Human Mars Mission Surface Power Impacts on Timeline and Traverse Capabilities

Michael B. Chappell
NASA Marshall Space Flight Center
Martin Road SW
Huntsville, AL 35808
256-544-8438
michael.b.chappell@nasa.gov

Stephen Hoffman
Aerospace Corporation
2101 Nasa Parkway
Houston, TX 77058
281-483-9264
stephen.j.hoffman@nasa.gov

Omar Bekdash
Aerospace Corporation
2101 Nasa Parkway
Houston, TX 77058
281-483-5433
omar.s.bekdash@nasa.gov

Abstract—**The National Aeronautics and Aerospace Administration's (NASA) Mars Architecture Team (MAT) developed a concept for power management operations to support a thirty-day, minimal infrastructure Mars surface mission. The surface elements in this minimal surface mission concept include three landers as platforms for surface operations, a crewed Mars ascent vehicle (MAV), an unpressurized rover, and a pressurized rover where the crew will live for the duration of the thirty-day mission. In this analysis the power system is a ten kilowatt fission power system, which has been selected for its resiliency to dust storms, and will provide power for all aspects of the surface mission including thermal management of propellant and electronic systems, communications, and battery recharge of mobile surface assets. Developing a power management plan with the consideration of the various elements and mission phases helps define the traverse and exploration capabilities for the crew in the pressurized rover. Also, considerations need to be made for the different power requirements for each phase of the surface mission including arrival, offload, surface exploration, launch preparation, and departure. The described analysis aims to achieve a balance of maintaining power to critical systems while enabling desired traverse and exploration range in the pressurized rover. Additionally, a few enhancing technologies were explored that could expand the power capability if the additional capacity is necessary in the future. This study is used as a baseline to understand the constraints on all aspects of the surface mission for a minimal surface infrastructure human Mars campaign if a ten-kilowatt fission surface power system is available on the surface.**

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1. INTRODUCTION

The NASA Mars Architecture Team seeks to define the available traverse distance and duration of crewed surface exploration to inform the science community of the human constraints of a Mars surface mission. This study is an attempt to balance three primary constraints levied on the study team to maximize the exploration capability: the schedule of activities for the crew, the available surface power to recharge the pressurized rover, and the mobility and life support hardware and capability. The primary requirement for the human Mars mission is to maintain the human life support and critical transportation systems for the safe arrival, sustainment, and departure of the human crew. Beyond these critical systems, any remaining capability can be used to conduct exploration activities. The goal of this study is to determine what time and mobility capacity are available within these remaining resources.

2. ASSUMPTIONS

Architecture Reference

The elements for the study are based on the architecture defined by a set of ground rules and constraints designed to explore an often overlooked portion of the architecture trade space. This mission is a minimum surface hardware, short-stay class (30 sol) mission. The crew will land and live in a pressurized rover and depart on a preplaced crew ascent vehicle. Deep space transportation does not impact this study.

10kW Fission Surface Power

The surface power architecture is based around the 10 kilowatt (kW) provided by a fission reactor. All of the surface elements and equipment must be supplied power from this source. A second 10kW will be present on the surface, but only as a backup to be used in contingency scenarios.

Crew Systems Power

The power determined to be necessary to maintain the pressurized rover as a habitable space without any mobility considerations is assumed to be 1.85kW.

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Power Margin

All surface elements requiring power must maintain a 30% power growth margin. For the purpose of this study, the margin of the available supplied power was reduced on the front end to use real power numbers throughout the calculations. For the 10kW total available power, a margin of 2.3kW was reserved to represent this assumption.

Surface Assets

All of the other elements of the surface architecture will require power for communication, sensors, thermal conditioning, and other electronics. Additionally, the Mars Ascent Vehicle (MAV) will require power to condition propellant and maintain an operational standby condition. All of these power needs will consume approximately 2.85kW.

Power Losses/Recharge Efficiency

For the purposes of this study, the losses from cables and recharge inefficiencies are ignored. Whatever power that is available after all other necessary systems have been accounted for will be available for use and applied at 100% efficiency. The numbers estimated for the required loads are not at the fidelity where determining a more precise power consumption would be more accurate or appropriate. Additionally, the whole system retains a 30% growth margin where some ignored losses could be absorbed.

