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Desert Research and Technology Studies (DRATS) 2008: Evaluation of Small Pressurized Rover and Unpressurized Rover Prototype Vehicles in a Lunar Analog Environment

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ACRONYMS

CxAT_Lunar	Constellation Lunar Architecture Team
DRATS	Desert Research and Technology Studies
EVA	Extra Vehicular Activity
HMP	Haughton-Mars Project
LAT	Lunar Architecture Team
LER	Lunar Electric Rover
PLSS	Primary Life Support System
ECLSS	Environmental Control/Life Support System
SPR	Small Pressurized Rover
UPR	Unpressurized Rover
USGS	United States Geological Survey

ABSTRACT

A system of two or more Small Pressurized Rovers (SPRs), also referred to as Lunar Electric Rovers (LERs), is an integral part of NASA's plans for returning humans to the moon. In the SPR concept, each vehicle includes a small pressurized cabin to safely sustain two crewmembers on the surface for 14 to 28 days. Through suit ports, crewmembers may rapidly egress and ingress the cabin for extravehicular activities (EVAs). In addition to achieving a surface exploration range that is potentially orders of magnitude greater than what was achievable during the Apollo Program, the SPR concept offers many other benefits, particularly with respect to the health, safety, and productivity of crewmembers.

The primary purpose of the Desert Research and Technology Studies (DRATS) 2008 field test, conducted at the Black Point Lava Flow in Arizona, was to objectively and quantitatively compare the scientific productivity and human factors during 1-day exploration, mapping, and geological traverses performed using Small Pressurized Rover (SPR) and Unpressurized Rover (UPR) prototype vehicles. The habitability, human factors, and performance characteristics of the SPR vehicle and crew were also recorded throughout a high-fidelity 3-day lunar traverse simulation. Before the field test began, a detailed test protocol and flight plan were developed including hypotheses, metrics, and prospectively defined levels of practical significance to be used in the testing of all hypotheses.

Quantitative assessment of crew productivity by an on-site team of expert field geologists found that compared with UPR traverses, the same crewmembers were 57% more productive during SPR traverses and used 61% less EVA time. The study also indicated that the SPR increased comfort and decreased fatigue over the UPR. The habitability and human factors of the SPR throughout the 3-day traverses was acceptable according to the prospectively defined human factors metrics and acceptability criteria, although suggested modifications to several vehicle subsystems were identified in the assessment.

1.0 INTRODUCTION

The Small Pressurized Rover (SPR), also known as the Lunar Electric Rover (LER), is an integral part of the lunar surface architectures that are under consideration by NASA. The SPR is expected to offer numerous health and safety advantages that will accrue from having a pressurized safe haven and radiation shelter in close proximity to the crew at all times during lunar surface operations. The SPR combines a comfortable shirtsleeve, sensor-augmented environment for gross translations and geological and mapping observations with the ability to rapidly place suited astronauts on the planetary surface using suit ports, to take full advantage of the unique human perception, judgment, and dexterity. This combination of features is expected to increase the productivity of crew extravehicular activity (EVA) time and provide significantly greater exploration ranges than an Unpressurized Rover (UPR).

To objectively evaluate the potential benefits of the SPR compared with a UPR, Earth-based functional versions of the UPR and SPR vehicles were designed and fabricated to support this study. The primary objectives of the study were to 1) evaluate the productivity of the SPR compared to a UPR on 1-day geological and mapping traverses and 2) evaluate the human factors and crew accommodations of the SPR and suit ports on 1- and 3-day science, exploration, and mapping traverses. Other objectives included evaluation of single-person EVA capability and assessment of nighttime operations of the SPR and UPR.

The primary objectives of this study were decomposed into specific hypotheses, which were tested with a combination of objective and subjective productivity, performance, and human factors metrics, which are detailed in Section 2.3. The study design incorporated a direct cross-over comparison between the SPR and the UPR, using two different crews, each made up of a professional field geologist and an active NASA astronaut with EVA experience. Because the number of subjects was limited, use of inferential statistics was not warranted. However, descriptive statistics were combined with prospectively defined levels of practical significance to test each hypothesis. As an example, the various human factors ratings are based on a 10-point scale, composed of five distinct categories that range from totally unacceptable to totally acceptable, and a categorical difference was considered practically significant. These metrics, procedures, and data collection methods will also be applicable to future science and engineering evaluations.

In this study the SPR was operated in a manner consistent with the SPR functional requirements in the Preliminary Report of the Small Pressurized Rover (IHMC, 2008). Detailed procedures and flight rules were developed to control the SPR operations within these constraints. The human factors and mechanisms of the suit ports to be used in this study were kinematically accurate and consistent with a fully pressurized engineering model of the suit port. The mockup suit port enabled quantitative evaluation of 12 different aspects of the preliminary suit port design related to suit donning and doffing and suit docking and undocking to and from the suit port. However, the Earth-based functional SPR and the lightweight EVA suits were not pressurized. Because of this limitation, the suit human factors in this study should not be considered representative of flight-like conditions.

In the Lunar Architecture Team (LAT) studies (Humphries, 2006), detailed EVA analysis and timelines were generated for a wide range of construction tasks across the six options evaluated, as well as for four representative science tasks that ranged from geological exploration to a variety of small and large instrument package deployments and assembly operations. The exploration, mapping, and geological tasks represented both high-frequency and demanding tasks for the SPR because of a combination of terrain, range, and observational demands. For this reason a geological, exploration, and mapping traverse was selected for the initial evaluation comparing the SPR with a UPR. Additional construction and science tasks and other engineering evaluations of the SPR are planned to take place in the Johnson Space Center "Rock Yard" facility.

1.1 BACKGROUND AND SIGNIFICANCE

Fewer than 20 lunar extravehicular activities (EVAs) were performed during the entire Apollo Program. Architectures considered by NASA's Constellation Lunar Architecture Team (CxAT_Lunar), which followed the LAT studies, could involve as many as 30,000 hours of lunar exploration EVA time. As Figure 1 demonstrates, these plans represent an enormous increase in EVA hours in an extreme and challenging environment. No previous astronaut or spacesuit has performed more than 3 lunar EVAs, yet future astronauts and their EVA suits must be capable of performing as many as 76 lunar EVAs during a 6-month mission. Damage to suit components and considerable dust contamination occurred during Apollo after only three EVAs; suit-induced trauma (e.g. finger nail delamination, contusions, lacerations, shoulder injuries) of astronauts in current EVA suits often occurs during a single EVA. Other challenges include the risk and consequences of a significant solar particle event, galactic cosmic rays, the need to extend exploration to potentially hundreds of kilometers from an outpost, and the increased decompression sickness risk and prebreathe requirements associated with 55 kPa (8 psi)/32% O_2 cabin pressure compared to Apollo's 34.5 kPa (5 psi)/100% O_2.

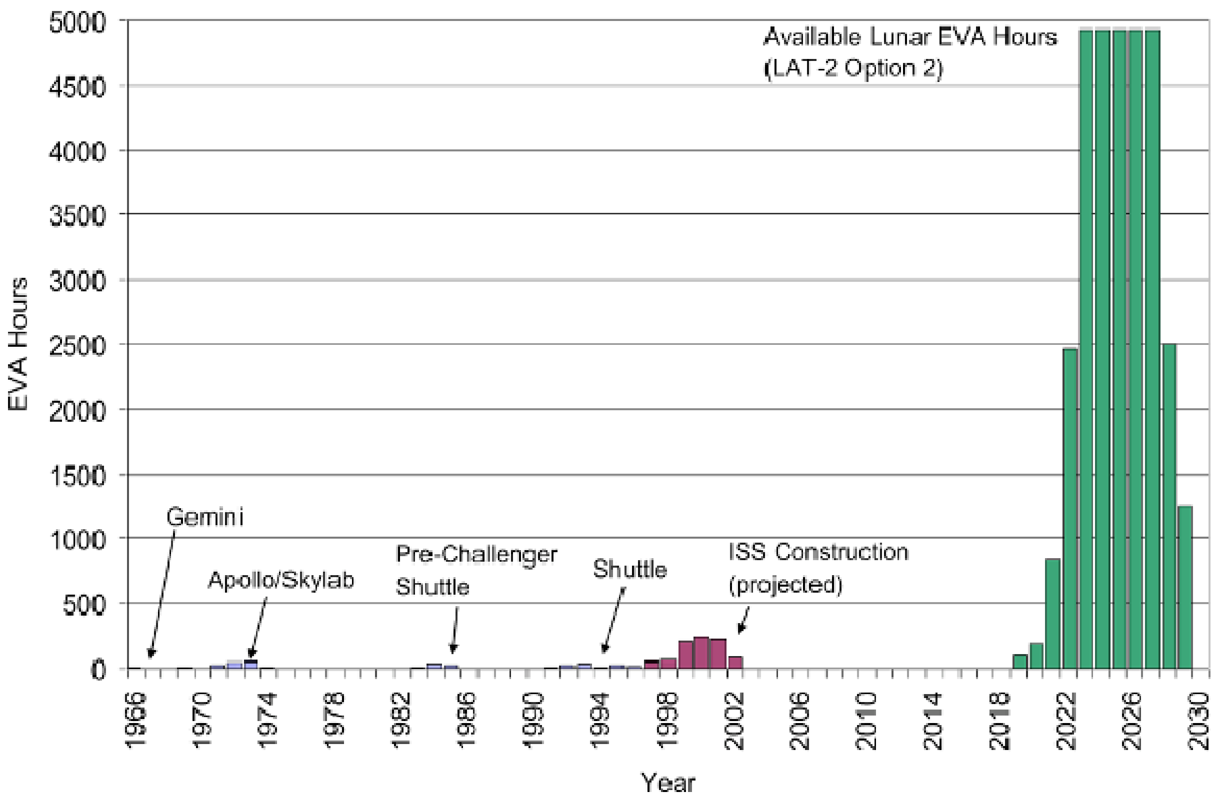


Figure 1 – EVA estimates for LAT-2 Option 2 lunar architecture.

A novel approach to optimizing human safety and performance during planetary surface exploration is currently being considered by NASA. The heart of the concept is a system of two Small Pressurized Rovers (SPRs), each of which nominally accommodates two astronauts in a shirtsleeve environment as they explore the planetary surface.

The SPRs (Figure 2) are intended to optimize human safety and performance in planetary exploration by combining a comfortable shirtsleeve, sensor-augmented environment for gross translations and geological observations with the ability to rapidly place suited astronauts on the planetary surface to take full advantage of human perception, judgment, and dexterity. As illustrated in Figure 2, each SPR is slightly larger than the unpressurized Apollo rover. The front cabin of the rover provides a pressurized shirtsleeve environment at the same pressure as the habitat or lander. Each SPR incorporates two suit ports, enabling both rapid egress to the planetary surface and rapid ingress to the shelter of the rover in response to solar particle events, suit malfunctions, or medical emergencies. A side hatch that mates with the habitat, lander, or other SPRs enables transfer of personnel and equipment under pressure. This capability, along with the capability to quickly step into the suits and perform surface operations, results in crewmembers “going EVA” for only the limited portions of an EVA sortie that require the superior perception, judgment, and dexterity of an astronaut in an EVA suit. It may also enable single-person EVA operations wherein one crewmember performs boots-on-surface EVA tasks with in situ intravehicular activity (IVA) support from a second crewmember that remains inside the SPR. The SPRs also incorporate an EVA driving station, and therefore can be operated with all the advantages of a UPR.

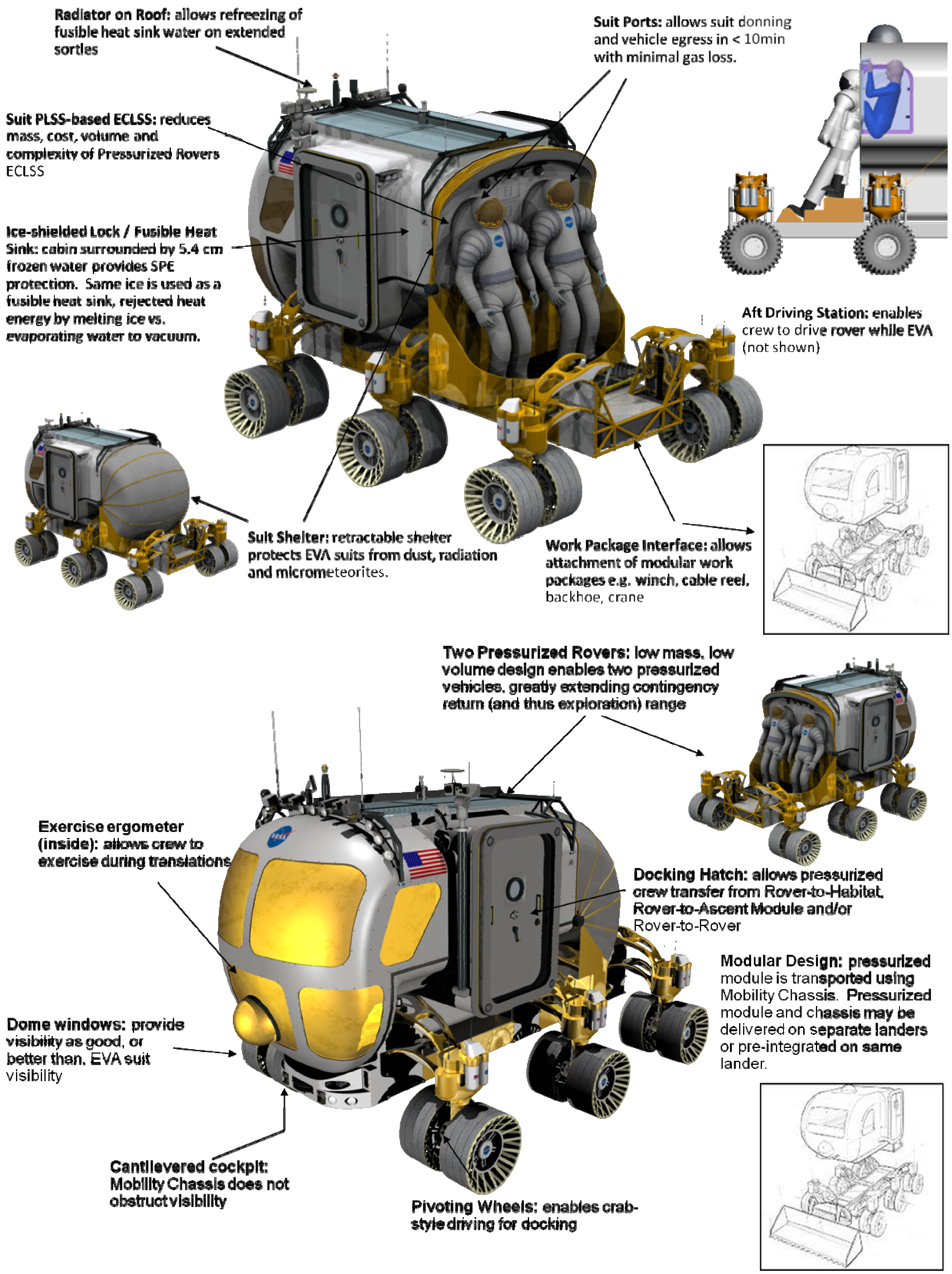


Figure 2 – Features of the Small Pressurized Rover (SPR) concept.

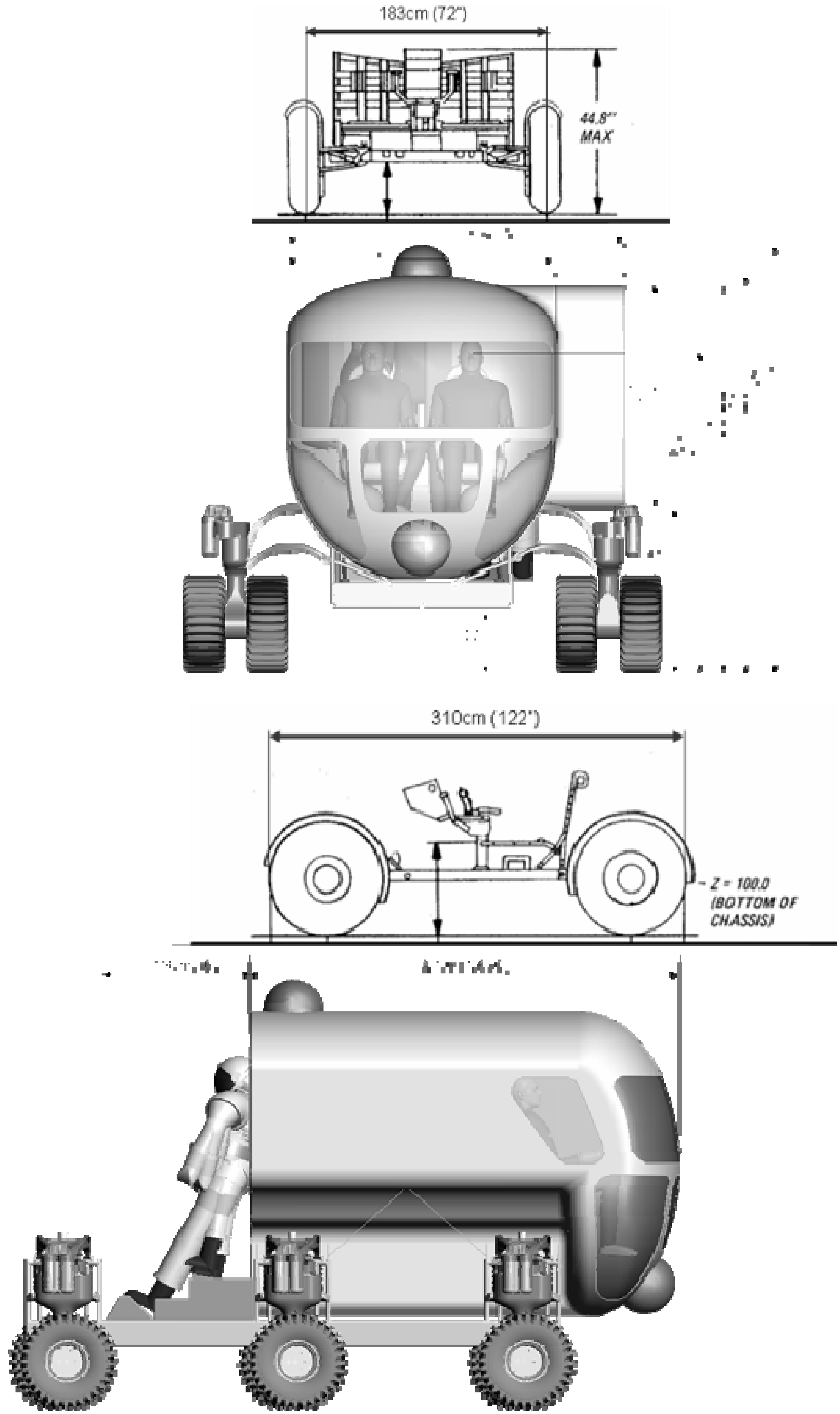


Figure 3 – Size comparison of Apollo Rover and SPR.

Because the SPRs are capable of multi-day or week-long sortie durations rather than the range-limited (8-hour) EVA activities achievable with a UPR, the overhead of returning to the outpost or lander at the end of each day will be avoided, and exploration range may be significantly greater than with UPRs. Furthermore, because each SPR is a backup to the other, and capable of supporting four crewmembers in a contingency return to the base or lander, the system of two SPRs provides greater range capability than a single larger pressurized rover. It is hypothesized that using SPR vehicles with this combination of features and capabilities will increase the safety and productivity of suited crew during exploration, mapping, and geological operations compared with using UPR vehicles.

The SPRs are a central element in the lunar architectures currently being developed and evaluated by NASA. For this reason there is an immediate need to verify the feasibility and operational characteristics of the SPR concept and to refine mass, volume, dimension, range, consumables usage, and cost estimates not only for the SPRs but also for the EVA suits and other vehicles and systems with which the SPRs will interact. Estimates of performance metrics - such as drive time, distance driven, range achieved, stationary time, and EVA time and EVA frequency during exploration, mapping, and geological traverses - are necessary inputs to models of surface mobility power and energy storage used by NASA's Lunar Surface Systems Project. EVA frequency and duration estimates are also sought by the Human Research Program for use in models of physiological adaptations during long-duration lunar missions. Quantifying the extent to which SPRs improve crew safety and productivity during lunar exploration over safety and productivity with UPR-based exploration is necessary to inform future lunar surface system architectural decisions.

Performing a comprehensive comparison of the SPR concept with a UPR alternative would require that each vehicle be evaluated and compared under the full range of nominal and contingency operational scenarios in which it might be used on the lunar surface, for example, payload offloading, pressurized or unpressurized payload transportation, payload deployment, crew transportation, solar particle event, incapacitated crewmember, incapacitated vehicle, scouting, scientific exploration, scientific instrument deployment, berm building, and terrain clearing and leveling. However, flight-by-flight development of detailed EVA timelines during the Lunar Architecture Team Phase 2 (LAT-2) Project indicated that more than 90% of total EVA time would be spent on science and exploration activities over a 10-year lunar surface program. Thus, the purpose of this study was to evaluate the human factors, performance, and productivity of the SPR concept in an operational environment and to quantify and compare the performance and productivity achieved during exploration, mapping, and geological traverses performed using UPR and SPR vehicles.

Baseline evaluation and comparison of the UPR and SPR vehicles was accomplished by planning and executing two 1-day exploration, mapping, and geological traverses with each vehicle on the Black Point Lava Flow near Flagstaff, Arizona (see Appendix A). Productivity, human factors, and performance metrics were also measured during a single 3-day SPR exploration, mapping, and geological traverse and during short ($\leq$ 3 hours) nighttime UPR and SPR traverses. A single-person EVA operation concept with in situ IVA support from inside the SPR was also evaluated. The study design and metrics used to quantify productivity, human factors, and performance during all traverses are detailed in Section 2.0.

1.2 HYPOTHESES AND TEST OBJECTIVES

The hypotheses and engineering objectives for this study are detailed below. The statistical analysis and the specific metrics associated with each hypothesis are detailed in Section 2.3.

Hypotheses:

1) Productivity achieved during 1-day exploration, mapping, and geological traverses using the Small Pressurized Rover (SPR) will be equal to or greater than the productivity achieved during Unpressurized Rover (UPR) traverses, with less EVA suit time.
2) The range achieved during 1-day exploration, mapping, and geological traverses in the SPR will be greater than during 1-day UPR traverses.
3) Subjective assessment of contextual observations from inside an SPR will be equal to assessment of contextual observations from inside an EVA suit.
4) Human interfaces with the SPR suit ports and alignment guides will be acceptable as assessed by human factors metrics.
5) The human factors and crew accommodations within the SPR will be acceptable to support a 3-day exploration, mapping, and geological traverse.

Other Test Objectives:

6) Perform nighttime driving and exploration, mapping, and geological sample collection and documentation tasks using SPR and UPR vehicles.
7) Measure performance metrics during 1-day and 3-day (SPR only) exploration, mapping, and geological traverses.

2.0 METHODS

The primary hypotheses (Section 1.2) were tested by planning and performing a series of 1-day and 3-day exploration, mapping, and geological traverses at the Black Point Lava Flow test site, during which productivity, human factors, and performance metrics, as well as other engineering data, were collected. The rationale for the use of the Black Point Lava Flow test site is described in Appendix A.

Preliminary data reduction and analysis began during the field test to enable verification of data quality. Comprehensive reduction and analysis of data were completed after the field test concluded, and each study hypothesis was tested as described in Section 2.3.

2.1 PROTOCOL DESIGN

2.1.1 ONE-DAY UPR AND SPR TRAVERSES

During the first of 2 weeks of testing at the Black Point Lava Flow test site, a series of four predefined 1-day exploration, mapping, and geological traverses were performed. During the pretest planning phase of the study, the Traverse Planning Team used photogeologic data to develop a detailed 1-day traverse plan designed to optimize scientific productivity based on clearly defined science objectives and the constraints and capabilities of the UPR. The same Traverse Planning Team also planned a 1-day traverse to optimize scientific productivity based on the same scientific objectives but the different constraints and capabilities of the SPR. The traverse planning and timeline development process is described in greater detail in Section 2.1.6.

Two crews of two people performed each of the planned 1-day traverses so that a total of two 1-day UPR traverses and two 1-day SPR traverses were performed; that is, each two-person crew performed a traverse in each vehicle. The productivity, performance, and human factors of the subjects and vehicles during all traverses were measured and compared.

2.1.2 THREE-DAY SPR TRAVERSE

In addition to the 1-day UPR and SPR traverses, the Traverse Planning Team planned – and detailed timelines were developed for – a 3-day SPR traverse that was performed during the second week of field testing. Because of time constraints the 3-day SPR traverse was performed by only one of the two-person crews. The same metrics were collected during the 3-day SPR traverse as during the 1-day traverses, with the purpose of evaluating the productivity, human factors, and performance in a way that was comparable with 1-day traverses. Furthermore, the 3-day traverse allowed investigators to assess the acceptability of the SPR human factors and crew accommodations for supporting 3-day traverses.

2.1.3 TEST OF CONTEXTUAL GEOLOGICAL OBSERVATIONS

A stand-alone protocol was developed to evaluate the hypothesis that subjective assessment of contextual observations made from inside an SPR will be equal to assessment of contextual observations made from inside an EVA suit. Members of the DRATS Science Team, all trained geologists, investigated a relatively small test site on foot and subsequently from inside the SPR. The objective was to compare the observational capabilities and constraints of the SPR cabin with the capabilities of an astronaut walking during an EVA. Because of practical constraints, the geologists did not wear the mockup suits, so the actual comparison performed was between the SPR and the “shirtsleeve” environment.

The test site was about 200 × 300 m in size and contained typical geologic features of the general area: it was placed on a gradually steepening slope that was characterized – close to the bottom – by an outcrop of red Moenkopi formation and capped – in mesa-type fashion – by the Black Point Lava Flow. Figure 4 illustrates typical scenes of the test area.

Figure 4 – Overview of the stand-alone test site, 4 km south of base camp and 1 km north of Spider Ranch road. The test area included the prominent red sandstone outcrops and stopped upslope just shy of the exposed basaltic caprock. The SPR is seen at the far southeast corner of the test area, and the Humvee is parked at the northwest corner.

Each of the three geologists first walked the entire test area for exactly 20 minutes and used a dictaphone to record verbal descriptions. No sampling tools were carried into the field and no rocks were collected, consistent with the objective of the test, which focused on observational capabilities only. Subsequently, each geologist spent up to 20 minutes inside the SPR, occupying the right-hand seat and the observation bubble, if so desired. The driver followed the geologist’s instructions on where to go and how to position the SPR windows. During the SPR portion of the protocol, geologists were instructed to make observations for 20 minutes. At the end of the 20 minutes inside the SPR, the geologists were asked to rate the quality of the contextual observations that could be made from inside the SPR using an index defined in Section 2.3.3. Written evaluations by each individual geologist were generated at the end of the test.

2.1.4 Nighttime Traverses

The ability to drive lunar rovers and perform EVA during darkness will be required during future lunar missions, during lunar night cycles and/or when it is necessary to operate in shadowed regions. Indeed, many sites of geological interest are situated in permanently shadowed regions of the Moon.

Nighttime UPR operations (with crew remaining on board the vehicle) were performed during the Human Robotic Systems (HRS) field test near Moses Lake, Washington, in June 2008 (Humphries, K., 2008). Lessons learned about navigation, lighting, and display colors and brightness during that exercise led to design modifications, which were tested during the performance of a short-duration (1-hour) nighttime traverse using the SPR vehicle. The traverse involved vehicle driving, IVA contextual observations, and EVA geological sample collection tasks (rock sample, soil sample, trench sample, photodocumentation). Human factors and performance metrics were collected during these tasks with the purpose of identifying any inadequacies with system designs or procedures.

2.1.5 Procedures, Mission Rules, and EVA Tools

A controlled and meaningful evaluation and comparison of the UPR and SPR, as well as safety of subjects and protection of equipment, required consistency in the way that different tasks were performed by all subjects. UPR and EVA mission rules and procedures, including geological sampling procedures, were developed and successfully used during Apollo. However, future lunar missions will use different vehicles, tools, and instruments; will involve larger crews; and may define different levels of acceptable risk. Indeed, no one has had previous experience operating pressurized rovers during lunar exploration.

Taking Apollo and comparable Shuttle and ISS procedures as a starting point, procedures and mission rules were developed, tested, and revised for UPR- and SPR-based EVA operations. Apollo-era EVA procedures for collecting geological samples (rock samples, soil samples, trenching samples, drive tube samples) were modified, documented, and used during the HRS Moses Lake field test. Apollo-style EVA tools were also used during sampling tasks. Putting into practice the lessons learned during Moses Lake testing (that is, excessive time spent on photodocumentation, inefficient use of the second EVA crewmember during sampling tasks, and inadequate information available to science CAPCOM/backroom), procedures were modified and EVA tools and camera equipment were developed and tested at field test on Devon Island, in the Canadian High Arctic, in August 2008. The Haughton-Mars Project (HMP) (Lee, P., 2009) test was also the first opportunity to test many mission rules and procedures not tested during the Moses Lake field test, such as "Targets of Opportunity", SPR checkout, SPR power-up, Suit PLSS/Suit Port checkout, Suit Port egress, and Suit Port ingress. Lessons learned during the HMP field test were then used to further refine procedures, mission rules, and EVA tools before testing at Black Point Lava Flow.

2.1.6 Traverse Planning and "Day-in-the-Life" Timeline Development

Traverse plans and detailed timelines were developed that were consistent with defined capabilities, constraints, and assumptions. The assumptions used when developing timelines for UPR and SPR traverses are listed in Table 1 and Table 2, respectively. The functional requirements of the SPR, as described in the Preliminary Report of the Small Pressurized Rover (IHMC, 2008), are described below:

Small Pressurized Rover Functional Requirements

- Contingency return capability always available
- Nominal 2-person crew per SPR, 4-person crew in contingency
- Power-up and check-out include suit and Portable Life Support System (PLSS) power-up and check-out: ≤ 1 hour
- Dock with or undock from habitat or lander:

- $\leq$ 10 minutes
    - $\leq$ 0.03 kg gas loss
    - Capable of several (TBD) dock/undock cycles per day
    - Robust to dust contamination
- Nominal velocity: 10 kilometers per hour
- Driving naked-eye visibility should be comparable to walking in an EVA suit; that is, eyes at the same level, and a similar field of view.
    - Augmented by multi-spectral cameras and instruments
- Visual accessibility to geological targets comparable to EVA observations; that is, naked eyes $\leq$ 1 m of targets
    - Possibility of magnification optics providing superior capability over EVA observations
- Suit donning and ingress or egress
    - $\leq$ 10 minutes
    - $\leq$ 0.03 kg gas losses per person
    - Capable of several (TBD) dock/undock cycles per day
    - $\geq$ 2 independent methods of ingress and egress
    - Robust to dust contamination
- Vehicle mass (excluding mobility chassis): $\leq$ 2400 kg
- Habitable volume: ~10 m^3
- 12 two-person EVA hours at 200-km range on batteries and nominal consumable load
- Ability to augment power and consumables range and duration to achieve $\geq$ 1000 km
- PLSS recharge time $\leq$ 30 minutes
- Crewmembers $\leq$ 20 minutes from ice-shielded lock radiation protection (including translation to SPRs and ingress)
- Heat and humidity rejection provided by airflow through ice-shielded lock and condensing heat exchanger

Table 1 – UPR Timeline Assumptions.

