Research Objectives for a Lunar Outpost Architecture with Extended Range Rover Capability

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Abstract - *Numerous mission concepts have been proposed for human lunar settlements dating from the end of the Apollo program up to the present day. These concepts have varied from Apollo-like walking sorties, to extended range rovers, to full-up surface bases. This paper will propose research objectives for a human lunar campaign based on a south polar outpost and multiple pressurized rovers capable of operating up to 480 km away from the outpost. Research objectives will include engineering and operations preparations for Mars missions, physiological response to low gravity, scientific understanding of the lunar environment, and pathfinding for commercial operations.*

Keywords: Lunar exploration, science, research, objectives, DTO, Detailed test objective, NSBE Visions for Human Space Flight Working Group.

1 Introduction

The Space Special Interest Group of the National Society of Black Engineers has commissioned a *Visions for Human Space Flight Working Group* to investigate technical challenges surrounding NASA human space flight and to identify an alternative path for the direction of United States human space flight. Research conducted by working group participants and documented in this paper represents volunteer labor executed on behalf of NSBE, a 501(c)3 nonprofit headquartered in Alexandria, VA. NSBE coordinates the inputs of aerospace industry experts to propose innovative solutions to complex technical challenges facing the United States. This paper, in coordination with six other Working Group papers, collectively encompasses the product of the Working Group's efforts. Recommendations, results, and conclusions in this paper do not reflect NASA policy or programmatic decisions.

1.1 History of Lunar Programs

In the wake of the Soviet Union's initial space successes of launching the Sputnik satellite in 1957, and sending Yuri Gagarin in orbit over the Earth in 1961, President Kennedy directed NASA to successfully send a man to the Moon and return him safely within a decade. [12] This led to the Apollo program, which conducted the first lunar landing in 1969. However, just a year later, three of the ten intended Apollo missions were cancelled due to budget [6] and in 1971 President Nixon considered (though ultimately decided against) cancelling two more. [3] The program was cancelled a year later in 1972, by which time the Apollo program had completed six of seven attempted lunar landings.

There have been numerous proposals for a return to the Moon since that time. Examples include Lunar Base Synthesis Study (1971) [9], Lunar Surface Research Base (1984) [10], Space Exploration Initiative 90-Day Study (1989), Lunar Campsite (1991) [7], First Lunar Outpost (1992), LUNOX (1993), Early Lunar Access (1993), Liquid Oxygen Augmented Nuclear Thermal Rocket (1994), and Human Lunar Return (1996) [20]. Most recently, NASA initiated the Constellation lunar program under the second President Bush, which was cancelled by President Obama.

1.2 Research as a Rationale for Lunar Presence

US Congressman Mel Watts (D-NC) stated that "they [NASA] need to be telling us what the case is for exploration of the Moon or stars or other planets. Politicians shouldn't be telling them that; they need to be telling us that and making the case for it and telling us what the potential is for discoveries that will be beneficial for us in our day-to-day lives...Without them making that case I think the level of support will diminish over time." [16] Thus, the federal budgetary priority placed upon any lunar outpost architecture is proportional to the Congressionally perceived research value.

This strongly implies that a key metric for assessment of a lunar architecture is its ability to support identified research objectives for that architecture. If the resources to conduct said research are cut from the spacecraft for mass, cost, or schedule reasons then the resulting value of that spacecraft may no longer merit continuing its development. Therefore, a key program success criterion is the accommodation of research objectives by the overall architecture.

The research objectives also help define the program's exit strategy. Using the Apollo program as an example, the key research objective was to demonstrate the technology to transport a man to the surface of the Moon and return him safely. This was met in Apollo 11. Subsequent Apollo flights demonstrated repeatability, but President Nixon could make a legitimate claim that the Apollo program had successfully accomplished its primary objective and should not continue indefinitely with no further purpose. Similarly, the space shuttle listed assembly of the International Space Station as a primary objective. Cancellation of the shuttle program was tied to completion of this objective.

