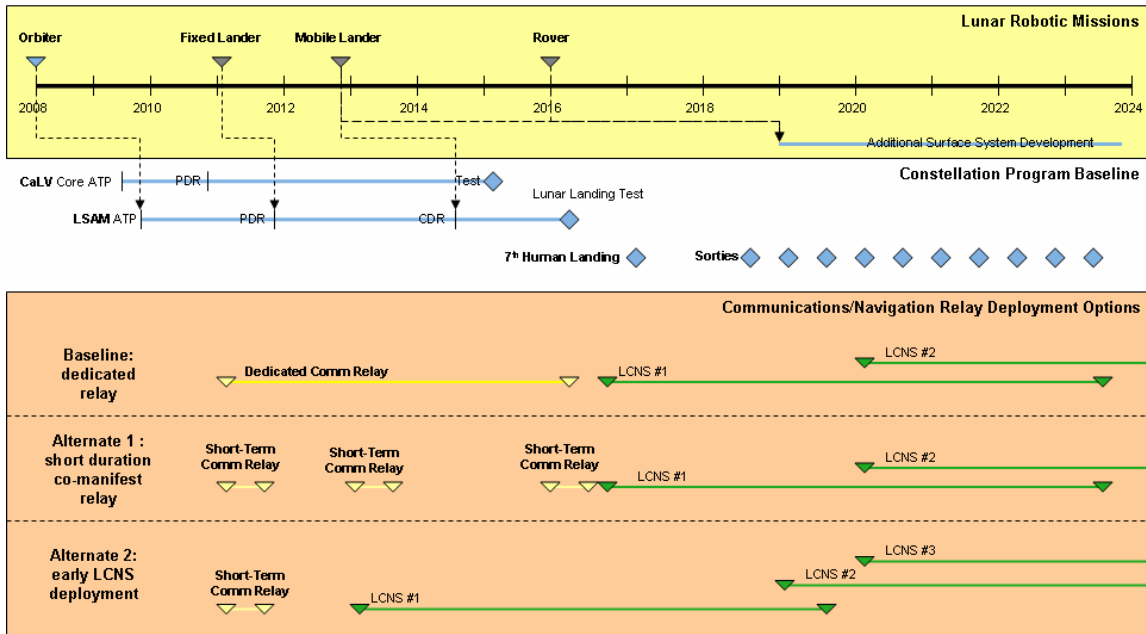


Figure D-2. Range of Lunar Relay Options Considered

A robotic lunar relay spacecraft is included in the architecture specifically to support the deployment of robotic landers to the south polar region, but it may also be leveraged to provide significant value to the overall robotic precursor program by:

- providing communication coverage for critical events on the lunar far-side;
- providing capability to perform gravity science by direct radiometric tracking of another spacecraft in lunar orbit; and
- reducing the communication burden on vehicles operating in the lunar vicinity.

Although these requirements were not deemed to be drivers for the robotic architecture, the relay satellite also provides a number of opportunities to reduce risks for the Constellation Program in the area of communication, navigation, and flight operations. Areas of interest to Constellation include:

- demonstration of communication and tracking to users in LLO or on the lunar surface through a relay;
- flight dynamics/operations experience with the lunar relay spacecraft;
- demonstration of Constellation C3I and IP at lunar distances; and
- enabling a capability to improve the lunar gravity model through tracking of another spacecraft in low lunar orbit.

Lunar Relay Trade Space and Recommendations

The SCAWG and the Lunar Communication and Navigation Systems (LCNS) Formulation Project have conducted extensive analysis and trade studies regarding lunar relay spacecraft concepts, deployment strategies, and operations concepts. Some of the key capabilities or characteristics that are part of the lunar relay trade space include:

- Required data rates and multiple access requirements (support for low-rate telemetry and/or voice communication, or high rate video and science data)
- Support two-way range and Doppler tracking of spacecraft in lunar vicinity
- Lifetime/redundancy requirements
- Orbit selection and maintenance requirements (circular, elliptical, or libration point orbits)
- Continuous or partial communication coverage, coverage of critical events
- Deployment/replacement strategy
- Similar or dissimilar spacecraft

The following section summarizes some of the key considerations in the development of the lunar relay, and previous analysis and trades that have been performed. More details are provided in referenced white papers from the LCNS project and reports developed by the SCAWG.

Spacecraft Capability and Lifetime

The capability of the lunar relay satellite is driven by the communication and tracking requirements as well as any technology demonstrations that will be flown. The coverage requirements drive the number and orbital location of satellites. In turn, the link distances from these orbits drive the size of antennas and transmitters on the relay, which impact the satellite power and attitude controls design. The number of users (multiple access requirements) further drives antenna design and power requirements. Orbit selection and spacecraft lifetime may be large factors in the size of the lunar relay spacecraft due to orbit maintenance requirements and the corresponding delta-V (net velocity change to the vehicle) required.

There are a number of other important drivers on the lunar relay satellite design. A lunar relay spacecraft that supports the Constellation C3I interoperability specification is expected to require a highly stable reference oscillator onboard the satellite for generation of reference frequencies and ranging codes. Data rates and multiple access requirements are key drivers to the communication system design, especially to the power subsystem and the antenna subsystem. To a first order, supportable data rate is linearly proportional to the spacecraft transmitting power and the antenna size. The antenna subsystem is often a critical factor in the spacecraft design because of its impact on total mass and stability, the possible need for stowage during launch and erection in orbit, and the requirement for accurate target pointing. A steerable high gain antenna provides high data rate performance, but it requires dedicated mechanical structure and pointing control, which adds weight and operational complexity to the spacecraft since both the lunar relay and the user spacecraft may be required to have onboard ephemeris for both vehicles. An omni antenna, on the other hand, has poor link performance but it has a wide beamwidth and does not usually require additional structure and complicated control. A phase array antenna can produce a large number of beams simultaneously, thus providing a multiple access function. They can be steered electronically over a rather large angular range without the need for mechanical pointing systems. The main disadvantage is the hardware complexity, as the signal path of each array element requires precisely controlled phase and amplitude that must be maintained over a wide range of temperature, signal level, and other space operation conditions.

An attempt was made to assess the range of spacecraft sizes/capabilities that might be considered for the lunar relay. The Team-X study provides the most recent data point on a lunar relay satellite conceptual design that meets the currently assumed Constellation lunar relay requirement. Tables 1 and 2 give some of the general trends one can expect for small, medium, and large satellites based on current Earth communication satellite systems and conceptual lunar communication satellite systems. Smaller satellites generally have lower throughput due to restrictions of mass and power. Less power typically results in lower-orbit (because of the shorter link distance) with a more stringent antenna-pointing requirement. To reduce the requirement for pointing of antennas (i.e., mobile users) a low-frequency communication

payload is generally chosen. The larger satellites have more capacity, allowing for greater throughput and life duration, but they also require greater power and mass, resulting in higher cost. The higher power allows for higher altitude satellites (for the longer link distance). The major advantages of high-frequency payloads are increased available bandwidth and decreased user antenna size. Moderate performance can be obtained with a medium satellite, at a higher cost than a small satellite and lower than a larger satellite.

Size	Name/Manufacturer	Mass (kg)	Life Cycle (years)	Link		Data Rates		Power (W)	Orbits
				Relay to Trunk	Relay to User	Relay to Trunk	Relay to User		
Small Relay (<250 kg)	XSS-11 Derivative (proposal)	<100	n/s	S	UHF	<1 Mbps	~1 Mbps	380	Frozen Elliptical (polar)
Mid (250 to 750 kg)	APL Big Sky	350	n/s	S/?	UHF/?	1 Mbps	1 Mbps	n/s	n/s
	GSFC RLEP2 Relay	400 kg (wet)	6	Ku	S (USB)	~3 Mbps	N chan at 300 kbps	400	Frozen Elliptical (polar)
Large (>750kg)	Team X	1240 (w/cont)	10	Ka/X	Ka/S	25-400 Mbps 10 Mbps	25-200 Mbps 25Mbps	1472	Frozen Elliptical (polar)

Table D-1. CN Lunar Relay Satellite Options (Based on Conceptual Lunar Communication Satellite System)

Comm/Nav Lunar Relay Satellite Options (Based on Earth Communication Satellite System)									
Size	Name/Manufacture (EXAMPLE)	Mass (kg)	Life cycle (YRS)	Link		Data Rates		POWER (W)	Orbits
				Satellites to Trunk	Satellites to User	Satellites to Trunk	Satellites to User		
Small <250 kg Relay	ORBCOMM	43	3	UHF/VHF	UHF/VHF	57.6 KBPS	4.8 KBPS	160	LEO
Mid <750 kg Network/interface	IRIDIUM	556	8	KA	K/L	~2.64MBPS	2.4 KBPS	1400	LEO
Large >750 kg Constellation Class	TDRSS	800	10	KA	S	25-300MBPS	300KBPS-6MBPS	1800	GEO

Table D-2. CN Lunar Relay Satellite Options (Based on Earth Communication Satellite System)

Orbit Design and Delta-V requirements

The selection of the relay satellite orbit and assumed spacecraft lifetime will be significant drivers for the spacecraft propellant mass fraction (propellant mass divided by initial spacecraft wet mass). Multiple relay orbit types were considered during the early stages of the Robotic Lunar Exploration Program - 2 (RLEP2) trade studies. These included circular orbits, elliptical orbits, frozen orbits, and 3-body orbits (Earth-Moon, L2, and Butterfly). The percent orbit visibility as a function of the propellant mass fraction was plotted in Figure 3 for all of the cases. The 718 x 8088 km frozen orbit exhibits the best characteristics; this represents a compromise between the low-ΔV circular orbits and the high-visibility elliptical orbits. Furthermore, the propellant mass fraction is less than 25 percent. While the Butterfly

orbit looks promising, additional analysis is required before it can be considered as a viable option for a relay satellite.