Description	Duration	Frequency
Crew Duty Day	900 mins	n/a
Post-Sleep	60 mins	Daily, before Hab Egress
Pre-Sleep	60 mins	Daily, after Hab Ingress
Morning Daily Planning Conference	15 mins	Daily, before Hab Egress
Morning Medical Conference	15 mins	Daily, before Hab Egress
Pre-EVA	120 mins	Daily, before Hab Egress
Science Briefing	15 mins	Daily, before Hab Egress
Hab Egress	45 mins	Daily, Start of traverse
UPR checkout	10 mins	Daily, immediately following Hab Egress
Driving Checkout	10 mins	Immediately following UPR checkout
UPR egress	2 mins	Before boots-on-surface
UPR ingress	3 mins	After boots-on-surface
UPR stowage & sample unloading	30 mins	Before Hab ingress
Hab Ingress	10 mins	End of traverse
Post-EVA	40 mins	Daily, after Hab ingress
Evening Daily Planning Conference	15 mins	Daily, after post-EVA
Evening Medical Conference	15 mins	Daily, any time after last EVA

Table 2 – SPR Timeline Assumptions.

Description	Duration	Frequency
Crew Duty Day	900 mins	n/a
Post-Sleep	60 mins	Daily
Pre-Sleep	60 mins	Daily
Morning Daily Planning Conference	15 mins	Daily
Morning Medical Conference	15 mins	Daily
Vehicle checkout	60 mins	Before each traverse
Undock	10 mins	At start of traverse
Driving Checkout	10 mins	Immediately following undock
Science Briefing	15 mins	Daily, before first EVA of the day
Vehicle Egress	10 mins	Before each EVA
Vehicle Ingress	10 mins	After each EVA
Dock	10 mins	At end of traverse
Vehicle Power-down	20 mins	Immediately following docking
Post-EVA	20 mins	Daily (assuming one or more EVAs performed)
Evening Daily Planning Conference	15 mins	Daily, after post-EVA
Evening Medical Conference	15 mins	Daily, any time after last EVA

The Desert RATS Science Team identified and prioritized specific sites of scientific interest in the test site region, using remote sensing data. The resolution of remote sensing data used was equivalent to that which is expected to be used before a crewed lunar mission that has not been preceded by robotic or crewed missions to that site. A traverse plan was then developed for a 1-day UPR traverse based on the assumptions, constraints, and capabilities associated with that vehicle. The process was repeated for the SPR vehicle. The Science Team planned traverses with the objective of maximizing productivity with each vehicle. Traverse paths for UPR and SPR 1-day traverses were expected to differ because of the differing capabilities of the vehicles. A 3-day SPR traverse plan was also developed by the science team based on the same set of predefined prioritized science sites and objectives.

Traverse plans included detailed timelines and EVA stations, each with specific tasks associated with the science objectives at those stations. Also included in traverse plans were "get-ahead" tasks, which were secondary tasks that would be accomplished if the nominal tasks were completed and the subjects were ahead of the timeline by a predefined amount of time.

Targets of Opportunity	Max Duration of Stay	GPS Fix	Video Priorities	Observations to Record	Collection	Deploy Marker
Groundwater	20 min	Yes	Context	Extent of flow. Assoc. fauna. Assoc. microbialites.	N/A	Yes
Datable Structure	20 min If collect - 30 min	Yes	Context	Morphology of microbialites	if > 35 m	No
Microbial Mats	20 min If collect - 30 min	Yes	Context Zoom	Extent, thickness. Color. Surface texture.	if > 35 m	No
Unusual Morphology	10 min	Yes	360 around structure	Gross morphology. Surface roughness. Mound relationships.	No	No

Figure 5 – Example of "Targets of Opportunity" from 2008 Pavilion Lake Research Project.

In addition to the nominal and "get-ahead" tasks, the Science Team developed a list of prioritized "Targets of Opportunity", which were defined as features of scientific interest that might be observed during a traverse but were not stated as traverse objectives in the detailed traverse plan. Mission rules were documented that defined the appropriate course of action when Targets of Opportunity were identified, based on the value of the Targets of Opportunity, the remaining traverse objectives, and the time remaining.

Figure 5 is an example of a traverse plan from the Pavilion Lake Research Project (nominal tasks and get-ahead tasks not shown). This format was modified to include specific nominal and get-ahead science objectives at each station. For each vehicle, the detailed timeline for the entire traverse day was also developed consistent with the current surface operations assumptions of the Lunar Surface Systems Project and with guidance from the Johnson Space Center (JSC) Mission Operations Directorate. Examples of a traverse plan and a "day-in-the-life" EVA timeline are shown in Figure 6 and Figure 7, respectively.

TRAVERSE OBJECTIVES		SCIENCE MERIT		PRE-FLIGHT	POST-FLIGHT			
TIMELINE	**LAT/LON**	**DISTANCE**	**LANDMARK**	**HEADING**	**PLANNED**	**BINGO**	**TET**	**ACTUAL**
Undck/Internal Cameras ON					0:15	-	0:00	
Drive Checkout to Sta 1	35.69/111.47	0.4 km	Edge of Flow	270	0:15	-	0:15	
EV2 Egress					0:10	-	0:25	
Station 1 - Edge of Flow					0:15	-	0:40	
Move Down Escarpment		0.3 km	EV2	270	0:30	-	1:10	
Station 1 - Base of Flow					0:20	-	1:30	
EV2 Ingress					0:10	-	1:40	
Drive Scarp Base to Nav-A	35.68/111.48	1.2 km	Base of Flow	190	0:25	-	2:05	
Drive West to Road (Nav-B)	35.68/111.49	1.6 km	N-S Road	270	0:35	-	2:40	
Drive South to Nav-C	35.67/111.50	1 km	Past Channeled	180	0:30	-	3:10	
Nav-D	35.66/111.50	0.7 km	Spider Ranch	210				
Drive to Sta 2 - Nav-E	35.66/111.51	0.8 km	Road	215				
Nav-F	35.66/111.51	0.4 km	-	190	0:40	6:10	3:50	
Station 2	35.65/111.50	0.4 km	Promontory	110				
Egress					0:10	-	4:00	
Station 2 - Vents					0:40	7:00	4:40	
Ingress					0:10	-	4:50	
Drive to Sta 3 - Nav-G	35.66/111.50	0.5 km	-	045				
Nav-H	35.66/111.50	0.8 km	Ranch	010	0:45	7:55		
Nav-I	35.66/111.48	1.4 km	Gate	090				
Station 3	35.66/111.48	0.4 km	Top of Flow	140			5:35	
EV2 Egress					0:10	-	5:45	
Station 3 - Top of Flow					0:20	7:45	6:05	
Drive to Sta 4 - Nav-I			Gate					
Nav-J			Base of Flow		0:35	8:20	6:40	
Station 4			-					
EV1 Egress					0:10	-	6:50	
Station 4 - Main Flow					0:50	8:20	7:40	
Drive to Station 5		0.5-1 km	Marbled	320	0:15	8:35	7:55	
Station 5 - Marbled Unit					0:40	-	8:35	
EV1/EV2 Ingress					0:10	-	8:45	
Drive to Hab - Nav-K	35.68/111.47	0.8 km	Top of Flow	070				
Nav-L	35.68/111.46	1 km	Top of Flow	030	0:35	-	9:20	
Hab	35.69/111.46	0.6 km	Camp	010				
Dock					0:15	-	9:35	

Figure 6 – Example of traverse plan format.

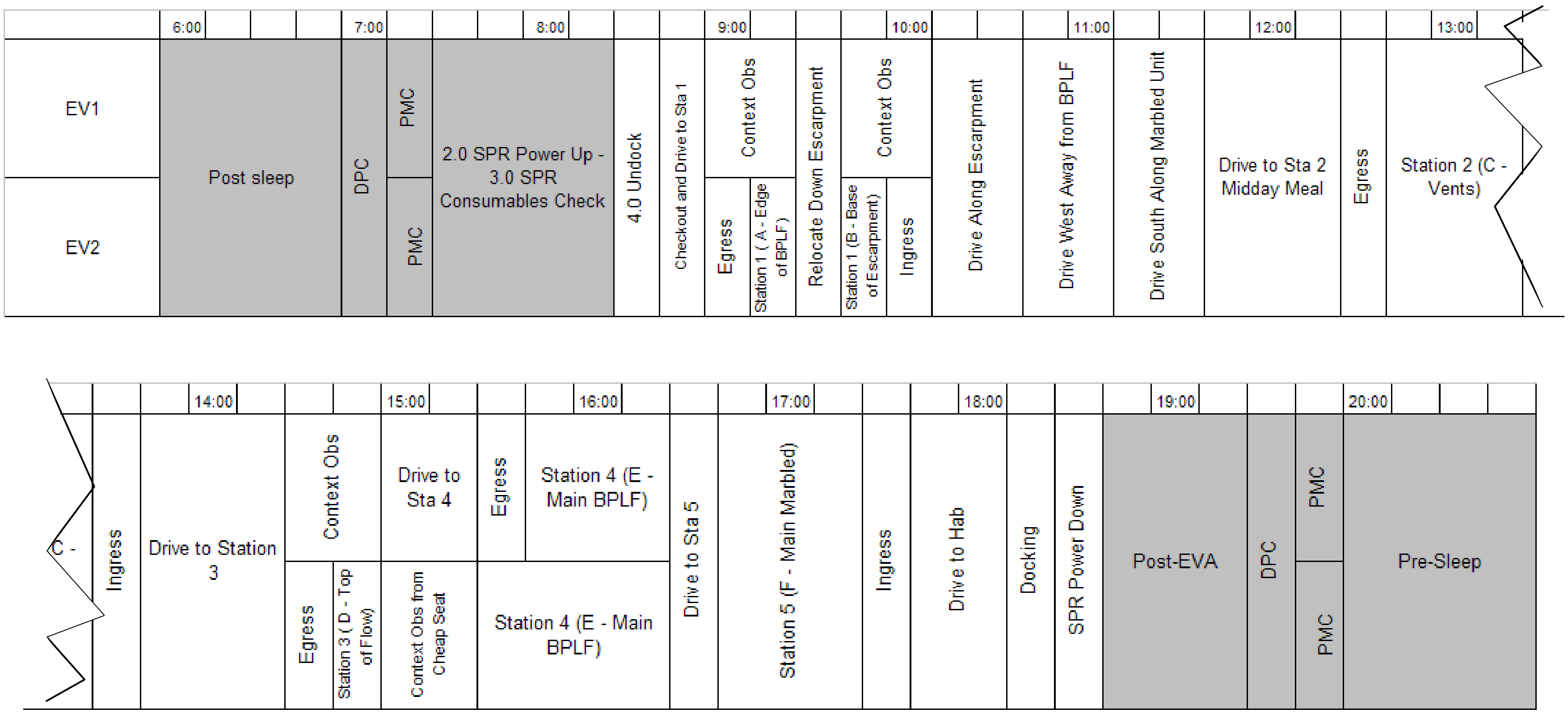


Figure 7 – Example of detailed "day-in-the-life" EVA timeline.

An annotated map of the Black Point Lava Flow test site is shown in Figure 8, and a brief overview of the geology of Black Point Lava Flow is included in the Science Team's report in Appendix D. The team developed the Science Traceability Matrix, which includes prioritized science stations and targets of opportunity, and is included in Appendix B. The matrix was derived from preliminary interpretation of a U.S. Geological Survey (USGS) aerial photomosaic of the test area. Using this preliminary interpretation, the Science Team identified the following geologic units and associated objectives:

Geologic Units

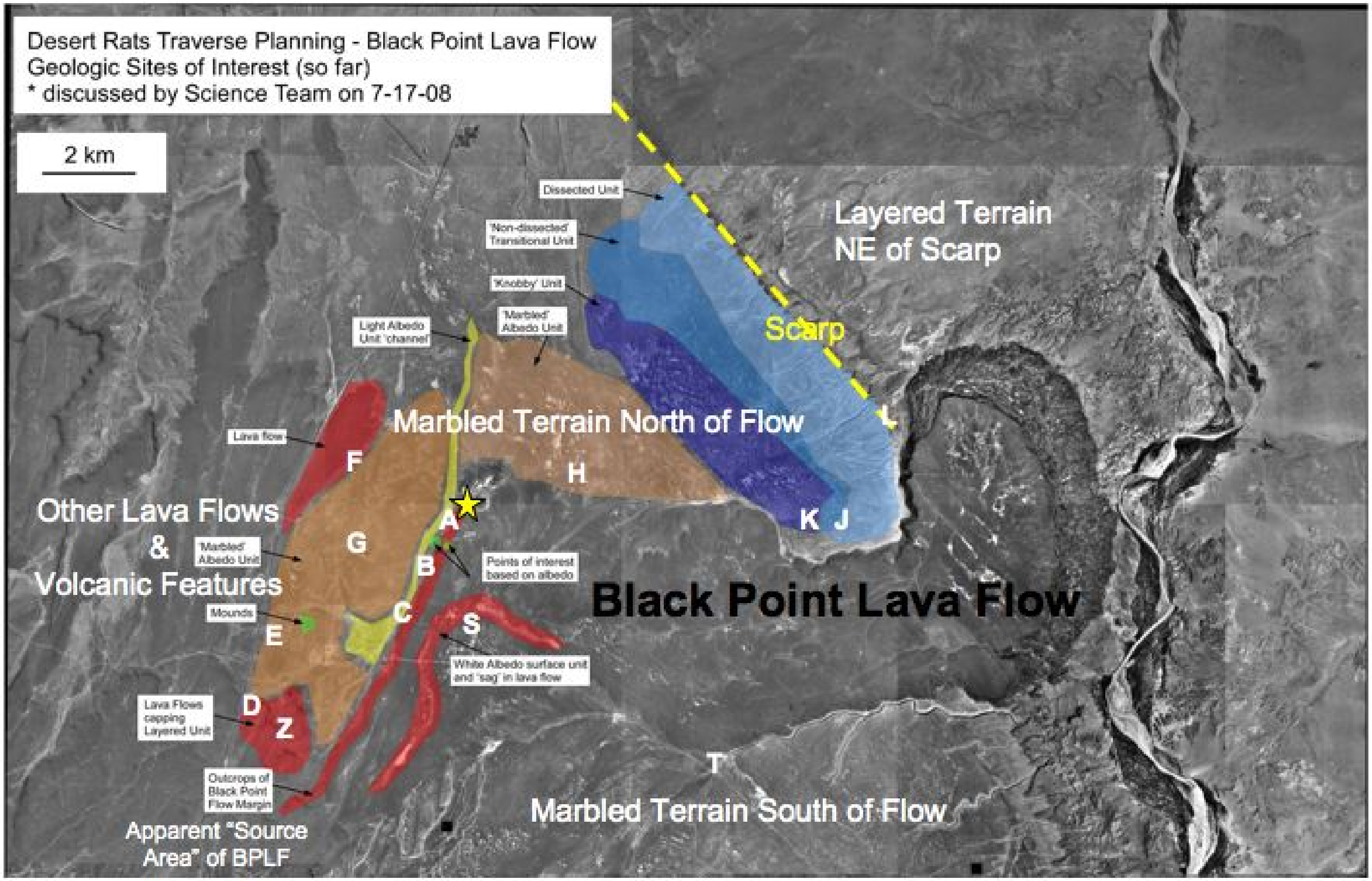
- Volcanics
    - Black Point Lava Flow or "The Flow"
    - Lava flows – undifferentiated
    - Cinder cones
    - Dissected layered unit and lava flow cap rock
- Undetermined (sedimentary? igneous?)
    - Marbled terrain north of flow (includes marbled albedo unit, dissected unit, nondissected transitional unit, and "knobby" unit)
    - Marbled terrain south of flow
    - Layered terrain northeast of ("below") scarp
    - More layered terrain – undifferentiated
    - Layered topographic highs
    - Chaotic terrain
    - Dissected layered unit and valley
- Other
    - High-albedo units
    - Fluvial channel

Overarching Scientific Objectives

1) Determine the origin and the nature of the geologic units represented at the site.
2) Understand age relationships and reconstruct the geologic evolution of the site.

Specific Scientific Objectives

1) Understand the geology of the Black Point Lava Flow (BPLF), in particular its morphology, structure, petrology, mineralogy, chemistry, age, and any spatial and temporal variations of these characteristics.
2) Understand the geology of other lava flows and volcanic features in the area and their relation to the BPLF in space and time.
3) Understand the origin and nature of other geologic units and features in the area and their relation to the BPLF in space and time.



Tentative EVA Stations as of 24 Jul 2008: A, B, C, D, E, F, G, H, J, K, L, S, T, Z
Refer to Science Traceability Matrix Table for Science Plan Details.

Figure 8 – Annotated map of Black Point Lava Flow showing tentative EVA stations.

2.1.7 CREWS AND CREW TRAINING

Before deployment into the field, four test subjects ("crewmembers") were identified. Each two-person crew included one astronaut with EVA experience and one field geologist. Subjects were briefed on the objectives and methods of the study and participated in a pretest training program that included review and practice of the following:

- Study hypotheses and objectives
- Metrics and data collection procedures
- Mission rules
- SPR procedures
- UPR procedures
- Mockup Mark III spacesuit fit check and familiarization
- Suit port ingress and egress procedures
- UPR driving
- SPR driving
- EVA geological sampling tasks
- Geological briefings
- Communications protocols

Upon deployment to the field test site, all subjects completed a brief refresher course. The combination of pretest training and the refresher course ensured the safety of the subjects and protection of the equipment, and minimized potential confounding of results because of time-varying crewmember learning effects.

2.2 TEST HARDWARE

2.2.1 UNPRESSURIZED ROVER / MOBILITY CHASSIS (AKA "CHARIOT")

A prototype of a lunar vehicle, known as Chariot,(Figure 9) was used throughout this test, first as an Unpressurized Rover (UPR) and then as the mobility base of the SPR. The Chariot is a new multipurpose, reconfigurable, modular lunar surface vehicle. The basic vehicle consists of a "mobility base"; that is, a chassis, wheel modules, electronics, and batteries. It is capable of multiple modes of operation: human direct control from on board, teleoperation with small time delays from a habitation module or lander, and supervision under longer time delays from Earth. With the right attachments and/or crew accommodations, the Chariot configuration will be able to serve a large number of functions on the lunar surface. Functions may include serving as a cargo carrier, regolith mover, and cable layer, and as human transportation.

Among the most important features of the Chariot chassis are the combination passive and active suspension and the crab steering. The suspension can lower the vehicle for easy mounting by the crew, then raise it to a height that provides optimum clearance but would otherwise be undesirable for crew accessibility. An active suspension provides the ability to dynamically level the body when the vehicle is traversing a slope, avoiding the feeling that one is about to fall out of the vehicle, which the Apollo crew had noted. Redundancy in wheel modules is enhanced through active suspension. If the steering, brake, or drive of a wheel module fails, that wheel can be lifted off the surface and the vehicle will go home on five wheels. This is not possible with a four-wheeled configuration. Crab steering means each of the six wheels can rotate 360 degrees, giving the vehicle the ability to move in any direction or rotate at any point. This makes maneuvering possible in tight places where a conventionally steered vehicle could not operate.

Figure 9 – Chariot lunar mobility prototype vehicle.

During testing, Chariot was first used in the UPR configuration (Figure 10), in which two suit attachment and support structures, or “turrets,” were attached to the chassis. The turrets are based on the Mark III (MkIII) EVA suit donning stand and allow users to dock the waist ring of the suit to the structure and thereby secure the suit in place and unload the weight of the suit from the crewmember. Each turret also incorporates a vehicle control interface, enabling either crewmember to control the vehicle and also allowing the turrets to be rotated through 360°.

After all UPR test conditions were completed, the turrets were removed and the SPR cabin was integrated onto the Chariot vehicle (see Section 2.2.2). Differential GPS data were collected from the Chariot during all test conditions.

Figure 10 – Chariot vehicle in Unpressurized Rover configuration (with Mockup MkIII spacesuits).

2.2.2 Small Pressurized Rover (SPR)

The SPR cabin used in this study was developed as a collaborative effort between JSC, Langley Research Center, Ames Research Center, and Glenn Research Center. The cabin was not pressurized but incorporated functional suit ports including alignment guides and clamping mechanisms, included all necessary crew accommodations to support a traverse of 3+ days, and was fully integrated with the Chariot chassis (Figure 12 and Figure 13) consistent with NASA's current lunar architecture assumptions. Rigorous testing of the integrated Chariot-SPR was performed at the JSC "Rock Yard" facility before it was deployed to the field.

For living accommodations, the SPR had two sleep stations with privacy curtains, a functional hot and cold water dispenser and waste containment system (WCS), functional floor and cabin stowage areas, and seven Crew Transport Bags (CTBs) filled with a variety of food, equipment, and other consumables.

Figure 11 – Interior photos of the SPR. Upper left, front cockpit showing redundant controls and touch-screen displays; upper right, view from front to rear; lower left, view from rear to front; and lower right, sleep station with privacy curtain partially deployed.

Six small cameras and one wide-angle dome camera were positioned throughout the SPR to record the internal interactions between the humans and the machine's habitable volume and systems (Figure 14). Of these six cameras, four small cameras were located in the front cockpit area of the vehicle – one focused on the participants while they were in the front seats, another focused outside the left front window panel to record the terrain, and the final two focused on both the starboard and port suit ports. The remaining two small cameras were mounted in the rear over each suit port and were focused forward to record such things as hand placement when participants entered the suit port and crew interaction inside the cabin (for example, meal preparation and sleep station setup). The wide-angle dome camera was placed aft of the vehicle center as a backup camera. This camera had a view of the entire vehicle from the port side hatch to the front windows. In addition, an array microphone was positioned in the front of the vehicle above the cockpit as a dual source of wireless radio communications and audio recording. Recording was accomplished by two digital video recorders (DVR) and a sound mixer positioned under the floor of the vehicle.

Figure 12 – Small Pressurized Rover cabin integrated with Chariot chassis.

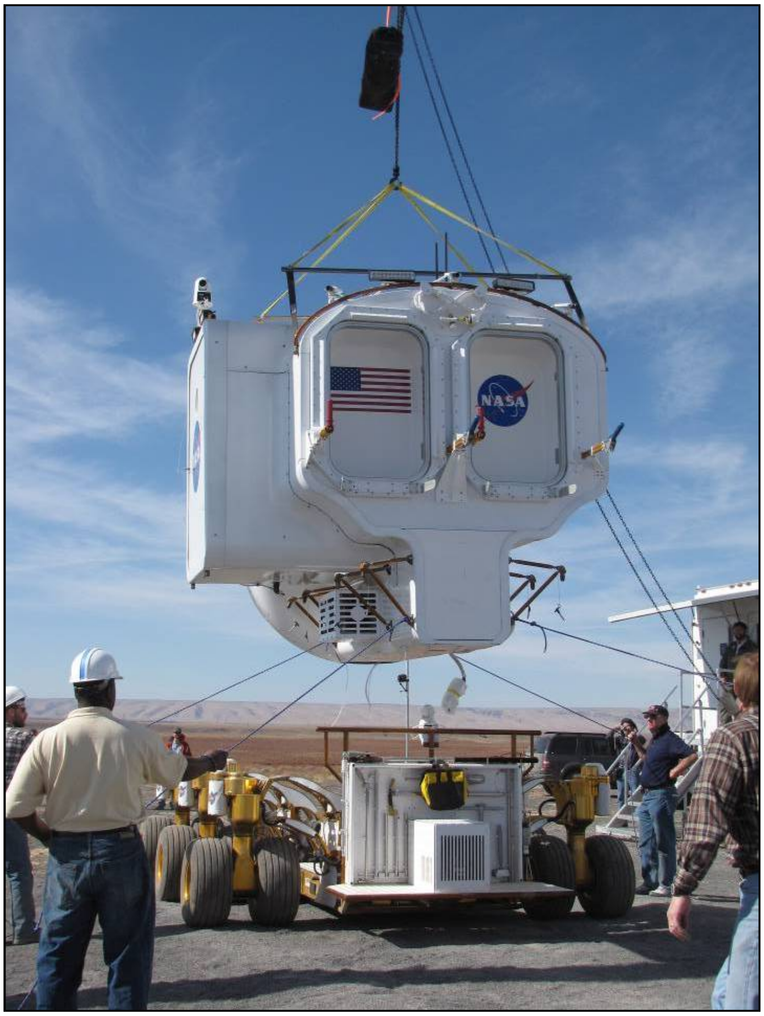


Figure 13 – Integrating the SPR cabin with the Chariot chassis at the test site.

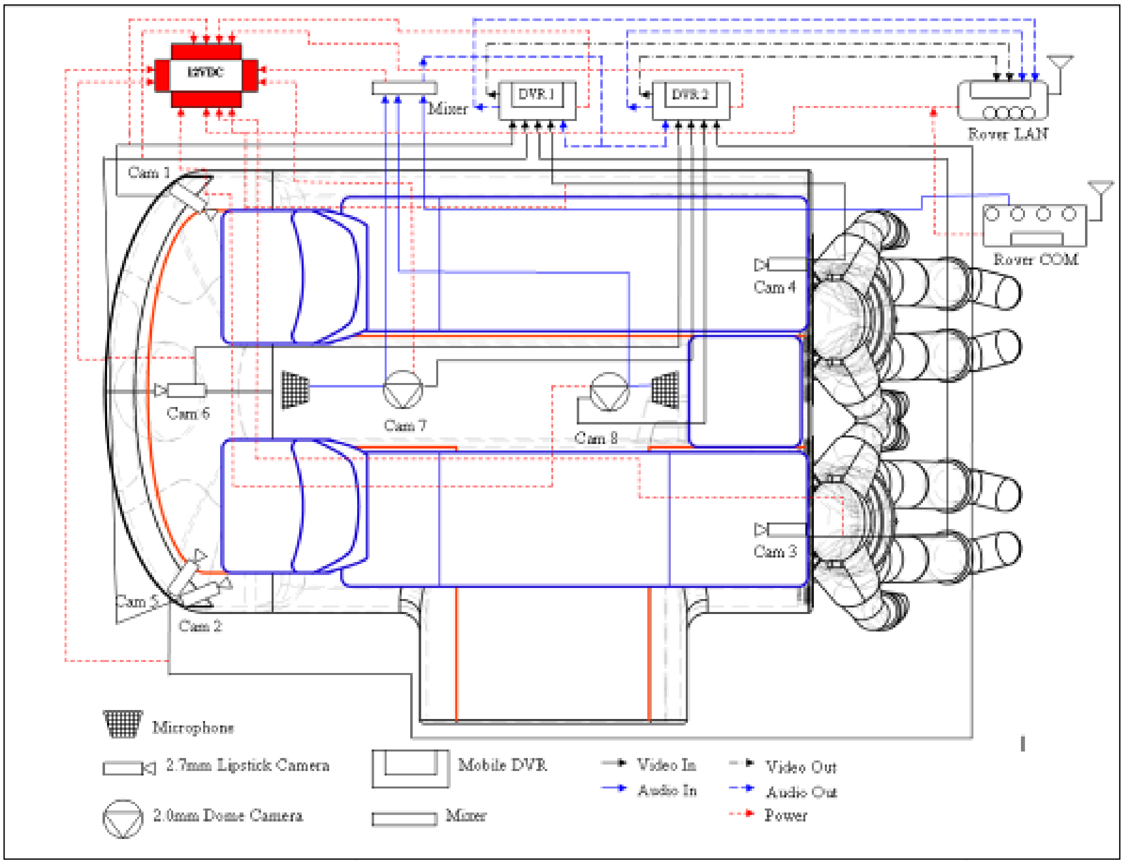


Figure 14 – SPR interior cameras and microphones for human factors evaluations.

2.2.2.1 Suit Port Mockup

The suit port is an element of the SPR by which the crew performs EVAs. The suit port mockup was located on the aft bulkhead of the SPR cabin structure and included interior suit don and doff aids as well as exterior platforms to accommodate crewmembers of different heights. The mockup suit ports are shown in Figure 15 and Figure 16.

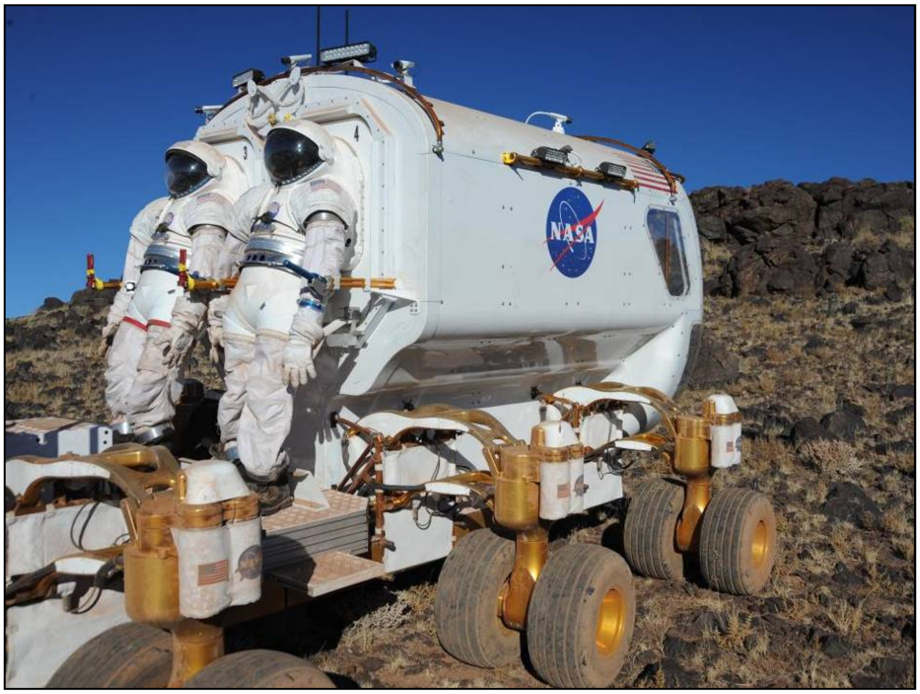


Figure 15 – Rear view of SPR showing mockup suits attached to suit ports.

Figure 16 – A crewmember detaching from the SPR suit port.

Initial human factors evaluation of the suit ports was performed at JSC in the Building 9 high bay and the "Rock Yard" facility. This testing continued during the October field test, when four crewmembers repeatedly used the suit ports during the 1-day and 3-day SPR traverses.

