Habitability Considerations for a Notional Five-Day Small Pressurized Rover Excursion

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Within the Artemis program, the Pressurized Rover (PR) is intended to support two-person mobile habitation up to roughly thirty days in duration. Lunar surface use of the PR, however, assumes a crew swap approximately halfway through a 33-day surface mission. Within that shorter duration, a rover crew may perform one or more excursions to remote sites in support of specific mission science or operational objectives. An important consideration in rover design is ensuring that the habitation accommodations in the vehicle support these types of missions. No pressurized rovers have ever been used in human spaceflight, but several have been proposed. The current NASA pressurized rover reference configuration is based on the third generation of the prototype small pressurized rover initially developed under Constellation. Using the NASA reference configuration, habitability considerations are discussed in the context of a notional five-day science excursion. The primary focus will be on the time the crew spends in the cabin, as opposed to time spent outside the vehicle on science-based EVAs. On each day of the excursion, the specific crew activities will be detailed. Crew activities that will be assessed include post sleep, EVA preparation, daily planning conference, private medical conference, traverse driving, EVA cabin egress, EVA cabin ingress, post-EVA activity, crew meals, pre-egress site observation and analysis, crew exercise, pre-sleep, and sleep. Considerations for crew fatigue will be discussed, including lessons learned from field testing. Finally, the assessment will identify hypotheses to assess in future analog missions and suitable test campaigns to evaluate them.

I. Nomenclature

ALSS	=	Apollo Logistic Support System
CLPS	=	Commercial Lunar Payload Services
DPC	=	Daily Planning Conference
DRATS	=	Desert Research and Technology Studies
EVA	=	Extra-Vehicular Activity
ISRU	=	In-Situ Resource Utilization
IVA	=	Intra-Vehicular Activity
LCVG	=	Liquid Cooling and Ventilation Garment
LED	=	Light Emitting Diode
LESA	=	Lunar Exploration System for Apollo
LTV	=	Lunar Terrain Vehicle
MCC	=	Mission Control Center
MOLAB	=	Lunar Mobile Laboratory
PAO	=	Public Affairs Office
PMC	=	Private Medical Conference
PR	=	Pressurized Rover
PSR	=	Permanently Shadowed Region

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PWD = Potable Water Dispenser
SH = Surface Habitat
SPLC = Suit Port Logistics Carrier
SPR = Small Pressurized Rover
SPTM = Suit Port Transfer Module
WCS = Waste Containment System

II. Introduction

The Pressurized Rover (PR) is a key component of NASA's Moon and Mars exploration plans. Surface mobility is a necessary capability in order to reach multiple locations of scientific interest. NASA first began researching the implications of habitation inside a pressurized rover in the 1960s. These vehicles give astronauts the ability to operate much further away from a lander or habitat than would otherwise be possible. They open a new mission paradigm as no space mission in human history has employed pressurized surface mobile assets. Their capabilities and mission impacts are substantially greater than that offered by unpressurized rovers, such as the Apollo Lunar Roving Vehicle. Depending on mission architecture, particularly number and type of vehicles present, PRs can enable traverses of 12, 20, or in excess of 100 kilometers, as measured along a known path. But during these traverses, the rover cabin is the sole habitable environment for the crew. It must support all of the crew's daily needs, both physical and psychological, while also enabling mission objectives. Thus, the habitability of a rover is just as, if not more important, than the vehicle's range and other performance statistics. Three major NASA studies have helped to shape the Agency's rover experience base and enable Artemis mission planning.

A. THE LUNAR MOBILE LABORATORY (MOLAB)

In 1964, NASA wanted to investigate if scientific investigation of the Moon was feasible for its Manned Lunar Exploration Program. Under the Apollo Logistic Support System (ALSS), a Lunar Exploration System for Apollo (LESA) was being studied. [1] This ALSS vehicle, shown in Fig. 1, would be designated the Lunar Mobile Laboratory (MOLAB). Its main objectives were to examine the possibilities of scientific exploration, long crew durations, and crew safety. [2] Housing a crew of two, the MOLAB would provide a shirt-sleeve environment for the crew to perform scientific missions. To accomplish this type of mission all forms of habitation had to be examined under laboratory conditions.

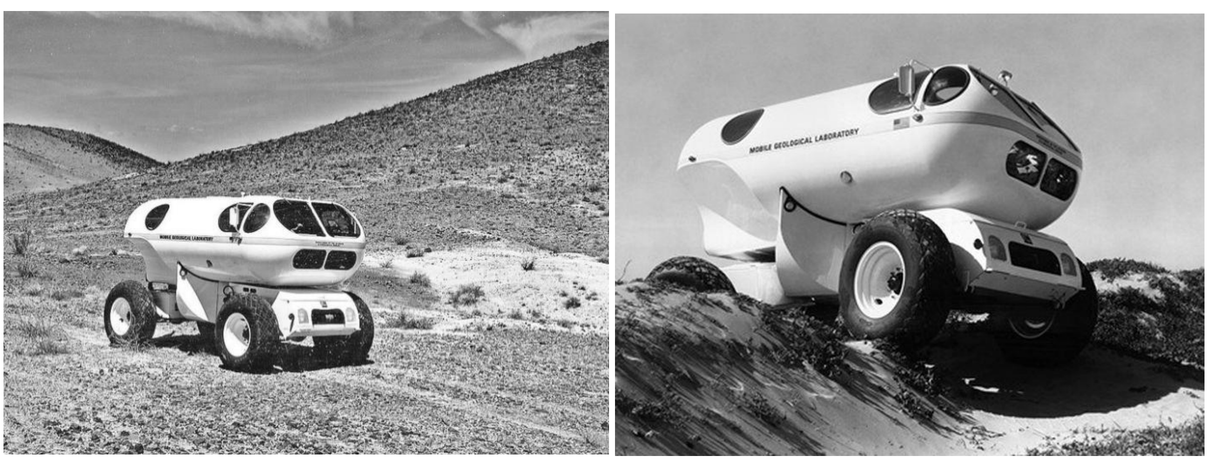

Fig. 1 The MOLAB Vehicle Testing in the Arizona Desert in the Late 1960s.

