

Training for Lunar Surface Operations

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With foreword by
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Frontispiece

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Abstract

Artemis lunar surface operations require the development and implementation of skills not utilized since Apollo. Here we review the skills and the protocols subsequently developed for a new generation of explorers engaged in longer duration missions and sustained lunar operations.

- The Artemis III landing site and an Artemis Base Camp within 6° of the lunar south pole will be in an impact-cratered terrain and, thus, crew should be given basic geologic training and conduct EVA simulations in appropriate analogue terrains.
- Based on Apollo experience, classroom, laboratory, and field-based training for lunar surface conditions may exceed 1000 hours and should begin immediately to meet the Artemis schedule. Crew, once selected for a mission, may need to be engaged in monthly field exercises.
- In addition to monthly field exercises, complex mission simulations should be conducted in analogue terrains with the integrated expertise of a broad group: the astronaut office, astronaut trainers, field geology trainers, site selection teams, geologists involved in surface operations planning, lunar sample analysts, *in situ* resource specialists when appropriate, equipment designers, flight controllers, and management. The simulations will uncover unanticipated challenges, produce a well-working team, and give that team the resiliency to successfully resolve unexpected conditions that may arise during a lunar surface mission.
- Constellation mission simulations demonstrated an integrated flight and science operations architecture greatly enhances mission productivity and will provide the crew with lunar surface expertise when engaged in lunar surface activities.
- Apollo experience and the nature of the Artemis polar terrain suggest the science team supporting training activities and subsequent lunar surface operations be led by a Principal Investigator with well-documented field experience in impact-cratered terrains, well-documented analytical experience with lunar samples, well-documented experience with analyses of lunar polar terrains, well-documented experience managing a large team, and, ideally, existing experience with the human exploration program at JSC.
- Constellation mission simulations demonstrated EVA training for crew is evolving from task-specific training needed for Shuttle and International Space Station activities to a skills-based training model needed for lunar surface exploration. Skills-based training will become increasingly important as the duration of lunar surface stay times increase.
- The development of EVA training needs to be initiated immediately to meet the Artemis schedule. It is important to develop the operational concept and applicable skills in parallel with hardware development.

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FOREWORD

By any measure the exploration of the Moon by the Apollo astronauts was a resounding success. Transporting humans to the Moon and back safely never had been done before, and to complete that task for the first time in history was a great accomplishment in and of itself. To add Apollo's science return, its other technological breakthroughs, plus the inspiration it gave to people all over the world, it can be said, "Apollo hit it out of the park!"

But Apollo happened fifty years ago, and today we are on the threshold of returning humans to the Moon with the Artemis program. Artemis (the twin sister of Apollo) will take us there with more advanced capabilities than Apollo to explore and understand our nearest neighbor in the solar system. Ultimately the goal is to establish a permanent presence on the Moon not only to explore it but also to understand its use in the future of human space travel beyond the Moon.

Apollo landed humans at six locations on the "front side" of the Moon, and because of performance capabilities, in locations not at or near either polar region. While we learned a lot about the Moon from Apollo's six landings, we really have only begun.

As a Flight Director during Apollo I can say unequivocally from my viewpoint that in the early missions my primary focus was on getting the astronauts to the Moon and safely back to Earth, and to get whatever "exploration/science" accomplished that we could. I believe that was a common perspective of pretty much everyone. While we had our eyes on exploration and science our predominant focus was on getting the astronauts back on the Earth in one piece.

I also can say that much of the success of Apollo from a mission operations perspective was due to the superb training we received before each mission. Hours and hours of integrated simulations with the Mission Control Center (MCC) fully staffed and the astronauts in the Command and Service Module Simulator and/or the Lunar Module Simulator really paid off in understanding the spacecraft systems and how to handle problems thrown at us by the simulation folks. To this day I'm amazed at the high fidelity of the Apollo integrated simulations. In the MCC we couldn't tell the difference between a simulation and a real mission. However, we didn't have the same integration capability to tie in the MCC with the lunar crews when they were training in the field for their lunar excursions in places like Meteor Crater in Arizona or Ries Crater in Germany. There was no way to connect the remote field training sites to the MCC. But, things got better starting with Apollo 15 which carried over to the final two missions, Apollo 16 and Apollo 17.

I was the Lead Flight Director for Apollo 15, and as soon as Apollo 14 landed in 1970 we started getting ready for Apollo 15. The Apollo 15 Commander, Dave Scott, reached out to me and told me that I should come with Jim Irwin and him on their next geology field trip to monitor and understand how they would be training to conduct a lunar excursion at Hadley Rille. I accepted Dave's invitation, and I not only watched and listen to them conduct the session, I also walked with their trainers and was able to listen to the trainers' real-time critique of the crew between themselves. I also was able to ask the trainers questions on the "what and why" of what Dave and Jim were doing. From that first training in the field I not only learned a lot about the ripe exploration site at Hadley Rille, I learned a lot about geology. From that time forward until the end of Apollo I became good friends with people such as Gene Shoemaker, Lee Silver,

Gordon Swann, and Bill Muehlberger...all giants in the field of geology. Most important of all...it changed my perspective on lunar exploration!

After my first field trip with the Apollo 15 crew I went back to Houston and told the other Flight Directors that they needed to “get out in the field with the astronauts and trainers”...and they did! Word trickled out to operations management people all the way up the chain of command to NASA Headquarters, and several of the senior people in the Apollo program attended geology field trips before the program ended in 1972.

The result? From my perspective, and I believe the perspective of most others, for Apollo 15-17 I could feel the focus move toward a feeling that we were going to the Moon to explore and understand, not to just get there and back safely. Could we take our eyes off the transportation system which had to get us there and back? Of course not, but we had a greatly enhanced feel for and focus on why we were going, what we were going to do when we got there, and how we were going to do it. I also learned I wished I had been exposed earlier to the crews’ field geology training.

Artemis necessarily will have some of the same “transportation focus” early on, and that’s okay. But I believe this is an area where Artemis can truly stand on the shoulders of her brother to learn an important lesson, to wit, *Earth-based field geology training of the explorers is essential before they go to explore another place in our Solar System. Also, while not every person on the mission operations team can experience crew field geology training, the Flight Directors and certain other key people in mission operations should be exposed to it to get the most bang out of our human space exploration buck.*

Gerry Griffin
Former Apollo Flight Director
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1. Introduction

This report addresses (i) geologic training of astronauts in terrains relevant to exploration of the lunar poles, (ii) operational training of scientists who may be assisting lunar surface missions, and (iii) mission simulations that develop team skills among crew, science operations personnel, and flight operations personnel. The document captures lessons learned during six years of work for the Constellation Program when we and others were developing capabilities to explore the lunar south pole, to deploy surface assets in that region, and, in parallel, develop the capabilities for a subsequent global lunar exploration program. Significant overlap exists between Constellation and Artemis objectives, so previously learned lessons are directly applicable to the current need to train staff for Artemis lunar surface operations.

In an early phase of the Constellation Program, an assessment was made of training activities needed for lunar surface operations (Kring, 2007a; attached as Appendix A). The findings were:

- All lunar surface activities will occur in impact-cratered and volcanic terrains and, thus, crew should be given basic geologic training and conduct EVA simulations in appropriate analogue terrains.
- EVA training in analogue terrains should involve the integrated expertise of a broad group: the astronaut office, astronaut trainers, field geology trainers, site selection teams, geologists involved in surface operations planning, lunar sample analysts, in-situ resource specialists when appropriate, equipment designers, flight controllers, and management (SMD, ESMD, SOMD).
- Field mobility is needed for crew and robotic assistants.
- Integration of human and robotic exploration components should be tested in analogue terrains with realistic simulations of lunar surface operations. Likewise, all tools to be used by crew in lunar surface operations should be tested in realistic simulations.
- Initially, missions will be of relatively short duration and, thus, traverse-dominated with backroom support, which requires training like that for the Apollo J missions.
- Training for extended duration missions will need to develop greater crew independence, because they will be operating in an exploration mode that (i) more closely mirrors terrestrial field work and (ii) takes advantage of the human ability to analyze in real time. Backroom assistance will still be important, but the crew will not require constant consultation over long durations (e.g., 30- to 180-day expeditions).
- Four-person crews should include mission specialists with advanced training in subjects like geology, resource recovery, and engineering. These individuals could potentially be involved in pre-mission scientific research and engineering trade studies associated with lunar surface operations.

Several of those findings were reflected in subsequent Constellation activities. For example, with support of Astronaut Selection and Training Manager Duane Ross, the training program for astronaut candidates was updated to reflect a potential lunar destination. That activity began with a meeting at the Lunar and Planetary Institute (LPI) in April 2008 that involved eight Apollo geology trainers, two Apollo surface crewmembers, and a lead flight director to ensure Apollo lessons were captured (Eppler, 2008). The revised curriculum, including a new geologic guidebook developed for Meteor Crater (Kring, 2007b), was used for the 2009 class of astronauts in a series of impact cratering exercises in 2011 led by Apollo 15

trainer Gary Lofgren, Apollo 16 trainer Fred Hörz, and Center for Lunar Science and Exploration (CLSE) Principal Investigator (PI) David Kring. After Constellation was canceled, scaled-down versions of that training were used for the 2013 and 2017 classes of astronauts.

The second, third, and fourth findings were reflected in lunar mission simulations developed by the Constellation Lunar Surface Systems (LSS) project, JSC's Desert Research and Technology Studies (DRATS), and Human Robotic Systems (HRS) project as part of NASA's Exploration Technology Development Program (ETDP), coordinated with Exploration Systems Mission Directorate's (ESMD's) Directorate Integration Office (DIO), NASA Headquarters (Doug Craig), and other agency institutions (KSC, ARC, GRC, JPL). A series of 1-, 3-, and 14-day-long lunar mission simulations (e.g., Abercromby et al., 2010, 2012, 2013; Eppler et al., 2013; Hörz et al., 2013) were produced at the Black Point Lava Flow (<https://www.lpi.usra.edu/lunar/analogs/blackpoint/>) in 2008 through 2011.

The experience gained during those training and mission simulation activities form the baseline for the current report, which re-examines training objectives in the context of Artemis and that program's objectives in the lunar south polar region.

2. Major Aspect 1 - Skills

2.1. Science

2.1.1. Background Knowledge

The lunar surface is a geologic surface and all Artemis activities will occur in that geologic environment. Scientific objectives, exploration opportunities (e.g., *in situ* resource utilization), and mission risks will be shaped by that environment. Thus, crew need to have a basic understanding of lunar geology and geological processes. Those skills will provide the foundation upon which mission-specific IVA and EVA training can be developed, as described further in **Section 3**. Other science and exploration objectives will require a complementary set of basic skills, such as an understanding of solar wind properties, radiation hazards, illumination conditions as a function of latitude, and properties of volatiles in sub-100K permanently shadowed regions.

Astronaut candidates are introduced to a subset of skills required for lunar exploration. That basic skill level needs to be enhanced among Artemis astronauts assigned to lunar operations. Those additional skills can be introduced through a well-designed set of classroom and laboratory exercises in Houston, integrated with field-based activities that develop the application of those skills in lunar-relevant terrains. We note that the basic skill level among existing astronauts is not the same. The Constellation-era astronaut candidates (the 2009 class) received a more thorough introduction to the basic skills needed for lunar missions than did those in later classes (2013 and 2017).

