A Mars-back Approach to Lunar Surface Operations

by

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Appendix C - CD with Code for Major Programs.

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ABSTRACT

The *Vision for Space Exploration* initiated a new space exploration program and called for a long term national commitment to space exploration starting with a return to the Moon and continuing with the exploration of Mars and beyond. The development and operation of the new space exploration system needs to occur within the confines of NASA's current funding. This funding restriction prevents the development of separate space exploration systems for both the Moon and Mars. Therefore, in order to explore both locations, it is necessary to adopt a "Mars-back" approach to lunar exploration, wherein a Martian system is designed and then applied to the Moon. The lunar missions will not require the entire suite of hardware that will be needed on Mars. This thesis describes the reasoning behind using a Mars-back approach and its application to surface operations, using a baseline surface architecture consisting of 5 crew staying on the surface of Mars for 600 days. The surface mobility system will consist of 5 all-terrain vehicles and two towable pressurized volumes, termed campers. The power and habitation requirements are discussed. The Martian surface architecture is then applied to the Moon, where the performance of the same equipment on the lunar surface is evaluated. A campaign of lunar missions is designed to take advantage of the staged development of equipment for the exploration system. While the entire suite of equipment will be needed on Mars, the lunar missions can accomplish useful work and perform real exploration using only a subset of the equipment, such as only the mobility equipment and not the habitat. The main goal of the lunar missions is to prepare for Martian exploration. The progress of the lunar missions towards accomplishing this goal is measured using the Mars Exploration Readiness Level (MERL).

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1 Introduction

The last time that a human walked on the Moon was at the conclusion of the Apollo space program in 1972. Since then, no human has left low Earth orbit. Deep space exploration has been limited to robots.

In January 2004, President Bush presented a new vision for United States human space exploration. This vision presented a new goal for the U.S. space program, consisting of advancing the scientific, security, and economic interests of the United States by the establishment of a robust space exploration program. In order to achieve this goal, the vision specified the following objectives:

- "Implement a sustained and affordable human and robotic program to explore the solar system and beyond.
- Extend human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations.
- Develop the innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.
- Promote international and commercial participation in exploration to further U.S. scientific, security, and economic interests."[1]

The second objective introduces the idea of returning to the Moon and then onwards to Mars. Accomplishing this objective while maintaining the sustainable and affordable nature of the first prohibits the development of a space exploration program on the scale of the Apollo program. Apollo occupied up to 5.7%[2] of the federal budget, as the cost was not as much of an issue as beating the Russians to the Moon. Unfortunately, the Apollo program proved to be neither sustainable nor affordable. The new space exploration system needs to be both sustainable and affordable. Development of separate exploration systems for both the Moon and Mars would surpass the budget allocated to NASA. Hence, it will not be possible to develop two unique sets of exploration hardware and conduct sustainable lunar and Martian exploration.

One way to produce an affordable system for both lunar and Martian exploration is to only design one exploration system and to use it in both places. Using this approach results in three options – designing an optimal system for the Moon and using it on Mars, designing an optimal system for Mars and using it on the Moon, or designing a system that is sub-optimal in both locations, but that will be functional in both locations. The third option was ruled out because it was decided that it is better to have optimal performance in at least one location than to have sub-optimal performance in both locations. The two remaining options can be termed "Moon-forward" and "Mars-back." The use of either of these options requires that alterations to the design be made for situations where one environment is harsher than the other. For example, more thermal protection will be needed on the Moon than on Mars due to the colder temperatures that are reached on the Moon. Therefore, a Mars-back approach would require some alteration to the equipment for that equipment to survive on the Moon. In general, however, designing for the Martian environment provides more challenges than the lunar environment. It was decided that the Mars-back approach should be used, since the goal of the exploration program is to explore Mars and beyond. Therefore, keeping the focus of the exploration program on Mars will help to keep it sustainable after a return to the Moon. This thesis focuses on the surface operations aspects of a Mars-back exploration system.

Developing a Mars-back system first requires an understanding of the Martian and lunar environments. Mars has a day length that is similar to that of the Earth. The Moon, on the other hand, has a much different illumination environment. On the moon, with the exception of the polar regions, the daylight last for 14 Earth-days, while at the lunar poles the daylight can last for 200 Earth-days. The thermal environment on the Moon is harsher, with equatorial temperatures rising higher during the day and lower during the night than on Mars and polar temperatures being consistently lower than Martian equatorial temperatures, especially during lunar night. The radiation environment is harsher on the Moon due to the lack of an atmosphere. The dust environment is worse on Mars due to the wind blowing dust around and the presence of large dust storms. However, given these environmental similarities and differences, it is still possible to design a system that is successful on both the Moon and Mars.

The next step in developing a Mars-back system requires determining the baseline surface architecture for Mars. The surface architecture consists of the surface mission duration, the number of crew, the surface mobility, the surface power system, the habitat, and the navigation and communication system. For this thesis, the surface mission duration was set at 600 days and the number of crew at 5. The best mobility option was determined to be 5 single-person all-terrain-vehicles along with 2 towable pressurized campers. The surface power system can be either a nuclear power plant or a solar power array. The choice will depend on the final power demand and effects of dust obscuration on the solar cells. The habitat was designed to be a 7.4 meter diameter by 7 meter tall vertical cylinder. The navigation and communication system consists of a direct Martian surface to Earth relay, a communications satellite, and on-board navigation systems for traverses.

After the establishment of the Mars baseline surface architecture, a Mars-back lunar campaign can be devised. A method is needed to describe the progress of the lunar campaign. The Mars Exploration Readiness Level (MERL) describes the campaign progress in terms of the completion level of the various objectives that are necessary for the surface exploration system to be ready to go to Mars. A polar landing site was selected for the lunar missions. All the missions will go back to the same site to take advantage of assets that will already be in place. The missions will be launched as soon the necessary equipment, such as the all-terrain-vehicles and the habitat are ready. This way, real exploration can occur while equipment that is not needed for that particular mission is still in development. The missions will test out the equipment required for Martian surface operations on the Moon to gain experience and evaluate the equipment performance. The missions will set the lunar architecture to be as similar to the Martian architecture as possible. The campaign consists of a short lunar return mission, a robotic mission to deploy the power system and perform site scouting, a 60-day mission to prepare a Mars analog environment on the lunar surface, and a 200-day Mars simulation mission.

This thesis was conducted as part of a contract given out by NASA to a team consisting of MIT and Draper Labs to study the implementation of the space vision. The Concept Exploration and Refinement study team was broken up into sub teams focused on Surface Operations, Transportation Architectures, Information Architectures, and Value delivery. The work for this thesis was done as part of the Surface Operations team.

2 A Mars-back Approach to Space Exploration

2.1 *The Future of Space Exploration*

The *Vision for Space Exploration*, released by NASA in 2004 lays out NASA's guiding principles for the exploration of our solar system and beyond. It calls for a return to the Moon, and the future use of the Moon as a testing ground for Mars and other destinations. It calls for the development of a sustainable exploration system that will also be affordable and flexible.[1]

The *Vision* goes on to lay out a plan for the return to the Moon, emphasizing that the "major focus of these lunar activities will be on demonstrating capabilities to conduct sustained research on Mars and increasingly deep and more advanced exploration of our solar system."[1] Scientific research on the Moon will also occur, but the main focus of lunar activities will be on developing the necessary strategies and techniques to pursue the further exploration of the solar system.

2.2 *Past Exploration Systems*

The future of space exploration laid out in the *Vision* provides a different path taken than the previous examples of manned space exploration. The Apollo program represents the only time that mankind has left low-earth orbit and proceeded onwards to a different planetary body. These missions occurred in a much different time in history than the time in which the *Vision* was laid out. The political climate was one of cold war tensions with the Soviet Union. The goal of the Apollo program was not exploration or science based. It was politically based. The United States had to beat the Russians to the Moon. Affordability was not an initial concern of the program, and neither was its long-term sustainability. The proof for these statements lies in the fact that the program was extraordinarily expensive, receiving 5.7% of the federal budget for 1-2 years[2], and that it was cancelled after Apollo 17, even though missions up through Apollo 20 had originally been planned. It should be noted, however, that President Kennedy's challenge had been fulfilled.

After Apollo, mankind has not returned to the Moon, nor moved onwards to any other planet. However, there have been many proposed missions with this intent in mind. One of these is *The Reference Mission of the NASA Mars Exploration Study Team*[3]. This mission plan lays out a return to Mars in great detail, listing necessary components and mission tasks. It calls for the development of a new heavy-lift launch vehicle, in-situ resource utilization, and a 619-day stay on the Martian surface for a crew of 6. This mission design does have some provisions for sustainability, calling for 3 crewed launches to the Martian surface. However, these launches all occur within a 5-year period, and the entire mission sequence is to take place over 10 years. There are no plans specified for continuing the system past the end of the third crewed mission. Furthermore, there are no direct specifications of estimated cost. However, with all the new modules that will need to be built, it can safely be assumed that the cost of this mission will be significant.

2.3 Definition of Mars-back

Designing an affordable system for the exploration of multiple destinations is not an easy task. Designing separate optimal equipment for each destination would be too expensive. Therefore, it becomes clear that the same equipment will need to be used at each destination. Designing only one set of equipment for two locations gives three possible approaches: design an optimal system for the Moon and use it on Mars, design an optimal system for Mars and use it on the Moon, or design a system that is sub-optimal in both locations. The third option can be quickly ruled out. A sub-optimal system will most likely incur mass penalties, and if the system is not optimized for either location than there are likely to be mass penalties in both locations. If a system is going to suffer mass penalties in one location, it might as well not suffer the penalties in the other location. There is no reason to suffer mass penalties in both locations if they can be avoided, and hence this option can be ruled out. The other two options can be termed "Moon-forward" and "Mars-back."

Both of these options will require the redesign of certain pieces of equipment such that they can survive in the harsher environments that may be present at one of the locations. For example, the thermal environment on the Moon is harsher than on Mars. The lunar equatorial temperatures reach higher temperatures during the day and lower temperatures at night than the Martian equator, and the lunar poles are consistently colder than the Martian equator. The higher latitudes on Mars are not in consideration for a first Martian landing, as will be discussed in section 4.2. Therefore, if a Mars-back approach is used, added thermal protection will need to be added to the equipment so that it can survive on the Moon. If a Moon-forward approach is used, the thermal protection system would be over-designed for Mars. However, the equipment might need to be altered to deal with the CO_2 atmosphere that is present on Mars. In general, it is harder to design for Mars than for the Moon. In both cases, changes to the designs will be necessary.

A Moon-forward system would design equipment for the Moon and then adapt that equipment to go to Mars. The main problem with this system is that it does not lend itself to be sustainable, as it keeps the focus on the Moon. Furthermore, the necessary changes to the exploration system to make it useable on Mars may not happen, as the interest in going to Mars could die off and the funding may not appear. Therefore, there may not be a large amount of interest in going to Mars once the Moon has been reached.

A Mars-back system, on the other hand, keeps the focus on Mars, which is important for the public perception of the entire space exploration program, as will be discussed in section 2.4.1.1. The system is optimized for Mars, and the Moon is used as a testing ground for the equipment and procedures that will be used on Mars. Only small changes to the equipment that are required for lunar survival will be allowed. Since it is much cheaper to send items to the Moon than to Mars, it will be possible to use this equipment on the Moon as it is developed, performing real exploration while testing the equipment and procedures. The primary goal of the lunar missions will be to prepare for the exploration of Mars. Furthermore, since the hardware for Mars will have already been developed, the substantial development costs will not exist when the time comes to go to Mars, making the program better able to survive budget cuts. The reasons for using a Mars-back approach are given in the next section.[†]

2.4 Reasons for a Mars-back Approach

As mentioned above, the *Vision for Space Exploration* calls for a return to the Moon and progress onwards to Mars. Furthermore, there is a requirement that this system be sustainable, affordable and flexible. It is these requirements that drive a Mars-back approach to the exploration system.

Obviously, a Mars-back approach does not make sense if the final destination of the exploration system is the Moon. However, the *Vision* clearly states that the Moon is only the first destination, not the final one. It is with this thought in mind that a Mars-back approach was decided upon. The reasons to support the Mars-back approach are given below.

2.4.1 Sustainability

A sustainable system is one that not only meets the current needs, but one that will also be capable of meeting the needs of the future. Applying this definition to an exploration system means that continuous exploration can be carried out over a long period of time. A Mars-back approach emphasizes a sustainable system. The needs of the future are going to Mars. By designing the lunar system to use the same components as a Mars mission, the technology will already exist to send a human crew to Mars. Therefore, the system will meet the current needs, going back to the Moon, and the future needs.

There are four key elements of a sustainable system: continuous delivery of value, policy robustness delivered through a steady cadence of successes, an understanding and minimization of risk, and affordability.[†]

2.4.1.1 Continuous Delivery of Value

Value must be delivered to the beneficiaries of the exploration system. In the case of space exploration, there are many beneficiaries, including the public. The beneficiaries must be made aware of the fact that they are receiving a benefit.[†] A lack of a system for continuously delivering value to the public was one of the problems with the sustainability of the Apollo program. After Neil Armstrong walked on the Moon during the Apollo 11 mission, public interest in the lunar landings decreased. This decrease in interest is evident even today. People still know that Neil Armstrong and Buzz Aldrin were the first two astronauts to walk on the Moon, but it is not as commonly known that Pete Conrad was the third, or who followed him. The issue was that the public had lost interest in what they

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[†] MIT/Draper NASA Concept Exploration and Refinement Proposal. August, 2004.

thought was essentially the same thing repeating itself. The Moon was no longer new and exciting to the public. The public was still interested in the Moon, they just wanted to see new things happening there, as can be seen by the fact that the use of the lunar rover on Apollo 15 is well known. Therefore, to keep a system sustainable, the public, and all other beneficiaries, needs to be made aware of the value that they are receiving from each stage of the system.

This need leads directly to a Mars-back approach. While using a Mars-back approach to lunar exploration, the majority of activities done on the Moon will have a definitive focus – preparing to go to Mars. The value delivered will be an increase in the readiness to go to Mars. The beneficiaries will see new elements tested out on the lunar surface with each mission, which will hopefully be enough to keep their attention and interest level. Keeping the focus on Mars allows the beneficiaries to see each mission prior to the first Martian mission as a step towards the completion of the goal. This method is contrary to the Apollo program, where the goal was completed with the first lunar landing. Instead, the goal is going to Mars and the lunar missions will be more similar to the orbital Apollo missions than the lunar landing Apollo missions. An added benefit of going to the Moon first is the ability to perform real exploration on the Moon while testing out the Mars components. This exploration has the possibility of leading to new discoveries that can serve to get the public excited about space exploration.

The inherent value associated with a manned landing on Mars would be high enough to attract attention regardless of its precursors. However, it will be difficult to keep a program sustainable long enough to reach Mars without first going to the Moon and using it as a testing ground.

2.4.1.2 Policy Robustness

Policy robustness refers to the ability of the exploration system to survive multiple different administrations. The plan laid out in the *Vision* calls for a return to the Moon no later than 2020. By that time, it will have been possible for four different presidents to have held office. Each president will have different views on space exploration, and there will be different political climates. Therefore, the exploration system must be robust enough to survive regardless of the administration.

One way to deliver a policy robust system is to have a steady cadence of successes[†]. An administrator will be less likely to cancel a succeeding program than a failing program. People want to know that their money is being well spent, so having successful demonstrations is key. This need for many successes once again leads to a Mars-back approach.

[†] MIT/Draper NASA Concept Exploration and Refinement Proposal. August, 2004.

As mentioned above, there will be a constant delivery of value when a Mars-back approach is used. Each of these instances of value delivery can be construed as a mission success. Furthermore, with a Mars-back approach, there will be a sequential development of the necessary components for a Mars mission (see section 2.4.1.4). The successful completion of each component offers a more immediate return, since it will be used on the Moon shortly after its completion, than if it had to wait for all the other components to be developed. With the Mars-back approach, a steady cadence of success is provided, thereby enhancing policy robustness.

2.4.1.3 Risk

Any space exploration system is inherently risky. Humans will be sent beyond Earth orbit, something that has only been done a few times in history. The goal of a sustainable system is to understand these risks and then to minimize them. An exploration system is very complicated, and therefore full of risk. Examples include the potential for injury or loss of the crew, loss of necessary equipment, such as a habitat, the inability to return from the surface, and a host of other things that can go wrong. These risks are amplified on Mars due to its distance. Using a Mars-back approach to the Moon will help to minimize the amount of risk in going to Mars by testing out the equipment and procedures that are to be used.

On the Moon, a situation that requires a mission abort involves a return time for the crew of only 3 days. Furthermore, it is possible to relatively quickly resupply the crew on the surface. On Mars, however, most travel times are on the order of months, making it much harder to abort back to Earth in a critical situation.

There is residual risk in the exploration system that affects the other beneficiaries of the exploration system. As stated earlier, the continuous delivery of value is one of the key elements of sustainability. One of the risks in an exploration system is not delivering value. Value may not be delivered in the case of an early-mission abort, for example. If value is not delivered to all the beneficiaries, then they will not be satisfied with the exploration system. The public and the other beneficiaries may then lose interest in the system and may feel that their time and money has been spent poorly. This situation would make it difficult to maintain a sustainable exploration system.

2.4.1.4 Affordability

The affordability of the exploration system is crucial to making it sustainable. NASA is going to have a limited budget for this phase of exploration, which is contrary to the budget that existed for Apollo. Apollo's budget grew as high as 5.7% of the nation's budget. This time around, the NASA budget is projected to be constant at less than 1% of the national budget[2], only increasing with inflation. The projected budget can be seen in Figure 2-1 below.

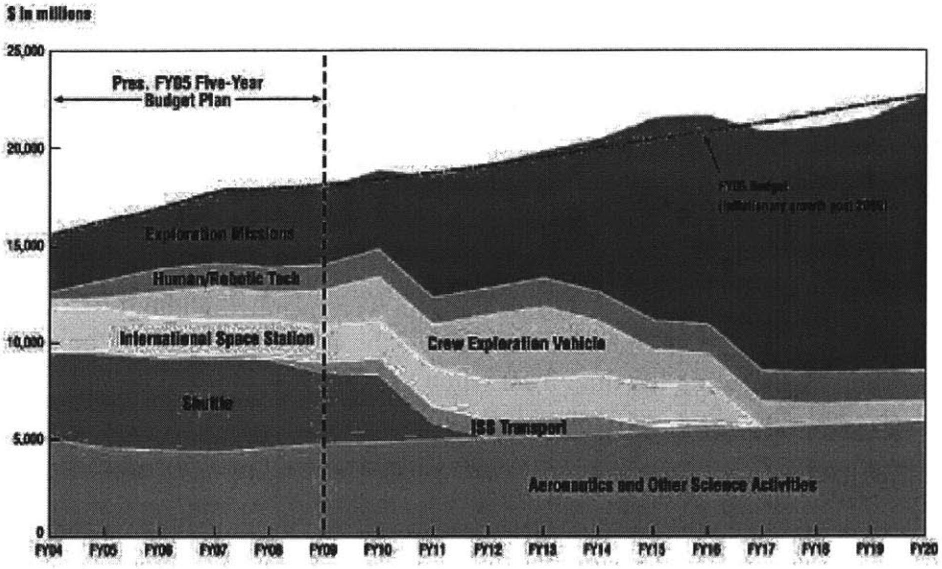

Figure 2-1 Projected NASA budget[1]

Exploration systems are expensive to develop. To explore the Moon and Mars without using a Mars-back approach would require the development of an exploration system optimized for the Moon, and a separate exploration system optimized for Mars. Two separate exploration systems will most likely not fit within NASA's projected budget. A Mars-back approach, however, only requires the development of one system. The system is designed for Mars and then tested, using the same components, on the Moon while doing real exploration, thereby reducing the need for the design of two systems.

Furthermore, in order to stay within this projected budget, it will be impossible to develop all the components necessary for the exploration system at the same time. Therefore, there are two options for planning missions. The first option involves creating all the necessary hardware for the mission and then launching the mission. In terms of a space exploration mission, this approach would involve waiting until the habitat, rovers, EVA suits, and other equipment was ready and then launching one large mission. The second option involves designing missions so that they use the components that are available. An example of this approach would be to send a mission as soon as the EVA suits were ready, then send another mission when the rovers were ready, and then send a third mission when the habitat was ready. For a Martian mission, the first option makes more sense. It is expensive to send crew and cargo to Mars, and therefore it does not make sense to send a crew to Mars without the capability to do useful work there, which requires multiple functional mission elements, such as mobility equipment and a habitat. Hence, it will be necessary to have the habitat, rovers, and other equipment ready to launch at the same time.

The Moon, on the other hand, is much closer. It then becomes more feasible to use the second option. Missions to the Moon can be smaller, sent with the components that are available. There is then value returned from the staged development of the components. Using this method, the limited budget is not as much of a problem. A component such as the habitat is developed, and then deployed and tested on the Moon.

