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Life Sciences Implications of Lunar Surface Operations

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1. Document Purpose and Scope

The purpose of this report is to document preliminary, predicted, life sciences implications of expected operational concepts for lunar surface extravehicular activity (EVA). Algorithms developed through simulation and testing in lunar analog environments were used to predict crew metabolic rates and ground reaction forces experienced during lunar EVA. Subsequently, the total metabolic energy consumption, the daily bone load stimulus, total oxygen needed, and other variables were calculated and provided to Human Research Program and Exploration Systems Mission Directorate stakeholders. To provide context to the modeling, the report includes an overview of some scenarios that have been considered. Concise descriptions of the analog testing and development of the algorithms are also provided. This document may be updated to remain current with evolving lunar or other planetary surface operations, assumptions and concepts, and to provide additional data and analyses collected during the ongoing analog research program.

2. Introduction

2.1. Background

Just over 80 hours of extravehicular activities (EVAs) were performed during the entire Apollo program. Scenarios that have been considered by NASA's Exploration Systems Mission Directorate could involve as many as 30,000 hours of lunar exploration EVA time over the span of the program. These plans represent a significant increase in EVA hours in an extreme and challenging environment. No previous astronaut or spacesuit has performed more than three lunar EVAs, yet under current assumptions future astronauts and their EVA suits must be capable of performing more than 600 hours of lunar EVA during a 6-month mission. Accordingly, it is critical to understand the effect that these mission scenarios will have on crew health and performance.

For example, it is important to understand the metabolic profiles of proposed EVAs to ensure that adequate life support, thermal regulation, nutrition, and hydration are available. The amount of cardiovascular and resistive exercise provided by EVA should be determined to ensure that exercise countermeasures will be adequate to prevent muscle and bone loss and limit overall crew deconditioning during long-duration missions. In addition, Apollo astronauts experienced suit-induced trauma to fingertips and other areas after only two or three lunar surface EVAs.[1] Countermeasures and/or operational procedures to limit trauma will therefore be necessary to enable crewmembers to perform the high frequency of EVAs envisioned for future missions.

Other challenges include the risk and consequences of a significant solar particle event (SPE), galactic cosmic rays, the need to extend exploration to potentially hundreds of kilometers from an outpost, and the increased decompression sickness risk and pre-breathe requirements associated with 55 kPa (8 psi) /32% O_2 cabin pressure compared to 34.5 kPa (5 psi) /100% O_2 in the Apollo Program. Activities being conducted in an attempt to address these risks include human testing in pressure chambers under controlled, scientific protocols, designed to better understand the risks so that surface systems can be designed to mitigate them. Additionally, novel surface systems are being designed to shield astronauts from SPEs by making areas of rovers and habitats "safe zones" in which they can wait out events (see 2.2.1, Space Exploration Vehicle). Also, should astronauts become incapacitated in spacesuits on the lunar surface due to system failure, injury, or illness, systems and techniques are being tested in analog environments to safely, effectively, and efficiently stabilize and transport them to an area where they can be treated and evacuated from the lunar surface.[2]

2.2. Lunar Surface Systems

The Lunar Surface Systems (LSS) Project Office was created in August 2007 with the following mission statement:

> Develop a sustained human presence on the Moon to promote exploration, science, commerce, and the United States' preeminence in space, and to serve as a stepping stone to future exploration of Mars and other destinations.

The LSS studied several possible lunar surface scenarios with the intent of fulfilling the above mission statement. Multiple scenarios were studied that reflected different priorities and technologies that may be available. The intent of developing multiple scenarios was to analyze and compare the ability to achieve exploration objectives in different ways to enable decision making. To provide context for the following discussions, one particular scenario, scenario 12, is described here in some detail. Scenario 12 should therefore be considered an example of a possible lunar surface scenario with the understanding that many aspects may change. As noted in Section 1, this document may be updated as necessary to reflect ongoing changes in the lunar scenarios.

2.2.1. Space Exploration Vehicle

The Space Exploration Vehicle (SEV) rovers (Figure 1 and Figure 2) are a key component of many of the scenarios studied for lunar surface operations. The SEV rovers are intended to optimize human safety and performance in planetary exploration by combining a comfortable shirtsleeve, sensor-augmented environment for gross translations and geological observations with the ability to rapidly place suited astronauts on the planetary surface to take full advantage of human perception, judgement, and dexterity. Each SEV rover is slightly larger than the unpressurized Apollo rover. The front cabin of the rover provides a pressurized shirtsleeve environment at the same pressure as the habitat or lander. Each SEV rover has two suit ports, enabling both rapid egress to the planetary surface and rapid ingress to the shelter of the rover in response to solar particle events (SPEs), suit malfunctions, or medical emergencies. A side hatch that mates with the habitat, lander, or other SEV rovers enables transfer of personnel and equipment under pressure. This capability, along with the capability to quickly step into the suits and perform surface operations, results in crewmembers leaving the rover for only the limited portions of an EVA sortie that require the superior perception, judgement, and dexterity of an astronaut in an EVA suit. It may also enable single-person EVA operations wherein one crewmember performs boots-on-surface EVA tasks with intravehicular support from a second crewmember that remains inside the SEV rover. The SEV rovers also have an EVA driving station, enabling them to be operated by a crewmember in an EVA suit, with all the advantages of an unpressurized rover (UPR).

Because the SEV rovers are capable of multi-day or week-long sortie durations, rather than the range-limited (8-hour) EVA activities achievable with a UPR, the overhead of returning to the outpost or lander at the end of each day will be avoided, and exploration range may be significantly greater than with UPR operations. Furthermore, because each SEV rover is a backup to the other and capable of supporting four crewmembers in a contingency return to the base or lander, a system of two SEV rovers provides greater range capability than a single larger pressurized rover. Data from the 2008 Desert Research and Technology Studies field test demonstrated that this combination of features and capabilities increased the productivity of EVA time by an average of 370% during exploration, mapping, and geological operations compared with using a UPR vehicle (3).[3] The SEV rovers are designed to support 3-day traverses away from an outpost or other location where power and consumables can be resupplied. To enable traverses of longer range and lasting up to 14 days, each SEV rover can carry a deployable Portable Utility Pallet (PUP), which incorporates a solar array, additional energy storage, gas and water consumables, and communication equipment. Thus, traverses up to 14 days are achievable with SEV rover and PUP combinations.

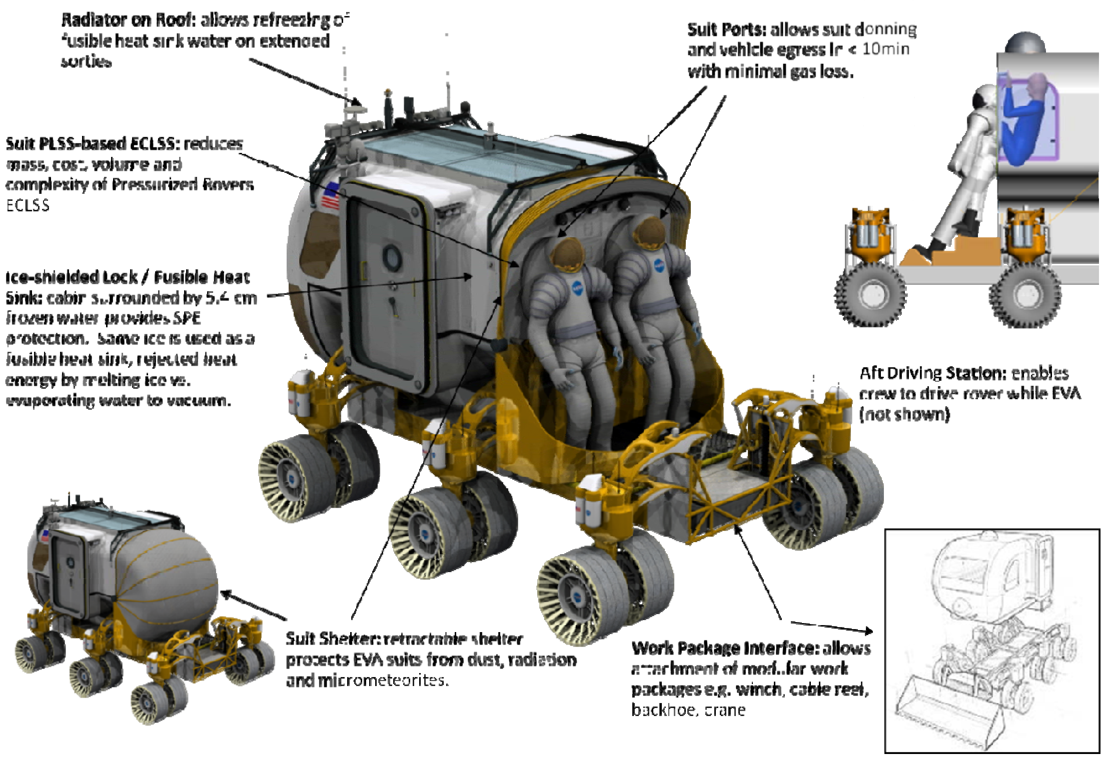

Figure 1 – Space Exploration Vehicle (SEV) Rover features, including ice-shielded lock for SPE protection

