AIAA SPACE 2008 Conference & Exposition
9 - 11 September 2008, San Diego, California

AIAA 2008-7914

Analysis of Architectures for Long-Range Crewed Moon and Mars Surface Mobility

Wilfried K. Hofstetter[1], SeungBum Hong[2], Jeffrey A. Hoffman[3], and Edward F. Crawley[4]
MIT Department of Aeronautics and Astronautics, Cambridge, MA, 02139

This paper presents an architecture-level analysis of a set of planetary surface mobility concepts for human exploration. The motivation for the analysis is two-fold: to gain an understanding of the limitations of different architectures for extended-range surface mobility and to assess the feasibility of global-scale exploration from a single site to reduce the requirements for surface infrastructure emplacement. Four architectural concepts are investigated, including unpressurized and pressurized mobility options. The primary metric for assessing system performance is the ideal exploration radius achievable based on operational and technological constraints, i.e. the exploration radius the system could nominally achieve on a smooth planetary sphere. The analysis results indicate that for both the lunar and Martian environment, significant exploration radii on the order of several 100 km can be achieved from a single location provided that two independent pressurized vehicles are available, and that pre-positioning of supplies and in-situ generation of power in the field is possible. From the perspective of accessible surface area, this makes a single base on a planetary surface superior to a sequence of missions to separate sites. The analysis also indicates that unpressurized mobility can achieve exploration radii on the order of several 10 km when using two independent vehicles and high driving speeds, i.e. the accessible exploration radius of an unpressurized mobility system can increase significantly due to familiarization with the terrain and resulting increased driving speeds. The paper is concluded by a summary of findings and suggestions for future work.

I. Introduction

The capability to explore the surface around a landing site must be considered one of the primary value-delivering activities during any human planetary exploration enterprise, such as the future human exploration of the Moon and Mars called for in the Vision for Space Exploration.[1] Surface mobility systems provide explorers access to areas which are beyond the immediate vicinity of the landing site and can therefore not be reached by walking alone; these systems are therefore key supporting systems for human planetary surface exploration operations. The J-class Apollo missions (Apollo 15, 16, and 17) demonstrated that even limited surface mobility in the form of one 2-person rover (the Apollo Lunar Roving Vehicle / LRV) can significantly enhance surface exploration capabilities[2]: Figure 1 shows a comparison between the Apollo 14 (walking-only) and the Apollo 15 surface traverses. It should be noted that even when using the Apollo LRV, walk-back constraints were still the limiting factor on the achievable exploration radius from the lunar module: in case of an accident with the LRV, the crew had to be able to walk back to the lunar module before their consumables ran out. However, due to the increased velocity on the outbound leg of the traverse, the accessible exploration radius could be significantly enhanced over walking-only traverses.

Extended surface exploration range does not only impact design and operations for individual traverses or missions, but also the architecture of the entire Moon and Mars exploration campaigns: concentrating surface mobility assets at a single site may enable significantly increased accessible exploration radii compared to distributing the surface infrastructure over multiple separated sites. Moreover, emplacing and maintaining a single

[1] Graduate Research Assistant, Department of Aeronautics and Astronautics, wk_hof@mit.edu, AIAA Student Member.
[2] Graduate Research Assistant, Department of Aeronautics and Astronautics, seungbum@mit.edu, AIAA Student Member.
[3] Professor of the Practice, Department of Aeronautics and Astronautics, jhoffma1@mit.edu, AIAA Member.
[4] Professor, Department of Aeronautics and Astronautics, crawley@mit.edu, AIAA Fellow.

surface infrastructure during a campaign can offer significant cost and risk advantages over campaign concepts that involve the emplacement, operation, and subsequent abandonment of infrastructure at multiple surface sites. This aspect is of particular relevance for a future Mars campaign because the dynamics of Earth-Mars-Earth transportation prohibit short-duration Apollo-style sortie missions to individual Mars surface sites, thereby necessitating the emplacement of significant surface infrastructure for each human Mars mission (this statement applies also for the case of opposition-class missions). For a future lunar exploration campaign, the use of sortie missions to access specific sites of high scientific value which cannot be accessed from a single base on the lunar surface is conceivable, although it would still require a significant investment of resources.

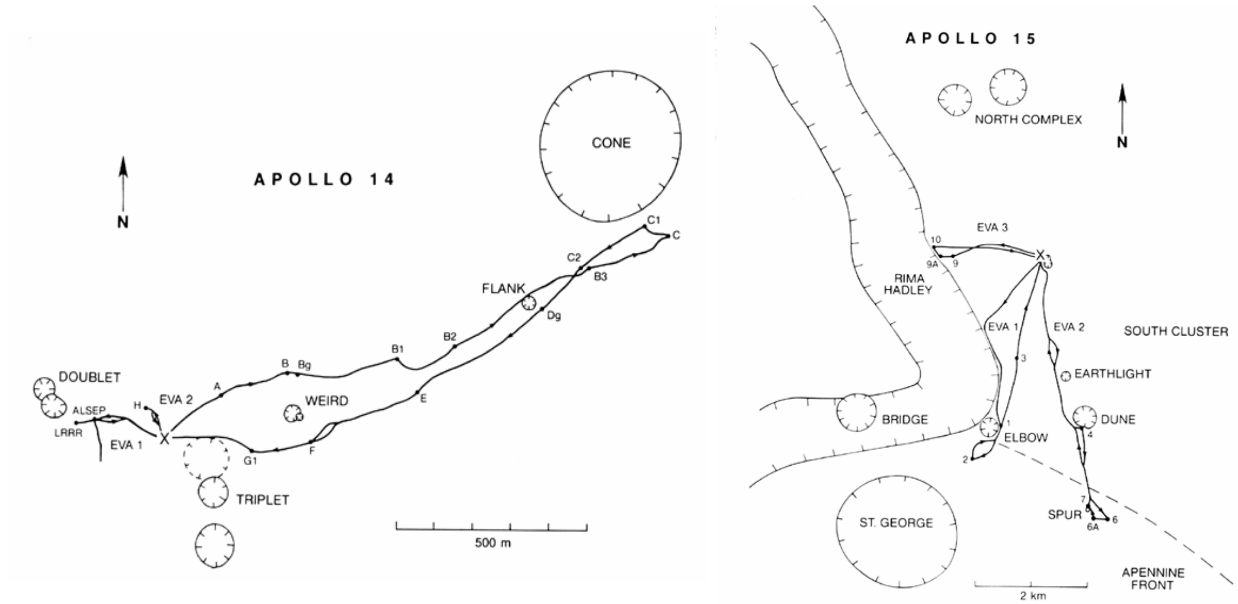

Figure 1: Comparison of Apollo 14 surface traverses on foot (left side) with Apollo 15 surface traverses using the Apollo LRV (right side)[3]; note the different levels of scale (500 m vs. 2 km)

The motivation for analyzing long-range planetary surface mobility options for human exploration is therefore two-fold: (1) to understand what the limitations on human exploration radius are for different surface mobility concepts, and (2) to assess the feasibility of conducting Moon and Mars surface exploration from a single surface site / base infrastructure. Previous work in the literature has been primarily based on conducting analyses of different mobility system point designs customized for particular surface mission requirements: for NASA's First Lunar Outpost, a single unpressurized rover capable of carrying up to 4 crew was considered with possible addition of a pressurized rover later in the campaign.[4] NASA Mars Design Reference Mission 1.0 considered operation of both unpressurized and pressurized rovers from a single base, enabling pair-wise operation starting with the 2nd human mission; however, very long-range exploration was assumed to be carried out by tele-operated robotic rovers[5]. Follow-on studies considered extended Mars surface exploration by using concepts such as the Mars field camp[6]; however these concepts were not focused on providing extreme exploration radii, but more on providing more endurance at intermediate distances. The somewhat more recent Draper/MIT CE&R study addressed lunar and Mars long-range surface mobility by conducting a comparative analysis of mobility system point designs; access to sites of interest up to 200 km from base was provided using a pair of pressurized campers with ATVs.[7] However, extension of the exploration radius was not considered. More recently, NASA has considered the problem of providing global-scale planetary exploration access from a single base as part of the lunar surface system architecting effort[8,9]; the baseline concept is to use a pair of small pressurized rovers (possibly with additional mobile power generation systems) for surface roves of up 7-days and up to 900 km exploration radius from a base at the lunar South Pole.

While this review of the literature indicates that initial work has been carried out to address the two above questions / motivations, a comparative analysis of different concepts for both the lunar and Mars surface environments is lacking. The work presented in this paper addresses both motivations through quantitative analysis of a set of surface mobility systems concepts for lunar and Mars surface environments. Section II introduces the surface mobility system concepts and associated modus operandi. In Section III results from the quantitative analysis of achievable exploration radii are presented, with associated comparative discussion across the concepts in Section IV. Section V provides a summary of major findings, as well as suggestions for future work.

II. Surface Mobility Concepts

The basic surface mobility capabilities provided by a system such as the Apollo LRV can be extended in a number of ways: by increasing the number of vehicles without changing vehicle capability, by adding additional capabilities such as a crew compartment for extended-duration traverses, or by combinations of the preceding options. Based on these extension options 4 specific concepts were created for the quantitative analysis of human planetary surface mobility systems. This set of concepts is not meant to be comprehensive, but rather to explore different parts of the architecture space for surface mobility systems as a precursor to a more detailed (and more comprehensive) analysis.

The following specific concepts were included:

- Unpressurized surface mobility using two independent vehicles on traverse
- Pressurized surface mobility using two independent vehicles on traverse
- Pressurized surface mobility with additional energy storage on trailers
- Pressurized surface mobility with pre-deployed power source, energy storage, and supplies

Each of these concepts and the associated vehicle configurations as well as nominal and contingency operations are described in detail in the following subsections. For each of the concepts variants can be generated with different technologies.

A. Unpressurized Mobility Based on Two Independent Vehicles

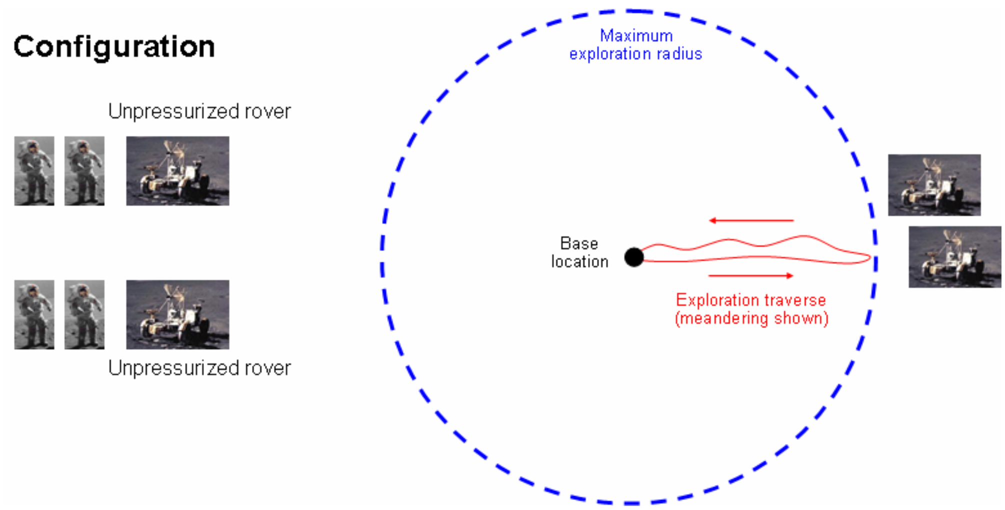

Figure 2: Unpressurized mobility concept based on the use of two independent unpressurized vehicles capable of carrying the entire crew back to base in the event of an emergency / contingency (images courtesy NASA)

This concept is based on the exploration traverse being carried out entirely during one EVA. Much as during the Apollo J-class missions, the crew would egress the habitat or lander, prepare and load the unpressurized mobility system, and then depart for the farthest point of the traverse. The major difference to Apollo is the use of two independent vehicles instead of just one: each vehicle would be capable of carrying the entire crew on traverse back to base in the event of an emergency. This way, the walk-back which still applied to the Apollo LRV traverses would be converted into a drive-back constraint, resulting in a substantial increase in accessible exploration radius (the case of losing both rovers due to an accident is considered unlikely). Figure 2 provides an overview of the configuration and operations for this concept.

