

Lunar Surface Mission Operations Scenario and Considerations

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ABSTRACT

Planetary surface operations have been studied since the last visit of humans to the Moon, including conducting analog missions. Mission Operations lessons from these activities are summarized. Characteristics of forecasted surface operations are compared to current human mission operations approaches. Considerations for future designs of mission operations are assessed.

INTRODUCTION

National Aeronautics and Space Administration's (NASA) efforts in human space flight are currently focused on the Space Shuttle and International Space Station (ISS) programs, with efforts beginning on the Constellation Program, in accordance with the President's "Vision for Space Exploration" (Bush 2004). The lunar phase of the Constellation Program begins with lunar "sortie" missions that consist of up to seven days on the lunar surface. The "sortie" missions are followed by the establishment of a lunar outpost.

Both the Space Shuttle and ISS programs are important to the development of a capability for human exploration beyond Low Earth Orbit (LEO). The ISS provides extensive research capabilities to determine how the human body reacts to long duration stays in space. Also, the ISS and Shuttle can serve as a limited testbed for equipment or entire systems that may be used on missions to the Moon, Mars, or to a near-Earth asteroid.

It has been nearly 35 years since the Apollo astronauts visited the Moon. Future space explorers will have to re-learn how to work and live on planetary surfaces, and how to do that for extended periods of time. Since the Moon is less than five days away by spacecraft, the lunar surface has much to offer as a stepping stone to other solar system destinations. Not only can the Moon be used as a testbed for planetary surface operations and equipment, but renewed lunar exploration may help address the many scientific questions about the Moon and the Earth-Moon system that remain unanswered.

During missions to the lunar surface, exploration crews will perform a wide assortment of scientific tasks, including material sampling and emplacement of automated instruments. Lunar surface mission operations include the activities of the crew living and working on the Moon, mission support from the Earth, and the operation of robotic and other remotely commanded equipment on the surface and in lunar orbit. Other surface activities will include the following: exploring areas surrounding a habitat; using rovers to collect rock and soil samples; setting up experiments on the surface to monitor the radiation environment and any seismic or thermal activity in the Moon's interior; and conducting scientific analyses and experiments inside a habitat laboratory. Of course, the astronauts will also have to spend some of their surface time "doing chores" and maintaining their habitat and other systems.

In preparation for the upcoming era of lunar exploration, NASA must design the answers to many

operational questions. What will the astronauts do on the lunar surface? How will they accomplish this? What tools will they require for their tasks? How will robots and astronauts work together? What vehicle and system capabilities are required to support the activities? How will the crew and the Earth-based mission control team interact? During the upcoming initial phases of manned lunar exploration, one challenge in particular is virtually the same as during the Apollo program: How can scientific return be maximized during a relatively short lunar surface mission?

Today, NASA is investigating solutions to these challenges by conducting analog missions. These Earth-based missions possess characteristics that are analogous to missions on the Moon or Mars. These missions are excellent for testing operational concepts, and the design, configuration, and functionality of spacesuits, robots, rovers, and habitats. Analog mission crews test specific techniques and procedures for surface field geology, biological sample collection, and planetary protection. The process of actually working an analog mission reveals a myriad of small details, which either contribute to or impede efficient operations, many of which would never have been thought about otherwise. It also helps to define the suite of tools, containers, and other small equipment that surface explorers will use.

This paper focuses on the lunar surface portion of a lunar "sortie" mission, meaning that there is no pre-established lunar base to incorporate into operations. The paper describes typical lunar surface operations, presents various operational considerations, and discusses how analog missions have addressed selected operational considerations. Some of the applicable lessons learned from the Shuttle, ISS, and Apollo programs, as well as analog missions, are presented.

SURFACE OPERATIONS CONSIDERATIONS AND CHALLENGES

Introduction

Lunar sortie missions will consist of a week or less of intensive surface EVA operations with the crew living and working out of the LSAM. Each sortie mission will be a rigorous test of the vehicles, EVA suits and equipment, and operational techniques. The desire to maximize the science return will intensify the pace of activity.

Vehicle capabilities are critical for maximizing scientific return. The needs of the scientific community should be represented during the design phase of the spacecraft and other equipment. For its part, the shuttle was designed with such a good payload support system (including mechanical, electrical, thermal, command, and telemetry interfaces) that almost no modifications have been required over more than 25 years of operations. The shuttle was also a fairly flexible vehicle allowing for the likelihood of mission success and optimization.

During the Apollo Program, there was a steady increase in scientific return per mission due to improved equipment, training, and mission operations. As political success (a single manned landing and return) became more likely, a process began in which spacecraft, space suits, and other equipment were improved or developed with science return as a goal. The most prominent examples of this are the J-Series Lunar Module (LM), the Scientific Instrument Module (SIM) bay of the Service Module (SM), the EV-A-7LB spacesuit, and the Lunar Roving Vehicle (LRV) ("rover").

These equipment changes were made because scientific return was not just a matter of returning a larger mass of lunar samples from the area immediately surrounding the LM. The strategy, rather, was focused on two areas. First, a greater variety, and not just mass, of carefully documented samples were to be collected from the landing site. This, in turn, naturally leads to longer EVAs, more EVAs, and greater surface mobility. Those requirements naturally lead, in turn, to an LM capable of longer duration surface stays, a rover, and an improved space suit. The second strategy was to use the orbiting Command Module (CM) as a platform for examining the lunar surface at large scale. This resulted in the development of the SIM bay in the SM and

the use of surface exploration to provide a ground truth calibration for the orbiting instruments (Worden, 2000).

Scientific community input had to be considered as part of these development programs. The lunar rover was a tremendously important tool for increasing scientific return on the later Apollo missions. The rover was preferred by the scientific community and it proved to be far more useful for exploration due to its ability to carry two people, which surface sampling work generally required, and a large quantity of equipment. Consider, as a simple measure of the rover's importance, that the Apollo 17 rover was driven for 22.3 miles while the Apollo 14 crew, on foot, ventured less than a mile away from the LM. The rover stretched consumables because the crew could ride rather than walk, provided accurate navigation, facilitated stowage for tools, samples, and science equipment, and supported a ground-controlled TV camera that was vital for the ability of the ground science team to support the crew.

Lessons learned during early missions may result in many improvements to equipment design, exploration methods, and habitat configuration for later missions. Changes in vehicle hardware, software, or crew interfaces ripple through to changes in simulators and additional crew and mission control center personnel training. This has occurred in the Space Shuttle and ISS programs.

During interviews on future exploration planning, Apollo crewmembers have stated that future lunar mission design philosophy should include the complete system, achieving a seamless integration of the crew into the facilities and the equipment, with the equipment designed to fit the tasks that the crew is assigned, rather than the opposite. Apollo astronauts also emphasized that simplicity and reliability were important, with routine tasks and simple emergencies driving equipment design and, not worst-case scenarios (Connors 1993).

The optimization of lunar surface operations is a function of many factors, including the following:

- The design of the LSAM spacecraft
- The design of the lunar rover, spacesuit, and portable equipment
- The training of science teams, flight controllers, and crews
- The techniques of lunar surface operations
- The selection of landing sites
- Design, selection, spacecraft integration, and training for experiment hardware
- Flight planning
- Flight rules, mission priorities, procedures, and other flight products
- Multi-mission integration
- Lunar sample transport and curation
- Interaction between the crew, flight control team, mission science team, and greater scientific community

Lunar surface mission operations include the activities of the crew living and working on the Moon, mission support from the Earth, and the operation of robotic and other remotely commanded equipment on the surface and in lunar orbit. Mission operations teams participate in mission architecture development, vehicle definition, mission planning, training, and real-time operations. The prime lunar mission objectives are lunar science, exploration, operational preparation, and technology testing for future missions to Mars.

The major goals for lunar sortie missions are:

- Scientific investigations to further understand lunar geologic development and to map lunar resources
 - Sample collection and documentation of samples and sampling sites
 - Crew observation of surface features
- Reduce risk associated with establishing a long-duration lunar base and martian

exploration

- By obtaining operational experience with equipment (landers, rovers, space suits, experiments) and flight techniques (precision landing)
- Prototyping in-situ resource extraction and utilization (oxygen extraction, solar cell fabrication, etc) *[not discussed in detail for this paper]*
- Maximize Crew Effectiveness
 - Design systems to minimize crew involvement with routine tasks so as to maximize their ability to observe, think, and sample (Apollo crews spent large amounts of time reading film magazine frame counts, voicing out rover system status, and taking pictures)

Surface Activity Planning (prior to crew arrival on surface)

To prepare for human missions, robotic orbiters and surface robots will study the lunar geography. The purpose of these robotic elements is to locate resources, identify scientifically interesting sites, characterize potential landing areas, create accurate lunar databases, and test technologies required for human landings and surface operations. The data from these unmanned missions will influence into subsequent mission architecture, vehicle design, and mission planning decisions.

Pre-mission planning will target specific locations for exploration but the real-time operations must allow flexibility for responding to unexpected discoveries.

Surface Activity Planning (after crew arrival on planetary surface)

During Apollo, all EVA operations were completely planned out minute by minute and there was little time for deviation from the plan. If a geologically interesting site was discovered real-time by the Apollo crew, they were allowed an extremely limited amount of time to explore it, about 20 minutes. Apollo astronauts felt that they had been too rigidly scheduled during their missions and that this should change for the future (Connors 1994). One of their suggestions was that there should be a daily planning meeting held between the crew, operations personnel, and science personnel to plot out the next day's activities based on previous results (Connors 1993). Results from previous missions and previous moonwalks will be discussed during the planning meeting in order to formulate the best plan possible for the next EVA. Crewmembers and the science team will be able to modify the EVA plan in response to operational circumstances and data acquired during the mission. EVAs should be planned in such a way that they are flexible enough to respond to anomalies, or to opportunities that arise from new discoveries. When the crew arrives at a geology stop, the science team will have just a few minutes to listen to the crew's description of the site, watch the downlink video, and decide if the tasks and priorities assigned pre-mission are still appropriate. Vehicle and EVA systems information from the flight control team will be integrated into the EVA plan.

This is a different concept from how operations are currently planned today for Space Shuttle and ISS, where the EVAs are planned out explicitly pre-flight and there is little modification to the plan real-time unless an off-nominal/contingency situation arises. Finally, it is the nature of exploration that the crew and science teams will generally not know exactly what to expect at the detailed level before they arrive on the surface. This is a substantially different way of operating than a typical space shuttle or space station EVA in which the location and exact configuration of every task and piece of hardware is known in advance.

In order for the ground science team to be effective in the EVA planning process, certain elements need to be implemented in order to maximize effectiveness of the team. The following are some of these operational elements...