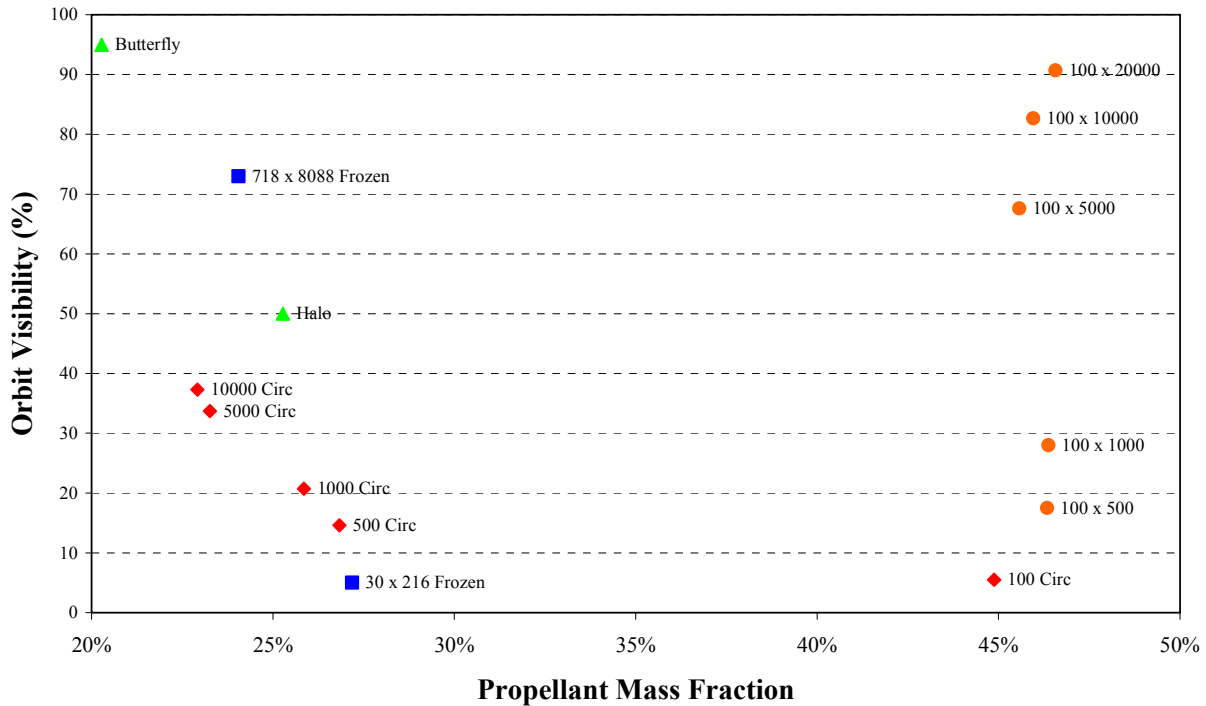


Figure D-3. Orbit Visibility vs. Propellant Mass Fraction for 6-Year Mission

Full Lunar Coverage vs. Re-Deployment of Assets

A study was conducted by the SCAWG to explore the feasibility of deploying communication relays to cover specific sortie regions, in which enough fuel was budgeted to maneuver the relay and change the orbit significantly to support follow-on sorties at different locations on the lunar surface. A set of scenarios, or sortie and outpost sequences, were assumed for comparison. The following are common assumptions for this set of scenarios: the period of interest is 12 years; the outpost location, after the sorties conclude, is at the south pole; and one mission is flown every six months. The various sequences are intended to span the relative difficulty associated with providing continuous coverage for missions, assuming that assets are deployed in conjunction with the mission flight if at all possible. For each sequence, where possible, several different approaches to providing coverage were explored. An example might be that south pole coverage could be provided by three relays in a circular polar orbit or by two relays in a highly inclined elliptical orbit. For each solution, the maximum ΔV requirement for a relay in the 12-year period was recorded, along with the total number of relays needed over the time span, and the wet mass of the largest relay.

When the results of this study are combined and compared to the results of the full coverage constellations developed in other SCAWG studies, several basic conclusions can be drawn. The first is that if the sequence of sorties results in a demanding (high total delta-V) set of maneuvers *and* there is a need to have relays revisit previous sortie sites on a more-than-infrequent basis for data collection from remaining assets, then the fuel penalty and number of relays required is often higher than would be the

case for simply deploying a full-coverage constellation to begin with. However, if the sortie sequence is less demanding (begins with several near-side missions that can use DTE comm) *and* infrequent revisit rates for previous sortie locations are acceptable, there are several more efficient solutions using the "re-deployment" approach—needing less propellant and/or fewer relays than deploying a full coverage constellation. The difficulty at the current juncture is that the exploration plan is still somewhat unknown, making it difficult to optimize the deployment approach and orbit selection.

South Pole Relay Configuration – Potential for Critical Event Coverage

Analysis was conducted to investigate the concern about the SCAWG recommended architecture for south pole exploration with respect to its ability to cover critical events for an orbiting spacecraft. The relay orbit configuration assumed for the study is two spacecraft in an elliptical-inclined orbit with apoapsis over the south pole region. This also assumes that near-side events are covered by direct-to-Earth (DTE) communication. The representation of a vehicle in a far-side maneuver is simplified as a low equatorial orbit (altitude 110 km). This configuration is illustrated in Figure D-4.

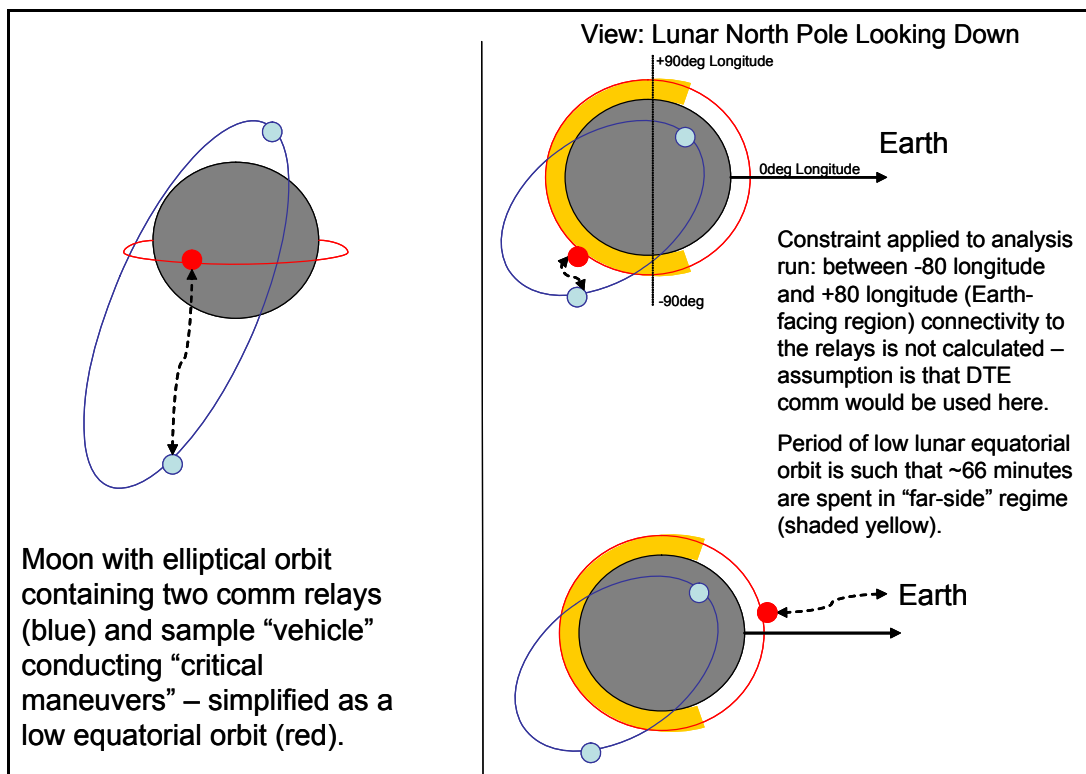


Figure D-4. Frozen Orbit Far-side Coverage

The results for contact times over a one-month period indicate that performance changes as the apoapsis rotates in longitude; when the apoapsis is “near-side” the far-side connectivity between the relays and the vehicle drops, and when the apoapsis is “far-side” the connectivity peaks. The results of the study show that there are multi-day periods of good connectivity (>90% of the far-side orbit covered) to vehicles in equatorial low lunar orbit, as well as multi-day periods of performance presumably not suitable to critical event coverage (<30%). Later investigation will use example lunar orbit insertion profiles or trans-Earth injection profiles as a more accurate representation of critical maneuvers.