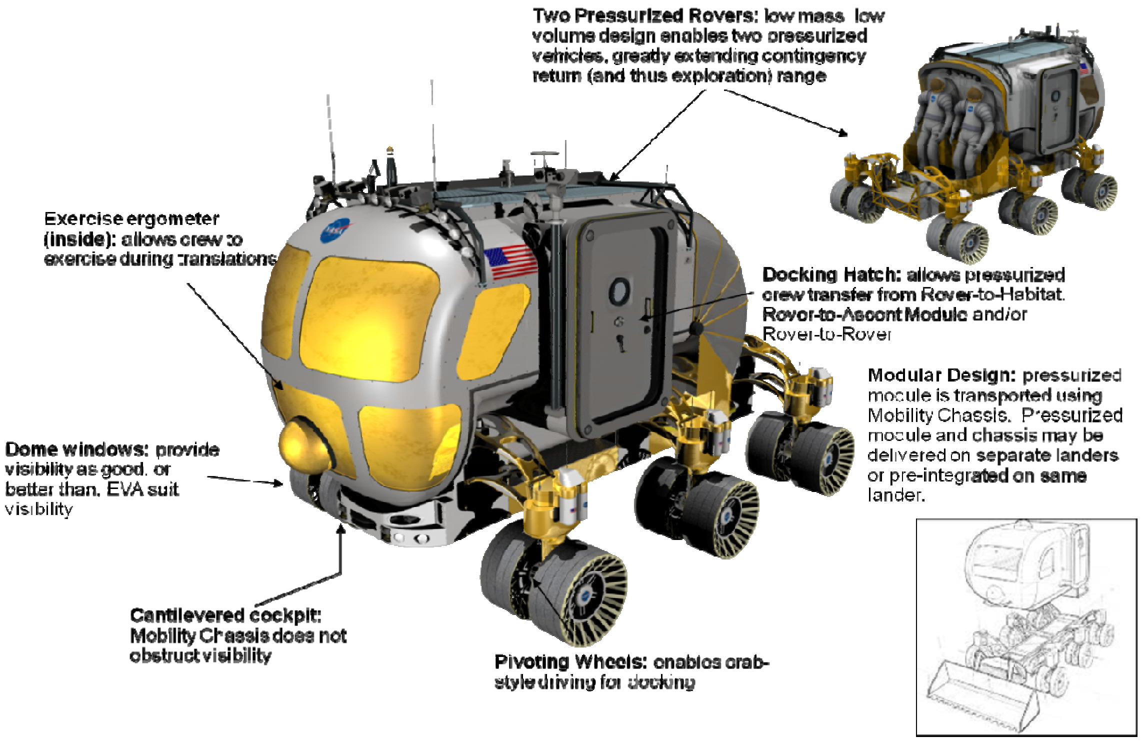

Figure 2 – Additional SEV rover features

2.2.2. Lunar Surface Scenario 12

Scenario 12 aimed to develop a fully functional polar outpost as early as possible. Several lunar sortie missions (landers with crew to utilize whatever surface components were available at the time) were included in the sequence, building up to establishment of a lunar base for use in long duration missions. A total of four SEV rovers were to be delivered on the first two missions. The SEV rovers were to enable the initial phase of extended surface exploration, serving as mobile bases prior to the deployment of habitat components. There were to be two missions per year in 2022 and 2023; three missions per year in 2024, 2025, and 2026; and four missions in each successive year after 2026. A continuous human presence was to be achieved in 2027, at which point the outpost habitation cluster was to consist of a Pressurized Excursion Module, Pressurized Core Module, and a Pressurized Logistics Module, along with the four SEV rovers. These rovers were to provide not only pressurized roving capabilities for exploration but also “private sleep quarters” for the crew. Upon delivery in 2028 of a nuclear power source, the Fission Surface Power System, extended-duration (60 to 90 days) excursions away from the outpost were to be possible.

> **The scenario 12 buildup sequence was designed so that the buildup could pause at any time and the loss of any one element would not hinder the functionality of the outpost. The core lunar surface systems technologies and outpost operations concepts are applicable not only to lunar exploration, but also to Mars exploration.**

Figure 3 shows a representative complete scenario 12 outpost.

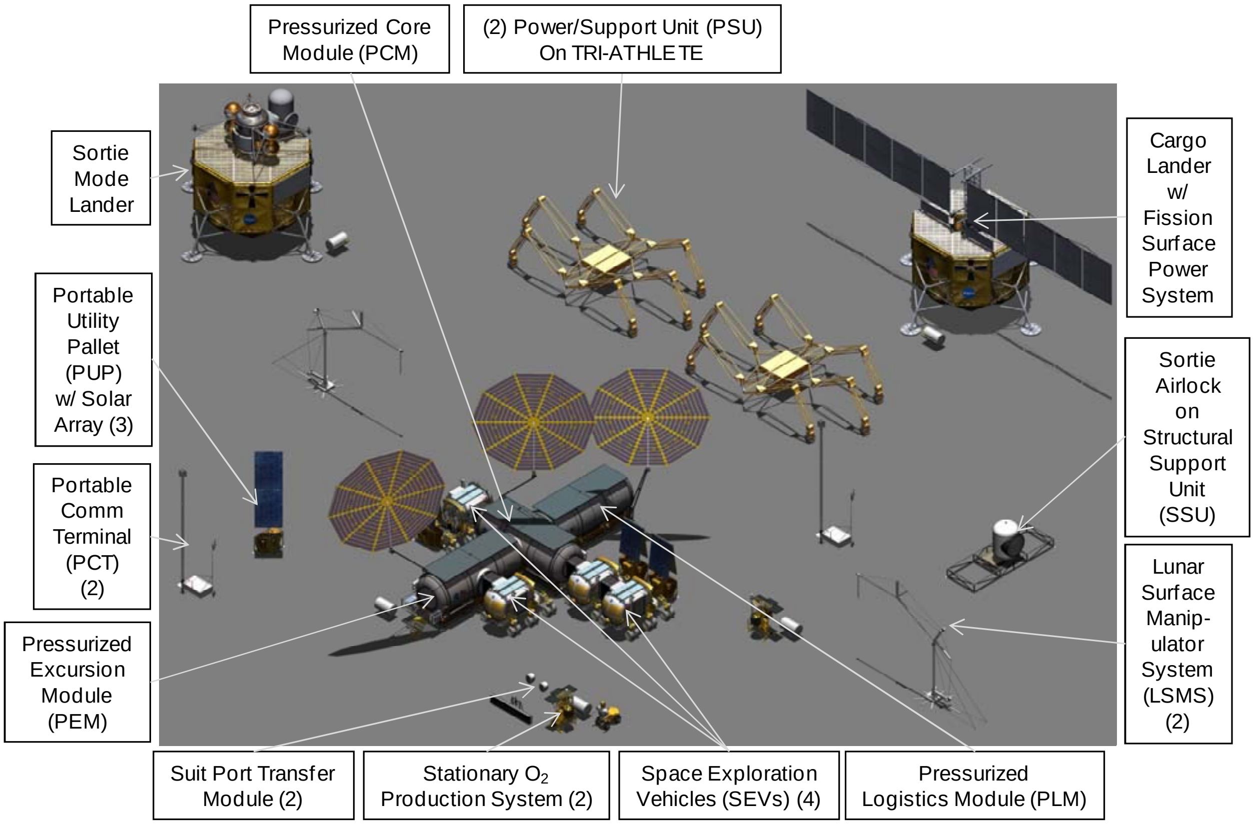

Figure 3 – Representative scenario 12 complete outpost

2.3. EVA Testing

The EVA Physiology, Systems, & Performance (EPSP) Project utilizes lunar analogs (such as parabolic flight aircraft, NASA Extreme Environment Mission Operations [NEEMO], the Neutral Buoyancy Laboratory, remote field test sites, and JSC's Partial Gravity Simulator [POGO] in the Space Vehicle Mock-up Facility) to characterize human performance and suit-human interactions during partial-gravity EVA. The project is working with the EVA Systems Project Office (ESPO) to develop and execute an integrated human testing program across multiple analogs. Along with the EPSP/ESPO tests that are providing objective human performance data, the Exploration Analogs and Mission Development (EAMD) team is working to evaluate EVA operational concepts that are based on the latest lunar surface scenarios. The results from these efforts are integrated to enable informed design decisions, thereby ensuring a surface EVA system that optimizes crewmember health, safety, efficiency, and performance.