B. Pressurized Mobility Based on Two Independent Vehicles

This concept is based on the use of two independent pressurized vehicles on traverse. Each vehicle would nominally carry two crew members, but have the capability to accommodate 4 crew members in the event of an emergency with the 2nd rover; this way, a drive-back constraint applies in the contingency case. Due to the availability of a pressurized module on the rover diving times exceeding the duration of a single EVA are possible, thereby enabling significantly increased exploration radii compared to unpressurized mobility.

The major components of the rover would be the crew compartment, the energy storage system, and the chassis with integrated drive system; Figure 3 shows the high-level configuration and the concept of operation for this surface mobility system.

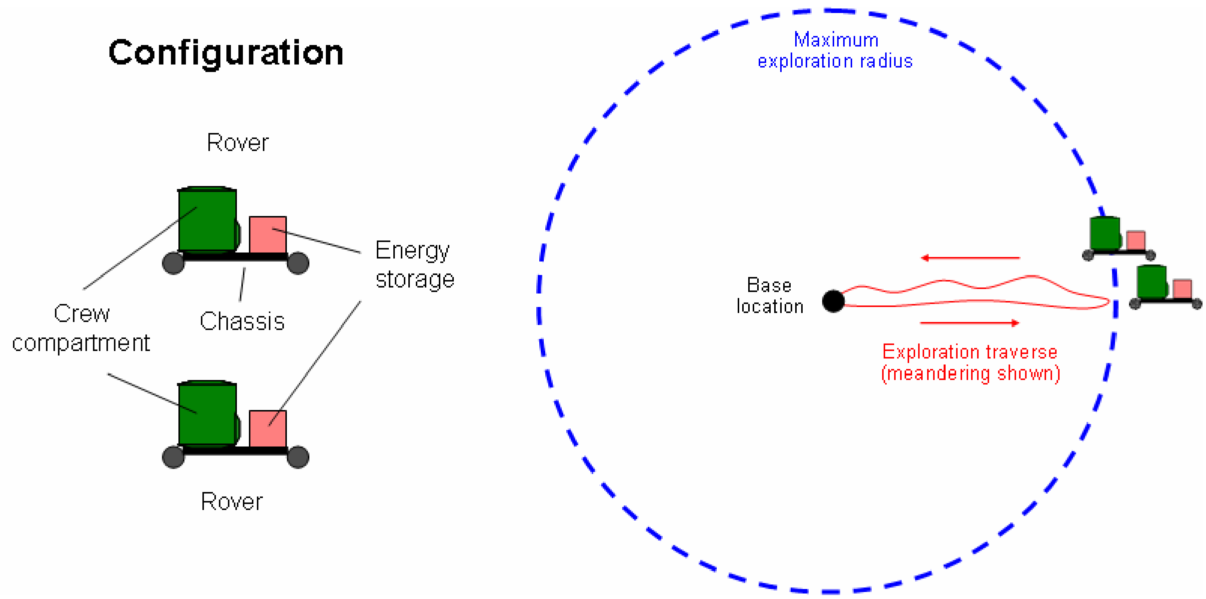

Figure 3: Pressurized mobility concept based on the use of two independent pressurized vehicles capable of carrying the entire crew back to base in the event of an emergency / contingency

C. Pressurized Rovers With Energy Storage Trailers

This concept is an extension of the previous one using a pair of pressurized rovers: we add a pair of chasses with additional energy storage, but no additional crew compartments, i.e. energy storage trailers. These trailers would be self-propelled, but guided by the pressurized rovers they are connected to. The rationale for using the trailers is that the additional energy storage available increases the achievable exploration radius. As with the previously described concept, each pressurized rover provides the capability for transporting the entire crew back to base in case of an emergency. Figure 4 shows the configuration for this concept, as well as an overview of the concept of operations.

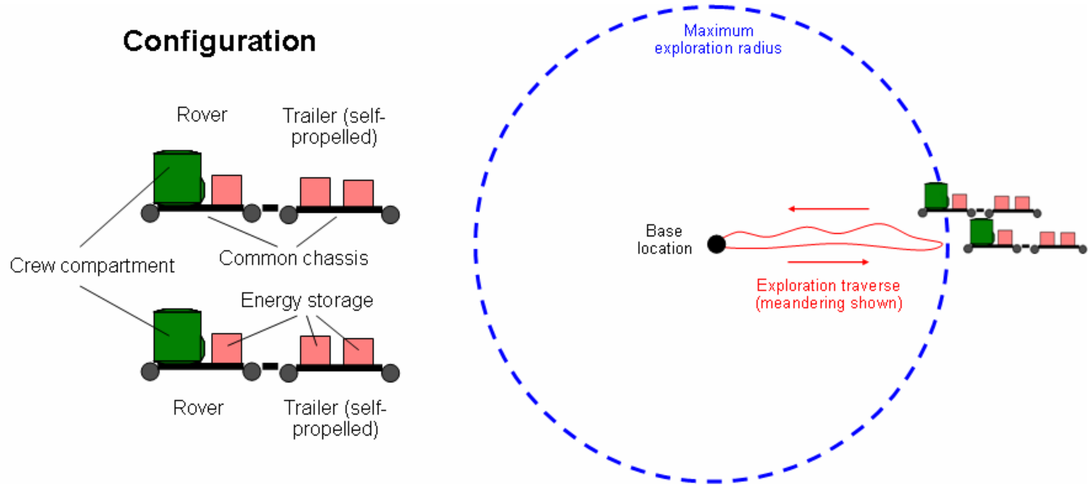

Figure 4: Pressurized mobility concept based on the use of two independent pressurized vehicles as well as trailers with additional energy storage for extended range operations (one or more trailers per rover)

D. Pressurized Rovers and Pre-Positioned Power / Consumables Re-supply

Instead of using trailers for additional energy storage, this concept is based on re-supplying a pair of pressurized rovers on traverse from pre-positioned chasses with power generation and energy storage capability, as well as consumables. These chasses would be driven to a pre-determined optimal distance under remote control, using the solar power generation system to re-charge as needed. Once the chasses are in place and fully charged, the crew would set out on the exploration traverse. When reaching the pre-deployed chasses, they would swap consumables and energy storage with the pre-deployed items in order to extend their exploration range. After the consumables on the chasses are exhausted, they are driven back to base and re-stocked for another deployment in the field.

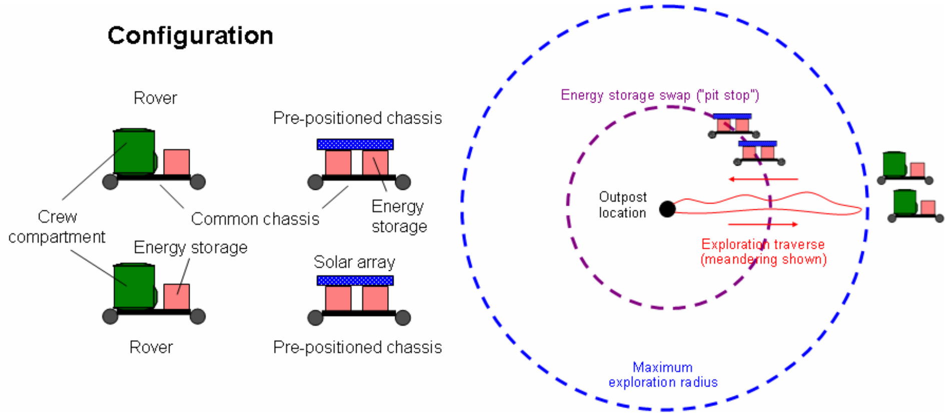

Figure 5: Pressurized mobility concept based on the use of two independent pressurized vehicles and two pre-positioned chasses with power systems and consumables (one or more pre-positioned chasses per rover)

III. Quantitative Analysis Results

This section provides the results of quantitative analysis of the surface mobility system concepts described above. The primary metric for the assessment of architecture performance is the ideal exploration radius achievable from a surface base location. The ideal exploration radius is the maximum distance achievable from base within operational and technology constraints (particularly energy storage technology), measured along a perfectly smooth planetary surface. The ideal exploration radius is not site-specific and can be converted into actual site-specific exploration radii based on site-specific driving overheads to account for obstacles.

In order to carry out the quantitative analysis, a number of design-related assumptions were made; these assumptions are documented in Table 1. The total "wet" mass of the pressurized rover (meaning the mass of the rover when completely filled with consumables, crew, science equipment and energy storage) was set to be 5000 kg, a mass that can easily be delivered by future lunar and Mars transportation systems as envisioned for human exploration.[10,11] Out of these 5000 kg mass, 1000 kg were assumed to be chassis, 2000 kg crew compartment, 400 kg science equipment, and 400 kg for 2 crew members and their EVA suits. As structures tend to be designed to Earth launch loads rather than to planetary surface gravity, these values are assumed to apply to Moon and Mars pressurized rovers. Several previous publications on the conceptual design of pressurized rovers show that total "wet" masses of rovers are estimated at 4000~7000 kg.[12] In addition, from the MIT study of a pressurized rover[13], the mass of chassis and drive systems is 650 kg and the mass of crew compartment is 1700 kg, and the rover can carry 480 kg of science equipment. Therefore, the assumptions on masses are reasonable if not conservative.

Table 1: Assumptions for quantitative analysis

Lunar surface mobility specific energy [Wh/kg/km][14]	0.15	Pressurized rover total "wet" mass [kg]	5000
Mars surface mobility specific energy [Wh/kg/km]	0.34	Chassis and drive system mass [kg]	1000
Average power requirement per crew [W]	250	Crew compartment mass [kg]	2000
Consumables requirement per crew per day [kg/p/d]	20	Mass crewmember + EVA suit [kg]	200
Power system mass for pre-deployed chassis [kg]	1000	Science equipment per rover [kg]	400

It was further assumed that a human required 20 kg/day of consumables while on a pressurized traverse, as well as an average power of 250 W. The specific energy required for movement along the lunar surface was assumed to be 0.15 Wh/kg/km, corresponding to the high-end value obtained from Apollo lunar rover operations[14]; the corresponding value for Mars was determined by scaling with the surface gravity level.

The following sections provide the results from the quantitative analysis of the concepts introduced in Section II.