Deployment Options and Tie to Constellation

The major deployment options for a lunar relay capability to support robotic precursor missions can be summarized as follows:

1. Each mission provides its own communication capability for the duration of the mission (LRAS Alternate #1). This approach has two sub-options:
 - a. *No* technology validation ties to the Constellation Program (current approach for LRO and RLEP2).
 - b. *With* technology validation ties to the Constellation Program.
2. Early mission(s) carry communication infrastructure that services the mission on which it is launched and subsequent robotic missions. Technology validation ties to the Constellation Program could be a subordinate decision; however, since this option is more expensive than deployment option 1, the additional investment strongly argues in favor of making the investment pay off by coupling it with the Constellation Program. This has three sub-options:
 - a. Provide short-term infrastructure (i.e., less than 3 years) that allows use of lightweight, single string spacecraft (modification to LRAS Baseline in which multiple small satellites are launched instead of one medium class orbiter);
 - b. Provide medium-term infrastructure (i.e., the 6-year duration of the Lunar Robotic Phase) that requires use of mid-size, dual string spacecraft (LRAS Baseline);
 - c. Provide long-term infrastructure (i.e., 10+ years) enabling the spacecraft to be used to support both the Lunar Robotic Phase and the Human Sortie Phase, requiring use of large, dual string spacecraft (LRAS Alternate #1).

Coupling the robotic communication and navigation (C&N) with the Constellation Program offers significant potential for risk mitigation and cost reduction during the human sortie and outpost phases but carries additional costs during the lunar robotic phase. The degree of technology validation plays a role in determining the benefits and the extent of programmatic interdependency created. Technology validation can include: measuring performance of prototype hardware and software, space qualifying components; demonstrating C3I Interoperability capabilities; and calibrating navigation techniques.

Determination of the sub-option for Option 2 is also partly a technology validation factor. Option 2a, using a 3-year spacecraft, provides an opportunity to fly an upgraded payload on the replacement spacecraft needed to cover the 6-year Lunar Robotic Phase. Option 2b does not provide the upgrade opportunity but costs less than Option 2a. Option 2c provides the least opportunity to evolve the C&N capability, costs less than Options 2a or 2b, and pre-positions at least one relay spacecraft prior to the first Constellation flight. Cost estimates of these options were performed as part of prior SCAWG studies.

Option 2c would couple the lunar robotic and human sortie phases for C&N operations. Thus, the LRAS spacecraft providing C&N capability for lunar robotic phase would have to meet performance requirements for the human sortie missions as well as either being placed into an orbit that satisfies coverage for both phases or is capable of being moved from its lunar robotic phase orbit to its human sortie phase orbit. The first case constrains the choice of orbits but does not impose additional mass penalties, while the second case relaxes the orbit choices but may impose significant additional burden on propellant (100-300 kg) for performing a plane change.

Summary and Recommended Next Steps

The Lunar Robotic Architecture provides a set of missions that satisfies a prioritized set of lunar precursor requirements, including opportunities to reduce risk related to implementing communication and navigation capabilities for the Constellation Program.

A lunar relay capability was included in the baseline architecture as a mid-sized spacecraft co-manifested with the second robotic mission (lander) in 2011. The relay satellite will require some level of redundancy of critical systems to provide reliable communication and navigation services to RLEP missions. The relay will provide several Mbps data rate likely at S-band, and be compliant with the Constellation C3I Interoperability Specification. The navigation payload will enable minimally two-way Doppler tracking of another robotic spacecraft and would support recovery of far-side gravity measurements (assuming availability of a low-orbiting spacecraft to track). The spacecraft and expendables will be sized to provide a 5-6 year lifetime in order to support the three landers identified in the baseline LRAS architecture. Development of the lunar relay spacecraft and primary payload is considered low risk, as all technologies have a high TRL, however the development timeline for such a spacecraft must start immediately to support availability for a 2011 launch.

In addition to the primary payload, the lunar relay should provide opportunities for technology demonstration payloads such as new antenna designs, optical communication elements, beacons, reconfigurable radio devices, and/or science payloads. The lunar relay satellite will also allow important experience operating a relay satellite and utilizing it for tracking and navigation functions at lunar distances.

A goal for the robotic lunar relay should be to realize a maximum level of extensibility to the eventual lunar relay satellites that will be deployed to support Constellation missions. In addition to providing the foundation for Constellation ground infrastructure and operational procedures, the robotic relay satellite may actually implement and demonstrate the specific communication frequencies and protocols specified in the Constellation C3I spec.

An important aspect of the LRAS communication and navigation architecture is a policy or set of guidelines for the advantageous use of secondary communication and tracking payloads on robotic precursor missions, thereby incrementally developing a communication and tracking infrastructure. This approach has been demonstrated very successfully at Mars with the incremental establishment of the Mars Network. The mission cost delta of a secondary payload may be as much as an order of magnitude less than the cost of a dedicated communication and navigation satellite. The suite of secondary payloads that may be launched with an orbiter, lander, or a residual asset (lunar landing platform, lunar delivery vehicle) includes a full up orbital communication and navigation relay payload, a navigation beacon or transponder, and a landed relay payload. For example, an orbiter can carry all three types of packages, while a lander platform may carry a beacon transmitter/transponder or a relay for landed assets. Even if the communication or tracking capabilities afforded by secondary payloads do not fully satisfy Constellation requirements, they may still provide significant advantage in terms of redundancy and flexibility.¹

Improvements to the lunar gravitation model will be important to executing precision landings and for providing robustness in the face of contingency situations for human missions to the moon. The LRO mission proposes to obtain moderate improvements in lunar far-side gravity errors through utilization of laser ranging measurements to the surface recorded on the far-side; however, significant improvements in lunar gravity models will require a dedicated gravity science investigation. The Japanese Selene mission promises to provide some additional lunar gravity science improvements, and NASA has been in negotiations with the Japanese to share data from this mission. Dedicated lunar gravity science proposals, providing the best opportunity to improve lunar gravity models, have been made to recent SMD calls. A novel proposal has also been made in which the Wind spacecraft could be maneuvered to the Earth/lunar L2 point and used to collect two-way Doppler data to the LRO spacecraft, thereby improving knowledge of lunar far-side gravity. Since the LRO mission will provide only a small improvement in the current

¹ See LCNS white paper.

lunar gravity knowledge and the LRAS architecture does not include a second robotic orbiter, a priority should be assigned to evaluating these and other options for improving lunar gravity knowledge to ensure this requirement will be met before lunar sortie missions begin.

Some key drivers for the lunar relay implementation were recognized to be undefined or at a low level of maturity, including:

- What will be done on the Moon (Doug Cooke study)? What is the specific Constellation mission manifest (landing locations, dates)? Is global communication coverage required, or only coverage focused on a particular landing site of interest, such as the lunar south pole?
- Detailed Constellation communication and tracking requirements for polar or backside landings, and for coverage of critical events.
- Detailed communication and tracking requirements for robotic precursor missions.
- Formal list of Constellation risks to be mitigated through robotic missions.

A high priority should be assigned to achieving better definition of some of these driving issues.

Launch of a relay satellite as a co-manifest with a fixed lander in 2011 or 2012 already represents a short design cycle. Pre-phase A activities should be initiated immediately to begin the processes of forming a team; defining and maturing requirements; vetting the spacecraft lifetime and deployment strategy against the evolving robotic and constellation mission set; maturing the architectural views for the robotic lunar relay; developing an operations concept; and identifying technology demonstrations that may be included as secondary payloads. Some key studies that should be conducted as a follow-up to the LRAS report include:

- Additional Team X or IMDC studies to investigate the range of spacecraft sizes/capabilities to support both robotic and Constellation requirements.
- A trade study to assess the requirements for radiometric beacons, either for landing aids or for navigation aids for orbiting vehicles and relay satellites.

