Habitability Lessons Learned from Field Testing of a Small Pressurized Rover

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Abstract— **From 2008 to 2010, the NASA Small Pressurized Rover was tested in the Arizona desert in anticipation of human lunar surface missions. These tests were multi-day mission simulations with crew living in and conducting simulated lunar surface EVAs from the rover prototypes for 3, 7, or 14 days. This two-person surface spacecraft represents a departure from most previous lunar architectures, which either featured Apollo-class unpressurized rovers or large pressurized rovers – in some cases up to the scale of being considered mobile outposts. This paper will discuss the history of the Small Pressurized Rover, some of the values of field testing, the rover's design evolution including the two prototypes tested in the field, key features and advantages of the SPR, the field test site location, the 2008, 2009, and 2010 field tests, habitability lessons learned from the testing, comparisons with follow-on laboratory/high bay testing, and recommendations for third generation rover design and flight vehicle development.**

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1. INTRODUCTION

Apollo Lunar Rover Vehicle (LRV) S History

Severely limited suit mobility led NASA to develop a lunar surface mobility aid requirement in the Apollo program. The proposed requirement stated the vehicle had to be capable of carrying two full suited astronauts, fit between two legs of the lunar module and have an unloaded weight of no more than 181.4 kilograms (kg) (400 pounds) [1]. It also had to be delivered within 18 months of the awarded contract. The solution was the Lunar Roving Vehicle (LRV). Boeing Aerospace Group won the contract in October 1969 and delivered the LRV on March 10, 1971, two weeks ahead of schedule [1]. Three flight vehicles had been built with an additional seven test and training units, spare components and related equipment [2]. It took a total of 13 months from concept to final product (Figure 1).

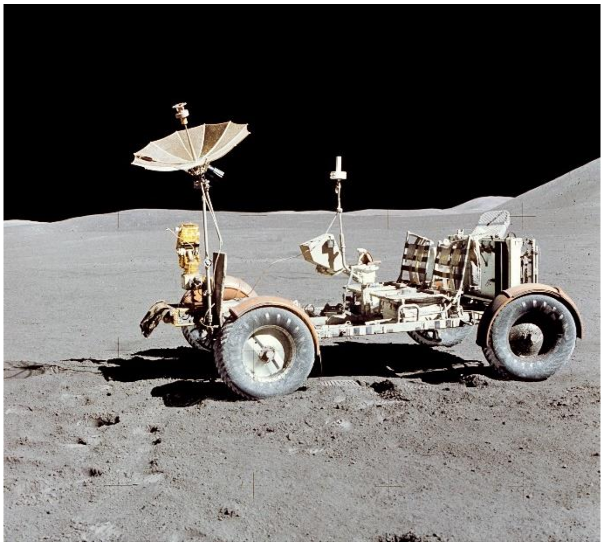

Figure 1. The Boeing Lunar Roving Vehicle (LRV).

The LRV measured 310cm (10 feet 2 inches) in length with a 183 centimeters (cm) (6 foot) tread width; a wheel base of 229cm (7.5 feet) and a height of 114cm (44.8 inches) [3] To provide the vehicle's power, two 36-volt batteries were employed. The wheels were individually power by a quarter-horsepower electric motor, giving the LRV a top speed of 13 kilometer per hour (kph) (8 miles per hour) (mph). Though weighting in at 27.2 kg (60 pounds) heavier than challenged (total weight of the LRV was 209 kg (460 pounds)), the vehicle could carry a total payload weight of 490 kg (1,080 pounds). The LRV was designed to operate for 78 hours during the lunar day with a range of 65 kilometers (40 miles) [2]. However, due to the limitations of the astronauts' portable life support system (PLSS) the vehicle's range was restricted to 9.5 km (6 miles).

The LRV flew on Apollo 15, 16, and 17. During each mission, the vehicle was used on three Extravehicular Activities (EVAs) totaling nine lunar traverses and allowing the astronauts to explore four times more lunar terrain than in the previous Apollo missions (Figure 2). Apollo 15 astronaut Dave Scott put it best stating, "*I think the vehicle is about as optimum as you can build.*" [4]. LRV performance parameters table for all the Apollo missions are in Table 1.

Figure 2. Commander Eugene Cernan driving the LRV during Apollo 17.

Table 1. *Lunar Roving Vehicle (LRV) Performance*

Parameters	Apollo 15	Apollo 16	Apollo 17
Total Driving Time (hr:mm)	3:00	3:19	4:29
Total Distance (miles)	17.3	16.5	21.6
Average Speed (mph)	5.8	5.0	4.8
Max Range from LM (miles)	3.1	2.8	4.7
Longest Traverse (miles)	7.8	7.0	12.6
Rock Samples (pounds)	170	213	249

Courtesy [5]

Unpressurized Rover (UPR) History

In January 2004, U.S. President George W. Bush tasked NASA to resume missions to the Moon and then to Mars by the 2020s. The program was named Constellation and consisted of a crewed spacecraft, a class of launch vehicles, and a lunar lander [6]. NASA was also challenged to establish a sustained human presence to promote exploration, science, and commerce [7]. Further refining their plans, NASA quickly became aware that surface mobility would be critical to the buildup of lunar surface assets and surface mobility would be needed to enhance lunar exploration activities. Much like the days of Apollo, NASA's Lunar Architecture Team (LAT) and Exploration Technology Development Program (ETDP) identified a range of vehicles for lunar surface operations.

The vehicles ranged from small (100kg) (220.5 pounds) robots to be used as crew aids to very large robotic carriers capable of transporting a lander [8]. Within this range emerged a lunar rover that is capable of moving suited crew and cargo. In 2007, NASA's Exploration Technology Development Program starting investing in a wide range of mobility assets for planetary surface exploration. An engineering design team at Johnson Space Center (JSC) developed a prototype surface mobility asset, which could carry two suited astronauts, called Chariot (Figure 3). Chariot was an unpressurized rover with six pairs of wheels, active and passive suspension, battery power, and control and navigational electronics. The vehicle was designed as a multi-purpose lunar surface device that could be reconfigured with multiple modes of operations such as direct human control and teleoperation from a habitat, lander, orbiting spacecraft, or ground personnel back in Houston. With the right attachments and/or crew accommodations, the Chariot was able to serve a multitude of functions such as cargo carrier, human transport, cable layer, mobile habitat, and regolith mover [8].

Figure 3. The Chariot chassis concept.

2. SPR DESIGN HISTORY

NASA engineers developing the Chariot, also known as the Unpressurized Rover (UPR), realized that the spacesuits placed an inherent limitation on the crew's ability to utilize the rover. As previously noted, the rover traverses are limited to the time the crew can spend on a Moonwalk. The traverse times between a habitat or lander and areas of scientific interest further consumes significant portions of this time. As they continued to develop the UPR, the team also began to explore the idea of a small pressurized rover (SPR).

Small Pressure Rover (SPR) Initial Functional Requirements

The following are the original eleven initial SPR functional requirements that emerged to guide the initial development of the vehicle concept:

- Vehicle mass, not including mobility chassis, shall be ≤ 2,400 kilograms (kg) (5,291.1 pounds).
- The vehicle shall have a nominal velocity of 10 kilometers per hour (kph) (6.21 mile per hour (mph)).

- Vehicle habitable volume shall be approximately 10 cubic meters (m³) (353.14 cubic feet (ft³).
- The vehicle shall have the ability to augment power and consumable ranges and duration to achieve a range [traverse distance] of ≥ 1000km (621.4 miles).
- The vehicle and systems shall be powered-up and checked-out, including suit/Portable Life Support System (PLSS) power up and checkout, in ≤ one hour.
- The vehicle shall mate/de-mate from a habitat or lander in ≤ 10 minutes with ≤ 0.03kg (0.66 pounds) gas losses.
- Driving the vehicle with naked-eye visibility shall be comparable to walking in a suit (i.e. eyes at same level with a similar field-of-view (FOV). Vehicle visibility can be augmented by multi-spectral cameras/instruments to further improve FOV.
- Vehicle visibility shall have visual accessibility to geological targets comparable to Extravehicular Activity (EVA) observations (i.e. naked-eyes ≤ 1 meter from the target. This may also include the possibility of magnification optics to provide superior capability over EVA observations.
- The vehicle shall accommodate suit don/doff with egress/ingress For suit operation with EVA suit prep completed and human at suit port hatch, time shall take ≤ 10 minutes to complete task with ≤ 0,03kg (0.66 pounds) gas losses per person and ≥ two independent methods of ingress/egress.
- The vehicle shall accommodate twelve two-person EVAs at a 200 km (124.3 miles) range [from lander or habitat] with a nominal consumable load.
- The vehicle shall provide for PLSS recharging to take ≤ 30 minutes.