The human factors evaluation of the suit port mockup (at JSC and during the October field test) focused on the following specific features and functions of the suit port:

Suit don and doff capabilities and features of the suit port architecture:

- Location and usability of interior handholds for suit don and doff
- Usability of an "ottoman" as an interior booster seat for suit don and doff
- Usability of exterior handrails for alignment guides and positioning during suited ingress operations
- Leg angle positioning for suit don and doff operations
- Adequacy of adjustable exterior platform heights for various crewmembers

Features of suit undocking from and docking to the suit port / hatch interface area:

- Usability of the actuator to unlock and lock the inner hatch
- Usability of the actuator to close and open the inner hatch
- Method of closing and opening the PLSS to the suit

- Usability of the actuator to unlock and lock the closure mechanism attaching the suit to the suit port entry hatch
- Ability of a suited test subject to detach and reattach the suit to the suit port
- Alignment guides and exterior platform height
- External umbilical access and functional operation characteristics

However, it is important to note that a) the suit port did not pressurize (a pressurized engineering unit has since been fabricated), b) the mockup suits were unpressurized and were not specifically designed for use with suit ports, c) the testing was performed in a 1-g environment, and d) the mockup suits and suit ports did not incorporate the additional complexities associated with an actual PLSS and the data, power, gas, and fluid connections between the suits and the SPR. Testing in a 1-g environment using unpressurized suits that are not specifically designed for use with suit ports is likely to increase the time and difficulty associated with suit port egress and ingress tasks, whereas the reduced complexity of the suit port mockup compared with that of a fully functioning pressurized version will mean that EVA overhead and technical challenges associated with this complexity were not identified during this study. Results of the suit port evaluation are presented and interpreted within the context of these limitations. Further discussion of the use of mockup EVA suits is in the following section.

2.2.2.2 Mockup MkIII Spacesuits and EVA Tools

The Mark III (MkIII) suit, also called the H-suit, represents a hybrid spacesuit configuration in that it is composed of hard elements such as a hard upper torso and hard brief section and of soft components such as the fabric elbows and knees. A key feature of the suit is its use of bearings in multi-axis mobility joint systems. The MkIII has bearings at the shoulder, upper arm, waist, upper hip, mid-hip, upper leg (3 bearing hip), and ankle joints. The suit is donned through a rear entry hatch. Subjects are integrated to the suit by a waist belt weight relief system and shoulder straps. The boots of the H-Suit are modified Extravehicular Mobility Unit (EMU) boots. The stiff fiberglass sole of the EMU boot was replaced with a commercial work boot sole. The MkIII suit weighs about 55 kg. Figure 17 below shows the MkIII suit as tested at the Desert Research and Technology Studies (RATS) 2006 remote field test.

Figure 17 – Mark III suit at Desert RATS 2006.

The MkIII supports testing that assists with requirements development for future exploration class EVA systems. Some testing requires a suit that weighs less than the MkIII but is similar in appearance and with similar mobility limitation features, such as the three-bearing hip. Using lightweight suits minimizes injury risk, and they more closely represent the suit weights that will be experienced by astronauts on the lunar surface.

Global Effects, Inc. designed and fabricated eight lightweight suits modeled after the MkIII to use in the movie industry. An additional suit was fabricated for NASA Headquarters to use as a Public Affairs Office display model. In June 2008, Global Effects, Inc. delivered four mockup suits to NASA JSC. These lightweight mockups were modeled after NASA's MkIII suit. Figure 18 shows two of the four MkIII mockup suits that were delivered.

Figure 18 – Two Global Effects, Inc. MkIII Mockup Suits.

The mockup suits weigh about 28 kg, are cosmetic representations of the MkIII suit, and have mobility limitations similar to those of the MkIII suit (for example, waist bearing, hip bearings, and shoulder convolutes). The suits have the following parts:

- Hard Upper Torso in fiberglass with correct hemisphere size, PLSS latch system, internal shoulder and waist harness, shoulder bearings, and a switch for the vent fan system
- Hemispherical visor with a simple smoke sun visor with lift tabs and sun visor cover
- Functional rolling convolute shoulders, with aluminum and cast metal
- Sleeves made from nylon with anodized aluminum bayonet-style wrist disconnects
- Glove Thermal Micrometeoroid Garments (TMGs) in Teflon with silicone palms
- Waist bearing
- Hip rotary joints with bearings in fiberglass
- Legs made from nylon fabric
- Shuttle-style PLSS volume with vent pressure fan system and batteries
- Removable and machine-washable liners for sleeves and legs
- Bearing spacers for torso and waist in 1″ and ½″ increments
- Combat-boot style integrated with ankle ring

Two of the four suits were modified to interface with the SPR suit port. Changes included the addition of an interface plate to the rear entry hatch, increasing the Portable Life Support System (PLSS) volume, and addition of a communication system, a GPS, and a data logger.

During EVA activities, subjects were prompted for self-reported ratings of discomfort and exertion (see Section 2.3.7). If a subject reported a discomfort rating > 7 (on the Corlett and Bishop 10-point discomfort scale) for two consecutive recording periods during suited testing, the subject was asked to doff the suit and continue the test wearing a lightweight backpack alternative that incorporated communications hardware and a GPS data logger. If a subject had reported a discomfort rating > 7 (on the Corlett and Bishop 10-point discomfort scale) for two consecutive recording periods during lightweight backpack operations, that specific test would have been terminated.

Although the mockup suits have mobility limitations similar to those of the real MkIII suits, it should be noted that the mockup suits have several additional limitations. The objectives of this study did not require a pressurized planetary spacesuit prototype such as the MkIII. Indeed, the crewmember fatigue that results from the ~100kg (220lb) pressurized suits would have made completion of this test impossible and would have confounded the data by simulating a suit mass of more than 1000kg (2200lb). The Mockup MkIII suits enabled evaluation of the suit ports while also enabling completion of simulated EVAs lasting up to 8 hours. However, human performance data in the Mockup MkIII suits during this test is not representative of performance in the lunar environment.

The EVA Physiology, Systems and Performance (EPSP) project has conducted studies which demonstrate the limitations of pressurized suits in 1-g test conditions and shows that no existing suit prototype or mockup suit accurately reflects lunar metabolic profiles. Detailed reports on these studies are available from the EPSP project.

2.2.2.3 Communications, Networking and Navigation Infrastructure

The Information Technology and Communications Directorate (ITCD) at Kennedy Space Center (KSC) was responsible for engineering, implementing, testing, and deploying operationally a diverse communications and networking infrastructure to support test operations. This infrastructure is known as a Lunar Communications and Network Emulator (LCNE), and the system was deployed to model an Agency Lunar Comm and Network architecture to evaluate the architecture and identify gaps in planning.

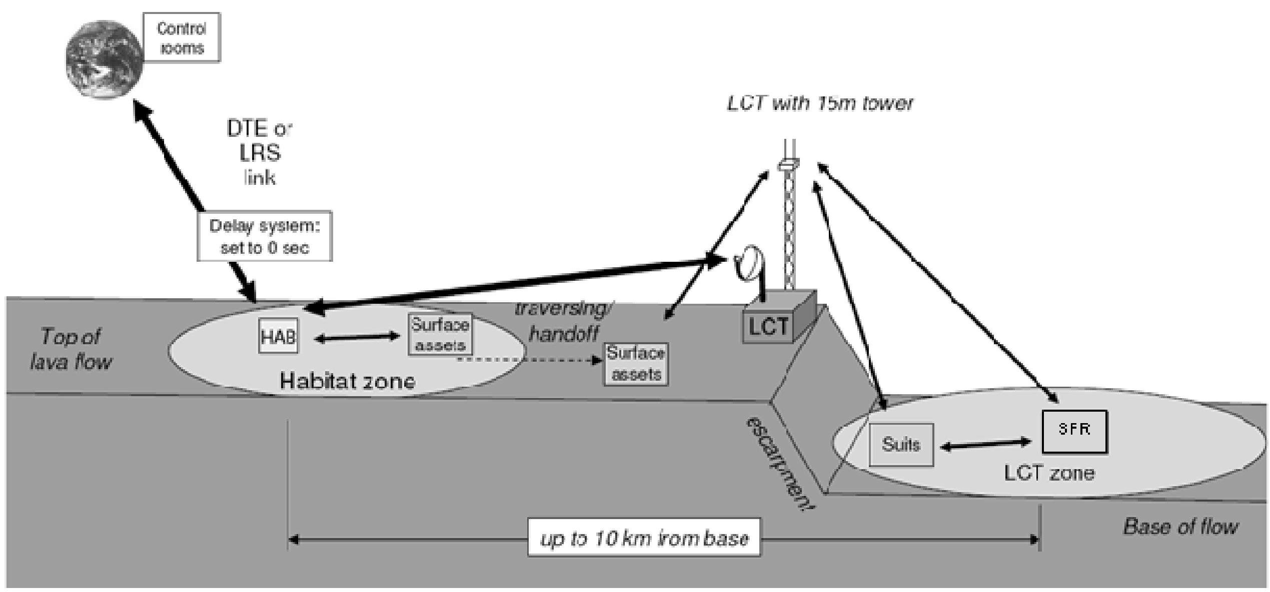


Figure 19 - Lunar communications architecture modeled at D-RATS 2008.

The KSC ITCD team provided the following major areas of support:

- Installed communication and networking assets on nearby Elden Mountain to serve as aggregate broadband network bandwidth to the field test from a commercial Internet service provider
- Secured the network from Internet attacks, and tunneled test site traffic back to NASA's networks
- Measured network utilization and performance useful for future lunar data requirements planning
- Engineered and deployed a duplicate network tunnel from a JSC location to allow engineers to test their field configuration before the outing during dry run operations
- Engineered, tested, and deployed the entire test site video, voice, and data network, which included multiple routers, switches, and even tactical fiber deployment at the test site
- Engineered, fabricated, tested, and deployed a mockup Lunar Communication Terminal (LCT)
- Provided spectrum management leadership for the entire D-RATS test team
- Engineered, fabricated, tested, and deployed pan/tilt/zoom cameras that were remotely controlled throughout the field test
- Engineered and fielded on-suit EVA megapixel science cameras and associated science CAPCOM image and video stream data display system
- Assisted with design and testing of SPR rover audio and radio system
- Validated performance of a low-data-rate high-definition mobile camera standard for lunar rovers and suits

Navigation and asset tracking and recording for the rovers at the field test was facilitated through the use of the U.S. Global Positioning System (GPS). Use of the U.S. GPS system was adequate for the purposes of navigating traverses during this test and recording the progress of the operations. Future tests will involve the utilization of navigation techniques that more accurately model the lunar navigation architecture.

2.2.2.4 Mobile Mission Control Center

The KSC ITCD Mobile Mission Control Center (MMCC – Figure 20) was deployed at the base camp to accommodate the test support team, which included Capsule Communicator (CAPCOM), Traverse Director, Human Factors, Rover, Science Backroom, and Networking personnel.

Figure 20 – Mobile Mission Control Center (MMCC).

2.2.2.5 SPR Exercise Ergometer

The SPR contained a fully functional exercise ergometer (Figure 21). The device and its integration within the SPR were included in the human factors evaluation of the SPR crew accommodations.

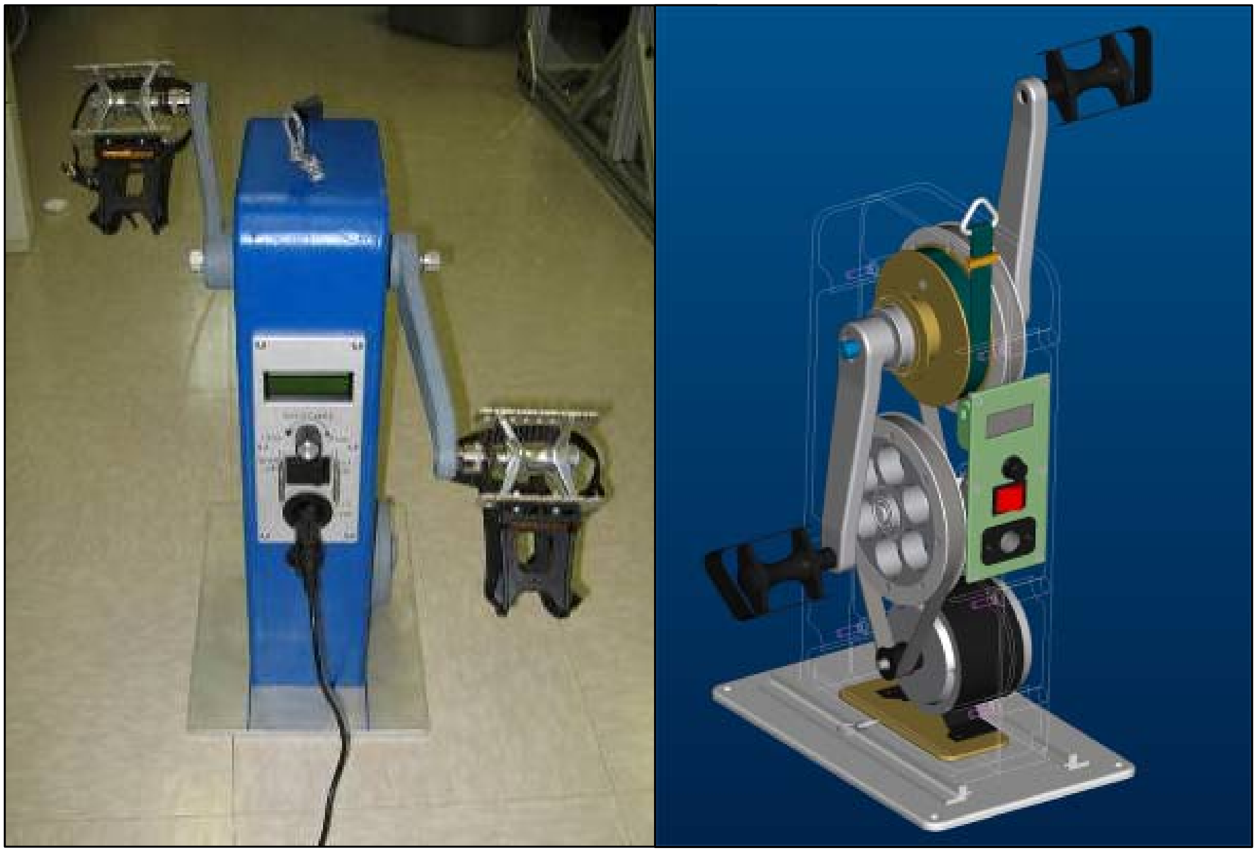


Figure 21 – SPR exercise ergometer.

2.2.3 Hardware Inspection

Before the start of each phase of this study, NASA Safety evaluated all hardware at test readiness reviews. Before and after each test session, the test operators visually inspected all testing equipment to ensure hardware safety.

2.3 METRICS AND HYPOTHESES TESTING

Descriptive statistics were used to characterize the performance, productivity, and human factors metrics under all test conditions. Inferential statistics were not utilized to test the study hypotheses (Section 0) because the study had low statistical power. Instead, practically significant differences in specific metrics were prospectively defined for the testing of the study hypotheses. This process has been used during previous EVA suit-testing protocols conducted by the EVA Physiology, Systems, and Performance Project in which small sample sizes precluded the use of inferential statistics. For example, a practically significant difference in metabolic rate has been defined as ≥ 3.5 ml/kg/min, which is about equal to a person's resting metabolic rate and also corresponds to the difference in metabolic rate that a person can perceive.

The specific metrics used to evaluate each of the study hypotheses are described in the following sections. For comparative hypotheses, the difference value for each metric that was considered practically significant is defined and the rationale explained. For noncomparative hypotheses, the absolute value of each metric that accepted or rejected each hypothesis is defined and the rationale explained.

2.3.1 HYPOTHESIS 1: COMPARING PRODUCTIVITY AND EVA SUIT TIME

Hypothesis 1: Productivity achieved during 1-day exploration, mapping, and geological traverses using the Small Pressurized Rover (SPR) will be equal to or greater than the productivity achieved during Unpressurized Rover (UPR) traverses, with less EVA suit time.

EVA suit time was recorded on data sheets during all traverse operations. Two methods of quantifying traverse productivity were used during this study: Pavilion Lake Research Project (PLRP) Traverse Science Merit Rating and Scientific Productivity Index (SPI). Each metric was developed and used to quantify a different aspect of the productivity, as described below.

Metric: Pavilion Lake Research Project Traverse Science Merit Rating

The Pavilion Lake Research Project (PLRP) uses a 1-5 Likert scale to quantify the scientific merit of submersible research traverses, shown in Table 3. The scientific merit of each traverse with respect to predefined scientific questions is rated before and after the traverse is performed. For each defined science question, the pre-traverse rating is a measure of the anticipated merit of that traverse with respect to that question. The post-traverse rating measures the actual scientific merit, that is, the extent to which that traverse will enable the science question to be answered. The merit of each traverse is also rated 2 years post traverse, after data from the traverse have been analyzed and possibly published. All ratings are based on the consensus of 4 or more subject matter experts. The PLRP Science Merit Rating was applied to each of the DRATS 2008 field test traverses. The science merit data sheet completed before and after each traverse is shown in Table 4, including the specific science questions identified by the DRATS Science Team.

Table 3 – Pavilion Lake Research Project Traverse Science Merit rating scale.

METRIC	DESCRIPTOR	DEFINITION
1	Limited	Data provide limited scientific value
2	Adequate	Data reaffirm existing hypotheses and facts
3	Significant	Data elucidate existing hypotheses in new areas or detail
4	Exceptional	Data resolve a major scientific question or highly significant hypothesis
5	Discovery	Data introduce a novel idea or hypothesis

Practically Significant Difference and Rationale

By definition, any change in category on the scale represents a qualitatively significant difference in the metric. The mean values of pre- and post-traverse science merit for traverses with each vehicle were compared, with a difference of 1 category or more being prospectively defined as a significant difference.

Table 4 – Science questions addressed by UPR and SPR traverses at Black Point Lava Flow.

	Science Question	Pre-Traverse Science Merit	Post-Traverse Science Merit
1	Will observations and samples collected allow characterization of Black Point Lava Flow (BPLF), in particular its age, morphology, structure, petrology, mineralogy, chemistry, and spatial and temporal variations?		
2	Will observations and samples collected allow characterization of the Marbled Unit, in particular its age, morphology, structure, petrology, mineralogy, chemistry, and spatial and temporal variations?		
3	Will observations and samples collected allow characterization of other geologic units and their relation to the BPLF in space and time?		
4	Will observations and samples collected allow determination of the geologic history of the site and determine the absolute ages of the major units in so far as possible?		

Metric: Scientific Productivity Index

The Scientific Productivity Index (SPI) metric enables relative comparison of the productivity of different traverses in the same region. Whereas the PLRP Science Merit metric quantifies the scientific merit of a traverse as a whole, the SPI provides a measure of the success with which each predefined traverse objective is accomplished. Each traverse objective is assigned a value (VTO) before the traverse begins and, for each objective, the quality of data (DQ) collected during the traverse is rated according to a data quality scale.

$$\text{Scientific Productivity Index} = \sum \text{VTO}(n) \times \text{DQ}(n)$$

where

VTO (n): value of traverse objective n, on a 1–3 scale

1 = low anticipated scientific importance

2 = moderate anticipated scientific importance

3 = high anticipated scientific importance

DQ (n): Quality of data collected at traverse waypoint objective n, on a 0–4 scale

The Pavilion Lake Research Project Data Quality Scale is a metric originally developed and used to quantify the quality of data collected during sorties performed by submersibles equipped with video cameras and manipulators. The scale is shown in Table 5.

Table 5 – Pavilion Lake Research Project Data Quality Scale.

	DESCRIPTOR	DEFINITION
0	No data	No data or other relevant observations were made.
1	Limited	Video and navigation did not support scientific observations and other relevant data was of limited use.
2	Adequate	Quantitative data adequate for general documentation of findings. Provides useful context and enables efficient return. Data is marginally publishable.
3	Significant	Quantitative data adequate to support specific documentation of scientific findings and yielding publishable results.
4	Exceptional	High quality video, navigation, and other quantitative data that supports and enhances scientific merit.

Thus, if no data were collected for a particular traverse objective of any value, the weighted sum for that objective would be zero. If exceptional data were collected for a traverse objective of high importance, a weighted sum of 12 would be assigned.

Practically Significant Difference and Rationale

The mean values for traverses with each vehicle were compared. A difference in SPI of 9 points reflected completion of one high priority science objective with high quality data and was considered a practically significant difference in productivity for the purposes of this test.

Metric: EVA Suit Time

Time spent inside the EVA suit increases suit-induced trauma and increases usage of consumables because of the evaporative cooling process. It was hypothesized that having the ability to make contextual geological observations from inside the SPR would mean that less EVA suit time would be required to achieve equal or greater productivity during 1-day SPR traverses than during 1-day geological UPR traverses. EVA suit time was manually recorded on data sheets during all traverse activities. The maximum and mean EVA suit time for each vehicle was calculated for the 1-day and 3-day traverses.

Practically Significant Difference and Rationale

A difference in mean or maximum EVA suit time of ≥ 10% was prospectively defined as practically significant. Although the relationship between EVA suit time and suit trauma is variable and difficult to quantify, the relationship between EVA suit time and consumables usage is better defined.

2.3.2 HYPOTHESIS 2: COMPARING RANGE

Hypothesis 2: The range achieved during 1-day exploration, mapping, and geological traverses in the SPR will be greater than during 1-day UPR traverses.

Metrics: Range, Distance Driven, Terrain Factor, Speed

The different capabilities of the SPR and UPR mean that greater range is achievable using the SPR. Range as well as distance driven and speed (average and maximum) of each traverse were measured using GPS. The means of the maximum range for each of the 1-day traverses using each vehicle were calculated and compared as the test of Hypothesis 2.

Practically Significant Difference and Rationale

A difference in mean of maximum range or distance driven of ≥ 10% was prospectively defined as being practically significant.

2.3.3 Hypothesis 3: Contextual Observations

Hypothesis 3: Subjective assessment of contextual observations from inside an SPR will be equal to contextual observations from inside an EVA suit.

Metric: Subjective Assessment of Contextual Observations

A Subjective Assessment of Contextual Observations scale (Table 6) was used to evaluate the ability of four subjects (members of the science team) to make contextual observations from inside the SPR compared with observations from inside an EVA suit.

Table 6 – Subjective Assessment of Contextual Observations scale.

	DESCRIPTOR	DEFINITION
1	Limited	Observation quality is significantly limited by the vehicle compared with that achievable by the same person, in the same amount of time, walking shirtsleeve.
2	Adequate	Observation quality is adequate; marginally limited by the vehicle compared with that achievable by the same person, in the same amount of time, walking shirtsleeve.
3	Shirtsleeve Equivalent	Observation quality is not limited by the vehicle; equivalent to that achievable by the same person, in the same amount of time, walking shirtsleeve.
4	Exceptional	Observation quality is enhanced by the vehicle; exceeds that achievable by the same person, in the same amount of time, walking shirtsleeve (for example, due to accessibility, use of cameras and sensors, elevation, intra-site translation speed)

Subjects rated their own Geological Observation Quality when inside the vehicle. The rating was not a measure of the quality of data collected nor was it a measure of the expertise of a crewmember; it was a measure of the extent to which the vehicle enabled subjects to make geological observations at a particular traverse station. A rating of 3 indicated that the quality of observations was equivalent to that which could be achieved by the same person, in the same amount of time, while walking in "shirtsleeves." Comparison with suited EVA operations was not performed during this test.

In addition to assigning a rating, reviewers made note of the significant factors that enhanced or inhibited subjects' ability to make geological observations, including vehicle features and capabilities (such as use of cameras and sensors, elevation of subjects, intra-site translation speed, and trafficability) and also features of the station (such as slopes, blockiness, and geology).

Practically Significant Difference and Rationale

By definition, any change in category on the scale represents a qualitatively significant difference in the metric. It was hypothesized that the mean rating among all geologists would be about equal to 3.

2.3.4 Hypothesis 4: Suit Port Human Factors

Hypothesis 4: Human interfaces with the SPR suit ports and alignment guides will be acceptable as assessed by human factors metrics.

Metric: Subjective Ratings of Suit Port Human Factors

The following Likert scale was developed to evaluate the acceptability of SPR suit ports and alignment guides:

Totally Acceptable-no improvements necessary		Acceptable-minor improvements desired		Borderline-improvements warranted		Unacceptable-improvements required		Totally Unacceptable-major improvements required	
1	2	3	4	5	6	7	8	9	10

Crewmembers were asked to evaluate the following aspects of the suit ports and alignment guides:

1) Overall human factors
2) Internal access
3) Interior handholds
4) General IVA operations
5) External access
6) External handholds
7) General EVA operations
8) Donning of suit
9) Doffing of suit
10) Interior vehicle volume for donning
11) Interior vehicle volume for doffing
12) Translation into suit port
13) Translation out of suit port

Hypothesis Accept-Reject Criteria and Rationale

To test the hypothesis, median ratings of overall human factors were calculated. By definition, ratings of ≤ 4 indicated acceptable human factors. However, even where median values were ≤ 4, the reasons for any outlying data points > 4 (that is, unacceptable human factors) were recorded to help inform the redesign of the suit ports and alignment guides.

2.3.5 Hypothesis 5: Human Factors during 3-Day Traverse

Hypothesis 5: The human factors and crew accommodations within the SPR will be acceptable to support a 3-day exploration, mapping, and geological traverse.

A combination of existing human factors metrics and customized questionnaires were used to evaluate the acceptability of the SPR and UPR human factors. Data collection intervals were incorporated into the detailed EVA timelines. Data were collected primarily using data sheets, but data from built-in video cameras inside the SPR (Figure 14) were also analyzed after the field test to yield additional usability information. Data were collected daily to assess any trends that might suggest that the acceptability of the human factors and crew accommodations were decreasing as the 3-day traverse continued.

Metric: Subjective Ratings of SPR Human Factors

A questionnaire and interview were completed at the end of each traverse day. Five groups of questions concerned the functionality of the SPR in the areas of driving, visibility, cockpit displays and controls, seating, and EVA. One group of questions focused on overall acceptability of each vehicle configuration. The same Likert scale used in assessing suit port human factors was used:

Totally Acceptable-no improvements necessary		Acceptable-minor improvements desired		Borderline-improvements warranted		Unacceptable-improvements required		Totally Unacceptable-major improvements required	
1	2	3	4	5	6	7	8	9	10

The post-traverse questionnaire also had four open-ended questions about the limiting factors for performance, the overall configuration, changes in configuration that could make traverses more efficient, and any additional comments that were not covered in the ratings.

Hypothesis Accept-Reject Criteria and Rationale

By definition, ratings of ≤ 4 indicated acceptable human factors. However, even where mean values were ≤ 4, the reasons for any outlying data points > 4 (that is, unacceptable human factors) were recorded to help inform the redesign of the vehicle.

Metric: Cooper-Harper Rating of Vehicle Handling Qualities

One aspect of the human factors evaluation is the handling qualities of the vehicle. The Cooper-Harper rating of vehicle handling qualities is shown in Figure 22 and was used in evaluating UPR and SPR vehicle handling qualities.

Hypothesis Accept-Reject Criteria and Rationale

As Figure 22 shows, a Cooper-Harper rating of 3 corresponds to “Satisfactory without improvements” with “minimal compensation required for desired performance.” For the purposes of this evaluation, a Cooper-Harper rating of ≤ 3 was therefore considered acceptable.

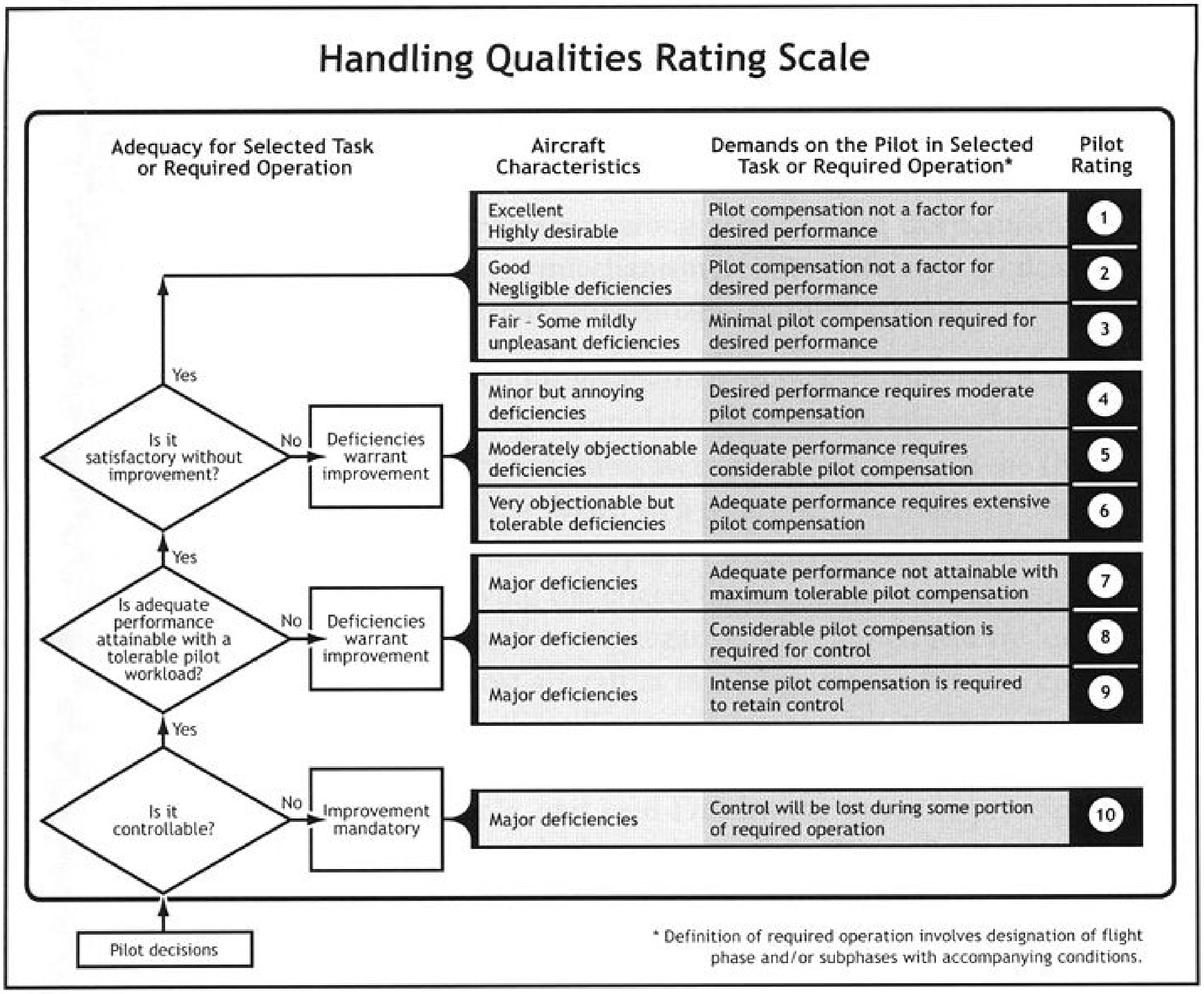


Figure 22 – Cooper-Harper rating for vehicle handling qualities.

Metric: Modified Cooper-Harper Rating

In addition to evaluating the vehicle handling qualities, the degree of operator compensation required for operation of SPR displays and controls was also quantified. The modified Cooper-Harper rating of operator compensation has been successfully used during multiple NASA/JSC Integrated Suit Testing protocols. The scale is shown in Figure 23.