- planning, training, and simulations will integrate the science community and flight control personnel
- design systems to allow ground science team members to feel as close as possible to being on the surface with the crew

- many video cameras (rover, helmet, microscope) with multiple feeds of real-time video
- ground controlled high-resolution digital camera with real-time downlink of images

EVA duration affects what tasks are placed on the activity plan. Short duration EVAs are about 4 hours in length and only local tasks (approximately 1-3 km walk/5-10 km rover) are possible. Long duration EVAs, lasting 6 to 8 hours, are needed when long traverses (approximately 10-15km) across the surface are planned. When asked about EVA duration, Apollo crewmembers felt that EVAs lasting seven to eight hours every other day were acceptable, and most of them felt that conducting them every day was the way to operate, but that it depended on the crew's autonomy (Connors 1993). It is important to give the crew the time necessary to document and investigate an exploration site that is discovered real-time during a surface EVA. However, based on Apollo experience, a geology stop may be as short as 10 minutes and is rarely longer than an hour. Geology stops often cannot be extended under any circumstances due to the decreasing radius of the walk-back limit. In addition, the crew will receive adequate information on consumable levels, metabolic rates, and overall time remaining in order to determine how much time they have available to change or add a task.

The design of the EVA plan and the LSAM vehicle are also influenced by the number of crewmembers that will perform a moonwalk at the same time and the timing of the EVAs in the lunar cycle. During interviews, the Apollo crewmembers stated that they thought a two person crew should be the basic unit although they thought that contingency EVAs performed by a single person were reasonable. In fact, an EVA every other day might be too few (Connors 1993). With that in mind there are various options of how EVAs can be performed with 4 crewmembers on the surface. The options include having two separate 2-man EVA teams (working different traverses), or a 4-man team on a single traverse, or having two 2-man teams in which one does a traverse (with rover) and one stays near the LSAM doing things like experiment setup and localized sampling. For a timeline that includes 7 days of EVAs, the work can be distributed among two 2-man teams as laid out in Table 1. Doing an EVA every day for seven days is maybe too hard and every other day gives too little return. Maybe this implies a schedule in which any team does a max of two back-to-back days leading to something like:

Table 1: Proposed EVA Schedule for Two 2-man Teams

Day	EVA Team 1	EVA Team 2
1	EVA	EVA
2	EVA	IVA
3	IVA	EVA
4	EVA	EVA
5	EVA	IVA
6	IVA	EVA
7	EVA	EVA

A proposed schedule like this should ultimately be verified via early simulated missions.

The timing of the EVAs relative to the lunar cycle can add more constraints to an EVA plan. EVAs will be more difficult to perform during lunar night and lunar noon because mobility, viewing, and EVA consumable usage will be affected during these periods. Therefore landing

constraints may be implied in order to maximize surface EVA efficiency.

The specific tasks that are planned during the lunar sortie EVAs will focus on geologic discovery and investigating operational concepts for lunar outpost and Mars missions. In order for these tasks to be efficient in aiding future mission design, any mission objectives need to be integrated with mission constraints (spacecraft, crew, etc.) and science goals in order to achieve maximum results. One way to aid in ensuring that every lunar surface EVA achieves maximum results is to minimize the mechanical actions that the crewmembers have to take, such as extensive setup for experiments, frame counts on cameras, long descriptions of sites when MCC can receive downlinked video, reading out gauges for systems without downlinked telemetry, etc. Thus it is critical that the rover, equipment, spacesuits, and tools be designed to reduce as much as possible the overhead tasks of a lunar surface EVA. This is to allow as much time as possible for the crew to think about the geological context of a site and to select good samples. Video, telemetry, communication links, and data recorders need to be in place for the MCC to remove some of this burden from the crewmembers. This was a failing of the Apollo program in that excessive time was spent doing routine tasks such as verbally reading rover system status and camera film magazine frame counts to the ground.

Some lunar surface operations should be dedicated to Mars simulations in which the crew performs most of their short term planning, and a significant communications time delay with the mission operations center is imposed, this is when data recorders should be utilized.

Geologic Science

Science operations will be limited for sortie missions, but may include emplacing surface experiments, conducting area geological surveys, selecting, collecting, documenting, and classifying samples, and a small amount of in-the-field analysis. There will not be time during sortie missions for any extensive analysis and most geology stops will be a "one shot only", so all tasks for that target location must be performed at that time. In addition, lunar sortie missions will be similar to Apollo in the fact that there is limited cargo mass and volume allocated for sample return. Different operational concepts might be tested where one or two crewmembers stay in the LSAM or habitat to sort out the best samples for return to Earth while two other crewmembers are out on an EVA.

Crews could collect lunar samples, perform limited analysis, deploy science packages, and explore the areas within a 10 km radius in unpressurized rovers. These missions could take place on both the lunar near side and far side without establishing any long-term outposts

Storing samples for return to Earth can be problematic. During Apollo, problems occurred during sample retrieval and storage because of the rushed EVA timeline, and for the disjointed process for sample retrieval and storage. This sometimes caused problems (as on Apollo 14) with trying to correlate samples with geologic sites that had been visited.

Prior to the lunar sortie missions, a documentation process for tracking samples and corresponding them to lunar locations must be fully established. Photos, sample bag numbers, sample description, lunar location description (to get the full context of a samples surroundings) and the lunar location are all pieces of information that need to be documented and correlated together in order to achieve the top scientific results. With advancements in photography, crewmembers will no longer report photo magazine numbers. Instead, the timetag on digital photos can be used to match them up with a particular lunar sampling site. This process can be thoroughly investigated during training and analog missions prior to lunar exploration.

EVA Suit Design

The planetary EVA suits must be designed to provide a level of comfort, and a range of motion that permit crewmembers to work a full duration EVA without excessive fatigue and consumables usage. The suits will be designed specifically for planetary EVAs with high mobility, durability, high frequency of use, and dust resistance.

The Apollo EVA suits have gained a reputation for being cumbersome and inflexible. There are numerous video footages of Apollo crewmembers tripping, losing their balance, or falling due to the fact that the Apollo suits were inflexible and the center of gravity was not placed at an operational optimal location. These situations often occurred when crewmembers tried to collect samples without a partner and the inflexibility of their suits prohibited them from being effective. Based on this experience, the Apollo crewmembers have made a number of suggestions for future planetary EVA suit design:

- simplicity and reliability are the most important factors
- suit flexibility
- pull the suit closer to the body and to reduce the inertia associated with starting, stopping and changing direction
- maintenance simplicity
- limit the amount of joints and bearings
- custom gloves (Connors 1993).

These changes suggested by the Apollo crewmembers will increase the operational capabilities of the EVA suit and allow for greater mission success. By designing the suits with simplicity in mind, the maintenance of the suit will be minimal allowing for quicker turn around between moonwalk excursions and limit the amount of time for EVA prep (ingress suit and depress) and post EVA (egress suit and repress) operations. Pulling the suit closer to the body, situating the center of gravity at an optimal location, providing flexibility, and custom gloves will allow the crew to perform the surface activities more effectively which in turn increases the number and quality of sample return.

Along with the comfort that comes with each crewmember having custom gloves, this will also provide better control of tools. However due to the inherent nature of EVA suit gloves, gripping tools will probably still be a chore and tool design must take this into account. Tools for surface activities should be designed to eliminate the need for continuous gripping of tools so as to prevent problems.

EVA Airlock

The LSAM serves as the EVA staging area and crew habitat for lunar sortie missions. As such, it requires more living and working area than it would if it were merely a crew cabin for ascent and landing. The LSAM will have an airlock for added safety and mission assurance, operation flexibility, and dust mitigation.

An airlock on the LSAM will maximize operational flexibility and crew safety. This will allow some crewmembers to remain inside the LSAM in a shirt-sleeve environment during EVA operations. This also prevents a suit failure, or an ill crewmember that cannot suit up, from scrubbing the remainder of the surface mission. An additional benefit is EVA crew rotation to maximize total EVA time in a single crew day. An early team could egress and work for hours before the second team joins them. After working together, or at different locations, the early team could then ingress before the late team. The IVA team would not have to be suited.

Egress and ingress paths should be as unobstructed as possible to avoid damage to EVA suits or the LSAM. The LSAM also carries unpressurized rover(s), EVA tools and equipment, and science and technology testing gear to the surface. The rover and some of the equipment will be stowed externally and must be easily accessible to the suited EVA crew for safe deployment.

The airlock and suit maintenance area also serves as a “mud room” to keep lunar dust out of the living quarters. It may be designed so that dust is expelled during depressurization and external hatch opening.

Dust Mitigation

During the Apollo missions, lunar dust was a major problem. It got into everything, jammed

moving parts, and was extremely abrasive. Part of the crew's time will be devoted to controlling lunar dust so that it does not pose a health hazard or degrade operational capability. Testing the effectiveness of dust abatement methods applicable to longer missions should be an objective of sortie missions. The EVA airlock should contain multiple tactics to aid in dust mitigation.

It has not been determined how dust will be mitigated on lunar missions but some possible solutions are to use an adhesive-type and sticky substance dust remover on the EVA suits to employ mechanical brushes, and to use a powerful vacuum cleaner mechanism. Dust suppression methods, such as deployable mats, might be used to reduce the amount of dust scattered by EVA crews and vehicles. These mats would be most useful in the immediate vicinity of a lunar outpost. In addition, research is being conducted on the use of electrical current to repel dust. Much of the finer dust particles are magnetically charged, so a mild current running through electrical wires imbedded in the outer layer of the spacesuit, could be used to repel lunar dust throughout the EVA.

Dust mitigation is one of the least studied areas of lunar exploration, but it could pose the greatest risk to mission success. More time needs to be devoted to developing strategies for mitigating dust prior to returning to the Moon in order to improve chances for successful lunar exploration.

Unpressurized Rover Design and Operations

A means of surface mobility, such as lunar rovers, maximizes the payoff of EVA by greatly extending the range and scope of operations. Crews can explore the area or get to and from work locations quickly, and with less consumables expenditure, than on foot. Rovers can also carry tools, equipment, and consumables that would otherwise burden the EVA crew. Moonwalks become more efficient because the rover provides the crew with a brief "rest" period (resulting in less fatigue), extends consumables by lowering metabolic rates on the crewmembers, carries tools, and reduces suit exposure to dust/regolith (abrasion, contamination). By utilizing the rover to supplement spacesuit consumables (power, cooling, oxygen), the crew's efficiency during an EVA is maximized.

During Apollo, the rovers used toward the end of the program were extremely beneficial in allowing the crew to cover more surface area and therefore perform more geologic mission objectives. However the capabilities of these rovers did not seem to match well with the terrain requirements which caused many operational constraints to be imposed on the crew operating the rover vehicle. For example, a more integration between terrain requirements and rover capabilities should occur in order to allow for maximized mission productivity.