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7. LCNS Beacon Whitepaper (draft), 11 April 2006
8. Draft Lunar Secondary Policy Statement

Appendix E. Mapping (Visual, Topographic, and Resources)

As NASA considers the next phase of lunar exploration, reflection on historical expeditions of exploration provides a touchstone for the utility of maps created in the course of exploration. The United States Exploring Expedition conducted by the U.S. Navy during 1838-1842 provides allegorical evidence of the enduring value of maps and related geographical data. The detailed maps of the South Pacific and geographical information generated during the course of this scientific expedition were still in use by the U.S. military a century later in planning and executing military campaigns during World War II. In short, it is difficult to overestimate the enduring value of applying state-of-the-art measurement techniques to best characterize terrain characteristics and distribution of potential resources in the form of maps and geographical information systems products.

Further lessons on the value of maps and their development come from comparisons of historical examples to help set the context and expectations for the current era of lunar exploration. Just as Lewis and Clark led the Corps of Discovery to first visit the vast, uncharted regions of the western U.S., the Apollo missions to the Moon (supported by launches of 21 robotic precursors, including impactors, orbiters, and landers) proved that it is possible for man to land on the Moon and safely return to Earth. Following Lewis and Clark's monumental achievement, more than four decades of intensive surveying of the western frontier ensued, which led to the development of the transcontinental railroad, the discovery of mineral resources, and the settlement of agricultural areas that have formed the bedrock of the most successful economy in history. Apollo did not lead to more detailed exploration of the Moon. Clementine in 1994 and Lunar Prospector in 1998 have marked the early stages of our return to the Moon and have provided resource maps that compel further exploration, particularly of the polar regions.

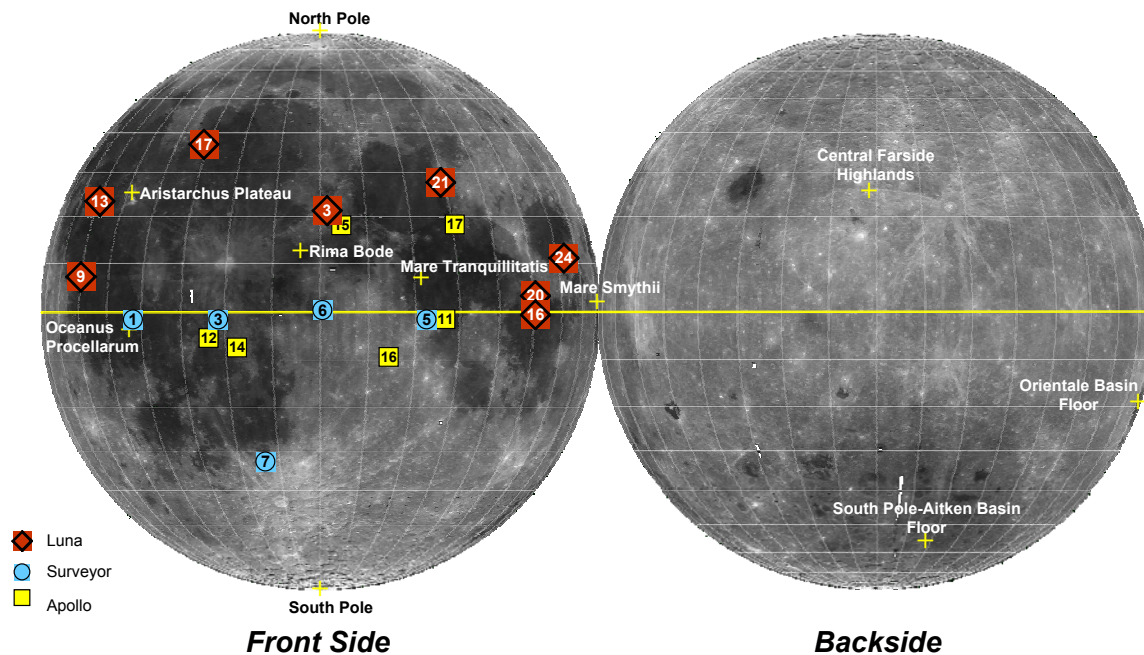


Figure E-1. Priority exploration sites identified by ESAS

The map resulting from the data gathered by remote sensors of a modern orbiting platform is the representation of knowledge from the combined data products. The lunar map should be a tool to enable cost-effective exploration both "now" and when routine human access is possible. A map that combines human-scale imaging of the Moon with the fine-scale topography provides both the context for safe exploration as well as information for autonomous precision navigation of both precursors and human landings. For near-term utility, an accurate depiction of the lunar topology will assist with the design and employment of low-cost landers that will provide "ground truth" to calibrate data collected from orbiting sensors. Adding resource information, to the extent that it can be assayed by remote sensors (and later calibrated by landers), would be a key ingredient for making assessments of future commercial activities on the Moon.

While the long-term value of commercial activities that are stimulated by detailed knowledge of the Moon is difficult to assess at this time, the near-term pay offs are clearly articulated through the satisfaction of requirements such as those levied on the Lunar Reconnaissance Orbiter (LRO). The LRO data products assimilated in a map of the Moon provide the following:

- recognition of landing hazards as well as those that could challenge EVAs
- navigation-scale topography in a center-of-mass coordinate frame at scales suitable to enable cost-effective and safe surface-based exploration
- information about local environments that could pose challenges to human spaceflight systems and habitats (i.e., cold surface temperatures, dust, steep slopes, huge boulders)
- information about local resources worthy of further in-situ reconnaissance

Intelligent exploration planning requires a map that is effectively a "data frame" in which information from a variety of sources can add to a more complete understanding of the lunar environment. The basis for a map with enduring value is a global topographic grid that is geodetically tied to the Moon's center-of-mass. Enabling navigation solutions for landing on the moon and planning traverses across the lunar surface are obvious valuable attributes of a map, but additional information tied to the grid makes a map strategically important for long-term utilization. Attributes of the grid resolution as will be provided by LRO are altimetry with sampling density at finer than 1 km globally and finer than 100m in the polar regions (i.e., latitudes above 75 degrees N or S), with vertical accuracy of ~ 1-3 m RMS, depending on local tilts and slopes. The map further consists of a global 100m scale visible wavelength imaging dataset under suitable illumination for documenting shadowed regions, with layers that represent the seasonal variation of illumination of the polar regions where permanently shadowed regions prevail. The LRO map includes a global, sub-km scale dataset of temperatures with finer than 5K accuracy, spanning the range from ~ 40K to 400K, with finer approximately 300m-range sampling in the polar regions as defined above. The LRO map further includes a simplified global oxygen resource map at scales finer than 500m that utilizes color ratios (UV/Vis) to isolate regions of elevated ilmenite and other titanium oxides in the lunar soils potentially suitable for ISRU extraction studies. Finally, the LRO map includes a 10km scale global dataset that describes the hydrogen (H) abundance of the sensible upper 1m of the lunar regolith at sensitivity levels as fine as ~ 100-200ppm, and an associated neutron albedo dataset that describes the neutron environment out to energies as high as 10 MeV (for purposes of human adaptation to the deep space lunar environment).

Layered on top of the LRO map will be hundreds to thousands of sub-meter resolution image mosaics that describe candidate human landing sites for sorties and outposts and associated hazards due to blocks and local landscape features. Each of these 10x10 km² samples will formally identify all 1m scale features within each candidate landing zone from which probabilistic models of landing hazards can be derived.

The definition of the LRO map will engage all baseline LRO datasets and will be augmented by an

affiliated global gravity field for the Moon, embellished by far-side gravity acquired by whatever means possible (e.g., potentially to include far-side tracking of the JAXA Selene sub-satellites, as well as topography-gravity solutions from LRO/LOLA).

Other datasets, as they become available, can be layered on top of the LRO map, as needed, including regolith characteristics from microwave imaging experiments on Chandrayaan, Mini-RF technology demonstration on LRO, and other orbiters. A global mineralogical map at sub-km resolution can also be attached, as acquired from the NASA-developed hyperspectral mineral mapper (MMM) onboard the ISRO Chandrayaan orbiter.

Another perspective on the value of the LRO base map is the sophistication and complete global coverage of the Moon when compared to the Apollo-era robotic precursors. During Apollo, 9 Rangers (6 of which failed), 7 Surveyors, and 5 Lunar Orbiters characterized the moon globally at a 4 km scale and at a limited number of equatorial landing sites at the 2-3m scale. (They achieved higher resolution at the lander sites.) As was evidenced by the Apollo 11 landing experience, a great deal of piloting skill was needed to avoid unanticipated hazards. For the cost of a single LRO mission, the knowledge of the Moon will greatly increase beyond what was learned during Apollo and the Clementine and Lunar Prospector missions that flew in the 1990s. As this enhanced understanding of relevant facets of the lunar environment is translated into exploration hardware development, the value of mission success and appropriate development cost can be realized for spacecraft and lunar habitat designs that are neither “over-designed” due to uncertainty in landing areas and habitat site nor “under-designed” in not accounting for hazards.