The initial requirements were intentionally kept small to allow the design team freedom to innovate.

Initial Sketch Concepts

The SPR was born through a series of brainstorm meetings and design sketches, with sketch concepts evolving as shown in Figures 4, 5, and 6.

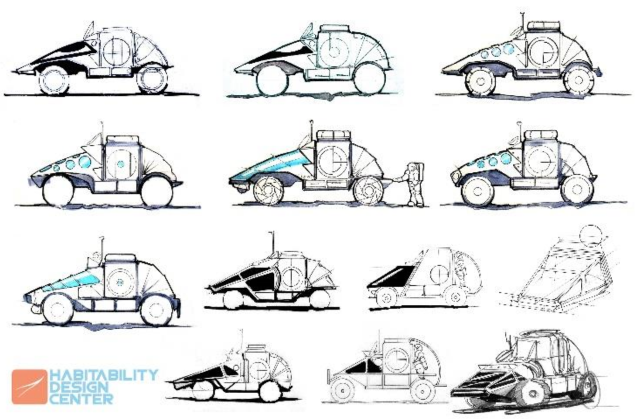

Figure 4. Early Concepts for the SPR.

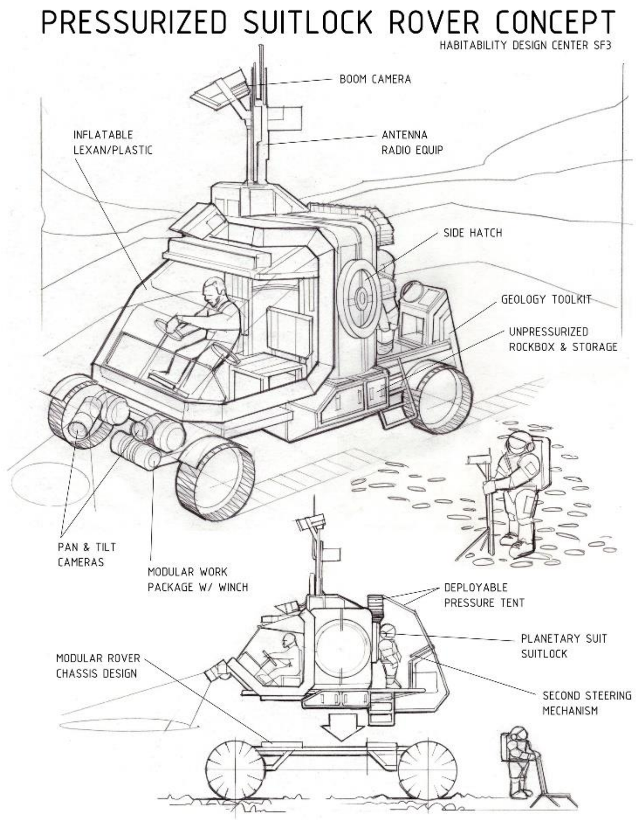

Figure 5. Early Concepts for the SPR.

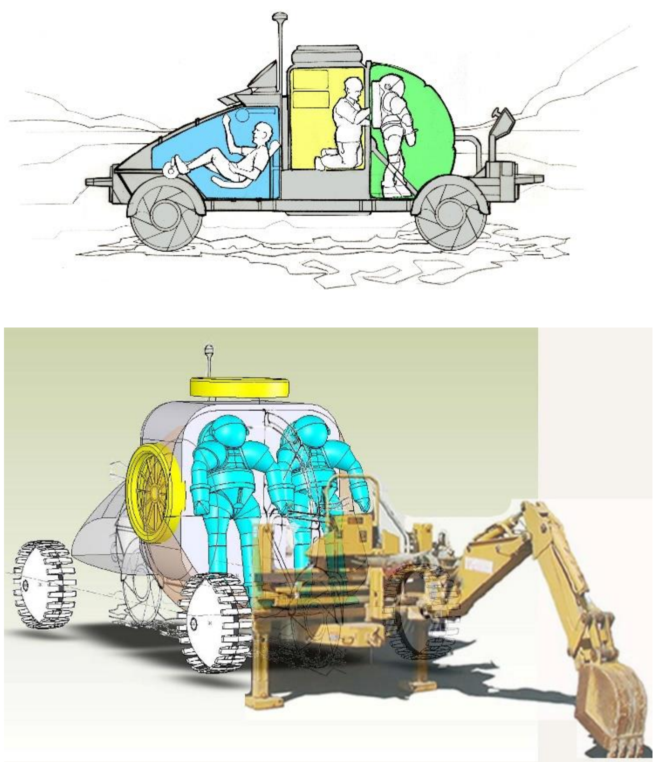

Figure 6. Early Concepts for the SPR.

Early Low-Fidelity Conceptual Studies

In January 2008, the first SPR conceptual study was conducted in the Space Vehicle Mockup Facility (SVMF) at Johnson Space Center (JSC) in Houston, Texas (Figures 7 and 8). With a low-fidelity, corrugated plastic and wood mock-up based on a Computer Aided Design (CAD) concept model, an initial functional volume test of sixteen dynamic tasks was used to collect preliminary human data on the habitable volume of the lunar rover. Tasks included: normal driving, driving using lower bubble, system monitoring, observational viewing using upper bubble, configure workstations for crew meetings/planning, configure for exercise, configure for sleep, storage, meal prep/group meal/cleanup, human waste management ops, configure for incapacitated crewmember, prep for dust removal, intravehicular activity (IVA) maintenance during deployment, IVA maintenance during docking; configure for sample testing/analysis and logistic resupply. The data collected suggested the habitable volume for the current rover configuration was acceptable for a three-day mission; however, some concern about a fourteen-day mission was expressed. Concerns mainly dealt with the stowage of the Environmental Control and Life Support System (ECLSS) and EVA spares needed for a longer mission as well as the containment of consumables and human by-products.

Figure 7. The first low-fidelity conceptual lunar rover mockup in JSC Building 9.

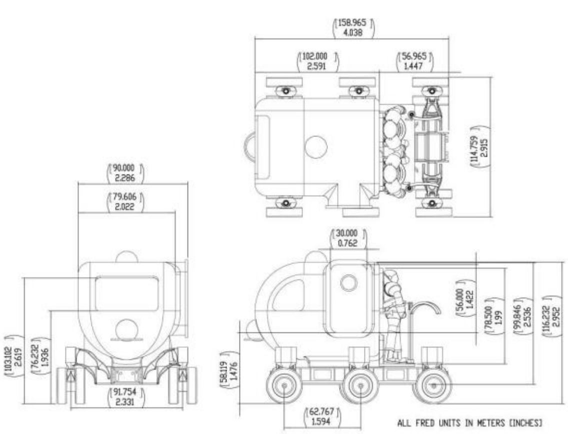

Figure 8. Dimensions of the first conceptual lunar rover.

Geometric design and some structural issues were considered borderline. The curvature of the front and side walls were uncomfortable due to incorrect ergonomic placement of the seats. Viewing from the lower bubble requires a prone position, which was uncomfortable. Redesign of vehicle structure would greatly improve crewmember performance. A lower front window along with helicopter-type side windows positioned near the feet, would improve the near field of view while in the driving position. Reduction of blind spots using cameras or mirrors and adding a rear window for rover tracking could increase situational awareness of the lunar surface environment. Displays and controls need to be portable, adjustable, and lightweight. Some type of automation was requested as well as simplicity to reduce control station clutter. Data analysis revealed that a new cabin design was needed due to excessive reconfiguration required to complete the sixteen tasks.