The second option follows in line with the Mars-back approach. Mission components will be developed for Mars and can then be tested on the Moon using only a subset of the entire suite of Martian hardware, where the smaller missions are more appropriate. If a Mars mission were planned without first using the Moon, it would be necessary to wait for the development of all the components, therefore wasting the time from when the first was finished until the last one was ready. Therefore, using the Moon before going to Mars makes sense.

2.4.2 Experience Gained

One thing that the Apollo missions showed is a progressive acceptance of more risk with experience gained. Each mission allowed more time for extra-vehicular activity and allowed the astronauts to move further from the base. This progression can be seen in Table 2-1. It should be noted that Apollo 15 featured the introduction of the lunar rover.

Table 2-1 Progression of time and distance from lunar module during Apollo missions[4]

Mission	Time Outside Lunar Module (min)	Max Distance From Lunar Module (m)
Apollo 11	152	61
Apollo 12	465	411
Apollo 14	563	1454
Apollo 15	1115	5020
Apollo 16	1214	4600
Apollo 17	1324	7629

A similar progression can be expected for the new exploration system. If a Mars mission was launched directly, it would take time to trust the equipment enough to launch long-range sorties from the base. However, having used the same equipment on the Moon would allow an immediate use on Mars, thereby limiting the time spent on the Martian surface that was not as productive as possible. The testing and validation of the equipment would occur on the Moon instead.

2.4.3 Flexibility

The Mars-back approach to lunar exploration is inherently flexible. Since the elements of the lunar exploration system will not be planned to be ready all at the same time, the order in which they are built can be changed, thereby adding to the flexibility of the system. For example, it may be desired to test a pressurized rover on the first lunar mission. However, the pressurized rover may not be ready in time. Since multiple missions are planned to the Moon, the mission to test the pressurized rover can be pushed back, thereby adding to the flexibility of the system on the whole.

2.5 Application of the Mars-back Approach to Surface Operations

To apply the Mars-back approach to surface operations, the Martian surface operations first need to be determined. The architecture for the Martian baseline mission will be discussed in chapter 4. This architecture is used to determine the necessary architecture for the lunar campaign, which is discussed in chapter 5. While determining these architectures, it is necessary to keep the principles of sustainability, affordability, and flexibility in mind.

Of the four components of sustainability, the surface operations have the most direct impact on the delivery of value and the affordability. The policy robustness of the exploration system is dependent on a steady cadence of successes. Surface operations only represent a portion of the cadence of successes of the mission, and will therefore have only a limited impact on policy robustness. The risk of the system is inherent to the system. Steps will be taken in all surface operations to minimize the risk, such as limiting the distance that surface vehicles can travel from the base. However, the majority of the risk is expected to occur during the transportation aspects of the missions. The delivery of value, on the other hand, is directly impacted by surface operations and is discussed below. The affordability of the system, especially the lunar system, can be influenced by surface operations by using a process of asset accretion on the lunar surface. The crew size also plays a role in the affordability of the system, as it is a large determiner of the mass that needs to be launched from Earth. The crew size is set by the surface mission requirements and will be discussed in section 4.3.

2.5.1 Delivery of Value

The surface operations portion of Martian and lunar missions can be a significant deliverer of value. Value itself is difficult to measure, but indicators can be chosen to represent the value delivery, and these indicators will then influence the choice of the design variables that will be used in creating the surface operations architecture.

For the new space exploration system, the MIT/Draper CER team identified many stakeholders and sources of value.[‡] Surface operations have the most impact on the sources of value relating to the visibility of the exploration program to the public, the increase of scientific knowledge, and the increase of exploration knowledge. It is difficult to measure directly the impact of any one of these sources of value, so indicators were identified for each of them. The public visibility is driven by the number of high visibility events. Such an event may consist of the first Martian landing, the exploration of trenches on Mars, or the first use of the surface vehicles. The indicators for the increase of scientific knowledge are the number and diversity of scientific sites that are visited and the mass of scientific equipment that is brought to the surface. The indicators for the increase of exploration knowledge are the mission duration, number of crew, and

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[‡] Rebentisch, Eric. Personal communication. December, 2004.

the surface mobility, since more exploration can occur with a larger crew, more mobility, and longer mission length.

Using these indicators drives the selection of the design variables for the Martian surface architecture. The desire for an increase in exploration knowledge leads to the selection of mission duration and crew size as design variables. In order to visit a large number of diverse sites, the crew on the surface will need mobility. Therefore, the surface mobility, consisting of the range of the vehicles and the type of vehicle (pressurized or unpressurized, for example), becomes a design variable. Furthermore, one of the key factors in determining the allowable length of the mission is the power supply that is available on the surface. Finally, the crew size and mobility both combine to help increase the possibility of performing highly visible events. These design variables were used in the determination of the Martian surface architecture, discussed in chapter 4.

On the Moon, there is less of a focus on the scientific value that is delivered. The Mars-back approach calls for the Moon to be a proving ground for the equipment and procedures that will be used on Mars. Therefore, the driving focus of the lunar campaign will be exploration, not science. Following this approach will reduce the scientific value from the lunar missions, but it will increase the exploration value. Furthermore, there will still be plenty of high visibility events on the lunar surface as each new piece of equipment and each new procedure is tested and new places are visited.

2.5.2 Asset Accretion on the Lunar Surface

The equipment that is used on the Moon, such as the habitat and vehicles will be the same equipment that will be used on Mars. It can be expected to see changes in the performance of the equipment with the change in location. These changes will be discussed in section 5.3.2.1. Using the same equipment keeps the systems affordable by limiting the number of new pieces of equipment that need to be produced. Affordability of the lunar campaign will also be increased by a process of asset accretion on the lunar surface. Unlike the first Martian mission, where the crew will have everything it needs for the mission on the surface when they land, earlier lunar missions will occur before all the equipment is developed. Each mission will use the available technologies. Instead of bringing new equipment to the lunar surface each time, the equipment will be left on the surface and thermally shielded, such that the next crew to arrive can reuse it. This process will result in a steady build up of capability on the lunar surface, until the full capability required for the first Martian mission is reached.

2.5.3 Deviations From a Mars-back Approach

There are certain situations that will occur on the Moon that prohibit the strict application of a Mars-back approach. These situations arise because of the different environments present on the Moon and on Mars. One of the prime examples of a need to deviate from the Mars-back approach is in the thermal protection of the habitat. As will be shown in section 3.2, the temperature at the lunar pole during the night is significantly colder than any temperature reached at the Martian equator. Therefore, a non-Mars-back thermal protection system will need to be instituted to insure that the habitat can survive the lunar night.

3 Comparison of Lunar and Martian Surface Environments

3.1 *Solar Power and Illumination*

The illumination conditions on the planetary surface are important because they help determine the amount of solar power that can be generated. Solar power will most likely be a large source of power for a base on either the Moon or on Mars. The amount of power that is needed for the base will obviously depend on the equipment at the base. The capability to generate that needed power will depend on the length of daylight at the base and on the solar constant.

A solar power array needs to be able to generate enough power to run the base, both during daylight hours and hours of darkness. Therefore, the length of daylight is important in determining the size of the array for two reasons – it sets the amount of time that the array can create power and it sets the amount of extra power that the array needs to generate to survive the night time.

3.1.1 Time scales

The Moon rotates slowly compared to the Earth, producing a lunar day that lasts for 29.53 Earth days. Since the Moon orbits with the Earth, the lunar year is the same length as an Earth year. Mars has a similar rotation period to Earth, resulting in a Martian day of 24 hours and 37 minutes. The Martian year lasts for 686.98 Earth days or 669.60 Martian days.[5]

3.1.2 Length of daylight

The length of daylight depends on the tilt of the axis of the planetary body relative to the sun. The Moon is tilted at 1.5 degrees, while Mars is tilted at 25.19 degrees[5]. The length of daylight can be calculated using the following equations[§], where θ is the angle of the axis of the planetary body relative to the sun, time is the fraction of the year that has elapsed, and length_of_day is in hours:

$$declination = \sin^{-1}(\theta * \sin(time)) \tag{3-1}$$

$$daylight\_hours = \frac{length\_of\_day}{\pi} * \cos^{-1}\left(\frac{-\sin(latitude) * \sin(declination)}{\cos(latitude) * \cos(declination)}\right) \tag{3-2}$$

Figure 3-1 below show the length of daylight at various latitudes for both the Moon and Mars, during the summer in the northern hemisphere. The daylight remains fairly constant with latitude on the Moon, until the polar latitudes are reached. Mars is more similar to Earth, with the daylight slowly tailing off as the latitude is increased.

[§] Byrne, Shane. Personal communication. February, 2005.

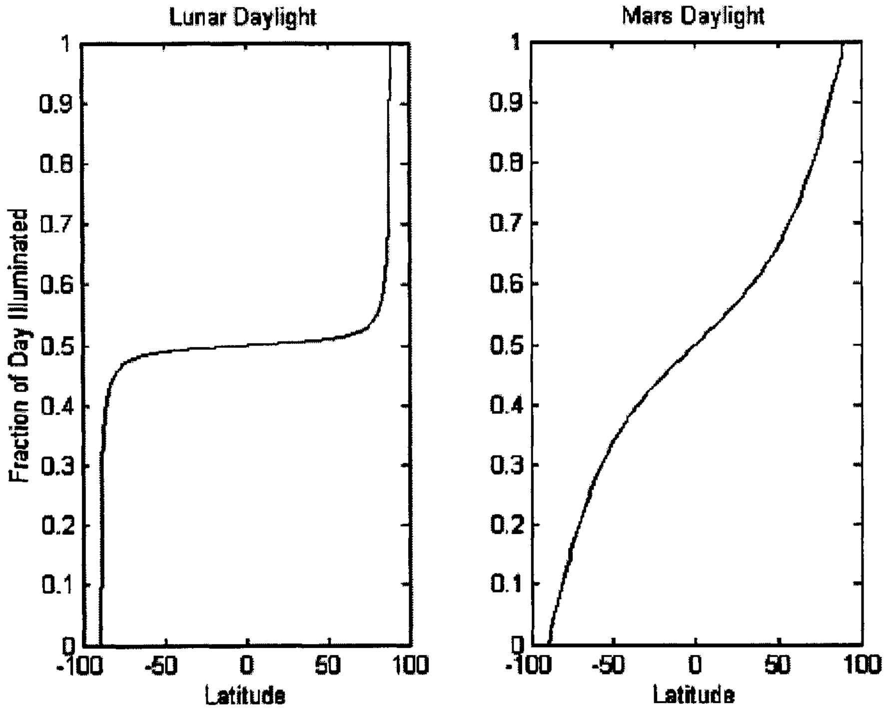

Figure 3-1 Length of daylight on the Moon and Mars, during summer in the northern hemisphere

3.1.3 Solar Constant

The solar constant is a measure of the power flux radiated from the sun. The power is inversely proportional to the square of the distance from the sun. On the moon, the power flux is 1368 W/m^2. This number can be assumed to be constant throughout the moon's orbit, due to the extremely low eccentricity of the Earth's orbit, where e = 0.017.[6]

Mars, however, has a more elliptical orbit, with an eccentricity of 0.093.[6] This increase in eccentricity, when added to the fact that Mars is 1.5 AU from the Earth on average, is enough to cause the solar constant to vary throughout Mars' orbit and to be considerably lower than the constant on the Moon. The variation throughout the year is shown in Figure 3-2 below. It can be seen from the figure that the Martian solar flux is significantly lower than the solar flux at the lunar surface.

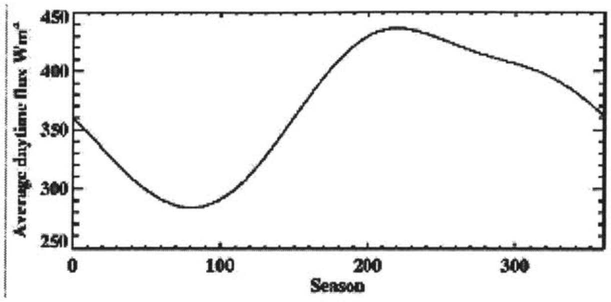

Figure 3-2 Average daily Martian solar flux[§]

3.2 Thermal Environment

The thermal environment on both the Moon and Mars is significantly different from that on Earth. Therefore, habitats, EVA suits, and other equipment will need to be designed to tolerate these different thermal environments.

The surface temperatures can be modeled by solving the one-dimensional heat diffusion equation to account for heat transmission to the subsurface layers. The albedo of the Martian surface is assumed to be 0.25, which is the planetary average and the emissivity is 0.9[§]. The model does not count take into account the radiation that is emitted, scattered, or absorbed by the Martian atmosphere, causing the Martian temperatures to be off by a few degrees. The results are presented in Figure 3-3 below.

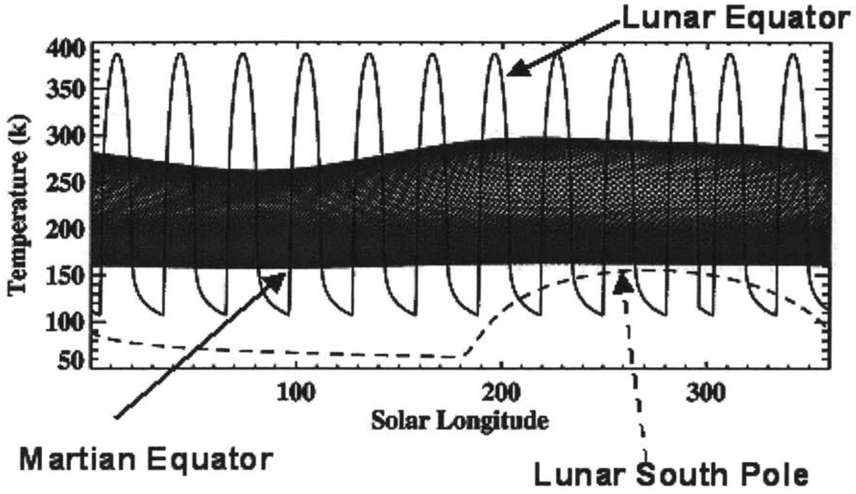

Figure 3-3 Temperature variation throughout the day at the lunar equator and south pole, and the Martian equator[§]

It can be seen from the figure that the nighttime temperatures on the Martian equator are close to the minimum daytime temperatures that can be expected on the lunar south pole, while the lunar equator has a higher daily variation than the Martian equator.

[§] Byrne, Shane. Unpublished work. February, 2005.

3.3 Radiation

3.3.1 Radiation Environment[7]

One of the key safety issues facing astronauts in space or on the surface is radiation. The radiation environment mostly consists of galactic cosmic rays and radiation associated with solar proton events. These two different types of radiation have different intensities and durations. Galactic cosmic rays (GCR) contribute less of a dose of direct radiation, but are constantly bombarding the surface, and therefore they become increasingly important as the length of the mission increases. Solar proton events (SPE), while somewhat rare and associated with solar flare activity, can deliver a much higher dose of radiation over a much shorter period of time. However, the particles associated with SPE's are of lower energy and easier to shield against. Therefore, when designing radiation mitigation strategies for either the Moon or Mars, it is necessary to account for both GCR's and SPE's.

The radiation environment varies considerably depending on the approximately 11 year cycle of solar activity. During times of minimum solar activity GCR flux reaches its maximum. During times of maximum solar activity, the probability of a solar proton event is greatest. Hence, there is an inverse relationship between GCR and SPEs, making it even more necessary to design for both situations.

Unfortunately, SPEs are currently unpredictable. They occur with different magnitudes and at different frequencies. In order to assess the radiation environment that such an event may produce, the large flares of February 1956, November 1960, August 1972, August 1989, September 1989, and October 1989 can be used as examples.

3.3.2 Exposure Limits

Radiation exposure limits have not yet been fully defined for deep space exploration missions, however the limits defined for low-earth orbit missions can provide a starting point for determining shielding strategies. These dose limits can be found in Table 3-1. The career BFO Dose equivalent varies with both age and gender.

Table 3-1 Ionizing Radiation Exposure Limits for Low-Earth Orbit[7]

Exposure Interval	BFO Dose Equivalent (cSv)	Ocular Lens Dose Equivalent (cSV)	Skin Dose Equivalent (cSv)
30-day	25	100	150
Annual	50	200	300
Career	100-400	400	600

The most important dose to look at is the blood forming organ (BFO) dose, which can be assumed to be equal to that delivered to the vital organs[7]. A 30-day dose limit is similar to the limit that would be allowed for a solar proton event.

The actual deleterious effects of radiation exposure depend significantly on the type of radiation. The effect can be measured through the dose equivalent. The dose equivalent, H, is related to the absorbed dose, D, through a quality factor, Q, according to the following expression:

$$H = Q * D \tag{3-3}$$

The quality factor is 1 for normal X-rays. The quality factor for other types of radiation is shown in Table 3-2. The dose is specified in Grays (Gy) and the dose equivalent in Sieverts (Sv). The effects of radiation exposure are listed in Table 3-3.

Table 3-2 Quality Factors, Q and Occurrence of Different Kinds of Radiation[8]

Radiation Source	Q	Occurrence
X-rays	1	Radiation belts, Solar radiation, Bremsstrahlung
5 MeV γ-rays	.5	Radiation belts, Solar radiation, Bremsstrahlung
1 MeV γ-rays	.7	Radiation belts, Solar radiation, Bremsstrahlung
200 keV γ-rays	1	Radiation belts, Solar radiation, Bremsstrahlung
Electrons	1	Radiation belts
Protons	2-10	Cosmic radiation, Inner radiation belts
Neutrons	2-10	Close to Earth, the Sun, and any matter
α-particles	10-20	GCR
HZE-particles		GCR

Table 3-3 One-time radiation dose effects.[§]

Dose (cSv)	Health Effect	Onset Time
5-10	Radiation burns, more severe as exposure increases. Changes in blood chemistry	
50	Nausea	Hours
55	Fatigue	
70	Vomiting	
75	Hair Loss	2-3 Weeks
90	Diarrhea	
100	Hemorrhage	
400	Death from fatal doses	Within 2 months
1000	Destruction of intestinal lining, Internal bleeding, Death	1-2 weeks
2000	Damage to central nervous system, Loss of Consciousness, Death	Minutes, hours to days

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[§] Byrne, Shane. Unpublished Work. January, 2005.

3.3.3 Transit Radiation Doses[7]

The most dangerous time for the crew in terms of radiation dose will be during the transit to Mars or the Moon. Both Mars and the Moon will serve to reduce the GCR dose by half, since the planet blocks half of the sky. During transit, this protection will not be there. Going to the Moon, the dose received by the astronauts will not be significant, since the transit time will only be 3 days. On the way to Mars, the accumulated GCR dose will remain below the annual limit for astronauts, as long as the transit time is short enough. The unshielded GCR dose in space is approximately 58 cSv/year, which is higher than the 50 cSv/year limit. This dose will only become a problem if the crew is forced to abort the Mars mission and return to Earth. Then, they will spend more than a year in space. To reduce the effects, the crew would then have to spend some of their time in the solar flare shelter.

The solar flare shelter will be needed to protect the crew in transit from a solar flare. The radiation dose given by a solar flare can be quite high, on the order of hundreds of cSv. Therefore a shelter will be needed in the transit habitat to Mars. The shelter is discussed in more detail in section 4.6.2. For the shorter lunar trips, the approach to radiation protection used by the Apollo program will be adopted. The Apollo program did not spend the mass to fully shield the astronauts from a flare during their mission. Instead, they relied on the fact that, statistically speaking, the chances of encountering a flare during a short mission were slim. Furthermore, if a flare occurred, the crew could receive medical attention on Earth after only a maximum of a few days.

3.3.4 Surface Radiation Doses[7]

The radiation dose on the surface of the Moon and Mars will differ due to the presence of the carbon-dioxide atmosphere on Mars. The atmosphere serves to reduce the effects of the radiation that reaches the Martian surface. At higher altitudes, the shielding of the atmosphere is reduced, since the shielding properties depend on the thickness of the atmosphere, which decreases as altitude increases. The estimated radiation doses received on the Martian surface are presented in Table 3-4 below. The doses are presented at different average altitudes above the Martian surface. For comparison, the expected GCR dose on the Moon is 29 cSv/year at solar minimum, and the solar flares can produce doses as high as several hundred cSv.

Table 3-4 Integrated BFO Dose (cSv) on the Surface of Mars Using Both High- and Low-Density Atmosphere Models and on the Moon[7]

Radiation Source	BFO Dose at 0 km	BFO Dose at 4 km	BFO Dose at 8 km	BFO Dose at 12 km	Lunar BFO Dose
GCR at solar minimum (annual)	10.5-11.9*	12.0-13.8	13.7-15.8	15.6-18.0	29
GCR at solar maximum (annual)	5.7-6.1	6.2-6.8	6.7-7.4	7.3-8.1	10
Feb. 1956 flare	8.5-9.9	10.0-11.8	11.7-13.6	13.4-5.3	50
Nov. 1960 flare	5.0-7.3	7.5-10.8	10.6-14.8	14.4-19.1	100
Aug. 1972 flare	2.2-4.6	4.8-9.9	9.5-18.5	17.4-30.3	400
Aug. 1989 flare	0.1-0.3	0.3-0.6	0.6-1.3	1.2-2.6	No data**
Sept. 1989 flare	1.0-2.0	2.0-3.8	3.7-6.5	6.1-10.6	No data**
Oct. 1989 flare	1.2-2.7	2.8-5.9	5.7-11.4	10.6-20.5	No data**

* High-density dose model estimate – low-density model dose estimate

**data was not found for the dose from these individual flares on the lunar surface, however the cumulative dose from the three flares has been estimated at 150 cSv[9]

Both the Moon and Mars will reduce the background GCR radiation by half, since the planet will shield half the sky from the crew. However, solar flares will still be a concern on the surface of both locations, as the Martian atmosphere will not fully protect the crew, as can be seen in Table 3-4. Therefore, the crew will have to use the storm shelter in the habitat in the case of a solar flare even while they are on the surface.