The development of an enhanced basic skill set will then feed into integrated mission simulations (**Section 3.2**). This is a lengthy process that should begin immediately. We note that Armstrong and Aldrin and the science staff supporting them had 5 years 4 months to develop surface science plans with the flight operations team before the first Apollo landing; and Cernan and Schmitt and the science staff supporting them had more than 8 years to develop surface science plans with the flight operations team for the final Apollo landing. To meet the Artemis schedule, it will be necessary to draw upon the nation's science and engineering expertise as soon as possible. A key lesson of Apollo was to engage early the diverse talents needed for a surface mission (Schaber 2005; Schmitt et al., 2011; Phinney 2015). As was true with Apollo, some of that talent today will be found outside the agency.

2.1.2. Field Application of Skills

Basic skills learned in Houston need to be applied and further developed in relevant field settings. That type of training may occur in a diverse set of geologic terrains. **Table 1** is a list of more than 40 sites compiled by the Constellation Geology Field Training Group and/or utilized during the Constellation Program. Many of the sites have Apollo heritage.

A broad range of training sites can be utilized when developing basic skills. However, as shown in **Section 2.1.3.** below, geologic conditions in the lunar south polar region, where Artemis landings and an Artemis Base Camp are to be developed (NASA, 2020a,b), favor training activities in a subset (~8) of the sites in **Table 1**, augmented by the Duluth Complex, Minnesota.

Table 1. Localities compiled by the Constellation Geology Field Training Group and/or utilized during the Constellation Program. Many of the sites have Apollo training heritage. Those sites of special interest for lunar south polar impact-cratered terrains are marked with an asterisk.

United States	United States (continued)
Meteor Crater, AZ*	Yellowstone Volcanic Field, WY
San Francisco Volcanic Field, AZ*	Stillwater Complex, MT*
Springerville Volcanic Field, AZ	Mt. Marcy, Adirondack Mountains, NY
Sentinel Volcanic Field, AZ	Katmai Volcanic Field, AK
Nevada Test Site, NV*	Mauna Loa, HI
Rio Grande Rift, NM	Mauna Kea, HI
Kilbourne Hole, NM	
Capulin Volcano Natl Mon, NM	Mexico
Zuni-Bandera Volcanic Field, NM	Pinacate Volcanic Field, Sonora
Jemez Volcanic Field, NM	
Great Sand Dunes Natl Mon, CO	Canada
Buell Park, CO	Sudbury, Ontario*
Long Valley, CA	Manicouagan Crater, Quebec
Death Valley, CA	Thetford Mines, Quebec
Coso Volcanic Field, CA	Rainy Lake, Ontario
Mono Lakes, CA	Devon Island, Nunavut
Algodones Sand Dunes, CA	Labrador anorthosite locales
Lassen Peak, CA	
Clear Lake Geothermal Field, CA	Germany
Medicine Lake Volcano, CA	Ries Crater*
San Gabriel Mtns, CA*	
Big Bend, TX	Australia
Sierra Madera impact structure, TX*	Gosses Bluff
Texas Hill Country	
Galveston, TX	Norway
Moses Lake, WA	Svalbard Archipelago

2.1.3. Artemis Landing Site Terrains

Impact-cratered terrains. An Artemis III landing site and Artemis Base Camp within 6° of the lunar south pole will be in an impact-cratered terrain (**Fig. 1**). Because impact craters are pervasive and occur at all scales, from micrometers to >1000 km, it is impossible for an astronaut to take a single step on the Moon without stepping into or onto an impact crater. Previous papers (Kring 2010, 2019, 2020a; Eppler et al., 2020) outlined a few steps needed to prepare for lunar surface science operations in that type of terrain. Here we expand those remarks and draw attention to specific training sites that are particularly relevant for south polar operations.

Impact cratering shaped the lunar south polar region in dramatic ways. That is evident in the immediate vicinity of the south pole where astronauts, peering into Shackleton crater, would find their gaze lost in an excavated cavity the diameter of Houston's 610 beltway and more than 3 times deeper than the Earth's Grand Canyon. Nearby, impact-generated massif summits rise ~6 km above the lunar datum of elevation (the Moon's 'sea level') and crater floors reside nearly as far below the lunar datum, producing elevation differences that exceed the height of Earth's Mt. Everest over sea level. Because that dramatic topography occurs in a polar region where the Sun never rises more than a few degrees above the horizon, long shadows stretch across the surface and in some cases permanently obscure topographic lows. Those permanently shadowed regions on the floors of impact craters may harbor important resources like water ice. Indeed, impact cratering is the single most important geologic process affecting ISRU prospects (Kring et al., 2020a; Kring, 2020b). For safe, efficient, and productive surface operations, it is necessary for crew to understand the basic properties of impact-cratered terrains (e.g., the types of consolidated and unconsolidated surfaces) and the distribution of high-priority scientific and ISRU-related materials.

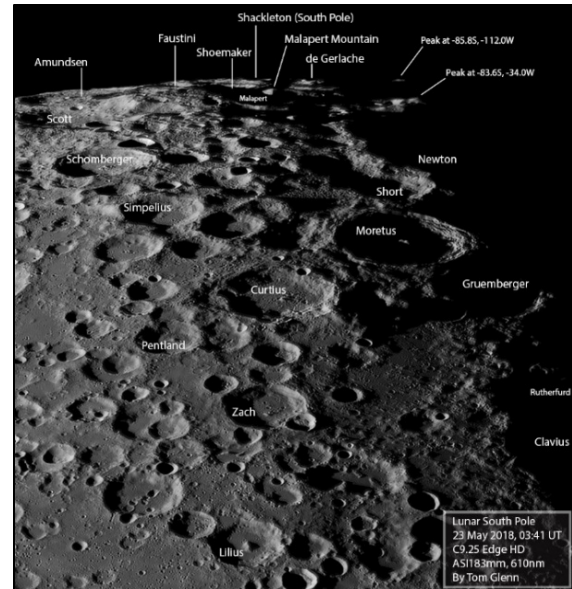


Figure 1. The lunar south polar region is an impact-cratered terrain. Photography by Tom Green.

It is important to recall the experience of Apollo astronauts who found field training and traverse exercises to be the most important component of their EVA preparation. Charlie Duke said “The geology field trips were outstanding. The monthly trips we did from the time we started on the crew were just right.” John Young added that a field exercise “helps you get a team work pattern and I think that’s real important. You are not very effective unless you’re working as a team up there. Otherwise you’re just going to be spinning your wheels on the Moon and that’s not where they want you to spin them.”

There are two broad classes of impact craters: those with simple, bowl-shaped morphologies and those with more complex central-peak or peak-ring morphologies. Training should expose crews to both types of lunar landscapes (**Fig. 2**) in terrestrial sites such as Meteor Crater, Sierra Madera Crater, and the Ries Crater.

The 1.2 km diameter Meteor Crater of Arizona (**Fig. 3**) is a perfect training site for the geologic processes that produced Shackleton crater at the south pole and smaller craters scattered throughout the south polar region. Meteor Crater was an Apollo training site. It is very much like North Ray crater at the Apollo 16 landing site, which was in a lunar highland terrain like that at the lunar south pole. As noted above, Meteor Crater continues to be used for basic training of astronaut candidates. The LPI-JSC Center for Lunar Science and Exploration (CLSE) also has an existing training program at the crater for graduate students. Thus, substantial experience and training materials already exist and can be used to provide crews with a more in-depth exposure to crater features that may affect lunar surface operations.

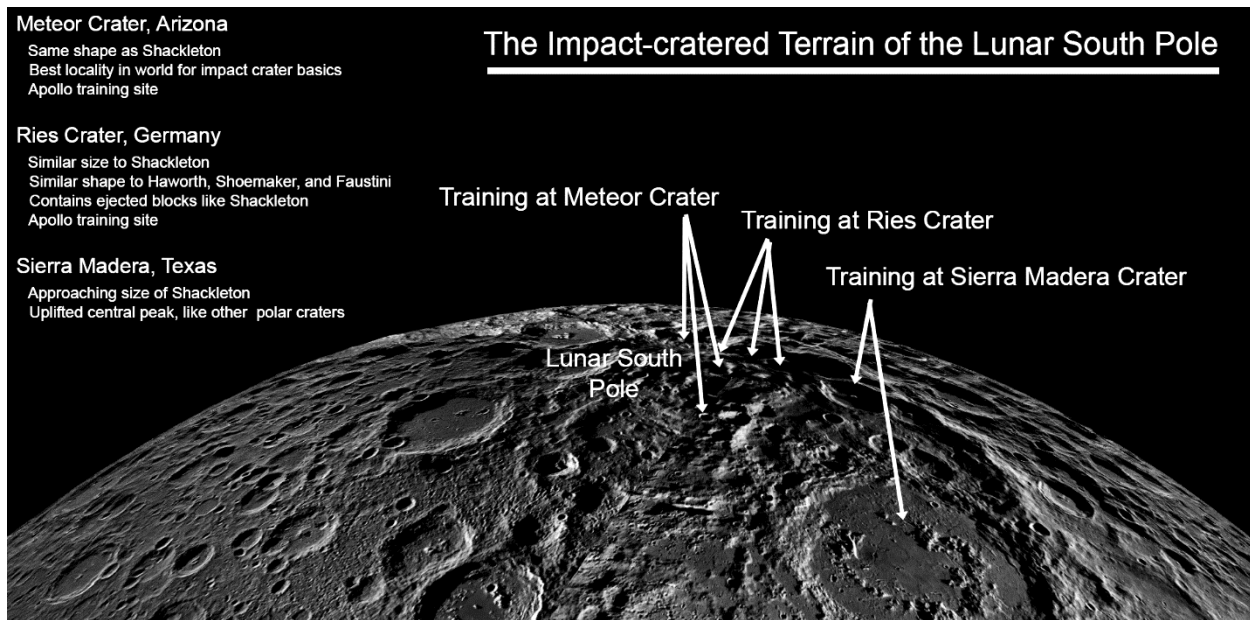


Figure 2. Shackleton crater and dozens of smaller craters around the south pole are similar to Meteor Crater, Arizona. Haworth, Shoemaker, and Faustini craters are similar to the Ries Crater in Germany. Amundsen crater and the Schrödinger impact basin have features like those accessible at the Sierra Madera impact structure in west Texas. The Schrödinger impact basin has been identified as a high-priority landing site for both human and robotic missions. It is the selected target for a CLPS landing in 2024.

Importantly, previous field studies at Meteor Crater (Kring 2007b, 2017; Kring and Hörz, unpublished training documents) were coordinated with field studies of nearby volcanic craters and lava flows (Kring and Hörz, unpublished training documents). The contrast between those volcanic features and Meteor Crater further clarified the unique and important properties of an impact-cratered geologic surface, while also providing an opportunity to introduce astronauts to volcanic geologic features that will be encountered in later missions beyond the lunar south pole.

It is useful to supplement field studies at Meteor Crater with field activities at the 300 m diameter Schooner crater (**Fig. 3**) at the Nevada Test Site. Schooner crater provides additional insights to lunar-like terrains (Kring, unpublished training documents), because it has fresh features like those observed by Apollo astronauts. Indeed, the site was utilized for EVA training during the Apollo era.

However, the dimensions of Artemis destinations, like Shackleton crater (21 km diameter), may require training activities at Sierra Madera Crater of West Texas (13 km diameter) and the Ries Crater of Germany (24 km diameter) to expose crew to features associated with craters produced by higher energy impact events and to explore the operational issues (e.g., communication, rover mobility, and supplies) that are affected by greater distances.

The Sierra Madera impact structure in west Texas is a complex, central-peak crater (Wilshire et al., 1972; Kring, unpublished training documents). The mountains (sierra) in the middle of the structure (**Fig. 3** inset) are the fairly well-preserved remnants of a central peak. The rim of the structure is more subdued. The structure provides an opportunity to work in a larger scale structure and see the types of rocks produced by craters larger than Meteor Crater.