1.3 Primary Research Objectives

The primary research objectives for the lunar outpost architecture proposed by the NSBE Visions for Human Space Flight Working Group fall into three distinct categories:

- Engineering and operations preparations for Mars missions
- Pathfinding for commercial operations
- Scientific discovery

These objectives are based on a lunar outpost located at the South Pole, specifically on the rim of the Shackleton Crater, supported by two pressurized rovers with an exploration range of 480 km from the outpost. [22] The approximate location of Shackleton Crater is indicated by the crosshairs on Figure 1, based on imagery from the Lunar Reconnaissance Orbiter's DIVINER instrument. [5]

This entire region lies within the South Pole Aitken basin region, which has been identified by lunar orbiting probes as having a different composition than any of the samples obtained from the Apollo or Russian unmanned Luna missions, or any of the lunar meteorites recovered to date. [4]

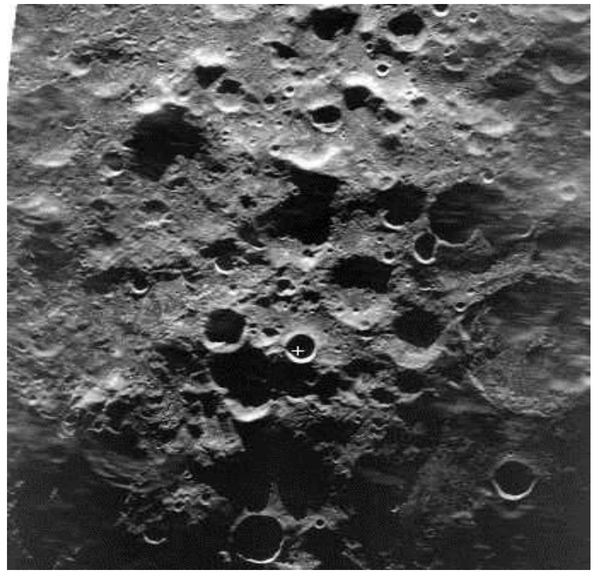

Figure 1. 400 km x 400 km map of lunar South Pole

2 Engineering and Operations Preparations for Mars Missions

While some have advocated a direct path towards Mars, most engineers believe that a Mars mission has a much greater likelihood of success if precursor missions are used to validate surface hardware and operational techniques. It is therefore arguable that the only responsible approach is to conduct precursor surface missions prior to committing humans to the risk of a Mars expedition.

2.1 Implications of Mars Requiring Precursor Preparation

The minimum communication delay occurs when the Sun, Earth, and Mars are positioned such that a straight line connects the center of all three, with Earth and Mars on the same side of the sun. At this point, Mars is one-half of an astronomical unit from Earth and one-way radio or laser communication takes four minutes to travel between the planets. The opposite of this is when the Earth, Mars, and Sun are on the same line, but Mars and Earth are on opposite sides of the sun. The distance between the two planets is 2.5 astronomical units and one way radio or laser communication time would theoretically take twenty minutes. However, this would require transmission through the sun, which is impossible. Relay satellites, perhaps at the Earth-Sun, Mars-Sun, Venus-Sun, or Mercury-Sun L4 or L5 points would be required, in all cases increasing the communication time further. These communication delays render two-way voice and video communication impractical and invoke more of a text messaging, email, social media paradigm. While such a paradigm was less acceptable a decade or two ago, there is still very little experience operating complicated machinery in an unforgiving environment under such communications restrictions.

The distance between Earth and Mars also has significant implications for the time the crew will spend in transit between the two planets. For instance, the notional 2037 Mars trajectory examined in Mars Design Reference Architecture 5.0 involves an outbound trajectory of 174 days and an inbound trajectory of 201 days, with a 539 day surface mission. [2] The United States has no experience with missions of such duration and even Russia has only a handful of Cosmonauts who have conducted missions greater than one year in length. Additionally, there is great uncertainty within the medical community regarding how crew can be protected against Galactic Cosmic Radiation during a transit of such length.

Substantial energies are required to place a spacecraft on a trajectory that departs the vicinity of Earth and travels to the vicinity of Mars. Because of this, once committed to a Mars trajectory it is very difficult to abort and return to Earth ahead of schedule. With most chemical propulsion architectures and many electric propulsion architectures it is either impossible or requires as much time as the original trajectory. In other words, if there is a crew injury or a vehicle failure, there is no escape. You must remain on the original mission timeline.

Further, it is difficult to estimate the reliability for equipment used aboard any spacecraft. Virtually every spacecraft ever flown has examples of entirely unexpected failures. ISS and Hubble have experienced control moment gyro (CMG) failures, space suits have exhibited various failures, the Falcon 9 booster has experienced engine failures, and the first generation station treadmill (TVIS) exhibited numerous hardware failures. Many of these failures were later resolved in future designs or in design modifications, but having an opportunity to drive out these failures in a less critical mission scenario than a Mars mission is preferable.

Finally, all Mars mission scenarios assume a very small number of expeditions. This limit in the repeatability of Mars missions suggests that many science opportunities will be one-time events, with very limited possibility for a repeat of any aborted science activity. Consequently it is important to drive out all of the operational concepts as well as implementation challenges in the most realistic simulation environment as possible, before committing to the actual Mars mission.