By March 2008, major design modifications to the vehicle configuration were made and a wood and foam core mockup was constructed (Figures 9 and 10). The same sixteen tasks were used to judge the required functional volume in the second iteration. The data collected suggested when comparing the two rover configurations, configuration two had better definition of volume and workspace. The layout was more efficient which improved predicted mission duration acceptability to 15-days over the earlier design. The redesigned vehicle cut the reconfiguration of the cabin to almost nothing. There was a more "open" feel to the interior volume with configuration two as compared to configuration one due to the better use of space for the upper body and legs. The larger window configuration added to the feel of the interior volume being more spacious over the first configuration. Suggestions for improvement included relocating the power distribution box from the cockpit to another portion of the vehicle, improving the accessibility of the trauma kit within the vehicle, more volume for accessing the waste containment system (WCS) during sleeping hours, translation paths for emergency contingencies, and improving volume to limit cross-contamination.

Figure 9. The second low-fidelity conceptual lunar rover mockup in JSC Building 9.

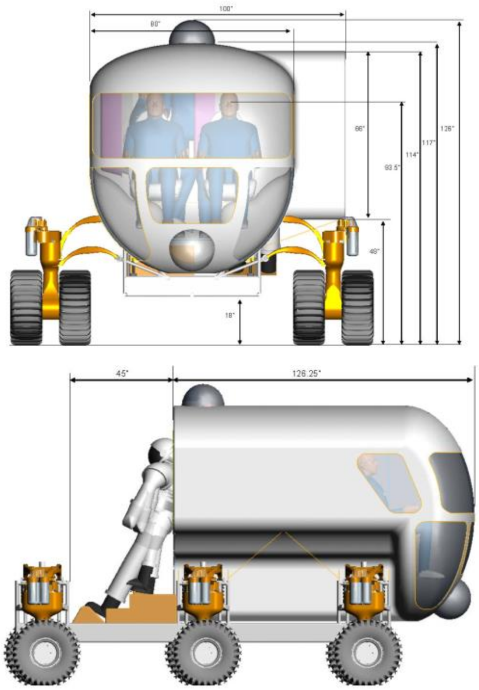

Figure 10. Dimensions of the second conceptual lunar rover.

Cabin 1A

The rover engineering team developed a prototype cabin based on the results of the low fidelity mockup and mounted it on the Chariot rover. Known as the GEN 1A (or Cabin 1A) SPR, it is a medium to high fidelity functional vehicle, which provides the crew a safe haven from the hazardous environment of the lunar surface, a living area for multi-day missions away from the lunar outpost, and a rapid EVA deployment system for scientific exploration of the surface (Figure 11). Using CAD of the SPR's interior volume, the total pressurized volume was calculated to be 10.8 cubic meters (381.4 cubic feet) with a net habitable volume (NHV) of approximately 8.6 cubic meters (304 cubic feet), resulting in about 79% functional volume. Net Habitable Volume is defined as the total remaining volume available to crew after accounting for the loss of volume due to equipment, stowage, and any other structural inefficiencies (nooks and crannies) which decrease functional volume [11]. Larger than the unpressurized Apollo rover, the SPR is capable of multi-day sorties rather than the limited EVA range of an unpressurized rover.

Figure 11. The GEN 1A SPR.

The GEN 1A SPR has two operational driving stations with computer displays for navigation, Global Positioning System (GPS) functionality, and vehicle system control. Located on the rear of the vehicle are two functional suit ports with latching mechanisms and the EVA suits used in the evaluation. For living accommodations, the SPR consisted of two sleep stations with privacy curtains, a hot/cold water dispenser, WCS, floor and cabin stowage areas, and seven Crew Transport Bags (CTB) filled with a variety of food, equipment, and other consumables gathered from the Master Equipment List (MEL) provided by the SPR Core Team (Figure 12).

Figure 12. Interior photos of the GEN 1A SPR.

Cabin 1B

Much like the GEN 1A SPR the GEN 1B SPR is a medium fidelity functional vehicle which provides the crew a safe haven from the hazardous environment of the lunar surface, a living area for multiple day missions away from the lunar outpost, and a rapid EVA deployment system for scientific exploration of the surface (Figure 13). The total pressurized volume of the GEN 1B SPR is calculated at 11.9 cubic meters (420.2 cubic feet) with a habitable volume of approximately 9.7 cubic meters (342.6 cubic feet) resulting in about 85% functional volume for the vehicle. The primary interior difference between the GEN 1A and the GEN 1B vehicles is the added volume from an additional side hatch, which adds an extra 1.06 cubic meters (37.4 cubic feet) of volume to the GEN 1B vehicle. The GEN 1B also added a deployable cabana on the aft deck to protect the suits from dust.

Figure 13. The GEN 1B SPR.

The GEN 1B vehicle retained all the interior assets as the GEN 1A vehicle, but with some refinements. For example, the cockpit seat adjustments and sleep curtains were redesigned. Stowage layout was also refined with the addition of removable soft lockers in the side hatches for crew's personal items. The number of cockpit displays increased to four and more robust adjustment mechanisms were added (Figure 14).

Figure 14. The newly redesigned GEN 1B cockpit.

Cabin 2A / Cancellation of Constellation

The Generation 2 (GEN 2A) vehicle is a medium-fidelity mockup located at the Johnson Space Center's (JSC) Space Vehicle Mockup Facility (SVMF), in Houston, Texas, developed by the Automation, Robotics, and Simulation Division (ER), the Space Suit and Crew Survival System Branch (EC5), and the Habitability and Human Factors Branch (SF3) (Figures 15 and 16). Initially, GEN2A was intended to be the next iteration on the path towards a flight SPR. The mockup is built of aluminum framing and panels with several working subsystems as well as volumetric subsystem mockups such as with the GEN 1 vehicles. The mockup consists of three major sections: a nose section, a cabin section, and an aft deck section. The mockup measures 3.30 m (130 inches) in length, 3.56 m (140 inches) in width, and 2.54 m (100 inches) in height with an estimated habitable volume of approximately 10.8 cubic meters (m^3) (380.8 cubic feet (ft^3)).

Figure 15. The GEN 2A vehicle in SVMF at JSC during RATS 2012.

Figure 16. The crew flying the GEN 2A vehicle near an asteroid.

The Constellation program was cancelled while work was in progress to develop the GEN 2A SPR. The crew cabin portion of the prototype was completed but adapted to a deep space asteroid mission – essentially a rover for use in space instead of on the lunar surface. The project team has continued to develop the cabin under different NASA programs and architectures, considering a variety of different purposes for the cabin including lunar lander, Mars Ascent Vehicle, spacecraft node, Phobos exploration vehicle and ultimately constructed a GEN 2B cabin as a Gateway airlock prototype. The team has come full circle under the Artemis program and is currently working on Cabin 3A pressurized lunar rover designs as the NASA reference configuration for the Habitable Mobility Platform. The GEN 3A rover has been modeled in CAD with limited Virtual Reality testing, but the second and third generation cabins were never utilized in field testing and are thus outside of the scope of this paper.

3. SPR Key Features and Advantages

Fusible Heat Sink

Houses a layer of ice on top of the vehicle beneath the radiator as part of the SPR's external thermal control system. The ice rejects heat energy from the cabin by melting, supplementing the radiator as a phase change material (PCM). Whether in solid or liquid form, the water also provides solar particle event (SPE) radiation shielding for the cabin.

Suit Ports

Enables spacesuits to dock directly to the aft of the cabin and open to the vehicle interior, enabling rapid cabin ingress/egress and minimizing dust intrusion.

Aft Cabana

Provides environmental protection for suits and other equipment stored on SPR aft deck.

Aft Driving Station

Edge key display and hand controller enables operation of the SPR from the suit ports. EVA crew can drive short distances without having to ingress the cabin.

Work Package Interface

Attachment system to augment SPR with modular systems (e.g. winch, cable layer, backhoe, crane, drill, sensors, etc.).

PLSS-Based ECLSS

Common subsystems component with spacesuits. Reduces mass, cost, complexity. Minimizes sparing strategy by allowing cabin ECLSS and spacesuit PLSS to share spares.

Driving Visibility

Cockpit windows sized to facilitate driving safety by maximizing driver visibility. Windows facilitate distant, mid-range, and short-range view. Drivers can see the front wheels to confirm obstacle clearance.

Dome Bubble

A bubble in the lower center window, similarly sized to a spacesuit helmet, allows a crewmember to lie on the floor and place his or her head in the bubble. With the vehicle pitched nose to the ground, the driver can place the bubble observer closer to the surface of a rock than is practical to do in a spacesuit during an EVA.