Two unpressurized rovers would be optimum for sortie missions. This would allow two separate two-person teams to operate simultaneously with full mobility, and provides a backup vehicle if one breaks down. By placing the four crewmembers into buddy pairs with each pair on a rover, twice as much surface area can be covered during a single EVA. In addition, if only two crewmembers are performing an EVA, each rover can carry a single crewmember, thus allowing each rover to carry an additional 150 to 200 kg more gear (experiments, tools, consumables, etc.) to a worksite, or to carry samples back to the LSAM or habitat.

Robotic Elements

Robotic elements were not a part of Apollo EVAs. Many Apollo crewmembers have commented during interviews that teleoperation of robotic rovers should be integrated into the operations planning (Connors 1994). If robotic elements are added to future lunar exploration flights, they will enable faster site surveys and data collection in teleoperated or autonomous modes, and enable technology testing and demonstration for robotics as future real-time EVA assistants. Robotic missions can also be used at surface locations to survey potential landing locations and characterize local surface environments to evaluate their potential for science and ISRU operations (AAS 2005).

There will not be any ISRU on the lunar surface for the initial lunar sortie missions. Once ISRU is added into the lunar exploration mission design, robots can be used to prepare an ISRU collection or processing site, deploy ISRU equipment, and maintain the equipment to some extent. They may collect and transport raw materials, and transfer products from the processing facility to storage tanks. Robotic rovers should also have the instrumentation and dexterous capabilities to perform general-purpose geological exploration such as, studying the depth and density of regolith, examining the chemical properties of rock and regolith, and microscopically determining regolith grain characteristics.

Planetary robotic orbiters can aid in providing detailed site mapping and altimetry which will be important at the Moon and Mars for site selection, outpost layout planning, and analysis of access routes to the surrounding areas.

Flight Controller Console Roles and Responsibilities

Currently, mission-specific program management provides program requirements to the operations community and sets priorities for each flight or mission. The MCC operations team provides the facilities and tools, training, and flight control personnel to plan and execute real-time operations of the assigned mission per the Program's requirements. Engineering teams provide the spacecraft design expertise to validate the operational plans and procedures fall within the limits and capabilities of the flight vehicle, especially in real-time in the presence of failures and/or degraded systems' capability

During planetary surface missions, the mission operations team in the control center monitors LSAM systems telemetry, assists with anomaly resolution, uplinks data and commands to the LSAM, and conducts voice and video communications with the crew when necessary. Crew and vehicles are more autonomous, and must deal with time-critical decisions on their own. In this mode, the Earth-based mission operations and science teams serve a more long term planning, science and engineering support, and detailed analysis role. For missions to Mars, the finite speed of light will make true real-time interaction with the crew impossible. Lunar outpost missions will simulate this mode of operations. In order for ground personnel to effectively communicate, there will be a bridge (or liaison) between science and engineering communities, someone who speaks both "languages".

During Apollo, the interaction between the flight control team and the science team was coordinated through a single personnel interface. The science team had a lead that integrated all of their inputs and objectives and worked with the liaison to ensure science objectives for the mission were achieved. The liaison brought operational and engineering expertise to the science team and represented the science community to MCC.

A person (or team) with credibility in both the operational and scientific communities needs to oversee the process of integrating scientific desires with limited operational capabilities. Science investigators are understandably narrowly focused on their specific experiment and are often unaware of the myriad limitations imposed by the manned spaceflight environment. Furthermore, they often need assistance to understand standardized operational procedures. When accepting operational limitations, the scientific investigator needs to know that the responsible parties understand his unique goals and problems and that within the context of limited resources he and his experiment are being treated fairly. For their part, the crew and spacecraft flight control team need to feel that the scientific team understands the relevant operational limitations. The key to achieving this credibility is to demonstrate visible technical competence in both spheres of operations. The primary goals for all involved are crew safety, vehicle integrity and mission success.

With this background, the role of the Lunar Surface Operations Officer in upcoming lunar exploration can be defined. In general terms, the Lunar Surface Operations Officer is the member of the spacecraft flight control team responsible for surface geology. In this role he represents the flight control team to the surface geology team and vice versa, so he is the

interface between the surface geology team and the flight control team. The PI (Principal Investigator) for Surface Geology leads the surface geology team. The Lunar Surface Operations Officer and the PI coordinate to accomplish the scientific goals of the mission. At each EVA science worksite, the Lunar Surface Operations Officer works with the PI to confirm sampling priorities and coordinate tasks for ground-controlled equipment such as video cameras. The Lunar Surface Operations Officer team also manages the geology time-line and the time allocated for each worksite and coordinates this information with the EVA Officer who manages the overall EVA plan, manages the rover systems, and monitors the spacesuit systems and consumables. In addition, the Lunar Surface Operations Officer keeps track of the stowage locations for geology tools and samples.

The Lunar Surface Operations Officer coordinates with the Experiments Officer who is, in turn, responsible for physical scientific payload devices such as those which may be operated portably by the crew, set up on the lunar, or which are installed on the LSAM or CEV (Crew Exploration Vehicle) spacecraft.

The science team will probably be distributed among NASA center and universities, therefore the Lunar Surface Operations Officer must integrate amongst all parties to optimize the scientific activities and mission objectives without compromising other aspects of the mission (vehicle systems and crew safety).

ANALOG MISSIONS

Categories and Sites

Earth-based exploration analog missions possess characteristics that are analogous to missions on the Moon or Mars. They provide a mission framework in which to exercise, evaluate, and refine operational concepts for human exploration beyond Low Earth Orbit (LEO). They also provide opportunities to test procedures, technologies, and field science techniques being developed for exploration.

The following are examples of what can be tested during analog missions:

- Earth-based exploration analog mission simulations, with crewmembers living in a high fidelity habitat mockup, and doing EVA in pressurized planetary suits, can demonstrate the maintainability of lunar surface infrastructure, such as habitats and rovers. Lessons learned from such simulations should influence designs and operational techniques. Analog missions are also used to validate or refine operational concepts.
- Team composition, leadership, and team dynamics studies can be conducted during multi-week analog missions. (NEEMO)
- Equipment stowage and deployment concepts can be tested using full scale mockups.
- Dust abatement equipment and techniques can be developed and partially tested terrestrially.
- The design and functionality of crew displays and controls can be tested during analog missions. The utility of this is directly proportional to the fidelity of the infrastructure available for the simulation. (Desert-RATS)

The sites and facilities used generally fall into one or more of the following four categories: landscape and geology, habitation, science operations, and engineering and technology field testing.

Landscape and geology: This type of field site has physical features that resemble conditions on another planetary body. The Haughton Crater area on Devon Island, Nunavut Territory, in the Canadian Arctic, and Barringer Crater, also known as Meteor Crater, east of Flagstaff, Arizona are examples of natural landscape analogs. Both locations were hit by large meteorites that

excavated craters and created other terrain and geological features similar to what we observe on the Moon and Mars. Haughton crater is more than 20 km wide and is old and weathered. The surrounding rocks exhibit shatter and shock characteristics caused only by massive meteorite impacts (Figure 3). The extremely sparse vegetation and dry, dusty conditions add to the Mars-likeness of Devon Island's environment (see Figure 2). Barringer Crater is about 1.86 km wide, and it retains the classic impact crater shape. The surrounding Arizona desert is also an excellent analog to the terrain, and dry, dusty conditions on the Moon and Mars.



**Figure 2 - Devon Island Terrain
"Mars on Earth"**



Figure 3 - Impact Shattered Rock

Accessibility is an important consideration for selecting geological analog sites. Devon Island is probably the best geological Mars analog site available. Unfortunately, it experiences only about a month of weather per year that permits reasonably safe operations, and its extremely remote location makes moving personnel and equipment in and out of there time consuming, complicated, and expensive. More easily accessible analog sites, such as the Barringer Crater region in Arizona, or the Mars Society's Mars Desert Research Station (MDRS) in the Canyonlands Desert of Utah, can host analog mission expeditions more frequently and at less expense.

Landscape and geology analogs may also be artificial. Both Johnson Space Center (JSC) and the Jet Propulsion Laboratory (JPL) use outdoor simulated Martian terrains to test surface exploration technologies and procedures in a somewhat realistic environment. Both "rock gardens" simulate the distribution of rocks of different sizes typically encountered by Mars surface rovers. These test facilities are reconfigurable to match conditions at specific landing sites. JSC is in the process of constructing a lunar surface area with craters. JPL also has a tilt table covered with simulated martian soil for testing the maneuvering capabilities of robotic rovers on slopes, and an indoor facility for testing robotic rover operations in an extremely dusty environment, and in lighting and color conditions that can be varied to closely approximate those at specific sites on Mars. Purely robotic technologies, human EVA equipment with suited test subjects, and combined human/robotic operations can be tested in these artificial environments under more controlled conditions, and without requiring extensive travel.

Habitation: These expedition sites have facilities that are analogous to life inside a space vehicle or a planetary surface habitat. Such facilities may also be surrounded by extreme environmental conditions that isolate the crew in a confined, controlled space for life support. A trip outside may require special equipment for survival. The Aquarius undersea research facility owned by the National Oceanographic and Atmospheric Administration (NOAA) and operated by the National Undersea Research Center (NURC) of the University of North Carolina at Wilmington (UNCW), is an excellent example of a habitat analog (Figure 4). The Aquarius habitat is approximately the size of an International Space Station (ISS) module, and supports a crew of six. Mars exploration studies have considered at least four and up to six personnel to be the most desirable crew size for work load, skill mix, and other human factors, depending on

mission duration (Operations 2000). The Aquarius habitat is moored to the ocean floor at a depth of sixty feet and three and a half miles off the coast of Key Largo, FL, in the Florida Keys National Marine Sanctuary. NASA Extreme Environment Mission Operations (NEEMO) missions to Aquarius typically last from ten days to two weeks. NEEMO-9, conducted during April of 2006, lasted for 18 days and was the longest mission conducted in Aquarius as of May 2006.