2.2 Spacecraft Verification and Validation

Essentially, the lunar outpost plays a key role in validation testing for a Mars surface base. Clearly there are significant differences between the lunar and Martian surfaces (e.g. gravitational force, surface material composition, atmosphere, etc.) but there is some commonality, even in the areas of difference. The Moon offers a unique low gravity data point, enabling a point of comparison between terrestrial (1G) and microgravity (0G) experience. This and other similarities allow a lunar surface outpost to perform validation tasks for a Mars surface outpost.

Component reliability can be monitored in the lunar architecture, as many components will be similar or identical between the lunar and Mars surface habitats [22]. Instrumentation of surface vehicles and landers combined with in-flight maintenance and fabrication research will provide a basis for reliability data to be used in Mars mission safety analyses.

Additionally, engineers will be able to verify subsystem functionality against lunar requirements in an operational setting. With proper consideration for the deltas between the lunar and Martian environments, this operational testing of spacecraft subsystems will provide greater understanding of how these subsystems will perform (or fail) when used on a Mars mission. Some subsystems may even be able to be tested on the lunar surface under simulated Mars conditions (e.g. glove box or centrifuge environments)

Finally, integrated system validation for deep space exploration will be able to be performed using the lunar base as an analog mission facility for Mars exploration. Full Mars mission expeditions can be evaluated as one or more lunar expeditions.

2.3 Preparatory Detailed Test Objectives (DTOs)

In general, DTOs should be incorporated into the lunar architecture where it is possible to verify or validate items that are mandatory or enabling for successful Mars missions. This might include technologies that are not needed for lunar missions due to a shorter lunar stay than a Mars mission or the ability to abort a lunar mission and return to Earth early. These technologies may be part of a lunar spacecraft subsystem, but their failure does not lead to loss of crew in a lunar context. An example might be a closed loop ECLSS system. Failure in a transit habitat en route to Mars could result in loss of crew, but failure in a lunar surface outpost might only result in a mission abort to Earth or an increase in logistics flights.

2.3.1 Engineering DTOs

Engineering DTOs address key technical capabilities that will increase performance or lower risk for a Mars mission. Lunar missions enjoy the advantage of both shorter flight times and near-anytime aborts, enabling missions that leave Earth more accessible in the event of emergencies. Engineering DTOs may also be performed for purposes of enabling future lunar missions of greater duration or with greater performance objectives.

2.3.1.1 Closed Air and Water Loop ECLSS

Closed loop life support is important even for a lunar outpost, but the proximity to Earth allows for greater levels of resupply or heavier subsystem mass than would be desired for a Mars mission. Lunar DTOs may test hardware and techniques to increase the rate of closure beyond that employed in the outpost's ECLSS.

2.3.1.2 In-flight Fabrication

In a Mars architecture it will not be possible to fly spares for every component in the surface architecture. Nor is it possible to predict with certainty which items will experience failures. Engineering DTOs in the lunar outpost can improve crew capabilities to restore subsystem failures through fabrication and manufacturing.

2.3.1.3 Teleoperations

Large robots such as the NASA JPL ATHLETE cargo manipulator and small robots similar to Mars rovers may be employed on both the lunar and Martian surfaces. Figure 3 shows a prototype ATHLETE in the foreground as it might be controlled by a crew member aboard a Space Exploration Vehicle rover, shown in the background. Control of these robots from a surface base may introduce unknowns not yet anticipated by vehicle designers. Teleoperations DTOs will help to derive the capabilities of surface teleoperations.

Figure 3. ATHLETE cargo manipulator with SEV pressurized rover in background

2.3.1.4 Human-Robotic Proximity Interaction

Another robotics issue is the interaction of robots in close proximity to human crews. NASA-developed robots like the Robonaut are intended to share tasks with human crews and can interact side by side. Even pressurized lunar rovers can have robotic modes where a rover follows an EVA crew. While significant testing would certainly occur on Earth and on ISS, lunar surface testing will provide additional lessons to improve system confidence prior to Mars missions.

Figure 4. Desert testing of human-robotic interaction

2.3.1.5 In-situ Food Production

Current food techniques for space food involve prepackaged food that is stored at room temperature. The NASA Space Food Laboratory currently rates such food systems to only be good for about eighteen months before expiration. Given that Mars mission profiles can be on the order of twenty-eight months, food advancements are a key requirement for Mars missions. A variety of in-situ food technologies may be explored in a lunar outpost architecture including plant growth, fish breeding, and other small animal breeding. The following figure shows a plant growth chamber inside the mockup Deep Space Habitat at Johnson Space Center. This chamber produced sufficient lettuce and radishes for the crew to enhance (but not replace) their prepackaged food for a couple of meals per week. Larger chambers could explore greater percentages of fresh food and develop mitigations for as-yet-to-be experienced food production contingencies.