Hypothesis Accept-Reject Criteria and Rationale

The study hypotheses required that the acceptability of human factors be assessed. For this purpose, a Modified Cooper-Harper rating of ≤ 3 was considered acceptable. As Figure 23 shows, a Cooper-Harper rating of 3 corresponds to “Satisfactory without improvements” with “minimal compensation required for desired performance.”

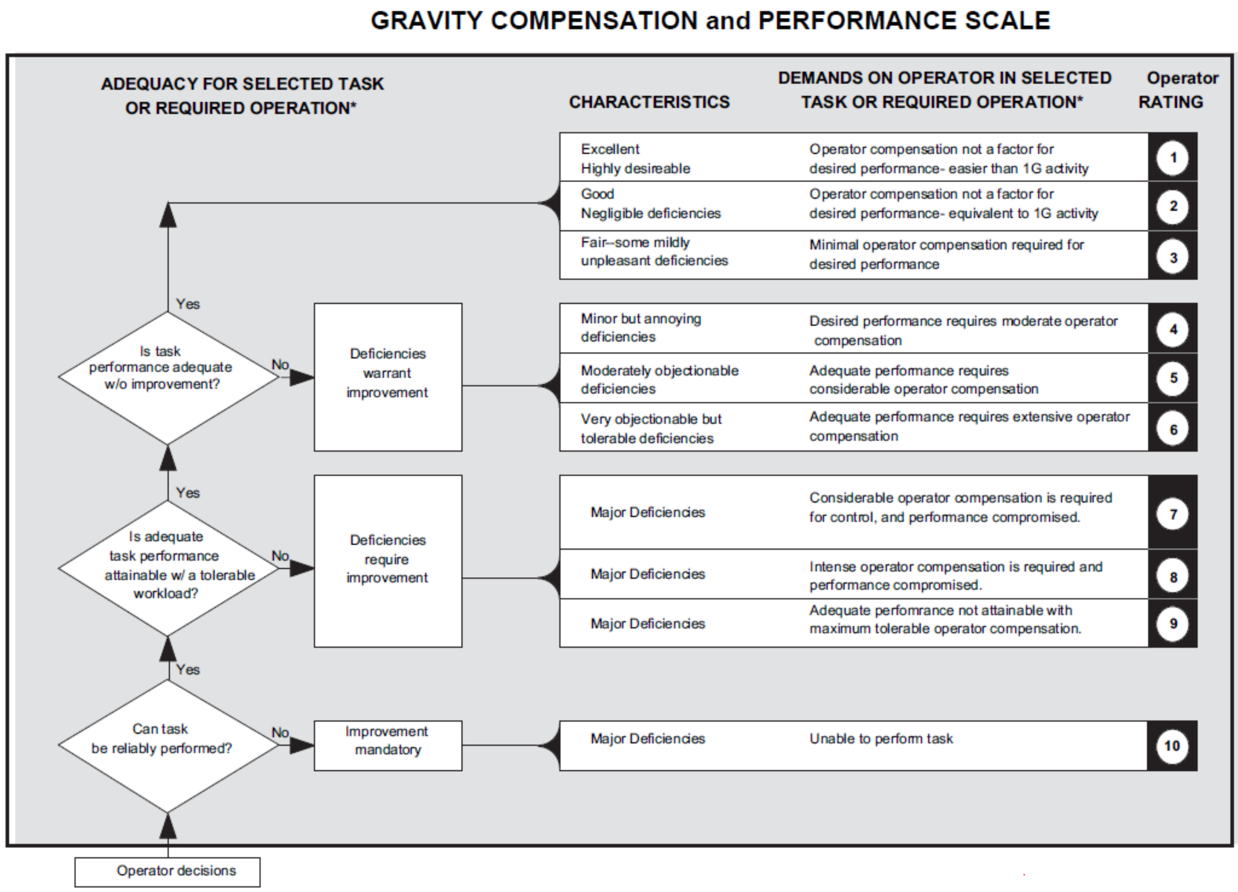


Figure 23 – Modified Cooper-Harper rating of operator compensation.

Metric: Fatigue Rating

The following Likert scale was defined to measure fatigue during the 1-day and 3-day traverses:

No Fatigue: performance not compromised		**Minor Fatigue:** performance not compromised		**Moderate Fatigue:** performance will likely be compromised if continued		**Significant Fatigue:** performance is compromised		**Extreme Fatigue:** unable to continue with adequate performance	
1	2	3	4	5	6	7	8	9	10

Unlike Borg's Rating of Perceived Exertion scale, which measures acute exertion during a particular activity, the fatigue scale measures the level of underlying fatigue that a crewmember feels while resting. Fatigue was measured at the beginning and end of each traverse day.

Hypothesis Accept-Reject Criteria and Rationale

By definition, ratings of ≤ 4 indicate that subjects are not fatigued to an extent that would compromise performance. A rating of > 4 would indicate unacceptable fatigue, which might indicate inadequate human factors or crew accommodations or an overly demanding traverse timeline.

2.3.6 Other Test Objectives

6) *Perform nighttime driving and exploration, mapping, and geological sample collection and documentation tasks using SPR and UPR vehicles.*
7) *Measure performance metrics during 1-day and 3-day (SPR only) exploration, mapping, and geological traverses.*

Several parameters were categorized as performance metrics. As described above, some metrics were used to test specific study hypotheses, while others were collected and compared with performance estimates used in existing Lunar Surface Systems and Human Research Program engineering and physiological models, as noted in the Hypotheses and Test Objectives (Section 1.2). Several metrics are inputs to engineering and physiological models used by the Constellation Program. The metrics not specifically used in the testing of study hypotheses but used to meet Test Objectives 6 and 7 are described below:

Metric: EVA Boots-on-Surface Suit Time

EVA boots-on-surface suit time is generally the time during which greatest scientific productivity is being achieved. Time spent inside the EVA suit during vehicle ingress and egress is considered nonproductive EVA time. By comparing EVA suit time to EVA boots-on-surface suit time, the efficiency with which EVA suit time is used may be quantified. Physiological modeling of the ameliorating effects of EVA exercise on bone and muscle atrophy also requires estimates of EVA boots-on-surface suit time.

Practically Significant Difference

Not applicable (metric not directly used in hypothesis testing).

Metric: Number of EVAs

The number of EVAs performed during traverses affects the consumables lost during ingress and egress operations, the energy required to operate gas reclaim pumps (with airlock) and the number of egress/ingress cycles on suit ports or the Mobile Habitat airlock. Although it was anticipated that having suit ports on the SPR would mean that EVAs from an SPR are typically shorter and more frequent, this had not been verified during operations. It was possible that the terrain and distribution of traverse stations would make even the rapid SPR egress and ingress an inefficient use of time.

Practically Significant Difference and Rationale

Not applicable (metric not directly used in hypothesis testing).

Metric: EVA Distance Walked

Physiological modeling of the ameliorating effects of EVA exercise on bone and muscle atrophy requires estimates of typical EVA walking distances. These data are also valuable in estimating the number of joint cycles on EVA suit components.

Practically Significant Difference

Not applicable (metric not directly used in hypothesis testing).

Metric: EVA Task Completion Times

Subjects verbally communicated to the CAPCOM when tasks were started and finished. Times were recorded using data sheets and the duration of each task was calculated.

Practically Significant Difference and Rationale

Not applicable (metric not directly used in hypothesis testing).

Metrics: Range, Distance Driven, Terrain Factor, Speed

Quantifying the range achieved and distances driven during multi-day exploration, mapping, and geological traverses in a lunar-like environment enables improved estimation of exploration range from a fixed lunar outpost and the development of a Global Coverage Map. The model used to size the solar arrays and energy storage systems on lunar surface mobility systems requires estimates of these metrics. Current inputs for this model are speculative and will be compared with field test data from this study. The range achieved and power usage are affected by vehicle speed and terrain factor, which is equal to the distance driven divided by range achieved (for a one-way traverse).

2.3.7 Subjective Crew Health Metrics

Subjects were prompted at intervals of not more than 30 minutes during all traverses for subjective ratings on each of the following scales: a) Thermal Comfort Scale (Bedford, 1936), b) Discomfort Scale (Corlett and Bishop, 1976), and c) Perceived Exertion Scale (Borg, 1982). Because of the limitations of the 1-g test environment and the mockup MkIII suits, the data were not used in a comparative sense; the data were used to ensure the health and safety of the subjects throughout the field test and to identify any deficiencies in test equipment. The use of subjective crew health metrics as Test Termination Criteria is described in Section 2.2.2.2. The scales are shown in Tables 7-8 and Figure 24.

Table 7 – Bedford Thermal Comfort Scale.

Bedford Thermal Comfort Scale	
-3	Much too cool
-2	Too cool
-1	Comfortably cool
0	Comfortable
1	Comfortably warm
2	Too warm
3	Much too warm

The Corlett-Bishop Discomfort Scale (Figure 24) is a subjective self-reported scale in which participants indicates their level of physical discomfort and the area of the body where the discomfort is located. Because of the limitations of the 1-g test environment and issues concerning the mockup Global Effects MK III suits, data from the Corlett-Bishop Discomfort Scale were primarily used to ensure crew health and safety throughout the field test. However, discomfort ratings at the start and end of each day during the 3-day traverse were used to determine whether any time-dependent discomfort was developing as the traverse progressed.

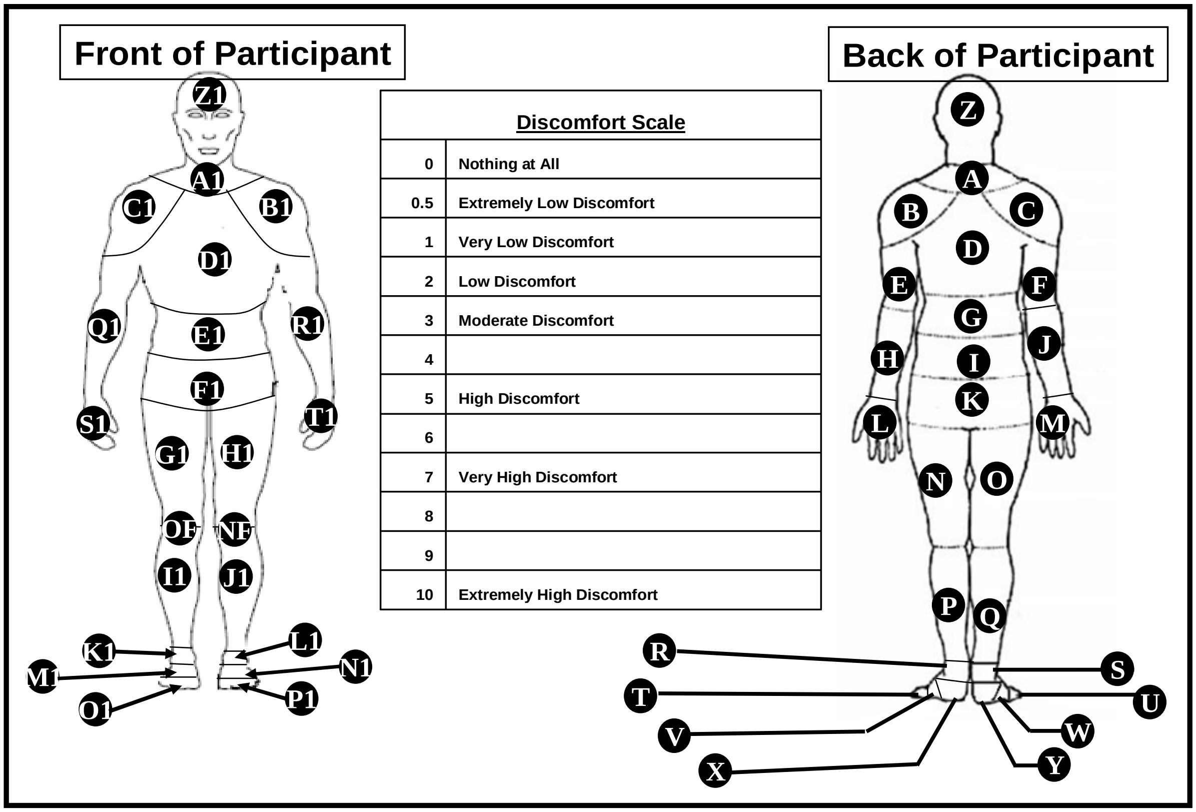


Figure 24 – Corlett and Bishop Discomfort Scale (Corlett & Bishop, 1976).

Table 8 – Borg Rating of Perceived Exertion Scale.

BORG RATING OF PERCEIVED EXERTION SCALE	
6	No exertion at all
7	Extremely light
8	
9	Very light (easy walking slowly at a comfortable pace)
10	
11	Light
12	
13	Somewhat hard (quite an effort; you feel tired but can continue)
14	
15	Hard (heavy)
16	
17	Very hard (very strenuous, and you are very fatigued)
18	
19	Extremely hard (you cannot continue for long at this pace)
20	Maximal exertion

3.0 RESULTS AND DISCUSSION

Results of the field test are presented and discussed in the following pages. Results are presented in order according to the hypotheses and test objectives described in Section 0.

3.1 HYPOTHESIS 1: COMPARING PRODUCTIVITY AND EVA SUIT TIME

Hypothesis 1: Productivity achieved during 1-day exploration, mapping, and geological traverses using the Small Pressurized Rover (SPR) will be equal to or greater than the productivity achieved during Unpressurized Rover (UPR) traverses, with less EVA suit time.

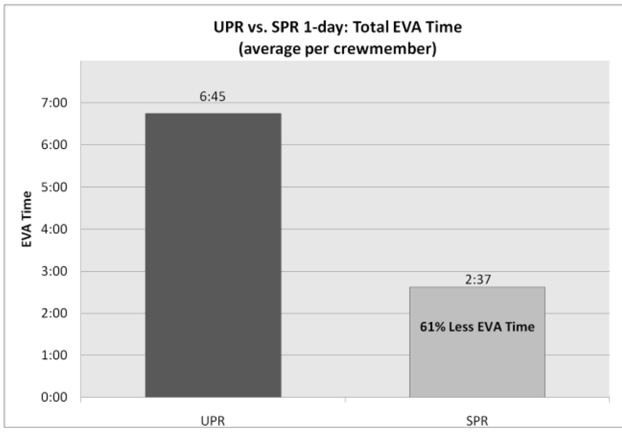


Figure 25 - UPR vs. SPR: Total EVA suit time (average per crewmember).

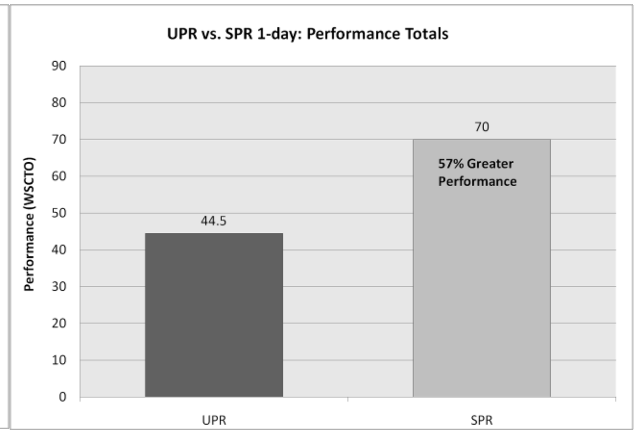


Figure 26 - UPR vs. SPR: Performance (Scientific Productivity Index).

Comparison of UPR and SPR traverse productivity as measured by the Scientific Productivity Index (SPI) showed that productivity during 1-day SPR traverses was an average of 25.5 points (or 57%) greater than during equivalent 1-day UPR traverses (Figure 26).

As described in Section 2.3.1, a difference in SPI of 9 points reflects completion of one high-priority science objective with high-quality data and was prospectively defined as a practically significant difference in productivity for the purposes of this test. Thus, a difference of 25.5 points meets and exceeds the prospectively defined criteria for significantly greater productivity and indicates that SPR 1-day traverses achieved almost three more high-priority science objectives with high data quality than the corresponding UPR traverses.

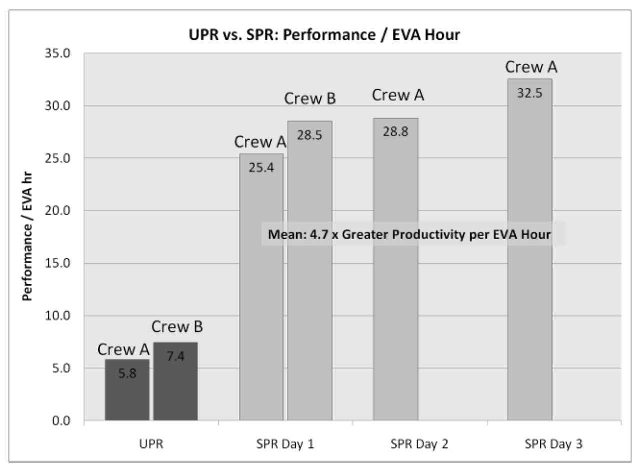


Figure 27 - UPR vs. SPR: Performance per EVA hour.

A difference in mean or maximum EVA suit time of ≥ 10% was prospectively defined as practically significant. As shown in Figure 25, EVA suit time during 1-day SPR traverses was 61% less than during the corresponding UPR traverses.

Normalization of productivity, as measured by SPI, by EVA suit time yields the performance per EVA hour. When combined with the productivity and EVA suit time data collected during days

2 and 3 of the 3-day SPR traverse, the average productivity per EVA hour during SPR traverses was 4.7 times greater than during UPR traverses (Figure 27).

There are several reasons behind the large increase in productivity per EVA hour. In addition to being inside the SPR during long translations, the ability to make contextual observations from inside the SPR means that boots-on-surface EVA time at each site – if any – is spent on refinement of those observations and targeted sample collection. And when intravehicular observations indicate that EVA is warranted, in many cases it is only necessary for one crewmember to egress the SPR. Subjects also noted that the ability to easily and clearly communicate with each other about geological observations while inside the SPR was greatly superior to the UPR, which in turn led to greater productivity.

Although the Science Merit Rating metric developed by the Pavilion Lake Research Project (see www.pavilionlake.com) was also used to compare the science merit of UPR and SPR traverses, the UPR and SPR traverses yielded consistently low science merit ratings because of the fact that the geology of the Black Point Lava Flow has already been extensively studied and the data collected during the SPR and UPR traverses added little to what was already known about the area. Of course, the purpose of the traverses was to compare the capabilities of the UPR and SPR vehicle concepts rather than to advance terrestrial scientific knowledge, and the science merit rating was intended only to provide another method of comparison. However, the metric did not prove useful in this respect as the science merit in all cases was consistently low.

3.2 HYPOTHESIS 2: COMPARING RANGE

Hypothesis 2: The range achieved during 1-day exploration, mapping, and geological traverses in the SPR will be greater than during 1-day UPR traverses.

The maximum range achieved during 1-day SPR traverses was 5.3 km compared with 5.0 km during UPR traverses. A difference of ≥ 10% was prospectively defined as a significant difference in range. The observed difference of 6% was therefore not significant. Average distance driven during each traverse was also compared, which showed 4.3 km (31%) greater distance driven during SPR traverses.

The observed increase in traverse distance without a corresponding increase in range was due primarily to communications constraints at the field test site. Although SPR operations in intentionally degraded communications coverage are planned for DRATS 2009, it was decided that the 2008 field test would be performed with continuous real-time communications between the rover vehicles and the MMCC, in which the mission operations and science teams were located.

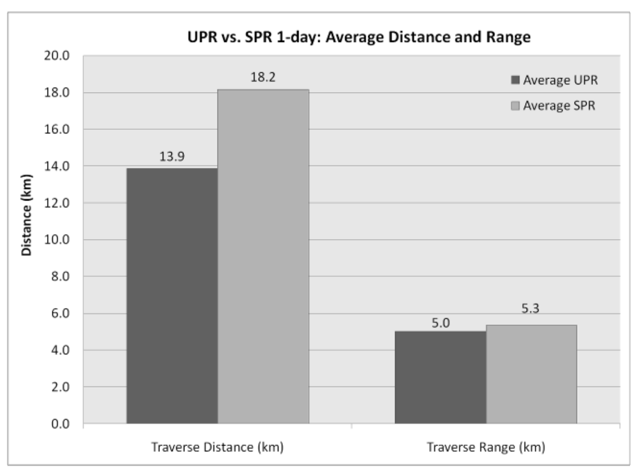


Figure 28 - UPR vs. SPR: Traverse Distance and Range.

The primary constraint limiting the distance and range of UPR traverses is the power and consumables in the EVA suit PLSS. Although the mockup EVA suits used during this test did not use an actual suit PLSS, the timelines were developed and executed based on flight-like constraints and assumptions. The assumptions used when developing timelines for UPR and SPR traverses are detailed in Section 2.1.6.

The limitations of the test therefore precluded valid testing of the hypothesis that SPR traverses would achieve greater range than UPR traverses. However, future analog testing without the same limitations is expected to confirm this intuitive hypothesis.

3.3 HYPOTHESIS 3: CONTEXTUAL OBSERVATIONS

Hypothesis 3: Subjective assessment of contextual observations from inside an SPR will be equal to contextual observations from inside an EVA suit.

Four experienced field geologists from the DRATS Science Team completed the stand-alone protocol described in Section 2.1.3, which compared the quality of geological observations from inside the SPR with observations made by the same person walking in shirtsleeves. Three of the four field geologists rated their observations from inside the SPR as a 3.0, indicating that "observation quality is not limited by the vehicle; equivalent to that achievable by the same person, in the same amount of time, walking shirtsleeve." The fourth geologist rated SPR observations as a 2.5, indicating slight decrements in observational quality from inside the SPR compared with shirtsleeve.

Particularly given that the comparison was made with shirtsleeve rather than suited performance, the hypothesis that subjective assessment of contextual observations from inside an SPR are equal to suited contextual observations was accepted. Future evaluations using lightweight EVA suits are required to assess whether SPR-based observations are superior to those made from inside an EVA suit.

The Moenkopi outcrop was readily reached by the SPR, yet the slope was too steep and bouldery to reach the basalts in the outcrop; the basalt outcrops were just outside the test area. As a consequence, all basalt observations related to dislodged float, a good analog for typical crater ejecta that cover most of the lunar surface.

All geologists elected to drive sideways along the outcrops with the front of the SPR facing the outcrops, starting with the Moenkopi sandstone and then getting as close as possible to the basalt outcrops. Most of the drive, however, was spent getting upslope and down again, and many observations related essentially to float mapping, with detailed descriptions of the diversity of basalt textures and purposeful searches for the basalt/sandstone contact, which happened to be buried under the float at this location.

Analysis of the post-test questionnaires completed by each geologist reveals that observations made from the SPR were superior in some respects and inferior in others; and the strengths and weaknesses balanced out overall.

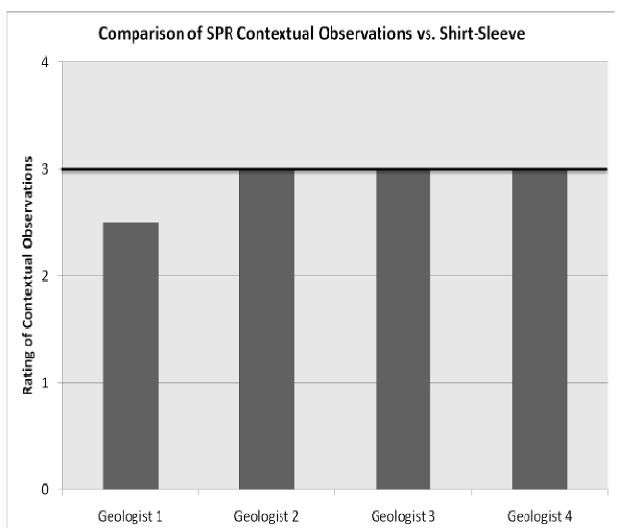


Figure 29 - Field geologist ratings of SPR contextual geological observations.

This is consistent with the philosophy of using SPRs to reduce EVA time by making preliminary contextual observations from inside the vehicles and using EVA for follow-up observations and sampling, particularly in less accessible areas. Overall, geologist feedback on SPR capabilities was very positive. All comments provided by the field geologists are included in Appendix C.

3.4 HYPOTHESIS 4: SUIT PORT HUMAN FACTORS

Hypothesis 4: Human interfaces with the SPR suit ports and alignment guides will be acceptable as assessed by human factors metrics.

Thirteen different aspects of the human interfaces with the SPR suit ports and alignment guides were quantitatively assessed using the acceptability rating defined in Section 2.3.4. Results of the assessment are summarized in Figure 30, which shows the median, maximum, and minimum acceptability ratings for each of the 13 aspects of suit port usability. Results are based on the 1-day and 3-day SPR traverses performed by both crews.

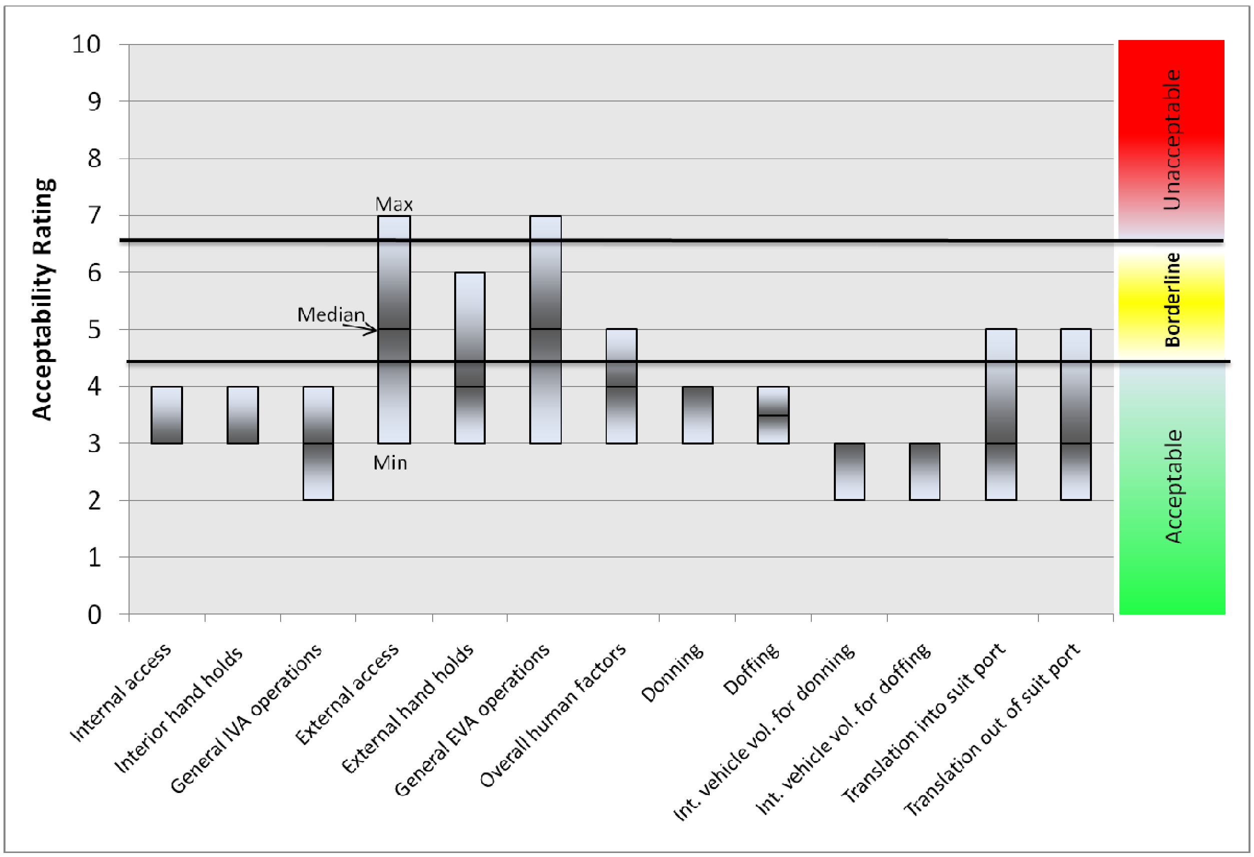


Figure 30 – Acceptability ratings for 13 aspects of SPR suit ports.

The median ratings indicated that the human interfaces with the suit ports were acceptable in all aspects except for external access and general EVA operations, which were in the Borderline Acceptable range. Median ratings of “overall human factors” were in the Acceptable range. Therefore, the hypothesis that human interfaces with the SPR suit ports are acceptable was accepted. However, the data and the follow-up questionnaires indicated that the suit port human factors could be further improved. The highest ratings for external access and general EVA operations were 7, indicating that, even although human factors were acceptable overall, in some instances these aspects of the suit port human factors were unacceptable.

The primary reasons reported for Borderline Acceptable ratings for external access were inadequate space between latching mechanism levers, which precluded simultaneous operation of levers on both suit ports, combined with minor deficiencies in the alignment guides. External handholds on the vehicle were also suggested to help maintain balance and each handhold should be strong enough for a crewmember to put all their weight on it if necessary.

Borderline ratings for general EVA operations were attributable in part to the aforementioned issues about external access and also to the fact that the mechanism for actuating the Marman bars on the suit ports was found to be unreliable and required occasional support from technicians to assist subjects in securing and releasing the suits from the suit ports. In a flight suit port this would represent a serious safety issue, but a post-test redesign of the actuation mechanism for the Marman bars has already yielded significant improvements, and a separate effort to develop and test a higher fidelity pressurizable suit port engineering unit is ongoing. The development and testing of a safe and robust suit port is a central component of the plan for a future SPR; the purpose of testing the nonpressurized suit ports at DRATS 2008 was solely to evaluate the human interfaces of the preliminary suit port design concept.

Human factors for translation into and out of the suit port were considered acceptable overall, although Borderline Acceptable ratings (5) were also recorded in both cases. Participants noted that donning or doffing the suit while the vehicle was on a slope was difficult because the PLSS hatch was continually falling in on them. They also reported that when doffing the suit they were physically using their head to initially open the PLSS hatch.

No issues arose with the internal volume in terms of donning and doffing of the suits. A cushioned ottoman was available to help aid suit translation but was used only 50% of the time. Participants reported that the interior handholds for the suit port and translating out to the suit port were acceptable. The chin up and dip bar were used the most when subjects were translating into or out of the suit in the suit port, but test subjects rarely used the side vertical bar.

Descriptive statistics regarding suit port egress and ingress durations and frequency are in Section 3.6.2.

3.5 HYPOTHESIS 5: HUMAN FACTORS DURING 3-DAY TRAVERSE

Hypothesis 5: The human factors and crew accommodations within the SPR will be acceptable to support a 3-day exploration, mapping, and geological traverse.

As detailed in Section 2.3.5, a combination of existing human factors metrics and customized questionnaires were used to evaluate the acceptability of the SPR and UPR human factors. Results of the 3-day evaluation of SPR habitability are also documented in a separate report (Litaker et al, 2008).

Overall, results indicated that the SPR prototype successfully met all objectives in terms of human performance and crew accommodations. In addition, the SPR adequately supported EVA operations through the use of suit ports and operational support for the EVA crewmember. However, several areas were identified where redesign could further increase performance and productivity.

For vehicle operations, participants needed better situational awareness of the SPR with respect to vehicle alignment capabilities and sideways driving. In addition, improvements in the displays and controls were suggested, specifically with respect to stability of the cockpit control and display quality in brightly lit conditions. Participants had difficulty with side window visibility that led to the issues with situational awareness and problems with the bright sunlight from the front windows that obscured the displays.