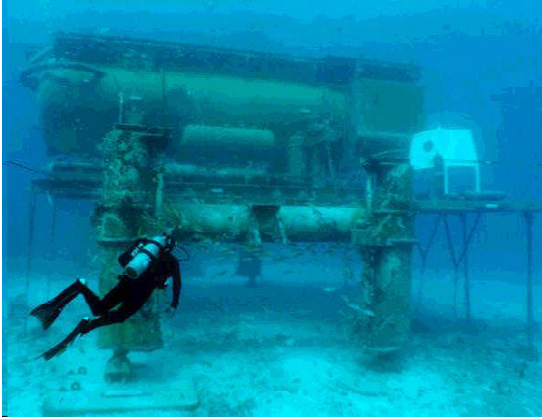


Figure 4 - The Aquarius Undersea Research Facility Near Key Largo, Florida

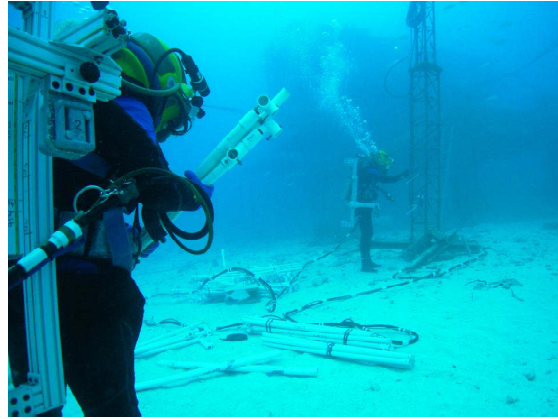


Figure 5 - Divers Weighted to Simulate Lunar Gravity (NEEMO-9)

Remaining at depth for these long periods of time (referred to as “saturation diving”) requires a lengthy decompression period before returning to the surface, so the Aquarius crew cannot immediately come home if something goes wrong. “Extravehicular Activity” requires suiting up in diving gear, and by its nature, entails certain physical risks. All of these elements contribute to a realistic analog for space flight, including EVA. These expeditions have a double role as crew training for the ISS, and as exploration analog missions. The hazardous environment requires that these missions be conducted with the same operational discipline and attention to safety as actual space missions.

Habitation analogs may also be located in more controlled, less hazardous environments, such as the simulated planetary surface habitat at the Johnson Space Center. There are many advantages of such facilities. They are much more easily reconfigurable and maintainable than field test sites and can therefore be used to test many different exploration analog mission architectures and scenarios. Their use is not at the mercy of the weather, which is an important factor for scheduling field activities and conducting operations. They can be operated in conjunction with outdoor field test sites, such as “rock garden” simulated Mars or lunar surfaces for EVA, telerobotic, and autonomous robotic operations. Simulation scripts, ground rules, operational plans, and objectives can be defined with no need to accommodate competing interests from other participants that may have partially incompatible objectives.

Science Operations: Although all exploration crews will include accomplished scientists, it will be impossible for a group of four to six people, no matter how experienced and well-trained, to know everything they might need to know on a long duration exploration mission. Therefore, remote science operations and interaction between the crew, robotics, and a geographically distributed science team will be necessary.

There are several ways to conduct remote science operations. One is for scientists, on Earth or some location other than the site being explored, to remotely command a robot as is currently done for NASA’s robotic exploration of the solar system. For a science team on Earth to command a robot on Mars, they must create and test a sequence of commands for uplink at least a day before the robot is to execute the commands. The finite speed of light and the desire to first evaluate the science and engineering data from the previous day’s activities, make this

delay unavoidable. After receiving the uplinked commands, the robot executes them on its own and later transmits the results to Earth. If the science team is close enough to command the robot without significant time delay, then remote robotic operations can be conducted in real-time using teleoperation or even telepresence technologies.

Another approach to remote science is “telementoring.” In tementoring, a crewmember at the exploration location can perform unfamiliar operations while being coached by an expert at a remote location. This may be done in real-time, or by training prior to the operation, or through some combination of both techniques. Exploration analog missions provide an excellent vehicle for testing the techniques and technologies needed for remote science and medicine. The NASA Oceanographic Analog Mission Activity (NOAMA) expeditions, that studied extremophiles and hydrothermal vents as an astrobiology analog, had none of the characteristics of geographical or habitat analog sites, but they were good examples of remote science operations conducted by an international science team (U.S., Australia, U.K., Russia) providing procedures to crewmembers who were not experts in the field (Figure 6). Remote medical and lunar science operations have also been conducted during NEEMO missions with great success (Figure 7 and 8).



Figure 6 - Sample Processing During NOAMA-1

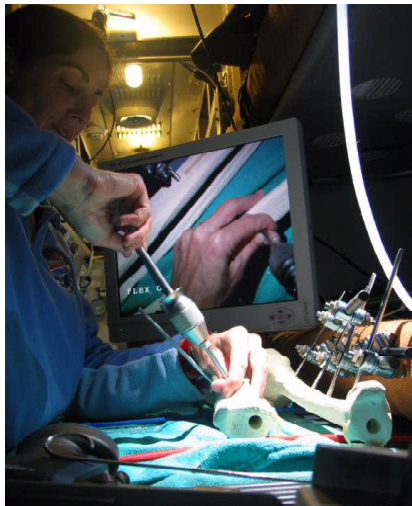


Figure 7 - Telemedicine Operations (NEEMO-9)

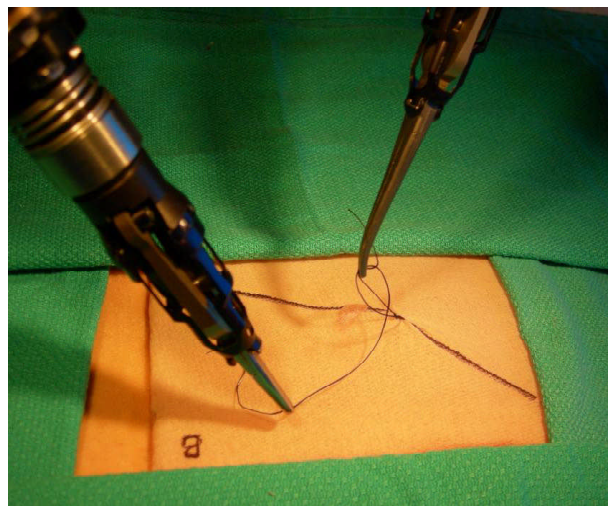


Figure 8 - Remote Suturing Using Robotics (NEEMO-9)

Engineering and Technology Field Testing: Some analog sites are particularly good for testing the tools, EVA suits, communications gear, rovers, robotic assistants, and other equipment that explorers will use on the Moon and Mars. Analog missions that are partly dedicated to engineering field tests subject the equipment and crewmembers to challenging terrain, dust and dirt, vibration and impacts, real lighting conditions, generally rough use, and sometimes

temperature extremes. Strengths and weaknesses in design or procedures, including telecommunications, quickly surface in natural test environments outside the laboratory. These tests are also good for evaluating the physical exertion and mobility capabilities of suited test subjects, and anthropometric and ergonomic factors in equipment design.

Engineering and field test sites may be natural or artificial. The annual Desert Research and Technology Studies (Desert RATS) expeditions occur at the Meteor Crater area in Arizona for field tests, but they also use the simulated Mars surface at JSC to prepare for the expeditions and for various tests throughout the year (Figure 9 and 10).



Figure 9 - SCOUT Rover at JSC Mars "Rock Garden"



Figure 10 - EVA Equipment Testing (Desert RATS '05)

Lunar Sortie Analogies

Analog missions have received broad support from the Johnson Space Center (JSC). Many JSC Directorates support analog missions in various roles, including the following: Mission Operations Directorate (MOD), Engineering, Space & Life Sciences, Astromaterials Research & Exploration Science Directorate, Safety and Mission Assurance, as well as the Astronaut Office, Extravehicular Activity (EVA) Office, Public Affairs, Education Outreach, and Office of Chief Counsel. In addition, the Information Resources Directorate, the Center Operations Directorate and the Office of Procurement provide information technology and facility development services. NOAA's on-site National Weather Service (NWS) Spaceflight Meteorology Group (SMG) provides weather forecasts. The analog missions provide benefits to the Space Shuttle Program, International Space Station Program, and the Constellation Program.

Other NASA centers participate with JSC in analog missions. These include Ames Research Center, Glenn Research Center, and Kennedy Space Center. The Jet Propulsion Laboratory (JPL) will likely participate with JSC in future analog missions. Other US government agencies (NOAA, US Navy, etc.) are also involved. In addition, universities, private industry, and research centers, both domestic and international, participate in various analog missions.

The Advanced Operations Cadre of the Mission Operations Directorate, which operates the Exploration Planning and Operations Center (ExPOC), has participated in sixteen missions as of May of 2006. This includes seven NEEMO missions, five Desert RATS missions, two Haughton Mars Projects (HMP), and two NOAMA missions. Each mission has specific lunar sortie analogies and applications.

The ExPOC consists of a flight control team with specific console positions (Figure 11). The Ops Director, Communications and Activities Officer (CAO), DATA, Remote Operated Vehicle (ROV), Science Officer, and various additional DATA positions with emphasis on EVA suits as appropriate for the given mission.

The ExPOC team develops procedures for the crew and for the ExPOC team itself. The team is involved in pre-mission planning, mission execution, and post-mission activities. Objectives and flight rules are also developed as appropriate for specific missions. In addition, the ExPOC team has a full set of console tools and applications such as interactive traverse mapping tools, EVA crewmember tracking tools, crew navigation tools, ROV driving software, data collection sheets, logging software, telemetry viewing systems, and procedure and timeline viewing systems. In addition, the ExPOC team uses the MCC voice communication system to the extent practical for the given mission. The ExPOC team conducts simulations by themselves and with the crew prior to the analog missions, just as is done with space missions.



Figure 11 - ExPOC Team

The following descriptions of analog missions focus on the characteristics of the analog missions that have parallels in lunar sortie “mission operations.” Various other aspects of the mission may be mentioned briefly, but not expanded upon in detail.

NASA Extreme Environment Mission Operations (NEEMO)

As noted earlier, the NEEMO missions are executed using the Aquarius habitat.

JSC conducted nine NEEMO missions between 2001 and April of 2006. The 18-day NEEMO-9 occurred in April, 2006 and was the longest mission in Aquarius to date. The IVA focus on NEEMO-9 was on telemedicine, telerobotics, and telerobotic surgery. NEEMO-10 and 11 will be entirely exploration focused and are scheduled for July and September of 2006, respectively. NEEMO missions are managed by a team from the Mission Operations Directorate, led by Training Division personnel. The MOD Advanced Operations Cadre (AOC) operates the Exploration Planning and Operations Center (ExPOC) as a Mission Control Center (MCC) for the EVA portions of the missions. Each crew consists of three astronauts, a scientist, and two NURC habitat technicians.

By virtue of the use of the Aquarius habitat, the NEEMO missions are an excellent habitation analog. Although the environment is different, the excursions outside the habitat provide a surface EVA analog.