B. LUNEX II ROVER SIMULATOR

NASA and the Honeywell Systems & Research Division conducted the first simulated lunar surface mission consisting of 18-days in duration to validate a cabin design for a lunar roving vehicle [1]. The simulator used in the experiment was designated the LUNEX II, shown in Fig. 2, which housed two NASA engineers as test subjects. Subjects were evaluated by performance using simulated driving and navigation tasks, general living within the cabin, EVA tasks, emergency contingencies. Data was also collected on physiological and psychological states. Conclusions made from the LUNEX II study showed the subjects were able to maintain satisfactory performance throughout the 18-day simulation with no adverse effects [1].

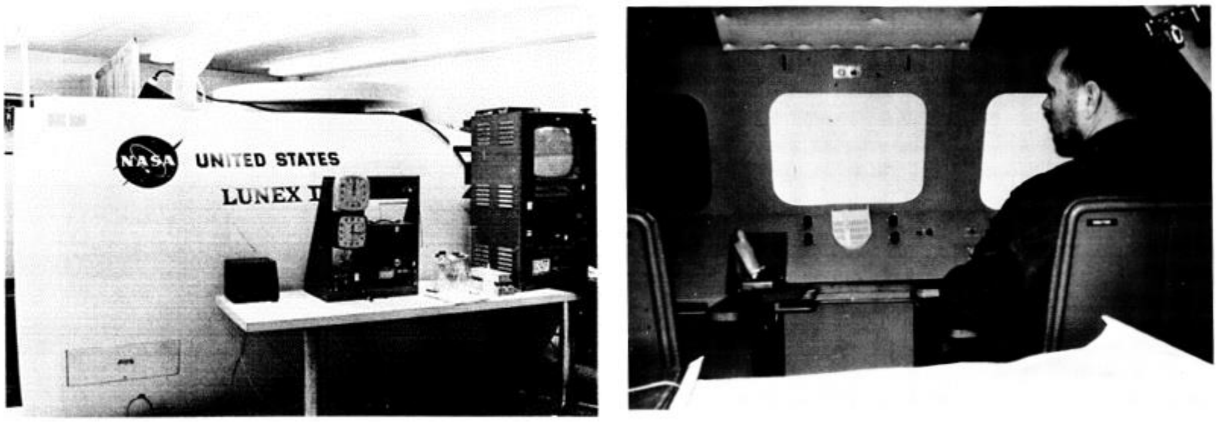

Fig. 2 The LUNEX II Lunar Rover Simulator.

C. NASA SMALL PRESSURIZED ROVER (SPR)

The NASA reference configuration of the PR was originally conceived as a Small Pressurized Rover (SPR) under the now-cancelled Constellation Program. Two first generation prototypes of the SPR were field tested in the Arizona desert from 2008-2011 under the Desert Research and Technology Studies (DRATS). Following the cancellation of the Constellation program, the SPR continued to exist and mature under various studies, leveraging the same cabin configuration as applied to a variety of missions including a lunar lander, Mars Ascent Vehicle, microgravity airlock, asteroid exploration vehicle, Phobos exploration vehicle, and the third generation design is now the Artemis program's NASA reference configuration for the PR.

The 2010 DRATS was a particularly useful analog mission because this expedition conducted two 7-day excursions using both rover prototypes, the GEN 1A and GEN 1B rovers, shown in in Fig. 3. Cabin 1A's interior volume was approximately 8.6 m^3 (303.7 ft^3). For Cabin 1B, the total interior volume was approximately 9.7 m^3 (342.6 ft^3). The difference between the two rover cabins is due to the extra 1.06 m^3 (37.4 ft^3) of volume from second side hatch, which was a design modification for Cabin 1B after the 2008 field trials.

Fig. 3 GEN 1A and 1B Rovers Used in the DRATS 2010 Field Trials.

The test environment for the two 7-day DRATS field trials occurred at the SP Mountain and Black Point Lava Flow test site; approximately 40 miles north of Flagstaff, Arizona, shown in Fig. 4. This test site has a wide variety of geologically relevant surface features that presented many opportunities to evaluate rover human performance, including both Intravehicular Activity (IVA) and Extravehicular Activity (EVA). Surface characteristics included 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 minimal vegetation.

Fig. 4 Black Point Lava Flow (left) as Viewed from the International Space Station and Ground View of the Actual Terrain as Traversed by the Rovers (right)

The DRATS excursions recognized and gave importance to understanding habitability inside the rover cabins. For a space or volume to be habitable to a human, three elements must be considered—visual, kinesthetic, and social logic. The visual aspect assesses how the inhabitants perceive the interior space as spaciousness or connotations. The suitability to accommodate human motion and movement is the kinesthetic aspect of space. How the geometric design and volume of the space for establishing social spatial proxemics, such as privacy, is the social logic element of habitation. [3] DRATS conducted comprehensive studies of lunar pressurized rover excursions and more than a third of the 182 elements tested at the 2010 DRATS examined human habitation.

During DRATS 2010, the crews spent just under 7 days in each vehicle. On the average, each crew spent approximately 14.39 hours driving, including general driving, aft driving, and traverse driving. They spent approximately 36 hours EVA, including egress, ingress, boots-on-the-surface, EVA science, and EVA translation. They conducted IVA operations for approximately 11.99 hours, including science/navigation and communications. Finally, their IVA off-duty time averaged 104.39 hours, which includes crew sleep. [4] Thus, the habitation time in the cabin during DRATS 2010 is significant, roughly 130.77 hours on average, or 78.4% of the total excursion time.

III. Artemis Notional Five-Day Science Excursion

A recent analysis performed by members of the NASA Lunar Architecture Team explored a five-day science excursion in the Pressurized Rover (PR). The analysis focused on extravehicular (EVA) activity and science objectives associated with different lunar sites of interest. The analysis demonstrated a compelling use case for the PR's ability to support geology science objectives in the lunar south polar region. Because the LAT analysis focused primarily on the science EVAs there is a need to also consider the crew habitation experience inside the PR cabin.