Figure 2. Plant growth chamber inside the Deep Space Habitat mockup at NASA Johnson Space Center

2.3.1.6 Mars Centrifuge

On Earth there are very few methods available for the approximation of Mars-equivalent gravity, limited essentially to free-fall facilities, parabolic aircraft flight, and load-relief testbeds. On ISS, centrifuges can be used to simulate Mars gravity, but only for small payloads.

The Moon, however, offers the ability to create very large centrifuges, large enough to place an entire module under Mars-gravity with the ability to sustain this gravity for months without interruption. Figure 5 shows an image from a YouTube video [13] demonstrating the basic principle of a large centrifuge, using a car in a non-scientific application.

Figure 5. Car using centripetal acceleration as a centrifuge in an entertainment application

As an example, a lunar rover chassis could propel an experiment module (perhaps a pressurized rover or a repurposed logistics module) at a velocity of approximately 5 meters per second (11.18 mph) in a 15 meter diameter track with a 26 degree bank – arguably using smoothed out walls of a crater – to act as a centrifuge to create Mars-equivalent gravity. If connected to a continuous power supply, such a rover could operate in a Moon-based Mars centrifuge essentially indefinitely. This could enable fluids, life science, subsystems, and even habitability testing on the lunar surface at Mars gravity conditions, though there would need to be accommodation for coriolis and vestibular effects.

2.3.1.7 Road Construction

Both the Moon and Mars have documented hazards associated with their regolith. An important engineering DTO involves the construction of paved roads on the lunar surface. If rovers and EVA crew can traverse frequently traveled routes on paved roads, maintenance issues related to regolith can be reduced substantially. Road construction DTOs would presumably involve autonomous systems operating both in the outpost vicinity (e.g. between a designated landing pad and the outpost) and as far as distances up to 500 kilometers from the outpost, such as at remote sights of interest for repeat visits (e.g. mineral deposits for mining operations and a route between such deposits and the outpost).

2.3.2 Operations DTOs

2.3.2.1 Autonomous Mission Replanning

Since the beginning of the space program, human space flight missions have been heavily planned by ground operators. Mars crews will require greater autonomy without flight control teams on Earth managing every hour of the crew’s day, particularly given the communications delay on Mars. Long duration missions on the Moon will enable flight teams to become more comfortable with handing crew schedules over to the in-space crew, enabling the lunar crew to make both tactical and strategic planning decisions.

2.3.2.2 Split Crew Operations

The lunar architecture involves a fixed outpost with multiple surface rovers, as shown in Figure 6, creating an option to explore operational DTOs with split crew. Rover excursions away from the outpost may involve split crews in any of several modes: two crew in one rover and two crew in the outpost, two crew in one rover and two crew in the second rover, or two crew in the outpost and one crew in each rover. Even with all four crew in the outpost, split crew operations may involve placing the crew on different shifts or scheduled crew activities that place crew members in separate areas of the outpost for extended periods of time.

Figure 6. Dual surface rovers during desert field testing

2.3.2.3 Crew and Mission Productivity

Operational DTOs may also involve measuring crew and mission productivity under varied conditions. These may include availability of Earth communication, crew decision making autonomy, sequencing of rover excursions, or in-situ versus Earth returned sample analysis.

2.3.2.4 Rover Maximum Range Extension

The dual-rover strategy assumes that in the event of a rover failure the other rover can recover the crew and return to the outpost. During the Apollo program in the late 1960s and early 1970s, the crews had either no rover at all or a single unpressurized rover. The rover had the ability to drive much further than the crew could walk, but if the rover had broken down, the crew would have been stranded, resulting in loss of life. Consequently, Apollo traverses had a “walk back” limit imposed on them. In other words, the astronauts could only drive as far away from the lunar lander as they could reasonably be expected to walk back unassisted if the rover had failed. This has been generally accepted as a very short distance, on the order of 10 km.

The dual-rover strategy extends this range by providing two pressurized rovers that operate in conjunction. Thus, if any one rover fails, the second one can recover the crew and immediately drive back to the outpost or lander. During the Constellation program, the Lunar Surface Systems project established a 24-hour period as the maximum return distance in such a scenario and conducted a desert analog mission demonstrating four crew in a single rover for a 24-hour period. At the rover’s predicted speed [22] this yields a range of about 480 km.