By virtue of operating with the Aquarius habitat, the crew experience is much the same as that of a space-based crew. A broad variety of life sciences, human factors, physiological factors, and psychological factors are assessed during a typical NEEMO mission. Many types of scientific activities have been conducted, including life science, telemedicine, and telerobotic activities (Figure 12). In recent missions, the exploration mission analog has focused almost exclusively on the use of dives as analogs to surface EVA's.

During NEEMO missions, the crew lives in the Aquarius Habitat for the entire duration of the mission, thus all of their activities are part of the analog mission. Their activities closely resemble the tasks of a lunar surface “sortie” crew and virtually every activity the crew performs has a lunar mission analogy.

IVA tasks include meal preparation, pre-sleep and post-sleep activities, private medical conferences, private family conferences, journals, PAO events, education outreach events, and

habitat maintenance. All of this is in addition to reviewing the daily activity plan, participating in DPCs with ExPOC / MCC, performing ROV operations, and, of course, conducting scientific experiments. Most activities documented by the crew with photos or video which must then be managed and distributed.

In addition, the crew conducts EVAs outside the habitat using scuba gear or helmeted diving systems with life support umbilicals. Even though the physical environments are different, the NEEMO EVA crews perform the same types of tasks that a lunar EVA team will perform. These include EVA prep (suit donning, etc.), EVA setup tasks (e.g. tool management, camera positioning), EVA surface activities (excursions, lunar samples, structure construction, etc.), EVA clean-up tasks (tool return, worksite cleanup, etc.) and post-EVA tasks (suit clean-up, equipment management and data downloads, etc.). The NEEMO crews have some additional considerations in terms of operating within specified depth limits and securing equipment so it won't float away. Other aspects of the underwater dive experience translate nicely to lunar analogies. These include operating in buddy teams of two, maintaining situational awareness, staying within visual contact of an excursion line so they won't get lost in unknown territory, maintaining contact with the IVA crew and/or MCC, managing air consumables during scuba EVAs, and re-filling air tanks during scuba EVAs from either the Aquarius habitat or a remote waystation. The ExPOC serves as the MCC during EVAs and formal communication protocols simulate space operations.

During NEEMO-9 a diver tracking system (IVA and MCC can see diver locations real-time) and diver navigation system (guides crew to waypoints, directs crew in a grid mode search pattern, allows crew to mark points of interest, records the crew's path and maps the terrain) were utilized for the first time. NEEMO-9 was the first mission test of these systems and uncovered some operational challenges. NEEMO-10 and 11 will provide a continued opportunity to assess the usefulness and robustness of these systems. While the technologies will be different, the same or similar functions will likely be available on the Moon. Both the ExPOC team and the crew found the Diver Tracking System to be useful during the mission to provide situational awareness. The navigation system was useful in terms of being able to mark locations in the field and send the data back to the ExPOC. In addition, the ExPOC could plan missions, upload them to the crew, and the crew execute the mission profiles during the EVA.

The NEEMO missions are overseen by a "distributed mission control team" consisting of the NASA Topside team (overall mission management, timeline updates, and on-site logistics), the ExPOC (MCC role for EVAs and primary for EVA content replanning), and the NURC watch desk (Aquarius systems monitoring and crew safety). There is also an international science team with some representatives on-site and others at their remote locations. While this model is different than that of a lunar control team, it provides experience with the distributed nature of future control teams (partners at multiple NASA centers).

As with all analog missions, an adequate communications network is essential. While greatly increased from previous years, the finite bandwidth limits the number of simultaneous activities and connections and affects the quality and update rates of the video. The communications network allows the crew to communicate by phone and internet (video, data, etc.). The ExPOC team talked with the crew by phone or internet voice during EVAs (dives) and talked with the crew during DPCs and other times.

NEEMO-9 exploration scenario was developed pre-mission, but much of the mission was dedicated to solving technical and operational issues with the new equipment. The following are some of the exploration analogs for NEEMO-9.

- ROV teleoperations (driving) by MCC/ExPOC
- Camera views for driving ROV – onboard and birds-eye
- Movable camera onboard ROV during EVAs commanded by MCC for MCC (and IVA) situational awareness and photo-documentation
- ROV technical capabilities required for exploration tasks (e.g. rock sample collection,

vehicle inspection)

- Crew and ROV/robotic interaction during EVA
- EVA crewmember navigation and tracking capabilities
- MCC and IVA interactions during EVAs
- Various EVA Suit center-of-gravity (cg) configurations were tested
- EVA Task efficiency and work efficiency



Figure 12 - ROV Driving, Lunar Science Tele-mentoring, Waterlab Construction

Desert Research and Technology Studies (Desert RATS)

As described earlier, Desert RATS missions are executed near Meteor Crater and Cinder Lake, which provide a lunar-like geologic and landscape test area (Figure 13). The focus of the tests is on Advanced EVA suit tests and the associated hardware and support systems. This includes a reconfigurable backpack that contains system monitoring software, crew position tracking and onboard navigation system, automated user interface software, voice recognition software for specific applications, and a wireless communication system. The specific applications are developed by other NASA centers, academia, and industry. The integration of the various systems is one of the challenges faced by the NASA JSC Engineering Directorate.

In addition to the EVA suit tests, a portion of Desert RATS is typically focused on the use of EVA robotic assistants and/or rovers that can transport the crew members. An EVA crewmember may also ride on a “chariot” pulled by an electronic tractor. In addition, a reconfigurable science trailer provides a basis for the science portion of a lunar science sample collection scenario. Depending on the equipment configuration for a given year, the science trailer may be pulled by a robot, rover, or the electronic tractor.

The Desert RATS field tests are managed by the JSC Engineering Directorate, but as with most analog missions, have broad participation from other organizations.

The mission operations scenario consists of the suited EVA runs and science planning meetings before and after the suited runs. These portions are high fidelity, but only capture a thin slice of a lunar mission. The short duration of the suited EVAs limits the duration of each test. The main focus of the mission operations analog was science procedures. High fidelity suits, science trailer, tools and sample bags were used.

The ExPOC Science Officer and Science Team, residing at the ExPOC, uses geologic lidar images and pre-mission flight rules and science priorities to select the coordinates for the sample locations and the type of sample procedure for the crew to conduct (rock, surface soil, etc.) (Arnold 2005).

The following were some of the exploration analogs for Desert RATS -05:

- Science scenario – lidar imaging. ExPOC science team selected sites. Science officer and science team worked together. Planning meetings with IVA team prior to EVA
- Communication bandwidth: data transfers were slow and took a lot of time in the evening
- Data management challenging with data (photos, lidar images, reports, files, etc.) stored in multiple locations
- Crew equipment and software (HUD, positioning system, system monitoring, voice activated system, etc) testing.
- Rover driving.
- ExPOC situational awareness (visual) was limited. Voice loops provided interaction, but the primary use was for the operational hardware field test.
- Data connections with ExPOC included rover driving (while manned), video cameras, audio, etc. EVA suit telemetry was not available due to the JSC firewall configuration.



Figure 13 – Desert RATS analog mission (overview pictures)

Haughton-Mars Project (HMP)

As noted earlier, the Haughton Mars Project is conducted at Haughton Crater on Devon Island in Nunavut, Canada. It is an exceptional geographical and science ops analog for Mars missions.

HMP tested concepts for human exploration operations with altered roles for the crew and MCC. During HMP 1999 and 2000, a subset of the field team participated in the mission operations scenario. There was a high fidelity Mars mission simulation, three weeks in duration.

The Mars time delays were simulated in a rigorous fashion by adhering to strict guidelines about communication. The entire mission was designed with processes similar to those anticipated in a Mars mission. For example, the data was sent from the crew to MCC overnight. MCC developed an activity plan for the crew for the next day. A formal file structure was in place on a common-

access server to accommodate data transfers.

ExPOC operations that were akin to lunar operations, even though it was an Mars simulation, included the following:

- Assisted with daily activity planning, traverse route planning, maintenance, weather forecasting, remote science, etc.
- Worked with HMP and university science teams on Devon Island and Principal Investigators in the U. S. and Canada
- Established daily communications schedules, formats, and protocols
- Imposed simulated light time delay for communications
- The ExPOC team developed an off-nominal situation for a weather station and the field crew was able to repair the weather station during the mission.
- Dust got into “everything” (tent zippers, equipment, etc.)
- Communication bandwidth: data transfers were “slow” and took a lot of field team time in the evening

During HMP 2006 (July), the ExPOC team has been invited to participate in a one-day emergency DTO (Detailed Test Objective) with ExPOC issuing commands to a rover.



Figure 14 - Ops Tent Laptops, Weather Station, and Ops Tent on Devon Island

NASA Oceanographic Analog Mission Activity (NOAMA)

NOAMA was a joint film-making and exploration activity at Atlantic and Pacific hydrothermal vent sites coordinated between NASA, Blue Planet Marine Research Foundation and XTREME Life Productions, Inc. (James Cameron, director). NOAMA was designed to be a science ops analog mission emulating astrobiology research in the solar system. It was primarily a science operations mission requiring extensive coordination between crew, the local control facility and

support scientists located around the world (U.S., Australia, U.K.). NASA personnel spent a lot of time being part of the documentary film on the geology and life forms surrounding hydrothermal vents.

The NASA JSC Crew performed science operations (sample recovery, processing, and preservation) aboard ship but did not dive in the subs.

ExPOC roles and lunar analogs:

- Coordinated international science team teleconferences between the crew and distributed Principal Investigators (PIs). The PI's were from Europe, Australia, and various parts of the US.
- Coordinated development and transmission of sample processing protocols for the crew with international PIs. It was necessary for the Science Officer to convert the inputs from the scientists into appropriate information (e.g. procedures) for the crew
- ExPOC team members participated in live educational outreach activities between the ship, JSC, and schools in the U.S. and Australia.
- Arranged for shipping, storage, and preservation of the samples post-mission.
- Coordinated weather forecast support with the JSC Space Flight Meteorological Group (SMG).
- Responded to crew requests to research information on biological and geological samples from the ocean floor with which none of them were familiar. Involved internet searches and finding researchers who were added to the remote science team.
- The voice communication with the field team was limited. Communication was primarily in the evenings and the schedule was not adhered to strictly due to the competing demands of the mission.
- The limited data transfer bandwidth meant that only a few low resolution photos were transferred during the mission. Most photos were transferred after the mission.

Lessons Learned

Human/Robotic Interaction and Situational Awareness

Joint human and robotic operations have been demonstrated during several exploration analog missions. The ninth NASA Extreme Environment Mission Operations (NEEMO-9) mission conducted during April 2006 demonstrated human/robotic interactions both inside the Aquarius undersea habitat and during EVA. A major objective of both NEEMO-9 and NEEMO-7 was to demonstrate telemedicine techniques. Surgical procedures could become necessary for a crew that is living for months in a spacecraft or a lunar outpost. During NEEMO-9, a cut in simulated human skin was successfully sutured using robotic manipulators in a simulator box.