Finally, the value of perceiving the Moon as another world in the context of human exploration will be realized through a map that layers multiple levels of information to spark popular imagination. By presenting facts about the lunar environment that leverage modern information technology, such as “Google Moon,” school children, academics, and stakeholders of future space commerce interests can study the Moon from a variety of perspectives and levels of sophistication. The value of stimulating education and potential business opportunities to maintain a growing economy cannot be solely attributed to a map, but one can argue that such a map may be the necessary catalyst to popularize the lexicon of exploration among NASA’s stakeholders: the American public.

Appendix F. Environment (Dust and Radiation)

The Moon provides a harsh environment: nearly non-existent atmosphere; intense ultraviolet (UV), galactic, and solar cosmic radiation; lack of liquid water; abrasive corrosive, potentially toxic dust; and large temperature extremes. In many ways, the environment of the Moon is even harsher than that of Mars, without the mitigating factors of an atmosphere to block radiation and an increased gravity environment. Assessment of lunar environmental effects on systems (human and physical) is an essential aspect of the development of innovative technologies, knowledge, capabilities, and infrastructures to support human and robotic lunar exploration. Apollo astronauts accepted a high level of risk for their short (3-4 days) stays on the Moon that will not be acceptable for longer sortie missions. Even more technical challenges must be overcome for longer-duration stays on the lunar surface; based on Apollo experiences, dust and radiation may be limiting issues that will determine the extent of capabilities and mission durations that can be supported. Requirements related to the lunar environment include better characterization of the environment, better understanding of its interactions with humans and machinery, and demonstrations of technologies for monitoring and mitigating environmental impacts. Environmental characterization should occur as early as possible in the robotic lunar architecture in order to provide significant risk mitigation and other benefits for the Constellation Program by informing technology development and the design of vehicles, suits, life support, and other systems.

Appendix G. In-Situ Resource Utilization (ISRU)

Even before the Apollo landing, in-situ resource utilization (ISRU) was proposed as a means to reduce to cost of establishing a permanent presence on the Moon. It has been extensively studied since that era and was a key element of the Space Exploration Initiative in the early 1990s. The value of ISRU is in exploiting local resources to provide materials that would otherwise have to be “imported” from Earth. Uses include consumables such as O₂ for life support and propellant, construction materials such as metals and glass, and radiation protection from regolith.

Overall, the elemental composition of the lunar soil (regolith) resembles that on earth: about 40% oxygen, with large amounts of silicon, aluminum, and iron, and lesser amounts of other metals such as titanium. While the mineralogical composition is also similar (complexes of metals and metal oxides), the exact form and concentrations can be somewhat different. Nonetheless, many processes have been developed to extract both oxygen and metals from the lunar regolith – typically producing ceramic or glass construction materials as useful byproducts. The merits of the individual processes are principally in their compatibility with lunar operations such as: sensitivity to size and composition of feedstock; consumption of material not readily available on the Moon such as carbon electrodes; energy consumption; and mass of a production plant and its ability to be shut down and re-started. Regolith also contains dissolved gasses primarily deposited by the solar wind that are easily extracted by heating the soil to about 700°C, though they are quite scarce. Hydrogen and helium are two of the more “abundant” gasses, but only exist in concentrations of about 50 ppm. As such, large-scale hydrogen production from lunar soil to complement oxygen production is not practical.

More recently, there has been indirect evidence of possible deposits of ancient cometary water that has survived in some isolated, permanently shadowed “cold traps” near the lunar poles, such as on the floor of the Shackleton crater. The evidence is principally based on abnormally high concentrations of hydrogen – much higher than the background – measured by the Clementine spacecraft in 1994. Subsequent radar data from the Arecibo observatory in Puerto Rico did not fully confirm the Clementine data, leaving the question open to further resolution. If water exists in sufficient concentration and near enough to the surface to be easily “mined,” it represents a potential source of rocket fuel (e.g., H₂/O₂). However, if it exists it is in a thermal environment of about 40K (-233°C), making mining operations potentially very difficult. In all cases, the potential value of ISRU is in the “economics”, not the “physics.” This, in turn, depends on the scale of human lunar presence, the frequency of transits between Earth and the Moon (or other destinations), and the specific composition of the lunar soil near an outpost.

The LRAS study assumed the eventual use of in-situ lunar resources to support lunar surface operations – and potentially, in the long-term, broader exploration goals – to be an integral part of the overall exploration program. However, it was not considered required for lunar sorties mission or an initial outpost. Further, the study considered two classes of ISRU: (1) a large facility nominally producing 50 to 100 metric tons/yr of O₂ from regolith, or possibly O₂ and H₂ from water existing in a permanently shadowed crater and alternately, and (2) a small-scale ISRU facility with a production capacity of about one to several metric tons/year. As a reference, the ESAS study determined that about 8 metric tons of O₂ would be needed to fuel two LSAM ascents per year and about 1 metric ton/year as a backup to closed-loop life support.

For all large-scale operations, critical constraints include plant mass, power consumption and amount of feedstock per kilogram of product. This tends to limit the range of processes and raw feedstock options that can practically be considered. Typically, production facilities could weigh tens of metric tons, process thousands of metric tons of material and consume about 50 kW to 100 kW, likely requiring a

nuclear reactor power source. Furthermore, if a reactor is required it will have to be shielded from the outpost at a distance of up to 2 km, either by natural features or a constructed shield (e.g., a regolith berm). All of this limits site options and greatly increases the need for in-situ validation of critical mining/production/storage technology and engineering systems. These requirements are carried over from the pre-landing robotic missions to the human sorties missions.

Small-scale ISRU operations can be more “forgiving,” putting fewer constraints on feedstock, requiring only about 10 kW to 15kW, (which could likely be achieved with solar power), and weighing less than a metric ton. This further relaxes constraints on where an outpost can be placed. However, for an equatorial site nuclear power may still be required to prevent frequent, harmful start/stop cycles imposed by the long lunar night. For both large and small-scale ISRU, mass and power requirements for water extraction from a 40°K environment may be much higher than for regolith.

About midway through the study, the LRAS team concluded that constraints and requirements for large-scale ISRU dominated the site location and subsequently the requirements on robotic precursor missions. As such, initial large-scale ISRU required an early commitment to build an outpost and focused most of the attention of robotic precursor mission requirements on supporting this decision. This was not the case for small-scale ISRU. As such, the LRAS study deferred the issue of large-scale ISRU and focused only on small-scale ISRU. Small-scale ISRU could remain an open option for sortie missions as well an outpost for all likely lunar locations, and would not preclude eventual large-scale ISRU operations. If an early decision was made to commit to large-scale ISRU, the scope of robotic precursor and sortie missions could be expanded and adjusted to accommodate this requirement.

As such, the LRAS study considered resource mapping to be a primary near-term requirement. While small-scale ISRU operations can be carried out in one form or another anywhere on the Moon, some regions are richer in different feedstock than others and may favor a different production process. For, example, Apollo found the lunar highlands to have much higher titanium content (e.g., ilmenite) than the lowlands. Mapping is much more critical if the use of lunar water-ice is considered a viable option, since its existence, if any, is in very limited spots. Lunar water restricts siting to the lunar pole regions, and more specifically requires a suitable human landing site be found near enough to a shadowed cold trap to make operations reasonable. This raises the question if ISRU is economically or operationally reasonable if water is accessible and sufficiently abundant but requires placing a sortie/outpost in a thermally hostile location. The question of lunar water can only be answered by direct in-situ survey. Remote sensing cannot provide the detail on depth of deposit or constituency in the soil (e.g., dispersed throughout or distributed as lunar “ice cubes”). Studies by Paul Spudis of JHU/APL indicate up to twenty samplings up to a few hundred meters apart are needed. Options for obtaining these data include a rugged, robust – and likely expensive – rover, possibly requiring an RTG power source; a rocket-powered hopper requiring development of a re-usable, deep-throttling engine; or a series of sophisticated surface-penetrating probes launched or dropped from orbit in the crater. All of these would be “firsts,” including digging or drilling up to two meters into 40K, highly compacted regolith.

For ISRU involving regolith, studies by the Johnson Space Center indicate small robotic demonstration plant could be developed in about 5 years. It would weigh about 50-100 kg and require less than a kilowatt of power. The same likely holds true for water-bearing material delivered from a crater. A full-scale plant could be developed in about 10 years. Accepting the general opinion that a demonstration plant should be about 20% the capacity of a full-scale plant, a small-scale ISRU facility is about the right size to serve as a demonstration for a possible large-scale facility beyond 2025.