It was discovered that the type of terrain did not adversely affect driving performance, but did have an effect on operating the display and controls because of vibration. With respect to EVA performance, the type of terrain was related to physical exertion and fatigue. In addition, participants had difficulty translating on and off the vehicle because of its height from the ground, and operation of the suit port external controls was problematic. Suggestions were to have more easily operated controls as well as guides for the crewmember sliding back into the suit port.

Overall, the interior of the vehicle was rated as acceptable. Suggested minor improvements included better adjustability of cockpit seats, addition of a foot rest, and improved stowage. Participants found that, despite adequate volume within the vehicle, built-in stowage was inadequate and access to the stowage compartments was problematic. In addition, inadequate stowage space was allocated for waste, which accumulated quickly over the 3-day mission. The sleeping accommodations were found to be comfortable.

The results of the SPR human factors evaluation are described in greater detail in Sections 3.5.1 to 3.5.6 (adapted from Litaker et al., 2008).

3.5.1 Driving-Related Human Factors

A total of 12.5 hours of driving time was completed during the 3-day SPR traverse over a variety of terrain. Cooper-Harper ratings indicated that, regardless of the type of terrain, driving performance was at a desirable level with minimal operator compensation required (Figure 31). The one Cooper-Harper rating of 4 was recorded during night driving operations. These results suggest that although acceptable performance was achievable with driving, improvements could be made, especially for dark or nighttime driving conditions.

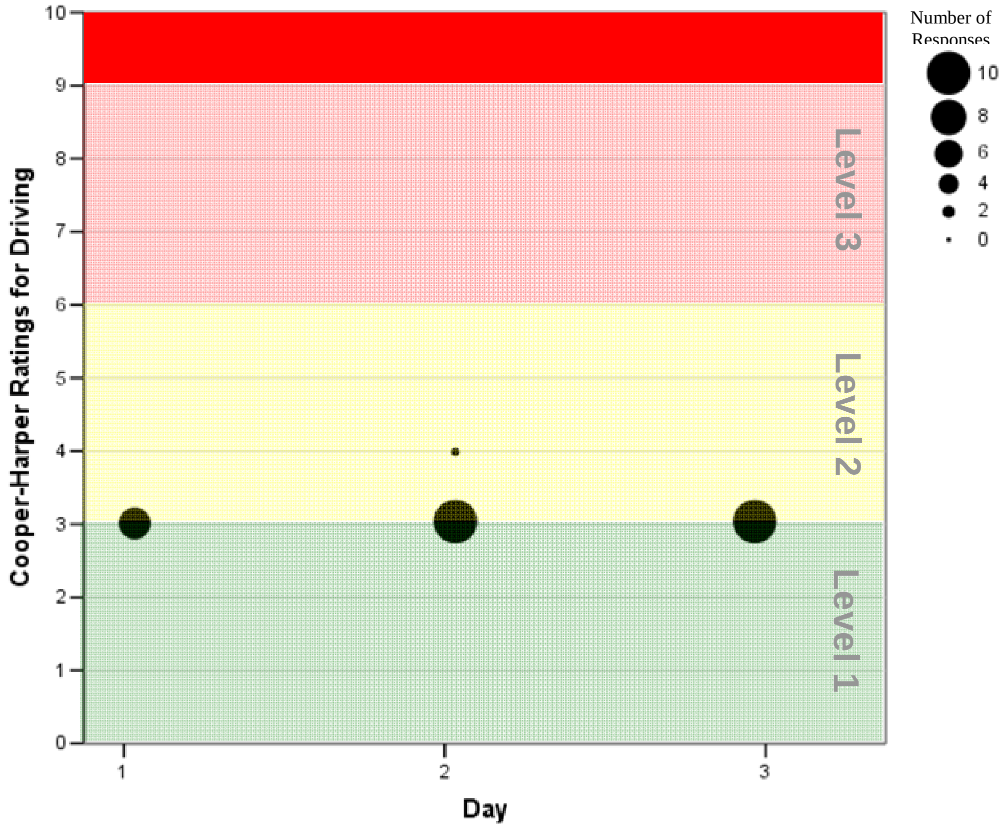


Figure 31 – Cooper-Harper ratings for driving the SPR during the 3-day mission; the size of the dot represents the number of scores at that rating (scale on top right). ***From Litaker et al, 2008.***

In addition to the Cooper-Harper ratings, 12 different aspects of driving-related human factors were rated by participants using the acceptability scale defined in Section 2.3.5. Results are summarized in Table 9. Ratings indicated that subjects experienced little fatigue while riding or driving. Straight forward driving, arc driving, and vehicle acceleration were all rated as acceptable. Participants indicated the need for better situational awareness by improving the lateral field of view (FOV) of the vehicle for crabbing and body alignment. Participants commented that for vehicle leveling, an inclinometer would be useful in the cockpit. In addition, they stated that minor improvements were needed for fine alignment driving and overall noise reduction, as well as vibration dampening, especially for the displays.

Table 9 – Acceptability ratings for SPR driving during 3-day traverse.

SPR Driving Tasks	Day 1	Day 2	Day 3	Average
Straight away forward driving capabilities	3.00	3.00	3.00	3.00
Arcing driving capabilities	3.00	3.00	3.00	3.00
Fine alignment capabilities for driving	4.00	3.50	3.50	3.67
Sideways driving capabilities	3.50	4.00	3.50	3.67
Overall vehicle handling and steering capabilities	3.50	3.50	3.50	3.50
Vehicle leveling capabilities	3.00	3.50	3.50	3.33
Vehicle acceleration capabilities	3.00	2.50	3.00	2.83
Sound installation for noise reduction	3.00	4.00	4.00	3.67
Dampening for vibration while driving	3.00	4.00	3.50	3.50
SA of vehicle body alignment while driving	5.50	5.50	5.50	5.50
Physical fatigue while driving	3.00	3.00	2.50	2.83
Physical fatigue while riding	2.50	2.00	2.00	2.17
Overall Average	3.33	3.46	3.38	3.39

Note: N=2. SA is situational awareness. Best = 1, Worst = 10.

3.5.2 Displays and Controls Human Factors

Subjects rated the degree of operator compensation required when operating the SPR displays and controls using the Modified Cooper-Harper scale. While most Modified Cooper-Harper ratings for displays and controls were a three (minimal operator compensation required), there was some variability in the ratings, particularly during the first 2 days with ratings ranging from 2 to 5 (Figure 32). This improvement in the consistency of ratings across the 3 days is assumed to be the effect of training or familiarity with the Displays and Controls as task difficulty did not change from day 1 to day 3.

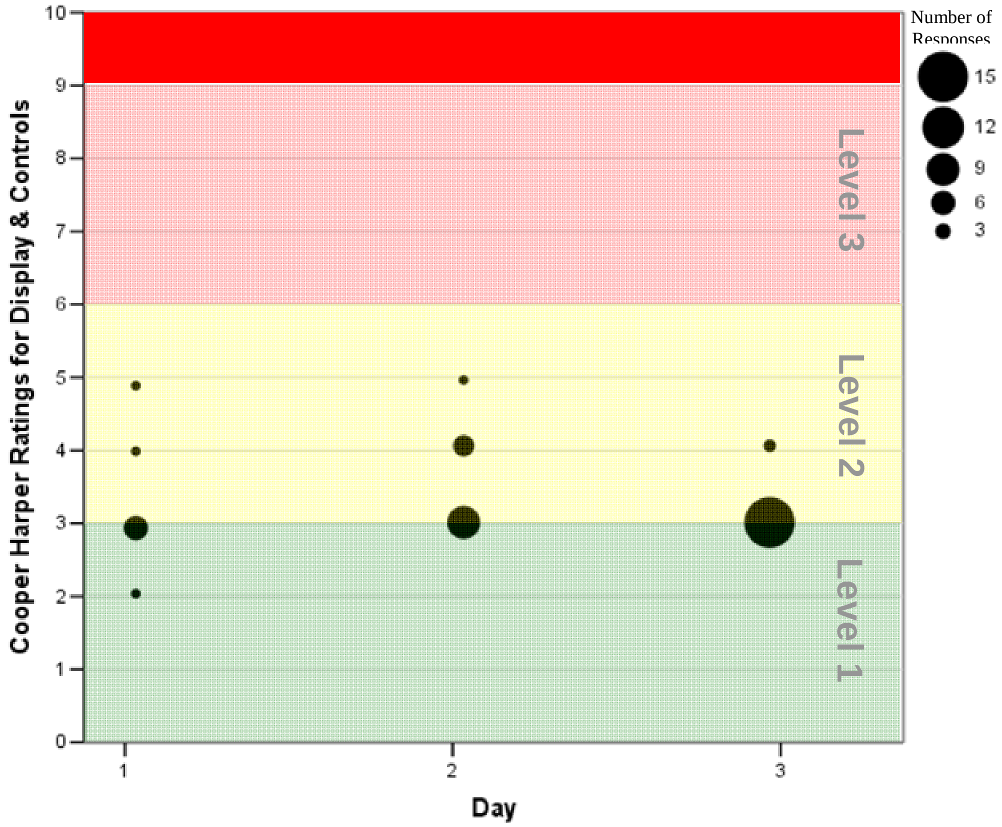


Figure 32 – Modified Cooper-Harper ratings for the displays and controls interface of the SPR over the 3 day mission.

Subjects also rated 16 different aspects of the displays and controls using the acceptability scale defined in Section 2.3.5. The acceptability data (Table 10) indicate that improvements are warranted with respect to a) responsiveness of the touch screen, b) stability of the displays and controls while driving, c) display brightness during day operations, d) readability of the display while driving, e) adjustability of the display, and f) navigation of the display menu.

Participants indicated that it was extremely difficult to accurately press a menu tab while both their body and the display were bouncing in the vehicle with bumpy terrain. Attempting to fine-tune a navigational waypoint or accessing the command menu was almost impossible while driving on certain terrains. At times, the participants had to stop the vehicle to access the menu. It was noted that a major issue was the stability of the arms that held the display, which tended to move up and down easily on bumpy terrain. Coupled with the already difficult task of accessing a specific menu, participants found the display frustrating to use while driving. Though participants rated the display adjustability unfavorably, they noted that it was easy to swivel their screen to another crewmember, which was helpful.

Other issues with the display included menu lockouts of navigational pages and the complexity of selections on command menus. Subjects found that having to drill down several pages to find a certain command or navigational menu was both time-consuming and frustrating, especially over rough terrain. In addition to the issues of display complexity and number of levels, subjects did not like the inconsistent use of color (such as black versus grey background, and each "button" being a different color), display density, and the replication of information on each display (for example, direction and waypoint indicator).

Some difficulty reading the displays during daylight operations also compounded performance issues when subjects interfaced with the displays. The crew reported that sun glare made the displays ineffective and suggested either adding another display position within the cockpit that was shaded from the sun or adding some type of sun shade to the front window. However, for night operations, participants reported the display readability to be effortless and clear. Overall, the Cooper-Harper scores were borderline in meeting the rating criteria of 3, suggesting improvements are warranted.

Table 10 – Acceptability ratings for SPR displays and controls during 3-day traverse.

SPR D&C Tasks	Day 1	Day 2	Day 3	Average
Layout of the D&C in the rover cockpit	5.00	4.00	4.50	4.50
D&C within reach of your seating position	4.00	3.50	3.50	3.67
Touch screen responsiveness to your commands	5.00	6.00	6.00	5.67
Navigation of the display menus	4.50	4.00	3.50	4.00
Vehicle navigation displays understandable	4.50	5.00	3.50	4.33
Communications with ground support/EVA support	3.50	3.50	3.50	3.50
Adjustability of cockpit D&Cs	4.50	5.00	4.00	4.50
Stability of cockpit D&C during nominal driving	6.50	5.50	5.50	5.83
Readability of displays during driving	4.50	4.50	5.50	4.83
Display brightness for day operations	6.00	6.00	6.50	6.17
Display brightness for night operations	2.50	2.00	2.00	2.17
Eye fatigue with display while driving	3.00	3.00	3.50	3.17
Hand fatigue with controller while driving	3.50	3.50	3.50	3.50
Hand fatigue with display while driving	3.00	3.50	3.50	3.33
Eye fatigue with display while riding	3.00	3.00	3.50	3.17
Hand fatigue with display while riding	2.50	3.00	2.50	2.67
Overall Average	4.09	4.06	4.03	4.06

Note: N=2. Best = 1, Worst = 10.

3.5.3 Visibility Human Factors

Subjects rated the acceptability of 12 aspects of visibility (Table 11) using the acceptability scale defined in Section 2.3.5.

On all days, the lack of window shading was found to be unacceptable with improvements mandatory. Currently, the SPR does not have any way of blocking sunlight from entering the cockpit. Some type of visor or film that could reduce the sun glare and reduce heat radiation within the vehicle is needed. Other suggestions included research on prototype window tinting, exterior vents or blinds, or reducing the size and angle of the front window. This issue alone caused problems with readability of display screens and increased eye fatigue. Particularly given the low sun angle at the south polar region of the Moon, further research is warranted to identify a solution to this problem.

Table 11 – Acceptability ratings for SPR visibility during 3-day traverse.

SPR Visibility Tasks	Day 1	Day 2	Day 3	Average
Visibility of front window for driving	2.50	2.00	2.00	2.17
Visibility of side windows for driving	4.50	4.50	5.00	4.67
Visibility of lower corner windows for driving	4.00	3.50	3.00	3.50
Visibility of lower bubble for observations	2.50	2.00	2.00	2.17
Overall visibility to avoid obstructions	4.00	3.00	3.50	3.50
Camera views for blind spots	5.00	5.00	4.50	4.83
Display brightness for night operations	4.00	2.00	2.00	2.67
Window shading during day operations	7.50	7.00	7.00	7.17
Interior lighting during night operations	3.00	2.50	2.50	2.67
External lighting during night operations	2.50	2.50	2.50	2.50
Eye fatigue while driving	3.00	3.00	3.00	3.00
Eye fatigue while riding	3.00	2.50	2.50	2.67
Overall Average	3.79	3.29	3.29	3.46

Note: N=2. Best = 1, Worst = 10.

Areas judged as needing minor improvements were eye fatigue while driving (mostly because of the shading issue previously discussed), visibility through the lower corner windows for driving and avoidance of obstructions, visibility of side windows for driving, and camera views for blind spots. Participants reported the lower corner windows were excellent for observing fine textures of soil but found them difficult to use for obstacle avoidance because they could not see the vehicle's wheels.

Side and aft views of the vehicle were difficult to nonexistent. A better lateral field of view out of the side windows for obstacle avoidance and vehicle body alignment for sideways driving is desired. Future side window concepts suggested were a bubble-type window similar to the lower bubble or a small diver-type mask inset in the window. Any window concept would need to be accessible from a seated position within the vehicle's cockpit and should provide the crewmember an extended view of the side of the vehicle and a downward view of the wheels. For aft viewing, camera views with dedicated displays in the cockpit would improve visibility, but it is likely that whenever possible crewmembers will simply turn the vehicle around to obtain superior visibility through the windows rather than drive backward with a camera view.

Participants rated visibility of the front windows for driving and lower bubble for observations as acceptable. Comments indicated enjoyment in the excellent viewing and likened it to watching an IMAX movie as they drove along the test site or observed some geological formation up close. In addition, the current window configuration contributed to the perception of the interior volume appearing more spacious. The lower bubble was found to enhance the ability to perform quality scientific study of sites to determine whether an EVA was needed, as well as allowing recording of the site as a reference for future geological activities. The geologist participants used the bubble extensively for observations and photographic archiving of geological points of interest (Figure 33).

Figure 33- Geologist using lower bubble to photograph a geologic item of interest (left). The SPR's panoramic front window enhanced driving and scientific observations (right).

Other highly acceptable ratings included the external and interior lighting during night operations, and display brightness for night operations. Participants found the interior cabin lighting (light-emitting diodes) comfortable for their sleep stations, and they found the lower floor lights extremely helpful for night driving operations (Figure 34).

Figure 34 – Night operations using the interior and exterior lighting of the SPR.

3.5.4 Suit Port Human Factors

The human factors evaluation of the suit ports and suit port interfaces was a stand-alone test hypothesis and results are in Section 3.4.

3.5.5 Habitability of Crew Accommodations

During the 3-day traverse, participants spent 64 hours and 24 minutes in the SPR vehicle and performing EVAs from the SPR (see Section 3.6.2 for detailed time breakdown). Evaluation of crew accommodations habitability was separated into i) daily operations within the vehicle, ii) sleep and general habitation, and iii) cockpit seating.

Habitability of Crew Accommodations: Daily Operations

Subjects rated 19 different aspects of SPR habitability during daily operations using the acceptability scale defined in Section 2.3.5. The results (Table 12) show that the primary aspects in which the human factors were borderline (acceptability between 3 and 6) were stowage and waste disposal. Stowage issues had the most negative ratings by far, with size of and access to stowage being the most significant issues. These were followed by location of the stowage compartments and access to food stowage. Crew transfer bags (CTB) were used as stowage containers for personal items, food, exercise equipment, EVA equipment, hygiene and WCS products, mission supplies (such as pens, pencils, and flashlights), and trash collection supplies. Seven CTBs of various sizes were arranged either underneath the aisle and cockpit floor, or underneath the benches (Figure 35).

Participants reported that CTBs needed to be packaged more efficiently for better utilization of the internal volume. For this field trial, products were placed in the bags without any compartmentalization of the items. CTBs were organized to some degree with respect to the articles inside (some were food CTBs, others EVA CTBs, and so on), and each CTB was numbered and labeled. However, the subjects were not familiar with the locations and contents of each CTB. In addition, the bags were rather large, and suggestions were to design smaller containers about the size of shoeboxes. Better access to the stowage containers was requested, as well as addition of stowage to the side hatch area. One suggestion was to create a soft wall locker where items could be placed for easier access and removal. For waste and trash management concerns, participants suggested designing an opening in one of the floor panels with a sealable flap to stow trash in a container under the floor or design a small manual trash compactor.

Table 12 – Acceptability ratings for SPR habitability during daily operations during 3-day traverse.

SPR Daily OPS Tasks	Day 1	Day 2	Day 3	Average
Access to food stowage	6.50	5.00	6.00	5.83
Volume for crew to prepare a meal	3.50	2.00	1.50	2.33
Volume for crew to eat together	3.00	2.00	1.50	2.17
Volume within SPR for meal cleanup	3.00	2.00	1.50	2.17
Accessibility to sink area for dispensing of water	5.00	5.50	3.50	4.67
Volume to deploy the WCS for use in SPR	3.50	3.00	2.50	3.00
Access to the hygiene area during normal crew OPS	3.50	3.00	2.00	2.83
Volume for using the WCS during sleeping hours	3.50	3.00	3.50	3.33
WCS area provided adequate privacy	3.00	2.50	3.00	2.83
Volume to stow WCS	4.00	2.50	3.50	3.33
Volume for general housekeeping activities	3.00	2.50	2.50	2.67
Volume for waste/trash disposal	4.50	4.50	5.50	4.83
Volume for waste/trash stowage	5.00	5.50	6.50	5.67
Location for daily trash collection	4.00	6.00	7.00	5.67
Access to stowage areas	6.00	5.50	6.50	6.00
Volume for personal stowage	5.50	4.50	5.50	5.17
Location of the stowage compartment within SPR	6.50	6.00	5.00	5.83
Size of the stowage compartments within SPR	6.00	6.00	6.00	6.00
Overall habitable living of the SPR	4.00	3.00	3.00	3.33
Overall Average	4.37	3.89	4.00	4.09

Note: N=2. SA is situational awareness. Best = 1, Worst = 10.

Figure 35 – Two CTB stowage areas: under the bench (left, shown as the bench is raised behind a cockpit seat) and under the floor (right).

Volume for meal preparation, eating together, meal cleanup, general housekeeping, access to the hygiene area during normal operations, and waste containment system (WCS) privacy received some of the best ratings from participants.

However, rating of the volume to deploy and stow the WCS, the ability to use the WCS during sleeping hours, and accessibility of the sink area were rated as needing minor improvements.

Participants reported that the sleep station rear curtains, when attached together across the aisle in front of the WCS, provided inadequate space when using the WCS. They also noted that when the curtains were down in the sleep station position, they tended to fold down over the WCS as well, thus reducing the ability to properly use the WCS. To gain better access to the sink and water station in the vehicle, participants suggested replacing the current levers with longer levers and hoses to fill drink cups and food bags.

Participants reported that over the 3-day mission the waste and trash accumulated quickly. Because of time constraints, the prototype vehicle did not include a dedicated waste and trash disposal system and the crew used large white plastic trash bags for disposal of the waste and trash.

Habitability of Crew Accommodations: Sleep Stations and General Habitat

Subjects rated 12 different aspects of the habitability of SPR sleep stations and general habitat operations using the acceptability scale defined in Section 2.3.5. Results are shown in Table 13.

Deployment and stowage of the sleep station were the only aspects that were rated Borderline. Participants indicated that the Velcro that attached the curtain sections together was difficult to match up, suggesting zippers as an alternative. Participants reported that deployment and stowage of sleep stations was easier with two persons. However, with more training, this could be done with only one person. Suggestions for redesigning deployment and stowage methods were to add stiffeners between the panels to make them easier for a single person to stow.

Table 13 – Acceptability ratings for SPR sleep stations and general habitat during 3-day traverse.

SPR Sleep and General HAB Tasks	Day 1	Day 2	Day 3	Average
Sleep station in the rover easily deployable	4.50	4.00	4.50	4.33
Volume for crew sleep station	2.50	2.50	2.00	2.33
Sleep station layout	3.50	2.50	3.00	3.00
Volume for personal privacy	2.50	2.50	3.00	2.67
Sleep quality while resting in rover	3.50	3.00	3.00	3.17
Sleep station in rover easily stowed	4.50	4.00	3.50	4.00
Volume for the rover habitat's workstation areas	3.00	3.00	3.00	3.00
Volume to limit cross-contamination	3.00	3.00	3.50	3.17
Volume for co-location of related functions/operations	3.00	3.00	4.00	3.33
Volume of SPR layout for a 3 day mission	2.00	2.00	1.50	1.83
Volume of SPR layout for a 14 day mission	2.00	2.00	1.50	1.83
Volume of SPR layout for a 30 day mission	2.00	4.00	3.50	3.17
Overall Average	3.00	2.96	3.00	2.99

Note: N=2. SA is situational awareness. Best = 1, Worst = 10.

Participants indicated that although the layout of the sleep stations was good, personal stowage within the station needed improvement (described in Section 3.5.5). Better access to light switches and holders for personal items such as water, iPods, and pens was also desired. With regard to the quality of comfort for sleep, participants reported the memory foam cushions were "very comfortable and made for a good night's sleep."

Test participants, vehicle engineers, and scientists involved with the vehicle over the 2 weeks of testing commented that from the outside the SPR looked small; however, once inside and working, the majority reported the interior volume was "spacious and comfortable." When asked what made the interior feel this way, they stated it was the color selection, textures of the fabric, and the panoramic windows in front of the vehicle. Participants reported that the cockpit and cabin were great, and the ability to fully stand up was the best quality. The multifunctional capability of the cabin area (for example, benches turned into beds) was also considered good and was relatively simple to change when needed.

Habitability of Crew Accommodations: SPR Cockpit

Subjects rated eight different aspects of the habitability of the SPR cockpit using the acceptability scale defined in Section 2.3.5. Results are shown in Table 14.

A wire for adjusting the seats broke during the mission and participants remarked that this mechanism needed to be more stable and robust for a seat adjustment system. Additionally, the crew requested that foot rests be added to the seats. Otherwise, the seats and cockpit were rated favorably, with participants particularly approving of the comfortable cushions and pleasing appearance (see Figure 11).

Table 14 – Acceptability ratings for SPR cockpit during 3-day traverse.

SPR Seating Characteristics	Day 1	Day 2	Day 3	Average
Comfortable cockpit seating for driving	3.50	3.00	3.00	3.17
Adjustability of cockpit seat	3.00	4.00	4.00	3.67
Stability of cockpit seat while driving	3.00	3.00	3.00	3.00
Foot and arm rest for cockpit seats	3.50	3.00	3.00	3.17
Height of cockpit seat	3.00	3.00	2.50	2.83
Width of cockpit seat	2.50	2.50	2.50	2.50
Depth of cockpit seat	3.00	2.50	2.50	2.67
Comfortable seating while doing OPS tasks	3.00	2.50	2.50	2.67
Overall Average	3.06	2.94	2.88	2.96

Note. N = 2.

Overall Habitability of SPR

Participants were asked to rate the acceptability of the overall SPR habitable volume and the overall acceptability of the SPR. Subjects were also asked whether or not they would recommend the SPR habitable configuration, overall.

For the overall habitable volume of the SPR, participants rated the volume as acceptable (mean = 3.17) with minor improvements to the stowage system desired for better efficiency and utilization of available space. Subjects commented that the overall volume of the cabin and cockpit was great, with the ability to fully stand up as one of the best qualities.

Overall acceptability of the vehicle was seen as "acceptable–minor improvements desired" (mean = 3.33). The test crew indicated that there were good human factors in the design for living comfortably in the vehicle, such as the multifunctional aspects and simplicity of rearranging functions in the cabin. Between the bench and the exterior hatch was space that could have been used for personal stowage, such as a mounted locker system. The participants suggested a double side hatch option for the vehicle (that is, a hatch on each side of the vehicle for docking SPR to SPR, or not limited to a single side for outpost docking), which would also provide more personal volume for each crewmember.

Participants commented on several factors that could cause issues for the crew, especially during longer duration missions. These included limited areas for personal hygiene, muscle fatigue climbing in and out of the suit port, waste and trash management, workload in getting to stowage, and crew dynamics. Waste and trash built up quickly over the 3-day mission. The ability to dispense the waste and trash at a reasonable rate to decrease crowding will have to be addressed. Personal preparation time for an EVA mission was a concern and the ability to resupply consumables was also a key concern. However, both subjects indicated they would recommend the current SPR configuration for a 3-day mission. Subjective fatigue ratings (see Section 2.3.5) collected throughout the 3-day traverse showed no increase in fatigue over the duration of the 3-day traverse (Figure 36).

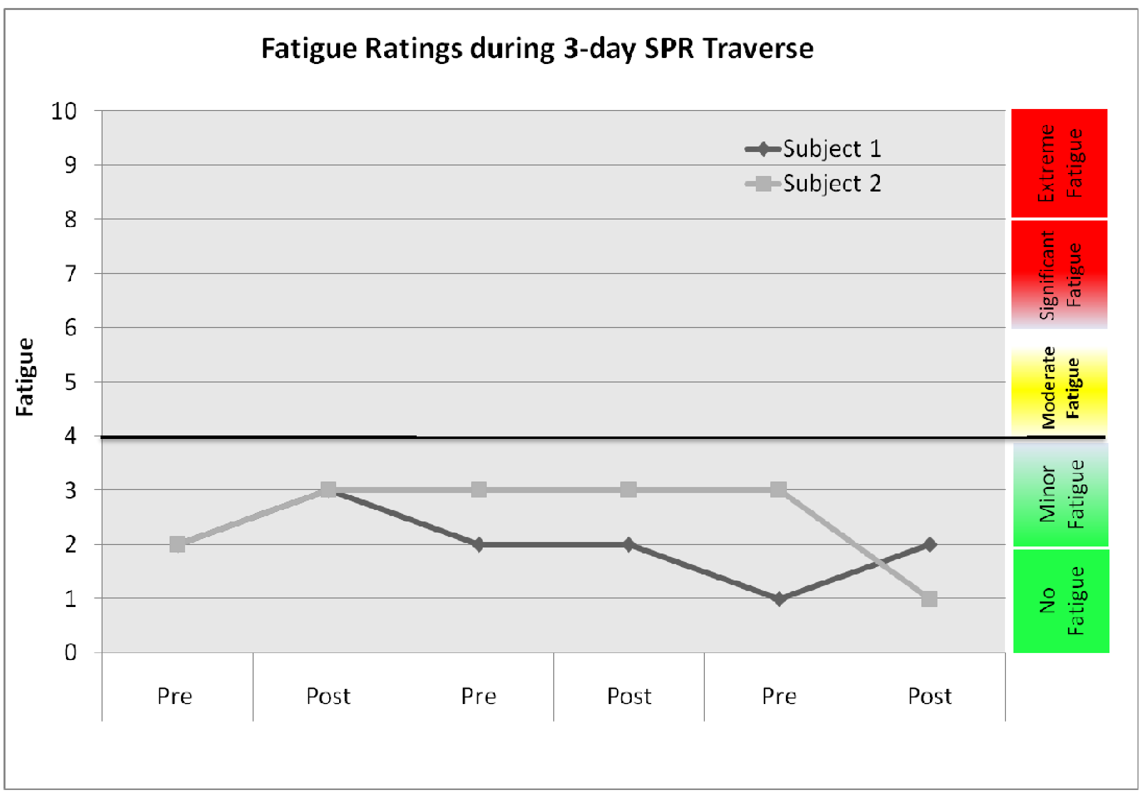


Figure 36 – Subjective fatigue ratings at the beginning (Pre) and end (Post) of of each of the 3-day traverse

3.5.6 SPR Exercise Device Human Factors

Upon completion of the 3-day SPR traverse, one subject completed an evaluation of the SPR exercise device. The subject unstowed the ergometer, completed a series of simulated aerobic and resistive exercises (actual exercising was not permitted during the field test without medical monitoring), then disassembled and stowed the equipment. The entire demonstration took about 45 minutes. The participant rated the exercise equipment on 16 factors (Table 15) using the acceptability scale defined in Section 2.3.5. The time to set up and break down the equipment was also recorded (Table 16).

All aspects of the exercise device human factors were within the acceptable range. The participant stated that the seat was simple to set up and was easily adjustable to his leg length; by moving the seat forward or aft by using the Velcro that held down the bench cushions, the participant was able to quickly adjust the seat and secure it. It was noted that the bench cushions could be used as a backrest, if needed. The participant felt there would be no problem exercising while the vehicle was moving. Figure 37 shows the participant simulating cycling and resistive exercise using the ergometer.

It was noted that another resistive outlet on the front of the device down near the base would be useful and that alignment guides on the base plate of the ergometer to assist in getting the machine into the correct position would also be helpful. Other suggestions for redesign were to have a bigger display in the front of the device, to provide a straight bar for resistive exercising, and using a pulley system for resistive upper body exercises (see example in Figure 38).

Table 15 – Acceptability ratings for SPR exercise device.

SPR Exercise Demo	Rating
Volume for 1 crew performing resistive exercise	2.00
Volume for 1 crew performing aerobic exercise	2.50
Design of ergometer to perform resistive exercise	2.00
Design of ergometer to perform aerobic exercise	3.00
Placement to secure equipment for resistive use	3.00
Placement to secure equipment for aerobic use	3.00
Accessibility to resistive exercise equipment	3.00
Accessibility to aerobic exercise equipment	3.00
Accessibility to workstations during resistive exercise	3.00
Accessibility to workstations during aerobic exercise	3.00
Stowage volume for exercise equipment	3.00
Comfort of the exercise seat	3.00
Stability of the exercise seat	2.00
Adjustability of the exercise seat	2.00
Setup of the exercise seat	2.00
Stowing of the exercise seat	2.00
Overall Average	2.59

Note. N = 1.