Operators in the Aquarius habitat and the Exploration Planning and Operations Center (ExPOC) in Houston remotely commanded an ROV during the NEEMO-9 mission. The ROV could either crawl along the sea floor or swim through the water. It had a steerable camera, a light with variable brightness, and a small gripper arm. The ROV's maneuverability and its camera made it useful for video-documenting EVA activities during construction of an underwater structure called WaterLab. The operators could monitor activity through the ROV camera, which improved situational awareness for the teams in the ExPOC and the habitat. The ROV also served as a robotic assistant delivering parts and tools to the EVA construction crew. While this was challenging for the small vehicle used during NEEMO-9, the activity demonstrated the feasibility of this type of robotic assistance.

In general, it was easier to operate the ROV from the habitat than from the ExPOC in Houston. This was because the Intra-Vehicular Activity (IVA) crew could see both the camera's video feed and the view out the habitat porthole, at least for part of the ROV excursion. The IVA crew also had the advantage of having performed EVAs themselves, and they were personally familiar with the sea floor and the obstacles in the area around the habitat. There was also a slightly shorter command-response delay for the IVA crew than for the ExPOC team, but the delay was short enough that it did not greatly impede the ExPOC team's ability to safely operate the vehicle. Command-response time is crucial for effective and safe telerobotic operations. During the 2005 Desert RATS expedition the communications link between the field site and the ExPOC caused too much command-response delay to allow the ExPOC operators to remotely command the manned rover effectively. The rover could be driven short distances and stopped. Once the video from the camera caught up, the operator could assess the rover's new location and plan another short move. Real-time, continuous operation was not safe with this command-response lag of several seconds. The rover team at the field site was able to remotely command the rover in real-time.

Various robotic assistants have been tested extensively during Desert RATS expeditions. These assistants have carried equipment for the EVA crew, and have also performed work. During the 2004 Desert RATS mission, a robotic assistant vehicle implanted a series of geophones in the ground, thus saving the suited EVA crewmember considerable physical exertion. For EVA, this translates into conserved life support consumables, and possibly less wear on the suit. Robots that do physical work must be able to exert as much force as is required to perform the most challenging task expected. Some of the soil encountered during the geophone exercise was too hard for the robot to firmly implant the geophones.

Desert RATS expeditions have also successfully tested technologies that enable a rover or robotic assistant to follow the walking crewmember and respond to both radioed voice commands and hand signals. A general finding about robotic assistants is that they are useful only if they are capable of moving at least as quickly as the walking suited crewmember, and can negotiate equally rough terrain. If the robot is too slow, or needs help getting over or around obstacles, the crewmember becomes the assistant for the robot.

The Influence of Communications on Crew and Mission Control Operational Roles:

Communications between the crew and the Earth for operations in Low Earth Orbit (LEO) are essentially instantaneous and almost continuous. Normal conversations are possible, and the crew can request information and expect a fairly quick response. The round trip communications time-delay for operations on the lunar near side is only about 2.5 seconds. When human crews venture deeper into the solar system the finite speed of light will impose an unavoidable communications time delay that is measured in minutes rather than seconds. A crew on a conjunction class mission to Mars would experience a communications delay of more than 40 minutes, not counting the time taken to formulate a reply, when Mars and the Earth are on opposite sides of the sun. This single factor will alter the traditional roles of the earthbound operations teams and the flight crew, and the capabilities that must exist aboard the spacecraft and surface habitat. The NASA HMP analog missions simulated a communications time delay to study this shift in operational roles. The NOAMA missions had such limited satellite phone communications, that the results were practically the same as they would have been with an intentionally simulated speed of light delay. Technical problems with the communications infrastructure can also result in significant interruptions to the normal communications flow.

The HMP mission plans defined specific blocks of time during which message uplinks from the Mission Control Center and downlinks from Devon Island were to take place. Direct, real-time communications were only allowed for scheduled planning conferences and for emergencies, during which the analog mission simulation would have been suspended. The planned downlink and uplink messages had predefined outlines. The content of the downlinks included consumables status data (food, fuel oil, water, etc.), EVA traverse reports (positioning data plus

narrative descriptions of discoveries and activities), field science reports (narrative, data, images), the status of equipment, summaries of the day's activities, safety reports, private medical data, requests for information or advice from the operations, science, or medical teams, and requests for assistance troubleshooting problems. The uplinks included daily plans for the coming day (science team requests and instructions, action items), including suggested traverse routes, answers to questions from the previous downlink, in-flight maintenance procedures, surface and solar weather forecasts, and consumables usage predictions based on observed trends. The MCC team also added some news items and humor to the uplinks, which is also done during Space Shuttle missions and International Space Station increments.

The time delay required disciplined communications protocols and skills by both the crew and the mission operations team. Early in the HMP missions there were problems with ambiguity in the message traffic that caused misunderstandings or forced the crew, the mission operations team, or the science team to ask time-delayed questions. Technical difficulties with communications equipment, mostly caused by the harsh natural environment, aggravated the problem. There were several mission simulations in preparation for these missions, and effective uplink and downlink message formats were developed, but the magnitude of the impact of non-real-time communications on operations was still underestimated.

Instructions in uplinks had to be reviewed before transmission to determine if there was more than one way to interpret them, and to make sure that all of the required information was included in the message. Incomplete instructions were just as much of a problem as ambiguous ones. Photographs and illustrations were helpful. An unplanned maintenance activity on the portable Devon Island weather station was a success because clear photographs of the correct equipment configuration were included with the narrative, and the instructions themselves were precise, and adapted directly from the user's manual. The mission operations team also successfully planned a traverse route for the all-terrain vehicles. The plan included an aerial photograph with the route marked on it, and the EVA team had no difficulty finding the route and executing the plan. The science team in Houston initially had trouble matching images of rock and biological samples in the downlink data with the locations visited by the EVA crews, because the image file names did not make this correlation, and the narrative descriptions provided in the downlinked science summaries were sometimes unclear. There were also ambiguities in the narratives about the locations of finds. In one case, the crew reported having stopped "by the lake" to perform a certain activity, but the traverse map showed several lakes along the route.

The teams on Devon Island and in Houston both improved their time-delayed communications skills fairly early in the missions. The Devon Island crew made the interesting observation that support from Houston was a positive morale factor. Just the fact of knowing that a team in Houston was continually aware of their presence and working issues they had identified made them feel better. There is a palpable sense of isolation from the rest of humanity on a barren island in the arctic where the weather is windy and cold even in mid-summer. Maintaining crew morale in the face of this effect should be a high priority for long missions to a lunar outpost, and especially for missions to Mars.

The shift in how operational responsibilities were divided between the crew and the mission operations and science teams was quite apparent during both the HMP and NOAMA missions. Instantaneous, real-time support was impossible, so any actions requiring on-the-spot decisions were completely up to the crew, and the planners in Houston had to adapt to any significant changes. As long as the top level objectives for the day were accomplished, it didn't matter how the crew chose to schedule their work, or which crewmembers performed which tasks. Micro-scheduling of tasks would have been futile in any case, because situations continually arose in the field that required flexibility and changes of plans. When top level objectives were not fully accomplished, the teams in Houston had to alter future plans according to mission priorities. Consumables tracking activities for the HMP were analogous to systems monitoring for the Space Shuttle or Space Station, with the difference that none of the data were observable in real-time. Trends were used to predict consumables quantities that would be available to the crew as

a function of time, which helped them to make decisions about usage rates.

The NOAMA missions, conducted in the Atlantic and Pacific Oceans aboard the Russian research vessel M. V. Keldysh, were work intensive for the NASA JSC crew, and the limited communications presented big challenges for the team in the JSC Exploration Planning and Operations Center (ExPOC). For sample processing they had to use the initially unfamiliar Russian laboratory equipment, which required creative improvisation for some tasks. NASA, university, and Russian science teams shared limited shipboard laboratory resources. The ExPOC served primarily as a center for coordinating science team activities, and as a kind of remote research assistant for the crew. The JSC crew (an astronaut/oceanographer and a planetary scientist) were not familiar with the types of geological and extremophile biological samples that were brought up from hydrothermal vents on the ocean floor. Although several sets of procedures for processing hydrothermal vent samples were created before the missions began, this was done without knowing exactly what would be discovered during the mission. The pre-existing procedures all turned out to be relevant and valuable, but new ones were essential as new discoveries came to light. To perform proper sample processing, curation, and cataloging the crew used detailed new procedures from the international science team, who were distributed across the U.S., Australia, and Great Britain.

These experts on hydrothermal vents and their associated ecosystems were not familiar with NASA operational procedures, and as individuals, lacked the “big picture” of all the activities that were taking place aboard ship. The ExPOC team’s challenge was to coordinate science planning conferences between the crew, the ExPOC, and the distributed team, and to translate instructions from diverse authors into standardized crew procedures, without omitting or altering important information in the process. Operating across time zones in the central U.S., the U.K., Australia, and the mid-Atlantic and east-Pacific oceans, was a challenge in itself. The ExPOC team also helped the crew to identify unknown samples and provided images from previous research of some of the life forms that were being brought up by the submersibles. Although there were some real-time planning conferences, the crew received no direct, real-time assistance from the ExPOC during science operations. This was analogous to science operations within a surface habitat on Mars.

After the NOAMA missions, the JSC crewmembers commented on how vital it was that their sample handling instructions had been reformatted into standardized procedures. Had this not been done, they might have fallen hopelessly behind in their laboratory work. The ExPOC team’s data gathering on samples unfamiliar to the crew, and the science planning conferences were also helpful.

Work Activities Scheduling and Mission Priorities

Because of the intense level of effort, and enormous expense of sending human explorers to other planetary bodies, there is an understandable desire to get as much productive work out of the crew as possible. However, experience with both actual space flight and exploration analog missions has clearly shown that if the crew’s work load is excessively burdensome, a densely packed schedule can quickly reach a point of diminishing returns. Excessively loaded schedules lack the margin needed to respond effectively to delays or contingencies that require replanning to meet the highest priority mission objectives.