A summary of lunar ISRU issues and conclusions considered by the LRAS is given below:

- Focused on O₂ from regolith or H₂/O₂ from water-ice in a lunar cold trap (crater)

- Two general classes of ISRU were considered:
 - Large-scale (several tens of metric tons of O₂/year; principally for propulsion)
 - Processing method very dependent on site and feedstock
 - Drives outpost: extensive specialized infrastructure for mining, processing and storing weighing a few to several thousand metric tons requires nuclear power, about 50-100 KW
 - This option was deferred
 - Small-scale (up to several metric tons of O₂/year for LSAM and life support; only about 1 metric ton/year needed for life support)
 - Site-independent, multiple processing options for regolith
 - Does not drive outpost site or infrastructure: a few hundred kilogram plant and several KW of power will produce several metric tons/year
 - Solar power suitable (nuclear may be desirable to prevent harmful start/stop cycles if subject to lunar night)
 - Small demonstration plant on the order of 50 to 100 Kg, can be developed in about 5 years
 - Full production capability requires about 10 years to develop

The biggest issue is the question of water: how much (if at all), how deep, how far away how to extract and transfer, and how equipment will survive at 40K.

- An ISRU demonstration mission to the Moon can wait until 10 year prior to capability need date.

Key questions include:

- Is H₂O present and accessible for ISRU/ISPP?
- Can O₂ be extracted effectively from lunar regolith at the planned outpost site?
- How is it best to validate these processes: rate, power, storage, and supply?
- Can regolith be excavated, manipulated, transported, and processed effectively?
- Is the assumed few-hundred-watts required for demonstration mission correct?
- Is the best scale for an ISRU demonstration mission at least 20% of full scale?
- How much is required to support environmental closed-loop life support?
 - A few-kilowatts for 8MT/y production rate of O₂?
- What are the tradeoffs and determining factors to consider in deciding between nuclear and solar power?

- Both electrical and thermal energy can be supplied by solar power if near constant illumination site.
- Is nuclear required to maintain ISRU reactor temperature throughout day/night cycle?
- 50-100 kWe is required for 50-100 MT/y in-situ propellant production of O₂.

Appendix H. Nuclear Power

The LRAS study team investigated the power requirements for lunar exploration in order to understand the potential robotic precursor requirements to support the development of lunar power systems. Several-kilowatt-class power will be required for small in-situ resource processing (less than 1 Mg/y O₂ production from regolith) and early nighttime operations at a human lunar outpost. Full-up outpost operations, which may involve significant processing of lunar resources (8Mg/y O₂ production from regolith), will require on the order of 15-70 kW_e, depending on the process used. This power could be supplied by solar energy, transformed into electricity using photovoltaics (PV), which is an attractive option below 50 kW_e, especially if the solar arrays can be sited in a region of the lunar surface that receives near constant illumination. An important requirement for a robotic precursor mission is the confirmation of the existence of these “peaks of eternal light,” and the mapping of their boundaries. Above about 50 kW_e the physical area required for the solar arrays becomes an issue of feasibility. However, the stated objective for the lunar exploration architecture is to enable sorties and an eventual outpost anywhere on the surface of the Moon. Away from the constant illumination region, the solar PV option is not mass-competitive with a nuclear reactor if energy storage is required to provide 50 kW_e during the 14-day lunar night.

A significant issue that will drive the decision between solar PV and nuclear power is the relative cost of the two systems. Recent cost estimates for a Fission Surface Power System (FSPS) are in the \$3B range, motivating the consideration of a foreign partnership to provide this capability. The feasibility of this partnership, as well as the credible potential to significantly reduce the cost of a domestic fission surface power system development, is currently under study. Alternatively, Radioisotope Power Systems (RPS) are an option to provide a few kilowatts of power (up to about 5 kW_e per unit). These kilowatt-class RPS systems could be brought by each sortie mission and left at the outpost site, eventually accumulating enough power capability to enable a human stay through the lunar night with minimal operations. Ultimately, however, a fission surface power system will be required to enable robust operations (greater than 100 kW_e) anywhere on the lunar surface.

Recent advances in Stirling power conversion technology offer opportunities to provide significant, affordable nuclear power using radioisotope energy sources. The only feasible radioisotope for use as a source of space power and heat is Plutonium-238 (Pu238) due to its long half-life (87 years), and relatively benign radioactivity (primarily alpha-particles which are easily shielded, and low-energy gamma rays). Pu238 is very expensive and in limited supply both domestically and internationally. The Advanced Stirling Convertor (ASC) project, run by the Science Mission Directorate (SMD), has recently demonstrated 38% heat-to-electricity conversion efficiency at the convertor level. Highly efficient Stirling power conversion is a key to increase power output from plutonium General Purpose Heat Source (GPHS) modules, and extend the limited Plutonium supply. Using ASC technology, about 1 kW_e can be produced from 7.8-8.4 kg of Pu238 fuel contained in 13-14 GPHS modules (each GPHS contains .6 kg of Pu238 fuel, produces 250 W_{th}, and costs about \$2M in FY06). The Advanced Stirling Radioisotope Generator (ASRG ~ 160 We BOL) is in development in SMD using the ASC technology.

Lunar surface validation of the ASRG flight system would be an important achievement. Currently the ASRG is caught in the usual advanced capability trap, where no potential user will consider employing it before it is flight proven, and it cannot be flight proven until someone commits to using it. By flying and ASRG on a lunar robotic mission as a primary or back-up power source, NASA would validate the advanced power system, making this new capability available for lunar robotic exploration, and

potentially for other planetary surface and deep space missions. Furthermore, by validating advanced Stirling dynamic power conversion in space using a radioisotope power source, NASA would support the development of larger, kilowatt-class systems, and perhaps the development of Stirling convertors for a fission reactor system.

Large-scale ISRU and outpost operations will require hundred-kilowatt class power, likely requiring a surface nuclear reactor. During the Exploration Systems Architecture Study (ESAS) a fission surface power system was studied and developed as a concept. Several issues were identified for further study, including the potential need for precursor missions. These were: the potential use of regolith for radiation shielding, the need to move the FSPS from the cargo lander and emplace it, and the end-of-life disposal of the FSPS. If regolith can be used as shielding it could save up to 10,000 kg of shielding mass that would otherwise need to be transported from Earth. Options for using regolith as shielding include: burying the reactor; “berming” regolith around the reactor; building a wall around the reactor using regolith in bags or in sintered bricks; and using natural terrain features between the reactor and the crew. Precursor missions are required to answer feasibility questions for: digging holes, moving significant amounts of regolith, sintering regolith bricks, and mapping the terrain in sufficient detail around potential outpost sites to identify advantageous terrain features where a reactor could be emplaced. The second issue identified during ESAS was the challenge of moving large, heavy masses on the lunar surface. Specifically, precursor missions will need to determine what soil bearing and traction is possible in order to design a surface mobility system. The final ESAS issue deals with disposal of the reactor at end-of-life, which likely requires burying the reactor, and has the same associated issues as burying the reactor for shielding purposes. In the development of a surface nuclear power system, the effects of lunar dust on power systems and potential strategies to mitigate those effects would also require data from robotic precursors.

Appendix I. Opportunity Science

The fundamental goal of the *President's Vision for Space Exploration* is “to advance U.S. scientific, security, and economic interests through a robust space exploration program.” NASA has clearly assigned the responsibilities and authorities to its Mission Directorates for achieving this. These responsibilities apply for planning future exploration architectures, formulating and implementing missions, and analyzing mission results. NASA makes architectural decisions concerning the implementation of the Vision for Space Exploration at the Agency level, and the Science Mission Directorate (SMD) has a vital role to represent the Space and Earth science interests of the United States’ scientific community. NASA conducts missions at the Mission Directorate level. SMD is responsible for formulating and implementing missions and for conducting scientific research and analysis that advance space and earth science interests. The Exploration Systems Mission Directorate (ESMD) is responsible for formulating and implementing missions and for conducting research and analysis that enable human exploration, including associated life and microgravity research.

Planning Future Exploration Architectures

The advancement of U.S. scientific interests is part of the fundamental goal for the Vision for Space Exploration. Future exploration architectures all require choices across a zone of intersection between science and exploration. Responsibility for planning future exploration architectures is held at the Agency level.

ESMD is responsible for refining these exploration architectures and for developing the exploration systems that implement these architectures. SMD is responsible for representing U.S. earth and space science interests in the development of these architectures and systems. For example, SMD participated in the Agency-level Exploration Systems Architecture Study (ESAS) and the Program Analysis and Evaluation (PA&E) Lunar Robotics Architecture Study (LRAS).