Table 16 – SPR exercise device set-up and break down times.

Task	Approximate Times
Unstow and Setup Time	10 mins
Seat Cushion Reconfig Time	4 mins 21 sec
Breakdown and Stow Time	2 mins

Figure 37 – Participant demonstrating the SPR exercise device during simulated aerobic cycling and resistive exercise.

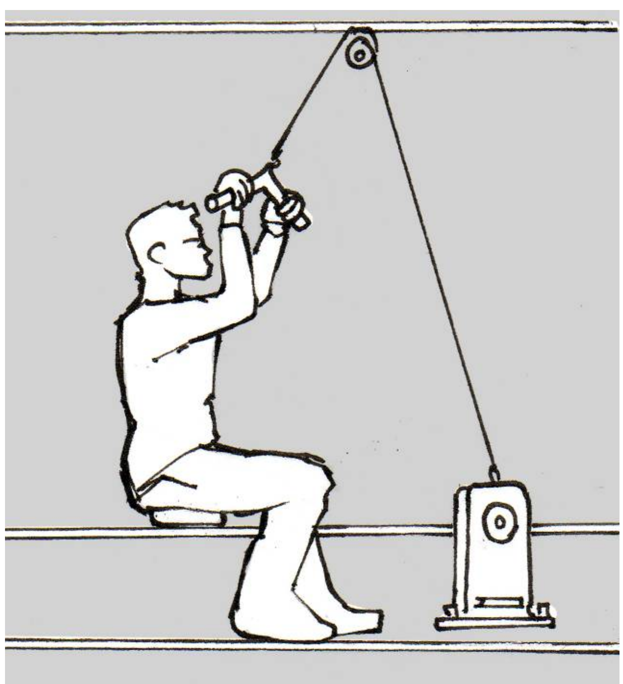


Figure 38 – Concept drawing of resistive upper body exercise with a bar and pulley system.

3.6 OTHER TEST OBJECTIVES

3.6.1 Nighttime Driving and Exploration, mapping, and geological Sample Collection and Documentation Tasks

One nighttime EVA lasting 25 minutes was completed during which one crewmember egressed the SPR via the suit port and performed a series of EVA tasks while the second crewmember provided support from inside the SPR (see Figure 34 and Figure 39). No nighttime EVAs were performed from the UPR. Illumination for the EVA crewmember was provided by lights on the helmet of the mockup EVA suit and flood lights mounted on the SPR. The illumination during nighttime EVA and driving was rated as acceptable using the same Acceptability Rating scale utilized in the other human factors evaluations. A Cooper-Harper rating of 4 for nighttime driving was reported indicating that moderate operator compensation was required to achieve the desired driving performance. The EVA crewmember successfully completed all geological sampling tasks.

As reported in Section 3.5, subjects reported that the external and interior lighting during night operations was highly acceptable with the lower floor lights being extremely helpful for night driving operations.

Figure 39- Nighttime EVA performed by one geologist with support from inside SPR.

3.6.2 Measure Performance Metrics During 1-day and 3-day (SPR only) Exploration, mapping, and geological Traverses

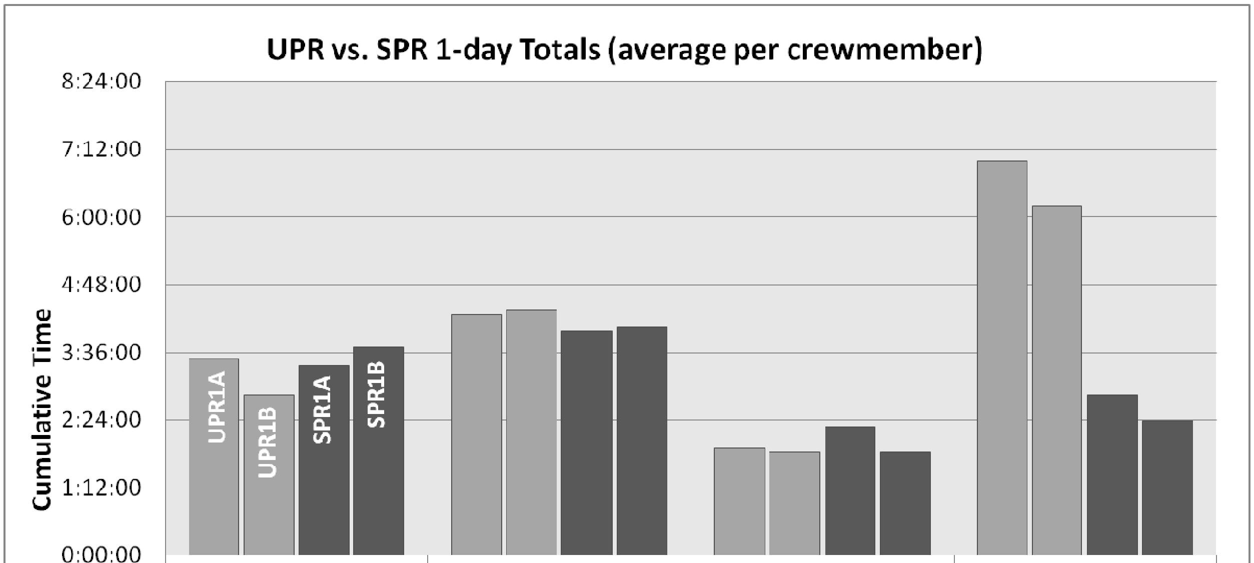
Performance metrics were collected for all UPR and SPR traverses throughout the field test. A summary of the metrics for each of the traverse days is shown in Table 17 and a graphical comparison of the crew time metrics for 1-day UPR and SPR traverses is shown in Figure 40. The average speed in motion of the vehicles is given to present an accurate notion of average speed; it does not include idle time because of EVA events. Figure 41 shows traverse paths of the SPR over the 3 day period, as denoted by the red (day one), green (day 2) and yellow (day 3) paths.

For the purposes of recording crew time classifications subjects verbally communicated to the CAPCOM when tasks were started and finished. Times were recorded using data sheets and the duration of each task was calculated. EVA Overhead was defined as tasks required before, during and after EVAs such as SPR egress, suit purge, tool retrieval, tool and sample stowage, and SPR ingress, which are necessary when performing EVAs but do not themselves directly accomplish any of the EVA objectives.

Table 17 – Performance metrics for UPR and SPR traverses at DRATS 2008.

	UPR1A	UPR1B	SPR1A	SPR1B	Average UPR	Average SPR	% Difference	SPR3A Day 2	SPR3A Day 3	Average SPR inc. 3-day
Vehicle Data										
Traverse Distance (km)	14.4	13.3	17.5	18.9	13.9	18.2	131%	17.6	16.3	51.4
Traverse Range (km)	5.1	4.9	5.3	5.4	5.0	5.3	107%	5.0	3.1	5.3
Vehicle Terrain Factor (non-dim)	2.8	2.7	3.3	3.5	2.8	3.4	123%	3.5	5.3	4.0
Adjusted Vehicle Terrain Factor	1.4	1.4	1.6	1.8	1.4	1.7	123%	1.8	2.6	2.0
Maximum speed filtered (kph)	20.2	14.4	15.0	15.0	17.3	15.0	86%	9.3	9.9	15.0
Average speed (kph)	1.9	1.9	1.5	2.0	1.9	1.7	92%	0.9	1.5	1.3
Average speed in motion (kph)	4.3	5.7	5.3	5.7	5.0	5.5	109%	3.8	3.8	4.3
% of time driving	44%	32%	28%	35%	38%	32%	83%	24%	41%	31%
% of time not in motion	56%	68%	72%	65%	62%	68%	111%	76%	59%	69%
Time spent in motion (mins)	200	139	198	199	170	199	117%	170	100	156
Crew Time & Performance										
Rover Driving & Contextual Observations	3:29	2:50	3:22	3:41	3:09	3:32	112%	5:44	3:40	**4:07**
EVA Overhead	4:16	4:21	3:59	4:02	4:19	4:00	93%	1:54	1:36	**2:52**
EVA Sampling, Translation & Contextual Observations	1:54	1:50	2:17	1:50	1:52	2:03	110%	1:44	0:42	**1:38**
Total EVA Time	7:00	6:12	2:50	2:23	6:36	2:37	40%	2:09	0:59	**2:05**
Productive EVA Time / Total EVA Time	27%	30%	80%	77%	28%	79%	50%	81%	72%	**77%**
Traverse Time	9:40	9:02	9:38	9:34	9:21	9:36	103%	9:22	5:59	**8:38**
Performance (WSCTO)	41	48	72	68	44.5	70	157%	62	32	**59**
Performance / EVA Hour	5.9	7.7	25.4	28.5	6.80	27.0	397%	28.8	32.5	**28.8**
Performance / Crew Hour	4.2	5.3	7.5	7.1	4.78	7.3	153%	6.6	5.3	**6.6**
Work Efficiency Index	1.64	1.42	0.71	0.59	1.53	0.7	43%	1.13	0.61	**0.8**
Boots-on-Surface Time	1:54	1:50	2:17	1:50	1:52	2:03	110%	1:44	0:42	**1:38**
Number of Egresses / person / day			6.5	5.0		5.8		4.5	3.0	**4.8**
Average EVA Duration			0:26	0:28		0:27		0:28	0:19	**0:26**
Egress Time (excl. backpack egresses):										
Mean			0:08	0:11		0:09		0:12	0:12	**0:11**
Max			0:11	0:16		0:13		0:15	0:14	**0:16**
Min			0:05	0:06		0:05		0:06	0:08	**0:05**
St. Deviation			0:01	0:03		0:02		0:05	0:03	**0:03**
Ingress Time (excl. backpack egresses):										
Mean			0:06	0:05		0:05		0:05	0:05	**0:05**
Max			0:08	0:07		0:07		0:06	0:08	**0:08**
Min			0:04	0:04		0:04		0:03	0:05	**0:03**
St. Deviation			0:01	0:01		0:01		0:01	0:01	**0:01**
EVA Walking Distance										
Mean	174	97	238	218	136	228	168%	218	310	255
Max	344	235	492	403	289	447	155%	403	387	427
St. Deviation	135	104	200	131	120	166	139%	131	83	138

EVA boots-on-surface suit time is generally the time during which most scientific productivity is being achieved whereas time spent inside the EVA suit during vehicle ingress and egress is nonproductive EVA time. By comparing EVA suit time to EVA boots-on-surface suit time, the efficiency with which EVA suit time is used may be quantified. As shown in Table 17, productive EVA time represented an average of only 28% of total EVA time during UPR traverses compared with 79% during equivalent 1-day traverses using the SPR.



	Rover Driving & Contextual Observations	EVA Overhead	EVA Sampling, Translation & Contextual Observations	Total EVA Time
UPR1A	3:29:00	4:16:30	1:54:30	7:00:00
UPR1B	2:50:30	4:21:30	1:50:00	6:12:00
SPR1A	3:22:30	3:59:00	2:17:00	2:50:30
SPR1B	3:41:30	4:02:30	1:50:00	2:23:30

Figure 40 - Comparison of crew time breakdown for 1-day UPR and SPR traverses.

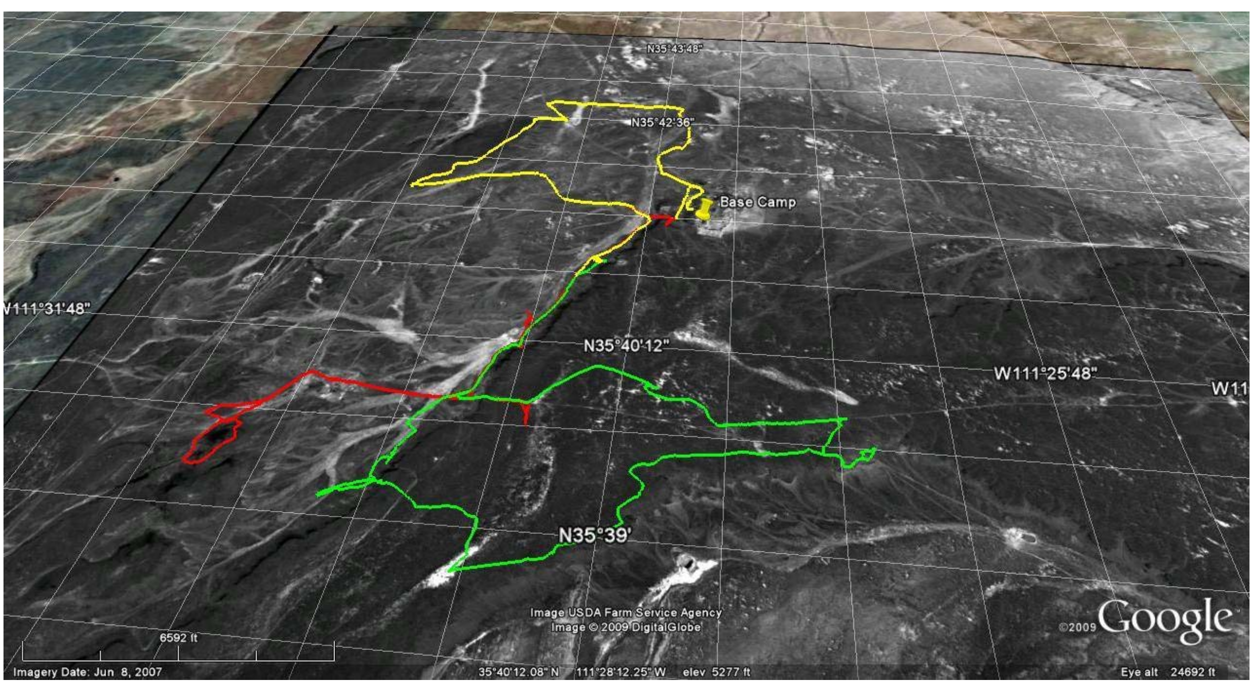


Figure 41 – Path of the SPR during the 3-day traverse (red: day 1, green: day 2, yellow: day 3).

The number of EVAs performed during traverses affects the consumables lost during ingress and egress operations, the energy required to operate gas reclaim pumps (with airlock) and the number of cycles on suit ports or the Mobile Habitat airlock. The SPR traverses planned by the Science Team and executed by the crews at DRATS 2008 averaged almost 5 EVAs per person per day. This high frequency of EVAs led to the total EVA overhead per traverse day being only slightly less than with the UPR traverses; however it was the ability to use EVA only when required that enabled the 62% reduction in EVA time while achieving 57% greater performance, as described in Section 3.1.

Over the 4 days of SPR traverses a total of 38 SPR egress/ingress cycles were performed. However, not all of these vehicle egress/ingress cycles were completed using the suit ports because of limitations of the Mockup EVA suits. Although intended to be lightweight, the fully instrumented EVA suits were too heavy for subjects to wear for all EVAs without risking unacceptable levels of exertion and/or discomfort. In accordance with the test plan (see Section 2.2.2.2), subjects were free to transition to the lightweight backpacks at any time and were required to use the lightweight backpack or terminate the test when reporting a discomfort rating > 7 (on Corlett and Bishop 10-point Discomfort scale) for two consecutive recording periods during suited testing.

During the four 1-day traverses, participants in the mockup EVA suits lasted about 5 hours 30 minutes in the UPR configuration before switching to lightweight backpack alternatives. By comparison, the same subjects during the SPR traverses lasted about 7 hours and 30 minutes before switching to backpacks. Because the lightweight backpacks cannot be used with the suit ports, subjects would egress the SPR via the side hatch and don the lightweight backpack. In all cases, the times associated with suit port egress procedures were followed to ensure that vehicle timelines were not biased by the side hatch egress/ingress cycles. Measured task time data from side hatch egress/ingress cycles were not included in any subsequent data analysis. The egress and ingress durations for the four 1-day SPR traverses, excluding side hatch egresses as described, are shown in Figure 42.

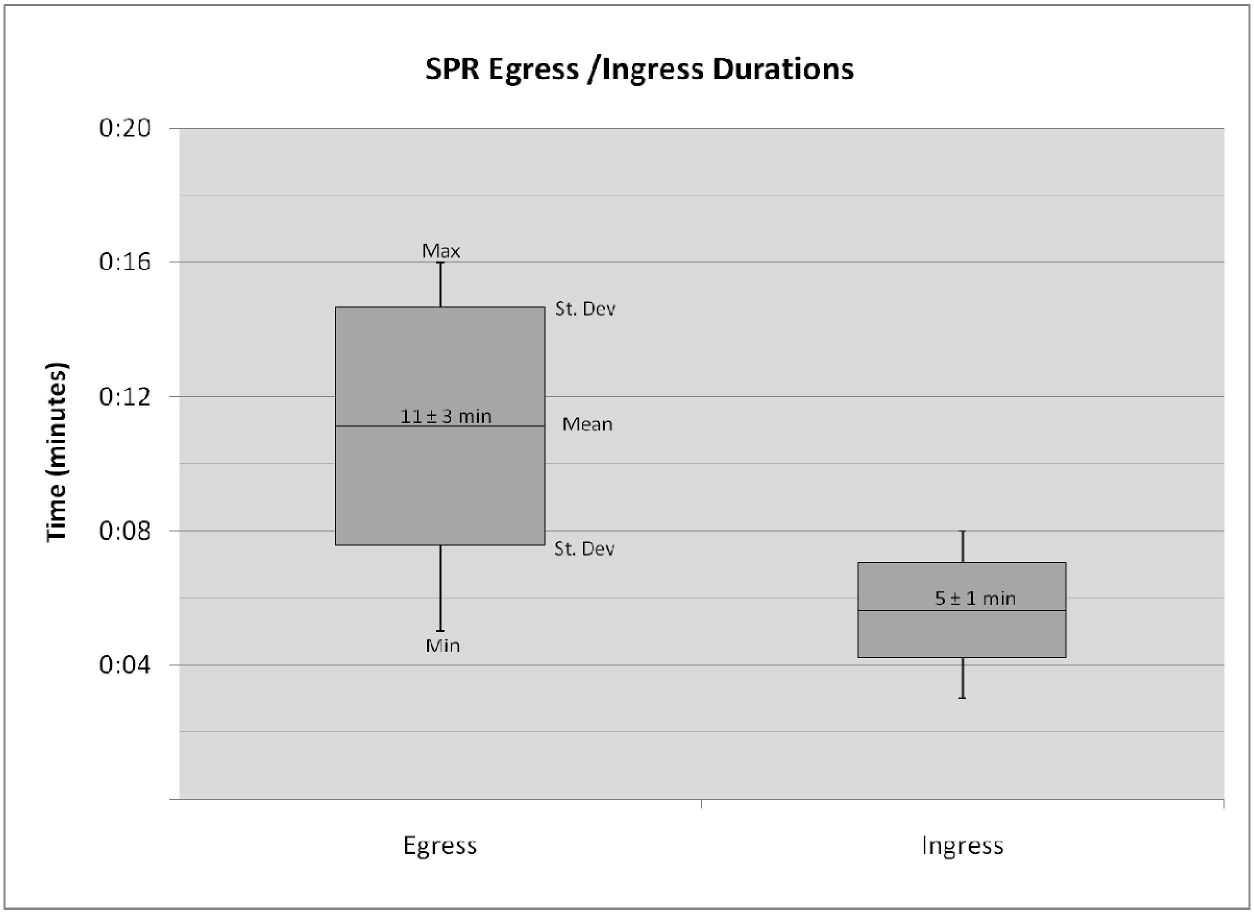


Figure 42 - SPR Egress and Ingress Durations.

During the Arizona desert analog tests, the SPR travelled 148 kilometers over 14 days. It is important to note that these numbers should not be generalized to a 14-day long-range traverse because the concept of operations and the traverse planning will differ significantly compared with a series of short duration (1-3 days) and short range (< 6km) traverses performed during this test. The relatively local exploration traverses conducted during this test are likely representative of those which would be performed early in the lunar architecture.

Although not included in this report, data was collected on all subsystems for use by engineers to both provide a baseline of operation and to improve upon the current SPR configuration. The chassis system provided data that illustrates how the vehicle operated in the analog environment. For example, the day one traverse occurred mainly on a ranch road that was flat, soft and consisted of fine dust-like particles. The average rolling resistance during this period of the day one traverse was 10.5%. The day 2 traverse occurred on a more firm, rocky surface. The average rolling resistance during this period of the day 2 traverse was 8.0%. These measurements show the difference in power required to drive the SPR on dissimilar terrains.

4.0 CONCLUSIONS

1) Productivity achieved during 1-day exploration, mapping, and geological traverses using the Small Pressurized Rover (SPR) was 57% greater than the productivity achieved during Unpressurized Rover (UPR) traverses, with 61% less EVA suit time. Excellent visibility from inside the SPR combined with the ability to rapidly egress and ingress the SPR via suit ports enabled utilization of high-frequency short-duration EVAs, including single-person EVAs performed with IV support from inside the SPR.

2) Range achieved during 1-day exploration, mapping, and geological traverses in the SPR was not significantly greater than during 1-day UPR traverses because of communications constraints at the field test site. Average distance driven during 1-day exploration, mapping, and geological traverses in the SPR was 4.3 km (31%) greater than during 1-day UPR traverses primarily because the 8-hr consumables limit on UPR traverses reduces the available driving time as compared with SPR traverses.

3) Subjective assessments of contextual observations from inside an SPR were approximately equal to walking shirtsleeve. A controlled comparison of contextual observations from inside the SPR with contextual observations from inside an EVA suit was not performed but it is anticipated that the added mass, limited mobility and reduced field of view in an EVA suit will make the SPR equal to or better than the EVA suit for making contextual observations.

4) Human interfaces to the SPR suit ports and alignment guides were acceptable as assessed by human factors metrics. Several modifications were identified to improve human factors and reliability in subsequent SPR suit port designs.

5) The human factors and crew accommodations within the SPR were acceptable to support a 3-day exploration, mapping, and geological traverse. Multiple modifications were identified to improve human factors and crew accommodations in subsequent SPR designs.

6) Nighttime driving and exploration, mapping, and geological sample collection and documentation tasks were performed successfully using the SPR with acceptable human factors.

7) Performance metrics were recorded during 1-day and 3-day (SPR only) exploration, mapping, and geological traverses. These metrics, combined with metrics from subsequent field test activities, will be used in the development of models by the Lunar Surface Systems Project and the Human Research Program.

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6.0 ACKNOWLEDGEMENTS

The authors would like to acknowledge the enthusiasm, dedication and excellence demonstrated by the entire Desert RATS Team throughout the 2008 campaign. And for their contributions to the preparation of this report, the authors acknowledge and thank Dale Ward and Jennifer Jadwick.

Figure 43 – Desert-RATS 2008 Team (many other team-members not shown).

7.0 APPENDICES

APPENDIX A: RATIONALE FOR USE OF ANALOG TEST SITE

FACILITIES AND PERFORMANCE SITE

Based on analyses performed during the LAT-2 study, science and exploration EVA could constitute more than 90% of total EVA time over a 10 year lunar architecture. A geologically relevant and scale-appropriate test site (such as Devon Island or Black Point Lava Flow) is essential when testing productivity, performance and human factors during exploration, mapping, and geological traverses.

Test subject training and dry-run activities were conducted at the JSC Rock Yard and in the Space Vehicle Mockup Facility (B9) at JSC. Testing occurred at the Black Point Lava Flow test site, about 40 miles north of Flagstaff, Arizona (Figure 46).

Detailed side-by-side comparisons of the SPR's and UPR's theoretical performance, productivity and safety capabilities and constraints have been performed and previously documented during the LAT-2 and CxAT_Lunar projects. This test was designed to validate previous findings and to add fidelity and realism to the comparisons, particularly with respect to SPR IVA productivity and human factors. Based on these objectives, the primary test site requirements with respect to EVA and Surface Operations are discussed and detailed below.

Geologically Relevant Terrain

Geologically relevant terrain was necessary to assess the ability of subjects to make geological contextual observations from inside the SPR compared with the UPR. It was also required to enable estimation of SPR performance and productivity metrics such as number of EVAs, maximum separation of EVA astronaut and SPR, boots-on-surface EVA time and average drive speed, all of which are largely terrain dependent. To the extent that performance metrics can be accurately estimated based on realistic field tests, the accuracy of estimated ranges, masses, dimensions and power, energy storage and consumables requirements produced by existing mobile surface systems models will also be improved.

The Black Point Lava Flow test site includes a wide variety of surface features with geological relevance. The geological features and terrain particularly along the edge of the lava flow provided many opportunities to evaluate the IVA and EVA science and exploration capabilities of the SPR during exploration, mapping, and geological traverses. Additional information on the geology of the Black Point Lava Flow test site is included in Appendix D.

Figure 44 – View of lava flow escarpment ~4 km (2.5 miles) from proposed base camp location.

Figure 45 – Examples of geological sites of interest at Black Point Lava Flow.

SCALE-APPROPRIATE TEST SITE

Theoretical UPR and SPR sorties developed during the LAT-2 and CxAT_Lunar studies involved driven distances of up to 40 km per day. There are several reasons that long-distance sorties must be performed during field testing, and they relate to the anticipated benefits of SPR-based traverses as compared with UPR-based traverses.

In a UPR, exploration traverses are limited to 8 hours, which is the maximum time that can be spent in an EVA suit. The capability to perform exploration traverses lasting many days is among the most significant benefits of the SPR concept as compared with a UPR alternative. SPRs also offer greater boots-on-surface EVA time during which to perform science tasks because of the EVA time that is saved by driving to and from exploration sites inside the shirtsleeve SPR environment. Furthermore, the shirtsleeve environment inside the SPR when driving between EVA sites potentially enables more productive use of crew time than is possible when performing the same drives on a UPR.

Evaluating the extent to which these perceived benefits are realized required that detailed and accurate exploration, mapping, and geological traverses were planned and executed on scales comparable to those which are anticipated during actual lunar traverses and that translation distances and times were not artificially constrained.

The size of the Black Point Lava Flow site and the abundance of exploration, mapping, and geological features would potentially enable extended range exploration, mapping, and geological SPR traverses (potentially > 100km+ driven distance with 7 -14 days of operational time).

Figure 46 – Test Site: Black Point Lava Flow, Arizona.

UPR AND SPR NEGOTIABLE TERRAIN CONDITIONS:

The slopes, soil mechanics, surface properties and existing terrain features of the test site were required to be negotiable by the UPR and SPR vehicles. The slopes from the top to the base of the Black Point lava flow vary from very slight (approx 6^{o}) to vertical. Terrain conditions vary from powdery sand with minimum to significant vegetation (< 12”) to harder packed ground with numerous small and medium-sized rocks and minimal vegetation (Figure 47 – Figure 49).

The base camp location was on top of the lava flow on a hard packed surface (193 kPa / 28 PSI load bearing capability) artificially created next to a gravel quarry. Vegetation was minimal in the base camp area and the nearby ash and gravel quarry but became denser in some locations.

Figure 47 – Test site base camp location.

Figure 48 – Looking south along the edge of Black Point Lava Flow; note varying slopes, varied geology, and representative vegetation.

Figure 49 – Example of slope variation, geological features and moderate vegetation at edge of Black Point Lava Flow.

APPENDIX B: BLACK POINT LAVA FLOW SCIENCE TRACEABILITY MATRIX

Table 18 – Black Point Lava Flow Field Test: Science Traceability Matrix.

Priority **1=high** **3=low**	**Science Question**	**Relevance to the Moon**	**Observation(s) & Analysis Needed**	**Traverse Task(s)**	**Traverse Tools Needed**	**Further Analysis**
Volcanics						
Black Point Lava Flow						
1	What is the absolute age of the BPLF?	Dating lunar volcanic events	Radiometric dating of a sample representative of the BPLF	**EVA Station A** Collect 2 fresh (edge of flow) hand samples from the BPLF	Positioning Tool + Camera + Rock Hammer (igneous) + Sample Bag	Radiometric Dating in Lab
1	What is the composition (mineralogy, chemistry) of the BPLF?	Composition of lunar volcanic materials	Mineralogy and geochemistry of a representative sample of the BPLF	**EVA Station A** Collect 2 fresh (edge of flow) hand samples from the BPLF	Positioning Tool + Camera + Rock Hammer (igneous) + Sample Bag	Mineralogy and Geochemistry Analysis in Lab

Priority **1=high 3=low**	**Science Question**	**Relevance to the Moon**	**Observation(s) & Analysis Needed**	**Traverse Task(s)**	**Traverse Tools Needed**	**Further Analysis**
2	Does the BPLF present spatial variations in composition?	Spatial variation in composition of materials from a single volcanic event	Mineralogy and geochemistry of a suite of samples collected along the length of the BPLF.	**EVA Stations A, B, C.** Collect 2 fresh (edge of flow) hand samples at each of at least 3 locations 1 km apart along the length of the BPLF	Positioning Tool + Camera + Rock Hammer (igneous) + 3 Sample Bags	Mineralogy and Geochemistry Analysis in Lab
1 Target of Opportunity	Does the BPLF contain large xenoliths?	Search for lunar mantle xenoliths in lunar volcanic materials	Look out for any occurrence of large xenoliths along length of the BPLF	**EVA Stations X** Collect 2 fresh hand samples from at least one location if encountered	Positioning Tool + Camera + Rock Hammer (igneous) + 3 Sample Bags	Mineralogy and Geochemistry analysis in Lab
2	What petrologic textures does the BPLF present? Any lateral variations?	Petrologic textures of lunar volcanic materials	Petrology of a suite of samples collected along the length of the BPLF.	**EVA Stations X** Collect 2 fresh hand samples of any instance of significant lateral petrologic variation along the length of the BPLF	Positioning Tool + Camera + Rock hammer (igneous) + 10 Sample bags	Petrology analysis in Lab

Priority 1=high 3=low	Science Question	Relevance to the Moon	Observation(s) & Analysis Needed	Traverse Task(s)	Traverse Tools Needed	Further Analysis
2 Target of Opportunity	What petrologic textures does the BPLF present? Any vertical variations?	Petrologic textures of lunar volcanic materials	Petrology of a suite of samples collected along one or more vertical sections of the BPLF	**EVA Stations X** If vertical variations in rock texture are found: Collect at least 2 hand samples at each of 3 levels along a vertical section of the BPLF. Repeat at other vertical section locations along the length of the BPLF if needed.	Positioning Tool + Camera + Rock Hammer (igneous) + 3 Sample Bags	Petrology analysis in Lab

Priority **1=high** **3=low**	**Science Question**	**Relevance to the Moon**	**Observation(s) & Analysis Needed**	**Traverse Task(s)**	**Traverse Tools Needed**	**Further Analysis**
2	What morphologic and structural features does the BPLF present? (Lava Tubes, Collapse Features, Sags, Faults, Joints, etc.)	Morphologic and Structural features associated with lunar volcanic units	Morphologic and Structural observations and analysis of the BPLF	**EVA Stations X** Document any significant structural features of the BPLF. **EVA Station S** Examine sag associated with high albedo feature on surface of BPLF 2 km south of camp.	Positioning Tool + Camera	Morphologic and Structural analysis
1	What features are present in the apparent "Source Area" of the BPLF?	Investigation of "Source Areas" of lunar volcanism	Geologic characterization of "Source Area" of the BPLF	**EVA Station Z** Document and sample materials from the apparent "Source Area" of the BPLF.	Positioning Tool + Camera + 10 Sample Bags	Radiometric dating, petrology, mineralogy and geochemistry of samples.