E. Unpressurized Mobility Based on Two Independent Vehicles

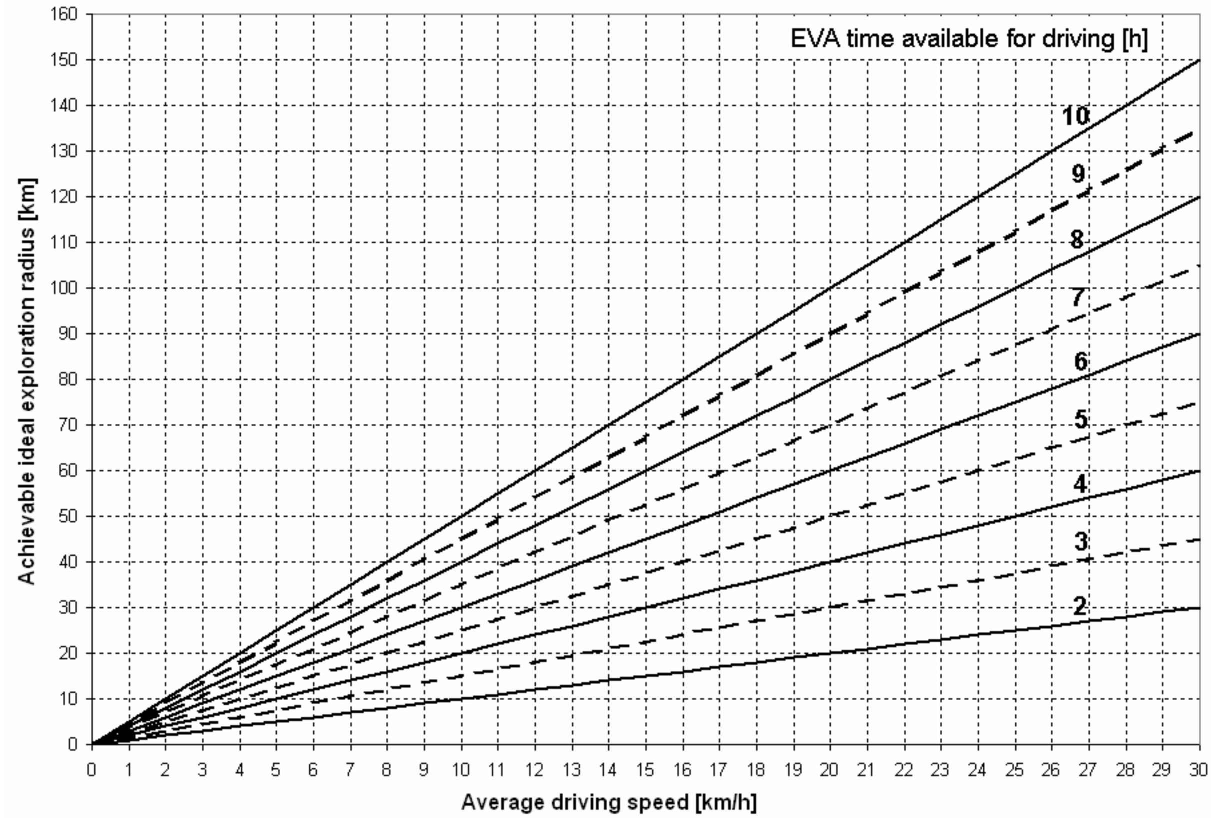

Figure 6: Ideal exploration radius accessible from a Moon or Mars surface base using two independent unpressurized vehicles as a function of average driving speed and the EVA time available for driving

The performance of unpressurized surface mobility architectures is not limited by the energy storage capability of the vehicles or the surface environment they are operating in, but by contingency constraints and limitations on EVA capabilities. The ideal exploration radius of a mobility system based on two independent unpressurized rovers, each capable of transporting the entire crew on traverse, can be calculated as a function of the EVA time available for driving and the average driving speed while on traverse independently of the planetary surface environment. Figure 6 provides an overview of the results:

For average driving speeds of 10 km/h and EVA driving durations of 4 hours (both comparable to Apollo operations[2]), an ideal exploration radius of 20 km is achievable. For a 10 km/h driving speed, each additional hour of EVA driving time will buy an additional 10 km of 5 km of exploration radius; this indicates that the extension of overall EVA duration by providing nutrition inside the suit may yield significant benefit with regard to unpressurized mobility. The same holds for an increase of average driving speed, which may be possible along routes that have been traveled before and are therefore familiar. For a 4-hour driving duration on EVA, each 5 km/h increase in average driving speed yields an increase of 10 km in exploration radius.

A. Pressurized Mobility Based on Two Independent Vehicles

For pressurized mobility systems performance is no longer limited by EVA system capabilities, but by the overall wet mass of the vehicle. Based on the maximum wet mass of the pressurized rover and the consumables and average power demands of the crew, the energy available for surface movement can be calculated and converted to an ideal exploration radius given a specific energy of movement, an energy storage density, and a traverse duration. Figure 7 shows the results of this calculation for lunar and Mars surface planetary environments. Also shown are the maximum achievable exploration radii based on two driving speeds averaged over the entire traverse duration (including stopping times). All other conditions equal, Mars exploration radii are smaller than corresponding radii on the lunar surface due to the increased specific energy required for movement. Enlarged versions of the diagrams from Figure 7 are provided in Figure 14 and Figure 15 in the appendix.

Note on how to read the diagrams: each capability diagram features to sets of curves. The black (descending) curves are exploration capabilities from a vehicle design perspective, i.e. they represent what exploration radius the pair of pressurized rovers can achieve based on consumables and energy storage without consideration for driving speed. Each black line corresponds to one energy density for the energy storage system; e.g. the 100 Wh/kg line indicates the achievable exploration radius for a pair of pressurized rovers using energy storage systems with a density of 100 Wh/kg. The assessment of the vehicle capabilities, however, is not sufficient information to determine feasible exploration radii because it does not take into account average driving speed: for a traverse duration of 0 hours, the 100 Wh/kg pair of pressurized rovers could achieve more than 75 km exploration radius – but would require to move at infinite speed. This is why a second set of red (ascending) curves is superimposed on the black lines: these lines indicate the exploration radius that is achievable for a given continuous driving speed averaged over the entire traverse duration, i.e. they represent kinematical constraints. Feasible traverses must lie at their intersection with the black lines or below.

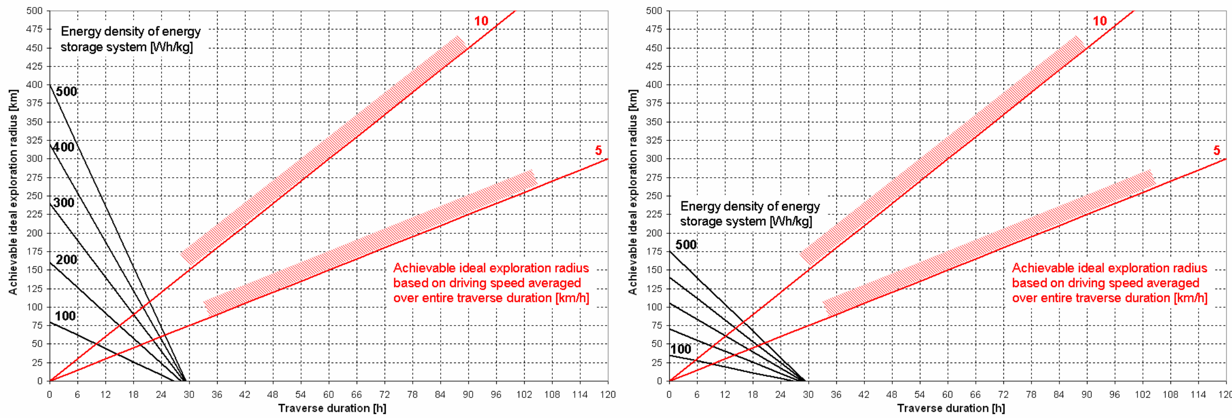

Figure 7: Ideal exploration radius from a planetary surface base as a function of energy storage density for a pair of pressurized rovers; lunar surface environment (left) and Mars surface environment (right). Also shown are the limits to exploration range based on driving speed averaged over the entire traverse duration.

B. Pressurized Rovers with Energy Storage Trailers

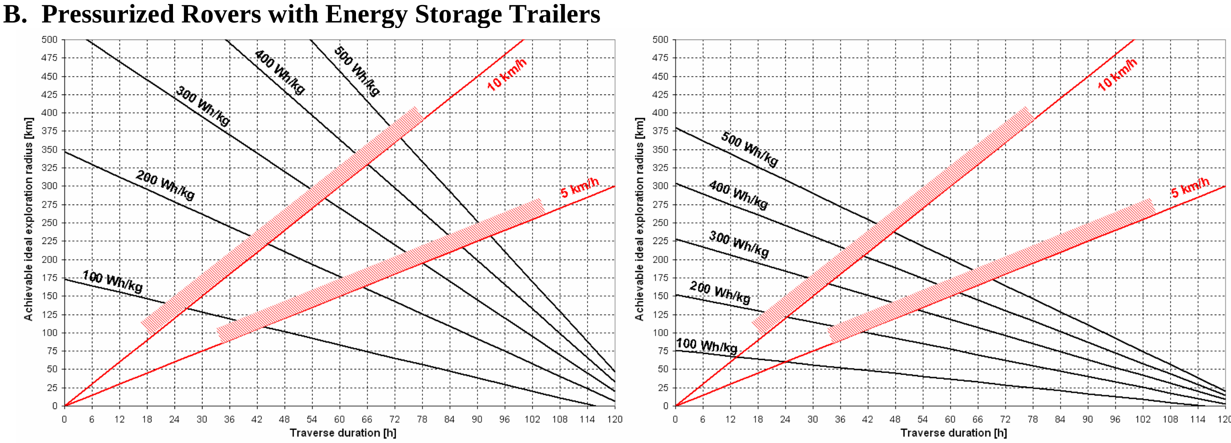

Figure 8: Ideal exploration radius from a planetary surface base as a function of energy storage density for a pair of pressurized rovers with one energy storage trailer each; lunar surface environment (left) and Mars surface environment (right).

By adding energy storage trailers to the pressurized rovers, an additional 4000 kg are available for energy storage; however, an additional 5000 kg must be moved on the planetary surface; the corresponding increase in surface exploration radius as a function of traverse duration and energy storage density is shown in Figure 8. If two energy storage trailers are used per rover, a further 4000 kg of energy storage system are available, however an additional 5000 kg need to be moved along the planetary surface; the corresponding increase in exploration radius is shown in Figure 9. Enlarged versions of the diagrams are provided in Figure 16, Figure 17, Figure 18, and Figure 19 in the appendix.

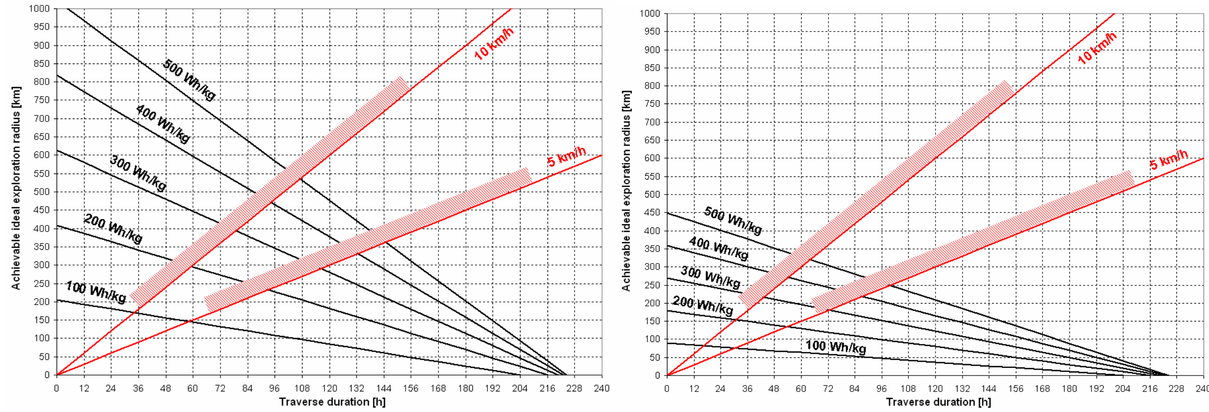

Figure 9: Ideal exploration radius from a planetary surface base as a function of energy storage density for a pair of pressurized rovers with two energy storage trailers each; lunar surface environment (left) and Mars surface environment (right).

C. Pressurized Rovers and Pre-Positioned Power Stations

Adding trailers to pressurized rovers results in diminishing returns because of the need to propel the trailer along with the rover. While this situation can be improved somewhat by dropping the trailer as soon as the energy (and possibly consumables) it carries are expended. A further increase in exploration radius for a given amount of equipment can be achieved by locally generating power at a pre-positioned station. This way, more energy is available at a greater distance from the base.