Cantilevered Cockpit

Placement of the cockpit in front of the chassis removes the chassis structure from being an obstacle to visibility and provides superior view of immediately adjacent terrain.

Exercise Ergometer

Stowable exercise device provides countermeasure to effects of low gravity. Maintains crewmember aerobic capacity.

Pivoting Wheels

Enables driving in any direction. Crab-style driving for docking and for maneuvering on steep terrain.

Active-Active Mating Adapter (AAMA)

Modular docking system reduces mass on the cabin and enables docking to habitats, other rovers, ascent vehicles, or other pressurized assets.

Docking Hatch

Hatch sized to enable suited crewmember translation. Hatch window provides additional visibility or camera mounting during docking.

Dual Rover Philosophy

Ability to rescue crew in the event of failure of one rover enables safe traverses beyond walk-back distance or unpressurized rover driving distance.

Private Sleep Stations

Facilitates crew behavioral health and ensures quality rest, enabling longer duration habitation and greater excursion distances.

Low Overhead for Habitation Tasks

Philosophy implemented in cabin design and layout. All daily crew activities are designed to minimize time and effort for reconfiguration.

Advantages

Health and Safety

Pressurized cabin enables exercise countermeasures and medical treatment while on traverses away from the outpost site. SPE shielding provides protection against radiation. Human-centered design promotes behavioral health.

Exploration

Dual rover strategy significantly increases the number of field sites that can be investigated from a single landing site. Pressurized rover enables improved crew performance during EVA activity than unpressurized rover.

Operational/Engineering

Chassis design enables traverse over rugged lunar terrain. Windows, cameras, and sensors provide situational awareness to crew. Suit Port Transfer Modules (SPTMs) support cabin logistics.

Architectural

Smooth, continuous interior surfaces inspired by sailboat cabins increase perceived volume and crew comfort. Soft, removable upholstery and versatile, adjustable surfaces for multiple uses. Cushioned seats fold down singly into beds. Removable floor panels for under-floor stowage access.

4. SPR FIELD TESTING AND TEST LIMITATIONS

NASA Desert RATS

From 2008 to 2011, annual testing for these (and several other Constellation-era) prototypes occurred during NASA's Desert Research and Technology Studies (DRATS, or Desert RATS). The 2008-2010 DRATS campaign represents one of a very small number of campaigns in the past twenty years (or more) where NASA has tested a spacecraft prototype in an analog environment in a multi-day, mission simulation context with crew living and working in the prototype with Agency intent to iterate the design based on habitability lessons learned. (The crews did not live in the SPR during the 2011 field test.) The authors have not found evidence of any other such campaign in Agency history, with the exception of 2012 testing of both the rover and habitat that continued one more year but restricted to high bays at Johnson Space Center. There are other NASA analog tests, but generally, the test chamber is not a spacecraft prototype tied to an active program, or the crew does not live in the prototype for multiple days, or the test does not incorporate a mission simulation.

Black Point Lava Flow

Desert RATS was conducted in September/October of each year at Black Point Lava Flow, approximately 64.6 km (40 miles) north of Flagstaff, Arizona. SP Mountain is the youngest volcanic feature in the northern San Francisco volcanic field with an age of 71,000 years. The volcanic cone is 1200 m (3,900 feet) across at the base and 250 m (820 feet) tall (Figure 17). The test site has a wide variety of geologically relevant surface features that presented many opportunities to evaluate human performance with both the Intravehicular Activities (IVA) and Extravehicular Activities (EVA) science/exploration capabilities of the rover.

Figure 17. This photo is a portion of the actual terrain traversed by the rovers.

Surface characteristics include slopes with an approximate range of 6° to 25°, soil mechanics ranging from lose grain to hard-packed, surface properties ranging from flat/smooth to rocky, and some minimal vegetation. The Black Point Lava Flow test site was also chosen for its historical aspects since it was a training site for Apollo scientific training missions in the early 1970s (Figure 18).

Figure 18. Apollo astronauts training at Black Point Lava Flow during the early 1970s (Courtesy NASA).

Test Limitations

Test Durations

The SPR field tests performed with human crews ranged in duration from as short as one day to nearly fourteen days. These tests simulated mission activity on the lunar surface or at an asteroid, but none of these included simulations of the crew time spent launching from Earth, traversing through space, landing on or lifting off from the Moon, or landing on Earth at the end of the mission. They also did not include the full 180 days the crew would spend on the Moon (under the Constellation program architecture). Further, while the 2010 test did include a brief visit to the surface habitat and the 2011 test did include crew overnights in the habitat, none of the tests simulated the repeating crew cycles alternating between time in the habitat and time in the rovers.

Crew Isolation

The crews did not experience an isolation representative of a true lunar mission. Each rover was followed by a chase team of support personnel with additional support provided by a large base camp. During each EVA, crewmembers were attended to by suit support techs. Wildlife and domestic animals were visible. A rock quarry was within sight of parts of the test area. Some parts of the traverses were near (or even crossed) public roads, enabling the crews to see and be seen by private vehicular traffic.

Prototype Fidelity

The SPR prototypes are low to medium fidelity mockups (depending on the component) and do not in all cases represent the mass, shape, volume, or operational characteristics of their eventual flight counterparts. Additionally, not all hardware was present in the proper number. For instance, there was only one Active-Active Mating Adapter prototype, which meant that only one of the two SPRs was able to truly tock to the Pressurized Excursion Module / Deep Space Habitat during the 2010 and 2011 tests. Additionally, neither of the GEN 1 prototypes included flight-like representations of their spacecraft subsystems.

Test Preparation Time

The GEN1A cabin went from a wooden mockup to a prototype in the desert in less than six months' time. The GEN 1B was designed, built, and deployed to the desert a year later. This rapid schedule caused some components to be hastily developed without rigorous design review from all relevant communities. For instance, the exercise seat was rapidly assembled and was able to pass a safety review but did not benefit from exercise community input to develop a more compatible seat with the ergometer. Another example is the lack of attention given to a waste/trash disposal system on both the 1A and 1B vehicles.

Resource Limitations

Both funding dollars and personnel availability were limited, with ripple effects throughout all years of the field-testing. This influenced design decisions, design reviews, fabrication, and test structure.

Environmental Differences

Despite the historic lunar relevance of Black Point Lava Flow, it is not the Moon. The most obvious environmental differences that have an impact on the test are the presence of an atmosphere, higher gravity, less extreme temperatures, higher sun angles (than the intended lunar polar destinations), and the presence of biological life.

2008 Field Test

The 2008 DRATS field test included two separate tests related to the SPR. The first test was a head to head competition between the UPR and the SPR. This test represented using either rover as a single-day excursion vehicle operating from a lander or habitat with no overnights in the vehicle. The second test was a three-day SPR excursion, representing the scenario where the SPR departed from a lander or habitat and did not return until after three days. Both tests included a detailed test protocol and flight plan, hypotheses, metrics, and prospectively defined levels of practical significance of all hypotheses.

Chariot/UPR vs. SPR Field Test

The primary purpose of the UPR vs. SPR test was to objectively and quantitatively compare the scientific productivity and human factors during 1-day exploration, mapping, and geological traverses performed using the UPR and SPR prototype vehicles [9] (Figure 19). The UPR had been tested a few months prior at Moses Lake Sand Dunes in central Washington state, while the SPR was still under construction, and had been viewed very positively as a significant improvement from the Apollo LRV. Consequently, there was a very high interest in determining which vehicle would perform better.

Figure 19. The photo shows a suited crew of two driving the UPR over rocky terrain.

Two crews of two, each consisting of one flight experienced astronaut and one professional geologist, performed four eight-hour predefined missions involving exploration, mapping, and geologic traverse. The mission plan was developed to prioritize specific sites of scientific interest. Human performance data was collected. Ultimately, the test crews believed either vehicle could be acceptable for a lunar mission; however, they preferred the SPR over the UPR configuration [10]. Primary rationale for their preference included the SPR causing less fatigue and enabling greater crew productivity (Figure 20).