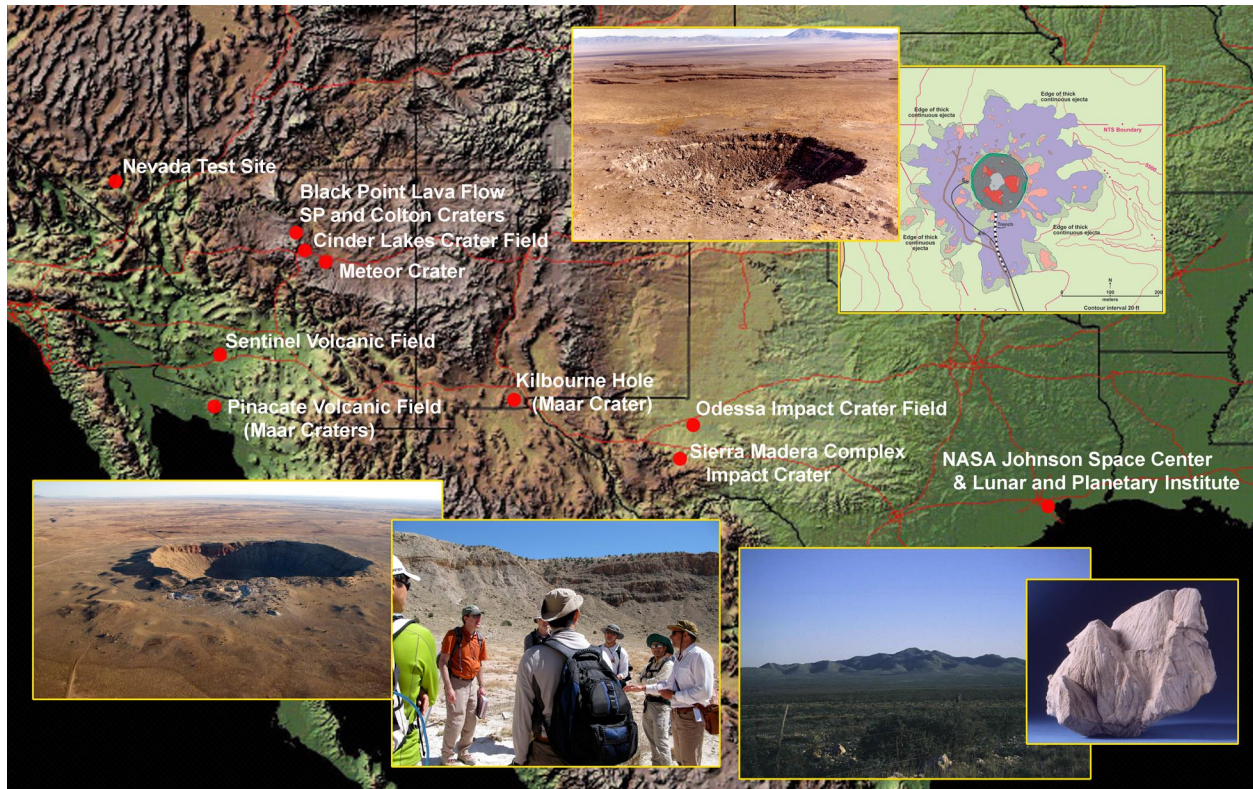


Figure 3. Training sites used previously by CLSE PI Kring. (insets, counter clockwise from lower left) aerial view of Meteor Crater; the 2009 class of NASA, CSA, and JAXA astronauts with Kring on floor of Meteor Crater; the central peak of Sierra Madera Crater and a sample of shocked rock from that portion of the crater; map of Schooner Crater, Nevada Test Site; aerial view of Schooner Crater. NASA's Solar System Exploration Research Virtual Institute (SSERVI) currently supports CLSE training programs at Meteor Crater and the Sudbury impact structure.

Sites like Meteor Crater, Schooner Crater, and Sierra Madera Crater in the American southwest are particularly attractive for lunar surface training, because the geology is magnificently exposed, like the geology of the lunar surface. The geology is not obscured by vegetation, as it might be in other parts of the world.

These activities should be led by a Principal Investigator (PI) of lunar surface science operations, similar to the PIs of Apollo (Gene Shoemaker, Gordon Swann, and Bill Muehlberger). The Artemis PI of lunar surface science operations should have extensive analytical experience with lunar samples and extensive field experience in impact-cratered terrains like that at Meteor Crater.

The Ries Crater in Germany is another classic impact site (e.g., Hörz et al., 1983; von Engelhardt 1990; Kring, 2005) used for Apollo astronaut training. The crater's geology is not as exposed as that at Meteor Crater and Sierra Madera, due to vegetation and human habitation, but CLSE has previously utilized (Kring, unpublished training documents) a dozen locations where suitable rocks are visible and can be studied under field conditions. Ries Crater training can be coordinated with CLSE international partner and European Space Agency astronaut trainer Prof. Harald Hiesinger.

Those field studies could be supplemented by exercises at the Sudbury impact structure in Ontario (e.g., Grieve et al., 1991; Abramov and Kring, 2004), which is an analogue for lunar basins 300 km or larger in diameter, such as the Schrödinger basin in the south polar region (e.g., Shoemaker et al., 1994; Kramer

et al., 2013; Steenstra et al., 2016; Kring et al., 2016). The LPI-JSC CLSE has an existing training program for graduate students at Sudbury that is coordinated with CLSE international partner and Canadian Space Agency astronaut trainer Prof. Gordon Osinski. Thus, again, extensive experience and materials are already available for Artemis training activities at that location.

Highland terrains. The impact craters at the lunar south pole excavated a lunar highland terrain. A lunar highland terrain is composed of primary lunar crust that crystallized from a lunar magma ocean more than 4 billion years ago. That crust was also intruded by molten material (magma) early in Solar System history. That ancient crust was exposed by the largest impact events, such as the South Pole-Aitken impact event, in large mountain massifs, such as the Malapert and Leibnitz β massifs, both of which occur within 6° of the pole. Moreover, Shackleton crater at the south pole appears to have excavated (Halim et al., 2020) one of those massifs and lobbed large boulders of primitive crust onto the surface (Fig. 4). Immense (100 meter-size) exposures of those rocks have been identified in images near the south pole (Gawronska et al., 2020). Multi-kilometer-long exposures of anorthosite and related lithologies also exist in the peak ring of the Schrödinger basin (Kramer et al., 2013; Kring et al., 2016, 2017). Thus, it will be important to train astronauts to recognize and work with such rocks. Classic Apollo-era training sites are the San Gabriel Mountains (California), Stillwater Complex (Montana), and the Duluth Complex (Minnesota). The lunar community visited the San Gabriel Mountains and Stillwater Complex in LPI-led field trips in the last decade, so they are known to be accessible today. We also confirmed that the Duluth Complex remains exposed and accessible for training. John Young, in an Apollo 16 debriefing commented “The ones [anorthosites] at the Duluth gabbro had a remarkable resemblance to the ones out there that we found at the 16 place,” which were small clasts in impact breccias. That was a fascinating comment, because, as one of the Apollo trainers reported (Phinney, 2015), the San Gabriel Mountains were included in the training program because the anorthosite there is more deformed than that in the Duluth Complex and thought to be more like the anorthosites that would be found on the Moon prior to the missions. Young reported the opposite in the small clasts he observed, illustrating the value of training at multiple sites.

The opportunity to study and sample large exposures of anorthosite and related rocks was not available at Apollo landing sites, so they will be an informative target for Artemis exploration.

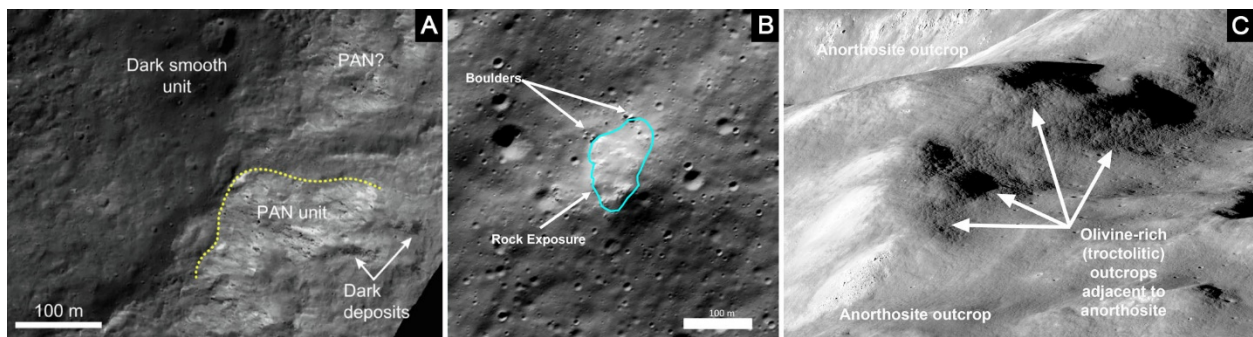


Figure 4. (A) Massive blocks of a rock type called anorthosite, labelled PAN for pure anorthosite, and potentially a remnant of the lunar magma ocean, are visible in the walls of Shackleton crater. (B) One-hundred-meter-size blocks of rock are also seen in Shackleton crater ejecta. (C) Multi-kilometer-long exposures of anorthosite are visible in the peak ring of the Schrödinger basin. These types of rock exposures were never seen at the Apollo landing sites and, thus, provide exciting new opportunities to study the composition of highland terrains. Images from Gawronska et al. (2020) and Kring et al. (2016).

Volcanic terrains. As the Artemis program matures and begins to access a broader range of lunar landing sites, it will be important to provide crews with field experience in volcanic terrains. They will

have had an introduction to that type of terrain in the vicinity of Meteor Crater, as described above, but activities in that area can be expanded to provide additional scope. Activities in the Rio Grande Gorge (near Taos, New Mexico) would also be relatively easy to arrange, because JSC and its partners have already developed materials to support an introduction to such terrains for astronaut candidates.

Terrain summary. Training at Meteor Crater, Sierra Madera Crater, the Ries Crater, and potentially Schooner Crater is appropriate for lunar surface operations in the heavily cratered south polar region. One can also use synthetic impact crater fields produced explosively in volcanic cinder, in the Flagstaff region during Apollo, to teach crew how to trace discontinuous horizons of regolith that will exist in lunar polar regions and elsewhere on the Moon. Training at a terrestrial analogue site for highland or anorthositic rocks, such as the Duluth Complex and Stillwater Complex, is appropriate for samples astronauts may encounter in the south polar region. Training in a larger impact basin (Sudbury) and in volcanic terrains will be appropriate for subsequent Artemis missions. To sharpen crew skills at describing breccias further, exercises in ash-flow calderas (Arizona, Nevada, New Mexico) might be explored. This list of field training sites is comparable to the number of sites used by the Apollo 16 crew (**Table 2**), but features sites more amenable to the terrain anticipated during early Artemis missions in the vicinity of the lunar south pole. Based on Apollo experience, such field exercises will be part of >1000 hours of crew training for lunar surface conditions and should occur at a monthly cadence.