Priority **1=high** **3=low**	**Science Question**	**Relevance to the Moon**	**Observation(s) & Analysis Needed**	**Traverse Task(s)**	**Traverse Tools Needed**	**Further Analysis**
1	What is the geologic relationship between the BPLF and underlying lithologic units? What is the geologic and evolutionary history nature of these underlying units?	Investigations of the geologic relationship between lunar volcanic flows and underlying lithologic units.	Geologic characterization of the contact between the BPLF and underlying lithologic units.	**EVA Stations A to C** Follow contact between BPLF and underlying lithologic units. Note dip and strike of any underlying layered units.	Positioning Tool + Camera + 10 Sample Bags	Dating (Absolute or relative), petrology, mineralogy and geochemistry of samples. Morphologic and structural analysis.
2	What is the nature of the High Albedo Features on the top surface of the BPLF? Do the albedo features represent eolian deposits?	Investigation of discrete and/or anomalous albedo features on the Moon	Geologic characterization of the High Albedo features on top of the BPLF.	**EVA Station S** Document and sample materials from the High Albedo Units on top of the BPLF.	Positioning Tool + Camera + 3 Sample Bags	Mineralogy and geochemistry of the High albedo Units materials.

Priority 1=high 3=low	Science Question	Relevance to the Moon	Observation(s) & Analysis Needed	Traverse Task(s)	Traverse Tools Needed	Further Analysis
Other Lava Flows and Volcanic Features						
2	What is the absolute age of Other Lava Flows and Volcanic Features near the BPLF?	Dating lunar volcanic events	Radiometric dating of samples representative of the Other Lava Flows and Volcanic Features near the BPLF	**EVA Stations D, E, F** Collect 2 fresh hand samples from the Other Lava Flows and Volcanic Features near the BPLF	Positioning Tool + Camera + Rock Hammer (igneous rocks)+Sample Bag	Radiometric Dating in Lab
2	What is the composition (mineralogy, chemistry) of the Other Lava Flows and Volcanic Features near the BPLF?	Composition of lunar volcanic materials	Mineralogy and geochemistry of a representative samples of the Other Lava Flows and Volcanic Features near the BPLF	**EVA Stations D, E, F** Collect 2 fresh hand samples from the Other Lava Flows and Volcanic Features near the BPLF	Positioning Tool + Camera + Rock Hammer (igneous rocks) + Sample Bag	Mineralogy and Geochemistry Analysis in Lab

Priority **1=high 3=low**	**Science Question**	**Relevance to the Moon**	**Observation(s) & Analysis Needed**	**Traverse Task(s)**	**Traverse Tools Needed**	**Further Analysis**
3 Target of Opportunity	Do the Other Lava Flows and Volcanic Features near the BPLF present spatial variations in composition?	Spatial variation in composition of materials from a single volcanic event	Mineralogy and geochemistry of a suite of samples collected along the length of a selected Lava Flow or Volcanic Feature near the BPLF.	**EVA Stations D, E, F.** Collect 2 fresh hand samples at each of at least 3 locations 1 km apart along the length of a selected Lava Flow near the BPLF and/or from distinct Volcanic Features near the BPLF	Positioning Tool + Camera + Rock Hammer (igneous rocks) + 3 Sample Bags	Mineralogy and Geochemistry Analysis in Lab
1 Target of Opportunity	Do the Other Lava Flows near the BPLF contain large xenoliths?	Search for lunar mantle xenoliths in lunar volcanic materials	Look out for any occurrence of large xenoliths along length of Other Lava Flows near the BPLF	**EVA Stations X** Collect 2 fresh hand samples from at least one location if encountered	Positioning Tool + Camera + Rock Hammer (igneous rocks) + 3 Sample Bags	Mineralogy and Geochemistry analysis in Lab

Priority **1=high** **3=low**	**Science Question**	**Relevance to the Moon**	**Observation(s) & Analysis Needed**	**Traverse Task(s)**	**Traverse Tools Needed**	**Further Analysis**
3	What petrologic textures do the Other Lava Flows near the BPLF present? Any lateral variations?	Petrologic textures of lunar volcanic materials	Petrology of a suite of samples collected along the length of a selected Lava Flow near the BPLF.	**EVA Stations X** Collect 2 fresh hand samples of each instance of significant lateral petrologic variation along the length of a selected Lava Flow near the BPLF	Positioning Tool + Camera + Rock hammer (igneous rocks) + 10 Sample bags	Petrology analysis in Lab

Priority **1=high** **3=low**	**Science Question**	**Relevance to the Moon**	**Observation(s) & Analysis Needed**	**Traverse Task(s)**	**Traverse Tools Needed**	**Further Analysis**
3 Target of Opportunity Target of Opportunity	What petrologic textures do the Other Lava Flows and Volcanic Features near the BPLF present? Any *vertical* variations?	Petrologic textures of lunar volcanic materials	Petrology of a suite of samples collected along one or more vertical sections of a selected Lava Flow near the BPLF	**EVA Stations X** If vertical variations in rock texture are encountered: Collect at least 2 hand samples at each of 3 levels along a vertical section of a selected Lava Flow near the BPLF. Repeat at other vertical section locations along the length of the selected Lava Flow near the BPLF if needed.	Positioning Tool + Camera + Rock Hammer (igneous rocks) + 3 Sample Bags	Petrology analysis in Lab

Priority **1=high 3=low**	**Science Question**	**Relevance to the Moon**	**Observation(s) & Analysis Needed**	**Traverse Task(s)**	**Traverse Tools Needed**	**Further Analysis**
2	What morphologic and structural features do the Other Lava Flows and Volcanic Features near the BPLF present? (Cinder Cones, Vents, Lava Tubes, Collapse Features, Sags, Faults, Joints, etc.)	Morphologic and Structural features associated with lunar volcanic units	Morphologic and Structural observations and analysis of the Other Lava Flows and Volcanic features near the BPLF	**EVA Stations X** Document any significant structural features of the Other Lava Flows and Volcanic Features near the BPLF.	Positioning Tool + Camera	Morphologic and Structural analysis

Other Geologic Units and Features						
Marbled Terrain North of Flow						
1	What is the nature and evolutionary history of the *Marbled Albedo Unit*?	General lunar geology science *operations*. Lunar regolith science *operations*.	Systematic geologic observations, characterization, and sample analysis.	**EVA Stations A, B, C, G, H.**	Positioning Tool + Camera + Rock Hammer (Sedimentary) + Trenching Tool + 8 Sample Bags	Dating (Absolute or relative), petrology, mineralogy and geochemistry of samples. Morphologic and structural analysis.
3	What is the nature and evolutionary history of the dissection in the *Dissected Unit*?	Lunar rill science *operations*.	Systematic geologic observations, characterization, and sample analysis.	**EVA Station J**	Positioning Tool + Camera + Rock Hammer (Sedimentary) + Trenching Tool + 4 Sample Bags	Dating (Absolute or relative), petrology, mineralogy and geochemistry of samples. Morphologic and structural analysis.

3	What is the nature and evolutionary history of the *Non-Dissected Transitional Unit*?	General lunar geology science *operations*. Lunar regolith science *operations*.	Systematic geologic observations, characterization, and sample analysis.	**EVA Stations J and K**	Positioning Tool + Camera + Rock Hammer (Sedimentary) + Trenching Tool + 4 Sample Bags	Dating (Absolute or relative), petrology, mineralogy and geochemistry of samples. Morphologic and structural analysis.
2	What is the nature and evolutionary history of the *Knobby Unit*?	Lunar hummocky terrain science *operations.*	Systematic geologic observations, characterization, and sample analysis.	**EVA Station K**	Positioning Tool + Camera + Rock Hammer (Sedimentary) + Trenching Tool + 2 Sample Bags	Dating (Absolute or relative), petrology, mineralogy and geochemistry of samples. Morphologic and structural analysis.

Layered Terrain NE of ("Below") Scarp						
2	What is the nature and evolutionary history of the Layered Unit Below	General lunar geology science *operations*. Lunar regolith science *operations*.	Systematic geologic observations, characterization, and sample analysis.	**EVA Station L**	Positioning Tool + Camera + Rock Hammer (Sedimentary) + Trenching Tool + 4 Sample Bags	Dating (Absolute or relative), petrology, mineralogy and geochemistry of samples. Morphologic and structural analysis.
Scarp						
1	What is the nature and evolutionary history of the Scarp separating the *Marbled Terrain North of the Flow* and the *Layered Unit NE of the Scarp*?	Lunar tectonics science *operations*. Lunar wrinkle ridge science *operations*.	Morphologic and structural observations and analysis.	**EVA Station L**	Positioning Tool + Camera	Morphologic and Structural Analysis.

Marbled Terrain South of Flow						
2	What is the nature and evolutionary history of the Marbled Unit South of the Flow.	General lunar geology science *operations*.	Systematic geologic observations, characterization, and sample analysis.	**EVA Station T**	Positioning Tool + Camera + Rock Hammer (Sedimentary) + Trenching Tool + 2 Sample Bags	Dating (Absolute or relative), petrology, mineralogy and geochemistry of samples. Morphologic and structural analysis.
Other Albedo Features						
3. Target of Opportunity	What is the nature and evolutionary history of the discrete and/or anomalous albedo features near the BPLF?	Investigation of discrete and/or anomalous albedo features on the Moon.	Geologic characterization and analysis of discrete/anaomalous albedo features near the BPLF.	**EVA Stations A to C.**	Positioning Tool + Camera + Rock Hammer (Sedimentary) + Trenching Tool + 12 Sample Bags	Dating (Absolute or relative), petrology, mineralogy and geochemistry of samples. Morphologic and structural analysis.

APPENDIX C: FIELD GEOLOGIST FEEDBACK ON SPR CONTEXTUAL OBSERVATION CAPABILITY

Field Geologist #1

Rating: 2.5

Overall Design: Windows presented an excellent view forward and to side for 10's of feet.

Mobility: The ability to get close when the terrain was suitable, was remarkable. View was clear. I could get within inches of the rock. Could really see rock details.

Cameras and Sensors: Did not use cameras and sensors.

Other: I think this is an incredible vehicle to scout a possible EVA and plan collection sites in advance and make the traverse much more focused.

Ability to observe across sufficient scales and/or fields of view: It was easy to move from the cm scale to the meter scale to the km scale and relate features to one another. It was comfortable to sit back and absorb the whole scene in front of you and synthesize your observations.

Ability to consider and communicate multiple working hypotheses on the fly: My mind usually soaks in the observations for a considerable time before I start drawing conclusions, but I do have a steady flow of ideas I am considering all the time.

Field Geologist #2

Rating: 3.0

Overall Design: Windows were very good for observing far field (seated view) and near (bubble) view. My only comment for improvement would be better ergonomic space between seats to access bubble view. The environment was very comfortable -- some heat on legs via sunny window while seated, but otherwise very, very nice.

Mobility: The mobility was good. Approach to rocks was possible and made better with lowering vehicle and bubble view while lowered. Could not get as close as a human to cliff face because of boulders in front, but view was adequate and we could get as close to ground clasts, maybe closer considering pack blocks my human ability to bend over. We did get stuck for a couple of minutes.

Cameras and Sensors: The camera worked well; we took one image of the caprock. Sensors seemed to work well also.

Other: Very comfortable, little to no human exertion; good way to cover a lot of terrain with adequate access to rocks.

Ability to observe across sufficient scales and/or fields of view: The vehicle compared very well to human walking in far and near field. The only difference was the vehicle's inability to reach cliffs because of obstructing boulders in front. So far and near field was equivalent. At cliff face the vehicle was limited.

Ability to consider and communicate multiple working hypotheses on the fly: The only difference is that a human could walk a bit faster and closer to red rock cliff -- perhaps observing rock geometries and contacts that would help in interpretation process. However, my observations did not change, nor did my interpretations using the vehicle, so the vehicle compared well and was shirtsleeve equivalent.

Field Geologist #3

Rating: 3.0

Overall Design: Windows provide excellent forward-looking views of both the horizon and ground within inches of the vehicle. The environment is cool and controlled. This probably makes a difference over long durations; it was not important during a 30-minute test.

Mobility: Fine.

Cameras and Sensors: Did not use cameras and sensors

Other: I think this is an incredible vehicle to scout a possible EVA and plan collection sites in advance and make the traverse much more focused

Ability to observe across sufficient scales and/or fields of view: I was able to evaluate models of regional topography and test them with outcrop and rock-scale observations.

Ability to consider and communicate multiple working hypotheses on the fly: Yes, this was possible (that is, nature of slope between red-colored bedrock bench and basalt bench above).

Field Geologist #4

Rating: 3.0

Overall Design: Windows provide an impressive view of the surroundings: greater than 180 degrees. Peripheral vision is nice, although the best feature of the windows is that they wrap around the bottom of the vehicle. This low view allows closer viewing of the ground and rocks than you would have walking. This is a huge geological advantage while driving. The vehicle is very comfortable and the ease of conversation provides lots of opportunity for discussion and collaboration during decision making and working through scientific ideas. The bubble window is a nice addition for looking up close. Might be nice to have more room at the front windows; being able to fold a seat up and sit or kneel on the floor of the vehicle would be awesome!

Mobility: Really great… smooth ride that encourages doing observations while traveling. The ability to turn easily in place enables relatively quick views of the surrounding environment. I was surprised at how close to the sandstone outcrop we could get. Mobility is really only limited when it comes to getting to outcrops at the top of steep slopes with lots of large rocks and boulders.

Cameras and Sensors: Did not use cameras and sensors

Other: The need for EVAs for doing geology will never be eliminated, however, this vehicle enables and encourages excellent geologic observations at an impressive spread of scales.

Ability to observe across sufficient scales and/or fields of view: This vehicle allows observations of cm to km scale features. This allows the observer to build up an adequate initial understanding of geologic context.

Ability to consider and communicate multiple working hypotheses on the fly: Yes, the comfortable interior of the vehicle will allow easy conversation between the crewmembers, which is likely to improve the quality of the field science. The context that can be gained in the vehicle will allow planned EVAs to be more focused and efficient, which will allow for a better investigation of multiple hypotheses.

APPENDIX D: SCIENCE TEAM REPORT AND COMMENTS

UPR/SPR FIELD TESTS

Flagstaff, AZ

Oct.18-31

SCIENCE EVALUATION:

BACKGROUND

INTRODUCTION:

The UPR/SPR field tests in the Black Point Lava Flow area, some 40 km N of Flagstaff, AZ, were primarily intended to evaluate the (lunar) surface mobility afforded by unpressurized (UPR) and pressurized (SPR) rovers, the latter critically depending on innovative suit port concepts for efficient egress and ingress. Predetermined test objectives and time lines were implemented remotely via trailer-housed mission control; the latter included a science team to monitor the geologic observations and sampling activities. The entire campaign was thus characterized by a very high degree of fidelity and realism relative to anticipated lunar surface operations.

This report summarizes the first order impressions of the science team regarding the utility of the tests. Time did not permit to produce a summary evaluation by the entire team in real time. Instead, the members of the science team were asked to individually compose their impressions, both positive and negative, on no more than two pages. This brief “background” document is intended to provide some general introduction for these evaluations, all part of this document, hopefully reducing wasteful introductions and redundancies in individual reports.

SITE GEOLOGY

The Black Point Lava Flow and its surroundings were recognized during the Apollo era as highly suitable analog for the development of lunar surface exploration activities; as a consequence, a detailed geologic map was produced by USGS, Flagstaff. The latter was recently augmented and expanded by M. Chapman, USGS, Flagstaff, to specifically support the present Human Robotic Systems (HRS) activities; Chapman was thus the resident local expert during the 2008 HRS tests.

The major geologic formations of interest were the Black Point Lava Flow and its substrate, the Moenkopi Formation. The latter is of Triassic age (some 220 to 240 MY old) and reflects a series of diverse sediments ranging in grain size from clay-rich mudstone deposits to sand-rich strata, some finely bedded at centimeter scales and easily eroded, others of more massive and indurated character, up to 5 meters thick, forming prominent cliffs and ledges that can be traced for kilometers in lateral continuity. A wide variety of sedimentary structures, such as cross bedding, pebble horizons, ripple marks, etc., are readily observed in the field, indicating an estuarine environment akin to Louisiana's present day Mississippi delta. Outcrops of these Moenkopi (MK) sediments are common in the area, allowing the collection of samples within stratigraphic context.

In contrast, the Black Point Lava Flow (BPLF) is a relatively recent feature, some 2.4 MY old; it is part of the regional "San Francisco Volcanic Field" that produced a number of well known basalt flows, some older, some younger than BPLF. The BPLF is more than 10 km long and in places as wide as 5 km; its actual source is buried by younger flows to the south of the test site. The thickness of the flow is highly variable, as it flowed and ponded in local topographic lows of an eroded surface in the MK formation. Most of the test traverses ranged along the exposed edges of the flow where basalt thicknesses are measured in a few meters. These exposures reveal a wide variety of basalt textures at scales < 1 m, ranging from dense to highly porous basalts, some displaying flow banding and lineation of vesicles, others more massive and vuggy; most basalts cooled sufficiently fast to yield "aphanitic" textures, implying that their component minerals are so small that they cannot be resolved by the unaided eye; on occasion cooling rates were sufficiently slow, however, to allow for millimeter size crystals that could be recognized in the field. Collectively, these textures suggest that the solidifying crust of the basalt flow was repeatedly broken and reincorporated into the viscous flow, thereby preserving a wide variety of textures and cooling phenomena in close juxtaposition.

TRAVERSE PLANNING

Traverse planning occurred in two discrete phases:

1) Photogeologic interpretation and prioritization of science objectives
2) Detailed traverse routes, station objectives, and time lines.

Re.1) The entire Science Team convened for 1 day to interpret the local geology from an aerial photograph at some 10 m resolution (see Figure 1). A topographic map was available as well and supported some of the interpretations. No field knowledge was allowed during this activity. The lava flow was readily observed and mapped, as was the sedimentary unit, yet its exact nature could not be discerned. The pre-mission photogeologic map produced by the science team is attached as Figure 2. A number of science considerations, too detailed for this report, identified the basalt flow as the highest priority objective, followed by the "Marbeled Unit" of poorly defined origin (and that turned out to be the MK sediments). Additional geologic units, such as the "channeled" and "chaotic unit" were differentiated and mapped as well, with both deemed of relatively low priority.

Re.2) Detailed traverse planning was conducted by a sub-group of the science team as it involved almost daily interaction with evolving operational constraints, such as total duration of each

EVA, available range of communications, expected rover speed, detailed time-lines for vehicle egress and ingress, including depressurization, local "logistics" related to trafficability such as fence lines and roads. These detailed traverse plans were then distilled into cuff-check lists for the crew and other operational products for the back room; they also formed the basis for the quantitative pre-mission and post-mission evaluations of both UPR and SPR. The detailed duration for science activities during a crew's workday was provided to the traverse planners by JSC-CB; the latter was also responsible for all other activities (and constraints) that were unrelated to science, and that needed to be accounted for during a full 15 hour crew day.
A total of 4 individual traverses were planned: a) "1 Day UPR"; actually some 6:30 hrs duration; b) "1 Day SPR" (actually: 9:30 hrs); both crews A and B each conducted identical UPR and 1-day SPR traverses for meaningful comparisons of UPR and SPR; the longer (18 km) SPR traverse included substantial portions of the UPR (12 km) traverse, again to allow meaningful comparisons, yet it ranged further and added an additional sampling station (see Figure 3). Two additional traverses supported the long-duration SPR tests which lasted 3 full days and 2 nights: day one coincided with the above SPR traverse, yet days 2 and 3 covered new territory and mandated dedicated traverses (see Figure 4) for a cumulative range of 56 km for the continuous 3-day test. A detailed traverse package, detailing way points, sampling stations, science objectives and timelines served as the basis for extensive pre- EVA science briefings of both crews.

SCIENCE OPERATIONS:

The science operations were substantially patterned after similar Apollo training exercises and focused on two basic functions: a) field observers and b) science back room.

Typically two field observers, one for each crew, followed the suited subjects in the field and made notes about the quality of observations, sample selections, and sampling procedures. These field observers were equipped with radios and thus able to listen to the crews' descriptions throughout the entire traverse, including the comments offered while driving.

The science back room consisted of a Field Geology PI and one or two CoIs, a Science Capcom, a Navigator, and a Note Taker. The table below identifies the individuals and their specific functions during diverse traverses; the objective of these rotating assignments was obviously to cross-train a number of individuals for future field tests of this nature. The back room was in continuous radio contact with the crew and able to advise the latter, if needed. Also, up to 5 video cameras were displayed in the back room: forward, aft facing and central mast-mounted devices on the rover (including panoramic capabilities), and especially two suit-mounted cameras, one each for a suited subject, that also could acquire single frame still images. These real time video capabilities imply vastly different back room operations and requirements relative to Apollo (which almost exclusively relied on verbal descriptions only). Typically, after completion of each traverse a science-debriefing re. operational science issues was staged during which field observers and back room personnel offered constructive critique. An overall science briefing was held on the last day of field camp (11/30). The science team concluded that suitable observations and samples were acquired to address all major pre-mission science objectives.

	EV 1	EV 2	FIELD, A	FIELD, B	CAPCOM	PI	CoI, A	Navigator	Notes
UPR, A	Gernhardt	Garry	Lofgren	Chapmann	Horz	Kring	Eppler	Wilkinson	Nelson
UPR, B	Walheim	Lee	Chapman	Kring	Eppler	Horz	Lofgren	Wilkinson	Nelson
SPR, B	Walheim	Lee	Eppler	Horz	Kring	Lofgren	Chapmann		

SPR, A	Gernhardt	Garry	Horz	Kring	Lofgren	Chapmann	Rice / Lee	Wilkinson	Nelson
Day2, A	"	"	Lofgren	Rice	Chapmann	Kring	Horz	Wilkinson	Nelson
Day3, A	"	"	Chapmann	Horz	Lofgren	Rice	Kring	Wilkinson	Nelson

SPR SCIENCE TEST:

Although not part of the initial test plans, most science team members were afforded the opportunity to ride in the SPR and to compare the observations from inside the SPR with those of a shirtsleeved geologist walking across a specific test site. The latter was some 200 x 200 m in extent and contained tell-tale sedimentary structures as well as a wide diversity of basalts, the latter in the form of dislodged float covering the local slope. During both activities, each lasting 20 minutes, the geologists verbalized their observations and recorded them via dictaphone, walking first, followed by observations inside SPR.

A general description of the test area is attached to this report; detailed analysis of this test is in progress, yet all participants deemed this test significant and highly beneficial. A dedicated report is anticipated.

SAMPLE STATISTICS:

All rock and soil samples collected during the 6 EVAs were placed into prelabeled bags and shipped to JSC for additional analysis that will be documented via a separate report. The following, first order results were obtained to date:

	Sample Bags	Total mass	average sample mass	EVA (hours)	n/hr	kg/hr
	n	kg	g			
UPR, A	26	12.410	477	6:30	4.0	1.91
UPR, B	33	18.147	550	6:30	5.1	2.79
SPR, B	52	20.787	400	9:30	5.4	2.19
SPR, A	37	18.056	488	9:30	3.9	1.90
SPR, Day 2	39	14.653	376	9:30	4.1	1.54
SPR, Day 3	19	7.128	375	7:00	2.7	1.02
Totals	206	91.181	442	48.5	4.3	1.88

Note: a) variance among crews with crew B tending to collect more samples and/or A being more selective. Also, crew B tended to collect modestly larger samples.

b) EVA time is total hours; n/hr and kg/hr should be recalculated for "boots on the ground" time (which was not readily available at the time of this tabulation).

c) Sample mass collected during approx. 50 hours of total EVA approaches the current limit for sample return mass (100 kg) for a base-line Earth return for Constellation (the field mass is pure sample and does not include additional containers and packing material, nor any biological specimen).

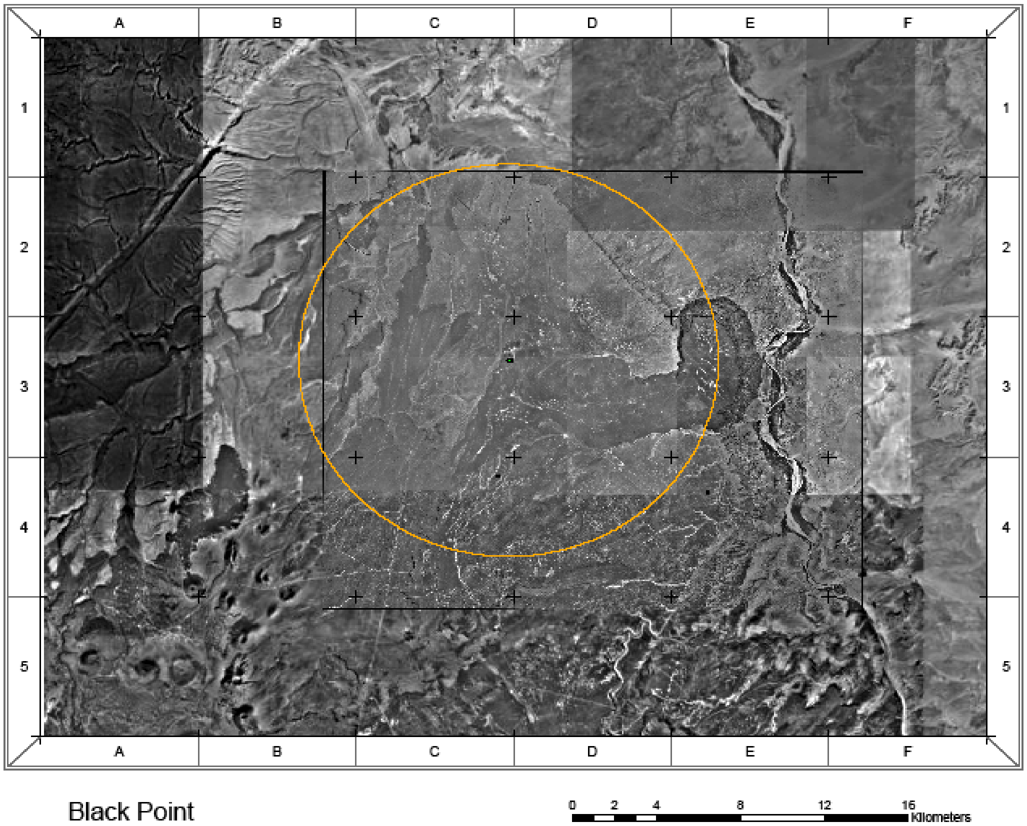


Figure D1: The Black Point Lava Flow and its surroundings; the circle is 10 km in diameter and centered on the location of base camp, at the western edge of this 2.4 MY basalt flow.

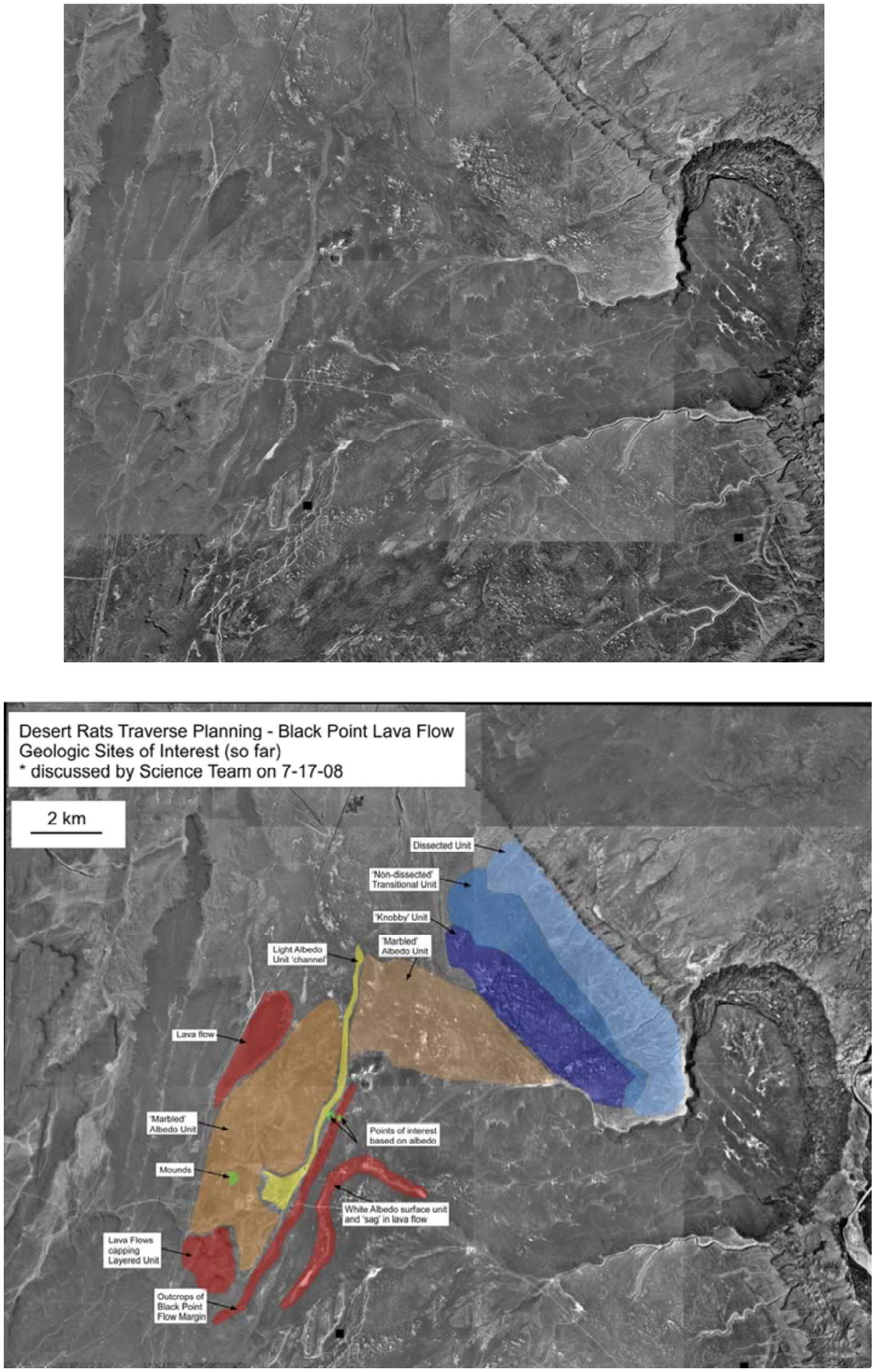


Figure D2: Detailed view of Black Point Lava Flow and photogeologic map produced by the Science Team; the actual basalt flow is not explicitly mapped in this rendition, but other volcanic features are (in red), suggestive of additional volcanic events. The detailed mapping concentrated on more subdued morphologies, suggesting different rock types. The traverses concentrated on the Western edge of the flow and the adjacent units (brown) to the West, as well as on the additional (red) volcanic formations.