2.3.1. Integrated Suit Tests

EPSP and ESPO initiated a series of tests collectively referred to as the Integrated Suit Tests in January 2006 with the EVA Walkback Test (EWT). Following the EWT were Integrated Suit Test 1 (IST-1), Integrated Suit Test 2 (IST-2), Integrated Suit Test 3 (IST-3), and the Integrated Parabolic Flight Test. EWT, IST-1, IST-2, and IST-3 were performed on POGO, a simulator in the Space Vehicle Mockup Facility that utilizes a pneumatic system to offload the weight of suited and unsuited subjects to produce partial gravity. The Integrated Parabolic Flight Test utilized the C-9 parabolic flight aircraft provided by the Reduced Gravity Office.

In the EWT, the feasibility of a suited 10-km ambulation was tested to represent a case in which a rover (without a second rover available to help) breaks down on the lunar surface and a crew is forced to walk back to their habitat or ascent vehicle. The EWT was also performed to determine physiological and biomechanical suit parameters (4).[4] The IST-1 objective was to identify the effects of weight, inertial mass, pressure, and suit kinematics on the metabolic cost of ambulation in a spacesuit, specifically in the MKIII spacesuit technology demonstrator that has a number of features that are expected in future spacesuit designs (5).[5] Identifying these effects enabled work toward another objective, to develop predictive models of metabolic rate, subjective ratings, and suit kinematics based on measurable suit, task, and subject parameters. Similar to IST-1, an objective of IST-2 was to establish the metabolic cost associated with changes in weight, inertial mass, pressure, and suit kinematics when performing exploration tasks such as shoveling, rock pickup, kneel-and-recover, and light construction tasks. The additional data furthered the development of the predictive algorithms initiated by IST-1 (6).[6] Unlike the EWT, IST-1, and IST-2, each of which had unsuited and suited components, IST-3 contained only an unsuited component because of POGO lift capacity limitations. For IST-3, the direction shifted toward exploring the effects of changes in center of gravity on human performance including metabolic rate, biomechanics, and subjective measures (7).[7] The Integrated Parabolic Flight Test used the superior partial gravity environment of the C-9 aircraft to determine the separate effects of changes in suited weight and mass as well as suited center of gravity (8).[8]

The data gathered from the Integrated Suit Tests will assist in determining how typical EVA work correlates with exercise. When the metabolic rates, biomechanics, and subjective measures during EVA-like activities (such as walking and shoveling) are quantified, exercise protocols for long-duration missions can be developed that work to supplement the exercise achieved during EVA.

2.3.2. Exploration Analogs & Mission Development: DRATS 2009

The main objective of the 2009 Desert Research and Technology Studies (DRATS) field test was to determine the adequacy of the human factors and crew accommodations in an SEV rover to satisfactorily support two crewmembers for a 14-day traverse. Along with a number of Lunar Surface Systems objectives, EVA frequency and duration estimates were sought by the Human Research Program (HRP) for use in models of physiological adaptations during long-duration lunar missions.

The test was accomplished by planning and executing a 14-day traverse with the prototype SEV rover on the Black Point Lava Flow near Flagstaff, Arizona. Productivity, human factors, and performance variables were measured according to the study protocol. Detailed timelines were used to plan crewmember days during the test, and metrics related to EVAs and other tasks performed were taken. Table 1 shows the durations and frequencies of EVAs for the 14-day SEV rover traverse. During the science and exploration EVAs, ambulation was performed for contextual observation and geologic sampling. When the global positioning system (GPS) data were processed after the test, taking into account data losses and accuracy fluctuations, the average distance translated was found to be 416 meters per EVA.

Table 1 – EVA durations and frequencies during 14-day SEV rover traverse

		14-Day Traverse (h:mm)													
	Avgs. (h:mm)	**Day 1**	**Day 2**	**Day 3**	**Day 4**	**Day 5**	**Day 6**	**Day 7**	**Day 8**	**Day 9**	**Day 10**	**Day 11**	**Day 12**	**Day 13**	**Day 14**
Total EVA Time	**1:22**	*0:21*	*2:06*	*1:46*	*2:20*	*2:43*	*0:47*	*0:56*	*0:58*	*2:51*	*2:18*	*0:28*	*1:20*	*0:25*	*0:00*
EVA Setup, Stowage, & Other Time	**0:31**	*0:12*	*0:31*	*0:19*	*0:45*	*0:33*	*0:11*	*0:15*	*0:17*	*1:21*	*0:57*	*0:23*	*1:14*	*0:25*	*0:00*
EVA Translation, Sampling, & Contextual Observations Time	**0:51**	*0:09*	*1:35*	*1:27*	*1:35*	*2:10*	*0:36*	*0:41*	*0:40*	*1:30*	*1:21*	*0:05*	*0:05*	*0:00*	*0:00*
Number of Egresses / person / day	**2.3**	*1.0*	*3.5*	*3.0*	*4.0*	*4.5*	*1.0*	*2.0*	*1.5*	*4.0*	*3.5*	*1.0*	*2.5*	*1.0*	*0.0*
Average EVA Duration	**0:31**	0:21	0:36	0:35	0:35	0:36	0:47	0:28	0:38	0:42	0:39	0:28	0:32	0:25	0:00

A representative example of a planned traverse timeline from day 5 of the 14-day mission is shown in Figure 4. An overview of the GPS tracks from day 5 EVAs are shown in Figure 5, and Figure 6 shows details of each EVA at a finer scale. The blue and red track lines in the figures indicate the positions of crewmembers, numbered EV1 and EV2, respectively. Figure 7 shows an example from day 5 of the detailed actual timelines that were kept for each day of the traverse.

The detailed data collected during field tests such as DRATS 2009 and from other analogs serve as a critical validation of operations concepts. When field test data are combined with IST data, modeling can be performed that provides valuable insight into the life sciences implications of lunar surface operations.

Crew A Day 5 Traverse	
TEAM	A
DATE	9/4/2009

TIMELINE	DISTANCE	LANDMARK	HEADING	PLANNED	TET
Drive to Station 1	1.1 km	Edge of Flow	200	0:17	0:17
EV1/EV2 Egress				0:15	0:32
Station 1 - Flow Strata				0:45	1:17
EV1/EV2 Ingress				0:10	1:27
Drive to Station 2	1.7 km	Flow to S	220	0:26	1:53
EV1/EV2 Egress				0:15	2:08
Station 2 - Flow Edge				0:45	2:53
EV1/EV2 Ingress				0:10	3:03
Drive to Station 3	1.4 km	Chanl unit	010	0:21	3:24
LUNCH				0:45	4:09
EV1/EV2 Egress				0:15	4:24
Station 3 - Layered Units				0:20	4:44
EV1/EV2 Ongress				0:10	4:54
Drive to Station 4	0.83 km	S of Road	010	0:13	5:07
EV1/EV2 Offgress				0:05	5:12
Station 4 - Stratified Mesa				0:20	5:32
EV1/EV2 Ingress				0:10	5:42
Drive to Station 5	1.0 km	Onto knobby	045	0:15	5:57
EV1/EV2 Egress				0:10	6:07
Station 5 - Knobby Unit				0:30	6:37
EV1/EV2 Ingress				0:10	6:47
Drive to Camp 5	1.6 km	Camp 4	160	0:24	7:11
EV2 Egress				0:20	7:31
PUP Operations				0:59	8:30
EV2 Ingress				0:10	8:40

Targets of Opportunity	Max Stay	Observations
Xenolith	30	Sample
Unique Lithology	30	Sample
Trench/Core Tube	30	Trench and/or Core
Addition Tasks	**TET Bingo**	**Observations**

Figure 4 - Representative planned daily traverse timeline from Desert RATS 2009 (Note: headings are in degrees and times are in hours and minutes; TET=traverse elapsed time)