Table 2. Apollo 16 Crew Training for Science Operations^{1,2}

•	Surface-related training (39 sessions, average 4 hrs/each) – 142 hrs
•	Simulations through Mission Control – 12 days
•	Orbital geology (12 sessions, average 3 hrs/each) – 36 hrs
•	Fly-over exercises – 18 days
•	Field trips – 36 days
○	San Gabriel Mtns, CA
○	Merriam Crater, AZ
○	Meteor Crater, AZ
○	Verde River, AZ
○	Capulin Mtn, NM
○	Cinder Lakes, AZ
○	Mono Craters, CA
○	Sudbury, ON
○	Rio Grande, NM
○	Nevada Test Site, NV
○	Coso Hills, CA
•	Geology lectures (45 sessions, average 2.75 hrs/each) – 124 hrs
•	Rock study (17 sessions, average 3 hrs/each) – 50 hrs

Total geologic training time from December 1970 to launch = 110 days

¹Mission training was preceded by hundreds of hours of pre-mission training

²Per Phinney (2015)

2.1.4. Science Leadership

During Apollo, it was recognized that significant expertise existed outside the agency. The Principal Investigators (PI) for Geology selected for the Apollo missions were, consequently, from outside NASA. Gene Shoemaker led the Apollo 11 and 12 geology teams. Gordon Swann and Bill Muehlberger were selected for subsequent missions. All were external to the agency.

During Constellation, the Chief Scientist was Wendell Mendell at JSC. Science operations during mission simulations were led by Gary Lofgren (an Apollo 15 trainer and, during Constellation, the Lunar Sample Curator) and Fred Hörz (an Apollo 16 trainer), both of JSC. However, all three of those scientists have since retired.

The bulk of the lunar expertise currently resides outside the agency, although that expertise often works closely with the agency through a series of grants and contracts. For example, in NASA's SSERVI program, which is the joint SMD and HEOMD program designed to bridge the science and exploration communities involved in human exploration, 10 of 12 (83%) of the program's PIs are from outside the agency.

It is essential that the person assigned to lead lunar surface science activities have (i) well-documented field geology experience. We note that at the time of Apollo, the geology teams drawn to support EVA came from traditional geologic backgrounds with field geology skills requirements. Because of Apollo's success, we have had an opportunity to analyze lunar samples and have those insights to guide future EVA and sample collecting activities, too. Thus, as noted already in **Section 2.1.3**, lunar surface operations in an impact-cratered polar terrain should be led by a PI with (ii) extensive, well-documented field experience in impact-cratered terrains, supplemented with (iii) extensive, well-documented analytical experience with lunar samples. The PI should also have (iv) well-documented experience with geologic studies of lunar south polar sites.

A coordinator of science training for Apollo astronauts, Bill Phinney, wrote in a review (Phinney, 2015) that field training should be led by people who have "experience both as good teachers and researchers," which suggests the PI should (v) have experience as a university professor. In the midst of the Constellation Program, Apollo 17 astronaut Harrison 'Jack' Schmitt wrote (Schmitt et al., 2011) "Instructors should be the best teachers who also are at the top of their fields of specialization. The best mix of NASA and outside instructors should be sought, since it is often difficult for NASA to employ the desired quality of experienced instructors across such a broad range of disciplines. Although there have been, and their remain, clear exceptions, the bureaucratic challenges that come with being a government employee do not interest most active geologists."

Because the bulk of the lunar expertise lies in the academic community outside the agency, the leading science PI may not be a civil servant. In that case, NASA may want to extract a model of leadership from the agency's robotic spacecraft missions. When NASA selects a mission PI from the academic community, where the expertise resides, it then assigns a civil servant as Program Manager or Project Scientist to represent the agency and take care of administrative issues that can only occur within the agency. That formula might be a solution for Artemis: i.e., an external PI for lunar surface operations and an internal Program Manager for lunar surface operations. Such a solution may mitigate some of the issues that arose during Apollo (Wilhelms 1993; Schaber 2005; Phinney 2015). The selected scientists should (vi) have experience managing a large team and, ideally, already (vii) have experience working with the human exploration program at JSC.

PI attributes (i) through (vii) are that of a senior lunar scientist, but science leadership should be designed to support a sustained Artemis Plan (NASA 2020a). A senior scientist may be able to lead a team during the first two or three missions, but additional talent will be needed for subsequent missions. Thus, early- and mid-career scientists should be engaged in training activities described here so that those scientists develop the skills needed to lead those subsequent Artemis missions.

2.2. Extravehicular Activities (EVA)

2.2.1. Background Knowledge

Prior to the Apollo era, little was known about EVA. The successful moonwalks performed during Apollo represented a significant increase in EVA knowledge for partial gravity surface operations. During the early Space Shuttle years, there was another steep learning curve, only this time for zero gravity spacewalks. Based on Apollo, Skylab, Space Shuttle, and International Space Station (ISS) EVAs over the years, as well as the crew training and hardware integration that supported those programs, a tremendous amount of knowledge was collected that should be incorporated into the Artemis exploration program. That said, it is also likely that NASA's current ready-use EVA knowledge base is filled with experiences that are different from those that will be required during the planetary EVAs of the future. The types of EVAs needed for a sustained program (NASA, 2020a) may be different owing to several factors, such as a much greater distance from Earth, the length of time astronauts will spend on the Moon, and the type and quantity of resources available. An important first step to prepare for exploration with a fully integrated EVA capability is for NASA to define and thoroughly understand the EVA requirements. This includes what physical environments we will operate in, what types of tasks to accomplish in what amount of time and what total capability will be provided for by the resources made available.

2.2.2. Application of Skills

NASA's Artemis program is currently addressing development of the EVA Concept of Operations (ConOps). The ConOps will address several questions such as: What sort of operations will be involved with assembly of habitation and science station hardware? What sort of operations will be required to troubleshoot or maintain items? What tasks will occur during a typical day's EVA sortie to collect data? What type of data will a space suited crewmember be required to collect? What equipment will the EVA crewmember interact with to make all these things happen? Intimately associated with the answers to these questions will be a definition of the training concept and all that it implies. This is the only way to ensure that the EVA ConOps can become a reality. The training concept should be considered a part of the overall ConOps that grows in detail and evolves right along with the ConOps itself.

Unlike an ISS assembly EVA, where hardware interfaces and tasks are extensively well known beforehand, future lunar EVAs will require more real time decision making. In fact, this attribute is one of those key aspects that make human presence worth the risk. Spacewalks performed in the Space Shuttle payload bay were trained using task-specific training of a detailed and well-rehearsed timeline. ISS assembly EVAs were trained using the same task-based approach, but augmented with EVA skills training (Ney and Looper, 2005). ISS maintenance training is provided using a predominantly skills-based approach in which EVA skills are taught using different types of realistic maintenance tasks as the training framework. The EVA skills training program currently used was developed at the Johnson Space Center by Mission Operations and Astronaut Office personnel. It utilizes a defined set of skills and associated levels of proficiency (Looper and Ney, 2005, 2006), consistent with ISS EVA requirements, for assessment of an individual trainee's proficiency in both the physical and mental aspects of a 6.5 hr-long EVA. This system can be easily adapted for training exploration skills. The obvious first step will be to define a skill set consistent with the EVA task requirements for exploration, be they related to science, assembly, maintenance, or troubleshooting.

Given the constraints that will be placed on performing lunar surface EVAs, it will be impractical to task train crewmembers to detailed timelines. Moreover, task-specific training, based on Shuttle and ISS experience, is typically more expensive by virtue of being time and resource consuming. This is especially true when timeline task content changes due to program needs. Accordingly, more emphasis will be placed on lunar operators having the skills required to effectively and safely revise and replan timelines to yield the most efficient results. The lunar environment will also be harsher on equipment than the zero-g

environments of Shuttle and ISS. This aspect, along with the difficulties of resupply, will place significant importance on *in situ* hardware troubleshooting and repair skills. **Figure 5** illustrates how EVA tasks associated with Space Shuttle, ISS, and exploration are anticipated to require progressively more focus on skills-based training. The ISS operations experience has shown that the scope of tasks potentially required of ISS crewmembers is well beyond any capability to task train. Even considering this, there should be some lunar hardware assembly tasks, such as setting up an instrument or communications system, which can be practiced by the operators assigned those tasks. Training for the initial excursion EVAs to be performed or for these types of part-task operations constitute the residual task training foreseen during exploration assembly.

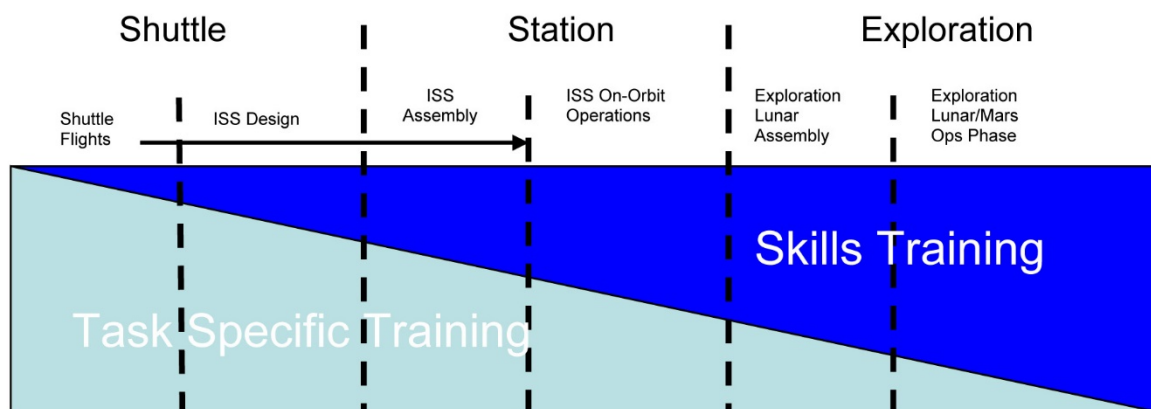


Figure 5. Predicted evolution of the Skills Training Philosophy.

The timeframe for implementing the needed infrastructure for EVA training is now. Previous programs have made the mistake of considering training and development testing to be separate and unconnected concerns and have waited too long prior to developing the training techniques and associated infrastructure. They use a sequence of events that develops a concept of operations, designs and tests individual pieces of hardware based on this concept, then, once hardware is built, define the training and associated training techniques. This concept has proven successful to various degrees so far, but a much more efficient approach is possible.

Through EVA development testing it should be determined how the training techniques will be implemented prior to the operational phase. This development of techniques cannot be a passing of information from one organization to another through a series of requirements and operational constraints alone. Instead it is imperative that these techniques evolve from the early stages of the program's hardware integration and testing activities with part ownership by the operations community. By developing the operational concept and the applicable skills techniques in parallel with hardware development, the later phases of the program will be faced with fewer instances of expensive hardware modifications made necessary due to operational limitations. This approach has been referred to as the Shared Hardware and Operations Concept Development with Training (SHOCDT) approach as described by Ney and Looper (2006).

In **Fig. 6**, the various phases of system development are used to demonstrate how the concept development, hardware development, and training methodologies can evolve in parallel over the life of the program through the use of testing.

In order to ensure that the exploration hardware and operational concept adequately represent the exploration EVA training efficiently, the training and testing must be done in conjunction with developing

the training concepts and methodologies. This concept of developing hardware, ConOps, and training concepts in parallel is different than that utilized in past programs.