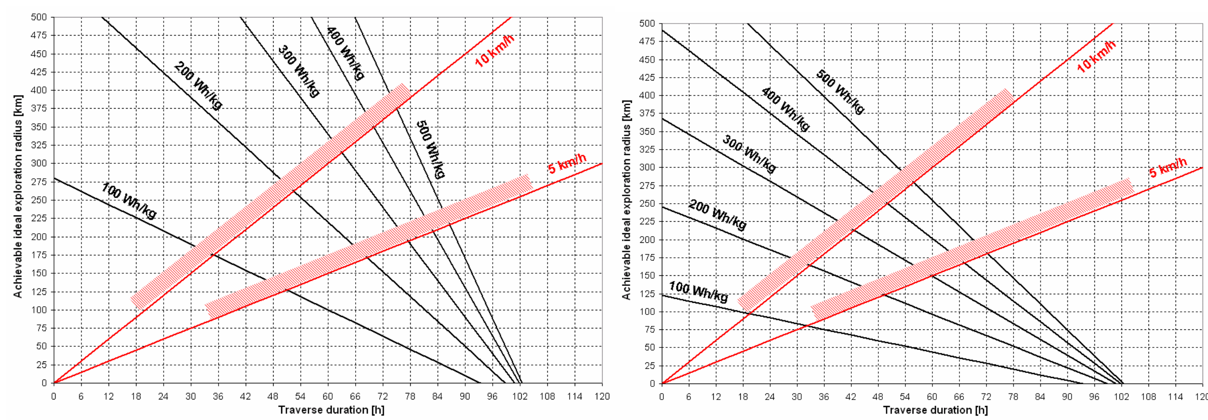

Figure 10: Ideal exploration radius from a planetary surface base as a function of energy storage density for a pair of pressurized rovers with one optimally pre-positioned power and consumables station each; lunar surface environment (left) and Mars surface environment (right).

Figure 10 and Figure 11 provide results for achievable exploration radii for the cases of 1 and 2 pre-deployed 5000 kg stations, each with a 1000 kg power generation system. This leaves 3000 kg of consumables and energy storage per station for swapping with the pressurized rovers. Figure 20, Figure 21, Figure 22, and Figure 23 in the appendix contain enlarged versions of the diagrams.

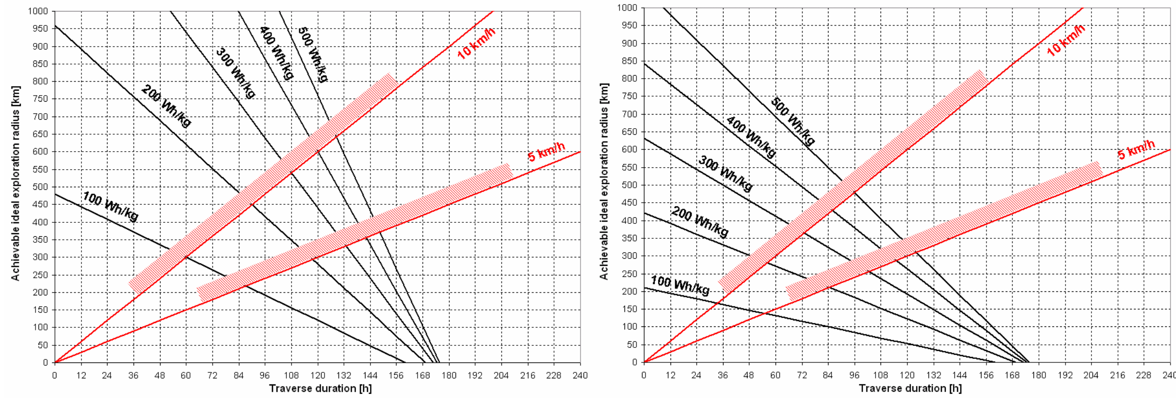

Figure 11: Ideal exploration radius from a planetary surface base as a function of energy storage density for a pair of pressurized rovers with two optimally pre-positioned power and consumables stations each; lunar surface environment (left) and Mars surface environment (right).

IV. Discussion of Analysis Results

The previous section focused on providing results from the analysis of the individual architectures for a variety of energy densities and traverse durations. In this section, we focus on a comparison of the different architectures for two levels of energy storage density: 200 Wh/kg (corresponding to high-performance future Li-Ion battery technology[9]) and 500 Wh/kg (corresponding to high-performance regenerative fuel cell systems[15]).

Figure 12 shows a comparison of achievable ideal exploration radii for the four surface mobility concepts as a function of traverse duration for pressurized excursions; the diagram on the left-hand side is for an energy storage density of 200 Wh/kg, the one on the right-hand side for 500 Wh/kg. Pressurized surface mobility using 2 pressurized rovers leads to significantly increased exploration radii compared to unpressurized mobility; however, the traverse duration is restricted to below 30 hours due to the consumption of supplies and power by the crew. As for unpressurized surface mobility, an increase in average driving speed (e.g. due to traveling on familiar routes) results in an increase in exploration radius. 500 Wh/kg compared to 200 Wh/kg energy density does not result in a significant increase in exploration radius due to the driving speed limitations.

When we go to using energy storage trailers, achievable exploration radius increases significantly, although the gains from adding additional trailers are clearly diminishing. Increased energy density also seems to have a significant impact on achievable exploration radii in case trailers are being used. The use of pre-positioned consumables and power stations clearly results in the most significant increase in exploration radius for a given 5000 kg of additional mobility infrastructure. Adding additional stations does not result in diminishing returns, but in a near-constant off-set in exploration radius. Increased energy density does not have the same impact as for trailers.

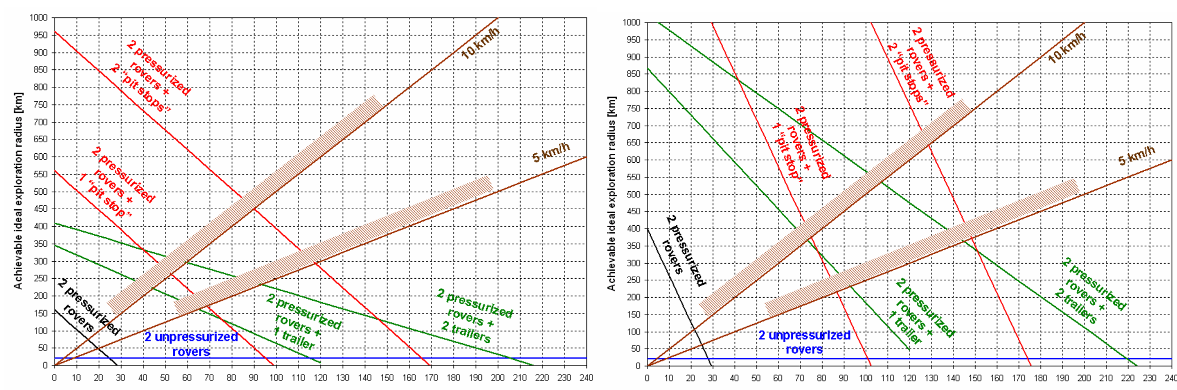

Figure 12: Comparison of surface mobility architecture lunar surface exploration capabilities; energy storage density of 200 Wh/kg (left) and 500 Wh/kg (right).

Figure 13 shows corresponding results for a Mars surface environment; due to the higher gravity and therefore higher specific energy of movement the achievable exploration radii are somewhat lower than the corresponding values for a lunar environment. The qualitative relationships between the architecture are, however, identical to those of a lunar environment.

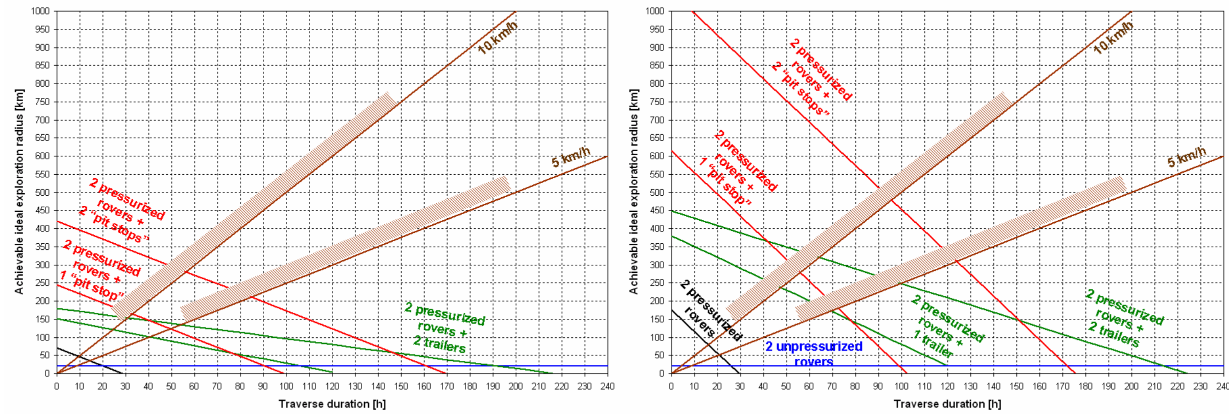

Figure 13: Comparison of surface mobility architecture Mars surface exploration capabilities; energy storage density of 200 Wh/kg (left) and 500 Wh/kg (right).

It is interesting to note that a pair of 5000 kg pressurized rovers each with a 5000 kg trailer or a pre-deployable station of 5000 kg can provide a surface exploration radius 2-3 times larger than that achievable using a pair of pressurized rovers only. This indicates that for the same mobility infrastructure mass deployed to a planetary surface, clustering this mass at a single site in the form of rovers and trailers / pre-deployable stations results in 2 – 4.5 times more accessible surface area than the deployment of two pairs of pressurized rovers to completely different surface locations. With increasing number of missions and associated deployment of mobility infrastructure, the accessible surface area for the single base grows with the square of the number of missions if the pre-positioning strategy is used, whereas that for separate sites grows linearly with the number of missions. If human-accessible surface area was the driving metric for value generation from planetary surface exploration, then operations from a single base would appear to be preferable.

V. Conclusion and Future Work

The comparative analysis of different surface mobility concepts above yielded a number of interesting insights and conclusions for planetary surface mobility system architecture, summarized here in a set of key findings:

- Unpressurized surface mobility using two independent vehicles, each capable of carrying the entire crew in an emergency, can provide exploration radii on the order of 10s of km from a base
- Unpressurized surface mobility exploration capabilities benefit strongly from increased EVA duration (for example through the availability of additional consumables on the rover and nutritional supplements in the suit) as well as from familiarization with the terrain, resulting in increased average driving speed
- Pressurized surface mobility enables exploration on the order of 100 km from base; the average driving speed during the traverse becomes the major limiting factor, indicating that with increasing terrain familiarity exploration radii will increase.
- Use of energy storage trailers or pre-positioned stations for consumable and energy re-supply can significantly enhance the exploration radii achievable with a pair of unpressurized rovers. If in-situ recharging of energy storage in the field is possible, then the pre-positioned stations are superior to energy storage trailers, which provide diminishing returns with each additional trailer.
- For the same campaign surface mobility system mass, concentrating surface mobility assets at a single location results in a significantly increased human-accessible exploration area compared to distributing them over multiple non-connected sites. Depending on the valuation of accessible exploration area, this may drive the campaign architecture to a single base (which also has other advantages unrelated to surface mobility).

Opportunities for future work include a more comprehensive assessment of surface mobility concepts (including concepts such as the planetary camper[7]), increase in modeling fidelity of design and operations (in particular for the pre-positioned consumables and power station), and test and validation of surface mobility design and operational concepts in analog environments on Earth.

Acknowledgments

This paper was prepared at the Massachusetts Institute of Technology, Department of Aeronautics and Astronautics under a research grant from NASA's Exploration Systems Mission Directorate (ESMD). The authors would like to thank NASA for the support of this work.