However, the lunar outpost can conduct operational DTOs to extend this range even further, whether by means of pre-positioning supply caches or man-tended habitats along select routes, supplemental onboard habitation capability, or other means. The greater this range can be extended, the more surface exploration can be conducted.

2.3.2.5 Surface to Surface Communication

With crew and hardware in separated locations on the lunar surface, operations DTOs will be needed to develop the proper networks and protocols for surface to surface communication. A rover could lose line of sight communication with a habitat simply by entering a valley or crater. Exploration of lava tubes, canyons, or other surface features on both the Moon and Mars will present similar challenges. DTOs will test the effectiveness of remote terminals, scheduled loss of communication and check-in periods, and other techniques to address surface communications challenges.

2.3.2.6 Parallel Deep Space Missions in Different Destinations

The former NASA Constellation program was based on missions to the Moon, Mars, and asteroids, but presumed that these missions would occur in serial. This DTO is overarching across lunar, Mars, and asteroid destinations and develops and validates the capabilities to conduct these missions in parallel, rather than in series.

2.3.3 Emergency Services DTOs

2.3.3.1 Abort to Orbit and Abort to Surface

Abort DTOs will develop procedures and techniques should it be necessary to evacuate the surface outpost and return to orbit or to evacuate an orbiting asset and take refuge on the surface. An abort to orbit is a premature departure from surface with a resulting wait in space before departure for Earth. This DTO requires a positioned asset in lunar vicinity such as a Cislunar habitat.

An abort to surface is an off-nominal departure from a transit vehicle resulting in either a planetary landing outside of the intended landing zone or a loss of return capability with a forced surface stay awaiting a rescue flight from Earth. Many abort to surface scenarios are presently non-survivable simply due to lack of resources to keep the crew alive. However, DTOs may validate new capabilities that can enable a crew to survive the initial abort and the resulting surface stay awaiting rescue.

2.3.3.2 Module and Element Recovery

Module and element recovery DTOs can develop and validate techniques to recover spacecraft elements that have been damaged through some failure or incident. For instance, the Mir space station suffered the permanent loss of the Spektr module and damage to one of its solar arrays when the Progress M-34 unmanned cargo ship collided with the module in 1997. [19]

Figure 7. Solar array on Mir Spektr module with damage caused by the Progress collision

Loss of a pressure vessel would be unacceptable in a Mars mission scenario. DTOs could evaluate procedures to repair damaged hulls, restore power generation, or other techniques to be applied after the initial failure response to fully recover a damaged system.

2.3.3.3 Search and Rescue

Search and Rescue DTOs can build the capability to respond to emergencies occurring away from the lunar outpost. This may include off-course landings, disabled rovers, crew injuries, or lost/separated EVA crew members. These are potential hazards to split crew operations, but may be of even greater importance in a future developed lunar scenario where multiple international or commercial operators have separate facilities on the Moon. An emergency at one facility may benefit from a response from another.

2.3.3.4 Medical Care

NASA currently defines levels of medical care associated with local and deep space missions. However, there are non-survivable gaps within any of these levels and certain injuries that would be treatable on Earth cannot be treated in space. A key DTO relates to expansion of this level of capability, developing hardware and processes to treat injuries that currently cannot be treated in anticipated deep space medical facilities.

2.4 Mars Mission Simulation

2.4.1.1 Surface Phase

The surface time of a Mars mission can be simulated on the lunar surface as a long duration outpost mission. This provides an evaluation of Mars protocols and procedures in relatively safer environment, where anytime abort and short transit times can enable recovery from any contingencies that may develop.

2.4.1.2 Transit Phase

The transit phase cannot be directly simulated on the Martian surface, but can be simulated in conjunction with a deep space facility positioned in Cislunar space, such as in a distant retrograde orbit.

3 Pathfinding for Commercial Operations

3.1 Commercial ISRU Development

If there is to be a commercial future for the Moon, there must at some point be practical opportunities for lunar industries. Numerous commercial opportunities have been suggested for the lunar surface, based on data recovered from the Apollo program and robotic lunar missions. Examples of processes with potential commercial application include concrete production, oxygen production, hydrogen production, aluminum production, iron production, glass production, and solar cell fabrication. [23] Lunar research to verify and validate cost-effective processes related to these potential lunar industries will open the door to lunar commercial industry.

3.2 Civilian-Government Crew Operations

The National Aeronautics and Space Act directs NASA to “seek and encourage, to the maximum extent possible, the fullest commercial use of space.” [18] This implies a civilian presence on the Moon.