Pressurized Rover Background

The pressurized rover (PR) concept is a crew transport vehicle for two crewmembers on a planetary surface. It has the ability to support site-to-site traverses in a rover cabin, observations from inside comparable to those in a suit, rapid EVAs and dust mitigation via suit ports with an approximate ingress time to the cabin of 20 minutes. It can also accommodate different payloads (e.g. science instrumentation, ice core and geology samples, etc.) in support of exploration activities. This rover concept has been under development at NASA for multiple years and has been repeatedly tested in analog environments (Figure 1) demonstrating its operational efficacy.

Image Credit: NASA

Figure 1. Pressurized rover prototype testing at the Black Point Lava Flow near Flagstaff, Arizona.

The PR provides multiple crew health and safety advantages. Since the crew is typically never more than 10 minutes away from a pressurized safe haven, incidents such as suit malfunctions, solar storms, or injury during Extravehicular Activity (EVA) can be more quickly responded to. Additionally, since EVAs are assumed to be performed via suitports with less overhead and gas losses than a traditional airlock, the PR enables rapid EVA on an as needed basis vs planning long duration EVAs while not precluding the ability to perform the latter. This rapid EVA ability results in less time in the suits leading to improved nutrition, hydration, lower risk of suit induced trauma, improved waste management, and lower wear time on the EVA suits [1].

Timeline Assumptions

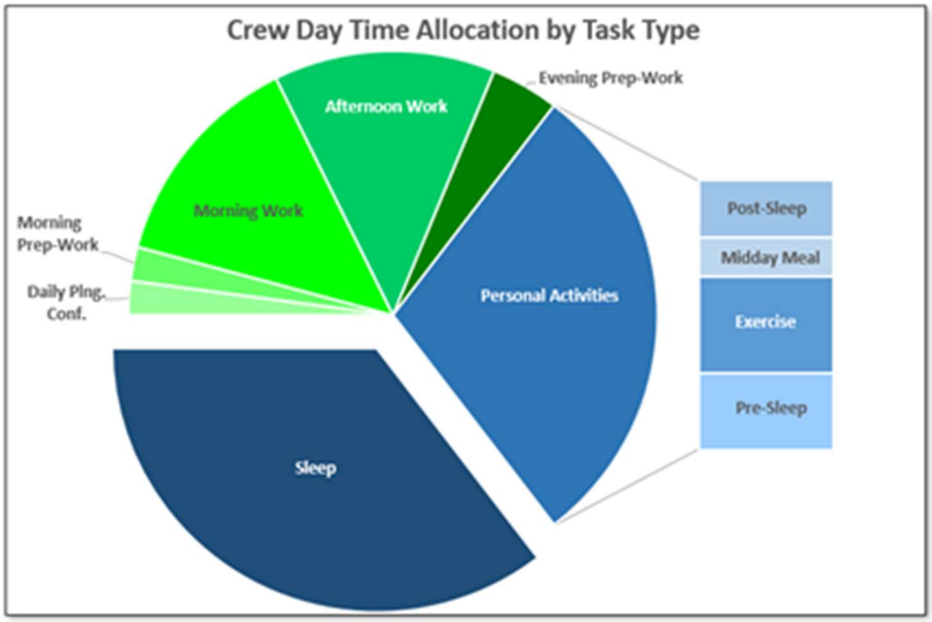
To build a realistic timeline, all the tasks the crew will perform need to be properly accounted for and the capabilities and limitations of a human crew need to be reflected in the assigned duration for these tasks. Lessons learned from decades of International Space Station (ISS) operations as well as surface mission analogs (e.g., NEEMO [2], BASALT [3], D-RATS [4], etc.) provide guidance for the type and duration of non-science driven activities that are likely to be independent of science driven activities (possibly constraining the science driven activities that can be accomplished). The primary source used for these guidelines is SSP 50261-02 “ISS Generic Groundrules and Constraints Part 2: Execute Planning” [5]; other sources are noted as they are applied.

The first planning assumption involves the length of a Martian day (or sol). A Martian sol is 24 hours 39 minutes and 35 seconds in length [6]. This has been rounded to 24 hours and 40 minutes in the timelines described in this paper. It is assumed that the Mars crew – both in orbit and on the surface – will operate on this length of a “workday.” Sleep shifting by the crew is assumed to begin several weeks prior to arrival at Mars. Because the activity durations described in SSP 50261-02 are based on a 24-hour day, the additional 40 minutes in the Martian sol is carried as timeline “reserve” for the purpose of this analysis. This reserve time can be considered for mission tasks (e.g., science operations, routine maintenance, conferences, etc.) when necessary but is otherwise allocated to crew evening/off-duty activities or additional sleep.