It is easy to underestimate the time overhead associated with operating in an alien environment. An activity schedule that would be perfectly reasonable on Earth in a controlled, low-stress setting, can be overwhelming to a crew in space or on another planet. During the NASA Haughton-Mars Project expedition in 2000, the harsh natural environment (cold temperatures, wind, rain, and fine, blowing dust) caused equipment problems that occupied a large percentage of the field team’s time. In order to accomplish mission objectives and keep everything working, the team put in extremely long hours, which resulted in excessive fatigue during the three-week mission. Blowing dust fouled everything from commercial off-the-shelf digital video cameras to

tent zippers. The cold caused intermittent failures in laptop computers that weren't specifically designed for extreme environments. Strong wind caused the satellite dish antenna to wobble, resulting in data dropouts and a general loss of bandwidth. At one point, rainwater had to be drained out of the satellite antenna's feedhorn. These problems made file transfers to and from Devon Island unreliable and extremely time-consuming. There were also difficulties in generating sufficient electrical power for all of the computers and other electrical equipment on the island, which caused brown-outs and slowed the work of archiving data and producing files and reports for the mission operations and science teams.

Besides the obvious need to ensure that all equipment is sufficiently robust to function reliably in the field environment, crew activity schedules must include time for rest, relaxation, personal hygiene, and margin for problem solving. When the finite speed of light, or other factors impose significant delays in two-way communication, the crew needs the authority and flexibility to schedule most of their own daily activities. The HMP science and mission operations teams provided the high level mission objectives and broad guidelines for attaining those objectives.

Because of the extremely limited communications available for the NOAMA missions all of the work scheduling had to be done aboard ship. This was a challenge because the JSC science analog mission competed for time, people, and material resources with the objectives of the team producing a documentary film, and the Russian and university science teams. Priorities had to be negotiated among all of the participants, with occasional non-real-time input from the ExPOC relayed through the JSC crewmembers. During an actual long-duration mission to the Moon or Mars, top-level mission priorities will have been decided before launch, but a mechanism must be in place for revising those priorities based upon significant new discoveries, or operational contingencies. Recommendations from the crew, the operations team, the science team, the flight surgeons, engineering support, and program management will all factor into the final decisions. Actions that can't wait for a decision from Earth will have to be taken by the crew, and the operations and science teams will have to adapt their planning accordingly.

Schedule overloading is not unique to space crews, but can also affect the operations team on Earth. During the NEEMO-9 mission, several dives had to be replanned when data sets required to create EVA mission profiles for an underwater navigation system for upcoming dives were not available to the operations team because of technical difficulties. The ExPOC operations paradigm for NEEMO-9 typically scheduled two shifts of three people, for approximately twelve hours of operations support per day. The ExPOC operations team positions were the Operations Director (OPS), the Communications and Activities Officer (CAO), and the data officer (DATA). For some shifts, a ROV operator joined the team. Software support personnel came in periodically to monitor the performance of developmental logging software being tested in an operational environment. When not on console, ExPOC personnel were doing other work, usually unrelated to NEEMO-9, in their offices. For most of the time during lunar outpost missions, and missions to Mars, a complete operations team will not be supporting twenty four hours per day, seven days per week. Many personnel will do other work and be on call except for scheduled mission support periods during special activities that require their presence.

NEEMO-9 was more dedicated to exploration analog operations than any previous NEEMO mission. As a result, the ExPOC team's role included more pre-mission and real-time operational planning than ever before. The potential for technical contingencies increasing the ExPOC team's real-time planning workload was anticipated, but the magnitude of its affect was underestimated in pre-mission planning, and resulted in insufficient team depth. When several future dives had to be completely replanned, the task fell to the operations team on-console. Fortunately, operations team members who were not on-console were able to help the on-duty team work on the EVA plans in the ExPOC's planning and conference area while real-time dive support was taking place in the operations area. The "Topside" team at Key Largo, Florida also assisted with replanning some dives. The EVAs were successfully replanned in time for the pre-dive conferences with the crew, but the extra team members required for this worked long hours at the expense of other tasks. It is normal and expected in human space flight operations to

work extra hours to resolve problems, but much of this work is often done by a backup team (Replan Team) designated for this purpose, and the replanning does not interfere with ongoing operations. The ExPOC had no such team, and the extensive replanning activity graphically illustrated the need for a Replan Team.

GENERAL LUNAR SORTIE SURFACE SCENARIO

A lunar mission consists of several phases. Figure 1 contains a notional illustration of a complete lunar sortie mission as depicted in April, 2006 on the public website http://www.nasa.gov/mission_pages/exploration/spacecraft.

A heavy-lift rocket blasts off, carrying a lunar lander and a "departure stage" needed to leave Earth's orbit (below left). The crew launches separately (below, center), then docks their vehicle with the lander and departure stage and heads for the Moon (below, right).



Three days later, the crew goes into lunar orbit (below, left). The four astronauts climb into the lander, leaving the vehicle to wait for them in orbit. After landing and exploring the surface for seven days, the crew blasts off in a portion of the lander (below, center), docks with the crew vehicle and travels back to Earth. After a de-orbit burn, the service module is jettisoned, exposing the heat shield for the first time in the mission. The parachutes deploy, the heat shield is dropped, and the crew vehicle sets down on dry land (below, right).



Figure 1 - Lunar "Sortie" Mission Overview

The lunar surface operations phase begins when the lander, also known as the Lunar Surface Access Module (LSAM) lands on the lunar surface and continues until the LSAM lifts off from the surface.

The LSAM serves as the crew's combined habitat and laboratory for the lunar "sortie" missions. It contains all required life support systems and associated consumables (air, water, etc). The LSAM has an airlock for crew Extravehicular Activity (EVA) ingress and egress. In addition, the LSAM may be required to transport the tools, robots, and rover as required for the mission, (unless a cargo vehicle is sent pre-mission to the lunar surface with this equipment).

Limitations to the amount of mass the LSAM can lift into lunar orbit will necessitate the selection of the best lunar samples for return to Earth. In addition, the crew may be forced to leave some items on the surface as was done during the Apollo missions. Candidates include the descent stage, dry trash, rover(s), and tools.

Initial Surface Configuration Activities

After landing on the lunar surface, the crew performs post-landing activities such as LSAM systems' reconfiguration for surface operations, cabin configuration, suit doffing and temporary stowage (if necessary), waste management center and galley activation, seat reconfigurations (if necessary), and a meal.

Daily Activities

While on the lunar surface, daily activities consist of postsleep activities, EVAs, LSAM daily systems' checks and reconfigurations, and presleep activities.

Once on the lunar surface, daily activities associated with the crew's health and well being are similar to those occurring on transit days between the Earth and the Moon with the addition of EVAs. Each day begins with postsleep activities including a meal, hygiene tasks, LSAM system and cabin configurations, and review of the daily changes to procedures and the day's activities. The bulk of the crew day is focused on preparation for and execution of EVA operations. A daily exercise routine is not required because the crew exertion during an EVA provides adequate exercise and satisfies the requirement for daily exercise. Following the EVA operations, pre-sleep activities include a meal, housekeeping, Public Affairs Office (PAO) events, a Daily Planning Conference (DPC), a Private Medical Conference (PMC), occasional Family Conferences, LSAM systems' configuration for crew sleep, and configuration of sleep accommodations. During the sleep period, at least one crewmember has the ability to hear audible caution and warning tones, if these annunciate, as well as communication capability with the ground.

Surface EVAs

The emphasis of the lunar surface activities is on EVAs and the scientific activities performed on each one. On the Moon, all four crew members of the LSAM have the capability to don surface EVA suits and egress the vehicle through an airlock to simultaneously conduct operations on the lunar surface. By operating in an EVA buddy-mode (two 2-person teams) with all four crew members on the surface every day, the scientific and operational value of the mission is maximized. The crew's activities focus on exploration science and technology demonstrations for further development of lunar EVAs and for preparing for Mars surface operations.

Sortie surface missions lasting four days will have EVAs each day. The first (landing) and last (ascent) days may have shorter duration EVAs of 4-6 hours, while the middle two days each have a full 6-8 hour EVA period. Longer duration sortie missions of 5, 6 or 7 days have additional EVAs, with the flexibility to conduct some of these EVAs with just two crewmembers to provide a rest day if needed for each crewmember, or a day when two crewmembers can stay in the LSAM and perform Intra-Vehicular Activities (IVA).

The IVA crew may directly support the EVA by tele-operating robotic assistants, transmitting data requested by the EVA crew, and monitoring their equipment and movements. Other IVA tasks could include maintenance and cleaning of EVA equipment not in use, remote operation of surface experiments, and some degree of sample screening in conjunction with the Earth-based science team to determine which specimens have the greatest merit for return to Earth. This assumes that sample handling can be done inside the LSAM without contaminating either the samples or the cabin environment. Such capability within the LSAM will be limited at best. During lunar outpost missions, the habitat will have laboratory facilities where analysis that is safe for both the specimens and the cabin environment can be performed.

Surface mobility systems, such as a rover, are used to allow all crew members to efficiently explore the local lunar area surrounding the LSAM. A rover plays a key role in providing EVA crew, tool, and geologic sample mobility on the surface, and also enables longer duration EVAs by alleviating crewmember fatigue, reducing suit consumable use, and possibly providing suit consumable resupply.

The LSAM has an airlock capability, so that the entire LSAM crew cabin does not have to be

depressurized when performing an EVA. This allows the flexibility of having some of the crew stay inside the vehicle in an IVA shirt-sleeve environment if needed during an EVA. An airlock also provides a staging area for checking out and servicing the spacesuits, and is a barrier for reducing the amount of lunar dust that enters the LSAM cabin. Various low volume airlock designs, that result in little loss of atmosphere during an airlock cycle, are being studied.

EVA Prep Operations

Prior to exiting the LSAM, the crew performs their suit configuration tasks and checkout activities. All critical life support functions including backup systems are verified and spacesuit pressure integrity is confirmed by performing a leak check. Suit telemetry during both checkout and surface operations is monitored by flight controllers in the Mission Control Center (MCC). When possible this data will be monitored real-time. Even if data is received real-time, all results from the checkout are downlinked to the ground for analysis.

Once the suits are donned, the crew pressurizes the suits. During prebreathe operations (if necessary based on vehicle design), the crew performs communication checks with MCC, the LSAM (if an IVA crewmember is present), and with each other. In addition, the crew will perform final checks of the suit and airlock systems to prepare for airlock depressurization and EVA.

At the completion of the prebreathe operations, the crew is ready to depressurize the airlock(s) to vacuum. Once an airlock is at vacuum, the crew transfers the suits from airlock umbilical power to internal suit power to initiate usage of in-suit consumables. The “outer” airlock hatch is opened and the crew egresses the LSAM.

EVA duration is determined by crew physiological limits, suit consumables, and scheduling limitations such as same-day lunar ascent. Past EVA experience indicates that continued useful work can be expected for EVAs no more than six to eight hours duration. This duration also allows daily non-EVA activities such as pre and post sleep operations, meals, etc. to fit within an acceptable crew day length. This time duration is longer than Apollo EVAs and back to back EVAs are beyond Shuttle and ISS experience. This EVA plan may have to be modified based on testing with 1/6th gravity. Modern surface EVA suits are expected to be more comfortable, provide a more extensive range of motion, and be less fatiguing to wear than Apollo-era suits.