Some implications of this excursion are dependent on the specific surface elements and infrastructure. It is possible for the PR to be the sole habitable element, in which case there is no secondary habitation volume from which the crew can begin and end their excursion. Other than logistics stored in Suit Port Logistics Carriers (SPLCs) or Suit Port Transfer Modules (SPTMs) – both are pressurized stowage containers (large and small respectively) that can be placed on a suit port – everything must be contained within the PR and all activity must occur within the PR volume. Alternately, it is possible for the PR to be supplemented by a logistics or airlock module. The PR may or may not be able to dock by either element. In this case, some logistics can be gathered and processed in a separate pressurized element and some suit activity can be performed in a separate pressurized environment. Finally, as with the current Artemis architecture, there can also be a Surface Habitat (SH) present, which the PR may or may not be able to dock with. The presence of an SH allows for potentially extensive science, medical, and maintenance support, as well as potentially greater logistics staging volumes

This analysis will be conducted under the surface architecture used for the prior LAT study. Both the PR and SH are part of the lunar surface infrastructure but are not capable of docking to each other. EVA is required to transfer between them. The SH does include an internal airlock. Logistics are delivered in SPLCs by Commercial Lunar Payload Services (CLPS) landers and any pressurized logistics transfer between the PR and SH must be performed with SPLCs. The Lunar Terrain Vehicle (LTV) accompanies the PR, enabling it to traverse up to 20 km away from the SH by a known path.

Humans perform a multitude of tasks every day for general living and for work, and crew activity inside the cabin must be considered to ensure that the crew will be able to complete the EVA activity needed to meet science objectives. The DRATS field tests provide a useful context through which to view the LAT five-day excursion and to aid in an assessment of habitability considerations relevant to this excursion. The crew activity timelines in the excursion timeline are reasonably close to that of DRATS 2010. In the LAT five-day excursion, the crew will spend 5.78 total hours driving, 27.5 hours EVA (including ingress, egress, and boots on the surface), 17.83 hours conducting IVA operations, and will have 67.5 hours off-duty time. Thus, a total of 91.12 hours is spent in vehicle habitation, or 76.8% of the total excursion time.

While this analysis focuses on the five days of the expedition, it is clear that the excursion cannot simply begin on day one, nor does it end on day five. There is an aspect of preparation that must begin prior to the excursion and closeout activity that must be completed after the excursion is completed. Those are not investigated in this study because in the Artemis architecture the crew has access to the resources of the SH, including the two crew members based at the SH, to help conduct pre- and post-excursion activity. During the expedition, however, the crew must rely entirely on the PR for all habitation needs.

The first day begins with departure from the SH and involves two EVA activities: a site visit and sample collection from an In-Situ Resource Utilization (ISRU) facility and trash and payload operations at a CLPS landing site. The second day is dominated by a nearly six-hour EVA geology investigation near a crater rim, involving at least one permanently shadowed region (PSR) and a technology demonstration deployment. Day three is focused on a series of shorter EVAs as the rover proceeds along crater rims and includes deployment of a communications relay. Day four is another nearly six-hour EVA, focused on boulder clusters and both small and large rock exposures. It includes an EVA Public Affairs Office (PAO) media event and a science instrument deployment. Day five includes a return to the day two EVA location to recover the technology demonstration and explore a PSR before returning to the SH by the end of the crew workday. This five-day excursion includes 27.5 hours of EVA time per crew member, of which 22 hours and 40 minutes is “boots on the surface” activity. The remainder of the time (roughly 91.12 hours) is spent inside the PR.

IV. Day One Crew Habitation Activities

For this assessment, a nominal lunar exploration day starts around 6:00 am local time, when the crew is awakened by Mission Control Center (MCC) with a specified piece of music pre-selected by the crew. Once up, the crew heads into a one-hour Post-Sleep task. At night, each crew member enjoys a private bunk volume, as shown in Fig. 5.

Fig. 5 Private Space Within Crew Bunks

After waking, the crew will each stow their sleep bunk curtains and bedding, as shown in Fig. 6. NASA studies involving rover prototypes have explored various versions of the curtains to improve their functionality. DRATS studies have confirmed that the curtains must be easy to deploy and stow, block light, and suppress sound. They must encompass the sleep volume without interfering with the rest of the cabin. Accomplishing all of this in a single system remains a challenging design exercise.

Fig. 6 Crew Member Stowing Sleep Bunk Curtain

The crew will take turns with morning hygiene – body cleansing, brushing teeth, changing clothes – potentially including donning of liquid cooling and ventilation garment (LCVG) – etc. If privacy is desired, they will deploy the privacy curtains dividing the cabin into cockpit and aft sections. Hygiene is performed in the aft section. The crew member waiting in the cockpit section will review notes and plans for the day, much like the test subject in Fig. 7 is doing in Cabin 2A rover prototype.

Fig. 7 Crew Member Working in the Rover Cockpit

Once both crew have completed their hygiene tasks, they will prepare a morning meal. In the prototype vehicles used at DRATS, the meal consisted of dehydrated and shelf stable foods, though the NASA Space Food Lab has indicated the crew may need thermostabilized foods added for a more balanced diet, which would require adding a food warmer or other heating system to the vehicle. The Potable Water Dispenser (PWD) under the starboard bench is used to rehydrate food. Only one crew member can access the PWD at a time so they will take turns until all of their food is hydrated. The crew will unstow a table or other surface to place the food on as it is prepared. After dining, the crew will stow their food trash in wet or dry trash bins, shown in Fig. 8, as appropriate and will stow the table used for dining.

Fig. 8 Wet and Dry Trash Compartments

After the morning meal is completed (or during the morning meal if dining was not completed in time), the crew has a one-hour time block for Conferences, Briefings, and Suit Checkout. The Daily Planning Conference (DPC) will include Mission control updates, science goals, traverse plans, and any other information relevant to the crew workday. Any needed briefings on equipment to be used during the upcoming workday will be given. The crew will perform checkouts on their spacesuits, ensuring both suits are ready for lunar surface EVAs.