References

[1]The President of the United States of America, Vision for Space Exploration, The White House, Jan. 2004.

[2]NASA, "Apollo Program Summary Report: Synopsis of the Apollo Program Activities and Technology for Lunar Exploration," NASA-TM-X-68725, Apr. 1975.

[3]Lunar and Planetary Institute, "The Apollo Landing Sites," URL: http://www.lpi.usra.edu/publications/slidesets/apollolanding/ApolloLanding/apollolanding_index.shtml [cited: 28 July 2008].

[4]NASA, 3rd SEI Technical Interchange Proceedings, NASA-TM-107979, 1992.

[5]Hoffman, S., Kaplan, D. (ed.), "The Reference Mission of the NASA Mars Exploration Study Team," NASA SP-6017, Johnson Space Center, Houston, TX, 1997.

[6]Hoffman, S., (ed.), "The Mars Surface Reference Mission: A Description of Human and Robotic Surface Activities," NASA/TP-2001-209371, Dec. 2001.

[7]Draper / MIT NASA-CER Extension Period Final Report, Cambridge, MA, Sep. 2005

[8]NASA Lunar Architecture Team (LAT), Briefing on Lunar Exploration Strategy and Architecture, 2nd Exploration Conference, Houston, TX, Dec. 2006.

[9]Cooke, D., "Exploration Systems Mission Directorate - Lunar Architecture Update," Presentation at AIAA Space 2007 in Long Beach, CA, Sep. 2007.

[10]Drake, B. G. (ed.), "Reference Mission Version 3: Addendum to the Human Exploration of Mars," NASA SP-6017-ADD, Johnson Space Center, Houston, TX, 1998.

[11]NASA, "NASA's Exploration Systems Architecture Study," NASA-TM-2005-214062, Nov. 2005.

[12]Zakrajsek, J. J., et al., "Exploration Rover Concepts and Development Challenges," 1st Space Exploration Conference: Continuing the Voyage of Discovery, AIAA, Orlando, FL, 30 Jan. – 1 Feb. 2005.

[13]Bairstow, B., et al., "Extensible Planetary Surface Mobility Systems," Massachusetts Institute of Technology, Cambridge, MA, May 2006.

[14]Larson, W. J., Pranke, L. K. (editors), *Human Spaceflight – Mission Analysis and Design*, Space Technology Series, McGraw-Hill, New York, 2000.

[15]Barbir, F., Molter, T., and Dalton, L., "Efficiency and Weight Trade-Off Analysis of Regenerative Fuel Cells as Energy Storage for Aerospace Applications," *International Journal of Hydrogen Energy*, Vol 30, No. 4, 2005, pp. 351-357.

Appendix

Figure 14 - Figure 27 in the appendix contain enlarged versions of the diagrams and data presented in Figure 7 - Figure 13 in Section III (Analysis Results) and Section IV (Discussion of Analysis Results).

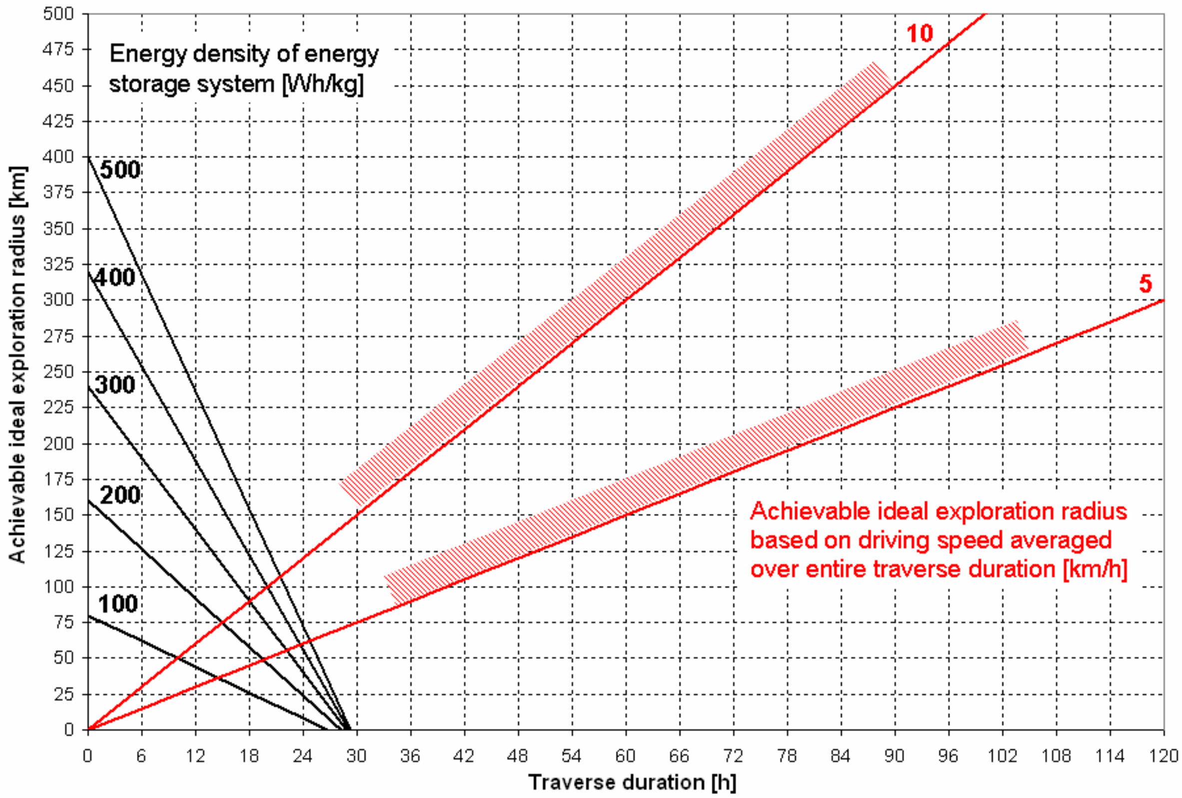

Figure 14: Lunar surface ideal exploration radius, 2 pressurized rovers

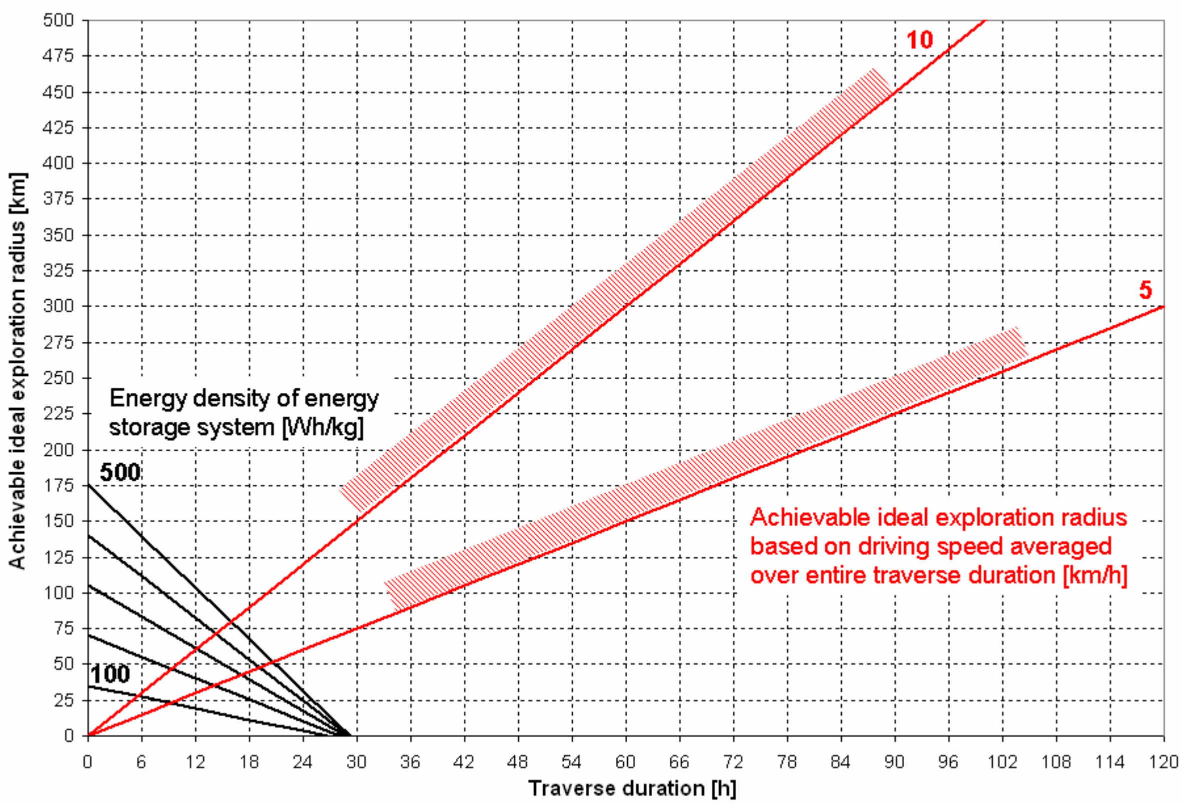

Figure 15: Mars surface ideal exploration radius, 2 pressurized rovers

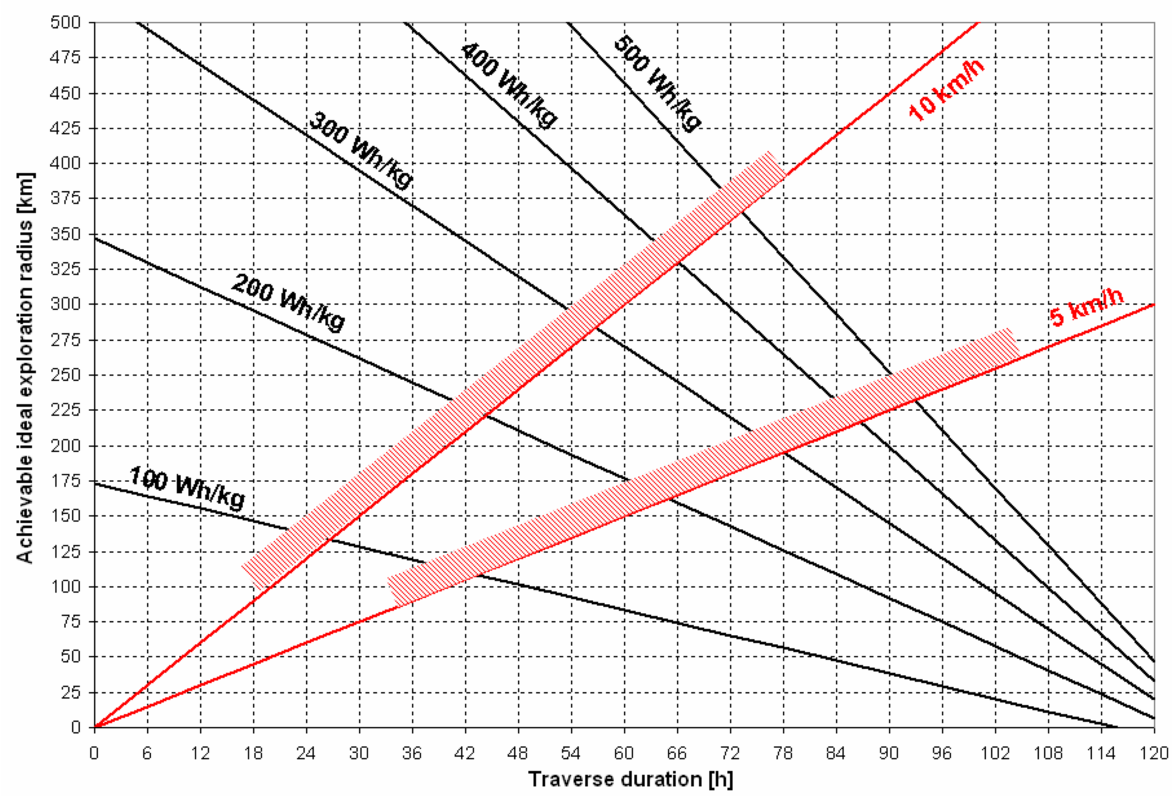

Figure 16: Lunar surface ideal exploration radius, 2 pressurized rovers with 1 trailer each