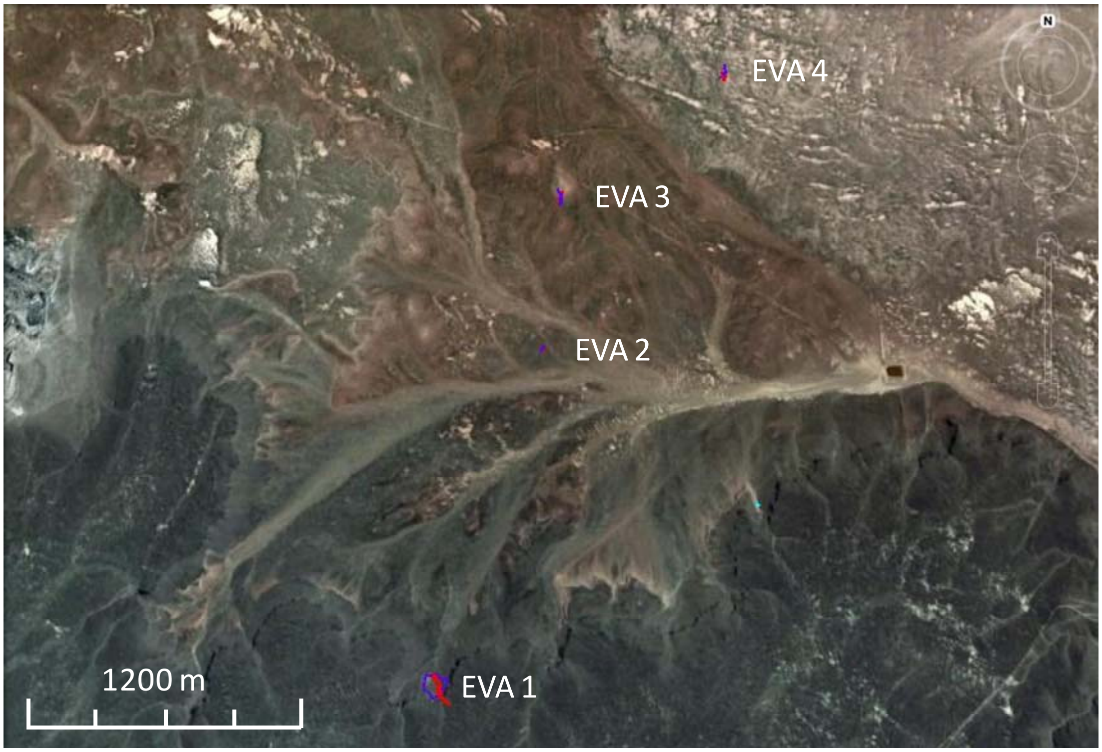

Figure 5 – DRATS 2009 traverse day 5 EVA overview map

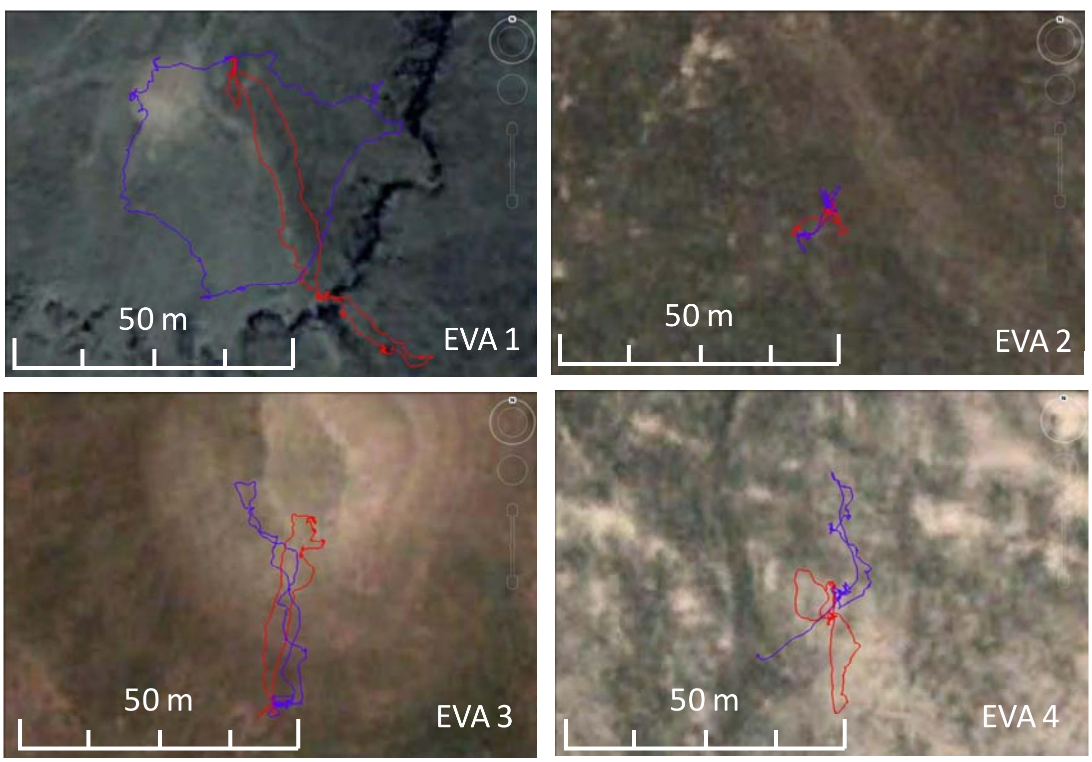

Figure 6 – DRATS 2009 traverse day 5 EVA detail maps

Total:
9:40
3:22

Traverse: 14 Day 5

TS=troubleshooting	Ec=EVA Contextual obs	RtE=Rover Translation EVA
In=IV non-productive	Es=EVA Sampling	RtI=Rover Translation IVA
En=EV non-productive	Et=EVA Translation	Rc=contextual obs from Rover
	Eo = EVA setup / cleanup (overhead)	Io=IV Overhead

Geophrase of the Day:
Cavernous Weathering

Total Time

EV1	START	STOP	Δ T (min)	Type of Work	Egres	Egress Time	Ingress Time
Traverse Start	8:00:00	8:00:00	0:00:00	N/A			
Morning briefing	8:00:00	8:30:00	0:30:00	Io			
Holding station, waiting for Go to roll	8:30:00	8:37:00	0:07:00	In			
LER rolling	8:37:00	8:57:00	0:20:00	RtI			
stopped for gigapan & geo obs	8:57:00	9:01:00	0:04:00	Rc			
still making geo obs	9:01:00	9:09:00	0:08:00	Rc			
comms flaky	9:09:00	9:11:00	0:02:00	Ts			
comm back	9:11:00	9:11:00	0:00:00	Ts			
conobs	9:11:00	9:17:00	0:06:00	Rc			
Holding station for gigapan	9:17:00	9:21:00	0:04:00	In			
Driving	9:21:00	9:30:00	0:09:00	RtI			
Holding station for another gigapan	9:30:00	9:35:00	0:05:00	In			
Driving	9:35:00	9:50:00	0:15:00	RtI			
Holding station for gigapan	9:50:00	9:57:00	0:07:00	In			
driving	9:57:00	10:05:00	0:08:00	RtI			
Station 2 EVA parking, egress preparatior	10:05:00	10:14:00	0:09:00	RtI			
begin egress	10:14:00	10:33:00	0:19:00	Io	1	0:19:00	
Boots on the ground, EVA activities	10:33:00	11:17:00	0:44:00	Es			
Ingress procedures	11:17:00	11:23:00	0:06:00	Eo			0:06:00
In cabin post-ingress activities	11:23:00	11:27:00	0:04:00	Io			
Rolling to station 3	11:27:00	11:41:00	0:14:00	RtI			
Holding for EV2 conobs	11:41:00	11:44:00	0:03:00	Rc			
Rolling to station 3	11:44:00	12:08:00	0:24:00	Rc			
all stop at station 3	12:08:00	12:10:00	0:02:00	Rti			
lunch called	12:10:00	12:30:00	0:20:00	In			
Egress preparations	12:30:00	12:35:00	0:05:00	Io			
begin egress	12:35:00	12:48:00	0:13:00	Io	1	0:13:00	
Boots on the ground, EVA activities	12:48:00	13:06:00	0:18:00	Es			
stowing tools, samples	13:06:00	13:06:00	0:00:00	Eo			
begin ingress	13:06:00	13:10:00	0:04:00	Eo			0:04:00
getting ready to roll	13:10:00	13:18:00	0:08:00	Io			
driving LER to station 4	13:18:00	13:25:00	0:07:00	RtI			
LER stopped for gigapan	13:35:00	13:36:00	0:01:00	In			
Egress preparations	13:36:00	13:40:00	0:04:00	Io			
begin egress	13:40:00	13:45:00	0:05:00	Io	1	0:09:00	
Boots on the ground, EVA activities	13:45:00	14:02:00	0:17:00	Es			
stowing tools, samples	14:02:00	14:07:00	0:05:00	Eo			
Ingress procedures	14:07:00	14:10:00	0:03:00	Eo			0:03:00
inside and ready to roll	14:10:00	14:15:00	0:05:00	In			
driving to station 5	14:15:00	14:42:00	0:27:00	RtI			
at station 5	14:42:00	14:42:00	0:00:00	In			
Egress preparations	14:42:00	14:44:00	0:02:00	Io			
begin egress	14:44:00	14:51:00	0:07:00	Eo	1	0:07:00	
Boots on the ground, EVA activities	14:51:00	14:55:00	0:04:00	Es			
sampling	14:55:00	15:10:00	0:15:00	Es			
ingress prep	15:10:00	15:12:00	0:02:00	Eo			
Ingress procedures	15:12:00	15:15:00	0:03:00	Eo			0:03:00
inside LER	15:15:00	15:15:00	0:00:00	In			
briefing for PUP docking	15:15:00	15:19:00	0:04:00	Io			
metrics	15:19:00	15:21:00	0:02:00	In			
ready to roll	15:21:00	15:25:00	0:04:00	In			
LER rolling	15:25:00	15:33:00	0:08:00	RtI			
LER stopped for gigapan	15:33:00	15:37:00	0:04:00	In			
LER rolling to station 6	15:37:00	16:00:00	0:23:00	RtI			
LER stopped at PUP	16:00:00	16:01:00	0:01:00	In			
tool transfer brief & EVA prep	16:01:00	16:15:00	0:14:00	Io			
cabana jam	16:15:00	16:16:00	0:01:00	Ts			
waiting for EV2 egress	16:16:00	16:21:00	0:05:00	Rc			
in LER for PUP docking	16:21:00	16:30:00	0:09:00	Rc			
trash transfer	16:30:00	16:34:00	0:04:00	Io			
EV2 support	16:34:00	16:45:00	0:11:00	Rc			
repositioning LER on other side of PUP	16:45:00	16:50:00	0:05:00	RtE			
waiting for PUP docking	16:50:00	16:52:00	0:02:00	Rc			
PUP docking	16:52:00	17:02:00	0:10:00	RtE			
PUP captured	17:02:00	17:04:00	0:02:00	Rc			
completing PUP docking procedures	17:04:00	17:06:00	0:02:00	Rc			
standing by	17:06:00	17:22:00	0:16:00	In			
metrics and debrief	17:22:00	17:28:00	0:06:00	Io			
standing by	17:28:00	17:30:00	0:02:00	In			
debrief with traverse planner	17:30:00	17:33:00	0:03:00	TS			
hf forms	17:33:00	17:40:00	0:07:00	TS			
	17:40:00		########				
	0:00:00		0:00:00				
	0:00:00		0:00:00				