Following SSP 50261-02 guidelines, the crew will have at least 8.5 hours of sleep per sol. They will also have 1.5 hours in the morning for breakfast and other personal activities before beginning work activities (referred to as “post-sleep”), 2.0 hours in the evening for an evening meal and personal activities before going to sleep (referred to as “pre-sleep”), and 1.0 hour for a mid-day meal. Pending further analysis, they are also assumed to follow the ISS protocol for 2.5 hours of exercise per person per sol on those sols when no Extravehicular Activity (EVA) is conducted and 1.0 hour of exercise on any sol that includes EVA activity (planned to occur after the EVA but before pre-sleep). Note that surface mission scenarios including just a pressurized rover (PR) as the primary habitable element will have limited habitable volume, so these exercise periods must be performed serially. This leaves 8.5 hours per sol (plus the 40 minutes of "reserve" time if needed) for "work" related activities. Figure 2 illustrates this allocation of time (not including the "reserve" time).

EVA hours carried out by the crew, and for the logistics needed to support this level of activity.

The final significant crew care assumption used in planning these timelines involves EVA frequency. EVA equipment for Mars surface missions is expected to build from experience gained during Artemis Program lunar surface EVAs. Details for Mars-specific EVA equipment are still conceptual, meaning that impacts on the crew from its use are unknown. But experience from Apollo, Space Shuttle, and ISS missions indicates that EVAs are likely to be taxing on the crew regardless. Consequently, the timelines described below assume that the crew will have at least one non-EVA sol between EVAs wherever possible. Where EVAs on consecutive sols are difficult to avoid, exceptions are made. But in these instances, the total EVA duration across consecutive sols is reduced as much as possible



Activity	Hours
Sleep	8.50
Post-Sleep	1.50
Daily Planning Conference	0.50
Morning Prep-Work	0.50
Morning Work	3.25
Midday Meal	1.00
Afternoon Work	3.25
Evening Prep-Work	1.00
Exercise	2.50
Pre-Sleep	2.00
Total	24.00

Category Totals:

Personal Activities	*7.00*
Sleep	*8.50*
Conferences, Prep	*2.00*
Available Work Hours	***6.50***

Figure 2. Example Crew Day Time Allocation

The crew is also assumed to follow the SSP 50261-02 guideline of an off-duty day following no more than six sols that include "work" related activity. This on-duty / off-duty cadence is assumed to be sufficient for surface missions measuring several weeks to a few months in duration; it has proved satisfactory for ISS expeditions – with infrequent EVAs – measuring four to six months in duration.

The transit from Earth to Mars is assumed to last for several months and to take place in a microgravity environment. Extended durations in microgravity are known to cause multiple changes in the human body that must be reversed after re-entering a gravity environment before the crew can safely carry out many activities [7]. Experience gained from decades of extended duration flights on ISS by scores of astronauts has led to a better understanding of these effects as well as countermeasures that can mitigate them during flight. But some period of time is still required by the crew after returning to a gravity environment to reacclimate to the point where they can safely perform important tasks, such as working in an EVA suit or driving a pressurized rover. The medical community has provided a 3- to 7-sol range for crew to readapt to a gravity environment as informal guidance; additional research into this topic is planned to provide more precise gravity re-adaptation protocols. For the purpose of this analysis, a 3-sol gravity re-adaptation period is assumed for planning, as this represents the stressing case for total

3. METHODOLOGY

Power

The total available surface power is 10kW. With the margin of 2.3kW and other element needs of 2.85kW, the power remaining to be used for mobility recharge is 4.85kW. The power draw for the life support and associated crew systems within the pressurized rover requires 1.85kW and will be consumed during recharge, which leaves 3kW to be devoted to adding energy into the battery.

Timeline Description

The timeline described in the following sections begins with two crew arriving at their landing site and concludes when the crew leaves in their Mars Ascent Vehicle (MAV). Each of the following sections describes crew activities during a portion of the surface mission; a graphical representation of those activities is also provided.

It must be noted that no final decisions have been made regarding the details described in these sections, and this schedule of activities is likely to change as systems are refined, science objectives are better defined, and integrated operations analyses are completed.