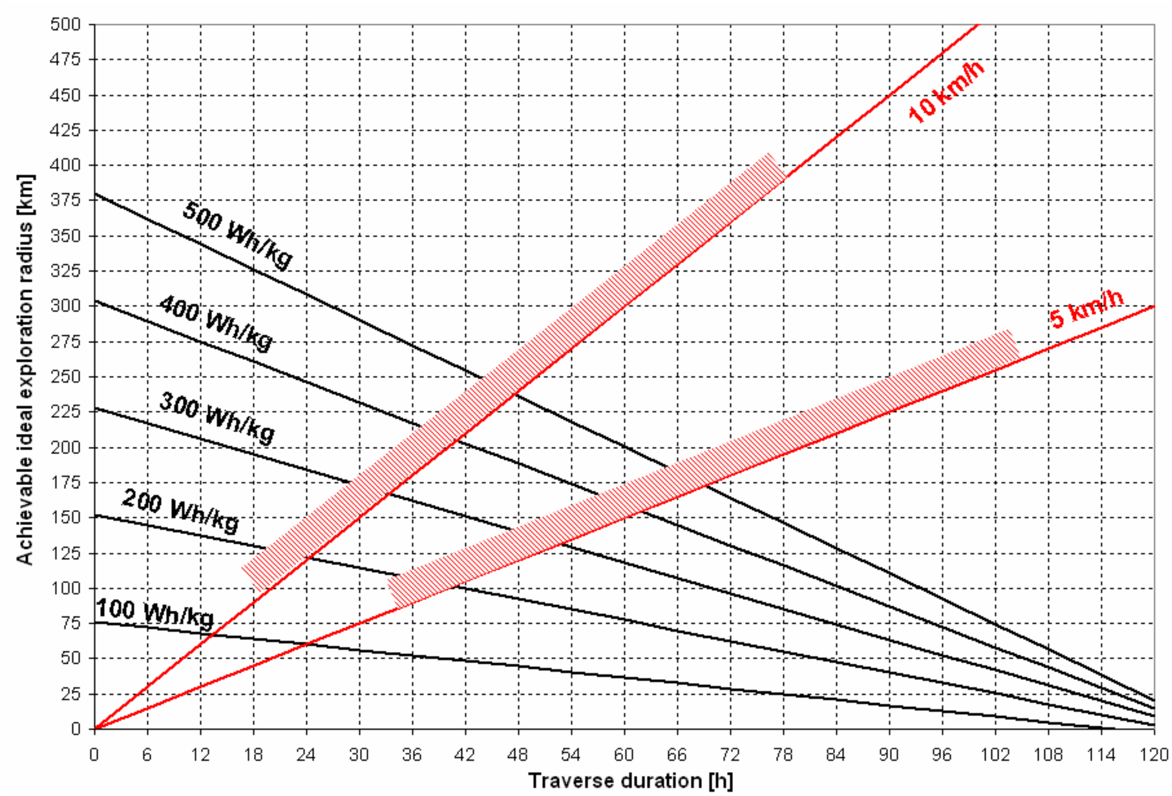

Figure 17: Mars surface ideal exploration radius, 2 pressurized rovers with 1 trailer each

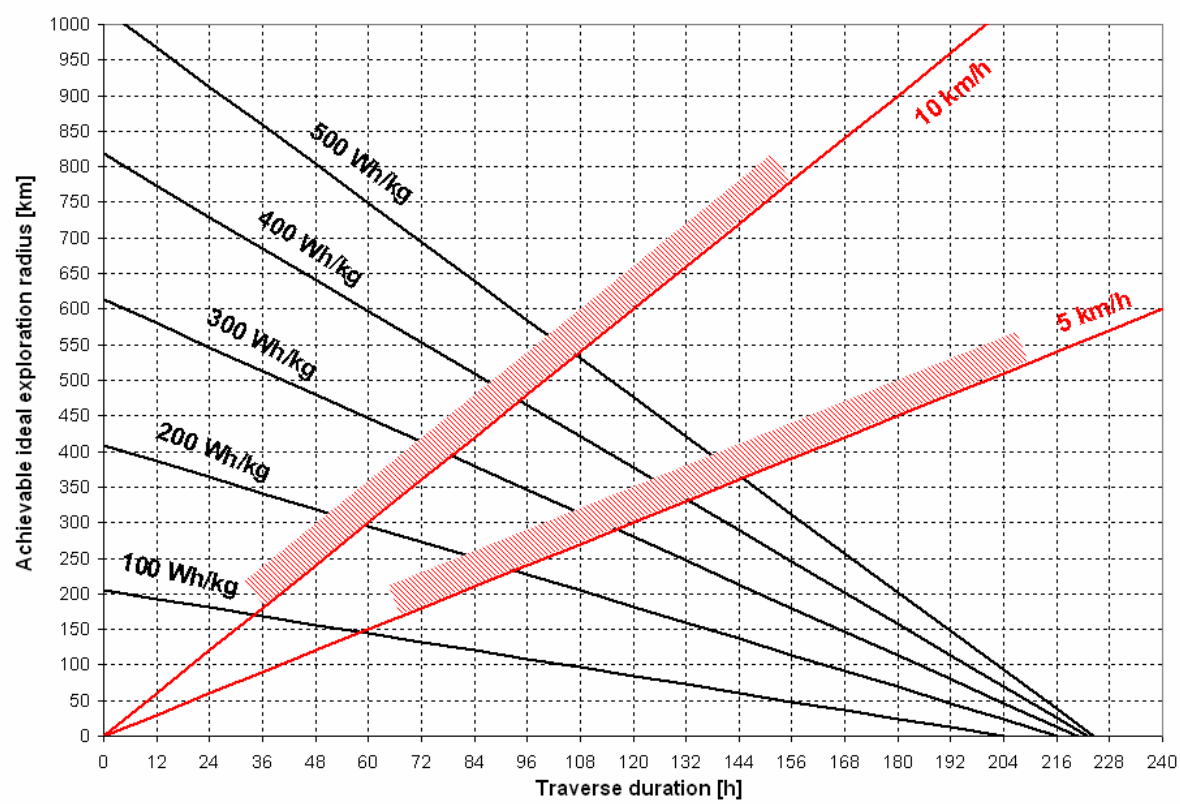

Figure 18: Lunar surface ideal exploration radius, 2 pressurized rovers with 2 trailers each

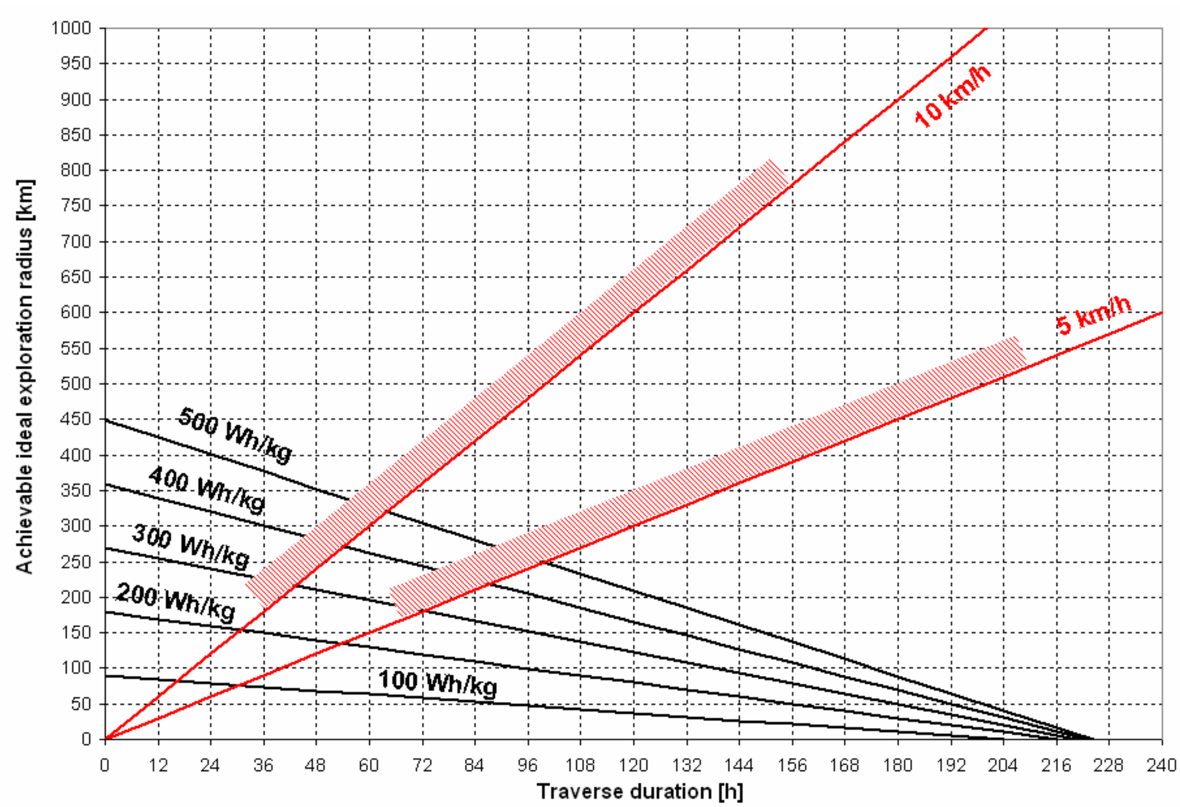

Figure 19: Mars surface ideal exploration radius, 2 pressurized rovers with 2 trailers each

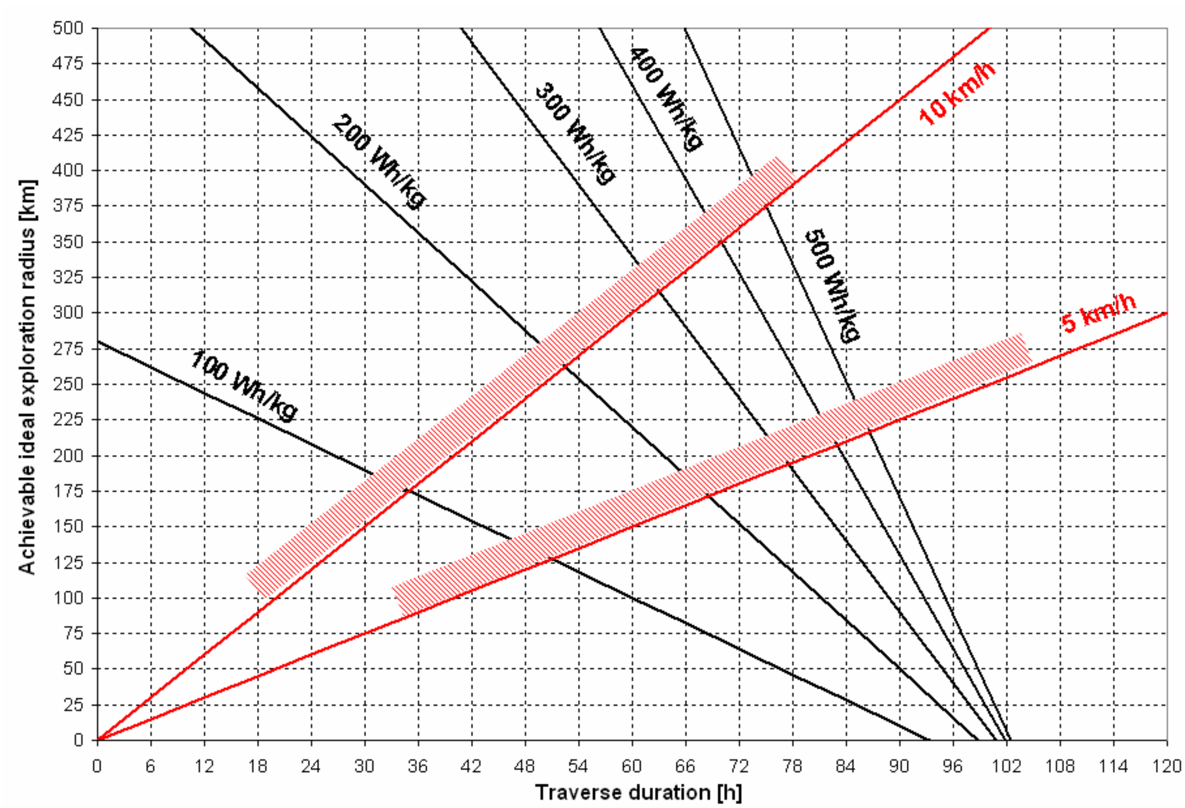

Figure 20: Lunar surface ideal exploration radius, 2 pressurized rovers with 1 pre-positioned station each