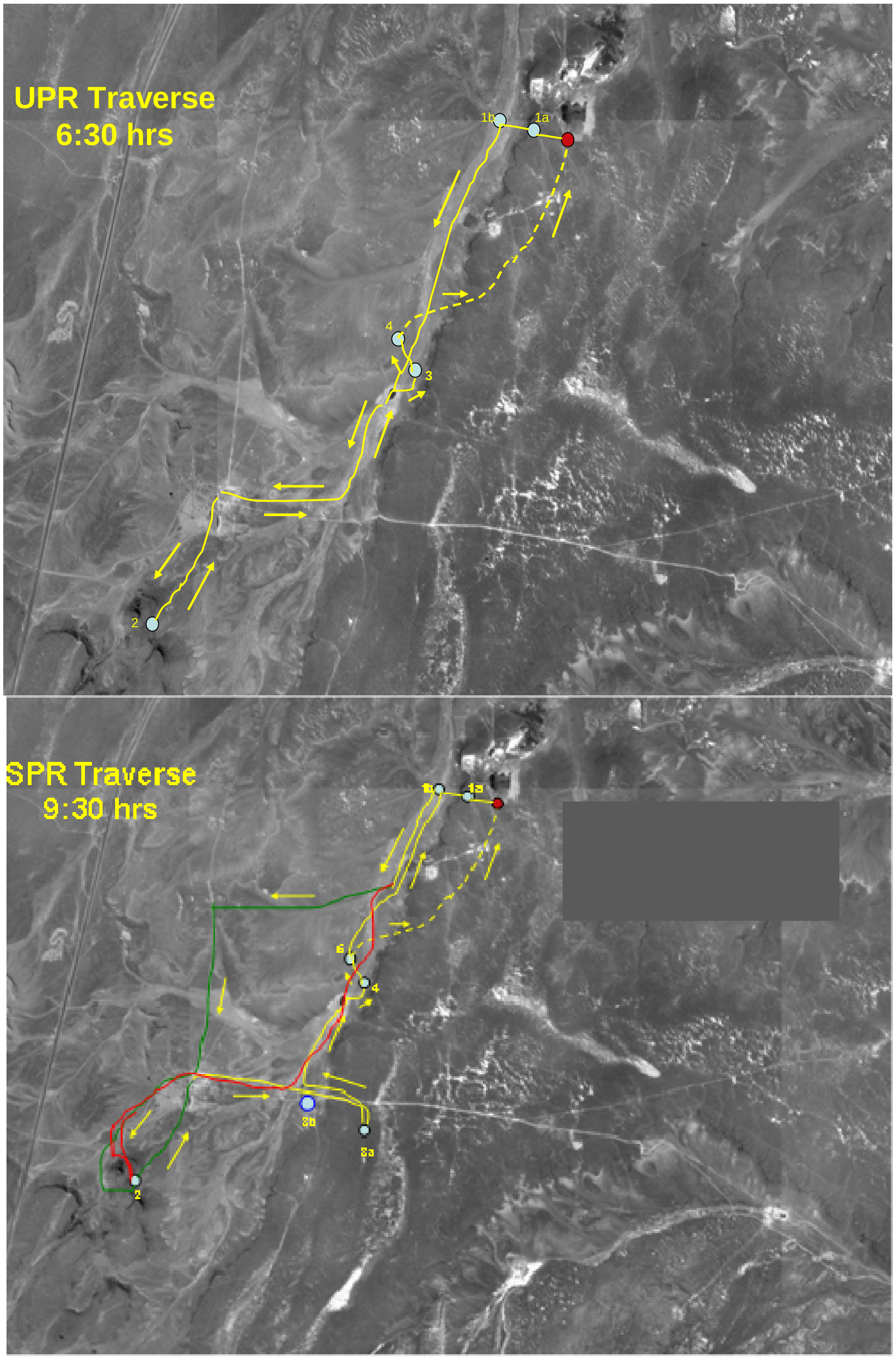
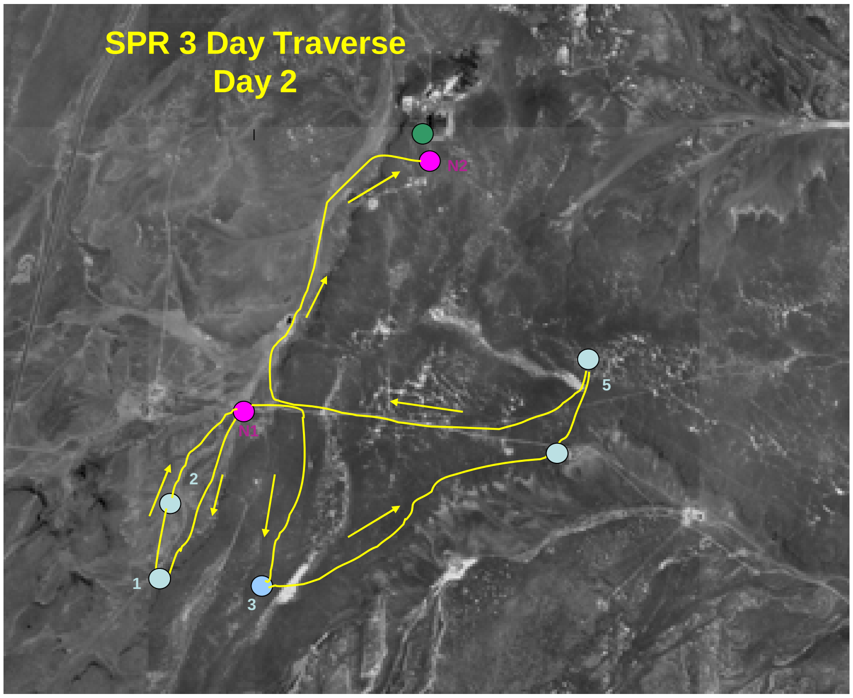


Figure D3: 1 Day UPR and SPR traverses; note the addition of Station 3 for SPR over that of UPR. Initially, the SPR traverse was laid out along the green line, which however was not doable because of too many fences; the red line suggests the fastest way back to base camp, in case of unforeseen delays. The actual traverse followed the yellow line with the exception of Station 2, where the green line was followed. This traverse constituted Day 1 of the long duration (3days/2 nights/56 km total travel) tests, yet SPR back tracked S (rather than towards base camp) from Station 5 for an overnight stop close to the blue spot (see Fig. 4).



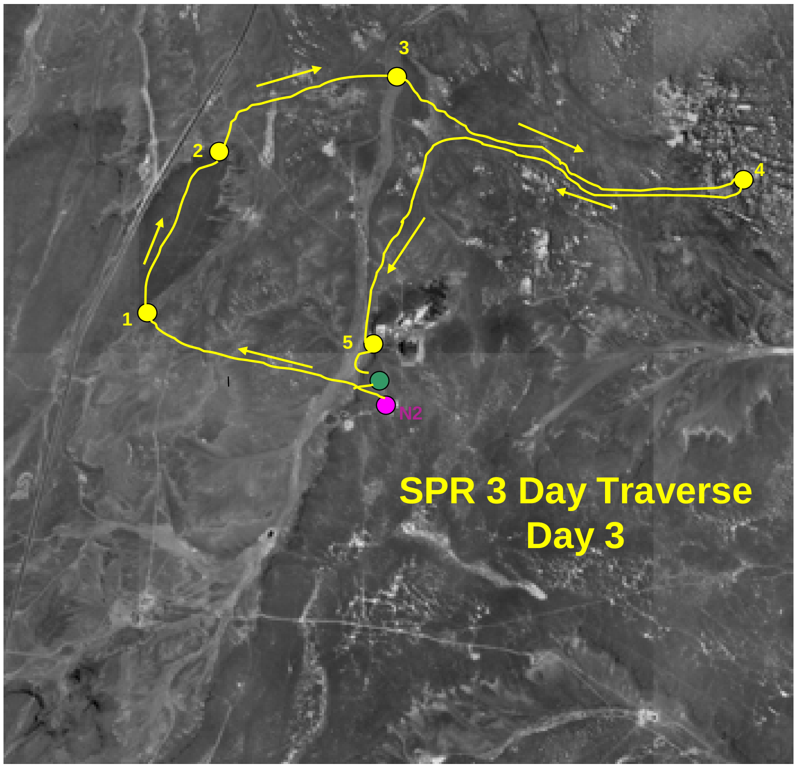


Figure D4: Traverses of Day 2 and Day 3 for the long duration (3 days/2 nights/covering 56 km) SPR tests; overnight camps are depicted in pink as night 1 (N1) and night 2 (N2).

INDIVIDUAL REPORTS:

MARY CHAPMAN

UPR/SPR Field Tests

Field Observer Comments for UPR, B:
Distances were hard for the subjects to judge, but overall the exercises went well. Bagging the samples seemed hard for all the crews each day including this one. The suit subjects were unable to walk the contact of the BPLF to find the pepperite at the base (10 feet away)—because of end of the day fatigue.

Field Observer Comments for UPR, A:
There were numerous problems with sound systems on this day (people talking over each other etc.).

Col, A Comments for SPR, B: This task was basically to make sure labels on sample bags were written down as they were received over the comm. system, keep track of timing between Engineering Capcom and training team, and observe the PI & CapCom. Not too much change in performance of the crew from the previous day.

PI, Comments for SPR, A day 1: This task was to keep track of cameras, take images as needed, and make science requests for CapCom to pass onto team. I thought the team did very well and even located a contact of BPLF with little coaching. There were lots of technical difficulties with cameras and sound systems on this day. Most of the day we were without suit cameras. Crew A took a different route and split up a bit to cover territory.

CapCom Comments for SPR, day 2: This task was to pass on requests from PI and Science team to training crew. I think the day went well, even when the crew got out of comm. range they were still able to function very well. This was one long day though, with some vehicle problems at the end of the day. The crew made some very good observations and interpretations on the top of the flow on this day.

Field Observer Comments for SPR, day 3: Short day, the crew performed very well. However the backroom left them very little rope for making their own decision, requesting pinpoint stratigraphic data on flows to the extent that the crew was overlooking very important inclusions/fabric of lava flow surface. I believe the crew would have performed better with less backroom requests.

SPR Science Test: I was very impressed with the SPR performance, the view from the bubble when SPR was lowered was excellent and the saving for human excursion was impressive. However, some cliff surfaces were out of reach because of large boulders obstructing the way of the SPR and the ergonomic space to get in and out of the floor bubble was awkward and tight.

My final comment is that it would be great if the Science Team had the ability to pinpoint objects and locales on the computer screen images of SPR & suits for transmission to the training crew, so the crew could route themselves onto requested targets.

DEAN EPPLER

TRIP REPORT:

This was a very impressive test, easily the best test since Joe Kosmo first took hardware to the desert in 1998. The things that stand out the most were having a limited, well-defined set of test objectives, participation by individuals and hardware limited to those groups and machines that would support those objectives, and very hard work by all the support people to be able to pull off the test. In the latter category, everyone stood out: Joe Kosmo and Barbara Romig for organizing and directing the effort, all of Rob Ambrose's people for support all the Chariot and SPR activities, Fred Horz and his entire science team, the SPR team under Mike Gernhardt and Andrew Abercromby, the communications folks under Mark Seibert that got the comms working, and Zane Ney and his folks for doing valiant data gathering on the operations in real-time.

Some specific comments as follows:

Suits – the suit mockups purchased from Global Effects probably worked as well as they could under the circumstances, but they were clearly not designed for such hard work under difficult environmental conditions. Having said that, they provided a good data set on the differences between using an unpressurized rover and the SPR, something that I was skeptical could be done from a limited run in one of the suits. The suit techs are to be commended for their heroic efforts to keep suits up and running. One issue I did note is that the accommodations in the suit necessary to test the ability to self-don in the SPR put a significant strain on the suit subjects, considerably more (in my opinion) that a real pressure garment would have. I think this was necessary for this test, but having proved the point, I think we should devote some time to figuring out a method of allowing a shirtsleeved subject to interface with the suit port hardware (for example, something similar to a conventional packframe with the appropriate interfaces that allows crewmembers to operate out of the SPR) without putting the unnecessary strain on the subjects. Something like this was developed to use in the Apollo geology joint-integrated-simulations (see attached photos) so the crew could practice with volumetrically and procedurally accurate hardware without the physical strain of a full A7LB and PLSS. I think some effort should be put into developing this kind of concept before the next field test, as I'm certain the SPR will be with us for some time.

SPR – Great vehicle, great concept. The SPR team is to be congratulated on putting together such a complete, functional mockup in such a short time. Its ability to do reconnaissance operations is unmatched – I think this is one of the best new approaches that has come out of the LAT process. The one issue I have with the vehicle is that while it provides a great platform for reconnaissance activities, the complicated geology of the Moon will still require boots on the ground work. The best illustration of this is that during the week I was on site, no rover crew accurately identified the location and altitude of the contact between the Blackpoint Lava Flow and the underlying member of the Moenkopi Formation. Identifying contacts is a critical activity in geology, and one that we will need to be able to do on the lunar surface. The disposition of considerable Blackpoint boulders on the slopes made finding this contact difficult, but it was possible to find it by doing what Dave Kring described as "looking for rattlesnake kisses." Finding this contact required a close-up inspection of the slopes that the SPR was not able to provide, and could only be done by getting out of the vehicle and walking the slopes until that contact could be established. This is something we will need to work into future field operations. Having said that, the SPR worked superbly, and it clearly will allow the crewmembers to do the initial reconnaissance in low-stress comfort so that, when they do egress and do the detailed geology, they will be more apt to make good observations.

Chariot – Again, great vehicle, great concept. Several things were very impressive to me: first, the ability of the vehicle to go into country that only the HumVee could adequately follow in; second, the robustness of the vehicle in spite of the punishment it took, and third, it's ability to be fixed without complicated procedures and tool sets, and to operate in degraded modes that still allowed the mission to be completed.

Science Operations – The science operations setup that Fred Horz and Gary Lofgren came up with worked very well, in my opinion, far better than we have been able to do in the past. I think it worked well because it had limited staff, and the positions rotated so each team member worked the back room and got into the field with the crewmembers. Some science operations practices that the crewmembers devised that "bleed over" into general operations need to be noted: first, parking the SPR facing the worksite the suited crewmember(s) will be working so that they can be observing and coming up with detailed plans was a great practice; second, conducting solo EVAs with one crewmember out, one in worked very well and should be part of the standard operations on the lunar surface; third, the use of a high resolution suit-cam that the backroom can do frame-grabs from proved to be extremely useful, both for backroom situational awareness, and for removing some of the documentation workload off the crewmembers.

Anyone that has any specific questions, please feel free to contact me.

Dean Eppler

SAIC-Constellation Lunar Surface Systems Office/Planetary EMU Crash Test Dummy (otp)
281-244-8216/dean.b.eppler@nasa.gov

Note from Eppler, dated 11/5, to Science Team:

The one point I'd like to make, relative to the science activities, is that one of the most important things one has to do in the field geologically is establish the geographic location of contacts. For the two SPR and two UPR runs, nobody ever established that contact, and at least one subject had a completely wrong impression of where it was. I was able to get close to it on a couple of occasions doing what Dave so aptly called, "kissing rattlesnakes", and it was not near where one would guess, based on the view from either SPR or UPR. I think we need to call out that particular point in our evaluation, to emphasize that the only way to find many kinds of geologic data is by getting out and poking around at a detail you cannot do by remaining in a rover.

FRIEDRICH HORZ

Science Related Impressions

Positive:

- The SPR/UPR is an amazingly nimble vehicle with outstanding terrain capabilities and excellent range and speed, far better than the Apollo rover.
- The SPR cabin allows for essentially unobstructed (> 180^0) views of the surrounding geology, including surface details (through the curved front window, a feature that must be preserved, yet I am not sure whether the "bubble" is really needed). The elevated viewing position in the cabin is highly suited for "float-mapping," the dominant mode of operation on the Moon because of crater ejecta.
- The SPR allows for longer ranges/more mobility than UPR, yet total "boots on the ground" time is only modestly longer; crew reports that shirtsleeved driving is a welcome reprieve from wearing the cumbersome suits during long station times.
  Thus SPR and suit port concept seem highly beneficial for science ops.
- One man EVAs on short stops seem promising, as is independent rock sampling by individual crews; these 1 man science-activities seem desirable, yet they need extensive practicing and associated procedures.
- Suited geologists in the field added considerable realism to these tests
- The SPR video cameras (mast; aft; bubble) are excellent and highly informative
- The suit mounted video cameras with still capability are very useful and a "must."
- Audio communications were excellent; the video stream suffered on occasion from camera-related failures.
- GPS navigation was excellent, accurate, and of great help to back room.
- The interaction of the "science" capcom with the "mission control" capcom was excellent and should be implemented during real lunar missions.
- "Can Do" team spirit was omnipresent and Apollo-like.
- Overall: this was a highly focused campaign; general operations proceeded nominally along well-perceived plans; most test objectives were accomplished, some exceeded. By comparison, Moses Lake was somewhat disjointed as too many tests/operations of diverse systems took place simultaneously.

Negative:

- Suit mounted video cameras failed too often; must be redesigned/ruggedized (note: kudos to the KSC folks involved in developing this capability with off the shelf hardware and software that were not intended for demanding field work).
- EVA tools and tool pallet were of low fidelity and must be improved; this includes provisions to attach diverse tools to the suit while EVA, especially for single man operations.

- The utility of the extensive/cumbersome Apollo-photodocumentation –including the gnomon device- must be reevaluated in view of the video capabilities which seem adequate to document the sampling process.
- Traverse planning could have been better re. trafficability, fence crossings etc; an advance team should have visited the site to lay out the final routes; some of this had to be done in real time and associated modification of existing traverses distracted from other activities.
- Science back room seemed understaffed (3 folks for 5 cameras etc), yet placing the science back room into the field (rather than Houston) was very beneficial.

SUGGESTIONS/LESSONS LEARNED:

Minor:

- Redesign surface tools and their mounting on tool pallet and suit
  - Larger rover-mounted bag to deposit all collected samples
  - Less friction in tongs; make second tong for independent EV1 and EV2 ops
  - Better mount for individual sample bags on suit
  - Better mount for sample collection bag (black nylon bag) on suit
  - Possible mounts/tethers for tongs and hammer on suit
  - Fixed mount of still cameras (if used) on suit
  - Ruggedize video suit cameras
  - Practice, practice, practice the use of tools and associated procedures

  A number of committees are looking into these general issues and need our collective input, notably CAPTEM.

* I was somewhat reluctant to buy into the quantitative evaluation of "science productivity" as it is an intrinsically difficult task, possibly flawed by subjective judgments; however, there was an unusual degree of internal consistency (identical traverses; identical personnel; well understood criteria etc) during these tests and I think the numerical rankings will be meaningful.

Major:

- Develop operational concepts and requirements for Science Back Room
  The advent of real time, digital imagery will make for dramatically different back room operations compared to Apollo; details need to be worked out.
- Hybridize UPR/SPR by advancing the "cheap seat"- concept to include the ability to drive the SPR externally, while suited.
- Provide for some mechanism external to SPR, most likely at the front that can grab rocks and soil samples while the crew is inside and shirtsleeved.
- Instrument assisted "high-grading" of rocks, such as via handheld XRF, IR or Raman devices, may be difficult to accomplish in real EVA time, as these analyses typically take minutes to complete, a rather long time compared to crew activities and observations (the crew is quickly on to another rock or topic; the back room was frustrated that it took a long 5 sec to capture and display a still-image). Point is:

instrument assisted highgrading seems most profitably done during sleep times etc. Efficient use of SPR suggests that considerable thought go into the design/development of rover-mounted analysis capabilities, such as close up photo-station, XRF or IR/Raman etc. Rocks that turn out to be duplicates/ uninteresting can be tossed by the crew, once EVA. I do not think that instruments taking longer than a minute to produce analyses should be carried by the crew.

DAVID KRING

Evaluation of Science Operations

Top-level Evaluation

- The science team was an excellent mix of Apollo-era geologists, mid-career lunar geologists, and students. The group provided experience with procedures that work, lunar-relevant geology, test-site geology, and exposure to new technical capabilities.
- The entire simulation team was excellent. The program managers identified people with the technical capability and can-do attitude needed to move the program forward in a substantive way.
- Collectively, the simulation integrated a broad range of expertise (for example, astronaut office, suit specialists, rover specialists, mission operation specialists, communication specialists, crew trainers, and geologists) to produce a realistic simulation and, thus, much better results than available previously. The outcome of the simulations verifies several of the conclusions in a previous report[1].
- It became clear that realistic lunar surface operations involving lunar-like geology affect traverse activities and, thus, need to be part of future simulations so that accurate accounting of traverse timelines, consumables, and crew exertion in different suit-rover combinations can be made.

Black Point Simulations vs. the Moses Lake Simulation[2, 3]

- The flight rules were much clearer in the Black Point simulations, greatly enhancing the flow of activity throughout the simulations.
- Having the science backroom in an on-site field trailer is much more productive than at a distant location. It provided the backroom isolation needed during a simulation, while facilitating communication with all other team members to upgrade operations during an extended (2-week) series of tests.
- Good traverse timelines are essential. This was a lesson-learned from the Moses Lake test of June 2008. The Black Point simulations demonstrated that a detailed traverse timeline provides a more realistic test, including serious trades between objectives when issues (like hardware problems or an unexpected science discovery) occur during a planned traverse.
- A geologist on the crew greatly assisted in station activities and the crew's ability to implement changes in planned activities that the local geology may dictate.

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[1] Developing a Concept for Astronaut Training and Analogue Studies for Lunar and EVA Surface Operations. Report from David A. Kring to Wendell Mendell, Constellation Systems Program Office, 22 September 2007, 5p.

[2] Science Operations during the Moses Lake Field Test, 9-12 June 2008: Perspective from the Science Backroom, JSC Bldg 9. Report from David A. Kring, 1 July 2008, 4p.

[3] Geologic View of the Moses Lake Test Site Based on K-10 Red Rover and Crew EVA Observations: Preliminary Report. David A. Kring, 1 July 2008, 5p.

UPR vs. SPR

- SPR is easier on crew; the crew had more energy at stations when traveling in SPR and, thus, was more productive at each station.

SPR vs. Geologist in Shirtsleeve

- The view from the SPR is very good. I saw most of the features seen in shirtsleeve at the scale of outcrops and individual rocks, although I was unable to rotate the latter in the light to better evaluate crystal morphologies.
- The SPR was nearly as good as shirtsleeve in the limited test site, but the result will be highly dependent on the complexity of the topography and geology. For example, I stepped over small vertical outcrops that were impassable for the SPR.
- The biggest difference between the two methods is reaction time. If I needed to turn to modify my view or walk in a different direction, I can implement that change immediately in shirtsleeve. In the SPR, there is a built-in delay needed to communicate an action to the commander and for him to make the mechanical adjustments needed to change the SPR's motion.

Operational Lessons Learned from the Black Point Simulations

- Rover imaging is critical to the success of the science backroom and its capability to advise crew with traverse activities. It provided the backroom, for example, the capability to examine the geologic context of a station and, thus, direct crew when they were inhibited by the "tunnel vision" that can occur within helmeted suits.
- If the SPR is oriented correctly at each station, EVA crew (and science backroom via video) can evaluate the station during the suit egress sequence.
- Suit video is also critical: it provided immediate documentation of sample context and the samples selected.
- A navigational GPS tracking tool should be available to the science backroom to maximize the value of its interaction with crew and adjust traverse activities if needed. A window with current crew position data on one of the two Science PI monitors will also help future simulations.
- Better science could have been accomplished by the crew if they were trained for that particular type of geologic site. In this case, a 3-hr training field trip to the nearby SP crater and lava flow would have enhanced crew capability during the UPR/SPR tests.
- Rotation of science team members through the positions of Science Capcom, Science PI, Science Co-I, and Field Geologist was very good. Not only did it provide an opportunity for cross-training and different perspectives, it also kept the team fresh over the course of a 2-week test with extensive overtime hours.
- Situational awareness and capability to multi-task are critical skills for the Science PI and Science Capcom.

- A new traverse option was identified: EV1 can scout a second station in SPR, while EV2 is conducting sampling and other EVA activities at the first station.
- Potential new rover tools: (i) A telescopic imaging system might assist crew on a rover and (ii) a robotic sample manipulator or rake with controls within SPR might assist crew when EVA is not an option.

GARY LOFGREN

Overall impression: This was an engineering performance test of two rover concepts, unpressurized (UPR) and small pressurized (SPR). The rover and a support crew of 10's of people provided the core of the exercise and they performed well keeping the rover working over very difficult terrain for the entire exercise. This was an engineering activity supported by mission operations people and evaluated by human factors people. The goal was to contrast the different modes of operation between the two rovers concepts and their relative merit. That goal appears to have been achieved.

Rover Operation and design: The rover is a complex machine designed to replace the Apollo Lunar Rover and it does that very well; I was very impressed with its capabilities. The rover in either of its configurations was able to traverse without difficulty very rough terrain littered with large, angular basalt boulders and steep slopes that stopped all but a Hummer. I found both the UPR and SPR to be functional and well thought out concepts. The standing position on the UPR was a surprise, but once explained and observed in operation was found to be a logical design. The supports that hold crew in place relieves them of much of the weight of their suit while they move. The only disadvantage I could see was the increased distance between the eyes of the crew and the ground. A forward looking camera with a display for the crew positioned like the bubble camera on the SPR (see below) would help the crew with a close-up view of the surface and the rocks thereon. The SPR design and concept has definite advantages. The crew has more EVA time for doing geology and drives between stations are done in shirtsleeve comfort. The EVA can be planned from the inside in conjunction with science support from an outpost or an Earth bound science support team. Clearly the 8 hours of EVA time can be used more effectively so that more time is spent doing science. I did an observation exercise from within the SPR and the visibility is superior as currently designed (hopefully that level of visibility can be maintained in the lunar version). The SPR had 5 video cameras, one on a mast that stands above the rover and has a 360 rotation; it is perfect to follow the activities of the crew. There is a camera in the bubble low and in front that points straight ahead and gives a good constant view forward and can be turned down to image a rock. There is a rear camera that functions mainly as an operations camera to watch the crew enter their suits, but gives a rear view when needed. The mast camera can also give a rear view.

Astronaut performance: For this exercise a trained geologist was teamed with an astronaut for the two person crew. Considering the lack of science training possible before the exercise, this provided a crew that could deal with the science in a meaningful way. Minimal training was given in the use of the geologic tools, which mimicked the Apollo tools, and sample collection techniques and documentation. It was noticeable how quickly the astronauts picked up the science from the geologists. The natural observation talent of the astronauts was also evident. Developing the common vocabulary, as was one important training activity during Apollo, was the obvious limitation. The enthusiasm for the activity was obvious. I think most people become so when learning more about the ground under their feet.

Science operations: My contribution was to help provide the Science reality of the exercise. The Chariot team wanted scientifically realistic traverses with science objectives of varying value and traverse stations of relative importance. They wanted to be able to grade the quality of crew performance in the UPR vs the SPR and needed basis for that evaluation.

Science objectives and Traverse planning: The first step was to find a location that provided challenging terrain and interesting and reasonably complex geology. The Flagstaff location near the Black Point lava flow is such a site. There are several geologic objectives of varying importance (dependent most on the point of view of the planners) that allows the definition of objectives of different value so that stations and station activity can be prioritized and their successful completion graded. We developed Apollo style traverses based on photo-geologic information and a produced a traverse map on such a photo base. A broad designation of overall science objectives for the area led to detailed traverse planning. Stations were chosen to provide the information necessary to answer the questions that met mission objectives. Nearly identical traverses were created to compare the effectiveness of the two different crews and to compare the UPR with the SPR. The crews were given overall site briefings and detailed station by station briefings on each traverse.

Science operation: Science operations attempted to simulate all aspects of science support for a mission. Four scientists participated throughout the 2 weeks, Horz, Kring, Chapman, and me. Eppler was there the first week and Rice and Lee (the latter after completing suited geologist activity), the second. Two scientists moved with the crews in the field and the remaining scientists provided the science backroom (SBR). Roles were rotated so that all scientists were both in the science support room and in the field. In the back room the responsibilities were rotated between being the science PI, support to the science PI, and the science capcom. Evaluations of the crew performance were completed from the point of view of the field observer and the SBR. Based on my Apollo experience, this was a very realistic science activity.

Having a science capcom that worked with a mission operations capcom was not something done on Apollo, but worked well in this exercise. Such close communication with the crew would be nice to have in the real case, if possible. Apparently this is done for station and for this exercise that was the model. The video cameras available on the SPR and the astronauts provided a marked improvement over Apollo video and clearly need to be the goal for this second exploration of the Moon. The suit cams allow the scientists to see what the astronauts were seeing. The cameras had the provision for the SBR to capture stills at their discretion and proved to be useful for documentation of samples collected and their setting. Collected samples could be held up to the camera for a close up. A mast video camera on the SPR allowed the SBR to follow the crew much as the TV camera on Apollo, but with much improved image quality and control.

Lessons learned: It is clear that the methods of sample documentation and general observations of the crew will be entirely different this time and deserve careful thought. For example, each camera on the Moon will require a single SBR person to accumulate the images and evaluate their content. The images will be an incredibly important resource and will need to be indexed for quick retrieval. The possible access to near real time imagery will allow much more meaningful interchange between the crew and the SBR both in real time and for near future traverse activity. This interchange could lead to effective high-grading during collection or at subsequent stations on a single traverse. The dominant rock types could quickly be established and then immediate recognition would be possible by the crew with some briefings from the ground. An XRF tool would serve us well to supplement the high-grading efforts. One point became clear, the gnomon needs to go and we need to find a way to capture the information provided by the gnomon that is necessary in other ways. Jack Schmitt has commented often about how onerous the documentation procedures were. Many things done for Apollo, however, will not change. The basic training should be the same, that is, to create the common science vocabulary and comfort with routine activities.

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13. ABSTRACT *(Maximum 200 words)*

A system of two or more Small Pressurized Rovers (SPRs), also referred to as Lunar Electric Rovers (LERs), is an integral part of NASA’s plans for returning humans to the moon. In the SPR concept, each vehicle includes a small pressurized cabin to safely sustain two crewmembers on the surface for 14 to 28 days. Through suit ports, crewmembers may rapidly egress and ingress the cabin for EVAs. In addition to achieving a surface exploration range that is potentially orders of magnitude greater than what was achievable during the Apollo Program, the SPR concept offers many other benefits, particularly with respect to the health, safety, and productivity of crewmembers.

The primary purpose of the DRATS 2008 field test, at Black Point Lava Flow in Arizona, was to objectively and quantitatively compare the scientific productivity and human factors during 1-day exploration, mapping, and geological traverses performed using SPR and Unpressurized Rover (UPR) prototype vehicles. The habitability, human factors, and performance characteristics of the SPR vehicle and crew were also recorded throughout a high-fidelity 3-day lunar traverse simulation.

Quantitative assessment of crew productivity by on-site expert field geologists found that compared with UPR traverses, the same crewmembers were 57% more productive during SPR traverses and used 61% less EVA time. The habitability and human factors of the SPR throughout the 3-day traverses was acceptable, although suggested modifications to several vehicle subsystems were identified in the assessment.

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