EV2	START	STOP	Δ T (min)	Type of Work	Egre	Egress Time	Ingress Time
Traverse Start	8:00:00	8:00:00	0:00:00	N/A			
Morning briefing	8:00:00	8:30:00	0:30:00	Io			
Holding station, waiting for Go to roll	8:30:00	8:37:00	0:07:00	In			
LER rolling	8:37:00	8:57:00	0:20:00	RtI			
stopped for gigapan & geo obs	8:57:00	9:01:00	0:04:00	Rc			
still making geo obs	9:01:00	9:09:00	0:08:00	Rc			
comms flaky	9:09:00	9:11:00	0:02:00	Ts			
comm back	9:11:00	9:11:00	0:00:00	Ts			
conobs	9:11:00	9:17:00	0:06:00	Rc			
Holding station for gigapan	9:17:00	9:21:00	0:04:00	In			
conobs	9:21:00	9:30:00	0:09:00	Rc			
Hodling station for Gigapan	9:30:00	9:35:00	0:05:00	In			
Conobs	9:35:00	9:50:00	0:15:00	Rc			
Holding station for gigapan, more con	9:50:00	9:57:00	0:07:00	In			
Driving	9:57:00	10:05:00	0:08:00	RtI			
conobs	10:05:00	10:10:00	0:05:00	Rc			
Station 2 EVA parking, egress prepar	10:10:00	10:14:00	0:04:00	Io			
begin egress	10:14:00	10:33:00	0:19:00	Io	1	0:19:00	
Boots on the ground, EVA activities	10:33:00	11:17:00	0:44:00	Es			
Ingress procedures	11:17:00	11:23:00	0:06:00	Eo			0:06:00
In cabin post-ingress activities	11:23:00	11:27:00	0:04:00	Io			
Rolling to station 3	11:27:00	11:41:00	0:14:00	RtI			
conobs, holding station	11:41:00	11:44:00	0:03:00	Rc			
Rolling to station 3, conobs	11:44:00	12:08:00	0:24:00	Rc			
all stop at station 3	12:08:00	12:10:00	0:02:00	Rc			
lunch called	12:10:00	12:30:00	0:20:00	In			
Egress preparations	12:30:00	12:35:00	0:05:00	Io			
begin egress	12:35:00	12:48:00	0:13:00	Io	1	0:13:00	
Boots on the ground, EVA activities	12:48:00	13:05:00	0:17:00	Es			
stowing tools, samples	13:05:00	13:07:00	0:02:00	Eo			
ingress procedures	13:07:00	13:11:00	0:04:00	Eo			0:04:00
driving LER to station 4	13:25:00	13:35:00	0:10:00	RtI			
LER stopped for gigapan	13:35:00	13:36:00	0:01:00	In			
begin egress	13:36:00	13:40:00	0:04:00	Io	1	0:09:00	
egressing	13:40:00	13:45:00	0:05:00	Io			
Boots on the ground, EVA activities	13:45:00	14:02:00	0:17:00	Es			
stowing tools, samples	14:02:00	14:07:00	0:05:00	Eo			
Ingress procedures	14:07:00	14:11:00	0:04:00	Eo			0:04:00
inside and ready to roll	14:11:00	14:15:00	0:04:00	In			
LER rolling to station 5	14:15:00	14:40:00	0:25:00	RtI			
conobs en route to station 5	14:40:00	14:42:00	0:02:00	Rc			
at station 5	14:42:00	14:42:00	0:00:00	In			
conobs	14:42:00	14:46:00	0:04:00	Rc			
begin egress	14:46:00	14:52:00	0:06:00	Io	1	0:06:00	
Boots on the ground, start EVA	14:52:00	14:54:00	0:02:00	Es			
conobs	14:54:00	14:55:00	0:01:00	Ec			
sampling	14:55:00	15:10:00	0:15:00	Es			
ingress preparations	15:09:00	15:10:00	0:01:00	Eo			
ingress procedures	15:10:00	15:15:00	0:05:00	Eo			0:05:00
inside LER	15:15:00	15:15:00	0:00:00	In			
briefing for PUP docking	15:15:00	15:19:00	0:04:00	Io			
ready to roll	15:19:00	15:21:00	0:02:00	In			
metrics	15:21:00	15:22:00	0:01:00	In			
ready to roll	15:22:00	15:22:00	0:00:00	In			
reporting geo obs to SCI	15:22:00	15:25:00	0:03:00	In			
LER rolling	15:25:00	15:33:00	0:08:00	RtI			
LER stopped for gigapan	15:33:00	15:37:00	0:04:00	In			
LER rolling to station 6	15:37:00	16:00:00	0:23:00	RtI			
LER stopped at PUP	16:00:00	16:01:00	0:01:00	In			
tool transfer brief & EVA prep	16:01:00	16:13:00	0:12:00	Io			
begin egress	16:13:00	16:15:00	0:02:00	Io	1	0:10:00	
cabana jam	16:15:00	16:16:00	0:01:00	Ts			
egress procedures	16:16:00	16:21:00	0:05:00	Io			
boots on ground	16:21:00	16:23:00	0:02:00	Et			
trash/sample transfer; PUP docking c	16:23:00	17:04:00	0:41:00	Et			
completing PUP docking procedures	17:04:00	17:13:00	0:09:00	Et			
opening marman	17:13:00	17:18:00	0:05:00	Eo			
ingress preparations	17:18:00	17:20:00	0:02:00	Eo			
ingress procedures	17:20:00	17:22:00	0:02:00	Eo			0:02:00
inside LER	17:22:00	17:22:00	0:00:00	In			
metrics and debrief	17:22:00	17:28:00	0:06:00	Io			
standing by	17:28:00	17:30:00	0:02:00	In			
closing cabana, leveling LER	17:30:00	17:33:00	0:03:00	Io			
hf forms	17:33:00	17:40:00	0:07:00	Io			

Figure 7 - DRATS 2009 traverse day 5 actual detailed timeline

3. Methods

Modeling was performed using timelines from DRATS 2009 and a reasonable estimation of a typical day-in-the-life of a crewmember on the lunar surface. Data from field tests were combined with physiological and performance data collected, during the Integrated Suit Tests, to project some of the life sciences implications associated with these lunar surface operations. A model was developed that takes into account such variables as subject mass, suit mass, suit pressure, gravity level, ambulation speed, ambulation distance, ground reaction forces, exploration task type, and time spent performing each exploration task. The model then outputs information such as metabolic energy consumed, oxygen used, water used, and accumulated load.

3.1. Crewmember Day-in-the-Life Assumptions

A typical day-in-the-life of a crewmember can be defined that is mostly independent of the lunar surface architecture that may eventually be achieved. The data from the 2009 DRATS field test[9] can be combined with informed assumptions to allow us to better define this day-in-the-life.

Table 2 shows assumptions for durations and frequencies of typical daily activities, and Table 3 shows the assumptions for EVA-related activities. Table 2 does not provide a detailed minute-by-minute breakdown, but rather provides durations and frequencies for required activities. This breakdown is based on field-test data from DRATS 2009 and informed assumptions determined by the Exploration Analogs & Mission Development (EAMD) team for a science exploration traverse day.

The maximum duration of a crew work day is assumed to be 900 minutes. Portions of the crew duty day not specifically accounted for in Table 2 could be allotted to other activities such as traverses of greater distance in the SEV rover, private medical conferences, meals, system checks and maintenance, and exercise. In addition, it is worth noting that some activities such as meals or exercise may be performed by one crewmember while the other is performing an activity such as driving between stations.