Mars Landing Day—Two crew descend inside a pressurized rover (PR) carried as payload on a Mars Descent System (MDS), landing no more than one kilometer away from two pre-deployed cargo landers. The crewed lander is robotically connected to the pre-deployed surface power grid. After allowing at least three sols for crew re-adaptation to Mars gravity, the PR and science equipment are off-loaded from the lander and the surface exploration mission begins.

Due to limited rescue options and contingency equipment assumed in this particular architecture and mission profile, crewed exploration around the landing zone is expected to extend to about 20 kilometers radius, though the crew may deploy robotic assets to explore farther. Crew will collect samples, take environmental readings, and conduct a host of experiments. An overview of surface activity is illustrated in Figure 3.

descending from the deck of the MDS to the surface. This will demonstrate the crews' ability to transition between the deck and the surface by EVA alone as well as conducting the first human exploration activities on the surface of Mars. The crew will return to the MDS deck and re-enter the PR cabin by way of the suitports for a mid-day meal. A second 4-hour EVA will be conducted in the afternoon to continue with tasks in preparation for off-loading the PR and other deck cargo such as science instruments and other utilization equipment. On Sol 5, crew perform another 2.5-hour EVA with the primary objective of off-loading the PR – an activity that is assumed to be carried out while the crew is outside of the PR. A second 1.5-hour EVA is conducted following a mid-day meal to complete off-loading other cargo from the MDS deck and any final PR preparations before extended traverses begin. An actual off-loading concept of operations is not yet defined, pending better definition of cargo off-loading systems the results of which could affect time allocations described here.

Sols 7-11—During Sol 7 the crew begin their first excursion away from the landing site, driving to Exploration Site 1 and conducting a 2.5-hour EVA reconnaissance before preparing the PR for an overnight stay. On Sol 8 the crew will conduct a 2-hour morning EVA, return to the PR for a mid-day meal, then conduct a 2.5-hour EVA in the afternoon. On Sol 9 the

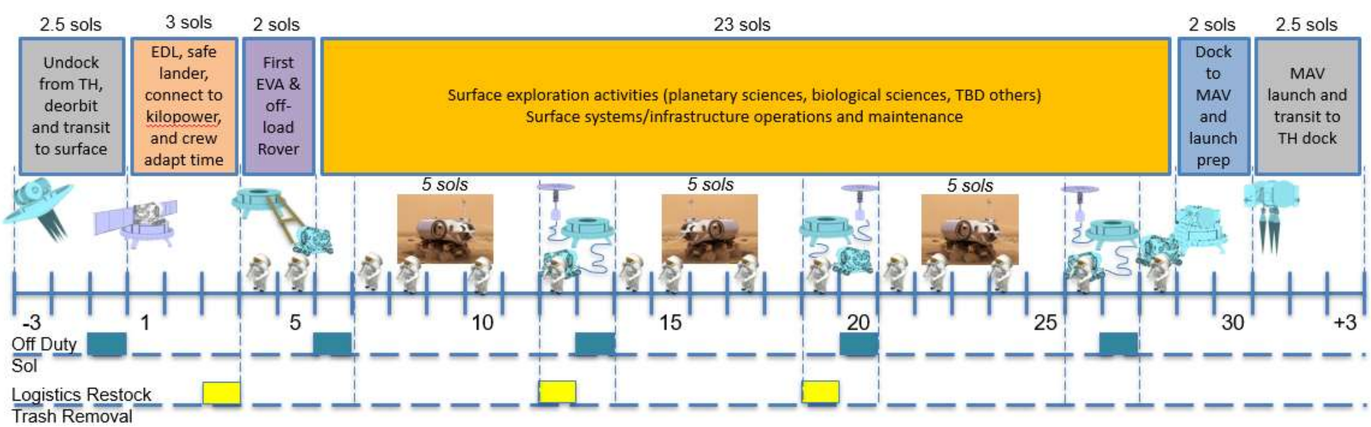


Figure 3. Surface Activities Summary

Sols 1-6—As depicted in Figure 3, Sols 1-3 are nominally reserved for crew re-adaptation to a gravity environment with no scheduled EVA activity. But there is one potential contingency situation that must be protected for: if robotic assets are unable to connect the MDS on which the crew landed to the surface power grid, crew may have to conduct a contingency EVA to hook up the power before the lander's on-board power supply is depleted. During the gravity re-adaptation period crew will exercise, reconfigure the PR cabin as needed, inspect and prepare their EVA equipment, and telerobotically inspect their surface equipment. Following medical clearance, the first EVA occurs on Sol 4, when the PR cabin is depressurized and both crew egress through the PR side hatch. The crew conducts a 2.5-hour EVA with a primary objective of testing suit functionality and their ability to function in the suit. This first EVA will include