3.4 Resources

One of the big aspects of a sustainable exploration system will be the ability use the resources of the planetary surface to produce propellants and consumables. This process is known as in-situ resource utilization (ISRU). Resources can be found in the regolith, buried under the surface, or, in the case of Mars, in the atmosphere.

3.4.1 Water

Possibly the most important resource that could be found on either Mars or the Moon is water. Water found on the surface can be used for drinking and can be broken down into hydrogen and oxygen to be used for either propulsion or breathable air.

3.4.1.1 Lunar Water

The presence of water has not yet been confirmed on the Moon, but it is thought to possibly exist in some of the permanently shadowed regions in the polar craters. The lunar hydrogen concentration is shown in Figure 3-4. High concentrations of hydrogen are indicated in dark red, and are thought to correspond to high concentrations of water. It can be seen that there are high concentrations of hydrogen centered on the poles. The existence of water in the polar craters has not yet been proven.

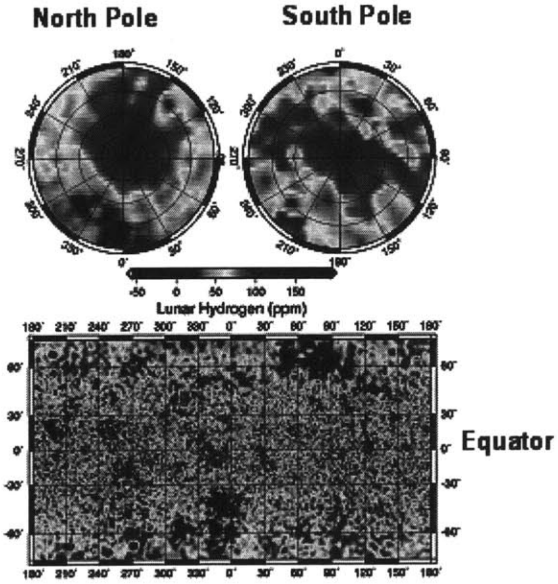

Figure 3-4 Lunar hydrogen count at the North and South Poles and the Equator. High hydrogen concentration is indicated in dark red.[§]

3.4.1.2 Martian Water[10]

On Mars, the current surface conditions do not support liquid water. However, there is extensive evidence that water once existed on the surface. There are valley channels and outflow channels, which indicate that there may be a large inventory of water on Mars. The sources of Martian water consist of the atmosphere, the polar caps, a deep subsurface permafrost layer, and the soil.

3.4.1.2.1 Atmospheric

The Martian atmosphere has a large amount of water in it, but at very low concentrations. The concentration in the atmosphere is shown in Table 3-5 as a function of the frost temperature, which is the temperature at which the atmosphere is saturated.

[§] Byrne, Shane. Unpublished work. February, 2005.

Table 3-5 Maximum water concentration in the atmosphere vs. frost point temperature[10]

Frost Temperature (°C)	Atmospheric Water
-40	1.6 %
-50	0.49
-60	0.135
-70	323 ppm
-80	66.7 ppm
-90	11.7 ppm

3.4.1.2.2 Polar caps

The Martian polar caps are composed of a permanent water-ice cap covered with the seasonal CO_2 cap in winter. The northern cap is about 1000 km in diameter, and the southern cap is about 350 km. The thickness of these caps is unknown, but they are a large source of water.

3.4.1.2.3 Deep subsurface

Evidence for a permafrost layer in the subsurface of Mars has been observed at latitudes above 40 degrees in both hemispheres. Geomorphology has been used to suggest 5-10% concentrations of ice in the soil in these regions. It is thought that water-ice could exist at depths of a few meters, while liquid water may exist at depths of a kilometer or more.

3.4.1.2.4 Soil

The Viking landers were able to release about 1% of water by weight from soils when heated to 500 degrees Celsius. It is thought, however, that the salts and clays in the soil could have water concentrations of up to 15%.

3.4.2 Soil Resources

The soil will be a large source of resources. As discussed above, the soil may be used to provide radiation shielding. It also contains many minerals and other substances that can be broken down and used. The elemental composition of the lunar and Martian soils are presented in Table 3-6. The Martian data comes from the Viking I lander site. Unfortunately, the Viking lander only measured the concentrations of elements with an atomic number higher than 12.[10] It is thought that most of these elements occur in the form of their oxides, making oxygen a primary ingredient in the regolith. On the Moon, the oxygen concentration has been measured to be 45% by mass.[8]

Table 3-6 Elemental composition of lunar and Martian regolith

Element	Lunar % by mass[8]	Martian % by mass[10]
Si	21	20.9 +/- 2.5
Al	13 (highlands) 5 (maria)	3.0 +/- 0.9
Ca	10 (highlands) 8 (maria)	4.0 +/- 0.8
Mg	5.5	5.0 +/- 2.5
Fe	6 (highlands) 15 (maria)	12.7 +/- 2.0
Ti	<1	0.5 +/- 0.2
Na	<1	--
S	--	3.1 +/- 0.5
O	45	--
Elements not directly detected	--	50.1 +/- 4.3

Simonsen presented a normalized composition of the regolith in both locations, with the elements in their oxide forms. This data is shown in Table 3-7.

Table 3-7 Oxide composition of lunar and Martian regolith[7]

	Composition, Normalized Mass Percentage
Lunar Regolith	52.6% SiO_2
	19.8% FeO
	17.5% Al_2O_3
	10.0% MgO
Martian Regolith	58.2% SiO_2
	23.7% Fe_2O_3
	10.8% MgO
	7.3% CaO

3.4.3 Atmospheric Resources

The lunar atmosphere is essentially non-existent. The concentration is only about 20,000 molecules/cm^3 during the night, and this concentration can be reduced by a factor of ten during the day. This concentration is about 14 orders of magnitude less than that of Earth, which results in the general statement that the Moon has no atmosphere[8]. Operations on the lunar surface are therefore assumed to occur in a vacuum.

Mars, however, has an atmosphere. The Mars pathfinder mission measured the atmospheric pressure on Mars to be about 7 millibars, or less than 1% of the atmospheric pressure on Earth[11]. As mentioned in Section 3.3.4, the atmosphere is composed mostly of CO_2. The concentration of the Martian atmosphere is listed in Table 3-8. The values listed are the volume fractions of the gases. These gases can be used to create breathable air, water, and propellants, as well as other useful compounds.

Table 3-8 Composition of Mars Atmosphere[10]

Gas	Concentration (%)
CO_2	95.3
N_2	2.7
Ar	1.6
O_2	0.13
H_2O	0.03 (variable)
CO	0.07
Ne	2.5 ppm
Kr	0.3 ppm
Xe	0.08 ppm
O_3	0.03 ppm (variable)

3.5 *Surface Gravity*

Mars and the Moon both have different surface gravitational environments than the Earth. The Moon has an environment that is only 1/6 the surface gravity of Earth. Mars has 38% of the surface gravity of Earth. It is not yet known what the long-term effects of partial gravity will be on explorers. The Moon will provide an excellent opportunity to learn about the effects of partial-g before sending astronauts to Mars.

3.6 *Dust*

Both the lunar and Martian surfaces are covered with fine-grained dust. During the Apollo missions, any activity by the astronauts on the surface of the Moon raised dust that covered the lower regions of the space suits. While a large portion of this dust was able to be removed by brushing the suit, the finer particles became embedded in the woven fabric outer layer[8]. This dust was then brought into the habitation compartment of the lunar module. On Mars, similar conditions can be expected. The effects of long-term exposure to the dust on either the lunar or Martian surface is yet unknown. The analyses performed by the Viking landers led to a conclusion that the Martian surface has some toxicity. The concentration of an active oxidant in the soil was measured to be 100 parts per million. Furthermore, the Viking measurements could detect no signs of carbon. According to the NASA Mars Surface Reference Mission, these results have been "interpreted to mean that the surface of Mars is sterile and that oxidation processes have destroyed any carbon that may have been brought to the surface from the interior or from outside by meteoroids."[12] These oxidants may have potentially dangerous effects on humans.

The surface dust may also impinge on solar panels, limiting their effectiveness. The dust can also affect the performance of rovers and robots as it works its way into the mechanical systems. On Mars, in addition to the dust storms discussed below, the surface winds can move dust around, creating a potentially worse dust environment than on the Moon.

3.6.1 Martian Dust Storms

On Mars, global and regional dust storms are prevalent. The regional storms consist of opaque clouds of dust that can be as large as a few million square kilometers. They appear every year and probably in every season. They tend to appear in three regions, located on the equatorial side of the edge of the seasonal polar ice cap in both the north and south hemispheres and in the southern subtropical region.[13]

The global dust storms are more rare, occurring only in some years. The storms are major and can take months to clear. They start in the southern hemisphere summer as a regional storm and then spread quickly over all latitudes, covering one or both hemispheres. The opacity of these storms increases as the lifetime of the storm increases, as suggested by measurements from the Viking I lander during the global storms of 1977.[14]

Kahn brings up three main points about the dust storms on Mars. First, one or more dust storms, either of regional size or larger, can occur in any year. The storms are not all the same, varying in their size, duration, and opacity. Second, the large, global storms do not occur every year. In fact, there may be some years where even regional storms do not occur. Third, the global storms tend to occur around the time of perihelion, which occurs during the southern spring and summer.

4 Mars Baseline Surface Architecture

The Surface Operations team of the NASA CER project determined a baseline architecture for surface operations on Mars. This architecture can then be used to create a Mars-back campaign on the Moon. The architecture consists of the mission duration, crew size, mobility capabilities, power requirements, and science activities on the surface. In-situ resource utilization (ISRU) is not a necessary part of the architecture, but its effects in some areas are discussed.

4.1 Mission Duration

The baseline mission duration that is chosen for the Mars mission is a 600-day surface stay. As is documented in the NASA Design Reference Mission, a long surface stay allows for a shorter time in transit and a longer time on the surface. Two transit and surface stay combinations are presented in Table 4-1 below.

Table 4-1 Typical Mars Mission Profiles[*]

	Typical Short Surface Stay Mission Profile (with Venus flyby on the inbound leg)	Typical Long Surface Stay Mission Profile
Outbound Transit Time (days)	221	150-250
Surface Stay Time (days)	60	500-700
Return Transit Time (days)	250	150-250
Total Mission Time (days)	531	About 1000

From this data it can be seen that the transit time requirements are actually smaller for a longer surface stay. Furthermore, the long surface stay mission allows for more time on the surface to do useful work and carry out scientific investigations, which can lead to higher value return for the mission. Therefore, the long mission profile is chosen as the baseline mission duration, with the surface stay being set at 600 days.

4.2 Martian Landing Site Location

The landing site for the Mars mission was chosen to be the equator. As was shown in Figure 3-3, the Martian equator has a relatively constant temperature range throughout the year. The mid-latitude regions, on the other hand will have Earth-like temperatures during the summer months. However, they will get significantly colder than Earth during the winter months. A long stay mission will occur during both summer and winter, and therefore it will be easier to design thermal control

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[*] Hofstetter, Wilfried. Email communication. March 23, 2005.

systems for Martian equatorial operations, where the temperature range is fairly constant throughout the year.

The surface elevations drive away from a southern hemisphere landing site. The southern hemisphere of Mars is generally at a higher altitude than the equatorial or northern regions. A low elevation is required for aerocapture, and therefore the higher southern latitudes can be ruled out, since aerocapture at Mars orbit is a technique that will be necessary to keep the mass of the system down.

Furthermore, the sun will be overhead a larger percentage of the time at the equator, increasing the availability of solar power in the equatorial region. While there may be more scientifically interesting sites on Mars that are further away from the equator, such as the polar ice caps, the operational considerations mentioned above argue for an equatorial landing site, at least for the early Martian exploration missions.

4.3 Crew Size

Once the mission duration has been chosen, the next parameter to be determined is the crew size. The most critical variable in determining the crew size is the amount of exploration that can be carried out.[◆] Thus, the ability to field two extra-vehicular activity (EVA) teams at the same time would markedly improve the exploration capability of the mission. This requirement sets a minimum of four crewmembers, since astronauts will not be allowed to conduct EVAs alone for safety reasons. However, the minimum crew size recommendation of the Surface Operations team is five crewmembers. This number was determined by analysis of the skill mix requirements, crew robustness, group dynamics, the requirement for performing highly visible events, and the mass cost of the mission.

4.3.1 Skill Mix of Crew

The NASA Mars Reference Mission lists the most technically relevant skills that need to be present in order to accomplish a successful Martian mission. It lists a mechanical engineer, electrical engineer, geologist, life scientist, and physician-psychologist and then draws the conclusion that a sixth crew member will be needed as a backup in the case of loss or incapacitation of one of the crew members.[3]

The Surface Operations team has altered the crew skills list suggested by the NASA Mars Reference Mission. The necessary tasks as viewed by the surface operations team are: pilot, engineer/mechanic, scientist, and medical assistant. Additionally, there is a high likelihood of interaction with robotic rovers on the surface, so a trained roboticist would be useful. Finally, each crewmember would need to be trained in communication skills, in order to effectively transmit information back to Earth and to interact with the public. Similar to the Reference Mission, each crewmember would be cross-trained and have at least two skills from

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[◆] Hoffman, Jeffrey. Personal communication. February, 2005.

the list. The differences from the Reference Mission lie in the belief that a mechanic/engineer can handle both mechanical and electrical repair tasks, and that piloting ability is called out as a distinct skill.[#]

A four-member crew would be composed of two mechanics/engineers and two scientists. The scientists would most likely consist of one geologist and one biologist. The piloting and medical assistant tasks would be shared across the crew. Adding another crewmember would allow for the addition of another scientist, since two mechanic/engineers would be enough to accomplish the repair and maintenance tasks on the mission. Adding additional crewmembers would allow for the addition of extra skills. Therefore, the crew skill mix requires a minimum of four crewmembers, but larger crew sizes are desirable.

4.3.2 Robustness of Crew

Much like the NASA Design Reference Mission suggested the addition of a sixth crewmember to keep mission performance at a high level in the case of the loss or incapacitation of a crewmember, the Surface Operations team has taken the robustness of the crew into account. Many of the tasks of the mission will necessitate the performance of EVAs. For example, the crew will have to perform science at many sites away from the base. Other tasks requiring EVA work include repair and maintenance activities and logistics activities. Therefore, the performance of the crew can be measured in the terms of the number of science-based EVAs that can be performed. Figure 4-1 below shows the number of science-based EVAs that can be performed as a function of crew size. These numbers were determined using the method for crew time breakdown presented by Lockheed Martin in their analysis of the First Lunar Outpost in 1992.[15]

[#] Lamamy, Julien. Unpublished work. February, 2005.

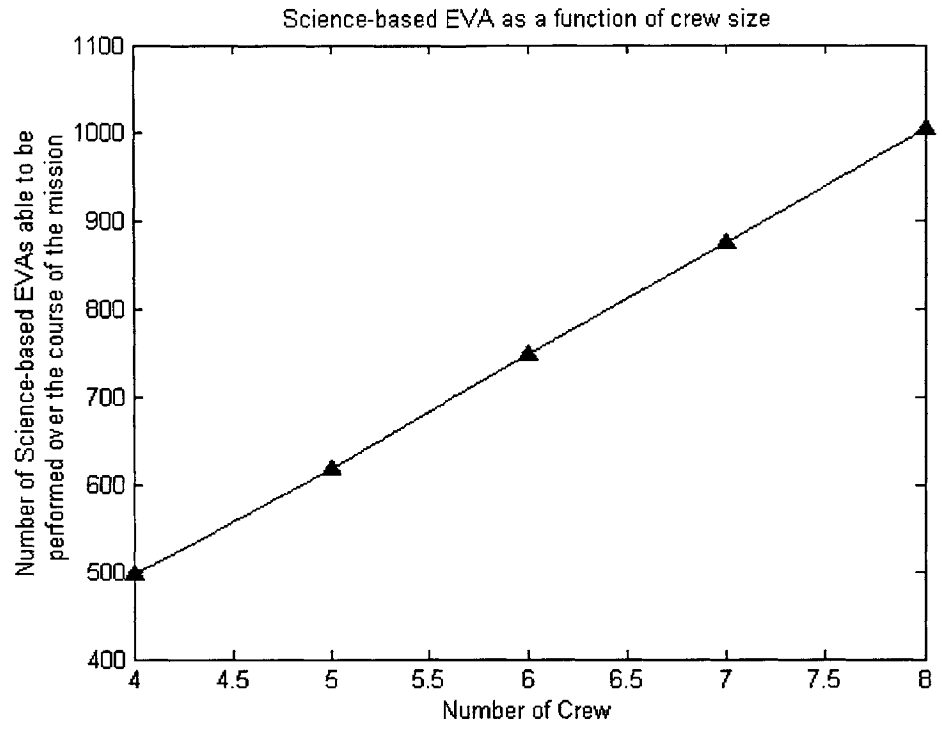

Figure 4-1 Mission performance, as indicated by number of EVAs, as a function of crew size

The number of science-based EVAs can be calculated using the following equations[15], where S_{EVA} is the number of science-based EVAs, $Total_{EVA}$ is the total number of EVAs that can be performed, M_{EVA} is the number of EVAs required for maintenance activities, and L_{EVA} is the number of EVAs required for logistics activities:

$$S_{EVA} = floor(Total_{EVA} - M_{EVA} - L_{EVA}) * t_{EVA} * CrewPerEVA \tag{4-1}$$

$$Total_{EVA} = \frac{floor\left(\frac{t_{stay}}{7} * WorkDaysPerWeek\right) * \frac{\#Crew}{CrewPerEVA}}{1 + DaysBetweenEVA} \tag{4-2}$$

$$M_{EVA} = floor\left(\frac{FailureRate * RC_{EVA} + t_{EVA\_M}}{t_{EVA} * \#Crew}\right) \tag{4-3}$$

$$FailureRate = \frac{24 * MonthsBetweenCrewArrival * 30 + t_{stay}}{MeanTimeBetweenFailure} \tag{4-4}$$

$$L_{EVA} = floor\left(\frac{t_{EVA\_L} * \#Crew}{t_{EVA} * CrewPerEVA} + 0.999\right) \tag{4-5}$$

For these calculations, t_{stay} is the surface stay length and was set at 600 days, t_{EVA} is the maximum EVA Time and is set at 8 hours, the Crew per EVA is set at 2, the work days per week is set at 6, the days between EVAs is set at 1, RC_{EVA} is the number of EVA Replaceable Components and is set to 591 (based on estimates by the First Lunar Outpost Study), t_{EVA_M} is the Maintenance EVA Time and is set at 2 hours, the Months Between Crew Arrival is set at 6, the Mean Time Between Failure is set at 75000 hours, and t_{EVA_L} is the Logistics EVA Time and is set at 10 hours. The "floor" appearing in the equations refers to the floor function where the answer is rounded down to the lower whole number.

The time breakdown is shown in Figure 4-2. The non-work time includes rest, meals, cleaning, and personal time. The inside work time includes lab work that will need to be done on samples gathered during EVAs. The inside work time and EVA time can be interchanged as necessary. The other EVA time includes the time for maintenance and logistics EVAs.

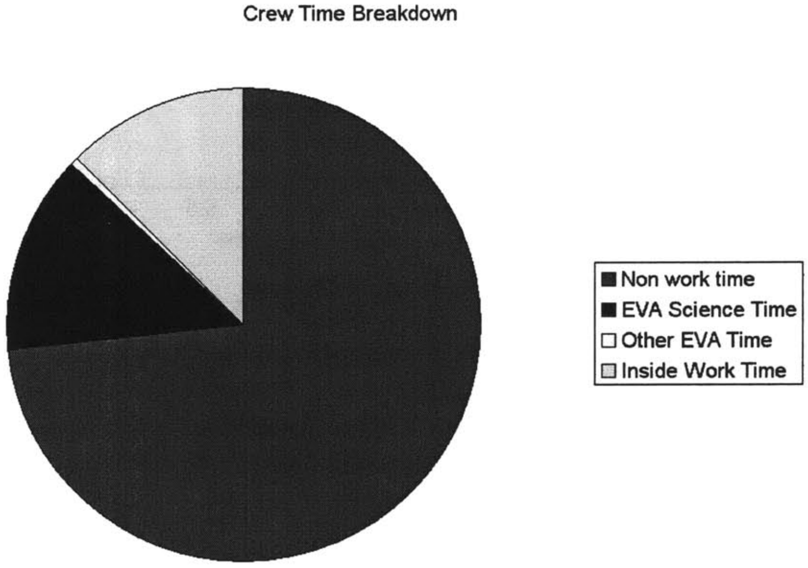

Figure 4-2 Crew time breakdown from the First Lunar Outpost Study

The performance will decrease if a crewmember is lost or incapacitated. Incapacitation or loss can occur due to disease or injury to a crewmember. There is also the possibility that an entire EVA team could be lost at one time due to an accident or possibly a sudden radiation storm. Figure 4-3 below shows the change in performance, in terms of EVA capability with the loss or incapacitation of crewmembers.