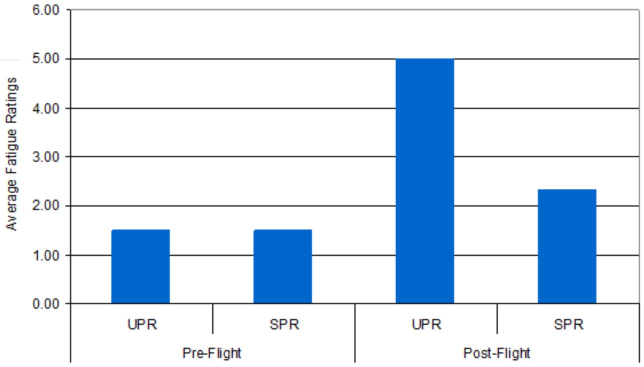

Figure 20. Pre- and post-flight fatigue for both vehicle configurations.

Post-test data analysis told an even more compelling story. The productivity achieved during the one-day mission indicated an increase of productivity by 57% in the SPR as compared to that achieved in the UPR with 61% less EVA suit time [9]. It required less operator compensation in the driving performance of the SPR over the UPR using the same traverse plans. There was no significant difference from perceived exertion scores between the SPR and UPR; however, there was more discomfort reported for the UPR due to the constant standing and lack of mobility provided by the turrets [10].

The average distance traveled during the one-day exploration mission indicated the crew in the SPR traveled 31% (4.3 km) (2.67 miles) further than in the UPR. This was primarily due to an 8-hour consumables limit on the UPR traverse reducing the available drive time as compared with the SPR [9].

The value of the SPR was so clearly established among the test team that one of the senior Chariot engineers half-jokingly suggested that the team might as well dig a hole and dump the turrets [the driving stations for the UPR] in them because there was no need to bring them back to JSC.

SPR Three-Day Test

Immediately following the one-day tests, a three-day lunar transverse simulation was performed with a crew of two, collecting SPR habitability, human factors, and performance characteristics data. Throughout the SPR's three-day traverses, data indicated the SPR met all necessary objectives in terms of human performance and crew accommodations according to the pre-defined human factors metrics and acceptability criteria (Figure 21). In addition, the SPR adequately supported EVA operations through the use of suit ports and provided operational support for the EVA crewmember.

Figure 21. The GEN 1A SPR during DRATS 2008.

However, there were areas identified where redesign could further increase performance and productivity. For vehicle operations, better situational awareness of the SPR in terms of vehicle alignment capabilities and sideways driving was needed. Suggested redesign of the display and controls in terms of stability of the cockpit control and display quality in bright-lit conditions. There was 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.

With driving, 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 due to vibration. In terms of EVA performance, there was a relationship between the type of terrain with physical exertion and fatigue. There was difficulty translating on and off the vehicle due to the 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 to help the crewmember slide back into the suit port. Overall, the interior of the vehicle was rated acceptable.

Figure 22. Trash and other personal articles added up quickly over a 3-day mission.

Minor redesign issues included better adjustability of cockpit seats and the need for a footrest, and improved stowage capabilities. There was not enough stowage and access to the stowage compartments was problematic. In addition, there was not enough stowage for waste that accumulated quickly over the three-day mission (Figure 22). The sleeping accommodations were found to be comfortable, if not pleasurable.

The field test had a significant impact on the Constellation architecture. Initially, the Constellation Lunar Surface Systems Project Office had not included a pressurized rover in the architecture, instead assuming an Apollo-style unpressurized rover.

2009 Field Test

Following the 2008 test, work resumed at a rapid pace at JSC to build the GEN 1B rover. Both Cabin 1B and its Chariot were completed in time for the 2009 DRATS but the two were not integrated into a single SPR. Instead, the Chariot was tested separately as a robotic device while Cabin 1B was placed on the 1A Chariot. Cabin 1A was only used briefly, and without a mobility chassis.

The 2009 test was a quantitative habitability and usability evaluation of the SPR GEN 1B prototype during a high-fidelity simulation of a 14-day exploration mission. Consisting of an astronaut and a field geologist, a two-person crew remained within the SPR, both day and night, for the entire 14-day mission only leaving the vehicle through the suit ports to perform EVAs [12] (Figure 23).

Figure 23. The GEN 1B SPR during the DRATS 2009.

Throughout the 14-day SPR mission, standard metrics were used to quantify habitability and usability of all aspects of the SPR GEN 1B prototype. Multiple design modifications were identified. Data indicated that the crewmembers found the overall SPR habitability and human factors to be acceptable for a 14-day mission [12], [13] and compared it to be more like a hiking trip where simple, lightweight, reusable items would be required for quick, easy accessibility, and consolidation [13] (Figure 24).

Figure 24. The crew prepping dinner during the 14-day mission.

Stowage reconfiguration for Extravehicular Activity (EVA) was a major issue affecting mission time. Assuming four EVAs per day, the crew would take approximately five minutes to reconfigure the cabin for one EVA event. Thus, it was calculated that 20 minutes per day per crewmember just to reconfigure the stowage for an EVA was a significant impact (18 hours and 40 minutes per mission) to crew time for a 14-day mission (Figure 25) [13].

Figure 25. The stowage after the crew reconfigured the cabin for EVA.

Information of this caliber would be used to completely redesign the entire stowage system from a Crew Transfer Bag (CTB) system to a more form-follows-function design. The sleep stations in GEN 1B were generally acceptable with some improvements requested in curtain design: a small zippered section for easier egress/ingress, better blocking of light and sound, and less ridged forward and aft curtains.

The test also examined the effect of degraded communications on crew productivity, particularly looking at the effect of communications outages. Comparison of the crew productivity metrics results showed no practically significant difference in crew productivity when the crew was operating for extended periods without space-to-ground communications compared with continuous space-to-ground communications [12]. It should be noted that the prototypes did not include simulations of vehicle subsystems so this test did not examine the effect of loss of vehicle systems support from Mission Control, only the impact of loss of direct communication with science support teams.

Also, found acceptable for the vehicle was a 24-hour rescue habitation of four-crew, which was conducted on the last day of the mission (Figure 26). Conducted on the final day of the test, Cabin 1A was "hidden" several kilometers away from the location of the GEN 1B SPR. One crew was placed in Cabin 1A with instructions to act as if their SPR had become disabled. With no radio contact, SPR 1B had to search based on a last known position to locate SPR 1A, rescue the crew, and transport them back to the lunar outpost. The successful outcome of this test demonstrated the SPR's dual rover strategy that enables exploration ranges in excess of 200 km from the lunar outpost.

Figure 26. The GEN 1B vehicle docking to the GEN 1A cabin during a rescue scenario.

2010 Field Test

In 2010, as a part of the Global Point-of-Departure (GPoD) architecture for future human lunar exploration, a pair of SPRs, two Portable Utility Pallets (PUPs), and a conceptual lunar habitat were used during two 7-day high-fidelity lunar mission simulations (Figures 27 and 28). This was the final DRATS test where the SPR crews lived inside the cabin for the durations of their simulated missions.

The quantitative evaluation of habitability and usability of the SPR prototype vehicles during high-fidelity mission simulations continued as with previous field-testing.

All of these lunar assets operated under different operational modes affecting both the extent to which the SPRs must maintain real-time communications with earth ("Continuous Communication" (CC) vs. "Twice-a-Day") and visual contact with each other ("Lead-and-Follow" vs. "Divide-and-Conquer"). It was assumed that no communication relay satellites were available [14].

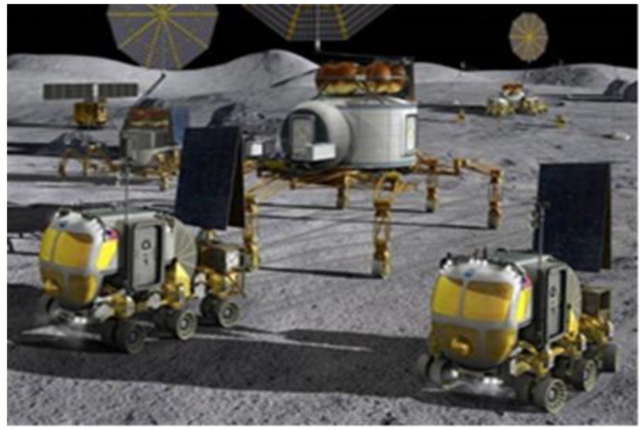

Figure 27. The LAT Lunar scenario 12.1 with habitat in "Lunabago Mode" along with two rovers.

Figure 28. Two rovers docked to a habitat during DRATS 2010 simulating the LAT Lunar 12.1 scenario.