crew will remain inside the PR and conduct Intravehicular Activity (IVA) activities. On Sol 10, crew will conduct a 3.5-hour morning EVA, then a second 2.5-hour EVA following their mid-day meal. On the morning of Sol 11 crew will drive the PR back to the landing site and connect the PR to the surface power grid to recharge its energy storage system. The remainder of the day will be used for housekeeping and routine maintenance on the PR and EVA systems.

Sols 12-21—On Sol 12 crew conduct their first logistics restocking and trash removal operation. During a 3-hour EVA the morning of Sol 12, crew will offload a Small Pressurized Logistics Container (SPLC) from the MDS deck for repositioning onto a PR suitport. Fresh logistics will be transferred from the SPLC into the PR, then the empty SPLC will be filled with trash. The now trash-filled SPLC will be placed at a location on the surface next to the MDS as its permanent disposal location. (Note: this disposal location reflects the current best guidance available, including planetary protection considerations. The approach to disposal will be revisited as new guidance becomes available.) Sol 13 will be an off-duty day for the crew, remaining inside the PR for the entire sol.

Beginning on Sol 14 the crew will traverse to a second exploration site. The pattern of activity and duration of EVAs will be the same as that described for the first exploration site (Sols 7-11). The crew returns to the landing site on Sol 18 and connects to the surface power grid at the MDS on which they arrived. Sol 19 repeats the logistics restocking and trash removal activities and EVA durations as described for Sol 12. However, during this restocking event, the crew will take on 14 sols of logistics; sufficient for both the traverse to the next exploration site and supplies needed in the MAV for the return flight to the Deep Space Transport (DST). Sol 20 is another off-duty day.

Sol 22-27—Beginning on Sol 21, the crew traverses to a third exploration site. The pattern of activity and EVA durations will be the same as that described for the first and second exploration sites (Sols 7-11 and 14-18). The crew returns to the landing site on Sol 25. The PR connects to the power grid at the MDS on which they arrived and conducts housekeeping and other IVA activities for the remainder of this sol. On Sol 26 the crew conducts a morning and an afternoon EVA (3 hours and 2.5 hours respectively) for final science and utilization tasks in the local landing site vicinity. Sol 27 is an off-duty day for the crew.

Sol 28-30—On Sol 28 the crew drives the PR to the MDS carrying the MAV, connecting to the ground power grid via this lander as well as docking with the MAV using a pressurized tunnel to connect these two vehicles. A 3-hour EVA is available for external preparation of the MAV for departure plus any other final EVA tasks required before departure. The remainder of Sol 28 plus all of Sol 29 are used for IVA activities necessary for MAV departure, such as transferring returned samples and logistics for the return flight, activation and checkout of MAV systems, closing down selected PR systems, such as the Environmental Control and Life Support System (ECLSS), to prepare this vehicle for uncrewed operations, etc. Prior to departure, return cargo and equipment that has been exposed to the Martian surface environment will be prepared in accordance with applicable planetary protection requirements and guidelines being developed under purview of NASA's Planetary Protection Officer. The crew will be wearing their clean launch/entry suits to mitigate dust transfer back to Earth, in accordance with anticipated planetary protection best practices. EVA suits are left behind on the surface to further mitigate dust transfer. On the day of launch (nominally Sol 31) the PR and tunnel will be undocked from the MAV and the PR will be driven (without crew on board) a safe distance away from the MAV (nominally 1 kilometer) to a location where the MAV launch can be observed. The crew launches in the MAV and spends the next 2.5 sols flying to the DST.

Transport Cost Equation Derivation and Calculation Constraints

To understand if the proposed opscon could be achieved with the pressurized rover, a simplified transport cost equation was used to calculate the energy expenditure during each traverse to understand achievable distances and recharge times at the base camp fission power source. While this equation does not take into account all terramechanics properties (e.g., bull dozing or soil compression effects) it provides an overall picture of power needed to complete the different traverse ops cons and what is achievable given the distance and power constraints.