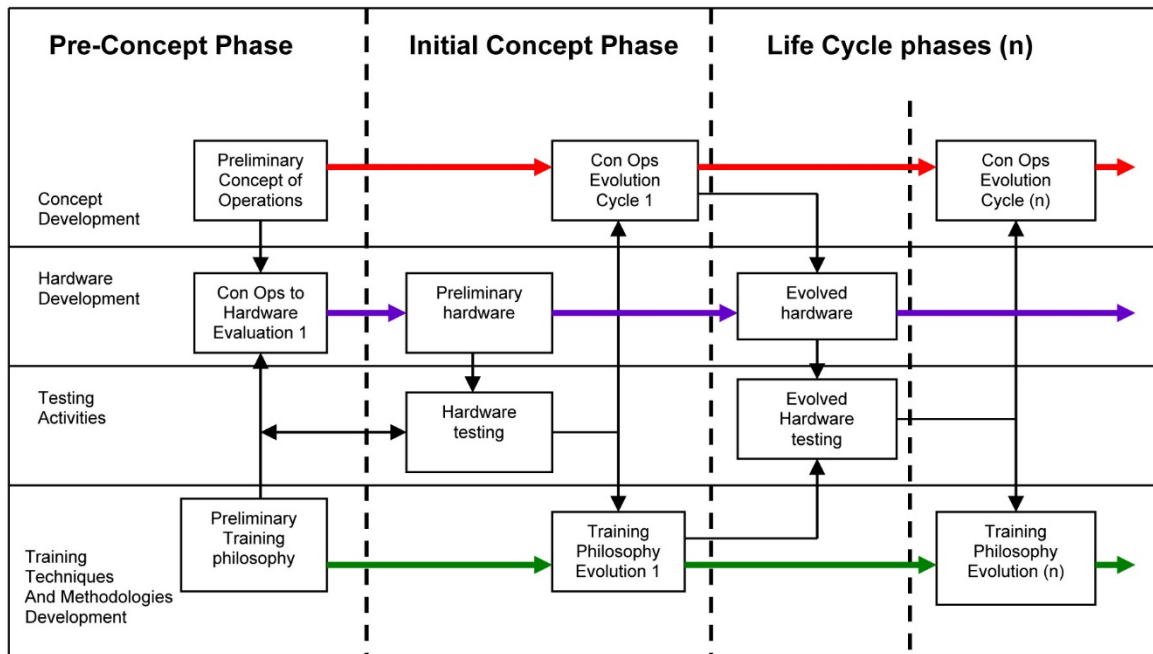


Figure 6. Shared hardware and ops concept development with training. From Ney and Looper (2006).

One of the most important aspects of the SHOCDT approach is to evolve the entire infrastructure at the appropriate time. It is very easy to overlook the need for a nonexistent capability or facility for the performance of either testing or training and then attempt to satisfy that need through a current facility that does not have the appropriate capabilities. The SHOCDT approach ensures that the facilities, the operational concept, and the training requirements evolve together. Built within this approach is the assurance that the appropriate facilities are identified based on data as it is collected. The approach serves to constantly evaluate and validate the capabilities of the facilities, the knowledge transfer methodology, and the specific skills required of crews to determine when new capabilities or resources are required. In the early phases of the program the facilities and test hardware are in their simplest conceptual forms. This allows for growth, or evolution, of the facility without expending too many resources on capabilities that may not ultimately be required. As facility capability and EVA requirement understanding grows, expansion of facilities or definition of new facilities will ensue.

3. Major Aspect 2 – Planetary Exploration Surface System Definition, Development, and Evolution

3.1 Training Scientists for Mission Operations

In a series of mission simulations between 2008 and 2011, we established protocols for an integrated mission control center with a science team and traditional flight operations personnel working side-by-side. In those simulations, when crew went EVA, the Flight Director turned operations over to a SCILEAD who managed a science team sitting at their own consoles.

This architecture was developed first in a field-deployed or Mobile Mission Control Center (MMCC) with consoles for both flight operations personnel and science operations personnel. Staff were trained in the unit at JSC in its analogue rock yard (**Fig. 7, top panel**). Staff and the MMCC were then deployed to northern Arizona where lunar mission simulations were conducted (**Section 3.2**). Subsequently, simulations in northern Arizona were conducted from Bldg. 30 at JSC, where an integrated flight and science operations center was installed in a next generation flight operations center (**Fig. 7, bottom panel**).



Figure 7. (top panel) Flight Control Room with integrated flight and science consoles in the Mobile Mission Control Center, during a training session in the JSC rock yard prior to a deployment to the Black Point Lava Flow, northern Arizona, for a lunar mission simulation. Apollo 15 trainer and then Lunar Sample Curator, Gary Lofgren (far end of top row) led the science team. (bottom panel) Astronaut Stan Love (middle) is the CapCom in a mission simulation within the next-generation Flight Control Room of JSC's Mission Control Center. David Kring (right) is the Science Lead (SCILEAD) in the simulation, which used a new operational architecture that integrates science and flight operations within a Flight Control Room. Then student, Jessica Watkins (front), sat at a console as part of Kring's science team. Her console monitored a crew member's suit camera (EV2 CT), which was capturing geologic sample data. She was recently selected to be an Artemis astronaut.

While that operational architecture was a success, it also revealed that scientists can be better trained to work in a mission operations environment.

With that objective in mind, science and EVA staff worked with the Flight Operations Directorate (FOD) to develop Space Flight Resource Management Training for Science Operations. This is a two-week, immersive training activity that utilizes capabilities in JSC's flight training facility, with additional instructional content presented at the LPI. Participants will be taught space flight resource management (SFRM) skills, learn to develop and share situational awareness in a complex mission environment, learn to develop better active listening skills, learn communication protocols, how to package comm-loop calls, and problem solving skills relevant to a human mission environment. In addition, participants will discuss Gateway-related operations, including a required tele-operation element, the evolving Design Reference Mission (DRM) for lunar surface landing sites and traverses, and an introduction to EVA ops that will utilize the new Exploration Extravehicular Mobility Unit (xEMU) for astronauts. Those activities will be integrated with two lunar mission simulations that FOD developed for training purposes.

Multiple editions of the training program are envisioned to develop the required talent for staffing Artemis missions.

In prior mission simulations, several consoles were developed to support lunar surface EVA. They included SCIENCE or SCILEAD, SCICOM, OPSLINK, EV1 CT, EV1 SAMPLE, EV2 CT, EV2 SAMPLE, (LER) MASTCAM, and (LER) GIGAPAN. That list of consoles will need to be evaluated further as the complement of surface instrumentation is better defined for Artemis III, with the recognition that it may need to be modified further for more complex surface missions after Artemis III. Once those

consoles have been refined, certification requirements for personnel staffing them will need to be developed.

3.2. Integrated Field Simulations

All personnel who will be involved with an actual lunar flight need to participate in mission simulations. The simulations will uncover unanticipated challenges, produce a well-working team, and give that team the resiliency needed to successfully resolve unexpected conditions that may arise during a lunar surface mission.

The simulations can be short day-long traverse exercises in relevant geologic terrains. They can also be longer-duration simulations that more closely mimic the timeline of a surface mission. Important insights were provided by Apollo crews. In general, they felt that “emphasis should be given to the integration of crew, equipment, and facilities as a total system” (Conners et al., 1994).

Apollo 15 and 17 Flight Director, Gerry Griffin: Earth-based field geology training of the explorers is essential before they go to explore another place in our Solar System. Also, while not every person on the mission operations team can experience crew field geology training, the Flight Directors and certain other key people in mission operations should be exposed to it to get the most bang out of our human space exploration buck.

Following the philosophy to have everyone involved in field-based mission simulations, Constellation staff were drawn from the Astronaut Office, Crew Branch, the Flight Operations Directorate, EVA group, and science community. The simulations were designed to conduct trade studies relevant to lunar surface operations, such as (i) the comparative utility of unpressurized and pressurized crew rovers, (ii) the potential value of robotic precursors prior to crew landing, (iii) lead-and-follow dual-rover ops versus divide-and-conquer rover ops; and (iv) continuous communication with crew versus twice-a-day communication with crew. But they were also designed to begin building the skills needed for staff with distinct talents to work together to support crew operations.

The integrated nature of the simulations was important. The 2009 exercise, for example, involved the following system components: Mission Manager (Joe Kosmo), Mobility (Rob Ambrose), SPR Surface Operations (Mike Gernhardt), Test Coordinator, Surface Suits, Suit-Port (Barbara Romig (Janoiko)), SPR Human Factors (Robert Howard), Mission Operations (Randall McDaniel), Science Operations (Gary Lofgren), K10 Operations (Terry Fong), Tri-ATHLETE Operations (Brian Wilcox), Communications (Marc Seibert), ISRU Operations (Rob Muller), Hybrid Battery/Fuel-Cell (John Scott), and Portable Utility Pallet (Sharon Jefferies). Each of those system components had supporting staff. A similar range of contributions was utilized in a 2010 lunar mission simulation and a 2011 near-Earth asteroid mission simulation.

During a simulated mission, a Flight Director, CAPCOM, and supporting console staff managed flight operations, including egress from a small pressurized rover (SPR). When crew stepped off the vehicle to conduct science station activities or a traverse, operations were picked up by a Science Leader (SCILEAD), Science Communication (SCICOM), and supporting console staff. Operations sequenced back to the flight operations personnel at the end of an EVA or if any anomalies occurred. An integrated flight and science operations architecture greatly enhanced mission productivity and provided crew with lunar surface expertise when engaged in lunar surface activities.

The field simulations are not simply geological training activities. Rather, they are designed to reduce risk and enhance productivity during exploration of the lunar surface. As learned during Apollo, when the Apollo 11 G mission and Apollo 12 & 14 H-I missions evolved to the more complex Apollo 15 through 17 J missions, it was important for flight operations staff to be engaged in the field simulations of EVA activities.

John Young summarized that finding in his classically informal way during an Apollo 16 debriefing: “It’s almost certain that the training we had was mighty detailed but on the other hand, on our mission, we had more than a hundred problems that I counted, counting a lot of them on the surface that nobody pays any attention to, and we solved them in real time with us and the lunar geology people in Mission Control. I can’t fault the training. I know you always do way too much. But it’s not the amount of training you do. It’s just how it prepares you. I think we were all well prepared.”

Apollo 17’s Harrison ‘Jack’ Schmitt explained (Schmitt et al., 2011) that “a lunar field geologist must always be aware that time is relentless, that consumables are limited, that fatigue can be fatal, and that, usually, returning to a location is unlikely. These cognitive realities add to the normal intellectual workload of doing field work.” For that reason, he added, “Planning, voice communication, automated location and sample documentation, and, most importantly, field experience all take on even greater importance than normal.”

The success of the Apollo 17 mission with a crew composed of a traditional flight commander with piloting experience (Gene Cernan) and a geologist (Schmitt) prompted Constellation to conduct its mission simulations with a crew of similar composition. EV1 was always a flight-oriented commander, while EV2 was always a geologist. We refer readers to *Apollo 17: Diary of the 12th Man* for a personal account by Apollo’s astronaut geologist of how that model works on the lunar surface.

At the moment, Artemis landing sites have not been selected and the details of EVA are not sharply defined. However, some insights exist. The Artemis III mission duration may be 6.5 days (NASA, 2019). The sun will be low in the sky, slightly less than the 5.1° during the Apollo 12 landing and the 7.5 to 9.5° during extravehicular activity (EVA) 1 by Apollo 12 crew, neither of whom reported any visual degradation or enhancement at those sun angles. If crew are limited to walking EVAs, then the Apollo 12 and 14 missions, albeit with shorter surface stays (1.3 and 1.4 days, respectively), may provide some operational guidance. Apollo 12 crew conducted two EVAs, the second of which was nearly 1.6 km-long, reaching a distance ~400 m from the lander, and included an ~100 m segment up a 14° slope, in under 4 hours. That EVA recovered ~18 kg of geological samples, including core ~60 cm deep, supplemented with a ~20 cm deep trench. Apollo 14 crew also conducted two EVAs, the second of which was ~2.9 km long, reaching a distance ~1.4 km from the lander in about 4.5 hrs. That EVA recovered ~22 kg of geological samples, including core ~60 cm deep, and produced an ~30 cm deep trench. The capability of the Artemis Exploration Extravehicular Mobility Unit (xEMU) is not yet fully known, but it should provide crew with greater capability than Apollo-era units. Thus, walking EVAs up to 2 km from the lander are plausible. If a Lunar Terrain Vehicle (LTV) is available, then the area to be explored might extend to distances of 10 km from the lander, based on the 10 km walk back limit established during Apollo.