To expand and validate SMD’s capacity to represent U.S. earth and Space science interests, NASA is committed to setting the science priorities jointly with the community via the National Academies of Science and the NASA Advisory Council (NAC):

- 1) SMD had tasked the National Research Council (NRC) to conduct a study of lunar science priorities in the context of its recent decadal survey for solar system science and NASA’s emerging exploration plans.
- 2) SMD and ESMD are jointly supporting the external Lunar Exploration Analysis Group (LEAG) under the NAC.
- 3) SMD is assisting ESMD and the NAC on exploration-related workshops and requests for information. Understanding these science priorities is also essential for guiding the formulation and implementation of science missions.

Formulating and Implementing Missions

SMD and ESMD formulate and implement space missions to fulfill their respective responsibilities. SMD’s responsibility is to formulate and implement missions that advance U.S. space and earth science. These science-driven missions address science that enables human space exploration as well as science that is enabled by human space exploration. SMD sets priorities for missions in the context of the Agency’s and the nation’s overall science priorities. NASA is committed to setting priorities jointly with the science community. It is absolutely vital that NASA draw upon the judgment of active members of

the research community in setting these priorities. NASA is dependent on the continued support and assistance of the broader science and industrial communities to successfully implement the highest priority science in a cost-effective manner.

SMD's science program includes missions to the planned destinations for human explorers. For the Moon, SMD competitively selected through the *Discovery* program the Moon Mineralogy Mapper (M3) as a Mission of Opportunity. M3 will fly on the Indian Space Research Organization's (ISRO) *Chandraayan-1* Mission. SMD will issue by the end of the year a request for studies of innovative "suitcase science" instruments and packages to accompany future lunar astronauts. For Mars, the *Mars Reconnaissance Orbiter* recently entered Mars orbit. This science mission will be followed by the launches of *Phoenix* in 2007, the *Mars Science Laboratory* in 2009, and the *Mars Scout* in 2011. Mars missions beyond 2011 are outlined in a community "road mapping" activity now undergoing review by the National Academies of Science. SMD's science missions will produce new knowledge that will be useful to ESMD for future human exploration. SMD works with the ESMD to seek the most effective approach to address the intersection of science and exploration priorities.

ESMD's responsibility is to formulate and implement missions that enable human exploration. ESMD is implementing precursor missions to obtain the strategic knowledge necessary to design and implement human exploration systems. ESMD's Robotic Lunar Exploration Precursor (RLEP) missions, including the Lunar Reconnaissance Orbiter (LRO) currently approaching mission confirmation, are focused on the essential knowledge needed to reduce risks and understand the design constraints for future lunar exploration systems operating on the Moon. SMD is supporting ESMD in a role similar to traditional program science role, by providing scientific advice on instrument selection, development, and related matters.

Analyzing Mission Results

NASA will take a shared approach to analyzing science and exploration mission results. SMD will support the analysis of scientifically valuable results from ESMD missions. Science enabled by exploration activities will compete in the same prioritization process as the rest of the SMD science program. For example, if confirmed and implemented, the results of the Lunar Reconnaissance Orbiter will address priority science objectives identified by the NRC in the 2002 decadal survey. As these data become available SMD will support their scientific analysis by funding proposals selected through openly competed solicitations for SMD's science research programs.

ESMD will support the analysis of results from SMD missions that address exploration system needs. Science lays vital foundation for exploration by providing the framework for the strategic knowledge that enables exploration. For example, SMD's Heliophysics research program is undertaking the scientific study of the radiation environments beyond the Earth's magnetosphere where future space explorers will live and work. It is vital to understand this environment in order to design missions and systems to mitigate its effects. SMD's Planetary Science research program will answer basic science questions about the Moon, Mars, and other solar system destinations, providing results that will inform the essential engineering decisions concerning the design and implementation of human exploration systems.

The *Vision for Space Exploration* provides a fresh impetus for the science that enables exploration and for the science that is enabled by exploration. Human exploration of space beyond low Earth orbit is a core element of NASA's strategic plan. SMD has a vital role in advancing the scientific interests of the United States as part of this national vision.

Appendix J. Space Radiation and Space Weather

Introduction

Space radiation and its effects on humans and on robotic systems are key drivers for the development of exploration systems, and will remain so for the foreseeable future. Mitigating space radiation risks will almost certainly require a mixed strategy of structural, operational, and countermeasure solutions. Enabling structural and operational solutions will place requirements on both the lunar and non-lunar robotic architectures. The LRAS team does not believe that the implementation of space radiation countermeasures will result in significant lunar robotic architecture requirements. For the lunar robotic architecture, the LRAS team has determined that these requirements are not near-term drivers, but can be addressed as part of the initial human sorties. However, the implications for the non-lunar robotic architecture were beyond the scope of the LRAS. The LRAS team recommends that the NASA Exploration Systems, Space Operations, and Science Mission Directorates (ESMD, SOMD, and SMD) jointly study and understand the requirements for space weather robotic systems needed to safeguard human voyages to the Moon, Mars, and other destinations.

Space Weather and the Space Radiation Environment

The overall space radiation environment can be categorized by the steady state galactic cosmic ray radiation, the relatively steady state solar wind, and the infrequent and difficult to predict large-scale coronal mass ejections that result in an intense flood of high-energy (Mev) protons and electrons. This last, time-variable aspect of the space radiation environment is referred to as “space weather.” For operations on or near the Moon, another consideration is secondary: backscattered albedo radiation from the lunar surface.

Galactic cosmic rays are ubiquitous, with very low particle fluences, but energies as high as several Gev/nucleon and a composition that spans the atomic spectrum. Hydrogen is the most abundant element though iron is typically considered the most “dangerous” when its higher atomic weight is considered. Overall, cosmic rays are not acutely lethal but they are very difficult to stop and over the long-term represent a measurable health risk. The steady state solar wind is far denser than cosmic rays but easier to stop. The primary solar risk is from large-scale coronal mass ejections that result in an intense flood of high-energy (Mev) protons and electrons. These events are infrequent, sometimes hard to predict and can be lethal, though they typically last only a few days.

Mitigation of Space Radiation Risks

Mitigation against cosmic rays and the steady state solar wind will almost certainly require a mix of structural shielding, operational procedures that limit time spent in less shielded environments, and possibly medical countermeasures to reduce or repair the damage caused by these particles.

Mitigation against large-scale coronal mass ejections will also require a mix of structural shielding, operational procedures, and countermeasures. Structurally, astronauts outside Earth’s protective magnetic field for extended periods must be provided with safe havens from these “storms.” Operations during the entire flight of human lunar missions will have to provide the assured capability to detect or predict impending events in time to alert the astronauts and allow them to secure themselves within their safe havens. This may place operational constraints on the astronaut activities such as EVAs and rover traverses. Options for robotic systems that increase warning time or reduce the time required to shelter

and protect astronauts will enhance the operational flexibility of future human exploration missions, increasing their value in addressing the fundamental goal for the Visions for Space Exploration.

Lunar Robotic Architecture Requirements

Providing structural protection against the steady state solar and galactic radiation fluence and providing safe havens against solar “storms” may have implications for the lunar robotic architecture. Future studies may indicate that the best way to provide this protection is to utilize in-situ materials for shielding. This will require considerable lunar robotic activity over an extended period to: measure and validate the shielding properties of the lunar regolith; test and demonstrate the capacity to adequately manipulate the regolith; and emplace and bury the sheltered structure. It is the assessment of the LRAS team that NASA does not need to begin these efforts prior to the first human return to the Moon. These efforts are not near-term drivers for the lunar robotic architecture.

Providing the assured operational capability to detect or predict impending events in time to alert and secure the astronauts implies demands for both the lunar and non-lunar robotic architecture. For the lunar robotic architecture, the primary implications are related to 1) providing timely alerts to astronauts regardless of their activity or location, and 2) safely conveying astronauts to a safe haven or robotically delivering safe havens to the astronauts. The first implication is covered by the requirement to provide continuous two-way communication with the astronauts, regardless of their location or activity. The second implication is closely coupled to the detailed design of the human systems; the LRAS team finds that the requirements for robotic companion systems to assist astronauts in sheltering from solar storms will have to be developed as part of the detailed lunar sortie and outpost design.

Providing medical countermeasures to reduce or repair damage caused by space radiation are not expected to have significant robotic architecture implications.