In this simplified transport cost calculation, for flat terrain, the interaction with soil can be modeled as a rolling resistance where drag force is proportional to a simplified coefficient of rolling resistance multiplied by the weight of the vehicle as shown in equation (1).

$$Drag\ Force\ (F_d) = rolling\ resistance \times mass \times gravity \tag{1}$$

The power to overcome this resistance is the drag force multiplied by the linear velocity:

$$Power\ to\ Overcome\ Drag\ (P_d) = rolling\ resistance \times mass \times gravity \times velocity \tag{2}$$

The integration of power as a function of time results in the energy consumption:

$$Energy\ Consumption\ (E_d) = rolling\ resistance \times mass \times gravity \times \int_0^t velocity \tag{3}$$

Finally, a general equation for transport cost in units of watt-hours can be derived from equations 1-3:

$$Transport\ Cost = rolling\ resistance \times mass \times gravity \times distance \tag{4}$$

Table 1 lists the various inputs and constraints used in the calculation of overall transport cost for each of the traverse options.

Table 1. Transport Inputs and Constraints

Transport Cost Calculation Inputs and Constraints		Description
Base PR Mass	5193 kg	Base mass of PR with 60 kW-H of batteries. Some opscons include additional batteries and mass is adjusted assuming a 150 wh/kg energy density.
PR Hotel Load	1.85 kW	Power draw of rover for all non-driving systems (e.g., avionics, habitation, etc.).
PR Speed	8 kph	Speed is fixed at an assumed average rate
Rolling Resistance	0.15	Dimensionless constant of lunar soil resistance to wheel motion. [8]
Solar Array Size	3.5 kW	Single solar panel on rover and it is assumed that it operates at an 80% effectiveness rate.
PR Solar Panel Power While Driving	50%	Solar panel can be deployed while driving and will not always be pointed optimally to the sun while in motion
Solar Flux to Array Panel on Mars Surface	30%	Surface level solar flux that hits panel
Fission Power Available for Mobility Recharge	4.85 kW-h	Balance of power available at the fission unit for PR
Mars Day Length	24.65hr	Length of day on Mars. Assumes 12hrs of continuous sunlight for solar recharge.

4. RESULTS

Opscon Transport Cost Modeling

The opscon for this calculation follows that described in section 3. The PR maintains 8hr per site, but distance driven is adjusted to ensure that full recharge is possible during the approximately 2.5 Sols when they are back at the lander in between excursion periods. Additionally, the traverse distance and power consumption allowed is constrained to always preserve enough power to perform up to a 20km drive back in the event of a contingency. Figure 4 shows the power consumption over the 3-week surface mission.

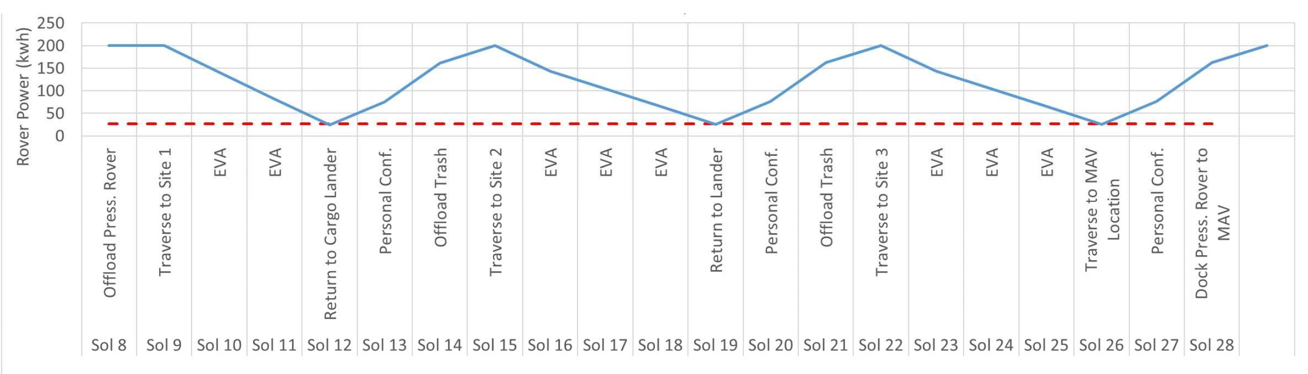


Figure 4. Rover Energetics

This simplified calculation of the transport cost indicates that in order to perform this opscons with the goal of remaining in the field for as long as possible between returns to the fission power. In this instance the traverse distances each day were adjusted to maximize the total distance in between returns to the fission power to recharge, To accomplish this we added an additional 140kW-h (933kg) of batteries to the PR. Without the additional batteries the distances modeled would not be achievable as the rover would need to be continually returning to the fission power to recharge.