Table 2 – Assumptions for some typical science and exploration daily activities and their durations

Activity Duration	Activity	Frequency
60 min	Post sleep	Daily
15 min	Morning planning conference	Daily
120 min	Pre-EVA (daily)	Daily before first EVA
10 min	EVA egress	Per EVA
45 min	EVA	As needed up to max time per day or week
10 min	EVA ingress	Per EVA
20 min	Post EVA	Daily after last EVA
15 min	Evening planning conference	Daily
60 min	Pre-sleep	Daily
540 min (9 h)	Sleep	Daily

Table 3 – Science and exploration day-in-the-life EVA assumptions

Guideline
A system of SEV rovers will be used for long-distance translation between exploration objectives.
On average, up to 4 EVAs of 45 min duration each may be performed per day, up to a maximum of 24 hours / person / week (DRATS 2009 data show that it may be possible to cut this maximum in half by doing shorter, more frequent EVAs).
At each exploration objective, on average 200 m of EVA translation (between objectives at the site) may be performed at a higher translation speed and another 100 m of translation (near objectives) may occur at a lower translation speed.
At each site, each crewmember may collect an average of 8 samples, 1/3 of which will be collected by hand without the need for tools in 0.5 min, 1/3 of which will require 1 min of hammering, and 1/3 of which will require 3 min of trenching
The average mass of samples collected may be 0.3 kg (based on average sample mass from DRATS 2009).

3.2. Assumptions for Modeling Surface Operations

To estimate the amount of exercise achieved related to EVA, using stated assumptions, data from the ISTs and field tests were used to predict the metabolic rate during exploration activities and the daily accumulated load (DAL) received from ambulation. For metabolic rates during the different activities, measured rates from IST-1 and IST-2 were used and correlated with tasks according to whether the tasks were mostly stationary or not and whether they required light or heavy work. A summary and description of the variables and constants used in the modeling are given in Table 4. Also, Figure 8 through Figure 13 are cited here in Table 4. Along with explanations in the "Source/Basis" column, those figures are included to further define the sources and bases of the variables and constants used.

Table 4 – Modeling variables and constants

Variable / Constant	Value	Source / Basis
General		
Subject mass	80.7 kg	Average from IST-1 for 120-kg suit[5]
Average walking speed	3.0 km/h	Apollo average of 2.9 km/h[11] and lunar surface scenarios; DRATS 2009 GPS data not used due to data dropouts
Suit mass	120 kg	MKIII Spacesuit Technology Demonstrator used in ISTs[4]
Water consumption (respiration & perspiration) during EVA	240 mL/h	NASA Human Systems Integration Requirements, # HS6063
Total walking distance per day	1.2 km	300 m for each of 4 EVAs based on assumptions in Table 3
Total walking time per day	0.4 h	Total distance at average speed defined above
Total EVA time per day	3.0 h	4 $\times$ 45 min EVAs per day based on assumptions in Table 3
Total IVA time per day	21 h	Remainder of day after EVA time per day
Ground Reaction Force (GRF)		
Foot strikes during ambulation	74/min	Average from IST-1 for speeds of 2.3–3.5 kph[5]; also see Figure 8
Peak vertical ground reaction force	197.1 N	Average from IST-1 for speeds of 2.3–3.5 kph[5]; also see Figure 9
Metabolic Rates		
Sitting in pressurized SEV rover	3.9 mL/kg/min (91.1 kcal/h)	Resting metabolic rate based on published research[10]
Walking during EVA	15.4 mL/kg/min (359.4 kcal/h)	Average from IST-1 data for speeds of 2.3–3.5 km/h[5] at lunar gravity; also see Figure 10
Stationary EVA task – light work (e.g., contextual observations, sample pickup without tools, setup or stowage of equipment)	13.2 mL/kg/min (308.1 kcal/h)	Average from IST-2 busy board (a light construction task)[6] at lunar gravity; also see Figure 11
Stationary EVA task – heavy work (e.g., hammering, trenching)	17.0 mL/kg/min (396.8 kcal/h)	Average from IST-2 shoveling task[6] at lunar gravity; also see Figure 12
Mobile EVA task – heavy work (e.g., sample transfer to FRED rover)	18.1 mL/kg/min (422.4 kcal/h)	Average from IST-2 rock transfer task[6] at lunar gravity; also see Figure 13

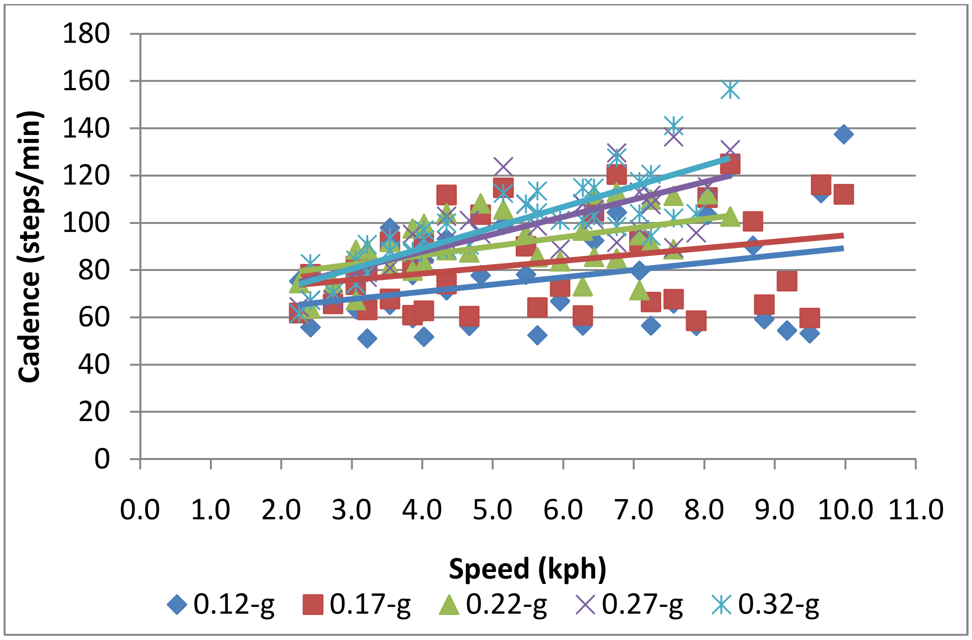

Figure 8 – IST-1 cadence versus speed as a function of gravity level for suited ambulation with suit mass of 121 kg and pressure of 29.6 kPa; scatter plot of all subject data with linear fits for each gravity condition[5]

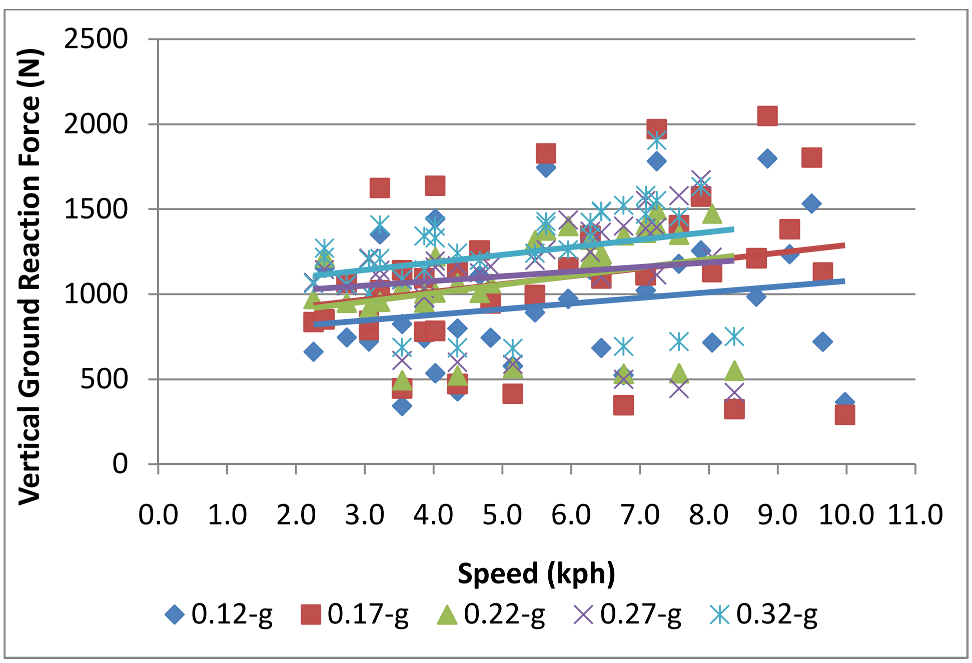

Figure 9 – IST-1 vertical ground reaction force versus speed as a function of gravity level for suited ambulation with suit mass of 121 kg and pressure of 29.6 kPa; scatter plot of all subject data with linear fits for each gravity condition[5]