Many Americans assume that one of the eventual outcomes of having a space program is that at some point in the future there will be widespread civilian activity in space. Tourism is often cited, but ultimately this could include mining platforms, commercial settlements, townships or even colonies.

The presence of commercial activity in a given location in space does not imply the absence of government activity in that same location any more than the presence of commercial activity on Earth implies the absence of government on Earth. The allocation of roles and responsibilities of industry and government in space is, however, a valid question and the Moon provides a unique opportunity to research this role allocation. [23]

3.2.1 Governance

An important function of government is to protect the rights and safety of individuals. While companies may to some extent perform these functions, it is often in response to federal regulations. A local government presence on the Moon provides a safety network for commercial employees. Governance roles on the Moon might include base administration, safety regulations, law enforcement, personal protection, mission planning, and disaster response. It should be noted that this does not imply which government agencies or even nations would be involved in such roles, only that they may occur and should be evaluated in a lunar outpost context as forward planning for eventual expansion of human presence on the Moon and elsewhere in space.

3.2.2 Technical Services

The government may also supply key technical services in an international, commercial lunar architecture. Should lunar commercial industries emerge, they will eventually be accompanied by service industries and other ventures that may be less capable of independent technical support (e.g. restaurants, churches, entertainment venues). Potential technical services for such commercial enterprises may include fault detection, engineering maintenance and repair, inspections, and safety certifications. A lunar outpost can begin to investigate the processes and constraints that would scope the level of technical support government might provide to industry on the Moon.

3.2.3 Medical Recovery

On Earth, many medical/health related services are provided by the governments of various nations. Even where private medical services are available, they generally exist alongside government counterparts. Some of the functions that may be valid deep space government functions include search and rescue, environmental monitoring, routine and emergency medical care, hospitalization, and rehabilitation. The latter two are often overlooked in spacecraft design studies and are important given that a crew member may sustain a serious, but treatable injury. However, there may be a recovery period before such a crew member is sufficiently healthy to return to Earth aboard a capsule such as an Orion, Dragon, or Soyuz.

3.2.4 Research

Many specific fields of research are detailed within this paper and for the sake of brevity will not be repeated here. While a given company may choose to conduct internal lunar research, it is important that there be fundamental research on the Moon that is not proprietary corporate knowledge, but is instead within the public domain. Consequently, Moon-based research will always be an important government function.

3.2.5 Planetary Protection/Quarantine

Should returning missions from Mars face initial quarantine on the Moon? This may apply to missions whether they are government or commercial in origin. On Earth, any airplane or ship entering the United States from another nation must pass through customs, with one of the concerns being to prevent the entry of harmful life. If a Mars mission finds evidence of life, can that life be exposed to Earth's ecosystem? Should any returning crews and samples should be housed on Moon for a specified period of time to ensure no adverse exposures? Oversight of this process and any necessary testing of samples would clearly be a government function and should not be a commercial responsibility.

4 Scientific Discovery

The lunar outpost on the rim of Shackleton Crater is located within rover range of numerous other significant lunar features, including Mount Malapert and the following craters: Caebus, Nobile, Shoemaker, Haworth, de Gerlache, Sverdrup, Faustini, Amundsen, and Scott. The relative positions of many of these features are shown in figure 8.

The diversity of these terrain features will enable a variety of scientific research activities, including both research of the Moon and its composition and research of non-lunar phenomena that uses this location on the Moon as a platform for research.

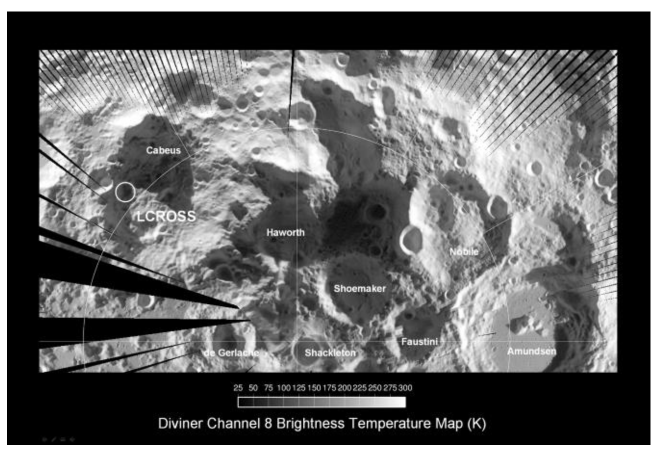

Figure 8. Lunar features near Shackleton Crater [5]

4.1 Life Science Research

The primary purpose of lunar life science research is to understand the effect of the lunar environment (gravity, radiation, atmospheric pressure and composition, etc.) on life processes. Most of our life science knowledge is based on terrestrial environments, with a growing body of knowledge also coming from microgravity environments aboard the International Space Station and to a lesser extent other spacecraft. Low gravity environments such as the Moon and Mars represent significant unknowns. Life science research generally falls within categories of plant science, animal science, microbiology, environmental science, and human physiology.