With this opscon the PR can achieve a total excursion time away from the fission power of 279 hr, spending 112 hrs at exploration sites performing science, and traversing a unique (i.e., does not retrace any previously driven terrain) cumulative distance of 194km. In order to repeat this opscon it would require 48hr of exploration stand-down for the PR to recharge at the fission power to a full state. If adding additional batteries to the PR is not possible due to limits on landed mass or impacts to PR layout, it is also possible to perform this opscon with the inclusion of a mobile power source that follows the PR and has it's own recharge capability (i.e., an independent solar array). This concept has been investigated in prior studies [9] and the inclusion of a portable utility pallet (PUP) which can provide recharge and act as a communications relay greatly improves exploration capability and flexibility.

Reintegrating the PR battery usage with the overall timeline generates an integrated result shown in figure 5.

Each of these opscons was evaluated using the same transport cost equation to understand how the surface assets were able to maximize their traverse capability.

Long Stay/Long Recharge

For this opscon the PR battery capacity was increased to 200 kW-h in order to spend a long duration away from the fission power. This opscon consisted of driving 12km to an exploration site of interest and parking to perform local EVAs. Each day the PR is then relocated 5km to an adjacent site. This is repeated for 3-4 days until the PR reaches a 10km drive back reserve limit before returning to the fission power for recharge. This opscon provides ample time in the field, however it results in a long time to recharge the PR

Commuter

This opscon looked at a single Sol exploration and recharge traverse plan with the PR having only 60kW-h of batteries on board. In this instance the PR can only traverse far enough away from the FSP before returning for recharging so that it was available the next sol. The PR drives 12km to a traverse site, where the crew can perform up to 8hrs of local EVA, before driving back.

Battery Swap

This opscon is similar to the commuter in that the PR is available at the start of every sol in a fully charged state. The only difference being that instead of waiting to recharge at

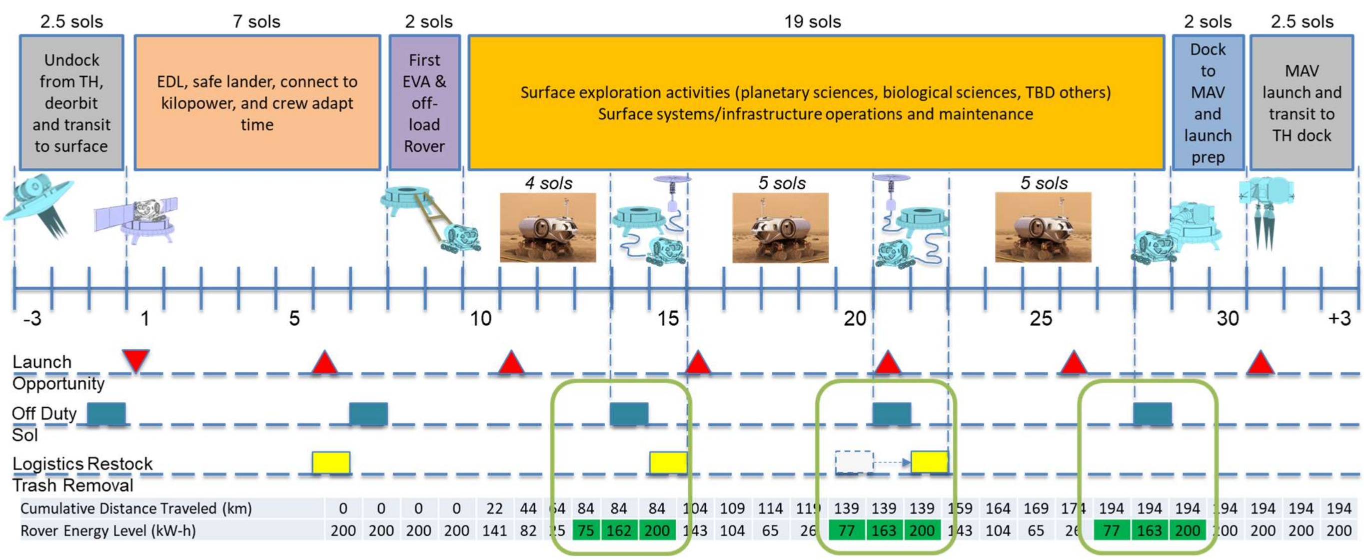


Figure 5. Integrated Timeline and Rover Energetics

5. ALTERNATE APPROACHES

In addition to a baseline opscon, several alternate traverse plans and surface asset combinations were explored in order to understand what the alternative options are for Mars surface exploration. A summary of these options is shown in table 2 and a summary of the key figures of merit are in table 3 at the end of this section.