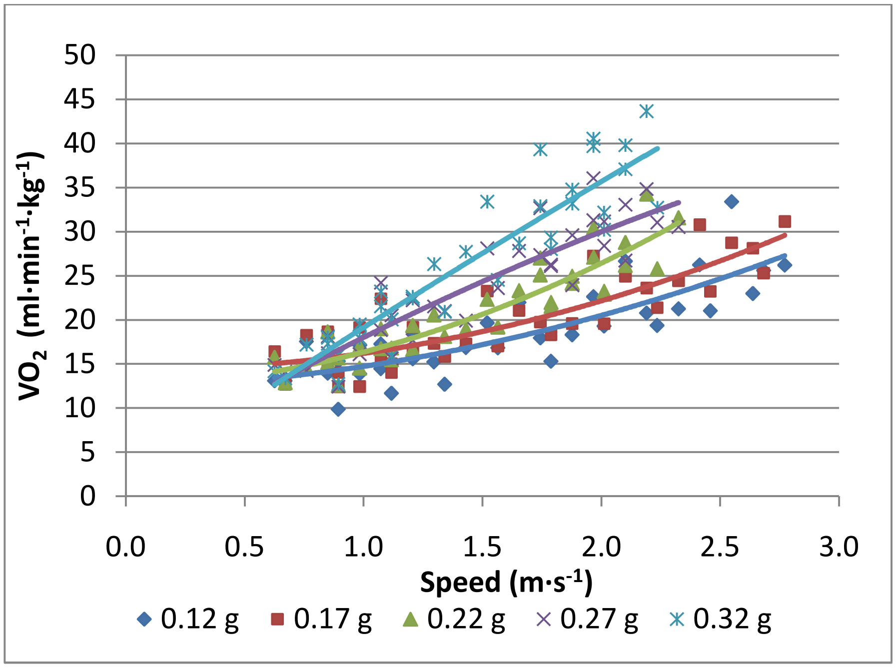

Figure 10 – IST-1 metabolic rate versus speed at different gravity levels during suited locomotion at a constant mass (121 kg) and pressure (29.6 kPa); scatter plot of all subject data with 2nd order fits for each gravity condition[5]

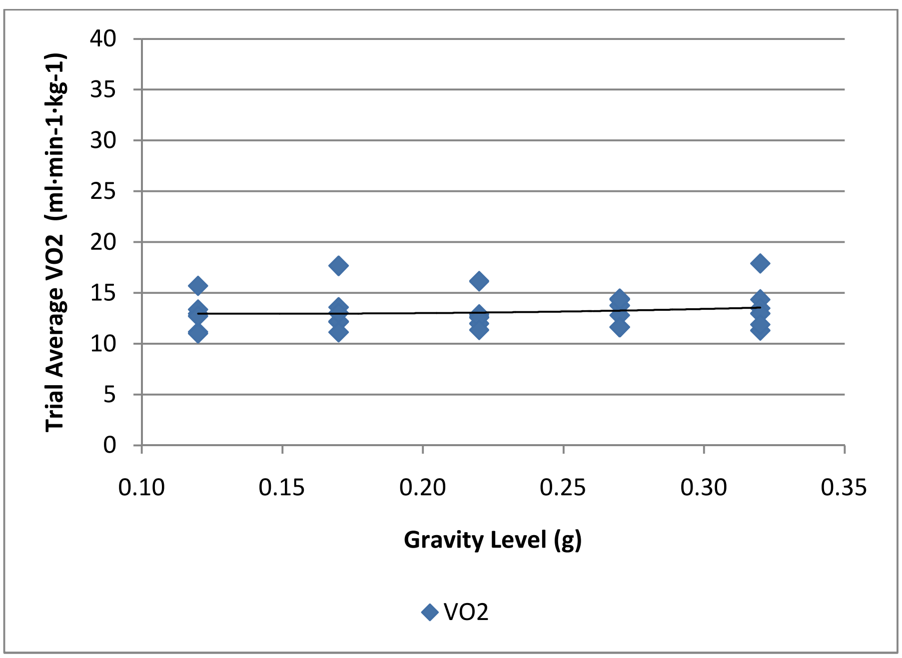

Figure 11 – IST-2 metabolic rate for the "busy board task" at different gravity levels at a constant suit mass (121 kg) and pressure (29.6 kPa); scatter plot of all subject data with 2nd order fit[6]

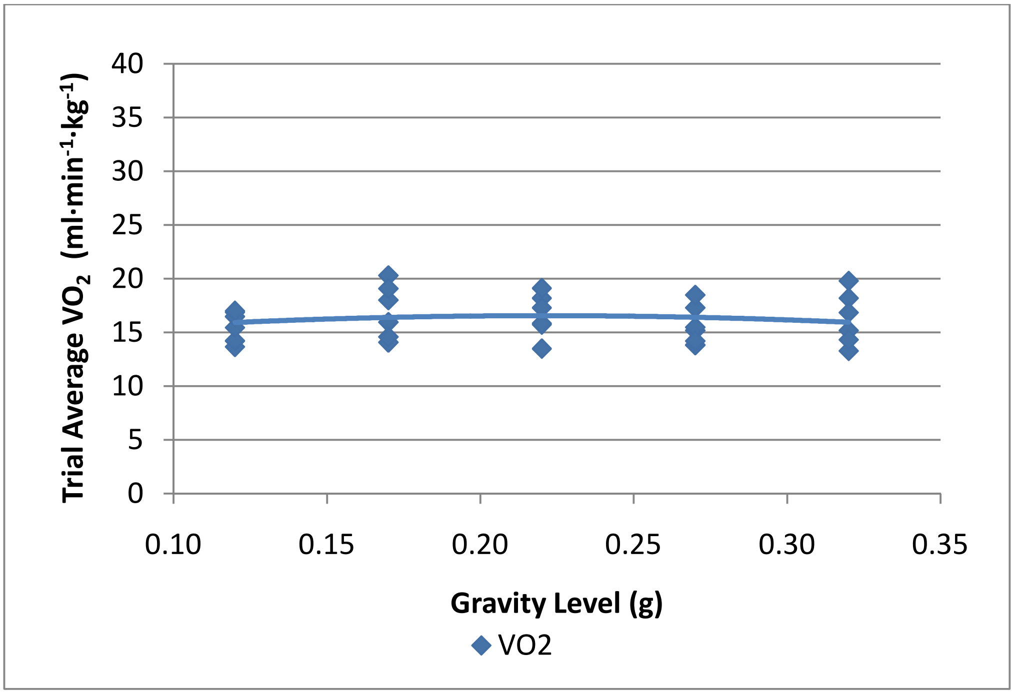

Figure 12 – IST-2 metabolic rate for the "shoveling task" at different gravity levels at a constant suit mass (121 kg) and pressure (29.6 kPa); scatter plot of all subject data with 2nd order fit[6]

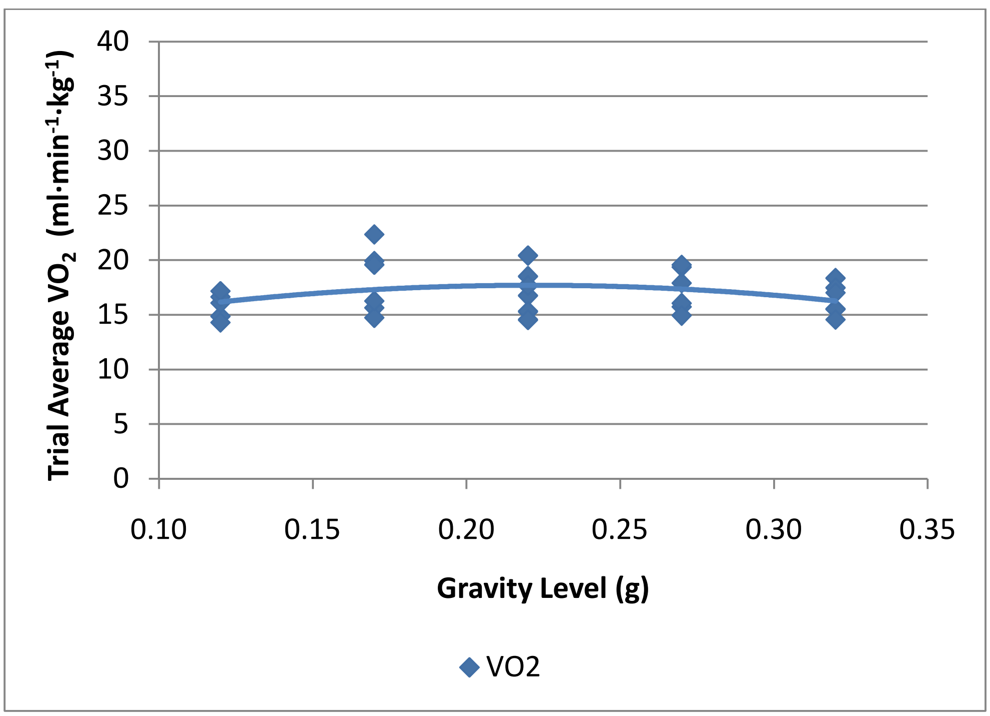

Figure 13 – IST-2 metabolic rate for the "rock transfer task" at different gravity levels at a constant suit mass (121 kg) and pressure (29.6 kPa); scatter plot of all subject data with 2nd order fit[6]

Computation of the total O_2 consumption during EVA for the typical day-in-the-life of a crewmember was based on the assumption of a constant 4.3-psi suit pressure at 80% O_2 for the duration of each EVA. The defined typical subject mass of 80.7 kg from IST-1 was used with the metabolic rates in mL/kg/min for walking, stationary light work, stationary heavy work, and mobile heavy work to compute kcal/h for each type of task.