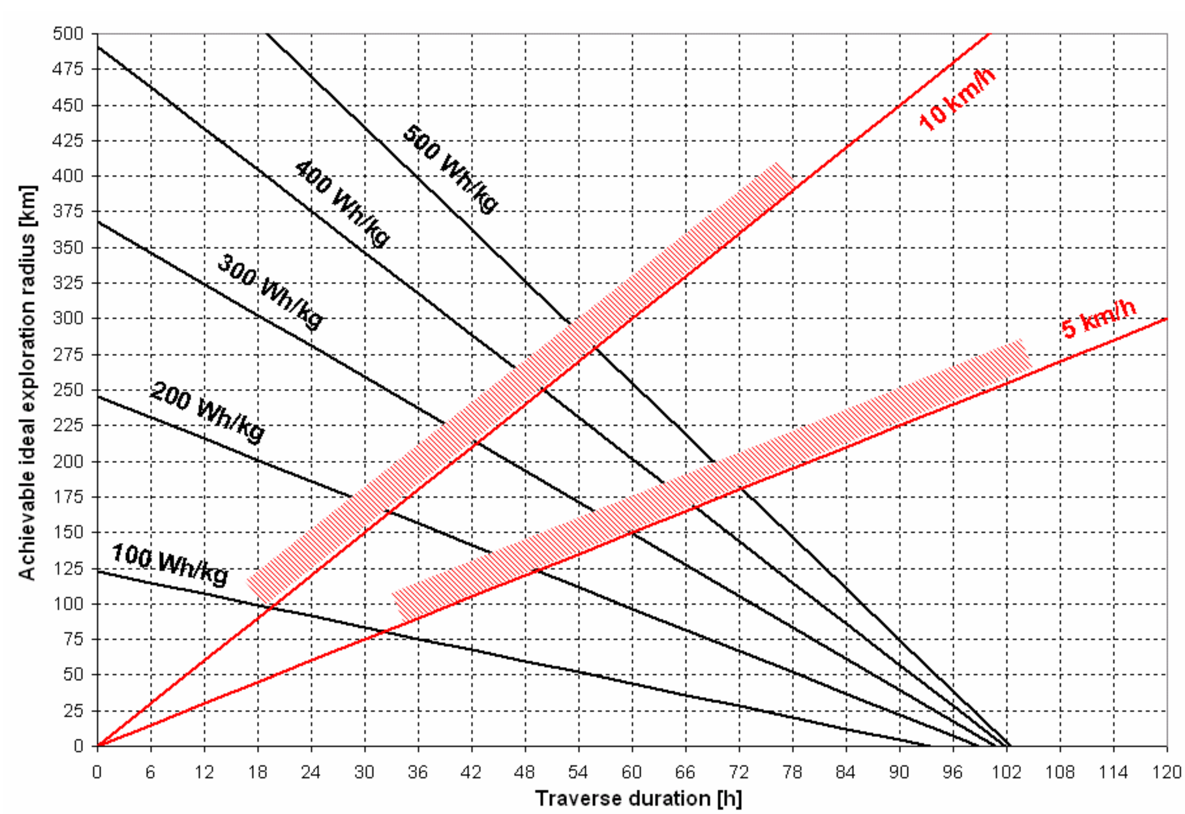

Figure 21: Mars surface ideal exploration radius, 2 pressurized rovers with 1 pre-positioned station each

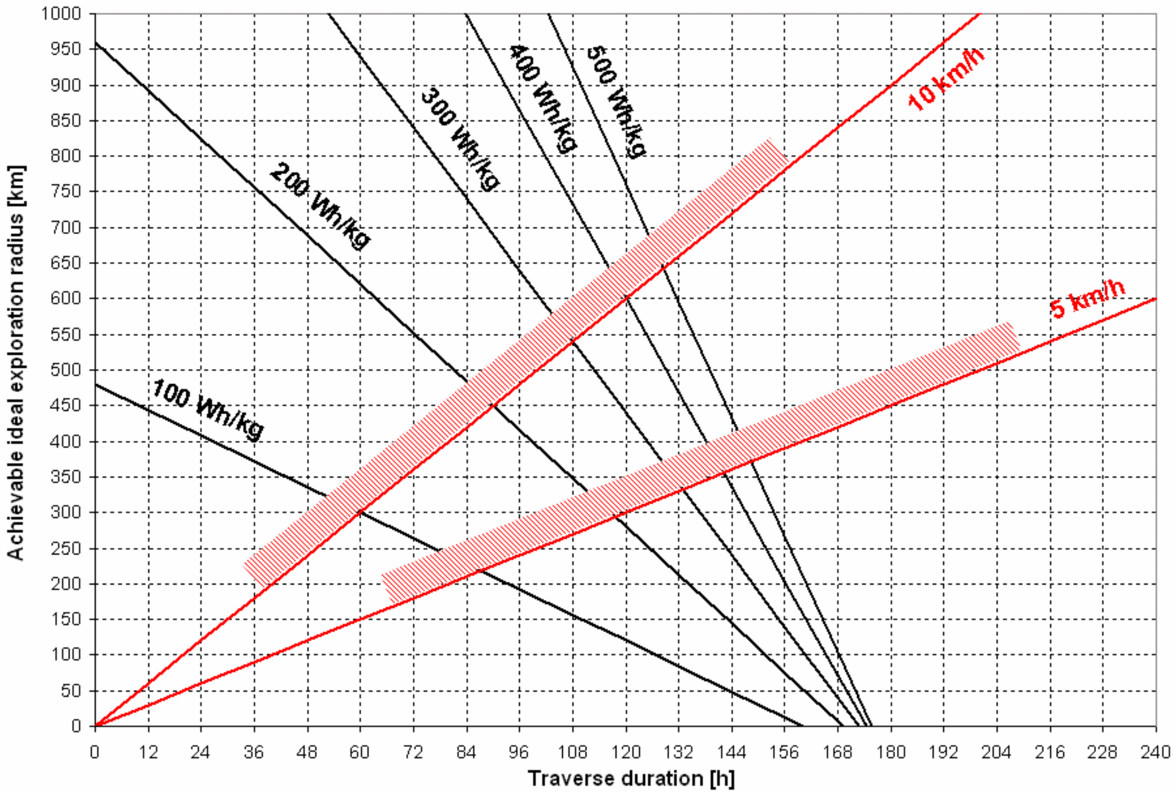

Figure 22: Lunar surface ideal exploration radius, 2 pressurized rovers with 2 pre-positioned stations each

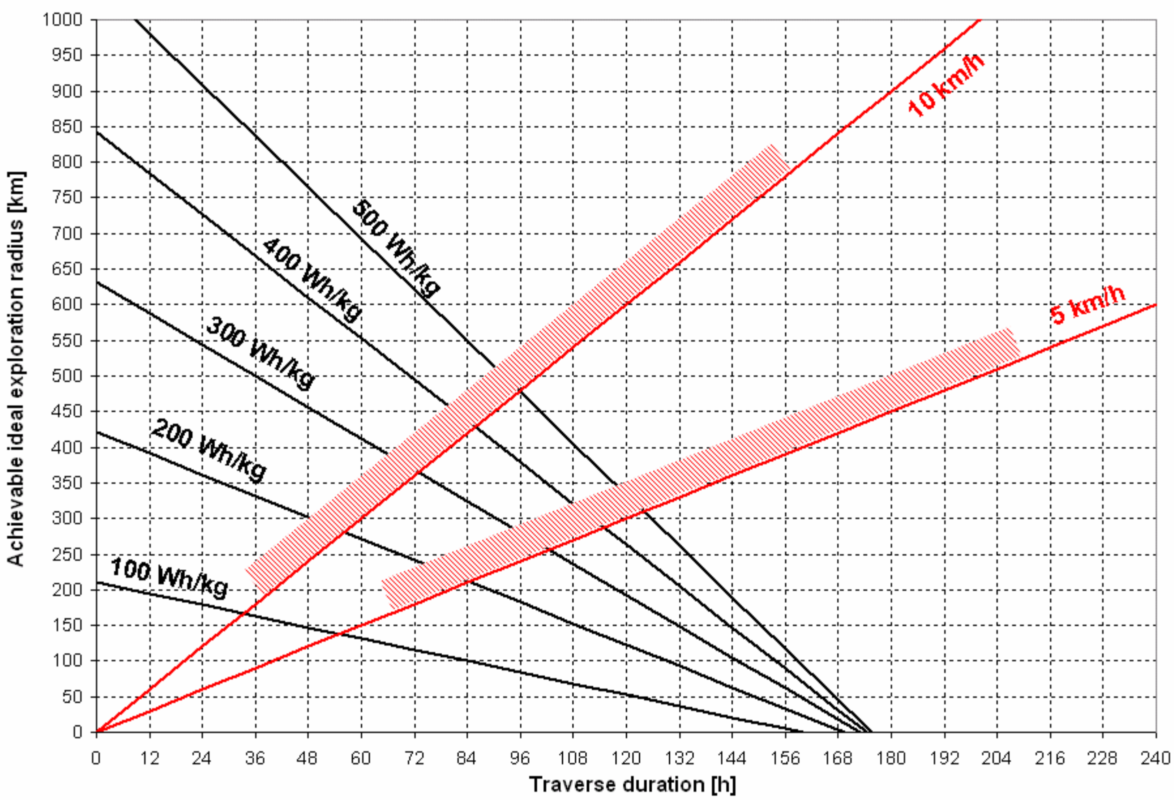

Figure 23: Mars surface ideal exploration radius, 2 pressurized rovers with 2 pre-positioned stations each