the FSP, a second set of PR batteries is waiting for the crew to perform an EVA swap when they return. While this opscon does add additional battery hardware and EVA time to the day, it does ensure that the PR is always fully charged at the end of the day which may be deemed advantageous by mission planners in the event of contingency.

Table 2. Pressurized Rover Operations Concept Options

Opscon Name	General Opscon	Philosophy
Long Stay/Recharge	Drive to exploration site, stay as long as possible on large battery, return to FSP for full recharge	Max duration with no additional hardware
Commuter	Daily (sol-ly?) drive to exploration site, perform exploration activities, return to FSP each sol for full recharge	Frequent recharge with no additional hardware
Battery Swap	Drive to exploration site, perform exploration activities, return to FSP, swap for fully charged battery, leaving behind depleted battery to recharge and return to exploration site	Add hardware to minimize battery turnaround
Mobile PUP	Drive both PR and PUP to exploration site, use the PUP to recharge the PR, PUP can return on its own to the FSP for recharge and return to the exploration site to serve PR	Add hardware to maximize exploration capability

Mobile PUP

This opscon provides the most flexibility and range distance for the PR to perform exploration, however it requires additional mobile assets to move with the PR. A PUP which has 195kW-h of energy storage on board follows behind the PR to provide it with power while on the traverse. This allows the PR to remain out in the infield for multiple days before returning to the FSP to recharge.

Table 3. Opscon Figures of Merit

OpsCon	Figure of Merit				
	Total Excursion Time (hr)	Exploration EVA Time (hr)	Total Traverse Distance (km)	Total Unique Traverse Distance (km)	Time to Full Recharge (hr)
Long Stay/Recharge	109	48	49	49	64
Commuter	11	8	24	12	13.65
Battery Swap	11	8	24	12	1.5
Mobile PUP	113	40	60	60	72*

6. CONCLUSIONS

The balance achieved using the available power, human operations, and mobility hardware reveals the available exploration capability in time and distance for a human mission on the surface of Mars. The capability is maximized by taking advantage of the time during crew operations while the pressurized rover is idle to recharge the rover battery. The analysis both proves that a minimal surface hardware Mars mission is achievable and defines the constraints of the exploration that can be conducted.

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BIOGRAPHY

Michael B. Chappell *earned his undergraduate and graduate degrees in Electrical Engineering from Mercer University. He began his career at the Advanced Missile Signature Center at Arnold Air Force Base as a member of the measurements team. Continuing as a civilian with the United States Air Force, Michael moved to Robins AFB where he worked in several engineering roles including avionics sustainment, industrial controls and electrical infrastructure design, and electronic countermeasures. After many years serving the Air Force, Michael moved to a position as a guidance, navigation, and control (GN&C) integration engineer for NASA's Space Launch System (SLS) at Marshall Space Flight Center (MSFC), eventually becoming the integration lead. Currently, Michael is the deputy lead of the Mars Architecture Team (MAT) developing crewed Mars mission concepts and project manager for the supporting activities at MSFC.*

Stephen J. Hoffman *received a B.S., M.S., and Ph.D. in Aeronautical and Astronautical Engineering from the University of Illinois in 1978, 1980, and 1984 respectively. Dr. Hoffman is a Senior Systems Engineer with over 40 years of experience working in civilian space programs performing tasks involving program management, interplanetary mission planning, preliminary spacecraft design, orbit mechanics, and planetary analog missions. Dr. Hoffman is currently supporting the Exploration Mission Planning Office at the NASA Johnson Space Center. He supports a variety of mission studies and concept assessments associated with human exploration beyond low Earth orbit for this office.*

Omar Bekdash *received his bachelor's and master's degrees in bioengineering from the University of Maryland in 2010 and 2012, respectively. He is currently working at the NASA Johnson Space Center supporting a variety of mission studies, analog research studies, and formulation of surface mobility concepts associated with human exploration beyond low Earth orbit.*