EVA opportunities at several sites in the south polar region have been studied within those 2 km and 10 km exploration limits (**Fig. 8**; Lemelin et al., 2014; Gawronska et al., 2020; Kring et al. 2020b-g). As the Artemis program matures, dual rover traverses with greater exploration potential may be possible. They may initially involve a single LTV with a single small pressurized rover (SPR) or Habitable Mobility Platform (HMP) (Gernhardt et al., 2020). The exploration architecture may eventually involve dual SPRs and redeployment of them between landing sites, as envisioned by Constellation, and examined for the agency (Allender et al., 2020) as a participant in the International Space Exploration Coordination Group (ISECG).

We note that the redeployment of mobile assets from Shackleton crater to Malapert massif, followed by a landing at Malapert with two 14-day-long SPR traverses (reviewed briefly by Kring, Gruener, and Eppler, 2020g), provided the template for the 2010 lunar mission simulation near Flagstaff.

Regardless of which lunar surface operational plan is being implemented, Apollo and Constellation taught us that integrated, field-based simulations are essential elements of mission success.

Thus, we consider a key “facility” for exploration EVA ConOps development, hardware development, and training is the large lunar mission simulation, such as those performed in Arizona during the Desert RATS series of events (Abercromby et al., 2010, 2012, 2013; Eppler et al., 2013; Hörz et al., 2013).

Any field-based lunar mission simulations will be developed in parallel with Neutral Buoyancy Laboratory (NBL) training. The NBL has evolved over the past 20 years and is a unique, world class training facility. Its success is evident in the large number of successful EVAs performed during ISS assembly and continuing ISS activities today. The strength of the NBL is its ability to simulate a real-world environment at a full-scale level to the astronaut (Fig. 9). It provides real-time communication capability, thereby simulating a real-time situation for each task in coordination with the appropriate level of control team interaction. In short, there is no comparison to the NBL for micro-gravity EVA training. However, even for micro-gravity EVA training the NBL has limitations. The effect of gravity is still experienced by an astronaut working within a suit, even though the overall suit and subject are weighted consistent with the desired simulated gravity environment. In addition, while many of the tools and tasks are a close representation of real conditions, they are not an exact duplication of the real-time on-orbit environment.

For lunar-based 1/6-gravity training, the NBL has an important training role, but will be limited. The first limitation is related to the scale of a task. The NBL was designed and built for the assembly of the ISS. For that task the NBL is somewhat smaller than the overall dimensions of the ISS in all axes. To overcome that limitation, full scale mockups are assembled in planned configurations to accommodate the inability to provide an end-to-end training operation. Lunar-based EVAs will take place over a much larger area than the ISS. Whether it be rover-type EVAs, or even lander-driven walking EVAs, the astronauts will travel farther distances than that within the NBL. As with ISS, that shortcoming of scale can be accommodated, but for lunar-based EVA, that accommodation will be a far larger departure from reality than the accommodation made for ISS-type EVA. The astronaut will not experience an adequate scale of environment relative to the reality of operations on the lunar surface.

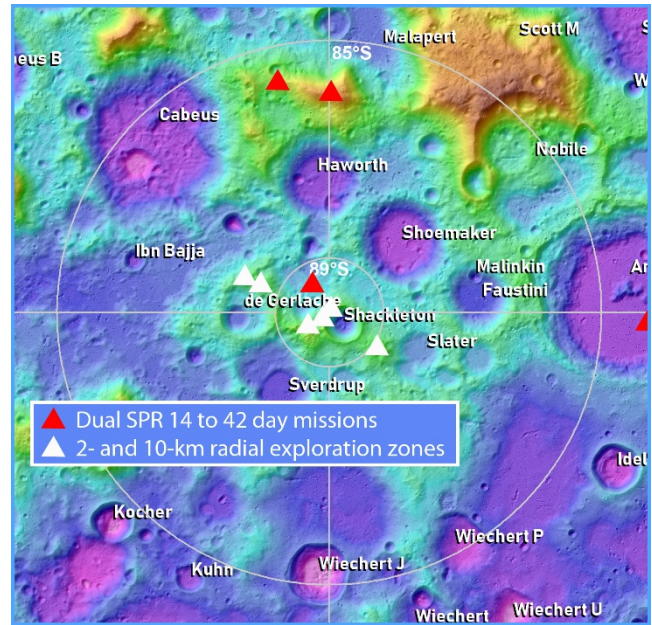
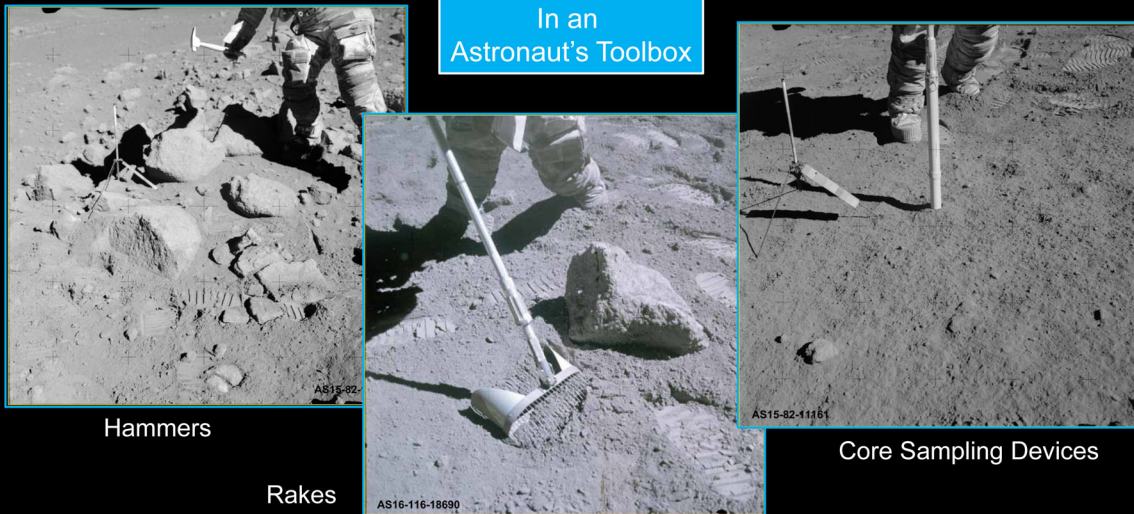


Figure 8. Potential landing sites examined thus far with 2-km walking EVA limits, with 10-km LTV-EVA limits, and for SPR-supported mission traverses with a distributed number of station EVAs.

Apollo Astronauts Explore the Moon – The Extraordinary Value of Lunar Samples



Astronauts Train Today for the Artemis Missions – Don Pettit in the Neutral Buoyancy Laboratory

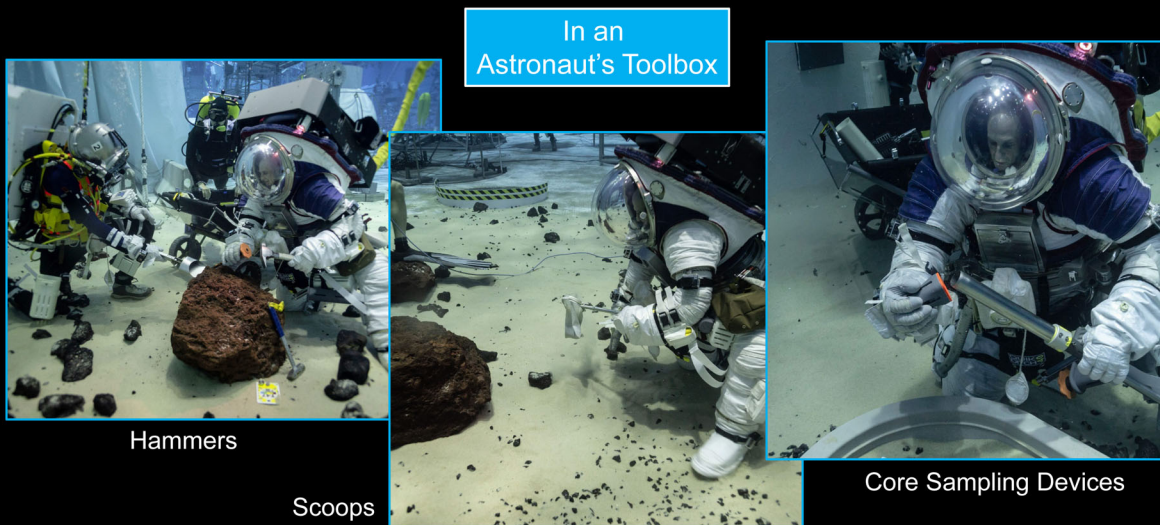


Figure 9. (top) Apollo astronauts utilized several tools and sampling strategies to recover geologic materials for return to Earth. (bottom) Astronauts, like Don Pettit here, are currently training in the Neutral Buoyancy Laboratory with a modern set of similar tools in preparation of Artemis EVA.

A second limitation with using the NBL versus an analogue-type training environment is the ability for complete end-to-end mission training. NBL runs themselves are limited to one EVA operation per day with the overhead of preparing for each run. Surface EVAs performed from a pressurized rover in an analogue-type environment provides not only a more realistic real-time environment for the astronaut, but also for the entire flight control team and science team. It might be argued that the NBL could provide this capability in a scripted, simulated operation, however the realism of sitting in a pressurized rover that does not really go anywhere severely limits the training opportunities for all involved.

Thus, while the NBL is essential, it cannot provide the necessary capabilities of a field-based mission simulation program.

An assessment of locations for field-based analogue mission simulations was conducted for Constellation and included many of the Apollo heritage sites in **Table 1**. The favored location for Constellation mission simulations was the Flagstaff region, where four sites were utilized during the Apollo era (**Fig. 10**, top panel). A land access agreement was obtained and infrastructure installed to support activities near the Black Point Lava Flow in the San Francisco Volcanic Field north of Flagstaff. One-, three-, and fourteen-day-long mission simulations were conducted around the Black Point Lava Flow (**Fig. 10**, bottom panel) in 2008, 2009, and 2011. In 2010, the test site was expanded to the west (Kring, 2008; Hörz et al., 2013) to accommodate a simulation of dual rover operations.