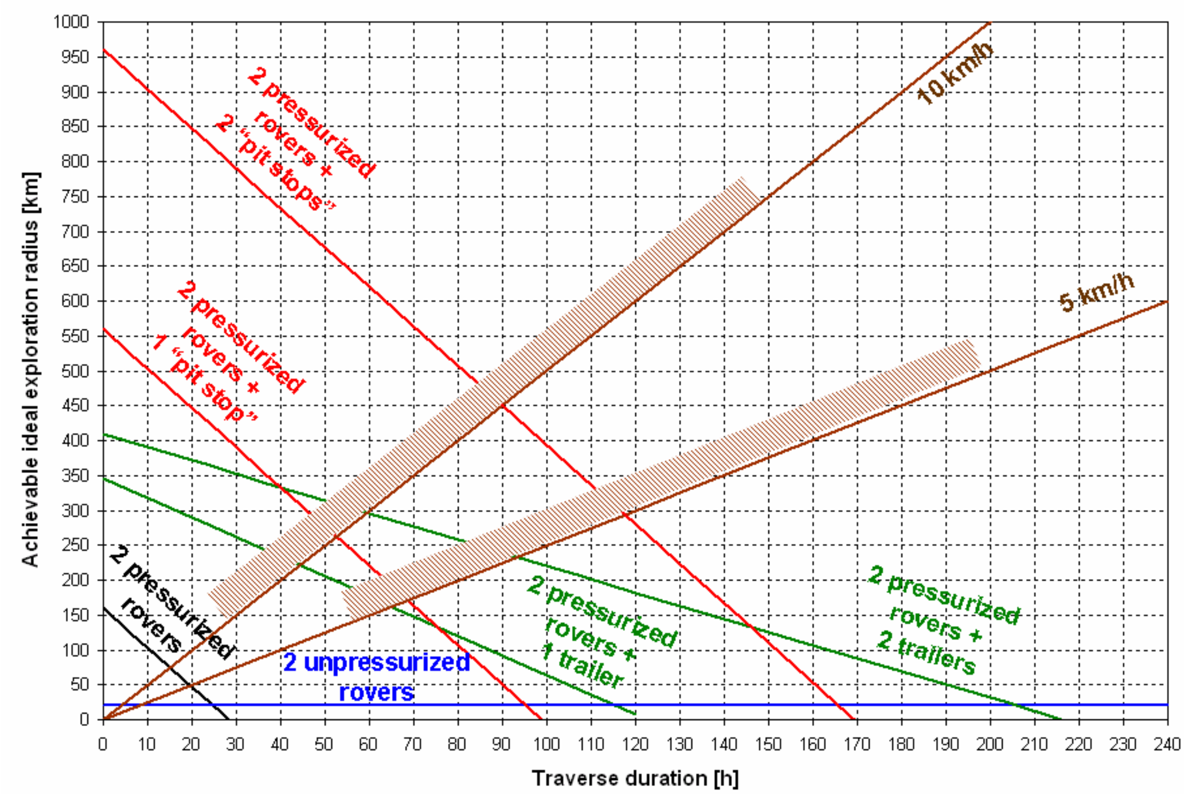

Figure 24: Comparison of lunar surface mobility system concepts for energy storage density of 200 Wh/kg

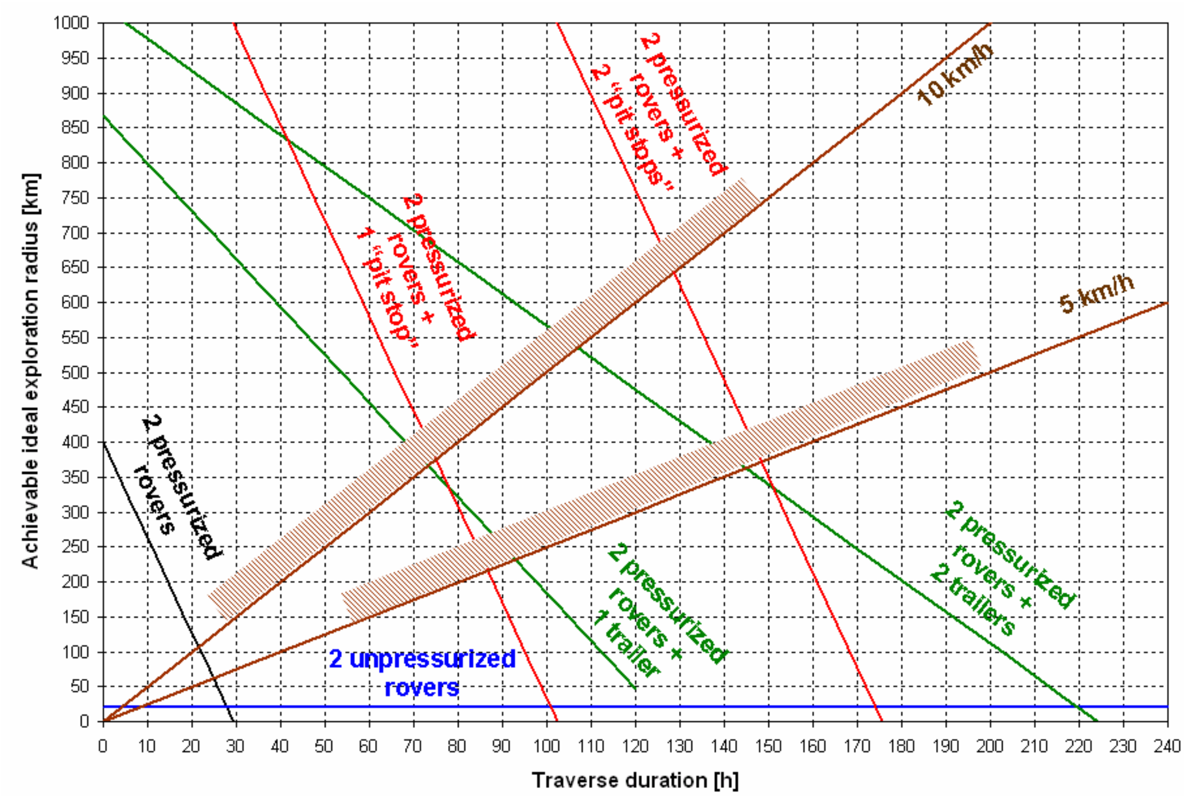

Figure 25: Comparison of lunar surface mobility system concepts for energy storage density of 500 Wh/kg

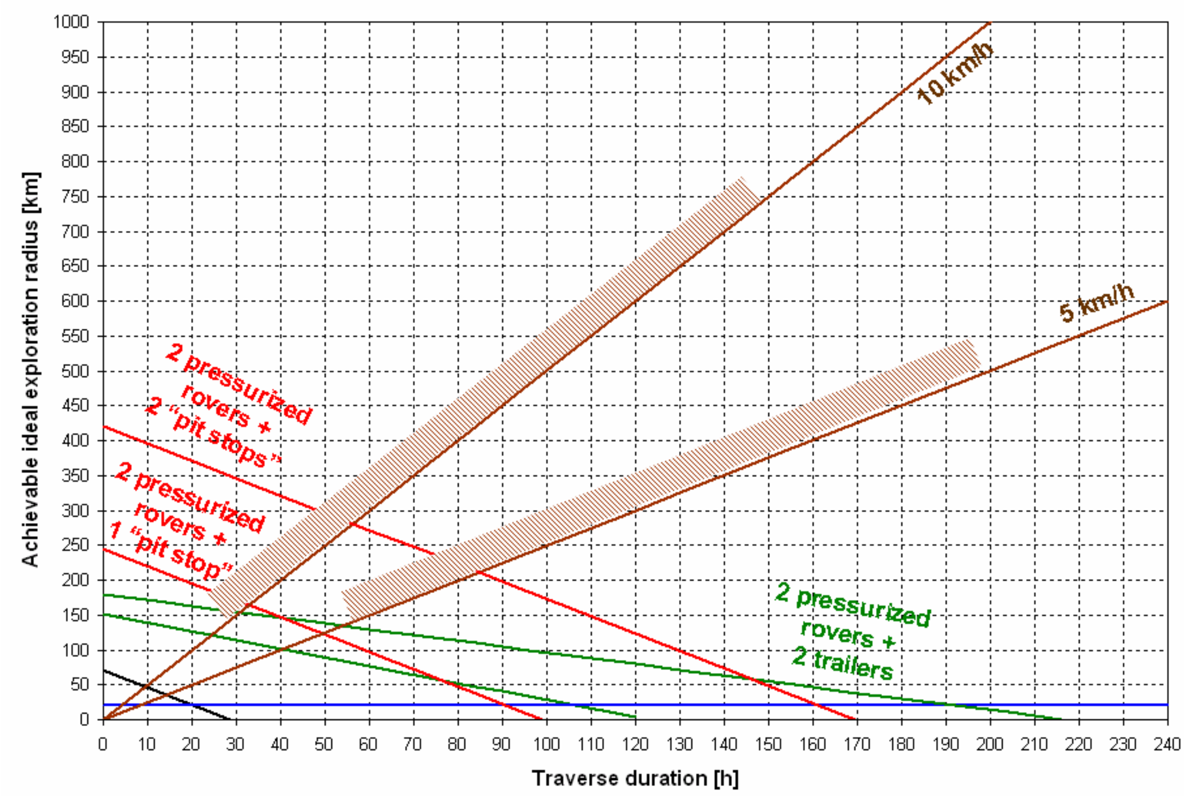

Figure 26: Comparison of Mars surface mobility system concepts for energy storage density of 200 Wh/kg

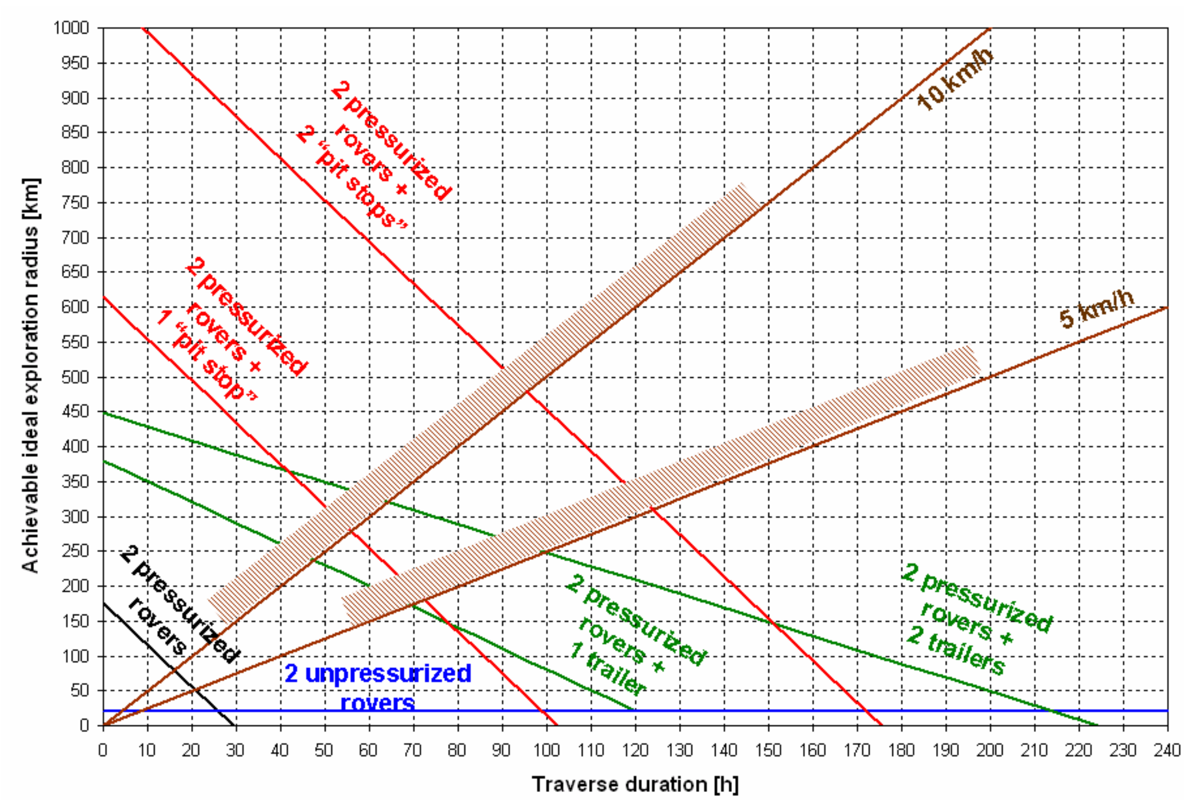

Figure 27: Comparison of Mars surface mobility system concepts for energy storage density of 500 Wh/kg