Non-Lunar Robotic Architecture Implications

As stated in the Study Charter and Scope section of this report (section 2.2): “LRAS discussed but did not address other robotic missions such as space weather sentinels that orbit close to the Sun.” As mentioned in the introduction of this appendix, the LRAS team recommends that the NASA Exploration Systems, Space Operations, and Science Mission Directorates (ESMD, SOMD, and SMD) jointly study and understand the requirements for space weather robotic systems needed to safeguard human voyages to the Moon, Mars, and other destinations. As a start to defining the focus of this study, the LRAS team has identified an initial set of study questions:

- What are NASA’s needs regarding operational space radiation and space weather for human and robotic missions as a function of time? How well defined are these needs for the various stages of exploration, and what additional work is needed to develop clear space radiation requirements for future exploration systems?
- What are the current and projected future limits on the predictability of large-scale coronal mass ejections? What science measurement and modeling investments are needed to accelerate the advancement of knowledge based upon the needs of human exploration missions? What technology investments are needed to implement these missions and advance this modeling capability?
- Are there exploration-driven instruments that should be considered for future missions throughout the solar system that would help in gathering statistics or other data related to future human exploration operations? To what extent is the ESMD-funded Radiation Assessment Detector (RAD) flying on SMD-funded Mars Science Lander (MSL) a precedent and model for how these instruments could be implemented?

- How quickly do large-scale coronal mass ejections move from the Sun to the Moon (and to other locations in the solar system where humans will be operating)? What is the natural variability in the velocity of these ejections? Is there such a thing as “space climate” or “seasons” on the sun, periods in which coronal mass ejections are certain to be slower or nonexistent, providing reduced operational constraints and greater flexibility for lunar EVAs and other operations?
- How early can these ejections be detected, and what robotic systems enable early detection and warning? What capabilities are within the scope of current and planned science missions? What operational capabilities for assured detection and warning are beyond the scope of research missions?

Appendix K. Prior U.S. Missions to the Moon

The Office of Space Science (OSS) managed the robotic data acquisition and used two previously funded independent programs to support the Office of Manned Spaceflight's (OMSF) Project Apollo. Fueled by the Cold War competition and the Soviet Luna program, Project Ranger began as a hard-lander exploration program led by the Jet Propulsion Laboratory (JPL) in 1959 to provide data on the lunar surface. JPL also started the Surveyor program as a soft-lander and orbiter mission to validate landing technologies and increase lunar environmental knowledge by 1960. Due to the initial failures in Project Ranger and development difficulties in the Surveyor program, OMSF requested OSS/JPL to prioritize Project Ranger and the Surveyor lander in late 1962. OSS eliminated the Surveyor orbiter because the projected data gained by an orbiter mission would apply to Apollo mission planning rather than the spacecraft design. In late 1963, the Lunar Orbiter program officially began at Langley Research Center (LaRC) in response to the high resolution photography necessary from the Requirements for Data in Support of Project Apollo (15 June 1962) and the August 1963 release of the request for proposals (RFP). The Boeing Company won the contract to build the Lunar Orbiter spacecraft that carried a flight photographic system with nominal 1-meter and 8-meter resolution from a 46-kilometer altitude. While the Surveyor landers essentially superseded the data from Project Ranger, the Surveyor experiments provided significant lunar surface information about mechanical properties and physical characteristics that complemented the high-resolution Lunar Orbiter images.

During the Space Exploration Initiative (SEI), Johnson Space Center's (JSC) Explorations Program Office evaluated the combined Surveyor and Lunar Orbiter robotic missions as "adequate" for Project Apollo and "absolutely necessary" in providing landing site surface characteristics and topography data. The JSC report also concluded that the Surveyor and Lunar Orbiter data did not affect Apollo component design, but played an important role by confirming the basic lunar surface model used for designing Apollo hardware and preparing topography models for landing site evaluation and crew training.

Overall, the Apollo robotic precursors applied not to the initial vehicle design, but to mission operations planning and design confirmation. For imaging, the SEI team recommended 1-to-2 meter resolution as adequate, but noted that resolution of greater than 1 meter seemed unnecessary.

Mission	Launch Date	Type
Ranger 3	01/62	Hard Lander (missed the moon)
Ranger 4	04/62	Hard Lander (hit farside)
Ranger 5	10/62	Hard Lander (missed the moon)
Ranger 6	01/64	Hard Lander (TV failed)
Ranger 7	07/64	Hard Lander
Ranger 8	02/65	Hard Lander
Ranger 9	03/65	Hard Lander
Surveyor 1	05/66	Soft Lander
Lunar Orbiter 1	08/66	Orbiter
Surveyor 2	09/66	Lander (crashed)
Lunar Orbiter 2	11/66	Orbiter
Lunar Orbiter 3	02/67	Orbiter
Surveyor 3	04/67	Soft Lander
Lunar Orbiter 4	05/67	Orbiter
Surveyor 4	07/67	Lander (crashed)
Explorer 35	07/67	Orbiter
Lunar Orbiter 5	08/67	Orbiter
Surveyor 5	09/67	Soft Lander
Surveyor 6	11/67	Soft Lander
Surveyor 7	01/68	Soft Lander
Apollo 8	12/68	Orbiter (1 st Human to orbit the moon)
Apollo 10	05/69	Orbiter Test LM in lunar orbit
Apollo 11	07/69	Mare Tranquillitatis (1 st manned lunar landing)
Apollo 12	11/69	Oceanus Procellarum (near Surveyor 3 spacecraft)
Apollo 13	04/70	Flyby (aborted mission after onboard explosion)
Apollo 14	01/71	Fra Mauro (1 st highland mission)
Apollo 15	07/71	Hadley-Apennines (1 st use of rover, extended LM)
Apollo 16	04/72	Descartes (Lunar highlands)
Apollo 17	12/72	Taurus-Littrow (Last Apollo landing, 1 st geologist lunar astronaut)
Explorer 49	06/73	Lunar Orbit radio astronomy explorer (RAE B)

Clementine	01/94	Orbiter (BiStatic radar indications of polar water)
Lunar Prospector	01/98	Orbiter (Neutron Spectroscopy indications of polar "water")

Table L-1. NASA Moon Landers (Source: Lunar Reconnaissance Orbiter Project Office)

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Appendix L – Acronyms

APL	Applied Physics Laboratory
ASC	Advanced Stirling Convertor
ASRG	Advanced Stirling Radioisotope Generator
ATP	Authority to Proceed
BUR	Bottoms-Up Review
C3I	Command, Control, Communication, and Intelligence
C&N	communication and navigation
CaLV	Cargo Launch Vehicle
CARD	Cost Analysis Requirements Document
CER	cost-estimating relationship
CEV	Crew Exploration Vehicle
CHF	critical heat flux
CLV	Crew Launch Vehicle
COSPAR	Committee on Space Research
CRISM	Compact Reconnaissance Imaging Spectrometers for Mars
DRM	design reference mission
DSN	Deep Space Network
DTE	direct-to-Earth
ECANS	Exploration Communication Navigation Systems
ECLSS	Environmental Control & Life Support System
EDS	Earth Departure Stage
EELV	Evolved Expendable Launch Vehicle
ESAS	Exploration Systems Architecture Study
ESMD	Exploration Systems Mission Directorate
EVA	extra-vehicular activity
FOM	figure of merit
FSPS	Fission Surface Power System
GCR	galactic cosmic ray
GNC	guidance, navigation, and control
GRACE	Gravity Recovery and Climate Experiment
GRC	Glenn Research Center
GSFC	Goddard Space Flight Center

HEND	High Energy Neutron Detector
ICSAT	Integrated Cost and Schedule Analysis Tool
IMU	Inertial Measurement Unit
IPAO	Independent Program Assessment Office
ISRO	Indian Space Research Organization
ISRU	in-situ resource utilization
ISS	International Space Station
LCNS	Lunar Communication and Navigation Systems
LEAG	Lunar Exploration Analysis Group
LEO	low-Earth orbit
LIDAR	Light Detection and Ranging
LCROSS	Lunar Crater Observation and Sensing Satellite
LLO	low lunar orbit
LOI	Lunar Orbit Insertion
LPRP	Lunar Precursor and Robotic Program
LRAS	Lunar Robotic Architecture Study
LRO	Lunar Reconnaissance Orbiter
LSAM	Lunar Surface Access Module
M3	Moon Mineralogy Mapper
MCO	Mars Climate Orbiter
MER	Mars Exploration Rover
MGS	Mars Global Surveyor
MPL	Mars Polar Lander
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
MVACS	Mars Volatiles and Climate Surveyor
NAC	NASA Advisory Council
NAFCOM	NASA/Air Force Cost Model
NASA	National Aeronautics and Space Administration
NRC	National Research Council
OMSF	Office of Manned Spaceflight
PA&E	Program Analysis and Evaluation
REDSTAR	Resource Data Storage and Retrieval
RF	radio frequency

RLEP	Robotic Lunar Exploration Program
RPS	Radioisotope Power Systems
RTG	radio-isotope thermal generator
SCAWG	Space Communication Architecture Working Group
SEI	Space Exploration Initiative
SMD	Science Mission Directorate
SOMD	Space Operations Mission Directorate
SRB	solid rocket booster
TDRS	Tracking and Data Relay Satellites
TOR	Terms of Reference
UHF	ultra-high frequency
VHF	very high frequency

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