Four anthropometrically diverse two-person crews (including the first all-female crew), each consisting of an astronaut and a field geologist participated in the 2010 field test. For each 7-day mission, a two-person crew operated within each SPR vehicle, day and night, only leaving the vehicle via the suit ports to perform EVAs similar to the DRATS 2009 mission (Figure 29).

A detailed mission timeline was executed in which crewmembers performed a range of IVA and EVA tasks consistent with the anticipated objectives of an early planetary surface exploration mission. These tasks included tele-operations, docking, maintenance, repair, science / exploration activities, briefings, food preparation, personal hygiene, and exercise activities. Performance of these tasks enabled a quantitative evaluation of SPR habitability and usability under a variety of operational modes while also enabling validation of specific SPR functional requirements (Figure 30).

Figure 29. Six of the eight DRATS 2010 crew members.

Figure 30. The left photo illustrates the crew in GEN 1A working in the vehicle's habitat volume. The right photo shows both the GEN 1A and GEN 1B rovers.

Data indicated of the two communications structures, the CC network structure was best for information sharing. This type of structure arising from well-defined procedures for eliciting clearly defined information are best used for relatively slow tempo operations, such as a lunar exploration mission [15], [16]. This concurs with the Science Data Quality metrics indicating that in the CC mode there was a marginal increase, while qualitative assessments suggested a practically significant difference [14]. Future testing to evaluate approaches for operating without real-time space-to-earth communications assessment the efficacy of mission operations, science operations, and public outreach.

During the 14-day high fidelity lunar exploration mission, having four diverse crew working and living in the SPRs enriched the field data for the understanding of the vehicle design, design trend comparisons, and identified vehicle elements, which needed improvements for the next generation of rovers [17]. The habitable volume of the rovers were rated as acceptable for a two-week mission; however, test data indicated longer 30-day missions could be difficult given the current GEN 1 prototype volumes.

5. SPR Lessons Learned

Cabin 1A Body Concept Evaluation

During the 2008 Pre-GEN 1A body concept evaluation, several improvements were made and incorporated into the GEN 1A body design. First, a better definition of interior volume and workspace was needed to further refine what tasks the crew would actually be doing in the rover. It was agreed that a total redesign of the rover cabin body into a T-shape with a central main aisle way optimized the internal habitable volume as well as accommodated for the chassis' suspension when the vehicle was raised or lowered (Figure 31). Nose geometry and the curvature in a cylinder body design proved problematic with the user's knees, feet and legs. To solve this issue, vehicle designers flattened the floor near the nose section of the vehicle to make operating the vehicle in a seated position more comfortable for the operator. An adjustable footrest across the bottom of the nose was also suggested as a design solution (Figure 32).

Figure 31. The GEN 1A vehicle shell redesign into a T-shape with a central aisle way.

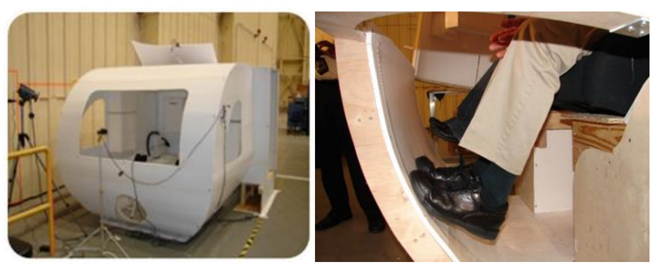

Figure 32. The early FRED vehicle prior to the redesign of GEN 1A showing the curvature at the feet.

When field-testing of the new GEN 1A cabin was conducted, the crew thought the T-shape body design was a big improvement on optimizing the interior volume as they indicated doing tasks was more efficient. The dedicated bench stowage was also considered acceptable and easy to use. It was also indicated that having dedicated sleep stations with deployable curtains provided much needed privacy. Night driving was also tested with the vehicle and it was noted that operators needed to see a minimum distance of 30 to 40 meters (98.4 to 131 feet) while driving (Figure 33).

Figure 33. GEN 1A conducting night operations.

Cabin 1B Body Improvements

Cabin 1B was constructed for the 14-day DRATS 2009 field test with several improvements to the vehicle's body. A second side hatch was added to the GEN 1B vehicle to improve the docking ability of the rover to other surface elements. It also added approximately 1 cubic meter of internal volume for the crew to use (Figure 34).

Figure 34. GEN 1B with extra side hatch that increased interior volume and improved docking.

It was observed with the GEN 1A vehicle, that large amounts of dust tended to cover the suits when installed on the suit ports during traverses over the desert terrain. To solve this issue, the GEN 1B vehicle added a deployable soft goods aft cabana cover for suit protection (Figure 35).

Figure 35. GEN 1B aft cabana to protect suits.

Additionally, external cameras were added to increase the crew's situational awareness and for added scientific observation capabilities

Cockpit Improvement

The area of the rover referred to as the "cockpit" is in the front of the vehicle where the business of driving, monitoring systems, and conducting scientific observations are accomplished. Over the years of field-testing, several lessons learned have been collected to improve future cockpit designs. Temporary soft stowage for the crew in the cockpit is very important. Having small stowage pockets to store notebooks, maps, pens, pencils, and sunglasses keeps the crew efficient and avoids having them to hunt for needed items (Figures 36, 37). To aid the crew in maintaining awareness of slopes, a manual inclinometer should be used. This helps with cross slope positioning for EVAs. Exterior cameras are also a major component of the cockpit. These cameras aid the crew in all types of situational awareness of both the vehicle and EVA personnel. It was reported that quad camera views greatly improved visual situation awareness of the vehicle when crabbing (a 45-degree sideways type of driving) and obstacle avoidance. Rover operators need the ability to configure all cameras views on any display (Figure 38). All the rovers tested had a center camera positioned above the nose windows for scientific purposes and safety. This camera needs to have gyro stabilized lens and Pan-Tilt-Zoom (PTZ) capabilities. External side cameras views need to incorporate a portion of the vehicle for more accurate vehicle positioning and clearance for docking and other surface operations.

Figure 36. GEN 1A cockpit crew-made soft stowage above the side window.

Figure 37. Improved SPR cockpit soft stowage.

Figure 38. The camera quad screen on the left display in the GEN 1B vehicle.

Displays

Stability and adjustability of the display mounting system was an important issue throughout field testing. Proper display positioning is important to reduce command input errors, reduce fatigue, and counter glare. Displays needs to have adjustability in the horizontal plane (left/right, x-axis), the vertical plane (up/down, y-axis), the z-plane (toward the body/back from the body, z-axis) and display screen tilt (back/forward) to reduce screen glare for either internal lighting or external sunlight. A minimum of four main displays (approximately 30.5cm (12 inch) diagonal) are needed to have two vehicle operational displays for redundancy and two center displays for navigation, crew situational awareness, camera views and science transverse planning. The display graphic user interface (GUI) should be simple for daily operations and should present information to the crew in a clear and intuitive manner (Figure 39). Font size should be appropriately sized for the operator to read while driving in rough terrain with minimal key inputs for all display functions to decrease crew fatigue.

Figure 39. The rover tested displays.

Controls

Adjustability in the control joystick is necessary to reduce hand and wrist fatigue. Adjustment directions should be in the x and z-axis so that the operator can find a comfortable position for long duration driving. In addition, the controller needs to be able to decouple pitch and roll functions for docking to avoid unwanted cross coupling. Vibration of the joystick controller in rough terrain was an excellent situational awareness cue for crew to slow the vehicle down. Two special modes for the controller were also introduced to aide in hand fatigue. “Car mode” sets the rover wheels up to act like a car and eliminates any type of misalignment. “Cruise Control” reduces both wrist and arm fatigue during long traverses and works much like the cruise control in modern automobiles. Both the GEN 1A and 1B prototypes used a joystick controller positioned on the outboard side of the crewmember with an armrest. (Figure 40).

Seats

Rover seating can be extremely important and has been one of the most challenging elements of the cabin interior. Adjustability and ease of use are the most important aspects of the seat. The seat needs adjustability with the seat pan, seat back and the armrest. It also needs a mechanism that is simple to use for adjustment with the seat pan forward/backward movement, the up and down movement, in tilting the seat back for full 180-degree deployment and lumbar support. Making the seat adjustment tabs akin to a car is one solution for the operator (Figure 40).