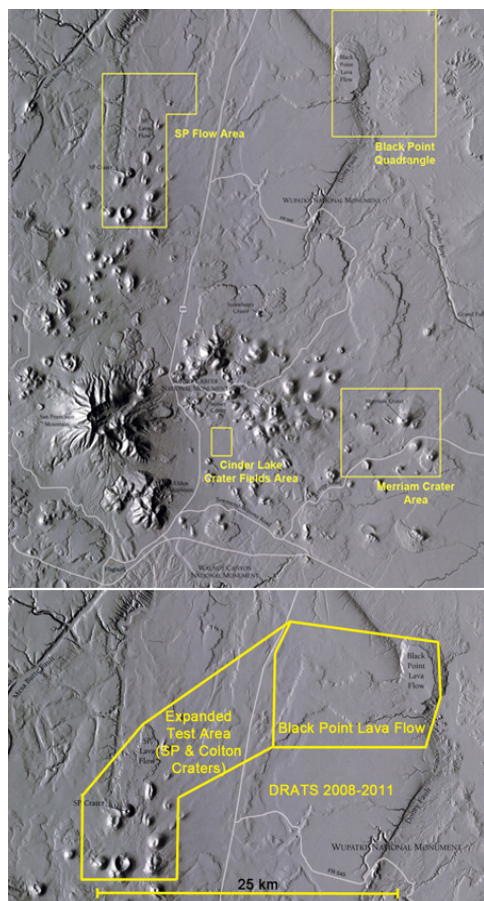


Figure 10. (top) Locations of four Apollo-era field test areas in the San Francisco Volcanic Field near Flagstaff, Arizona. (bottom) The test areas in the northern part of that region used for lunar mission simulations during the Constellation Program.

While it is essential that Artemis crews be trained in impact-cratered terrains (**Section 2.1.3.**), the expanded test site in the volcanic terrain near Flagstaff remains the best location for integrated lunar mission simulations. The area provides a broad range of geologic and topographic diversity for testing hardware and human mission systems.

It contains at least ten lava flows of different ages and different types of rocks. It contains over a dozen volcanic vents. The most spectacular of those vents, SP crater, is a good analogue for the ISRU-relevant pyroclastic vent in the polar region's Schrödinger impact basin (**Fig. 2**). Slopes in the area host boulder trains that mimic boulder trains on lunar massifs and the flanks of impact craters in the south polar region and elsewhere on the Moon. The area also contains two types of layered terrains and two types of channeled terrains, which provide additional diversity for any geologic training, but also provide a realistic Mars-forward geologic opportunity. The area is crosscut by structural elements, such as folds and faults, which are relevant to any planetary surface. One of the most spectacular features in the area is Colton Crater. This crater was produced by a relatively unusual type of explosive volcanic eruption, which produced a crater that mimics an impact crater. The 1.2 diameter explosive volcanic crater provides the topographic challenges of an impact crater, like the 1.2 km diameter Meteor Crater, also in northern Arizona, or North Ray Crater at the Apollo 16 highlands landing site.

The Flagstaff site is attractive for several operational reasons. The distance between the eastern lobe of the Black Point Lava Flow and the western flank of Colton Crater is about 25 km, comparable to distances envisioned for an initial phase of lunar exploration. There is enough acreage to support multiple traverse designs. Trafficability for lunar proto-type

mobility assets is good, as previously demonstrated by Constellation's Chariot and Lunar Exploration Rover. Primitive, but passible, roads crosscut the site, providing access for support vehicles. Communication equipment to allow time delayed (if applicable) connection with remote users, such as those located at JSC Bldg. 30, is installed on Mount Elden in Flagstaff, and the terrain of the test area provides for communication and navigation challenges similar to those that will be encountered on the lunar

surface. Moreover, the test site contains several good locations for an analogue Artemis Base Camp and additional sites for rendezvous of surface assets.



Figure 11. (A-B) Trade study between unpressurized rover and small pressurized rover with suit ports; (C) Rock sampling, evaluating a crew with astronaut pilot and astronaut geologist, and evaluating digital imaging vs photography; (D) Rake sampling of regolith, observed by Test Coordinator Barbara Romig (Janoiko); (E) EV1, Mike Gernhardt, describing field observations to the science ops center; (F) EV1 Stephanie Wilson and EV2 Kelsey Young are one of two crews in a simulation of four astronauts on the surface; (G) EV1 Stan Love making a field note using a cuff recording device; (H) Evaluating dual rover operations. The selected fidelity of the suit, tool, and mobility hardware used in such simulations depend on the objective of the simulation. Debriefings of Apollo astronauts (Connors et al., 1994) suggest flight-like conditions in geologic terrains are important as training proceeds.

Within that terrain, missions can be conducted with flight-like surface activities with flight-like schedules over periods of days to weeks.

Also within Flagstaff's San Francisco Volcanic Field are the Sunset Crater cinder fields. Those fields were modified with explosives during Apollo to produce cratered terrains (e.g., as reviewed by Kring, 2007-2008). The proximity of those cinder fields to the Black Point Lava Flow test site make them an attractive site for additional mission traverse simulations. Indeed, those cinder fields were the final sites of Apollo's monthly geological exercises (Schmitt, *Apollo 17: Diary of the 12th Man*, Chapter 4). Two days of traverses, with 5 to 6 hours EVA each, were conducted as a final tune-up for the Apollo 17 mission. The craters in the cinder fields were refurbished during the Constellation Program for lunar surface training.

An important outcome of such mission simulations is a mutual understanding between crew and supporting science operations staff. That is, crew develop an ability to communicate observations and think through, with the science operations staff, implications for measurements, photography, and the selection of samples. An important level of trust is established.

The simulations do not need to be a precise rehearsal of a mission, but should be designed to prepare crew and the supporting operational staff for anticipated operational issues and deltas that unexpected conditions may warrant. Thus, while it will be important for the simulation team to review the scientific and exploration potential of a landing site and its EVA options, they can utilize a variety of analogue terrains to develop the integration and training needed to function as a team on the lunar surface.

The San Francisco Volcanic Field near Flagstaff remains the best site for field-deployed mission simulations, but we also point out that other sites, such as Schooner Crater and Sierra Madera Crater, would further enhance mission simulation outcomes. Completing mission simulations at these sites would complement the crew's shorter duration training exercises (**Section 2.1.3**). A combination of training and testing in multiple high-priority locations will leverage the strengths of each to best develop Artemis hardware, ConOps, and training concepts for crew and ground support teams.

4. Conclusions

The lunar surface is a complex and demanding operational environment. For crew to work efficiently, productively, and safely in that terrain, field-based training will be required. Apollo and Constellation experience indicate that training should include a regular cadence of short-duration exercises and less frequent integrated mission simulations. Those field-based activities will complement classroom, laboratory, and NBL activities in Houston.

It is essential to develop early (i.e., now) a dialogue between all elements involved in lunar surface operations.

The development of lunar surface ConOps should occur with the development of hardware and training, not in a serial manner.

Science and flight operations should be integrated in a flight control room to provide crew with the lunar expertise needed when operating in a lunar surface environment. As in Constellation, that architecture should be incorporated into lunar mission simulations, so that personnel and their supporting equipment develop the capability to function well together prior to Artemis landings.

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6. Author Biographical Sketches

David A. Kring. Dr. Kring is a Harvard-trained planetary geologist. He is an Apollo sample Principal Investigator (PI) with over thirty years experience analyzing lunar samples. He has extensive field experience in impact-cratered terrains like those at the lunar south pole. He has helped trained three classes of astronauts and served as a Science Leader (SCILEAD) during Constellation lunar mission simulations. He is the founding PI of the NASA-supported Center for Lunar Science and Exploration in Houston and the recipient of NASA's Michael J. Wargo Exploration Science Award for significant contributions to the integration of exploration and planetary science throughout his career.

Chris A. Looper. Chris Looper has worked at the Johnson Space Center as both a contractor and Civil Servant for thirty-three years, twenty-seven of which have been spent working EVA hardware development, EVA operations and Astronaut Training. He has supported JSC's Engineering, Flight Operations/Astronaut Office and Safety and Mission Assurance Directorates while working on the Space Shuttle, International Space Station, Constellation and Artemis Programs. He was the first non-Astronaut to perform Ground IV duties performing real-time space to ground coordination during ISS assembly EVAs, and has served as the Astronaut Office's Chief Engineer of EVA and Chief Engineer of Training. He is the recipient of the NASA Exceptional Service Medal and two Spaceflight Awareness Awards including the Silver Snoopy.

Zane A. Ney. Zane Ney has worked at the Johnson Space Center for twenty-five years, supporting JSC's Flight Operations/Astronaut Office in ISS Assembly, Payloads, and EVA. He has worked on the Space Shuttle, Mir, International Space Station, Constellation, and Artemis Programs. He co-created and led the EVA Skills Training Program, developed and implemented the Astronaut Candidate POGO Evaluation, and co-created the European Space Agency SCUBA EVA Preparatory Course. He is the recipient of the NASA Exceptional Public Service Award, NASA Silver Achievement Medal, and three Spaceflight Awareness Awards including the Silver Snoopy.

Barbara A. Janoiko. Barbara Janoiko has worked at the Johnson Space Center, Headquarters, and Langley Research Center as a NASA Civil Servant for twenty years, ten of which supported, coordinated, and led Desert RATS and JSC RATS testing. Barbara has also supported and led NASA Extreme Environment Mission Operations (NEEMO) and has supported other NASA analog activities such as Pavilion Lake Research Project (PLRP), In-situ Resource Utilization (ISRU) demonstrations, and International Space Station Testbed for Analog Research (ISTAR).

7. Acronyms

ARC	Ames Research Center
ATHLETE	All-Terrain Hex-Limbed Extra-Terrestrial Explorer
BPLF	Black Point Lava Flow (Arizona)
CAPCOM	Capsule Communicator
CLSE	Center for Lunar Science and Exploration
CONOPS	Concepts of Operations (also written ConOps)
CSA	Canadian Space Agency
CT	FCR console providing Camera Technical support
DIO	Directorate Integration Office
DRATS	Desert Research and Technology Studies
DRM	Design Reference Mission
DV	Distributed Version
ESMD	Exploration Systems Mission Directorate
ETDP	Exploration Technology Development Program
EV1	Extravehicular crew member 1
EV2	Extravehicular crew member 2
EVA	Extravehicular Activity
FCR	Flight Control Room
FOD	Flight Operations Directorate
G	An Apollo designator for a land and return mission
GIGAPAN	FCR console providing GIGAPAN support
GRC	Glenn Research Center
H-I	An Apollo designator for missions that deployed ALSEP, had 2 EVAs, and had longer surface duration than a G mission
HEOMD	Human Exploration and Operations Mission Directorate
HMP	Human Mobility Platform
HRS	Human Robotic Systems
ISECG	International Space Exploration Coordination Group
ISRU	In Situ Resource Utilization
ISS	International Space Station
IVA	Intravehicular Activity
J	An Apollo designator for missions to complex geological localities that were supported with a lunar roving vehicle
JAXA	Japan Aerospace Exploration Agency

JPL	Jet Propulsion Laboratory
JSC	Johnson Space Center
KSC	Kennedy Space Center
LER	Lunar Electric Rover
LPI	Lunar and Planetary Institute
LSS	Lunar Surface Systems
LTV	Lunar Terrain Vehicle
MASTCAM	FCR console supporting LER mast camera system
MCC	Mission Control Center
MMCC	Mobile Mission Control Center
NASA	National Aeronautics and Space Agency
NBL	Neutral Buoyancy Laboratory
NEA	Near-Earth Asteroid
OPSLINK	FCR console providing communication between SCILEAD and the Flight Director
PAN	Pure Anorthosite
PI	Principal Investigator
SCICOM	Science Communicator
SCILEAD	Science Leader
SFRM	Space Flight Resource Management
SFVF	San Francisco Volcanic Field (Arizona)
SHOCDT	Shared Hardware and Operations Concept Development with Training
SMD	Science Mission Directorate
SOMD	Space Operations Mission Directorate
SP	SP (name of a cinder cone)
SPR	Small Pressurized Rover
SSERVI	Solar System Exploration Research Virtual Institute
xEMU	Exploration Extravehicular Mobility Unit

8. Appendix A (attached)

Technical Memorandum, *Developing a Concept for Astronaut Training and Analogue Studies for Lunar and NEA Surface Operations*, Dr. David A. Kring for Dr. Wendell Mendell, Chief, Office for Lunar & Planetary Exploration, Constellation Systems Program Office, NASA Johnson Space Center, September 22, 2007.