At 8:00 am local time, the crew workday begins. The crew configures the LTV to autonomously follow the PR and they drive the PR away from the SH, headed towards the ISRU processing plant. Located 1.68 km from the SH, the plant is a 12-minute drive. One crew member (designated EV1) will drive while the other (EV2) conducts a last-minute review of procedures. The cockpit, shown in Fig. 9 is designed to give the crew an unobstructed view of the lunar terrain.

Fig. 9 Cabin 1B Cockpit Illustrating Wide Field of View Provided to Crew

At 8:12 am they arrive at the plant, where they are to perform an inspection and sample retrieval. The first 45 minutes of the ISRU plant visit is a maintenance inspection. This begins with a slow drive around and photo documentation of the plant. As EV1 maneuvers the vehicle, EV2 trains the PR's high resolution, steerable cameras and other imagers on mobile and fixed ISRU assets. Upon completion of this task, EV1 will drive over to the ISRU plant and park. The two will then open the suit port hatches and ingress their spacesuits for the sample collection portion of the site visit.

At 10:12 am, EV1 and EV2 will return to the PR and will complete ingress by 10:32. They will have a seventeen-minute drive to the CLPS landing site. EV2 will use the traverse time to prepare and transmit reports on the ISRU activity. By 10:50 am, they will have arrived at the CLPS lander.

The two will re-enter their spacesuits and egress the cabin. They will spend ninety minutes performing tasks related to SH trash disposal (having carried SH trash to this site on the LTV), landing beacon deployment, and retrieval of science and technology demonstration payloads from the lander to be used during the five-day excursion. They will return to the cabin by 12:40 pm to begin ingress.

The crew will have their midday meal at 1:00 pm. Just as with breakfast, the crew will set up a table and alternate using the PWD to rehydrate their food. Preparing and eating their meal and performing post-meal clean-up will likely not take the entire hour and any additional time will be available for the crew to rest and reset for the remainder of the day. This small amount of intentional downtime will help the crew to sustain high levels of performance for the tasks later in the day. It gives them time to refresh and collect their thoughts about the morning activity.

At 2:00 pm, the crew will depart the CLPS landing site and begin a 53-mintue drive to the first science site. EV2 will conduct opportunistic observations of the lunar terrain as they drive, but there will be no option to divert for opportunistic science EVAs along the way. Any interesting observations will be flagged for follow-up in future traverses. EV2 may also take advantage of the traverse time to clean the interior and PLSS of his or her spacesuit and prepare it for the next day. EV2 may take over driving to allow EV1 to do the same.

At 2:53 pm the PR will arrive at the first science location. The crew will spend the next two hours conducting pre-egress observation and analysis. They will drive the PR and teleoperate the LTV into at least one permanently shadowed region, through at least four boulder fields, and along a crater rim. They will scout potential EVA sample collection sites and candidate sites to deploy a technology demonstration package.

At 4:53 pm they will park the PR and LTV with the solar arrays facing the sun so the vehicles can recharge overnight. They will have until 6:00 pm to perform any suit cleaning and will change out of their LCVGs.

From 6:00 pm to 6:30 pm the crew will have an evening DPC and science briefing. These meetings will recap the day's activity and provide any additional information the science teams on Earth will need for overnight processing. Between 6:30 pm and 8:30 pm the crew will conduct their daily exercise and have their evening meal. Exercise protocols may be adjusted as needed but will generally consist of 30-45 minutes of aerobic and resistive exercise.

At some point during the day, the crew will have each held a Private Medical Conference (PMC) with the flight surgeon. The small size of the PR makes such a conversation difficult to hold privately. To the extent possible, these will be scheduled where the crew is divided as possible. The best candidates are to hold them while one crew member is either engaged in personal hygiene or exercising, leaving the other crew member in the cockpit with the best privacy available.

Pre-sleep begins at 8:30 pm and lasts until 10:00 pm. This is unregulated free time for the crew and includes any pre-sleep tasks such as hygiene, organizing notes, maps, photos, etc. for the next day, and recreational activity, much like the test subjects shown in Fig. 10. Crew have been known to watch movies or just discuss general topics.

Fig. 10 Crew Relaxing During Unscheduled Time

The crew sleep period begins at 10:00 pm and lasts until 6:00 am the following morning. The crew will not be contacted by Mission Control during this time unless there is a vehicle emergency or condition that requires immediate response. Quality of sleep is an important vehicle consideration and has led to many redesigns of the NASA prototype rover's sleep curtains. As previously mentioned, ease of setup, sound attenuation, interference with cockpit seats, and prevention of light leaks, shown in Fig. 11 and Fig. 12, are major concerns that still to some extent remain unresolved.

Fig. 11 Interference Concerns and Light Leaks in Rover Cabin Crew Bunk Curtains

Fig. 12 Modified Sleep Curtain Configuration Intended to Reduce Light Leaks

V. Day Two Crew Habitation Activities

Day two begins at 6:00 am with another musical wakeup call from MCC. As before, the crew will reconfigure the cabin from night ops to day ops, engage in hygiene, don LCVGs, and have breakfast. As mentioned previously, this will often involve one crew member accessing items in the rear of the cabin while the other crew member is busy in the cockpit, shown in Fig. 13. The curtains continue to be useful to provide privacy or when toilet ops are needed, as shown in Fig. 14.

Fig. 13 Morning Cabin and Cockpit Activity

Fig. 14 Use of Privacy Curtains for Toilet or Hygiene Activity

The 7:00 am conferences will discuss specifics for the day's surface EVAs. The overnight science teams will have spent the night reviewing video and other sensor data collected by the PR and LTV yesterday and will issue specific guidance for the day's EVA and sample collection goals. Following the briefing the crew will conduct suit checkout.

At 8:00 am the crew will egress the cabin and at 8:30 am will begin a five-hour and forty-five-minute EVA. The crew will be operating within a roughly 1500-meter diameter. Aside from surface science the EVA may involve PR aft station driving (driving the vehicle from the aft deck of the vehicle), LTV driving, and accessing tool and equipment stowage on both vehicles, but the crew will not ingress the PR at all during this time.