The following equation was then used to calculate total kcal used per day during EVA:

$$[(T_w \times M_w) + (T_{LS} \times M_{LS}) + (T_{HS} \times M_{HS}) + (T_{HM} \times M_{HM})] \times \text{number of EVAs per day}$$

where

T_W = time spent walking during each EVA, in hours
M_W = metabolic rate while walking during each EVA, in kcal/hour
T_{LS} = time spent on stationary light work during each EVA, in hours
M_{LS} = metabolic rate during stationary light work during each EVA, in kcal/hour
T_{HS} = time spent on stationary heavy work during each EVA, in hours
M_{HS} = metabolic rate during stationary heavy work during each EVA, in kcal/hour
T_{HM} = time spent on mobile heavy work during each EVA, in hours
M_{HM} = metabolic rate during mobile heavy work during each EVA, in kcal/hour

The energy consumption for each of the subtasks is more simply determined by multiplying the number of EVAs per day by the relevant subpart of the equation to obtain the total kcal used per day for that subtask.

The average number of foot strikes during EVA per day was computed by multiplying the assumed number of foot strikes per minute from
Table 4 by the amount of time spent walking during EVA on a typical day. The foot strikes during EVA were then combined with the average peak ground reaction force in
Table 4 using simplified accumulated load calculations (based on the equations in Genc K, et al. The Enhanced Daily Load Stimulus (eDLS): Accounting for Saturation, Recovery and Standing. At American Society of Biomechanics Annual Conference; 2007; Stanford University.) that accounted for the load achieved through walking during EVA:

$$T_W \times (\text{average foot strikes per minute}) \times [(\text{peak GRF}) / (\text{subject mass})]^4$$

This simplified equation does not account for the effects and benefits of standing, but it does allow an estimation of the accumulated load from EVA. Further modeling with a more complete inclusion of all variables that could affect accumulated load was left for future work.

4. Results & Discussion

The modeling results presented in this section represent some of the life sciences implications of a typical day-in-the-life of a crewmember on the lunar surface performing science and exploration, based on testing results from analog environments and the assumptions documented in sections 3.1 and 3.2.

Table 5 – Crewmember day-in-the-life modeling results

Variable	Modeling Result	Basis
General		
Total O_2 used per day during EVA	0.05 kg	From metabolic rates, using data from ISTs (3 hours total of EVA at a workload breakdown as detailed below)
Total H_2O used per day during EVA	0.72 L	HSIR[12] and total EVA time of 3 hours per EVA assumptions in section 3.1
Metabolic Energy Consumption		
Total kcal per day for EVA	1,120 kcal	Total of all EVA activities, based on IST data and categorization of activities as detailed below (3 hours total of EVA per assumptions in section 3.1)
Average kcal per EVA	280 kcal	Average for each of 4 EVAs (based on 0.75 hour EVAs per EVA assumptions in section 3.1)
Average kcal per day from walking during EVA	143 kcal	From EVA walking time without samples per day (0.13 hours or 4.4% of total daily EVA time; per EVA assumptions in section 3.1)
Average kcal per day from stationary EVA tasks – light work (e.g., contextual observations, sample pickup without tools, setup & stowage)	582 kcal	Based on EVA time not spent hammering, trenching, walking, or transferring samples per day (1.89 hours or 63% of total daily EVA time; per EVA assumptions in section 3.1)
Average kcal per day from stationary EVA tasks – heavy work (e.g., hammering, trenching)	282 kcal	Based on EVA hammering & trenching time per day (0.71 hours 23.7% of total daily EVA time; per EVA assumptions in section 3.1)
Average kcal per day from mobile EVA tasks – heavy work (e.g., sample transfer to within site and to FRED rover)	113 kcal	Based on EVA translation time at a site and to SEV rover per day (0.27 hours or 8.9% of total daily EVA time; per EVA assumptions in section 3.1)
Bone Maintenance		
Average number of foot strikes during EVA per day (total for all 4 EVAs in a day)	4,795 steps	From time spent walking during EVA, average speed, and number of foot strikes from ISTs
Accumulated load per day from walking during EVA (total for all 4 EVAs in a day)	10,300 kg	From foot strikes during EVA walking and accumulated load equations

The results shown in Table 5 provide estimates of EVA consumables usage, metabolic energy consumption, and potential bone maintenance related to loading effects. The consumables usage results may be useful for estimating the breathing gas and water that will be needed on an ongoing basis during typical EVAs. The computed metabolic energy consumptions offer insight into the exercise achieved and nutrition requirements related to EVA for a typical day. The average modeled kcal expended per EVA is comparable to the amount computed from Apollo missions, which was about 200 kcal for a 45-minute EVA, excluding time spent traversing on the rover (Scott-Pandorf, M., et al., Lunar Explorations During Apollo: Velocities and Metabolic Rates. Unpublished NASA paper, 2006). The bone maintenance results may be used to estimate the need for measures to counteract bone loss during lunar stays.

Assumptions based on scenario 12 can be used to define the number of days that may be spent performing assembly, maintenance and logistics, and science and exploration for missions of different durations. In the buildup sequence, cargo landers that deliver components were alternated with crewed landers to bring crewmembers to the lunar surface. The crewed missions were to be of varying durations with a general trend toward longer missions. Early missions in the buildup sequence were centered on assembly, and many of those missions were to be of shorter duration. As the outpost was built up, mission duration was to increase and more time was to be spent on maintenance and on science and exploration. It may be assumed that the need for maintenance time increases with the total amount of time that equipment is operational on the lunar surface, and a reasonable assumption may be that maintenance time is 5% of the cumulative surface time of the outpost. In actuality, maintenance time will be a function of the types of components and their frequency of use; this level of modeling may be included in future revisions of this report. The assumption for mission days spent on assembly is currently based on a minimum of 1 day to be spent on assembly, setup, or checkout for each new component (such as SEV rover or PSU) that is delivered to the surface. Again, further modeling may be completed to revise these estimates, if detailed timelines can be developed for each type of task.

Table 6 – Estimated percentage of days spent performing different types of activities, by mission duration, for scenario 12

Mission Duration (Days)	Assembly Days (%)	Maintenance & Logistics Days (%)	Science & Exploration Days (%)
7	9%	46%	45%
14	64%	10%	26%
28	27%	13%	60%
45-50	7%	18%	75%
180	0%	31%	69%

Note that the activity percentages depend heavily on the particular buildup sequence and may vary significantly for other scenarios.

The typical day-in-the-life results apply to the science and exploration days shown in Table 6. The percentage of days spent on science and exploration along with the mission duration can be used to get a partial look at the results shown in Table 5 across an entire mission. As future work defines assembly, maintenance, and logistics tasks, additional modeling can be performed to provide a complete picture of the life sciences implications across entire scenarios.

5. Future Work

Further modeling may be performed as analog testing is completed and as surface operations timelines are further developed. EVA timelines for relevant tasks may be included in future revisions of this analysis. These may include the following:

- Assembly tasks
  - Large payload (e.g. SEV, habitat modules) offload from cargo lander
  - Crane deployment and relocation
  - Consumables systems offload from cargo lander, and setup
  - Ladder detachment and relocation
  - Berm building
- Logistics and maintenance tasks
  - Logistics offload from cargo lander
  - Logistics transfer and utilization
  - Small payload (such as geologic samples) onload and offload from lander
  - SEV rover repair
  - Module maintenance
  - Suit maintenance
- Science and exploration tasks
  - 1, 3, 7, 14, and 28-day SEV rover science and exploration traverse
  - Sample handling and classification

6. Contact

Feedback and questions regarding this report are expected and encouraged, to further the cross-disciplinary collaboration necessary to make informed decisions on future life sciences research as well as systems testing and design. Contacts: Steve Chappell, steven.p.chappell@nasa.gov; Andrew Abercromby (andrew.f.abercromby@nasa.gov); Jason Norcross (jason.norcross-1@nasa.gov); Mike Gernhardt (Michael.l.gernhardt@nasa.gov).

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13. ABSTRACT *(Maximum 200 words)*

The purpose of this report is to document preliminary, predicted, life sciences implications of expected operational concepts for lunar surface extravehicular activity (EVA). Algorithms developed through simulation and testing in lunar analog environments were used to predict crew metabolic rates and ground reaction forces experienced during lunar EVA. Subsequently, the total metabolic energy consumption, the daily bone load stimulus, total oxygen needed, and other variables were calculated and provided to Human Research Program and Exploration Systems Mission Directorate stakeholders. To provide context to the modeling, the report includes an overview of some scenarios that have been considered. Concise descriptions of the analog testing and development of the algorithms are also provided. This document may be updated to remain current with evolving lunar or other planetary surface operations, assumptions and concepts, and to provide additional data and analyses collected during the ongoing analog research program.

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