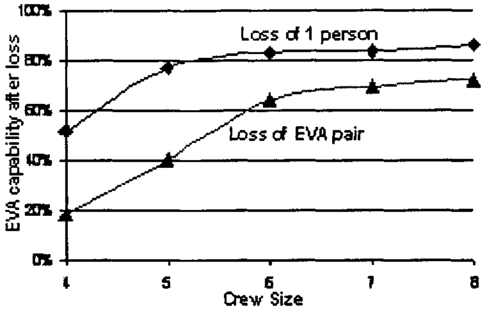

Figure 4-3 Effects of losing crewmembers on the capability to perform EVAs[#]

Figure 4-3 shows that the effects of losing one person are fairly constant once a five member crew is reached and that the effects of a losing a pair of crewmembers levels off after a six member crew is reached. This effect can be explained by the fact that even with only four crew members, two EVA teams can still be sent out. With only four crewmembers, however, the performance of the mission would be severely affected by the loss or incapacitation of only one crewmember. Hence, the requirement for the robustness of the crew imparts a requirement of at least five crewmembers. However, six or more crew would be ideal.

4.3.3 Group Dynamics

Many studies have been performed to analyze the effects of group dynamics. One of these was performed by Marilyn Dudley-Rowley and was based on Apollo 11, Apollo 13, Salyut 7 and seven polar expeditions. This study measured the number of deviances that occur based on the crew size. Deviances are defined as actions that are detrimental to the survival of the crew. Some examples of deviances are actions stemming from mental disorders and actions involving physical violence or verbal abuse.[16] Figure 4-4 below shows the number of deviances per person per thousand crew days as a function of the crew size. It can be seen that there was no significant difference in the rate of deviances for crews with more than four members. Hence, group dynamics suggest a minimum crew size of four.[¨]

[#] Lamamy, Julien. Unpublished work. February, 2005.

[¨] Catanzaro, Sandro. Unpublished work. February, 2005.

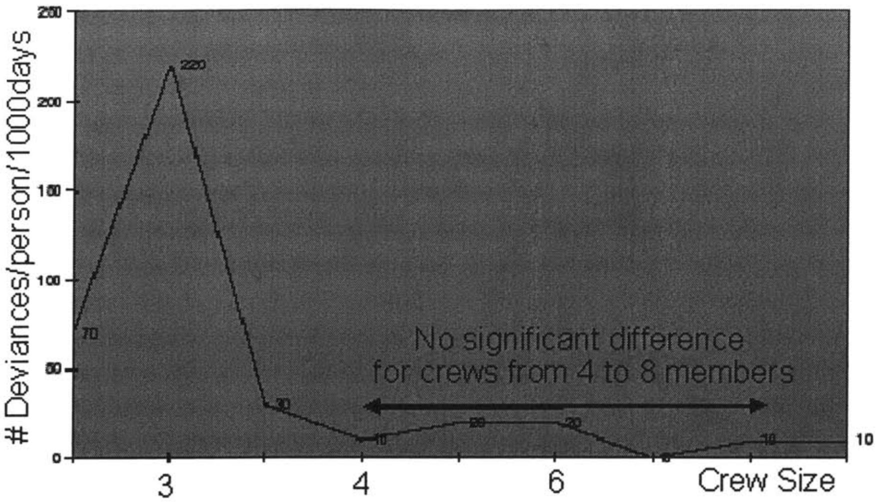

Figure 4-4 Group dynamics as a function of crew size[16]

4.3.4 High Visibility Events

The performance of highly successful, highly visible events is one of the keys to keeping the Mars exploration system sustainable. The crew size and composition plays only a small role in the ability to perform these events. A more diverse crew, in terms of gender and nationality may be more appealing to the public as a whole and may therefore garner more interest in the exploration system. Furthermore, having more crewmembers will allow for the option of performing more highly visible events. Although, as long as multiple EVA teams can be supported, the effect of adding more crewmembers is reduced in this regard.

4.3.5 Mass Cost and Crew Size Recommendation

All the metrics for determining crew size presented so far have argued for larger crew sizes. The problem with increasing the crew size is that each additional crewmember requires significant additional mass to be launched from the Earth's surface. Figure 4-5 shows the cost of adding a crewmember to the mass needed in low Earth orbit (LEO) and the performance benefit of adding the crewmember in terms of the EVAs. It can be seen that adding a crewmember requires an additional 74 mT to be launched into LEO. This mass is due to the required consumables and support structure for the crewmember, and the fuel mass that will be needed to transfer the mass to the surface of Mars. It does not take into account the required increase in size of the habitat for the additional crewmember.

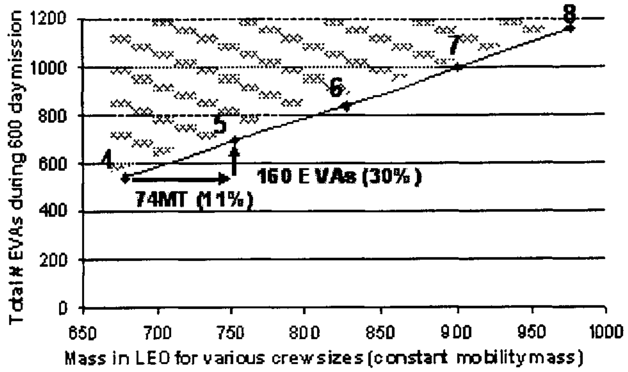

Figure 4-5 Mass cost in low-earth orbit (LEO) of adding a crewmember[#]

An increased mass of the system leads to an increased cost of the system. Therefore, the mass metric argues for a smaller crew size. When balancing the mass with the other metrics for determining crew size, the recommendation is a crew of 5. This crew size performs acceptably in all the other metrics and produces a smaller mass than 6 crewmembers.

4.4 Martian Surface Mobility

The crew on the surface will not be very effective without the ability to move to sites away from the base and landing site. The ability of the crew to reach different sites of scientific and exploration interest depends on the configuration of mobility that will be on the surface.

4.4.1 Types of Mobility

Surface mobility can be divided into three categories: walking, unpressurized vehicles, and pressurized vehicles. The mobility can be considered to increase as the type of mobility goes from walking to an unpressurized vehicle to a pressurized vehicle. The distance from the base that the crew can travel will increase as the mobility levels are increased. However, the mass needed on the surface and the power requirements will also increase. The types of mobility are discussed in the following sections.

4.4.1.1 Walking

The simplest form of mobility that the crew can have on the surface is the capability to walk around the base. The equipment required for walking mobility is an EVA suit. The maximum time for an EVA is set at 8 hours. This number is dependent on the characteristics and life support of the suit itself. For safety reasons, astronauts with walking capability will not be allowed to exceed a walk back distance from the base. The walk back distance is defined as the maximum distance that the crew can walk back to the base with the remaining life support in the EVA suits. Given a walking speed of approximately 3 km/hr, the max range of a walking astronaut is a half-day's walk, or 12 km.

[#] Lamamy, Julien. Unpublished work. February, 2005.

4.4.1.2 Extra-vehicular Activity (EVA) Suits[8,♦]

All the types of mobility listed below will require the crew to be outside a pressurized environment for some period of time, and will therefore require the use of EVA suits. The current EVA suit designs, the space suits used on the space shuttle flights and the International Space Station, are inadequate for use on Mars for several reasons. First, the EVA suits are not designed for use in a gravity field, and therefore are not very mobile around the legs. As was seen on the Apollo missions, the astronauts had to 'hop' to be able to move on the surface. The hopping was due more to the limitation of the suit than to the low gravity of the lunar environment. If the EVA suits are to be used for any sort of long work outside on Mars, walking in them will need to be made significantly easier.

A second problem with the current EVA suits is the heat rejection system. It is desirable to maintain the interior temperature of the EVA suit at room temperature, or around 293 K. The current system is designed to use a sublimator, where excess heat is rejected by sublimating water, to control heat flow, whether the excess heat comes from the astronaut or from the sun. However, on the Martian surface, the atmosphere prevents the use of a sublimator – the water won't directly boil off with the pressure of the atmosphere[17]. Furthermore, sublimators use too much water to be practical for the duration of the Martian exploration. Water will be a precious resource on the Martian surface, unless the crew can access Martian ground water. Therefore, a sublimator will not be the best option for heat control.

It is possible to use a radiator to reject heat during certain portions of the Martian day. However, as shown in Figure 3-3, there are times of the day where the outside temperature reaches higher than 293 K and the radiator will not be as effective. The excess heat generated by the astronauts will be at a relatively low temperature. To eliminate this heat with a radiator would then require a radiator that would be too large to be practical on the Martian surface. Therefore, an active heat rejection system will also be needed to prevent the astronaut from being overheated due to the suns rays.

The current EVA suits are also quite massive, having a mass of about 75 kg. On the surface, this mass will serve to tire the astronaut out quicker. Dust abrasion of the suit will also be a prime concern, since the EVA suits will be used many times throughout the mission. Finally, the controls for the EVA suit need to be made easier to use for the astronaut and need to be integrated into the habitat systems. Instead of chest controls, a wrist-mounted device could be used, allowing the astronaut to better see the readings of gauges and to control robotic elements of the mission.

The EVA suits need significant further development before they can be used on Mars.

[♦] Hoffman, Jeffrey. Personal communication. March, 2005.

4.4.1.3 Unpressurized Vehicles[%]

The next step in increasing the mobility of the astronauts is to add an unpressurized vehicle. These vehicles do not have long-duration life support capabilities and their duration of use is limited to the duration of the EVA suit.

4.4.1.3.1 Apollo-style Rover

This unpressurized vehicle is a two-person rover. Similar to the Apollo Lunar Roving Vehicle, pictured in Figure 4-6 below, it would carry two crewmembers on the surface, along with tools and science equipment. The mass of the Apollo-style rover is estimated at 270 kg. This vehicle is also referred to as an open rover.

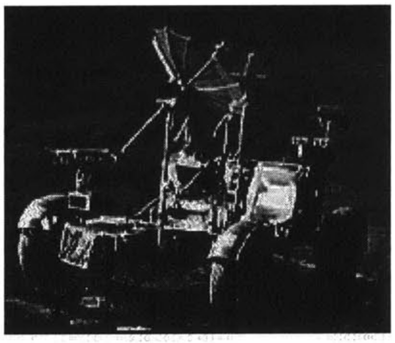

Figure 4-6 Apollo lunar rover. [18]

In case of a breakdown of the vehicle, the range needs to be limited to a distance such that the astronauts can walk back to the base. Since the duration of an EVA is set at 8 hours, the distance that the vehicle can be away from the base will decrease as the time spent on EVA increases. The max distance that the vehicle can be from the base is plotted in Figure 4-7. The rover is designed for a travel speed of 10 km/hr.

[%] Siddiqi, Afreen. Unpublished work. February, 2005.

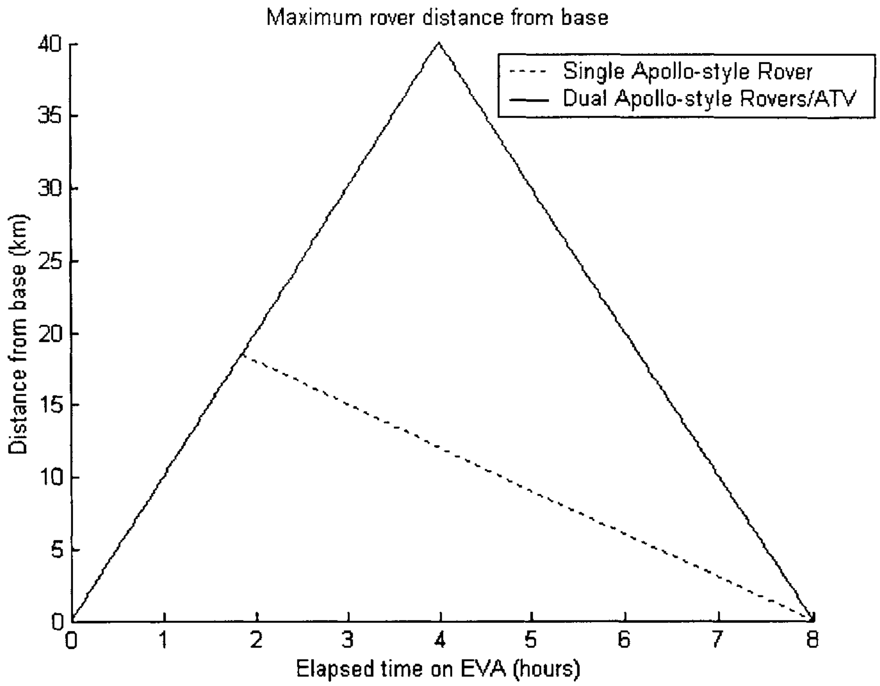

Figure 4-7 Maximum distance that unpressurized vehicles can be from the base. With only a single vehicle, the distance is subject to the walkback requirement. Multiple vehicles are not subject to this requirement since they can rescue each other.

With only one rover, the range is limited to the walk-back distance of the astronauts, or the distance that the astronaut can walk with the amount of life support available in their EVA suits. The walking speed is assumed to be 3 km/hr. Adding a second rover increases the distance that the rover can be from the base, because the second rover could be used to rescue the first crew in the case of a breakdown. The dual Apollo-style rover case is also shown in the figure. The max range in this case is limited by the half-day driving distance of the rover.

Figure 4-8 shows the amount of time that can be spent at a site using an unpressurized vehicle based on the distance the site is from the base. The time that can be spent decreases with distance due to the travel requirements of reaching the site and the limitation of the total amount of time that can be spent on a single EVA.

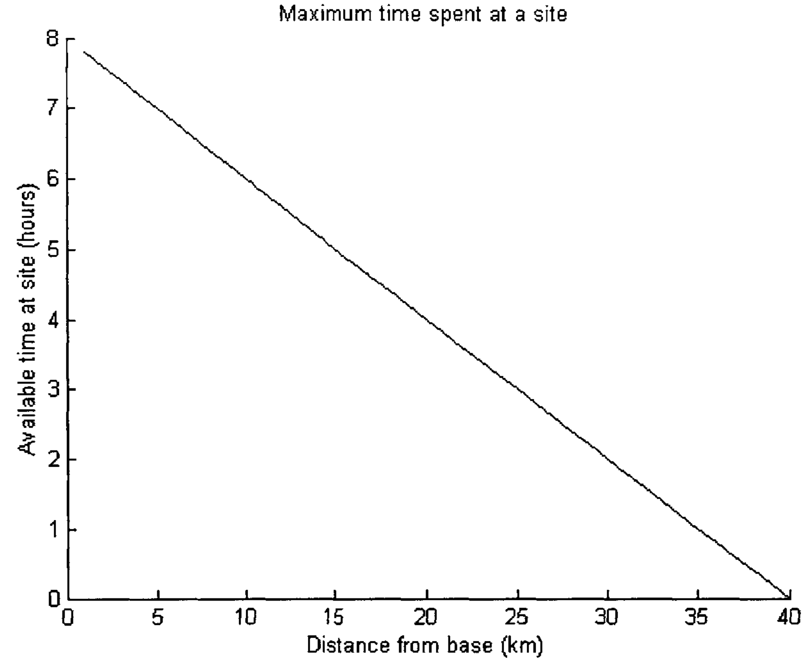

Figure 4-8 Maximum time that can be spent at a site that is reached using an unpressurized vehicle.

4.4.1.3.2 All-terrain vehicle

The all-terrain vehicles (ATVs) are similar to the Apollo-style rovers in that they are unpressurized. However, the ATVs only carry one person apiece and would be sent out exploring in pairs. This method of exploration serves to increase the allowable range of the vehicles. If one ATV were to break down, the other is capable of carrying both astronauts back to the base. Therefore, the maximum range of an ATV is the driving distance from the base, since the walk-back constraint is removed. Figure 4-7 shows how the range of an ATV changes throughout the course of the day. Figure 4-8 shows the amount of time that can be spent at a site using the ATVs. The time is the same for the ATVs as for the Apollo-style rovers because they travel at the same speed. The ATVs have been designed to be capable of towing a 2 metric ton payload at 10 km/hr. An ATV that was not designed to be able to tow would be less massive. The ATVs will be able to travel faster, reaching a maximum speed of approximately 40 km/hr, when they are not towing a payload. However, traveling at 40 km/hr will not happen all the time. That speed would be difficult to achieve on the rough Martian terrain and would make it difficult for the crew to see sites of scientific interest as well as potential hazards. Therefore, the ATV travel speed when it is not towing a camper will be set to the same speed as the Apollo-style rover, 10 km/hr. However, if the crew was traveling along a well known path, from the base to the power station for example, the ATV would be allowed to travel faster. The ATV is also designed to be able to have attachments such as trailers for equipment, excavation tools, and tow-hitches. The mass of the ATV is estimated to be approximately 560 kg. The large mass is due to the need to tow the large camper. The ATV concept is picture in Figure 4-9 below.

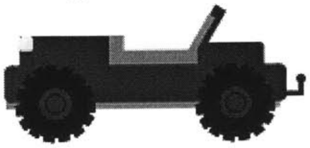

Figure 4-9 All-terrain vehicle concept[#]

4.4.1.4 Pressurized Vehicles[%]

Pressurized vehicles are vehicles that contain pressurized compartments where the crew can take off their EVA suits. The vehicles have their own life support systems. This capability allows for overnight stays away from the base and longer traverses. The maximum range of a pressurized vehicle depends on the life support capabilities of that vehicle. The maximum range will be the range that the vehicle can reach while using up only half of its life support. For example, if the pressurized vehicle contains enough life support capability for 7 days, it will be allowed to travel the distance it can cover in 3.5 days.

4.4.1.4.1 Pressurized Rover

A pressurized rover is a self-contained mobile habitat. It has a drive system capable of traversing large distances on the order of hundreds of kilometers at speeds up to 10-15 km/hr. The rover is sized for a nominal crew of two people and excursions of up to 7 days. The pressurized rover can be outfitted with laboratory equipment for on-site experimentation. The mass of the pressurized rover is estimated to be 3400 kg. A standard concept of a pressurized rover is shown in Figure 4-10. The NASA Mars Reference Mission uses pressurized rovers as the primary form of mobility.

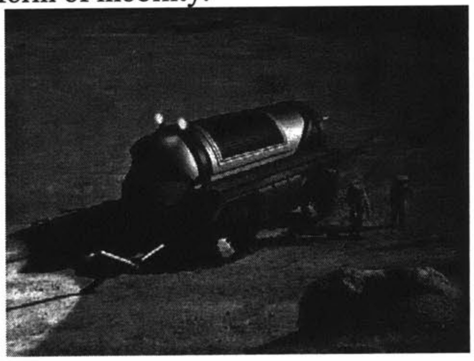

Figure 4-10 Typical pressurized rover design. [19]

4.4.1.4.2 Camper

[#] Lamamy, Julien. Unpublished work. February, 2005.

[%] Siddiqi, Afreen. Unpublished work. February, 2005.

A camper is a non-self-propelled pressurized vehicle. It would be moved from site to site by being towed by ATVs. It is designed to minimize volume, and would therefore not be the as comfortable for the crew as a pressurized rover might be. There would not be laboratory capability in the camper. The camper is estimated to have an empty mass of 1250 kg and a mass of 2000 kg when it is loaded with the necessary consumables for an excursion. The main use of a camper would be in setting up field camps and remote sites. The camper would be towed into position by the ATVs. The crew would then use the camper as their pressurized habitat and be able to stay at the site for many days, with trips back to the base to gather new supplies. The camper is sized for a 7 day stay. At the end of 7 days, the crew can go back on ATVs to the base and get supplies for the camper. Multiple campers may be placed sequentially to extend the radius of exploration. It should be noted that the ATVs capable of towing the camper would be larger than ATVs that are not designed to have towing capability. The camper carries solar panels with it to provide power. A conceptual sketch of the camper is shown in Figure 4-11.