The crew will return to the PR at 2:15 pm and will complete their ingress by 2:35 pm. They will have an hour for their midday meal and to recover from the long EVA.

At 3:35 pm they will begin a 27-minute traverse to the next science site, a crater rim, arriving by 4:02 pm. They will conduct a 30-minute driving inspection of a portion of the rim and a boulder cluster. During this time, they will also survey the terrain to identify a location to deploy a communications relay. At the end of this inspection and survey they will park both the LTV and PR such that their arrays face the sun for overnight charging.

The workday will conclude at 4:32 pm. This will give them a little more time to complete suit cleaning activity before the evening DPC and science briefing at 6:00 pm. The evening briefing will primarily focus on the morning EVA at site 1, but science teams will be able to share preliminary information on the survey the crew just completed on site 2. Following the DPC and briefings, the same evening schedule of exercise and evening meal from 6:30 - 8:30 pm will repeat, with unscheduled pre-sleep free time from 8:30 - 10:00 pm and crew sleep from 10:00 pm to 6:00 am.

It should be noted that at some point in the surface mission, some degree of personalization will begin to manifest within the cabin. Even during the DRATS and local JSC field tests, the crews were inclined to set up personal items surrounding their bunk/bench, as shown in Fig. 15.

Fig. 15 Setup of Crew Personal Items Within Bunks During Analog Missions

At some point during either the exercise/meal period or pre-sleep they will conduct some cabin housekeeping. Over the course of the busy expedition days it is easy for things to not get put back in their proper places. As Fig. 16 shows, without scheduling time for housekeeping the rover can become uncomfortably cluttered. As with Day One, the PMCs will be scheduled as discreetly as possible.

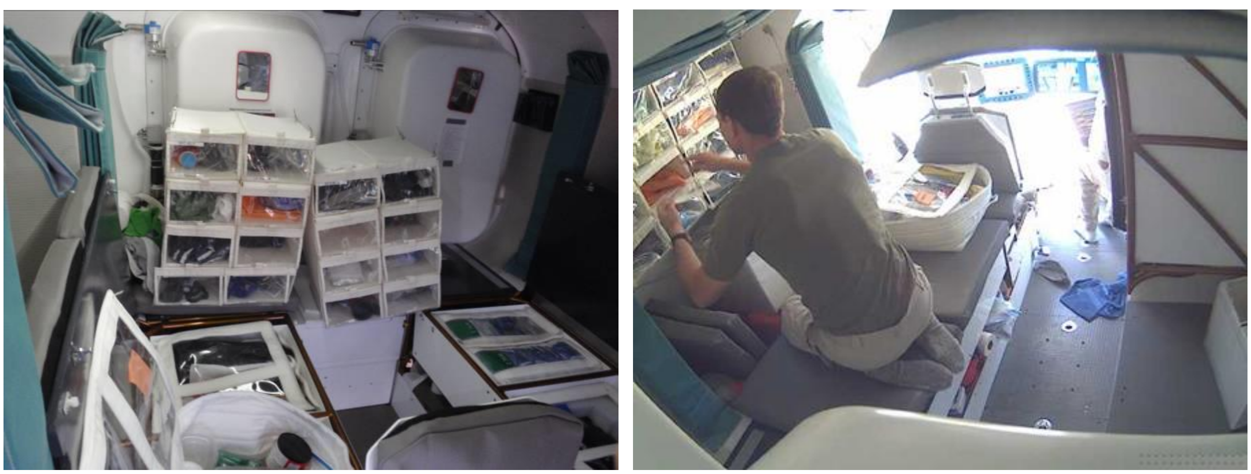

Fig. 16 Rover Cabin Requiring Housekeeping

VI. Day Three Crew Habitation Activities

Day three will feature a third musical wakeup call from Earth, again at 6:00 am. The morning routine will be identical to the prior two – sleep station stowage, personal hygiene, LCVG donning, and breakfast, followed by a 7:00 am conference with Earth. An image of Cabin 1A from desert testing in Fig. 17 shows the starboard sleep station with the privacy curtains folded up but bedding not yet stowed and seat not yet reconfigured for daytime ops. Day three includes a number of short EVAs so the morning briefing will divide its time to give brief treatment to each exploration site. The briefings will be concluded in time for the crew to perform their suit checkouts prior to 8:00 am.

Fig. 17 Sleep Station Just After Starboard Station Curtain Stowage

At 8:00 am, the crew will ingress their suitports to begin the first EVA. This is a two-hour and fifteen-minute EVA that will investigate a boulder cluster, deploy a communications relay, and deploy a science instrument.

At 10:45 am the crew will return to the PR and ingress the cabin. At 11:05 am they will begin a 20-minute drive to the next science site – a broad area of isolated boulders and boulder clusters. Arriving at 11:25 am, they will observe and analyze this area for 15 minutes, driving the PR and teleoperating the LTV, using their capabilities to survey the region and prioritize EVA locations.

The second EVA of the day will begin at 11:40 am and will last for 45 minutes. The crew will ingress the cabin at 12:45 pm and begin the midday meal at 1:05. An hour later, the crew will depart the site and begin a twenty-minute drive to the next science location. At 2:26 pm, the crew will begin a 15- minute driving survey of the site to scout for the next EVA.

At 2:41 pm one crew member will egress the cabin for the third EVA of the day. At 3:01 pm that crew member will begin a 65-minute EVA. The first 20 minutes of this EVA will involve PR trash operations. DRATS testing revealed that after several days of living in the cabin, the smells of accumulated trash and waste had become intolerable. Thus, trash removal was incorporated into rover expeditions, conducted at crew discretion every two to three days.

The EVA crew member will retrieve a SPTM and position it on the vacated suit port. The IVA crew member will gather wet trash, dry trash, and human waste from their respective receptacles, as shown in Fig. 18, and place them in the SPTM. The EVA crew member will then remove the SPTM from the suit port and stow it on the rover aft deck, like the DRATS test subject in Fig. 19. Trash will remain in that SPTM until the rover reaches a location where it can be dumped.