Plant research includes large scale growth of fruits and vegetables for non-critical crew consumption as well as investigative research for plants such as thale cress, rapeseed, and yeast. Animal research includes insects such as beetles and fruit flies, small invertebrates such as rats and mice, and avian eggs (Japanese quail). Microbiology research includes bacteria, viruses, and other microbes, as well as plant and animal cells and tissues. Environmental research includes radiation and toxicology. Human physiology research includes anthropometry and ergonomics, bone, cardiology, EVA physiology, exercise physiology, neuroscience, nutrition, pharmacotherapeutics and immunology, and behavioral health and performance. [21]

4.2 Earth Science Research

Earth sciences can benefit from the ability of scientific instruments on the lunar surface having field of view of the whole disc of the Earth. This enables scientific research requiring global, continuous full-spectrum views of Earth, detection and analysis of time dependent atmospheric composition, ecosystem monitoring, cryosphere monitoring, atmospheric structure, and a full-spectrum signature of a life-bearing planet. [8] This will allow studies of the Earth's vegetation, polar caps, weather, and other environmental conditions. Observations may also be conducted of pollution, RF signal generation, and other man-made phenomena on the Earth.

Integrating Earth imagery from the Moon with heliophysics and aernomical data could potentially help to better understand the interactions of space phenomena with Earth weather processes. Observation of the Earth from the Moon may also help to refine techniques for detecting Earth-like extra solar planets. [14]

4.3 Astronomy and Astrophysics Research

Scientists have recommended the lunar far side for decades as an ideal location for establishing telescope arrays. In addition to visual light telescopes, radio telescopes should also be deployed as they in particular have unique opportunities due to the lack of interference from radio signals of Earth origin. [17] Radio telescopes on the near side of the Moon will enable studies of the sun that are not possible on Earth. [15] New equipment is needed on the lunar surface to continue gravitational physics research begun in the Apollo program with laser range finding. [11]

4.4 Lunar Science Research

The Moon and Earth form the only two-body planet-moon system in the solar system (given Pluto's reclassification as not a planet). As such, there is unique scientific interest in study of the Moon itself.

Lunar geology research, including seismology, geochemical remote sensing, geophysics, and gravimetric techniques, may help answer questions related to the origin and formation of the Moon and its interior structure. [1] There is interest in studying certain geophysical properties for enough time to encompass at least one lunar tidal cycle (six years). [8]

5 Research Accommodation in a Proposed Lunar Architecture

As previously stated, it is important to ensure that the lunar architecture is capable of accommodating the research objectives that justify its existence. While much of this research is ongoing, it is unreasonable to assume that it can all be completed – or even initiated – in a single crew mission. Each research objective is therefore mapped to begin in a specific flight in the lunar architecture.

The NSBE Visions for Human Space Flight Working Group recommends a total of ten lunar surface missions in parallel with NEA and Mars expeditions. [22] The NEA missions are shown extracted from the recommended mission manifest in Table 1.

Table 1. Recommended Lunar Surface Missions

Year	**Mission (includes transit times)**
2027	95-Day Lunar Expedition
2028	365-Day Lunar Expedition
2029	730-Day Lunar Expedition
2031	730-Day Lunar Expedition
2033	860-Day Mars Dry Run at Lunar/DRO/NEA
2035	730-Day Lunar Expedition
2037	730-Day Lunar Expedition
2039	730-Day Lunar Expedition
2041	730-Day Lunar Expedition
2043	730-Day Lunar Expedition

5.1 Unmanned Cargo Deployment Flights

Beginning in 2025, a series of unmanned cargo flights are launched to the lunar surface to deploy the surface outpost. As soon as each component is activated, data collection will begin to establish component reliability histories and subsystem functionality data. This will be important in conducting risk management analyses for Mars expeditions. Additionally, the robotic assets will be controlled remotely from Earth to execute some outpost assembly tasks, enabling researchers to begin a series of teleoperations DTOs. It should be noted that accommodation of Earth Science research objectives requires access to an Earth-facing location, such as in the case of a polar outpost providing access to Mount Malapert near the lunar South Pole. [8]

5.2 95-Day Crew Mission (2027)

The NSBE Working Group recommends the first crew landing in 2027, after the surface outpost has been deployed. This mission will continue the previous autonomous research activities and will facilitate a closed air and water loop ECLSS DTO. It will also enable several DTOs to begin that will require multiple missions to complete, including: medical care and human-robotic proximity interaction DTOs. It will begin life science and geology research, and will begin validation of the integrated space system. Surface rover sorties away from the outpost will enable the initiation of deployments for astronomy, astrophysics, and earth science research.