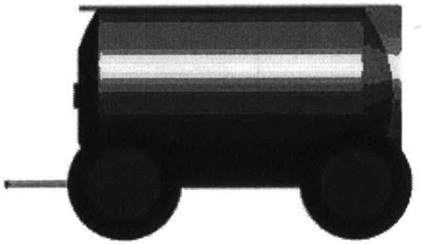

Figure 4-11 Conceptual design of the camper.♠

4.4.2 Mobility Options

The types of mobility sited above can be combined in many ways to produce a net mobility on the surface. The Surface Operations team came up with 21 different combinations that are listed in Table 4-2 below. In evaluating the mobility options, the level of risk that goes along with each also needs to be discussed. If no breakdowns are assumed, the mobility can extend further away from the base. However, assuming no breakdowns greatly increases the risk of the mission. The mobility options are listed along with their tolerance to system breakdowns and the maximum range that the mobility system can obtain. A breakdown tolerance of 0 is defined as the inability to recover from a failure to the primary vehicle. A breakdown tolerance of 1 is defined as being able to recover from a breakdown to the primary vehicle, while a breakdown tolerance of 2 is defined as being able to recover from a breakdown to the primary and secondary vehicles. Recovery is defined as the ability to safely bring the entire crew back to the habitat. Hence, the higher the breakdown tolerance, the less risk is involved. The downside of increasing the breakdown tolerance is that the range of the mobility system becomes more limited, as is shown in Table 4-2.

♠ Graphic by Bill Nadir. December, 2005.

Table 4-2 Mobility configurations with system masses and ranges[+]

ID #	Mobility on Surface	Breakdown tolerance	Vehicle Mass	Max Range (km)
1	Walking	2	--	12
2	Apollo-style rover	0	270	40
3	Apollo-style rover	1	270	18
4	2 Apollo-style rovers	0	540	40
5	2 Apollo-style rovers	1	540	27
6	2 Apollo-style rovers	2	540	18
7	2 ATVs	0	1120	40
8	2 ATVs	1	1120	40
9	2 ATVs	2	1120	18
10	4 ATVs	0	2240	40
11	4 ATVs	1	2240	40
12	4 ATVs	2	2240	27
13	1 Pressurized rover with unpressurized vehicle in tow	0	3670	840
14	1 Pressurized rover with unpressurized vehicle in tow	1	3670	80
15	1 Pressurized rover with unpressurized vehicle at base	0	3670	840
16	1 Pressurized rover with unpressurized vehicle at base	1	3670	40
17	1 Pressurized rover with unpressurized vehicle at base	2	3670	24
18	2 Pressurized rovers	0	6800	840
19	2 Pressurized rovers	1	6800	560
20	Camper and 2 ATVs	1	2380	80
21	2 Campers and 4 ATVs	1	4760	160

The calculations for determining the max ranges can be found in Appendix A.

For the purposes of the study, the mobility options that were tolerant to a single breakdown of the main mobility system were considered. Choosing a zero breakdown tolerant system was considered to be unrealistic, since the lives of the astronauts would not be risked by letting them get too far from the base, following the precedent of the Apollo missions. The two breakdown tolerant systems were deemed to produce requirements on the system that were too stringent, as they significantly lowered the range of exploration. Furthermore, it was assumed that with the testing on Earth and the Moon that would occur before the vehicles were launched to Mars that at most a single breakdown would be expected.

[+] Arnold, Julie. Unpublished work. February, 2005.

4.4.3 Analysis of Mobility Options

Having the ability to access both local (less than 50 km from the base) and regional areas would greatly benefit the surface exploration. An expanded area of coverage would increase the diversity of scientific sites that can be reached by the crew. It would also increase the ability of the crew to perform high-visibility events. Therefore, after looking at the ranges presented in Table 4-2, it becomes clear that having a pressurized vehicle would significantly benefit exploration.

To compare the mobility options against each other, the metric of number of sites visited versus mobility system mass will be used. The mass for each of the mobility options is also presented in Table 4-2. In order to determine the number of sites that can be visited with each mobility option, a landing site needed to be chosen. The landing site at Cerebus Fossae, which is a site of volcanically generated flooding, was chosen as an example and can be seen in Figure 4-12 below. Around the landing site, several sites of scientific interest were identified, as can also be seen on the figure. The sites were categorized based on the primary type of science that makes the site interesting. An activities model was then created to determine the number of sites that each mobility option could reach.

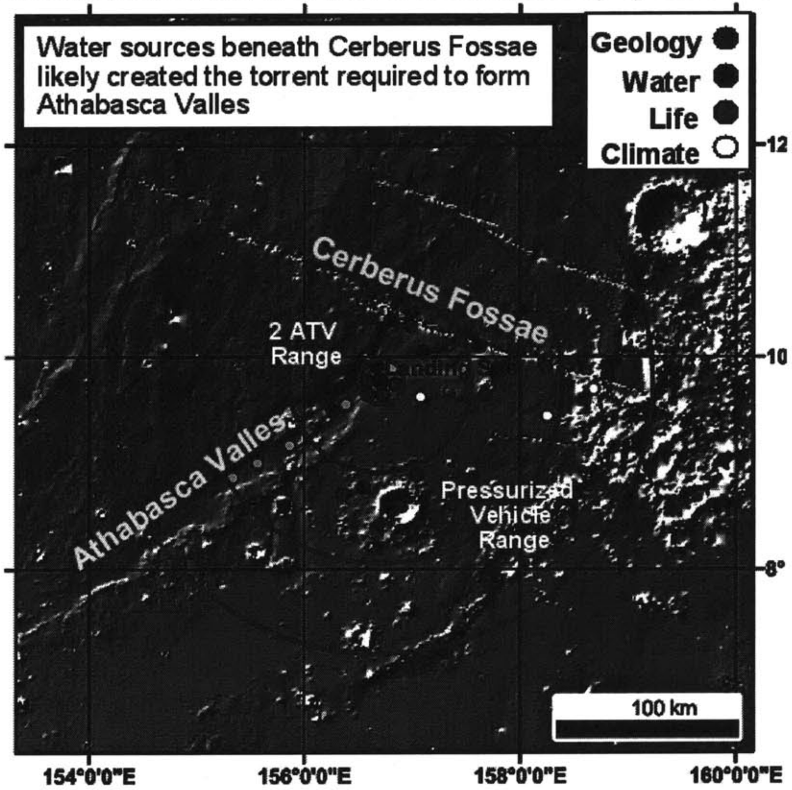

Figure 4-12 Cerebus Fossae landing site. The circles are at radii of 12.5 km (walking distance), 50 km (2 ATV distance), 100 km (1 pressurized vehicle distance), and 150 km (2 pressurized vehicles distance). The location of sites of scientific interest are identified along with the main scientific interest point at each site.[§]

[§] Byrne, Shane. Unpublished work. February, 2005.

4.4.3.1 Activities Model

4.4.3.1.1 Information Flow

The information flow through the activities model can be seen in Figure 4-13 below. The inputs, shown in the bold boxes, are used to calculate the number of sites that can be reached and the amount of time that it would take to reach all of those sites. If this time is longer than the preset mission length, the site of the lowest priority is removed, and the time is recalculated. This process is repeated until the total time required is less than the mission length. It should be noted that not all of the mobility configurations will be able to reach all of the sites. The model then outputs the number of sites visited and the science mass required on the surface.

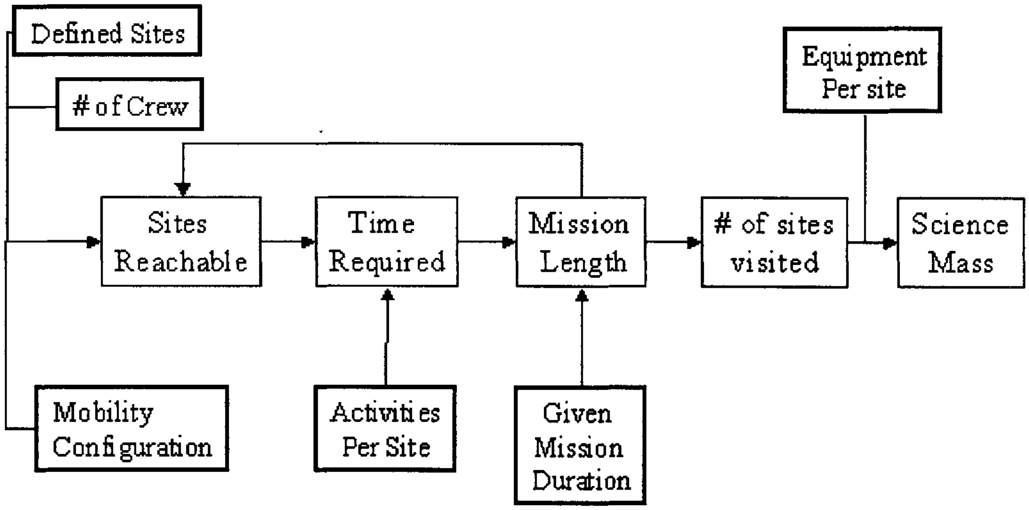

Figure 4-13 Information flow in the activities model. Inputs are shown in the bold boxes

4.4.3.1.2 Inputs

The activities model takes as input the number of crew, the mission duration, and lists of the sites of interest and desired activities to be performed at each site. The list of sites is separated into different scientific categories. These categories were based on the NASA/JPL model of Martian exploration, using water as a common thread throughout the sites. The sites were categorized as a geology, water, life, or climate site, and then ranked within each category, but not across the categories. The categories themselves are equally weighted. The activities to be done and equipment to be used at each site are specified. The activities include estimates of the time that it will take to complete the activity, and the equipment includes an estimate of the needed mass. The activities and equipment used in this study are listed in Table 4-3 and Table 4-4, respectively.

Table 4-3 Activities used in the activities model study.

Activity	Person-hours per site[§,$]
Autonomous sampling station placement	6
Rock and soil sampling	24
Geologic mapping and photography	6
Coring	6
Drilling	48
Active seismic experimentation	12
Excavation	48
Ground penetrating radar use	24
Environmental measurements	6

Table 4-4 Equipment used in the Activities Model Study.

Equipment	Mass (kg)[§,$]	Number
Drill	25	1
Corer	15	1
Autonomous sampling stations	30	1 per site
Camera	1	1
Shovels	10	1
Tools	10	1
Active seismic stations	25	1 per site
Radar stations	30	1 per site
Measuring devices	5	1
Sample containers	20	1 per site

For the Cerebus Fossae landing site shown in Figure 4-12, 31 sites of scientific interest have been identified.

4.4.3.1.3 Outputs

[§] Byrne, Shane. Unpublished work. December, 2004.

[$] Garrick-Bethell, Ian. Unpublished work. December, 2004.

The activities model outputs the number of sites visited for each mobility option given the inputs. It also calculates the total mass of science equipment that will be needed for the mission. Furthermore, it returns a timeline of the order in which the sites are visited and which vehicles are used to visit that site.

4.4.3.1.4 Assumptions

Several assumptions went into the activities model. The maximum length of any one EVA was set at 8 hours, and each EVA would consist of two crewmembers. It was assumed that there would be a maximum of two EVA crews out at any time. The available time for work for the astronauts was determined using the time estimates made by Lockheed Martin's First Lunar Outpost study. It was assumed that the pressurized rover would take three days to refuel and resupply at the base. EVAs on successive days for astronauts were not allowed unless the astronaut was on an excursion away from the base. It was assumed that one hour of intra-vehicular lab work would be required for each hour of EVA work. The time required for the crew to adjust to the Martian gravity after transit and the time required to prepare for departure were not considered in this study. Down time due to events such as dust storms was also not included.

4.4.3.1.5 Analysis Method

For each mobility option, the activities model calculates which of the specified scientific sites can be reached. This procedure is done by comparing the distance to the site to the maximum distance that can be reached by the mobility configuration. The maximum ranges of the mobility configurations were shown in Table 4-2. After determining whether or not the site can be reached, the model determines the amount of time that can be spent, per day, at the site. For example, with an unpressurized vehicle and a site that is a 2 hour drive away, the crew could spent a maximum of 4 hours per day doing science at the site, due to the 8 hour max EVA and the 4 hours (2 hours each way) of driving time to reach the site.

After determining the daily stay time of the site, it is possible to estimate the number of days that it takes to fully explore the site. The time to fully explore the site is determined by adding up the time it takes to do all the desired activities at the site. This time is then divided by the time spent per day at the site to find the number of days needed. Even if the same time is desired to be spent at multiple sites, the number of days it takes to explore each site may differ based on the distance of the site from the base. A description of the functions used to create the activities model can be found in Appendix B.

After the number of days needed for each site is determined, it can be seen if there is enough time in the mission to go to all the sites. A timeline is determined by adding the days required for each site and including the recovery time for the crews and the mobility equipment. If going to each site requires more days than the length of the mission, the process is reevaluated with sending out a second EVA crew. Figure 4-14 and Figure 4-15 show graphical representations of the timeline, showing where each vehicle is at any point in time. Figure 4-14 shows the timeline for mobility option 20, which is the one camper and two ATVs configuration. Not all the sites can be reached with this configuration, since there are sites that are beyond the 80 km max range. Figure 4-15 shows the timeline for the two campers and 4ATVs configuration. Here, all the sites can be reached, but doing so requires sending out multiple crews at the same time. There turns out to be additional time in the schedule with this set up, so more sites could be visited. It should be noted that there are situations where the mobility configuration does not allow all the desired sites to be reached.

In the figures, the sites are listed in order of decreasing priority as they go up the left side of the graph.

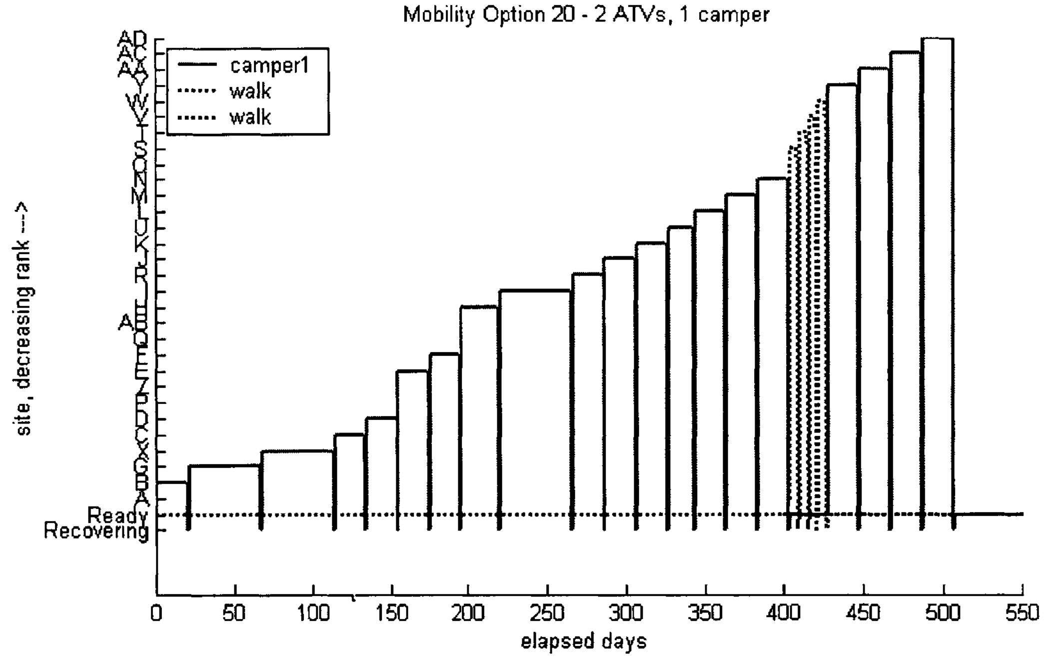

Figure 4-14 Timeline of visited sites for one camper, two ATV configuration. The sites visited with the mobility vehicles are in solid red, while the dotted black indicates the sites that the crew walks to.

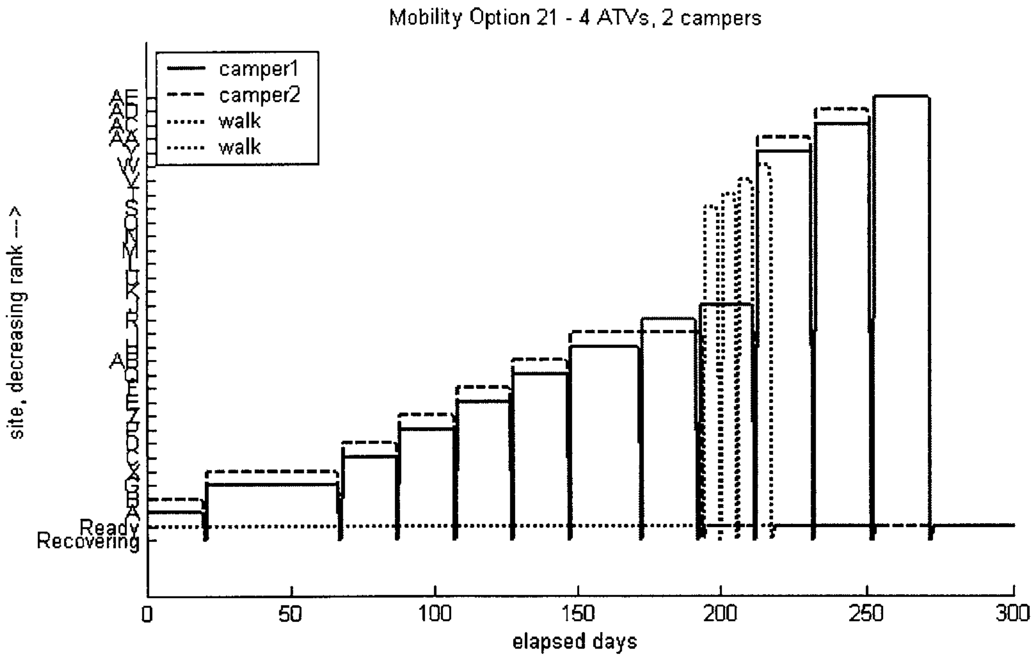

Figure 4-15 Timeline of visited sites for the two camper, four ATV configuration. The two campers are indicated by the solid red and dashed blue lines and walking sites are indicated in dotted black.

4.4.3.1.6 Results

Running the activities model with the Cerebus Fossae site, a five-member crew, and a 600-day mission yields the results shown in Figure 4-16. This figure shows the number of sites visited for each of the mobility options that are tolerant to a single breakdown of the mobility system. It can be seen that the pressurized vehicles can visit the most sites, with the two-pressurized surface vehicle options, the top two bars in the graph, being able to visit the most sites.

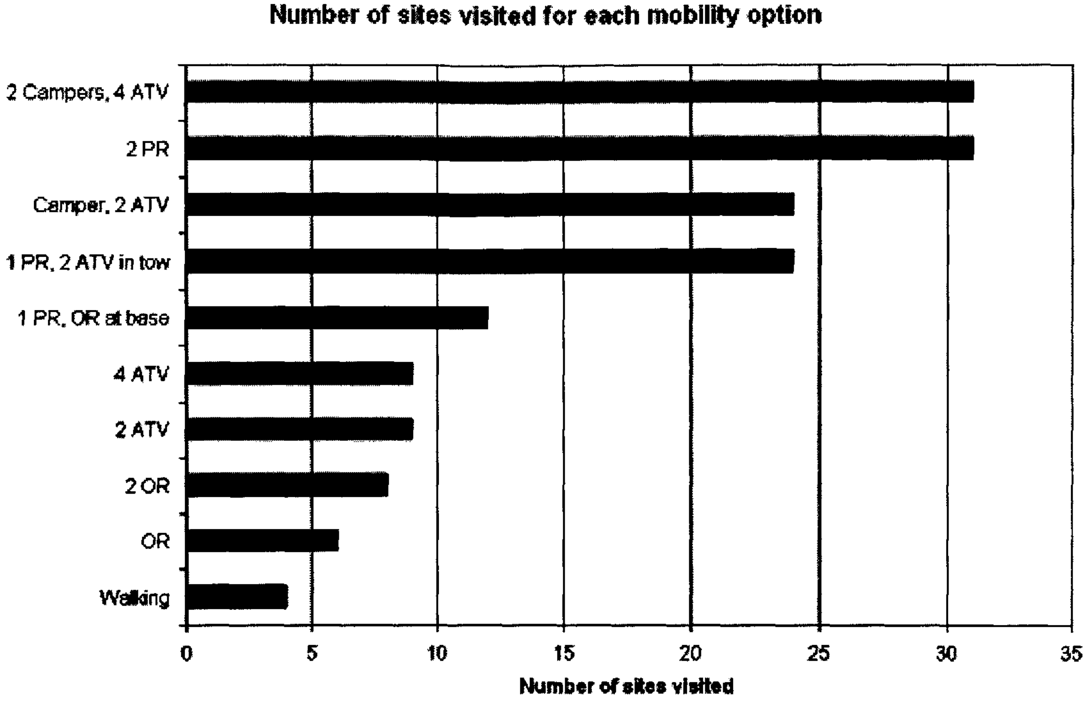

Figure 4-16 Results of the activities model, presented as number of sites visited versus mobility option. The options with a pressurized vehicle are shown in red. (PR = pressurized rover, OR = Apollo-style rover, ATV = All-terrain vehicle)

In order to accurately compare the mobility options to each other, a metric of number of sites/mobility system mass has been developed. Figure 4-17 shows that the best mobility option according to this metric is the two campers, 4 ATV option, giving the largest number of sites at the smallest mass. The dashed lines in the figure represent constant mass/number of sites ratios. The best result is the smallest mass for the most sites, or the top left of the figure. Using this mobility configuration, it was determined that approximately 3300 kg of science equipment would be needed for the mission.