NASA has not yet determined how it will dispose of trash permanently. The idea of open dumping on the lunar surface is occasionally raised but is generally not taken seriously. On the Moon, burying trash is a possible option, but this is not considered a Mars forward solution. A potentially promising option is to hold the trash until the rover can travel to a discarded Human Landing System or CLPS lander. There, the crew can cut open and use a propellant tank of the spent lander as a location to dump trash. This option, of course, assumes that there are spent landers on the lunar surface. Some commercial providers are proposing reusable landers that could launch back into space and those would not be available. Another option simply leaves the trash in the SPTM. When a SPTM is filled with trash it is retired from use and simply stockpiled at the basecamp or in a crater. Final disposition of trash remains a forward work item and will be driven by other architectural decisions. However, none of these trash disposition options change how trash is removed from the cabin interior.

Fig. 18 IVA Crew Member Loads Trash and Waste into SPTM

Fig. 19 EVA Crew Member Waiting to Remove Trash-Filled SPTM

The IVA crew member will remain in the cabin and support the EVA crew member from the cockpit for the next 45 minutes. This single-person EVA will investigate broad area of isolated boulders and boulder clusters. The EVA crew member will ride on the rover aft deck to be transported between sample collection sites of interest within this site. It is faster to complete this EVA as a single-person EVA than to take the time for the other crew member to egress the suit port.

At 4:06 pm the EVA crew member will ingress the cabin. At 4:26 pm, the crew will drive another twenty minutes to the next site of interest. Upon arrival at 4:46 pm, it is near the end of the workday and too late to begin any activity at this site. They will park both LTV and PR with the arrays positioned to charge their batteries.

The crew will have until 6:00 pm to clean their suits and prepare them for the next day's activity. The evening DPC and science briefing will recap the sample collections and discoveries made over the course of the day and MCC will end communications and leave them to their evening at 6:30 pm. As with the previous two days, the next two hours will be allocated to exercise and their evening meal, with the PMCs potentially occurring during exercise periods with the non-exercising crew member. At 8:30 pm, pre-sleep and free time will begin, with the crew once again going to sleep at 10:00 pm.

It is important that the crew be able to sleep uninterrupted and as such a key design driver for the sleep stations has been for neither station to interfere with the waste containment system (WCS) when deployed. The idea was that either crew member could open their sleep station at night, such as shown in Fig. 20, translate to the WCS, and use the facility without physically disturbing the other crew member. The camera in Fig. 20 is behind and above the WCS, looking down at the WCS and the sleep bunks to either side of it. The crew member in the port bunk is opening his or her sleep station and can access the WCS while the starboard bunk remains undisturbed. Another camera view from a Cabin 2A human-in-the-loop test in Fig. 21 shows a test subject headed towards the WCS after having already egressed her crew bunk while the second crew member remains undisturbed.

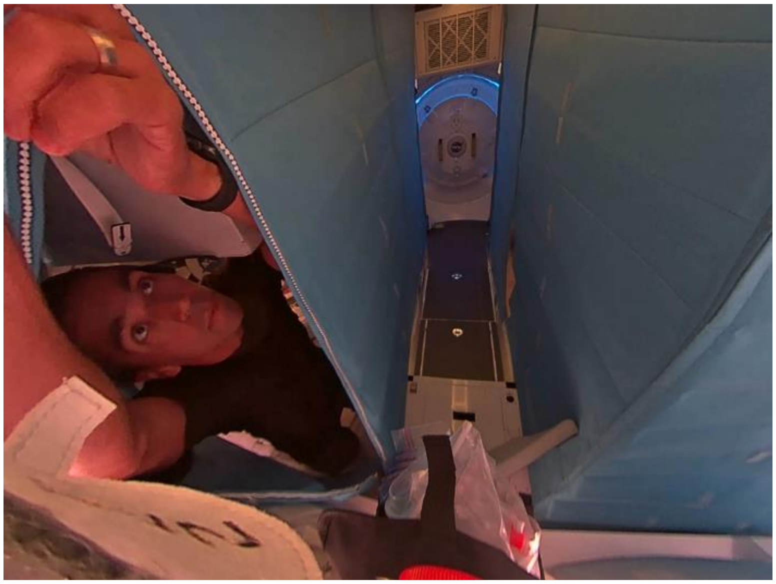

Fig. 20 Crew Member Opening Sleep Curtain Adjacent to WCS Without Disrupting Other Crew Member

Fig. 21 Crew Member Headed to WCS at Night Without Disrupting Other Crew Member

VII. Day Four Crew Habitation Activities

Promptly at 6:00 am, the crew will be awakened by Mission Control. Moving into their post-sleep routine, the two crew will trade places between the front and back of the cabin, like in Fig. 22, as they perform personal hygiene, don their LCVGs, configure the cabin for daytime operations, and have breakfast.

Fig. 22 Crew Members Using Privacy Screens to Separate Front and Back of Cabin

At 7:00 am they will participate in the daily DPC and science briefing. The entire day will be spent at one large site; thus, the briefing will recap the operational details and science priorities to focus the crew's time. The balance of the hour will be spent preparing their suits for EVA.

The crew will activate the mobility systems of the PR and LTV at 8:00 am and begin an 80-minute observation and analysis of the site. This will include multiple boulder clusters and large rock exposures.

At 9:20 am the crew will park both vehicles with arrays positioned for charging and head for the suit ports to egress the PR. By 9:50 am they will have stepped out onto the lunar surface to begin their EVA activity. For the next 5 hours and 45 minutes they will configure and deploy a science instrument, conduct a public outreach event, and conduct field science throughout the site area. Because this is a large area, they will periodically relocate the vehicles, either driving the PR from the aft driving station or driving the LTV, with the other vehicle autonomously following behind. Each time they will park the vehicles in an orientation where the arrays can charge from the sun.

At 3:35 pm they will return to the suit ports for ingress. By 3:55 pm they will have completed their ingress and will prepare a late midday meal. They will clean up from their meal at 4:55 pm. From this time until 6:00 pm they will clean and service the interior of their spacesuits and their PLSS.