5.3 1-Year Crew Mission (2028)

Continuing the research begun in the preceding missions, this mission will begin combustion and physics research. It will also begin DTOs related to in-flight fabrication, mission replanning, and split crew operations. At the end of the year-long stay, the crew will terminate the mission with an abort to orbit DTO.

5.4 2-Year Crew Mission (2029)

The first two-year mission will begin with an abort to surface DTO. It will conduct DTOs for module recovery, in-situ food growth, and search and rescue. It will also add Earth science research to the staple of crew research activity. Most of the surface stay will serve as a mission simulation of a 470-day Mars surface expedition.

5.5 2-Year Crew Mission (2031)

The second two-year mission will occur in parallel with a deep space asteroid mission, beginning multiple parallel deep space operations. In addition to previously initiated research, it will include a mixed government and commercial crew, beginning civilian-government crew operations and will begin concrete production ISRU research.

5.6 2.36-Year Crew Mission (2033)

The duration of this mission enables a full Mars mission simulation, including outbound transit, Phobos and Deimos operations, surface operations, and inbound transit. The transit, Phobos, and Deimos portions will be simulated in Cislunar/Translunar space, using a captured asteroid to simulate both Martian moons, and the surface portion will be simulated on the Moon. In addition to previously initiated research, it will begin cryogenics research and oxygen production ISRU research.

5.7 2-Year Crew Mission (2035)

This mission will begin parallel lunar and Mars crewed operations, with human crews at both destinations during this period. New research introduced during this mission includes hydrogen, aluminum, iron, and glass production ISRU research.

5.8 2-Year Crew Mission (2037)

This mission is the seventh human mission to the lunar surface and completes more than 10 years (~3880 days) of lunar surface operations. Solar cell fabrication ISRU research is initiated during this mission.

5.9 2-Year Crew Mission (2039)

This mission continues aluminum, iron, and glass production research. Specific mission activities include the formation of aluminum, iron, and glass into shaped members. This includes structural members, sheet metal, pressure vessels, window panes, brackets, and fasteners.

5.10 2-Year Crew Mission (2041)

This mission continues ISRU research by leveraging the previously explored production research to fabricate one or more aluminum and iron pressure vessels with windows and of sufficient volume for crew member ingress and utilization.

5.11 2-Year Crew Mission (2043)

This mission is the tenth lunar surface mission and marks the completion of primary research objectives and marks the exit point for this lunar architecture. This mission will install docking hardware to the previously fabricated pressure vessel and mate it to the outpost. IVA activity will include installation of ECLSS hardware, food production facilities, and monitoring instrumentation.

Assuming sufficient success with commercial pathfinding and science research, there may be government, commercial, or joint follow-on programs using assets deployed for this lunar architecture or entirely new architectures.

6 Conclusions

It has been said that the Apollo missions to the Moon have barely scratched the surface of important lunar research. This is both literally and figuratively true.

Lunar research focused on engineering development for Mars will enable human expeditions to Mars to begin in the mid 2030s. This research will enable verification and validation of many elements within the Mars spacecraft architecture and will enable testing of unique Mars-hardware in environments not possible on Earth or at the International Space Station. A key test will include a full Mars mission simulation using the lunar environment to explore the Mars mission prior to sending a crew beyond safe return and rescue range.

With long-term commercial operations being a goal, lunar research will also help to resolve some of the technical challenges associated with utilization of local lunar resources. Research will also develop some of the processes and philosophies for governance of an increasing population of humans on the Moon.

Lunar research will begin to address open questions within four major scientific domains, including life sciences, Earth sciences, astrophysics, and lunar science. Many unknowns in these arenas cannot be addressed in any location other than the lunar surface.

This research is fully accomplished during the 2027-2045 period, involving ten lunar surface missions with 16.5 cumulative years spent on the lunar surface. However, it should not be assumed that even this level of activity would fully exhaust the range of potential uses for the Moon. The goal would be that this research would not only enable Mars exploration but also identify future government lunar research priorities and initiate permanent commercial utilization of the Moon.

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