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To: Dr. Wendell Mendell
Chief, Office for Lunar & Planetary Exploration
Constellation Systems Program Office
NASA Johnson Space Center

Subject: Developing a Concept for Astronaut Training and Analogue Studies for Lunar and NEA Surface Operations

Date: 22 September 2007

Dear Wendell,

Per our conversation last fall, I have been reviewing Apollo-era documents regarding crew training for lunar EVA and evaluating those documents in the context of future crew training exercises needed for the projected Constellation missions. My principal conclusions are:

- All lunar surface activities will occur in impact-cratered and volcanic terrains and, thus, crew should be given basic geologic training and conduct EVA simulations in appropriate analogue terrains.
- EVA training in analogue terrains should involve the integrated expertise of a broad group: the astronaut office, astronaut trainers, field geology trainers, site selection teams, geologists involved in surface operations planning, lunar sample analysts, in-situ resource specialists when appropriate, equipment designers, flight controllers, and management (SMD, ESMD, SOMD).
- Field mobility is needed for crew and robotic assistants.
- Integration of human and robotic exploration components should be tested in analogue terrains with realistic simulations of lunar surface operations. Likewise, all tools to be used by crew in lunar surface operations should be tested in realistic simulations.
- Initially, missions will be of relatively short duration and, thus, traverse-dominated with backroom support, which requires training similar to that for the Apollo J missions.
- Training for extended duration missions will need to develop greater crew independence, because they will be operating in an exploration mode that (i) more closely mirrors terrestrial field work and (ii) takes advantage of the human ability to analyze in real time. Backroom assistance will still be important, but the crew will not require constant consultation over long durations (e.g., 30 to 180 day expeditions).
- Four-person crews should include mission specialists with advanced training in subjects like geology, resource recovery, and engineering. These individuals could potentially be involved in pre-mission scientific research and engineering trade studies associated with lunar surface operations.

I provide an expanded description of these issues below with a few concepts for implementation. Some of this information will be self-evident to you, but I have tried to provide a generalized summary in case you want to communicate it to others.

Geologic Field Training in Analogue Terrains

An astronaut cannot take a single step on the lunar surface without stepping into and onto hypervelocity impact craters. The excavated cavities, uplifted rims, and distributed ejecta of impact craters dominate the lunar landscape. Impact processes are even responsible for the lunar soil. Volcanism is the source of most other topographical constructs and also contributes to lunar surface lithologies. Because all lunar surface activities will traverse, collect, or modify these impact and volcanic materials, a basic geologic education about them is required for safe and productive lunar surface operations. Because the surfaces of NEA are also dominated by impact craters, the same training will be appropriate for a possible NEA mission.

Apollo astronauts found field training and traverse exercises to be the most important component of their EVA preparation. After a crew and back-up crew were selected, those activities became a regular part of the crew schedule. Bill Phinney pointed to Charlie Duke's reaction: "The geology field trips were outstanding. The monthly trips that we did from the time we started on the crew were just right. In 2 or 3 days you could come up to speed." And John Young added that a field exercise "helps you to get a team work pattern and I think that's real important. You are not very effective unless you're working as a team up there. Otherwise you're just going to be spinning your wheels on the Moon and that's not where they want you to spin them."

A variety of excellent analogue terrains exist in the vicinity of the southwestern United States: Barringer impact crater (aka Meteor Crater), Sierra Madera impact crater, the Nevada Test Site for the Danny Boy, Schooner, and Sedan explosion craters, Kilbourne Hole volcanic maar, San Francisco volcanic field, and the Pinacate volcanic field. Most of these sites were used during Apollo. As you probably know, I taught graduate students how to solve lunar and Martian science problems at those sites for nearly 18 years, so I can confirm that they remain good analogues. Other good, albeit more distant, analogues to consider are Kilauea volcano, Haleakala volcano, the Ries impact crater, and possibly the Lomar impact crater. Other analogue sites exist and can be visited to fulfill specific needs, but most training will be satisfied at the above localities. Although impact cratering and volcanic processes are the foci of these training sites, they lend themselves to general geologic preparation, including a variety of other relevant topics like sedimentology and tectonics.

One of the challenges that will need to be faced is the expanded geographic scale of future lunar surface operations. Excursion distances are likely to be far greater than those of Apollo and even some of the topographical features have greater dimensions than those encountered during Apollo. For example, the 1.25 km diameter Meteor Crater of Arizona is a perfectly good proxy for Apollo 16's North Ray Crater. It is even a good analogue for many of the morphological features of Shackleton Crater at the lunar south pole. However, the size of Shackleton Crater (approximately 19 km diameter) may also require training activities at Sierra Madera Crater (13 km diameter) and the Ries Crater (24 km diameter) to capture the scientific and operational (e.g., traverse timing) issues that are affected by greater distances. These training exercises should be led by geologists familiar with the analogue sites and the exploration issues related to those types of sites on the Moon.

In all cases, field training should include access too and interpretation of aerial photography and/or satellite imagery.

Furthermore, we should take advantage of new technology to explore the concept of conducting some training activities within full-scale (i) photographic and video models of the Apollo landing sites and (ii) in computer-simulated models of future landing sites.

Laboratory and Class Room Components

Field exercises should be supplemented with a small amount of class room and laboratory activities. In many cases, it may be good to precede a field exercise with a class room activity. For example, one

might organize a discussion of the lunar cataclysm hypothesis and examine hand-specimens of impact melt breccias, so that the crew can recognize them during a simulated field exercise and understand why they are important.

These components should include other (e.g., non-geologic) information needed for successful surface operations. For example, it might include an introduction to regolith processing to derive resources needed for extended exploration and habitation.

The laboratory and class room components should take advantage of the Apollo missions. They should include (a) a study of Apollo samples and (b) a study of Apollo traverses and the science and exploration lessons learned from those traverses. The latter is particularly important, because it builds a practical and intellectual connection between surface operations and mission outcomes.

Research Component

Training at analogue sites can contain a meaningful research component that (i) provides crew members with a sense of ownership and (ii) develops an intuitive understanding of the relationship between field work and laboratory analyses and, thus, the implications sample selection on the Moon will have for mission success. Depending on operational decisions, these types of projects might involve an entire crew or only mission specialists with advanced training.

Finally, it is important to get everyone involved at the beginning: science trainers, operations trainers, other operations representatives, equipment specialists, and science and exploration management. This type of transparency will help educate all those involved and make it easier to discern what is and is not possible during lunar surface operations.

Evolving CONOPS

There should probably be a discussion of training operations that focuses on the evolving nature of lunar surface operations. I foresee that the initial set of missions will be of relatively short duration (4 to 14 days), which implies traverse-style surface activities with a strong ground interface and, thus, training operations similar to those for the Apollo J missions. However, as the exploration initiative matures, I foresee longer duration activities that rely on in situ decision-making by the crew and increasing independence from back-room specialists. This stage of the exploration initiative will require a different type of training. This issue should be discussed among scientists, science and exploration managers, and the architects of the lunar program before any firm decisions about a second stage of training is implemented.

With four-person crews there may be a need for differential training: Crews, for example, may be divided between (i) construction and infrastructure tasks and (ii) science and exploration tasks. Both groups will need an understanding of lunar surface conditions and the regolith effects of impact cratering and volcanic processes, but the level of geologic training required for (ii) may be significantly higher.

Integrating Robotic and Human Exploration

Apollo-LRV and Luna-Lunokhod rovers demonstrated the advantages of mobility and the capability of rovers as useful instrument platforms. A robotic rover system can be deployed in several modes to facilitate human exploration:

(i) As a mobile experiment platform that can accomplish some of the science objectives of LAT, while also accomplishing the exploration objectives that must be met in preparation of future human operations.

(ii) As a transport vehicle that can deploy static science and exploration platforms, during both the robotic and human exploration phases.

(iii) As a scout deployed prior to a human flight. For example, one of the highest science priorities is to determine the impact flux in the Earth-Moon system, which will require a diverse set of samples from multiple impact craters. A robotic lander-rover system can survey potential sampling sites and determine routes to them in advance of human collection during an astronaut-led mission. Furthermore, it can expand the geographic coverage of human-led sorties by collecting, caching, and potentially returning samples from other lunar locations.

(iv) As an astronaut assistant during the human exploration phase. A rover will augment surface operations so that an astronaut has more time to explore the geology of the lunar surface and conduct other exploration activities. This strategy will maximize the time available for astronauts to utilize their unique human capabilities by assigning many mechanical and analytical tasks to a robotic rover.

(v) As an extended mission partner with human sortie efforts, deployed to further explore the lunar surface around a sortie landing site after astronauts have returned to Earth. Post-human mission processing of lunar surface materials might also be accomplished with a robotic component.

(vi) As a surrogate explorer deployed by astronauts on extended (e.g., 30- to 180-day-long) missions, particularly during lunar nights and when hazardous conditions exist.

These are, however, hypothetical system integrations. Within this framework we need to develop requirements, evaluate training sites, and develop training materials that expand beyond those used for Apollo. Integrated robotic and human exploration strategies should be tested with hardware in realistic simulations in appropriate analogue terrains.

Surface Communications

One of the uncertainties in lunar surface operations and, thus, training, is the mode of communication during EVA. It is not yet clear how crew will communicate with each other during an EVA or with crew that may remain at a distant landing site or habitat. A non-line-of-sight communication system needs to be developed so that crew can communicate among themselves on the topographically-complex lunar surface. Even if an orbiting satellite system is eventually installed, this type of surface communication system reduces risk and better ensures mission success. Once this type of system is developed, it needs to be folded into analogue training exercises.

Recommendations

Per your request, I am also outlining a small program that will develop a concept of operations for the training of astronauts who will be working on lunar and, potentially, NEA surfaces:

- Create a dialog with the diverse group of participants who may be needed for lunar surface training exercises.
- Recover and digitize Apollo-training documents and geologic treatises of analogue training sites. (I note that I have already gathered some of these documents and they will be posted next week on the new USRA-LPI lunar exploration web site at <http://www.lpi.usra.edu/lunar>.)
- Obtain existing aerial and satellite imagery of analogue training sites; determine data gaps and fill them in.
- Review property ownership and permits needed to access analogue training sites.
- Outline 1 to 3 analogue training exercises and select one for development after consulting science trainers, operations staff, equipment managers, and exploration managers.

- Prepare a training exercise that integrates class room preparation, science objectives, equipment, and operational requirements. There should be a science or exploration goal to the exercise; it should not be a simple test of equipment and traverse timing.
 - Pre-test the training exercise with science and operations trainers.
 - Engage a small group of astronauts (e.g., 2) for the training exercise, so that we can get their perspective on the efficiency and utility of the training exercise.
 - Evaluate the test and determine how future exercises should be modified to better address crew training needs for the Constellation Program.
-
- At the same time that this field-based analogue training exercise is being developed, the application of video- and computer-rendered simulations, particularly those that utilize lunar imagery, should be explored.

Please let me know if there are any questions about the issues I outlined above or if you would like me to expand any of the points further.

Best regards,

{electronic}

David A. Kring, Ph.D.
Visiting Scientist for the
Lunar Exploration Initiative

C: Dr. Stephen J. Mackwell, Director, Lunar and Planetary Institute (USRA)
Dr. Daniel D. Durda, Special Advisor for NEOs and Human Spaceflight (SMD)