Figure 40. Cabin 1B seat and joystick controller.

Windows

The GEN 1A nose design provided effective operator visibility. The lower observation bubble was acceptable for scientific observational use (Figure 41).

Figure 41. Crewmember taking science observations from the GEN 1B bubble.

With the helicopter-type design lower side windows, visibility of the wheels was acceptable. Between GEN 1A and GEN 1B, it was determined the mass of the two large front windows needed to be reduced. The team tested a reduction of 10 to 15 cm (4 to 6 inches), covering the upper portion of the front windows with small stowage lockers. This obscured from view anything above 30 degrees (Figure 42).

Testing with GEN 1B determined that the side windows (Figure 36) needed to be increased to improve lateral field-of-view (FOV) from a seated position, especially during crabbing operations and docking.

Figure 42. GEN 1A window view on the left, while on the right the GEN 1B window view. Note the reduction in the front window view.

Interior Refinement

Having previously discuss the cockpit area, the following sections will discuss lessons learned in the habitation portion of the vehicle. This will include stowage, the galley and water dispenser, trash management, the sleep station, the waste containment system (WCS), exercise, suit umbilicals, the overall volume, suit ports and the aft deck.

Stowage Accommodation

The stowage evaluated during DRATS field tests included crew personal stowage, vehicle stowage, and consumables stowage (Tables 3 and 4). The benches have been used for stowage locations in both GEN 1A and 1B with positive ratings for efficiency and accessibility. Floor stowage was originally used for such items as trash and exercise equipment.

Table 3. *Overall Stowage Volume per Rover*

Vehicle	Volume meters (m^3)	Crew	Mission Duration
GEN 1A	0.74	2	3-days
GEN 1B	0.91	2	7-days
GEN 1B	1.18	2	14-days

Table 4. *Comparison of Rover Consumables*

Consumable	LSS Baseline	DRATS '09	DRATS '10	DRATS-modified Baseline
	kg per person per day	*kg per person per day*	*kg per person per day*	*kg per person per day*
Water, Food Prep	0.50	0.57	0.27	0.42
Water, EVA (drinkable water)	1.71	0.86	0.64	0.75
Water, Hygiene	0.40	0.12	0.11	0.12
Food/Packaging	2.06	0.47	0.85	0.66
Clothing/Supplies	1.10	0.86	0.76	0.81
Total without Drinking Water	6.27	2.88	2.63	2.76

To enhance crew stowage in the GEN 1B cabin, a soft personal locker system hung on tracks in the side hatch alcoves of the vehicle (Figure 43). The crew liked the 16 individual stowage cubbyholes with clear front panels, which made it easier for the crew to know what items were stowed where. The soft lockers could stow all crew personal items for a 14 to 16-day mission as well as up to two days' worth of food. Improvements included replacing the Velcro front closures with quarter fasteners closures for noiseless access into the cubbies as night. Though this concept was acceptable for crew stowage, it was highly unacceptable when it came to cabin reconfiguration for EVA.

As a safety measure, at least one side hatch must be available for use during any EVA. This provides an alternate means of cabin entry if the suit port system fails. The soft lockers block the hatches when installed and therefore must be removed from at least one side hatch prior to each EVA.

During the DRATS 2009 14-day mission, the soft locker stowage reconfiguration took 5 minutes per EVA. There were four EVAs per day. When calculated, over a 14-day mission with four EVAs per day it would take 18 hours and 40 minutes of crew time for stowage reconfiguration per mission. This is an unacceptable use of extremely valuable crew time on the lunar surface.

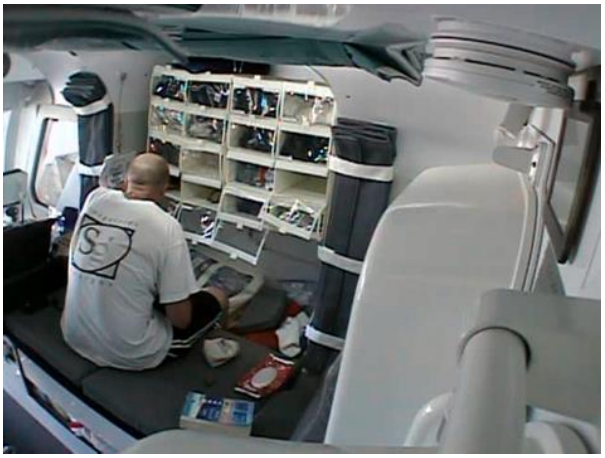

Figure 43. Crewmember packing personal items into the soft locker system in GEN 1B for a 14-day mission.

Galley Water Dispenser

The galley water dispenser is located in the starboard bench, immediately behind the seat (Figure 44). Crews have suggested that they would prefer for the water dispenser to be placed at chest level, but no suitable location has been found in the cabin to relocate the water dispenser. Any wall location would place the galley inside one crew member's bunk space and there is no overhead space to mount the galley in the ceiling.

Figure 44. The galley water dispenser.

Trash and Waste

Table 5 and Figure 45 show the amount of trash for a crew of two during the DRATS 2009 and 2010 testing. This trash included wet trash, dry trash, and human waste. (The prototype SPRs used a desiccant bag system for human waste that was thrown away with the trash after use.) Since the rover is such a small vehicle, crews wanted trash to be taken out either daily or at minimum every third day. This was mainly due to odor. Floor stowage was a good solution for trash management and reducing any type of cross-contamination.

Table 5. *Comparison of Rover Trash Volume*

Trash	LSS Baseline	DRATS '09	DRATS '10	DRATS-modified Baseline
	m^3 per person per day	*m^3 per person per day*	*m^3 per person per day*	*m^3 per person per day*
Dry, Volume	-	0.002	0.003	0.003
Wet, Volume	-	0.021	0.003	0.012
Individual Totals, Calculated	-	0.023	0.006	0.015

Figure 45. Trash amount for a crew of 2 during a 14-day mission.

Sleep Station

Sleep stations in the rover consist of the bench area on either side with a sleep curtain closing off that area for crew privacy. The GEN 1A curtain design was the most acceptable in reducing light and sound, though the GEN 1B curtain was slightly easier to deploy and stow. The larger main side curtain should be separated into two smaller sections using magnets or zippers for ease of egress or ingress by a crewmember without distributing the other crewmember. The main side curtain should be pleated for easy deployment or stowage, whereas the smaller front and rear curtains should be less ridged. Curtain attach points should be ease to operate. Rails or track should not bind when deploying the curtains. The curtain length should be at a minimum of 198 cm (78 inches). Also, to aid in reducing light and sound into the sleep station, simple soft covers over power panels and AC controls is suggested as well as relocating any AC controls and individual lighting controls higher on the sleep station wall to reduce accidental operation.

Waste Containment System (WCS)

The WCS is located at the rear of the cabin in the aisle. It was learned that the aisle width should be increased by 2.54 to 5.1cm (1 to 2 inches) for easier operations (Figure 46). When examining the privacy curtain, designs should keep the vehicle cabin flexible for dual operations and contain biological contamination if the situation arises. The urine funnel stowage needs to be incorporated into the closeout panel around the toilet. Needed hygiene supplies for WCS operations need to be integrated in the closeout panels around the unit, as well as behind the urine hose, and if possible, on the aft bulkhead between the two suit ports.

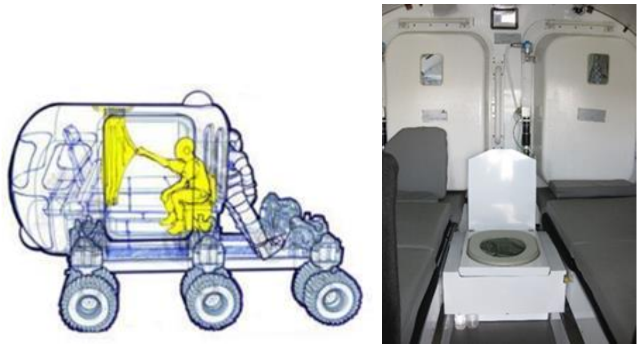

Figure 46. The left photo show the original WCS concept, while the right photo shows the GEN 1B WCS area.