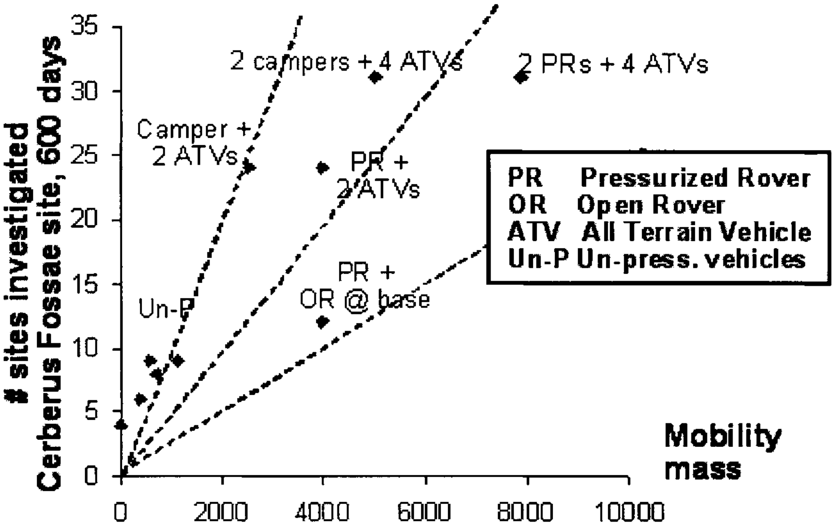

Figure 4-17 Number of sites visited versus the mass of the mobility system.#

4.4.4 Surface Mobility Selection

As a result of the analyses described above, the best mobility option would appear to be the two camper, 4 ATV option. However, a slight change to this option is recommended. For redundancy purposes, it will be desirable to have a fifth ATV. Having the extra ATV will allow for tolerance of a breakdown in an ATV without the significant delays in exploration that may occur if an ATV needed to be repaired.

4.5 Martian Surface Power

There are two main types of power systems that are in consideration for the Martian surface operations: solar and nuclear. The nuclear power plant would need to be developed from scratch to operate on the Martian or lunar surface. A team in association with the CER project designed a surface nuclear reactor that could be used on Mars or the Moon. Solar cell technology is fairly well developed at this point in time, but newer, lighter, more efficient cells are being designed. The full development of these cells to work on the surface would also require a financial investment. Therefore, these cells were considered for the solar array, since both they and the nuclear plant would require new technology development.

4.5.1 Nuclear Surface Power

The nuclear power plant that the nuclear team designed was scaled for a 5-year lifetime. This lifetime is most likely shorter than that which would be required for a Martian campaign. However, it provides a good starting point for the comparison of solar and nuclear power systems. The size and power levels of the reactor are presented in Figure 4-18.

Lamamy, Julien. Unpublished work. February, 2005.

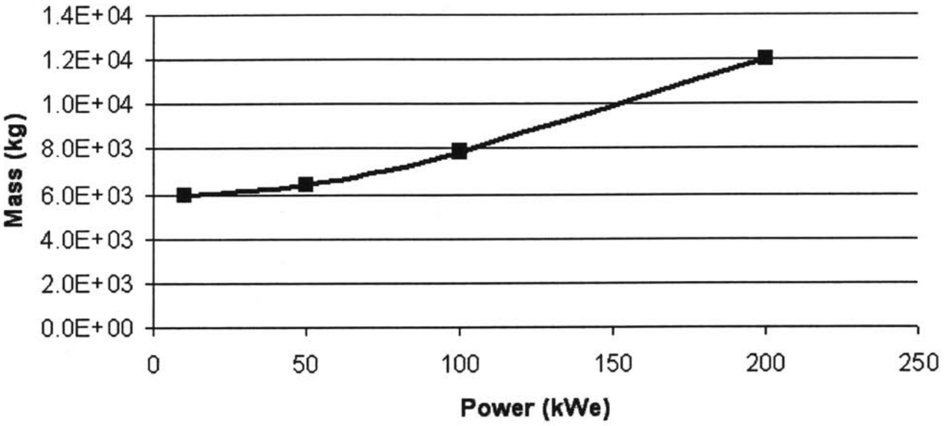

Figure 4-18 Nuclear power plant mass[&]

In order to limit the mass of the reactor, a shielding system was designed where the maximum shielding would only be present on 120 degrees of the reactor surface. This shielding would create a zone of 1 km on the unshielded side of the reactor that would be unapproachable by the crew, except for short durations of time, as can be seen in Figure 4-19. In the figure, the excluded zone is the area that the radiation is too high to allow human presence. The limited zones are areas where humans can be for short periods of time. There is a danger inherent in this design of possible harm to existing life on the Martian surface. With this design, the power plant would have to be situated at a minimum of 1 km from the habitat, creating a need for either very long power cables or strict precision landing requirements.

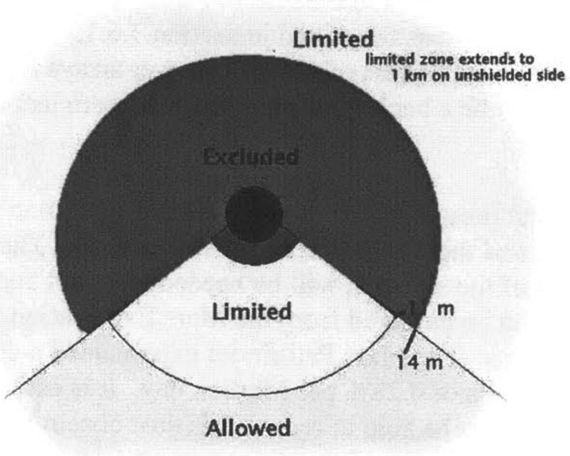

Figure 4-19 Accessible area around surface nuclear reactor.[&]

[&] Nuclear power sub-team of MIT/Draper CER team. Unpublished work. December, 2004.

4.5.2 Solar Surface Power

The solar plant faces more variables than the nuclear plant does on the Martian surface. First of all, the power provided by the sun varies as the year progresses. This variation is due to the fact that Mars does not have a purely circular orbit. The eccentricity of the Martian orbit is 0.093[6]. The eccentricity of the orbit causes Mars to be at different distances from the sun at different parts of its orbit and therefore there is a variation in the solar constant, which is a measure of the power radiated by the sun and is inversely proportional to the square distance from the sun. The Martian solar constant was plotted in Figure 3-2.

To size the solar array, the worst-case scenario was chosen. By choosing this situation, the array can be guaranteed to provide enough power to get through the entire year. The worst case is when Mars is the farthest away from the sun, and the solar constant is approximately 285 W/m^2. The area of solar array needed to supply the necessary power can be calculated from the following equations from *Human Spaceflight: Mission Analysis and Design* (HSMAD)[17]:

$$A = \frac{P}{I \cos \theta \eta} \tag{4-6}$$

where P is the required power output after accounting for losses in the system, I is the solar flux in W/m^2, θ is the angle between the normal of the panel and sun incidence angle and η is the conversion efficiency of the panels. η can be calculated as follows:

$$\eta = \eta_0 (1 + T_C [T - T_0]) \tag{4-7}$$

where η_0 is the standard efficiency, T_C is the normalized temperature coefficient, T is the operating temperature of the array, and T_0 is the temperature at which the standard efficiency is measured, which is usually 298 K.

4.5.3 Effects of the Martian Environment on Solar Power Generation

Mars is subject to dust storms as described in section 3.6.1. These storms have the potential to reduce the effectiveness of the solar power arrays for several days. Therefore, there needs to be a backup power storage system large enough to run the habitat for several days.

Dust on Mars is not just present in the dust storms. The Martian surface winds blow the dust around, and the dust can coat the solar panels. The exact effects of the dust on the panels of the size that will be needed have not been measured yet. However, some data can be gathered from the Mars Exploration Rovers and the Mars Pathfinder missions. The Mars Pathfinder experienced a decrease in the efficiency of the solar cells of 0.28% per Martian day. It is estimated that special coatings and cleanings may be able to reduce this dust obscuration by 95%, or to 0.014% per Martian day. This loss in performance translates to 8% over the course of a 600-day mission.[20] The Mars Exploration Rovers have shown an overall

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[&] Nuclear power sub-team of MIT/Draper CER team. Unpublished work. December, 2004.

reduction in the power from the panels of approximately 30% over the course of 300 Martian days.[21] The power loss can be seen in Figure 4-20.

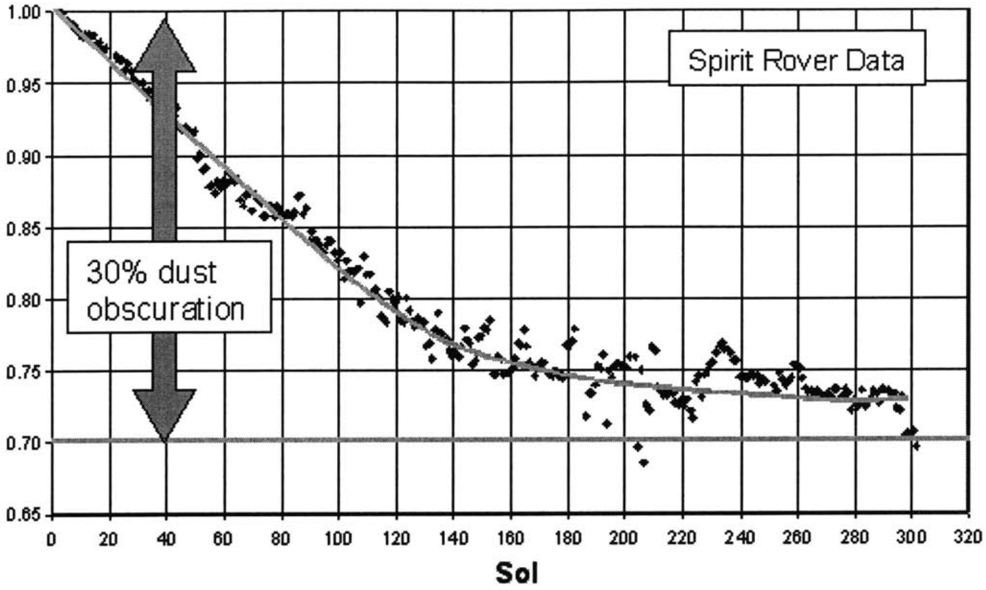

Figure 4-20 Dust obscuration observed on the MER solar panels. [21]

The dust obscuration presented in Figure 4-20 is based on the Spirit rover. The Opportunity rover shows a smaller effect of the dust. However, the Spirit rover recently had an increase in power as the cells appeared to be cleaned by winds.[22] While the full effect of dust obscuration on the size of panels that will be needed for this mission is not known, it is possible that wind will help to keep the panels free of dust.

The equatorial location of the Martian base provides advantages and disadvantages to the solar power generation. The advantages consist of the fact that the base will see approximately the same amount of sunlight per day throughout the year. Therefore, there will be a relatively steady supply of solar power each day. A more polar location would see significantly less sun during the winter months. The disadvantages of the equatorial location have to do with the need to provide energy during the night. While rovers will not be in use during the night, the habitat will still need power for thermal control and other habitat functions. Therefore, the solar array needs to be large enough to generate enough energy to last through the night.

4.5.4 Solar Array Area and Mass

Using the equations listed in section 4.5 above, it is possible to calculate the area needed for the solar array. The area will depend on the choice of solar cell. There are several different cell options. Three types of cells were considered for this study – commercially available Gallium-Arsenide (GaAs), thin-film alpha-silicon (A-Si), and thin-film Indium Phosphate (InP). The thin film cells have been tested in laboratories but are not currently commercially available. The decision to include these cells was based on two factors. First, by the time the solar arrays are built, these cells may be commercially available. Second, it is clear that an investment will need to be made in nuclear technology to develop a working power plant, so planning on a solar power plant that needs technology development was considered acceptable.

Table 4-5 Solar cell characteristics[17]

Cell type	Blanket Mass (kg/m^2)	Standard Efficiency	Normalized Temperature Coefficient, TC (x10^{-3} per K)
GaAs	2.05	18.5%	-2.2
A-Si	0.6	12%	-2
InP	0.6	18%	-2.6

The area needed depends mostly on the efficiency of the cell – the more efficient the cell, the fewer cells will be needed to generate the necessary energy. Furthermore, the area needs to be sized to generate enough energy while the sun is out to power the surface infrastructure when the sun is not out. Examining Figure 3-1, it can be seen that on the Martian equator, there is daylight for about half of the day, or close to 12 hours. Since the array panels will not track the sun, they will not be able to generate much energy when the sun is close to the horizon. Therefore, it is assumed that the array will only be able to generate power for 8 hours in any day.

Another parameter in choosing the cell is the mass of the cell. Some of the more efficient cells are more massive. Since the array needs to travel all the way to Mars, it is preferable to make it as light as possible. The mass of the array consists of more than just the solar cells. The supporting structure for the cells, the energy storage system, and the power distribution and management systems need to be accounted for. The mass for the array includes estimates for the panel mass, support structure, power management and distribution systems and power storage systems for nighttime operations. The mass of the cables needed to hook up the array to the habitat is not included. The mass estimates were made using the method presented by Kerslake and Kohout[20].

The array area for the different types of cells is shown in Figure 4-21a, and the mass in Figure 4-21b. These calculations are shown for a dust obscuration of 8% over the course of the lifetime of the array.

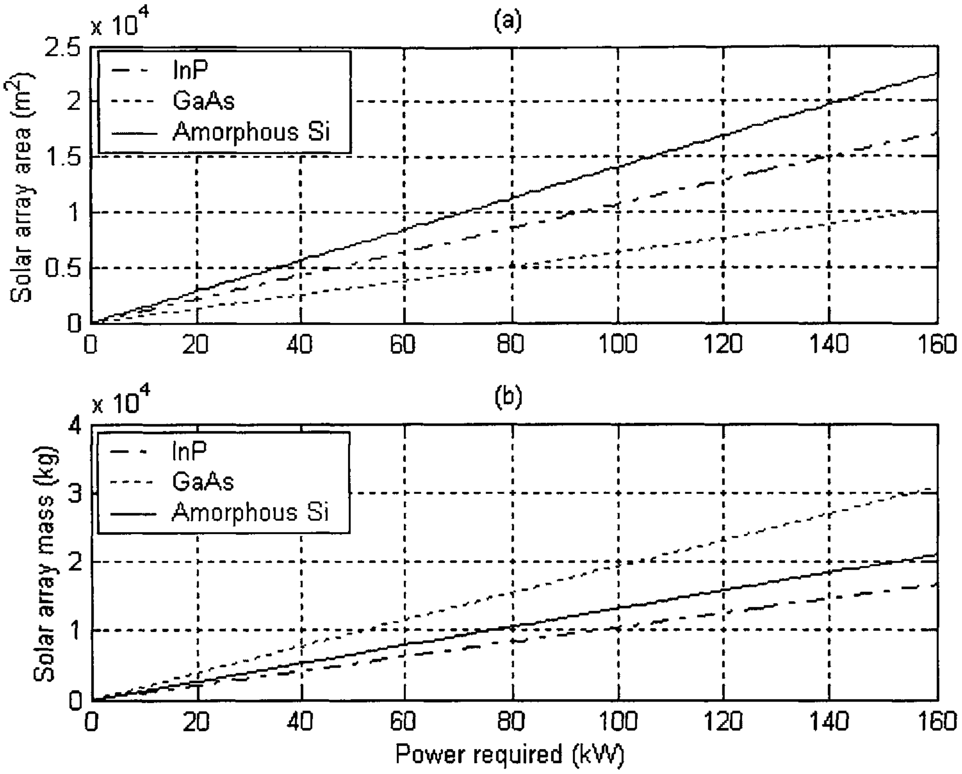

Figure 4-21 Solar array area (a) and mass (b) requirements for Martian surface power

As can be seen from the graphs, while the Indium Phosphate cells do not have the smallest array in terms of area, they produce the lowest mass array, and therefore are the cells that will be selected for the array for the mission. The arrays are assumed to lie flat and not to track the sun, as a tracking mechanism for the size of the array would be difficult to produce.

4.5.5 Power Demand on the Martian Surface

The power generated by either the solar array or the nuclear power plant will be used to power the habitat, recharge the mobility equipment, and to run an in-situ resource utilization (ISRU) plant, if one is brought to the surface. The details of the power demands of the habitat will be discussed below in section 4.6.1. The end result is the habitat requires approximately 9 kW of power to run. However, the habitat will also need to be powered throughout the night, so the array will need to generate enough energy during the day to charge up the energy storage system. As was stated above, it was estimated that the solar power plant could generate power for about 8 hours throughout the day. Assuming no losses in the overnight power storage system, the power plant needs to generate 27 kW during the time the sun is available to insure that it can operate throughout the night during all times of the year. However, it is also likely that the habitat will have its own power source. Since the same habitat will be used in transit to Mars as on the surface, the habitat will need a power source during transit. This power source will most likely consist of a solar array. Therefore, the habitat can also use this array on the surface to generate power.

To keep the ATVs functional, their power supply will need to be recharged. The power source for the recharging will be the main power system. Ideally, the ATVs would be able to be charged in a minimum of time, such that they can be used for consecutive days without significant down time. The ATV needs to have 13 kW-hr of power from its fuel cells during the possible 8-hour drive time. Therefore, it is this power that must be replenished. Figure 4-22 below shows the amount of time it would take to recharge the ATVs at different power levels. At 5 kW of recharge power, it takes less than a day to recharge the ATVs. Recharging two ATVs would therefore require 10 kW of power from the power plant. The campers will not need to be recharged. They require small amounts of power and will have their own solar cells to provide that power.[%]

The ISRU plant would be designed to process the CO2 in the Martian atmosphere and turn it into oxygen. If water is found, the ISRU plant could be used to turn the water into hydrogen and oxygen. Improvements to the design would entail the processing of the Martian soil. The plant is estimated to require at least 100 kW of power to run properly. The actual power demand of the ISRU plant will depend on the scale of ISRU required.

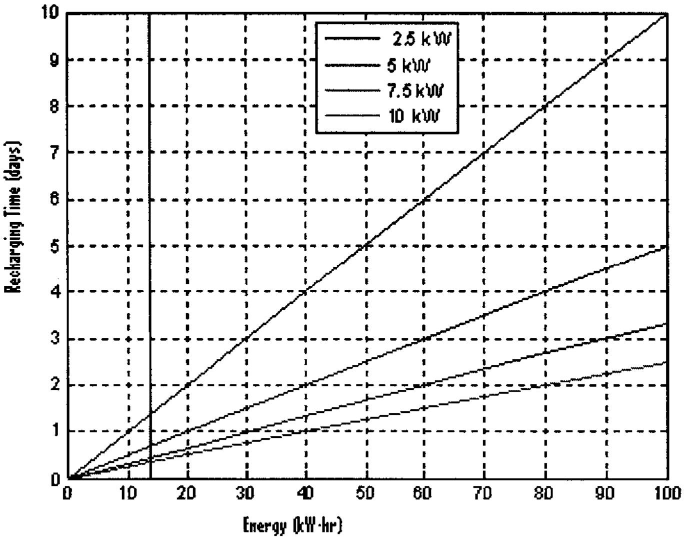

Figure 4-22 Recharging time requirements for the ATVs at varying power levels[%]

4.5.6 Comparison of Solar and Nuclear Power Sources

The power demands listed in the previous section and the equivalent masses of the solar array and nuclear plants are shown in Figure 4-23 below. The solar arrays are shown for the two cases of dust obscuration – 8% and 30%. The figure plots the

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[%] Siddiqi, Afreen. Unpublished work. February, 2005.

masses for the ATV case, where only 10 kW are needed to be produced by the power plant since only the ATVs would be recharged, the Habitat case, where 27 kW are needed to be produced to provide power for only the habitat, and the ISRU case, where 100 kW of power are needed to power the ISRU plant.