The ground will contact them at 6:00 pm for the evening DPC and science briefing. At 6:30 pm the exercise and evening meal period will begin, though it is likely that given the late midday meal, the crew will only exercise during this period and move the evening meal to later. This will effectively begin the post-sleep free time early. As some time has passed since the last housekeeping activity, the crew will use some of this time for housekeeping and will have the evening meal at some point prior to 10:00 pm, when crew sleep begins.

VIII. Day Five Crew Habitation Activities

The final day of the excursion will begin with the 6:00 am wake-up from Mission Control. Executing the post-sleep routine, the crew will complete their cabin reconfiguration, personal hygiene, dressing, and breakfast activity in time for the 7:00 am DPC and science briefing. The briefing will include not only science objectives but also key vehicle safety discussions due to the nature of the upcoming EVA.

At 8:00 am the crew will begin an 89-minute traverse to the location of the final science investigations of this excursion. Upon arrival at 8:29 am, the crew will begin a driving survey of the area, with emphasis on all sample collection sites, several of which are inside a PSR.

At 10:29 am, the crew will enter their spacesuits via the suitports and by 10:59 am will begin their EVA. They will spend 45 minutes recovering and stowing a previously deployed technology demonstration package and will then drive into a PSR – either driving from the PR aft driving station or driving the LTV. Inside the shadowed crater, they will spend two hours conducting scientific investigations. They will exit the PSR by 1:44 pm.

At 1:44 pm, the crew will ingress the PR cabin and at 2:04 pm they will begin their midday meal. At 3:04 pm they will begin an 83-minute traverse back to the SH, arriving at 4:28 pm, parking with LTV and PR arrays facing the sun. This is sufficiently close to the end of the crew workday that there will be no further mission activity until the next day, when they will join the SH crew to take part in post-excursion basecamp operations.

From 4:28 pm to 6:00 pm they will clean and service their suit interiors and PLSS. At 6:00 pm they will have their final excursion DPC and science briefing with the ground, reviewing the day's mission activity and any final details related to the prior four days.

The crew will have their daily exercise and evening meal period from 6:30 pm to 8:30 pm. At 8:30 pm they will begin their pre-sleep, free time period. This will likely be an opportunity for a social videoconference with the SH crew, who will also be in a free time period. Within their private sleep stations, they have access to all of their personal items, as shown in Fig. 23, and thus have numerous options for use of personal time. At 10:00 pm the crew will begin their sleep period.

Fig. 23 Access to Personal Items from Inside Private Bunks

IX. Fatigue Considerations

Given the high intensity of the PR excursion, it is important to consider the possibility of crew fatigue. During the DRATS 2010 field test, human factor engineers and operational planners learned quite a bit about timeline flow, task quantity and habitability factors that affect the crew's fatigue. The Fatigue Rating Scale is a 10-point Likert scale (1 – 10) where 1 means "no fatigue-performance not compromised" and 10 is "extreme fatigue-unable to continue with adequate performance." This subjective scale was developed to measure the amount of fatigue or energy required to perform each mission operation at a specific time. Over the course of 14-days (two 7-day excursions with two vehicles and four different crews) the DRATS data set collected consisted of obtaining crew fatigue ratings before the mission duty day began (pre-mission) and after the mission duty day ended (post-mission) for the entire mission.

The terminology used to identify the crews during the 2010 field test is as follows:

- A Crews = Crews of Cabin 1A during first and second 7-day excursion
- B Crews = Crews of Cabin 1B during first and second 7-day excursion
- Crew A1 = Crew of Cabin 1A during the first 7-day excursion
- Crew A2 = Crew of Cabin 1A during the second 7-day excursion
- Crew B1 = Crew of Cabin 1B during the first 7-day excursion
- Crew B2 = Crew of Cabin 1B during the second 7-day excursion

The typical duty day for the crew was 12 hours during the field trial from 6am (post sleep) to 9 pm (the sleep period). For pre-mission data, crews for the first seven-day mission tended to fall within the "no fatigue performance not compromised" range of scores. These crews reported getting good sleep during most of the mission. They did indicate that noise from the AC vent fans and lights from the cockpit area occasionally disturbed them. This low average score also indicated the crews were able to recover from their EVA events as well throughout the mission. As for their post-flight fatigue, the A1 crew stayed steady throughout their mission at a minor fatigue or lower rating. However, the B1 crew recorded a spike of 5.0 indicating moderate fatigue where performance would likely be compromised if continued. On this day, the B1 crew embarked on a 3 to 4-hour EVA down into Colton Crater, shown in Fig. 24, which was reported by the crew as physically demanding. However, when examining this same crew's pre-fatigue score, they were able to recover with ease.

Fig. 24 Crew B1 Starting their Descent into Colton Carter on DRATS Mission Day 5.

The second set of crew for the last two seven-day missions on the pre-flight fatigue scores shows some mixed but steady ratings. Crew A2's pre-flight fatigue matches very close to the previous A1 and B1 crews with the score at the no fatigue level. Crew B2, however, recorded a steady score of 3.0 to 3.5 indicating they showed minor fatigue with performance not compromised. As for the 2A and 2B crews' post-flight data, both crews indicated a fatigue spike on Days 10 and 11. For crew A2, they had two EVAs that were physically demanding and long in duration. One EVA being on steep slopes while the other was a repeat of the Colton Crater EVA completed by Crew B1 several days earlier. Crew B2 also reported physically demanding EVAs on these days as well. In both cases, each crew was able to fully recover for the following day.

Pre- and Post-Flight mission fatigue data was also collected during the 2008 and 2009 field trials [5], [6]. A comparison both from a daily crew perspective and from a mission duration perspective was examined. Over the course of crews' mission duration, pre-flight fatigue ranged from no fatigue, as indicated by the 3-day missions, to minor fatigue, as indicated by the 7- and 14-day missions. This indicates the crews were able to recover from EVAs or just normal daily activities and started the next day renewed. Post-flight fatigue comparison data shows a mix of scores between crews. Crews who participated in 3-day mission durations tended to score their post-fatigue lower than crews who participated in longer duration missions. Crews who participated in the 14-day mission recorded the highest post-fatigue scores of 5.0 indicating moderate fatigue where performance would likely be compromised if continued. It should be noted that mission fatigue encompasses all crew activity. Differences between scores are anticipated due to the variety of EVA apparatus used by the different crews on different missions. On the 14-day mission, the crew also had a cabin air conditioner failure which caused the cabin of the vehicle to remain hot for most of the mission. For the 7-day crews, their missions had the most physically demanding EVAs out of all the missions and traversed more rugged terrain than the crew before them. However, by the end of their missions, the crews reported the post-fatigue at a more acceptable score.