Exercise

Most of the exercise accomplished in the field trials was with an ergometer (Figure 47). Originally, it was hoped that exercise could be accomplished while traveling on a long traverse. However, vehicle motion made this more difficult than anticipated. The exercise protocol accordingly indicates that exercise should only be performed while the vehicle is stationary. Crews also used resistive bands for upper body workouts. To improve these types of workouts, crews suggested increase the vehicle interior height by 5.2 cm (2 inches). In addition, to aid in resistive type exercises more attach points need to be positioned throughout the cabin.

Figure 47. Prototype ergometer developed at Glenn Research Center ergometer being used in GEN 1A.

Overall Volume and Acceptability

The DRATS 2008 3-day mission using GEN 1A demonstrated that the overall volume allocated to habitability was acceptable for a 3-day mission (Figure 48). DRATS 2009 extended that acceptability to 14 days using the GEN 1B vehicle (Figure 49). Testing in both cabins in 2010 demonstrated acceptability for 7-day missions.

Figure 48. Crew working and relaxing in GEN 1A.

Figure 49. Crew relaxing in GEN 1B.

Table 6. *SPR Habitable Volumes*

Vehicle	Habitable Volume Meter³	Common Cabin Outfitting	Notes
GEN 1A	8.6	Planetary Rover	Original IML design
GEN 1B	9.7	Planetary Rover	Added a side hatch to IML design = 1.06m³ (37.4 ft³)

Field testing provided one data point for 3 days, four data points for 7 days, and one data point for 14 days. The 2010 test crews were generally in agreement that 14 days was viable for the SPR but did express some concerns with a 30-day mission in the vehicle. However, there is no actual test data for missions exceeding 14 days.

Aft Deck and Suit port

From an interior perspective, the suit port translation and mobility aids were considered acceptable. When testing GEN 1A, it was noted that handholds were needed around the internal suit port hatch to aid suit entry and exit. During later testing, additional handholds where put in place, namely the overhead pull up bar and the lower and side dip bars for egress and ingress of the suit (Figure 50).

Figure 50. GEN 1B interior suit port handholds.

Aft deck translation of a suited crewmember will require external handholds in various locations around the aft deck, especially near step-off points, and near the suit port. Volumes of the aft deck also need to increase for improved translation paths (Figures 51, 52, 53).

Figure 51. GEN 1A Aft Deck

Figure 52. GEN 1B Aft Deck

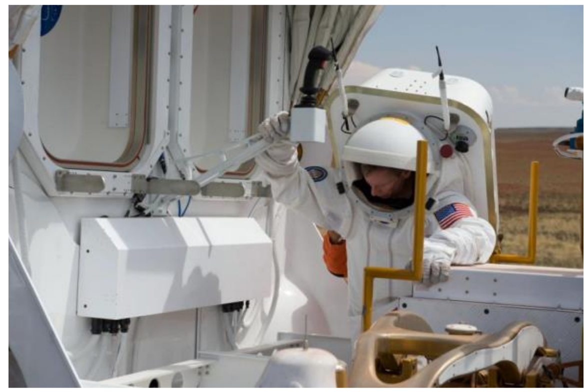

Figure 53. GEN 1B Aft Deck

For suit port operations, including suit port transfer module (SPTM) operations, GEN 1B added external displays and controls the crew can use. (The GEN 1A suit ports are entirely manual, while the 1B suit ports are motor-driven.) The GEN 1B vehicle has a single large display mounted above the suited crew. (Figures 54, 55) This display location proved troublesome. Often when translating past the display, crew members would inadvertently strike the display with the suit port interface plate (SIP) on the suit's PLSS. Crew comments suggested replacing the single shared display with a smaller display for each crew member, located near wait height. This solution was never tested in desert field trials but has been explored in high bay testing with mixed results – display visibility can be blocked depending on crew member height and chest-mounted obstructions.

Figure 54. Aft display use during suit port operations

Figure 55. Aft display use during SPTM operations

Any type of control, such as a joystick, needs to be located as close to the suits as possible with an armrest (Figure 56).

Figure 56. GEN 1B EVA joystick controller.

A visual alignment line on the aft deck representing the center point of the suit port opening provides a good visual aid for gross alignment. For finer adjustments, guide rails to help the crew member back into the suit port, mirrors on either side of the suit, and aft camera views will aid in both situational awareness and alignment for final capture.

An adjustable boot platform will be required to allow crew members of different statures to use the suit port (Figure 57).

Figure 57. GEN 1B EVA boot step.

6. Conclusions

The SPR team used a design-build-test philosophy to rapidly create a spacecraft concept unlike any the Agency had developed before. Design cycles blending mechanical, electrical, software, and human centered design culminated annually with field testing of the SPR prototypes in a multi-day, relevant mission context. Lessons learned from these simulated missions, the quantity and quality of human-in-the-loop (HITL) data collected, and the use of multiple mock-ups of varying fidelity guided subsequent development. Each design tested benefited from the iterative HITL analyses and evaluations. Thus, providing design and management teams with an enhanced ability to make a knowledgeable informed decision in how to mature the vehicle design, reduce design costs, and create an environment of efficiency for crew mission success.

Recommendations for Gen 3 and Flight Vehicle Development

The specific test conclusions from the prior HITL tests should obviously be used as guidance for Gen 3 and eventual flight vehicle development. There are also several open issues that have not yet been resolved.

Some design issues have never truly been resolved in the cabin. The sleep station curtains are the most significant of these. The curtains have three key design functions that to an extent conflict with each other, despite all being absolutely necessary: prevent light leaks, form an acoustic barrier, and deploy/stow with ease. Failure in any of these three areas makes the curtains unacceptable.

Additionally, WCS privacy has not been well implemented. Test subjects have been predominantly male and have to some extent dismissed the need for effective privacy. No DRATS missions involved mixed gender crews and only one field test involved an all-female crew. Mixed gender crews will, however, fly to the Moon and Mars. Additionally, all field tests were very short in duration. The cabin will be used on the Moon and Mars in missions that in some cases will have the crew in space for a year before reaching the surface. At that point in a mission, even minor nuisances can have severe behavioral health impacts. The WCS needs a deployable system that provides privacy, includes enough room for all waste and hygiene operations, and is easy to clean. Easy to clean is often overlooked in design efforts but its significance is apparent when visiting any poorly maintained public restroom – imagine living on Mars in such an environment for thirty days without interruption.

Though the cabin is an inherently small pressure vessel, it is important to develop a design that minimizes cabin reconfigurations. Each reconfiguration requires crew time to perform and adds design complexity, with associated cost and schedule impacts. In virtually all instances, the reconfigurable aspects of the cabin (seat conversion to bunk, bunk curtain deployment, etc.) exhibited human interface problems requiring redesign, some of which are still not fully resolved going into Gen 3 development. It is likely impossible to completely avoid reconfiguration, so each reconfigurable element will require increased attention in design and testing.

The design should also be robust to major architecture changes. From the early concepts shown in Figures 4-6 to today, the cabin has been redirected through program changes from small pressurized rover to asteroid free flyer, lunar lander cabin, Mars ascent vehicle cabin, planetary airlock, microgravity habitable airlock, node, surface habitat module, logistics module, docking tunnel, and is now back to small pressurized rover. If the team had started over with reach redirection any progress made would have been lost. And if the cabin can maintain commonality with all these different elements there is potential for massive program cost and schedule savings.

HITL testing in a relevant environment has been invaluable and should continue to refine numerous habitability details in further development towards a flight configuration. This requires living in a prototype in a field setting on a mobile chassis in relevant terrain. Some aspects of cabin habitability cannot be observed outside of a multi-day, relevant mission simulation including flight-like traverses. Additionally, the duration of the test should be representative of the space mission. Even higher fidelity results are achieved if external habitation systems are also considered – for instance a field test that not only includes the crew time spent in the rover, but also includes simulations of launch and cislunar travel in Orion as well as landing in the Human Landing System (HLS) cabin. It is recommended that before committing to a final design configuration that a desert field test be performed including a 5-day Orion mission, 12-hour HLS mission, 30-day rover mission, 12-hour HLS mission, and 5-hour Orion mission thereby encapsulating the entire launch to landing experience. Optionally, this could also include a simulated mission of 2-4 days at Gateway both before and after the lunar landing if a crew stop at Gateway is part of the architecture. This approach will help to identify aspects of transferring the crew across vehicles that may have design impacts but would not be observed in tests of the rover by itself.

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