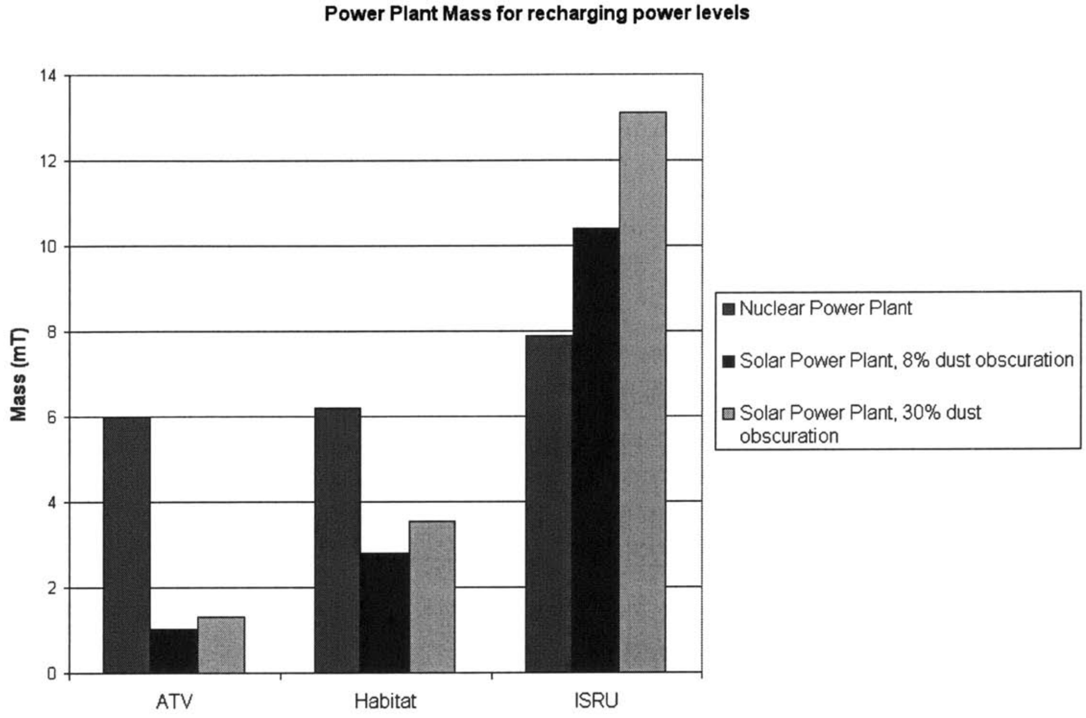

Figure 4-23 Masses of solar and nuclear power plants for different power demands

Figure 4-23 shows that for lower power levels, the solar array can be competitive in terms of mass with the nuclear power plant. At higher power levels, the nuclear plant clearly is less massive.

Mass is not the only consideration that needs to be taken into account, however. The large area needed for a solar array can cause difficulties in deployment and keeping the arrays clean. The arrays will also see fluctuations in power supply due to the weather conditions on the surface and will not function during the night. A nuclear plant will not see a drop in performance due to weather or time of day. The ATVs could be charged at a faster rate using the nuclear plant. However, as mentioned above, the radiation issues with the nuclear plant are more severe. The nuclear plant is also more likely to survive for multiple Martian missions.

Taking all these factors into account, the power system choice should depend on the power demand. It may not make sense to spend the money to develop and bring a nuclear plant to Mars if the only use is going to be to recharge the ATVs. The solar cell technology would already need to be developed for the habitat for use in transit. However, as the power demand increases, the need for the nuclear power plant becomes clear as the solar arrays increase significantly in both size and mass, making them impracticable to use.

4.6 Martian Surface Habitation

On the Martian surface, the crew will live in the same habitat that was used during the in-space transfer. The specifics of the habitat are documented in Table 4-6 below. Reuse of the habitat allows for a reduction in the mass that needs to be launched from Earth. Reusing the habitat also allows for the same radiation protection strategies that were used during transit to be used on the surface. Since the radiation conditions are worse in transit than they are on the surface, the radiation shelter in the transfer habitat should be sufficient to provide solar flare protection on the surface. The thermal protection of the habitat is also discussed.

Table 4-6 Martian habitat parameters

Mass (kg)	43000
Pressurized volume (m^3)	300
Radius (m)	3.7
Length (m)	7
Power (kW)	8.9

4.6.1 Martian Habitat Design

The Martian surface habitat is planned to be the same habitat that is used by the crew during the transfer from Earth to Mars. Therefore, the habitat needs to be of a functional design in both zero-g and on the surface. The surface is the more restrictive of these design areas, since, in zero-g, all of the walls can be used, while on the surface, the floor and ceiling cannot be used as functional surfaces.

4.6.1.1 Habitat Sizing

Many estimates exist as to the proper size for a habitat. The original design of the International Space Station (ISS) called for a pressurized volume of 1217.6 m^3 for 7 crewmembers.[23] Two-thirds of this pressurized volume can be assumed to be taken up by equipment, leaving one-third of free volume for the use of the crew.[17] Applying this assumption to the ISS results in 58 m^3 of free volume per crewmember. HSMAD produces an estimate of 20 m^3 of free volume needed per crewmember for a Martian transfer vehicle. This volume would be increased to 100 m^3 on the surface through the use of inflatable structures. Both of these estimates are for a space habitat, and do not consider the effects of living on the surface.

On the surface, in a gravity field, it is not the volume of the habitat that is as important as the floor area. The ceilings will be of the same height throughout the habitat, and therefore the amount of space is determined by the floor area. This method is how the size of houses on Earth are specified. Since the habitat will be used both during transfer and on the Martian surface, the design should be driven by the floor area requirements, not the volumetric requirements. However, the area requirements can be calculated from the volumetric requirements, if the desired height of each level of the habitat can be determined.

4.6.1.1.1 Habitat Size Constraints

The first step in determining the needed floor area of the habitat is to figure out how tall to make the ceilings. Micheels estimated that the needed ceiling height is 2.66 m.[24] This estimate was reached by setting the maximum height of a crewmember to 1.9 m (6 ft, 2 inches) and then estimating their range of motion to be 0.76 m. For this study, a height of 2.4 m was used for the ceiling to correspond to the 8-ft ceilings found in many houses on Earth.

The next step is to decide on the overall size requirement. It was decided to use the HSMAD design of 20 m^3 of free volume per crewmember. The ISS design was not chosen because, once mass is considered, it becomes too large. The ISS is assembled piece by piece and is not designed to be moved out of orbit, and therefore it can afford to be much larger. Landing something as large as the ISS on Mars would prove to have significant difficulties. Furthermore, the ISS design includes laboratory space that will not be included in the transfer habitat. The laboratory can be an inflatable structure on the surface of Mars. The total volume requirement of the habitat is therefore 300 m^3 (5 crewmembers at 60 m^3 of total volume each). The requirement for free volume is 100 m^3, which translates to a free area requirement of 42 m^2 for use by the crew.

Also unlike the space habitat designs, on the surface the crew will need actual beds to sleep in, as opposed to the 'bags' on the wall that are used in the space shuttle. Since the mission will occur over such a long time, it will be desirable for each crewmember to have their own room. The needed size of the crew rooms has been estimated to be 5.76 m^2 by Micheels. This number helps to set the outside dimensions of the habitat, as blocks of at least 5.76 m^2 need to be available. Micheels also estimates that the body envelope of a human being is about 0.7 m. This number was used to size the passageways between rooms and levels. The area required for the walkways was not counted as part of the free area for the crew.[24]

A further constraint on the habitat design is the need for a radiation shelter, which will be discussed in section 4.6.2. This shelter will need to hold all five crewmembers at the same time, for durations up to 10 or 12 hours. Again, from Micheels, the minimum area for a person is estimated to be 1.022 m^2. For five crewmembers, the minimum area of the radiation shelter is then required to be 5.11 m^2. This area is not counted as part of the free area for the crew, since it is only intended to be used for radiation protection.

Furthermore, in order to minimize the amount of thermal and radiation protection that will be needed, the habitat configuration that satisfies the area and volume requirements and results in the smallest surface area should be selected.

4.6.1.1.2 Habitat Orientation

There were three main orientations of the habitat that were considered – vertical, horizontal, and modular. Each of these orientations has separate advantages and disadvantages. To determine which orientation would be the best to use, the options were evaluated against the following criteria: human factors, ease of landing and deployment, the size required to meet the volume and area constraints, and the functionality of the habitat in both zero-g environments and the Martian surface environment. The human factors criteria include items such as the size of the crew rooms, the ease of access to the habitat, and the amount of extra free space available to the crew. The ease of access is probably the most important aspect of human factors to be taken into consideration. After long duration missions on the ISS, crewmembers have difficulty walking on Earth. It sometimes takes a couple of weeks for them to return to full functionality.[◊] Therefore, on a Mars mission, where the transfer time is equivalent to the 6-month ISS missions, it can be expected that it will take the crew some time to recover from their flight. Therefore, the fewer steps that they will have to use during this time, the easier it will be for them.

The ease of landing and deployment criteria include items such as whether or not the habitat needs to be removed from the lander and how easy that would be, how hard it is to land the habitat in its desired configuration, and how many, if any, connections need to be made on the surface. The size criteria was set up so that a smaller surface area is better. The total volume is fixed by the needs of the crew, so the discriminator for size is the interior area and the surface area. Minimizing the surface area minimizes the amount of thermal and radiation protection that is needed and is therefore beneficial to the exploration system. The available interior area was calculated by determining the total interior area, subtracting two-thirds for equipment, and subtracting out the size of the radiation shelter. The height (or length) of the habitat was then set to insure that the area requirement was met. The distribution that gave the maximum floor area, while maintaining the desired height, was chosen. All habitats were assumed to have a cylindrical shape, and that inflatable structures could be used to increase the size once on the surface.

The requirement that the habitat function both on the surface and during transit places some limits on the design. The habitat needs to have sufficient space in both locations, and the transport between sections of the habitat needs to be designed such that it can be accomplish in a gravity field as well as in zero-g. For example, passageways on the ceiling with no ladders would not be allowed, since they could not be reached when the habitat is on the surface.

[◊] Liu, Andrew. Personal communication. March, 2005.

Table 4-7 Evaluation of habitat orientation possibilities

	Human Factors	Ease of Landing/Deployment	Small size	Dual-use capability
Vertical	Med – many stairs, lot of free space when minimum size is met	Med – can put on top of lander and land vertically. However, may want to remove it from the lander to allow easier access.	High – the habitat can meet the size requirements with a surface area of 250 m^2	High – same system can be used regardless of gravity
Horizontal	Med – There may be multiple levels present and the free space will consist of long corridors	Med – can land vertically on top of lander and then lower to surface or can use larger lander to land it horizontally, would still want to place on surface	Med – the habitat can meet the size requirements with a surface area of 280 m^2	High – same system can be used regardless of gravity
Modular	High-No stairs, lot of free space when minimum size is met	Low - Requires landing multiple elements with extreme precision or significant reconfiguration of the habitat on the surface	Med – the habitat can meet the size requirements with 6 modules, each having a 6 m diameter and a height of 2.4 m	Low - Using in transit would require multiple landing elements, inter-module connections in space, or reconfiguration on the surface

Looking at Table 4-7, it is clear that the modular habitat scores the lowest and therefore would be the worst choice. It is very difficult to set up on the surface and provides little in the way of dual use capability in space and on the surface. The horizontal and vertical habitats both have similar scores. To decide between the two orientations, the size parameter was chosen to be the deciding factor. To determine whether the horizontal or vertical configuration was better, the first step is to determine if one of the orientations will provide more interior space for a specified volume. To make this determination, a MATLAB program was written to calculate the free space available to the crew in each orientation. The code for this program can be found in Appendix B. The results of the program are shown in Figure 4-24, and show that the interior area for a given volume is similar for either orientation.

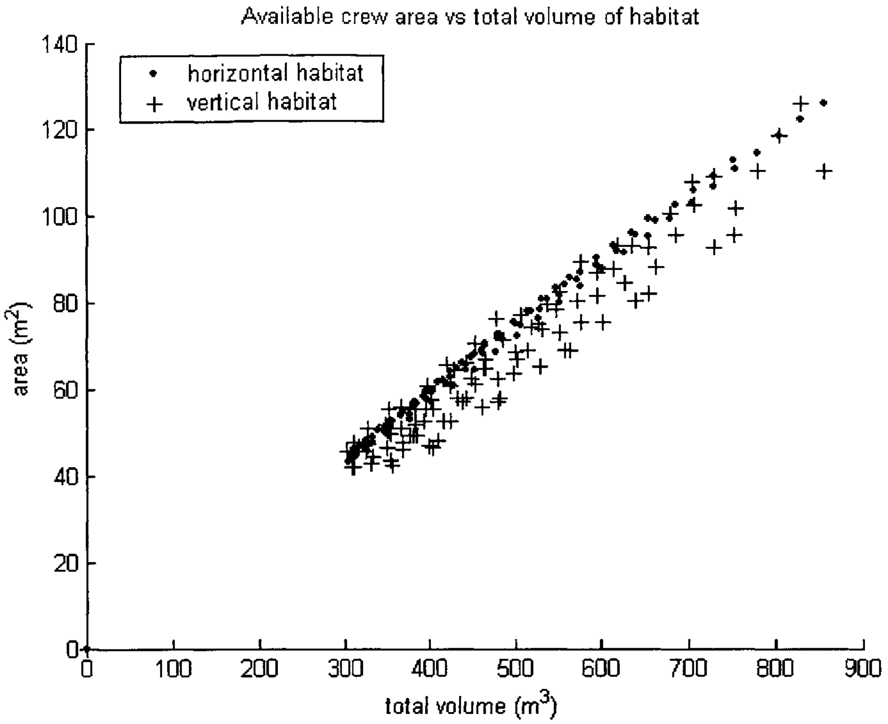

Figure 4-24 Available floor area inside the habitat as a function of the total pressurized volume.

Therefore, in order to determine the proper orientation to use, the exterior constraints on the habitat size need to be taken into account. Using the 5 m diameter limits of the current launch vehicles, the Delta IV Heavy and the Atlas 5[25], the horizontal configuration is the best option, producing a 5 m diameter habitat with a length of 15 m. Expanding the diameter still results in a horizontal habitat, although a shorter habitat, until a diameter of 7.4 m is reached. At this point, the vertical configuration produces the most interior area. The 7.4 m diameter habitat has a height of 7 m. Allowing the diameter to expand further still results in a vertical habitat, although it will get shorter as the diameter expands.

The diameter turns out to be the driving factor in determining which orientation provides more interior area. This result occurs because increasing or decreasing the diameter has a much greater effect on the volume of the cylinder, which is proportional to the radius squared, and on the interior area, which in the vertical habitat is proportional to the radius squared. In the horizontal habitat, the diameter is what determines how many levels can be present and how wide the levels can be, thereby having a large effect on the interior area. Changing the allowable maximum length does not have as large an effect on the orientation choice. The effect of the diameter on the interior area and on the orientation of the habitat can be seen in Figure 4-25. The 7.4 m diameter vertical habitat is chosen since it gives a larger interior area than the horizontal habitat configurations while keeping a low surface area.

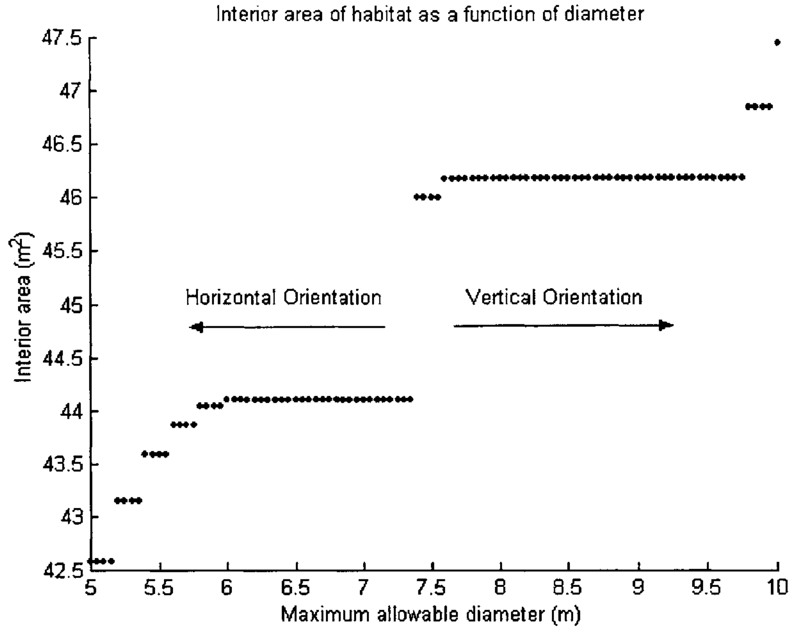

Figure 4-25 Habitat interior floor area as a function of the maximum allowable diameter for a 300 m^3 habitat.

A potential horizontal habitat configuration is shown in Figure 4-26. There is only one level in the habitat, with the area above and below the level available for the storage of equipment. The interior space has been divided into crew rooms and a radiation shelter according to the area requirements cited above. It should be noted that the space required for an airlock has not been taken into account.

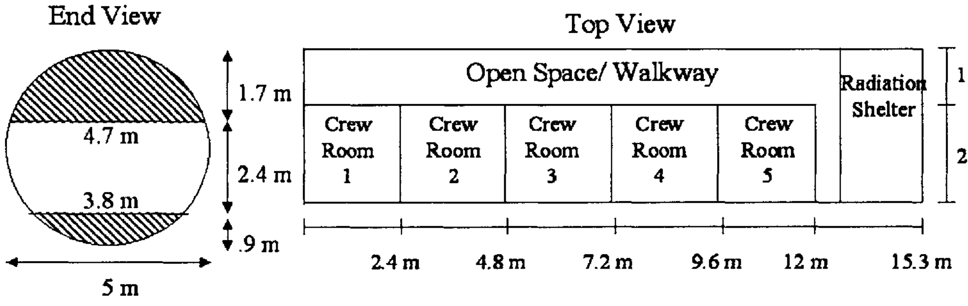

Figure 4-26 Potential horizontal habitat layout.

A potential vertical habitat configuration is shown in Figure 4-27. The diagonally shaded area in the side view represents space that can be used for storage of equipment. In the views entitled Floor 1 and Floor 2, the shaded area represents the area that would be needed for a ladder and walkway to permit transit around the habitat. This area is the same size for both floors, with a diameter of 2.1 meters. Again, the crew rooms and radiation shelter have been sized according to the requirements outlined above. The crew rooms are placed on the first floor to minimized the amount of climbing up and down ladders while the crew is adjusting to the Martian gravity field. Furthermore, having the crew rooms on the first floor will allow for additional radiation protection from galactic cosmic rays, as some of the radiation will be attenuated by the structure of and equipment in the habitat. The radiation shelter on the second floor is sized to adequately protect the crew from a solar flare without the extra attenuation that could be received if it was on the first floor.

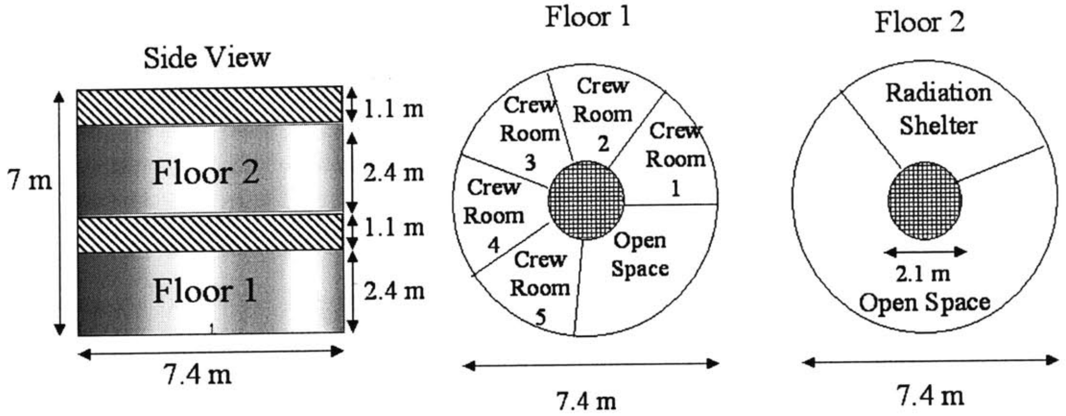

Figure 4-27 Potential vertical habitat layout.

Looking at Figure 4-26 and Figure 4-27 reveals that, while the horizontal habitat sized for the current launch capabilities can meet the interior area requirements for the crew, the area outside of the crew rooms will mostly consists of a long corridor, and therefore would not be very useful as common space. Therefore, it will be necessary to launch a horizontal habitat with a diameter larger than 5 meters to be able to make more use of the interior space. The open space in the vertical habitat, on the other hand, will be more conducive to group gatherings. As shown is Figure 4-25, the vertical orientation will have more interior area once the diameter reaches 7.4 meters. Hence, it is recommended that the current launch capabilities be grown to accommodate a diameter of at least 7.4 meters. The best habitat orientation will then be the vertical orientation. The habitat with a 7.4-meter diameter and 7 meter height will be used for the analyses conducted in the rest of this thesis.

4.6.1.1.3 Habitat Subsystems and Mass and Power Requirements

The subsystems and mass of these systems for the habitat can be calculated using the model presented in HSMAD and summarized in the Table 4-8 below. All of the subsystems will need to function both on the surface and during transit. Care must be taken when designing these systems to account for this fact. For example, the Environmental Control and Life Support System (ECLSS) for the International Space Station was not designed to be able to function in a gravity field. Therefore, it would not be a good choice for the habitat ECLSS. Rather, the habitat should follow the design of the space shuttle ECLSS, which functions in Earth's gravity field while the shuttle is awaiting launch and in the micro-gravity of LEO when the shuttle is in orbit. The detailed components of each subsystem can be found in HSMAD[17].

Table 4-8 Martian habitat subsystem mass and power

Subsystem	Mass (kg)	Power (W)
ECLSS	18000	3950
Structure	9000	--
Communication	500	1000
Thermal	2000	1000
Crew Accommodations	6600	2468
EVA/Airlock	2000	--
Radiation Protection*	--	--
EPS	4516	--
Avionics	200	500

* The drinking water will be sufficient to provide radiation protection around the shelter

4.6.1.1.4 Use of Inflatable Structures

To increase the size of the habitat once it is landed on the Martian surface, inflatable structures can be used to increase the space available to the crew. The best use of the inflatable structures would be for the parts of the habitat that will be required on the surface but not during transit. Examples of these parts of the habitat are the laboratory, repair facilities for the mobility equipment, and a garage structure to protect the mobility equipment from the dust storms.