In the event, that an EVA crewmember needs to recharge their suit consumables while they are outside the LSAM, recharge stations can be provided at various locations. Possible locations for these recharge stations are on the vehicle (e.g., LSAM exterior), on the rover, or in designated spots on the lunar surface. If a recharge capability exists on the rover, this would allow the EVA crew to recharge suit consumables while driving around the lunar surface, thus minimizing the timeline impacts for the recharge.

As with the Space Shuttle spacesuit, consumables are automatically monitored and estimated remaining operating time is presented to the crewmember as part of the suit system status. When combined with location data from the rover’s navigation system, the time to return to the LSAM can be estimated. The advanced in-suit caution and warning monitoring of suit consumables, as well as crew locator system data is downlinked to the MCC in order to safely manage the EVAs. This automated system can alert the crew when it is necessary to travel back to the LSAM airlock, based on consumable levels and the crew’s distance from the vehicle. Crew locator systems can also be used to pinpoint the location of the EVA crew when they are beyond the IVA crew’s line-of-sight. This provides a valuable safety feature if a crew rescue or assistance from a robotic surface rover is required. Even without line-of-sight communication on the lunar surface, such data could be relayed to the IVA crew from Earth, at least for a mission to the near side of the Moon.

EVA Tasks

Tasks performed by the crew during the EVAs can be divided into the following five categories:

1. Setup tasks performed on the first EVA only
2. Setup tasks performed on every EVA

3. EVA surface tasks
4. Cleanup tasks performed on every EVA
5. Cleanup tasks performed on the final EVA only

Setup Tasks - First EVA Only:

There are some setup activities required at the beginning of the first EVA to establish an infrastructure to support all of the EVAs. These activities include:

- External light fixtures and video cameras unstow and deployment - External lighting illuminates areas outside of the LSAM that are visited frequently by the EVA crew, such as LSAM ladders (for descending out of the vehicle), suit consumable recharge stations, and a rover parking/servicing area. Video cameras on the lunar surface provide the MCC the capability to monitor the EVA, as well as for public affairs requirements.
- Rover unstow, deployment, activation and checkout
- EVA tools and equipment unstow

Setup Tasks - Every EVA:

At the beginning of each EVA, the crew will perform the following setup tasks:

- Rover activation - For rover-based EVAs, the crew may need to power up the rover and perform a quick systems check. This is a shorter checkout than the one performed on the first EVA.
- Science experiment equipment unstow - Packages of the scientific experiments are unstowed from the LSAM and secured to the rover or to the EVA hand carts for transport to the worksites.
- Equipment necessary for collecting and documenting lunar samples

EVA Surface Tasks:

The crew ventures away from the LSAM either by walking or via the rover to pre-determined locations to conduct their science activities. These worksites are located with the use of maps and electronic navigation equipment that resides on the rover and/or the suits. Some science worksites may not be determined pre-flight, but are selected by the crew and MCC science team, based on their observations during the mission. Some science tasks may involve scouting worksites for experiments to be performed on later EVAs or later missions. In addition observations of by unmanned robotic pre-cursor missions will drive some of the site selection.

The MCC plays a significant role in managing EVA operations. EVA flight controllers carefully monitor spacesuit consumable levels and suit performance. Since the lunar suit life support system may not be able to support a complete EVA without a recharge (to minimize the crew's "on-back" weight-carrying load), the MCC has a critical responsibility in managing the EVA systems and ensuring the crew does not travel too far from a recharge station. In addition, the crew has the ability to view timelines and detailed procedures while performing an EVA via printed or electronic checklist.

There will be built in flexibility in the mission timeline should the need arise for real-time changes. An example of a real-time change is when the crew finds a site that is more scientifically interesting than those previously planned. In addition, the science community supporting on the ground may want to make changes to the timeline, based upon what they discover during the mission. Real-time requests from the science community are coordinated with the Lunar Surface Operations Officer and EVA Officer consoles in the MCC. For more details on the Lunar Surface Operations Officer and EVA Officer consoles, see the "Considerations and Challenges" section above.

Having communication with the ground, although highly desired, should not be required to

continue an EVA. The crew should be free to continue an EVA if communication with the MCC is lost due to planned communications outages or unanticipated short communications outages, as long as remaining nominal conditions exist. The crew is trained to work completely autonomously if communication is lost with MCC, although nominal operations may cease depending on reasons for the communication outage.

Lunar exploration EVAs conceivably could have integrated EVA and robotics operations, in order to allow for most efficient time usage while crewmembers are out on an EVA. Robotic equipment assists crewmembers with scientific experiments and scouting out significant geologic sites. The rover itself may become a platform for unmanned robotic exploration after the crew departs the surface.

EVA science activities include making observations and compiling a comprehensive survey of the local surface geology, including collecting samples of the different geologic characteristics, rocks and regolith. Subsurface investigations are also conducted by geophysical profiling, drilling, or trenching techniques, and by observing natural depressions in the surface such as impact craters or lava channels. Experiment packages are deployed in order to monitor geophysical and space physics characteristics of the Moon. One type of experiment package would be ISRU (In-Situ Resource Utilization) technology demonstrations include the mining, movement, and/or manipulation of the lunar regolith, the chemical processing of the regolith to produce useful materials such as oxygen, hydrogen, and metals, and regolith stabilization techniques for constructing roads and/or landing pads.

The EVA crew may also perform technology demonstrations in addition to exploration science activities.

Cleanup Tasks - Every EVA:

At the conclusion of each EVA, the crew returns to the LSAM and performs the following cleanup tasks:

- Rover servicing - Nominally, minor servicing, such as battery recharging, prepares the rover for the next EVA. In a contingency, more significant servicing, such as replacing a tire may be needed.
- Scientific samples stow - Collection bags and containers of lunar samples collected during the EVA are stowed in the airlocks, and then brought inside the LSAM for cataloging and return. Samples will be sealed in such a way as to avoid O₂ contamination and to preclude lunar dust from being introduced into the crew cabin when the vehicle regains a zero-g environment in lunar orbit.
- Equipment stow - Any small pieces of scientific equipment that collected/recorded data that needs to be brought back to Earth are also stowed in the airlocks. Or equipment that has data recorded which may need to be downlinked to MCC for evaluation. The scientific data may influence the EVA plan for the rest of the mission.
- Suit dust removal - The removal of dust from the suits is a multi-phase operation. First, the crew removes as much dust as possible from their suits, by stomping their boots and by using special brushes. Air hoses or devices utilizing advanced technologies may also be provided for dust removal. A more thorough cleaning of the suits is performed post EVA after suit doffing.

Cleanup Tasks - Final EVA Only:

There are some cleanup activities that are only required at the end of the final EVA to conclude the lunar surface operations and prepare for return. These activities include:

- Final sample bag and equipment stow - Any sample bags and containers, and scientific equipment that need to return with the crew are stowed.
- LSAM inspection and configuration for liftoff - The crew inspects the vehicle and surrounding area to make sure that there is no debris that could interfere with liftoff.

Items left on the lunar surface that could possibly be of use on later missions, such as the rover, need to be moved to a safe distance away from the LSAM, so that they are not damaged by the LSAM exhaust plume or blowing dust.

- EVA Equipment removal and jettison - To reduce liftoff weight and save propellant, items no longer needed can be discarded on the lunar surface to reduce the LSAM liftoff mass.

Post EVA Operations - Every EVA

After removing as much dust from their suits as possible, the crew ingresses the airlock(s), closes the outer hatches, and initiates repressurization. The repressurization may include a hold at an intermediate airlock pressure to perform an airlock integrity leak check.

Once the airlock pressure reaches the LSAM cabin pressure, the crew depressurizes their suits and opens their airlock inner hatch. The crew can then doff the suit and other associated EVA equipment/garments in order to dress into their "regular" clothes.

Prior to ending their day, the crew performs a thorough cleaning of the outside of the suits. Connectors and seals are inspected and cleaned to remove any remaining dust contamination. In addition, suit life support consumables are replaced or recharged.

During crew sleep, MCC will uplink any updates to timelines and detailed procedures for the next day's EVA activities to the LSAM. The ground reviews these changes with the crew prior to them being performed the following day.

LSAM Lunar Ascent Preparations

The crew dons their launch/entry/survival suits prior to LSAM liftoff. All spare components and equipment are stowed prior to LSAM liftoff. These items have to be secured for a dynamic flight environment with appropriate restraints or stored in dedicated stowage volumes. In addition, lunar samples and scientific equipment that will return to Earth with the crew, are stowed and secured in a similar fashion.

CONCLUSIONS

Every lunar mission must also be regarded as a rigorous flight test of the vehicles, equipment, procedures, flight rules, and operations concepts. Lessons learned must be captured and applied to later vehicle designs, mission architectures, and operations plans.

The decision to establish a lunar base for long duration missions at a single site would be driven by the desire to delve deeper into lunar science and exploration, or by the need for larger scale technology testing and more Mars-like experience in planetary surface operations.

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ACRONYMS

AAS	American Astronautical Society
AOC	Advanced Operations Cadre
CAO	Communications and Activities Officer
CEV	Crew Exploration Vehicle
CM	Command Module
DATA	Data Officer
Desert RATS	Desert Research and Technology Studies
DPC	Daily Planning Conference
DTO	Detailed Test Objective
EVA	Extra-Vehicular Activity
ExPOC	Exploration Planning and Operations Center
HMP	Haughton Mars Project
HUD	Heads-Up Display
ISRU	In-Situ Resource Utilization
ISS	International Space Station
IVA	Intra-Vehicular Activity
JSC	Johnson Space Center
JPL	Jet Propulsion Laboratory (NASA)
LEO	Low Earth Orbit
LM	Lunar Module
LRV	Lunar Roving Vehicle
LSAM	Lunar Surface Access Module
MCC	Mission Control Center
MDRS	Mars Desert Research Station
MOD	Mission Operations Directorate
NASA	National Aeronautics and Space Administration
NEEMO	NASA Extreme Environment Mission Operations
NOAA	National Oceanographic and Atmospheric Administration
NOAMA	NASA Oceanographic Analog Mission Activity
NURC	National Undersea Research Center
NWS	National Weather Service
OPS	Operations Director
PAO	Public Affairs Office
PI	Principal Investigator
PMC	Private Medical Conference
ROV	Remote Operated Vehicle
SIM	Scientific Instrument Module
SM	Service Module
SMG	Spaceflight Meteorology Group
U.K.	United Kingdom
UNCW	University of North Carolina at Wilmington
U.S.	United States of America