The implication gleaned from the DRATS experience is that the PR cabin provides a place of rest and recovery for the crew. The prototype cabins were designed specifically to achieve high levels of crew comfort and usability. According to test data they were successful. Depending on the type of EVA and design aspects of the spacesuit, the actual crew fatigue may vary from mission to mission and may deviate from pre-mission predictions. However, assuming the flight vehicle has comparable habitability to the ground prototypes, the time spent in the rover between EVAs will have a therapeutic effect on the crew, preparing them for the next EVA.

X. Conclusions/Recommendations

Rover cabin design is very important in ensuring that the pressurized rover can remain habitable over the course of an excursion. The DRATS field testing was invaluable in refining the design of the NASA PR reference design.

Comparing habitability data from the PR prototype testing, over the course of 3-, 7-, and 14-day mission durations, sleep station curtains, stowage, and trash/waste management are the issues crews cited the most frequently as habitation issues needing to be improved. (While this indicates these issues as areas of focus for the NASA reference design, a clean sheet rover concept would need a similar level of testing to drive out its areas of concern, which may or may not be the same.)

Both environmental and architectural factors can have an effect on the quality of sleep a crew member receives during their mission. During the DRATS 2010 mission, the main issues with the sleep station dealt with seat reconfiguration for sleep station setup, sleep quality, lighting quality within the sleep station, and lighting control within the sleep station.

Noise was a major issue impacting sleep quality, especially noise caused by the air conditioner compressor and communications speakers. Velcro on the GEN 1 sleep station curtains tended to be noisy when getting in or out of the sleep station, disturbing the sleeping crew member. Crews suggested a draw string or zipper on the curtains would be less disruptive. (Zippers and magnets have been implemented in the second-generation cabins.) Lights from the cockpit area were also noted as affecting their sleep. The quality and control of lighting in the sleep station was a concern as well. Crews wanted a way to control the vehicle's general interior lights from within the station. Both vehicle crews noted there were a lot of Light Emitting Diodes (LEDs) blinking around the vehicle at night and wanted a way to control the intensity. The crews suggested placing the lighting for each side of the vehicle under separate controls so the crew member can control the lights of one side without affecting the lighting on the other.

These and other crew comments were implemented in each successive generation of rover prototype as the NASA team progressed through the GEN 2A and GEN 2B cabins. It is at this point unclear if the GEN 3A cabin will be built, but its design represents nearly fifteen years of lessons learned from human-in-the-loop testing.

According to the DRATS crews, the internal volume of the rover would be tolerable for a two-week mission especially when a routine develops amongst the crew and stowed items. However, they also felt the length could be an ordeal if performing EVAs were not possible. This, and several other open issues lead to a number of important, unanswered questions that impact pressurized rover habitability on the lunar surface:

1. How long can the crew operate effectively in the PR before needing to transfer to a more habitable surface facility? And once there, how long do they need to recuperate before going out in the rover again?
2. How much activity is required at the Artemis Basecamp to complete post-excursion activity and pre-excursion actions for the next one?
3. How much time is required for maintenance between excursions? This may include repair of known failures, inspection of vehicle systems, and general housekeeping/cleaning and consumable item replacement.
4. The crew activity during the five-day excursion is intense. How many times can such an excursion be repeated before there is a performance decrement in the crew?
5. Will the pace of EVA activity in the five-day excursion leave the crew too tired for the indicated IVA activity?
6. How will the actual fatigue of lunar surface crews compare with the fatigue experienced during analog tests?
7. If one or more days of EVA are cancelled due to solar particle events, how will this impact crew habitation?
8. If one or more days of EVA are cancelled due to spacesuit failure, how will this impact crew habitation?
9. If one or more days of EVA are cancelled due to crew injury, how will this impact crew habitation?
10. If non-EVA days are scheduled to conduct IVA science in the cabin (e.g. human research, biology, physics), how will this impact crew habitation?
11. If one or more days of EVA are cancelled due to scheduled or unscheduled IVA maintenance or repair, how will this impact crew habitation?
12. If one or more days off are scheduled in lieu of EVA activity, how will this impact crew habitation?
13. How will dust mitigation be maintained if the PR cabin is used as an airlock? (e.g. as a contingency operation to ingress a crew member due to inability to use the suit port, or if a suit must be brought into the PR cabin for maintenance that cannot be conducted at the SH)

There is room to believe that non-EVA days might have either a positive or negative impact on crew habitation, depending both on the reason and frequency for those days. These questions present hypotheses that could be tested in DRATS-style campaigns. Perhaps as a bookend, it might be valuable to create a five-day PR science excursion that is entirely based on IVA science with no EVA activity other than that required for trash removal. Additionally, two full 33-day lunar simulations could be conducted in a DRATS campaign: one with alternating 5-day IVA and EVA science excursions, and one with repeating 5-day EVA excursions with minimum pre-/post-excursion activity.

Finally, the five-day excursion discussed in this paper was based on an Artemis suit port assumption that the first EVA of the day will require 30 minutes to egress the cabin via the suit port and 20 minutes to ingress. Subsequent EVAs during the same day will require 20 minutes for cabin egress. These durations are EVA program assumptions that have not been validated with high fidelity spacesuit and suitport integrated tests. During the Constellation Program, the Small Pressurized Rover team carried an assumption of 10 minutes each for cabin egress and ingress via suitport. These estimates can not be verified until high fidelity surface suits and suitports exist, but any changes in their values have the potential to create ripple effects throughout the five-day excursion.

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