Inflatable structures take advantage of the lower pressure of the Martian atmosphere to require less pressure to expand than they would need on Earth. The structures can be rigidized after inflation and connected to the main habitat through inflatable connectors. Inflatable structures serve to significantly expand the volume and area of the habitat for a small launch penalty.

4.6.2 Martian Habitat Radiation Precautions

As discussed in section 3.3, the radiation environment consists of both galactic cosmic rays and solar proton events, or solar flares. The environment in transit to Mars will be much harsher than the environment on the Martian surface itself. Therefore, the habitat will need to have proper radiation shielding. Analysis of the radiation environment stated by Simonsen[7] shows that the galactic cosmic ray dose during the transit stage will not exceed the limits established by NASA. The dose received by the crew from the cosmic rays is shown in Table 4-9. On the surface of Mars, the atmosphere helps to significantly reduce the effects of both cosmic rays and flares. The surface dose is also shown in Table 4-9, and it is clear from the table that the total dose is under the limits established by NASA. Therefore, the main radiation source that needs to be protected against is the solar flares in transit.

Table 4-9 Galactic cosmic ray radiation dose received by crew on Martian mission

	Days	Dose (cSv/day)	Total (cSv)
Transit (round trip)	400 (estimate)	0.1589	63.56
Martian Surface	600	0.0326	19.56
Mission dose			83.12

As was shown in section 3.3.2, negative effects of radiation exposure begin with a one-time dose as low as 5 cSv. These effects increase as the exposure increases. Therefore, it is desirable to keep the dose received by astronauts below this level. Simonsen, et al.[9] performed an analysis of several different shielding materials and their effectiveness in reducing the dose absorbed from the solar flare events of 1989. The amount of shielding for each material, listed in g/cm^2 is summarized in Table 4-10. Table 4-10 also shows the thickness and mass of the shield that would be required to shield the entire habitat.

Table 4-10 Shielding thicknesses required on the Martian surface to reduce the 1989 solar flare dose received to 5 cSv.

Material	Mg Hydride	Li Hydride	Water	Polyethylene
Amount (g/cm^2)[9]	33	30	30	28
Density (g/cm^3)[9]	1.6	0.82	1	0.92
Thickness (cm)	20.6	36.6	30	30.4
Mass required to shield entire habitat (kg)	82000	74600	74600	69600
Mass required to shield storm shelter within habitat (kg)	9700	8800	8800	8200

It is clear from the results of the Table 4-10 that several tons of shielding will be required to adequately protect the entire habitat during transfer. Launching this additional mass and then landing it on the surface would incur severe mass penalties. Therefore, it is only necessary to have a storm shelter within the habitat. To determine the shielding material, it is important to note that several metric tons of water will already be launched for consumption by the crew. This water can be stored in such a way that it surrounds a safe haven within the habitat that the crew can use in the case of a solar flare. As the water is used, the amount that is not recyclable will be turned into waste. This waste can also be stored around the safe haven, maintaining the radiation shield. Once the habitat is landed on the surface, it will come with this pre-existing radiation shield in place. As discussed in section 4.6.1.1.1 above, the radiation shelter will need to have an area of 5.11 m^2 to provide space for all of the crew. The amount of water needed to create a shield of 30 cm thickness made out of water can be calculated from the following equations:

$$ShelterRadius = \sqrt{\frac{A}{\pi}} \tag{4-8}$$

$$SurfaceArea = 2\pi(ShelterRadius)^2 + 2\pi(ShelterRadius) * height \tag{4-9}$$

$$mass = density * SurfaceArea * thickness \tag{4-10}$$

where the height is the level height, set at 2.4 m. It may be possible to reduce this height and thereby reduce the amount of shielding required.

It turns out that approximately 8800 kg of water will be needed to create the shield, as shown in Table 4-10. For the Martian mission, the habitat will come with approximately 13000 kg of water, which is more than enough to provide for the shelter.

On the surface of Mars, there is the chance that the crew will be caught away from the base during a solar flare. However, the crew should have approximately ten hours of warning on Mars to get back to the base.[§] Therefore, as long as the crew is within one day's driving distance from the base, they can use the habitat safe haven as shelter. If the crew is further away, which will occur if they are using the second camper in a string from the base, an alternate safe haven will be needed. Only a few of the worst of the solar flares recorded would have penetrated the Martian atmosphere with enough radiation to cause immediate harmful effects to astronauts on the surface. Therefore, there is a good chance that astronauts caught exposed to a solar flare would not suffer any adverse effects. However, to mitigate the chances of any effects, the camper will come equipped with tools such that the astronauts can pile Martian regolith onto the camper to help with protection as much as possible.

4.6.3 Martian Habitat Thermal Protection

The temperature at the Martian equator varies significantly throughout the day, as shown in section 3.2. It reaches a low level of approximately 150 K at night. This temperature is about the same as the temperatures that would be seen on the lunar poles during the day. The habitat, while it is populated, will need to be kept at a temperature above 150 K. Therefore, a thermal protection system will be needed. Unfortunately, multi-layered insulation (MLI) will not be effective on Mars, since the atmosphere will conduct heat away from the insulation, and the main effectiveness of MLI is its low radiative emissivity. Furthermore, the relatively large gravity of Mars will cause more contact points within the layers of the MLI, again reducing its effectiveness.[17] Therefore, on the Martian surface, more traditional forms of insulation will be needed in order to keep the habitat warm at a moderate power level. It should be noted that although the Martian atmosphere will reduce the ability to use MLI for insulation, the habitat will transfer significantly less heat to the atmosphere through convection and conduction than

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[§] Byrne, Shane. Personal Communication. February, 2005.

through radiation, due to the low density of the atmosphere. Therefore, it can be assumed that the heat lost by the habitat occurs via radiation, once outside the insulating material. The steady-state habitat temperature can be calculated according to the following equations.

$$\text{Radiation: } InsulationTemp = \left(\frac{HeatingPower}{\varepsilon\sigma * SurfaceArea} + OutsideTemp^4 \right)^{1/4} \qquad (4\text{-}11)$$

$$\text{Conduction: } HabTemp = InsulationTemp + \frac{HeatingPower * t}{k * SurfaceArea} \qquad (4\text{-}12)$$

In these equations, ε is the emissivity of the outer layer, σ is the Stefan-Boltzman constant, t is the insulation thickness, and k is the thermal conductivity of the insulation material. To decrease the radiative heat loss, the habitat was assumed to be coated with gold foil, which has an emissivity of 0.023.

The insulation material was assumed to have a conductivity of 0.026 W/mK, which is the conductivity of air.[27] Air would be a low-mass way of insulating the habitat. Figure 4-28 below shows the habitat temperature for an insulation thickness of 0.1 m. At night, with these conditions, around 2 kW of heating power would be needed to keep the habitat at a comfortable temperature for the crew.

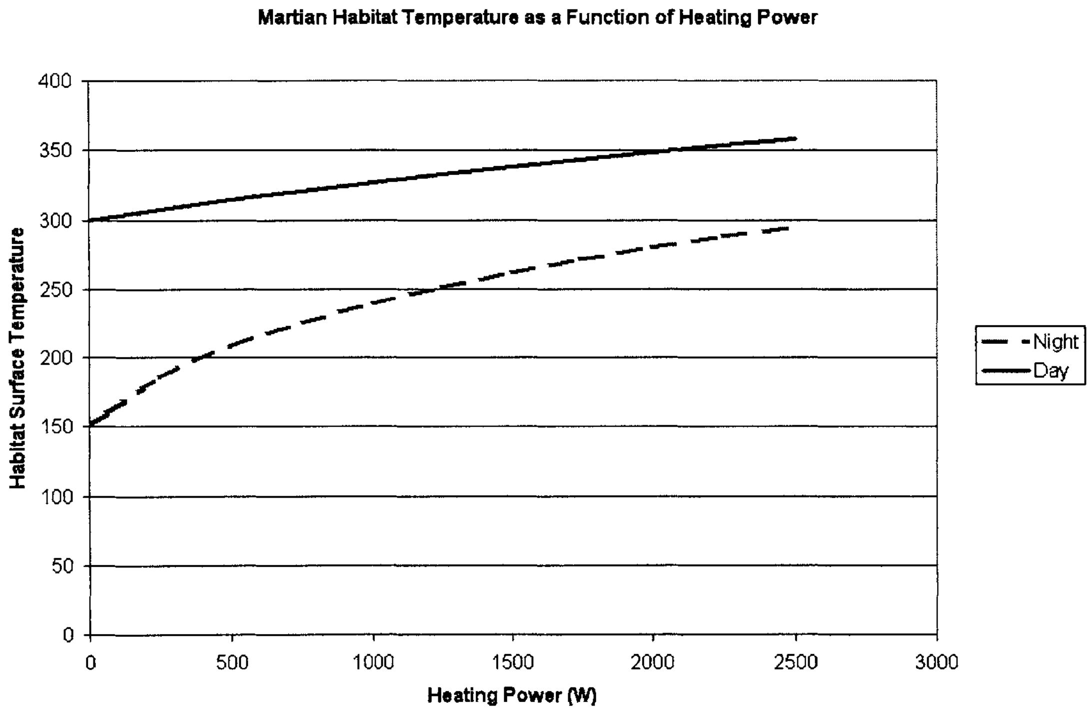

Figure 4-28 Temperature of the surface of the Martian habitat during the day and night.

During the Martian day, the temperature will only reach as high as 300 K. If the heaters are shut off, the habitat should remain at a comfortable temperature.

4.7 Martian Navigation and Communication System

The surface navigation and communication system was studied by the Information team of the CER project. The goals of the study were to develop an integrated communication and navigation systems that provided continuous communication between crew performing EVA activities and the surface base, provided a data rate of at least 10 Mbps from Mars to Earth, and provided navigation accuracy on the order of one hundred meters for traverses away from the base. The results of the study showed that for Mars, the best communication architecture would be a direct communication relay to Earth, a satellite in a synchronous orbit, and on board navigation systems for traverses. This architecture provides navigation accuracy to within 20 m with a satellite fix, the capability to send 10 Mbps from Mars and to receive 1 Mbps from Earth, and a communications coverage area on the surface of several hundreds of kilometers. With this architecture, there is a maximum communications gap time between Earth and Mars of under 2 hours. The navigational and communications coverage on the surface can be enhanced by placing surface beacons along the traverse routes.[~]

4.8 Mars Science

The Mars Exploration Program Analysis Group (MEPAG) laid out the objectives and goals of Martian scientific exploration in 2004. The MEPAG report identified four main goals for scientific study. The goals are preparing for human exploration, determining if life ever existed on Mars, understanding the processes and history of climate on Mars, and determining the evolution of the surface and interior of Mars. The goals are not given any priority relative to each other, however it is clear that the missions geared towards preparing for human exploration would have to occur before the manned mission is launched.[28]

4.8.1 Preparation for Human Exploration[28]

The preparation for human exploration will mainly consist of precursor robotic missions. These missions will gather more detailed information on the Martian environment, such as the exact radiation environment on the surface. They will also play a critical role in scouting potential landing sites and identifying sites of scientific interest nearby those landing sites. These missions could also determine the potential of the surface to support in-situ resource utilization projects.

Another aspect of the preparatory missions will be to demonstrate technologies that will be essential to a manned Martian mission. For the manned mission, it will be necessary to perform precision landings, in order to have all the surface assets near each other and accessible to the crew. The preparatory missions can demonstrate this capability. Furthermore, it is likely that a manned Martian landing will make use of aerocapture.[3] This technique has not been fully tested yet and will need to be perfected before it is tried with a manned lander.

[~] Information sub-team of the MIT/Draper CER team. Unpublished work. February, 2005.

Preparation for human exploration that does not involve Mars-specific assignments, such as the testing of the surface mobility equipment, will occur on the Moon, in accordance with the Mars-back approach.

Once humans have landed on Mars, there are still many scientific goals that can fit in the preparing for human exploration class of missions. For instance, the crew may need to locate and extract resources to be used to create fuel or life support materials. The first crew will also be performing tests, such as testing the full capability of the ATVs, which will enhance the exploration capacity of future missions. While resource location is a scientific activity, it enhances exploration as well.

4.8.2 Determining if Life Ever Existed on Mars[28]

The search for life on Mars will take on two forms – the search for current life and the search for evidence of past life. Both of these searches are equally important and can be conducted in parallel. On Earth, water is essential to most forms of life. Therefore, it is likely that if life exists or existed in the past on Mars it would be found near sources of water. Hence, it is essential to the search for current life to locate and investigate areas that are suspected of having liquid water. As the water on Mars is all thought to be below the surface, investigating these areas will require the use of drilling and sophisticated subsurface detection techniques.

The search for past life requires the location and investigation of areas of sedimentary deposits that are likely to contain fossils. The fossils may be difficult to locate, as life on Mars may have looked significantly different than that which evolved on Earth. Furthermore, the fossils may be of single-cell organisms similar to the type of life found in Precambrian fossils on Earth, and will therefore be hard to see. An additional part of the investigation for life consists of determining the levels of organic compounds and other elements that are thought to be precursors to life on Earth. If significant amounts of these compounds are found, it may indicate that life did not arise on Mars, as early life would have consumed these compounds. However, the record of these chemicals will give a greater understanding of the processes that led to the evolution of life on Earth.

4.8.3 Understanding the Process and History of Climate on Mars[28]

Similar to the search for life, the understanding of the Martian climate has current and past components. The most important of the current components is the determination of the water, carbon dioxide, and dust cycles. Long term habitation of Mars will require a full understanding of these processes so that resources can be used and dangerous dust storms, as described in section 3.6.1 predicted and avoided. Furthermore, it will be useful to identify the actual composition of the atmosphere for use in resource extraction. Finally, the location of micro-climates could be of great value to science. The micro-climates of greatest interest would include areas that were recently wet or warm, and areas where there has been significant change in the levels of volatiles and dust.

The understanding of the ancient Martian climate will help to determine if life ever existed. Evidence of a past, wet, climate would indicate a greater chance of life having existed on Mars. Also, an understanding of the history of the changes in the Martian climate will lead to an understanding of what sorts of climatic conditions to expect during the long-term human occupation of Mars.

4.8.4 Determining the Evolution of the Surface and Interior of Mars[28]

The evolution of the surface and interior of Mars is the province of the geologists. The main objectives to achieve this goal are the determination of the sequence of geologic events that have modified the Martian surface and interior and the characterization of the structure, composition, dynamics, and history of the Martian interior. Meeting the first objective involves understanding the present water cycle on Mars, due to the large influence that water can have in shaping the surface of a planet, as is easily visible on Earth. Understanding the water cycle can lead to an understanding of the sedimentary processes that have occurred on Mars. The locations of sedimentary sites may then be easier to identify, and as mentioned earlier, these sites are excellent locations to find potential traces of past life.

Another important aspect of the investigation of the Martian surface is to determine the evolution of the surface over the course of time. The method of establishing the time scale for Mars will be through the calibration of the cratering record. This calibration will occur by the analysis of surface rock samples from known crater ages and checking the crater date with radiometric dating of the sample. Once the time scale is established, the history of volcanic and seismic activity can be determined. Other investigations of the Martian surface can include the study of the surface and atmospheric interactions and the chemical and mineralogical composition of the crust.

The study of the Martian interior involves understanding the thermal and chemical evolution of Mars and the history of the Martian magnetic field. The thermal and chemical evolution is important because of its relationship to the evolution of the surface and the possible release of water and volatiles to the surface. The history of the Martian magnetic field is important because the magnetic field would have provided shielding against the radiation environment, similar to the way that Earth's magnetic field provides shielding. This shielding would have made it easier for life to evolve since the radiation environment would not have been as harsh.

5 A Mars-Back Lunar Campaign

5.1 *Lunar Campaign Rationale*

The lunar campaign will be significantly different than the first Martian mission. All the needed technology and equipment will most likely not be ready in time to launch with the first lunar mission, due to budgetary constraints. Instead, there will be a phased development of the components that will be used on both the Moon and on Mars. However, to avoid having completed equipment sitting around and not being used and to keep a high level of interest in space exploration, it is necessary to launch lunar missions with the resources that are available.

The lunar campaign will be structured as a progressive campaign, gradually establishing the full capability on the Moon that will be needed to explore Mars. Each mission will take advantage of the more recently developed technologies. Assets will be accreted on the Moon as they are developed on Earth such that the amount of new equipment that needs to be launched with each mission is minimized.

Finally, the Moon provides a location to test the equipment and procedures that will be used on Mars in an operational environment. The Mars baseline surface architecture outlined in chapter 4 is fairly ambitious and needs to be evaluated before spending the time and money to send it all the way to Mars.

5.2 *Mars Exploration Readiness Level (MERL)*

In order to determine the effectiveness of a lunar campaign in preparing for a Martian expedition, an evaluation system needed to be created. This system is the Mars Exploration Readiness Level (MERL). The MERL works by establishing a list of necessary objectives for Martian exploration and then evaluating their completion level as the lunar campaign progresses. These objectives consist of the tasks that will be necessary on the Martian surface, demonstrations of the equipment and procedures that will be used on the Martian surface, and the precursor steps that are needed. The objectives used in calculating the MERL for the lunar campaign are presented in section 5.5.1.

After the objectives are specified, the next step is to evaluate the completion level that each objective is currently at. These completion levels were developed to be analogous to NASA's technology readiness levels, except on a five-point scale. The levels are listed in Table 5-1. While work on many of these objectives has not been done, almost all of them can proceed to a certain level on Earth. The contribution of development and testing on Earth will produce a certain completion level for each objective before any lunar mission is launched. Then, each lunar mission will have specific objectives to accomplish, raising the completion level of several Mars necessary objectives at the same time, and increasing the MERL. The overall mission MERL and campaign MERL can then be calculated, and the progression towards being ready for Mars can be charted.

Table 5-1 MERL completion levels[+]

MERL Completion Level	TRL Equivalent	Definition	Characteristics
1	2	Proof of ability to carry out critical functions	Uses technology components or element of processes that are not representative of what will be carried out on Mars, but does carry out the critical functions we want to perform on Mars
2	4	Mars subsystem validation	Validates basic technology components and/or process elements that are representative of the technology components and/or process elements to be used on Mars
3	5	Validation of Mars subsystems integrated with supporting elements	Validates that representative technology components and/or process elements integrate successfully with representative supporting elements
4	7	Mars prototype demonstration in operational environment	Demonstrate the integration of technology components and/or process elements to form a functional prototype relevant to Mars
5	8	Mars-qualified systems	Systems made of integrated technology/processes has been proven to work in its final form and under expected conditions for Mars

5.2.1 Calculating MERL

The MERL is calculated as a percentage. It sums up all the level of each of the Mars necessary objectives and divides by the total possible. A 100% level will only be achieved when all the objectives have reached an individual level of 5. The objectives are evenly weighted with each other, since all are deemed necessary for Martian exploration. The MERL does not indicate the cost or difficulty of completing an objective, just the level of completion. It should be noted, however, that an individual lunar mission need not raise the level of all of the Mars objectives to a 5. Instead, progressive lunar missions will each raise the MERLs of different Mars objectives. At the end of the lunar campaign, all the levels should be fully raised.

5.3 *Necessary Lunar Tasks*

Examining the baseline Martian architecture described in the previous chapter yields a set of tasks that will be necessary to perform on the lunar surface in order to prepare for Martian exploration. First, a landing site on the Moon must be chosen that resembles as closely as possible the potential Martian landing sites,

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[+] Arnold, Julie. Unpublished work. December, 2004.

which are situated on the Martian equator. Next, the equipment that will be used in common on Mars and the Moon must be tested. This equipment includes the habitat, the mobility systems, and the EVA suits. Finally, a Mars analog environment should be created on the Moon such that a Martian mission simulation may be carried out in as authentic an environment as possible.

5.3.1 Lunar Landing Site[$]

A south polar lunar landing site has been selected as the site for the establishment of the lunar base. While a near-side equatorial landing site, similar to the Apollo landing sites, might prove to be easier to implement with a constant communication capability with Earth, the Mars-back approach strongly favors a polar site.

As was shown in Figure 3-3, the thermal conditions during summer at the lunar pole closely resemble the low end of the daily Martian equatorial temperatures. Also similarly to the Martian equator, the temperature at the lunar pole remains constant throughout the summer. The lunar equator, on the other hand, sees wildly fluctuating daily temperatures that exceed the Martian equatorial conditions on both the high and low ends. The lunar equator provides a harsher thermal environment than both the pole and the Martian equator. However, a base situated at the lunar south pole will need to be insulated such that it can survive the winter, where the conditions are harsher than those found on Mars.

The most important resource that could be used on either the Moon or Mars is water. While on Mars the water is thought to be spread throughout the planet in different forms, on the Moon, if there is water, it is concentrated at the poles. It is at the poles that the craters of perpetual darkness, which are the most likely locations for lunar water ice, are found.

The evidence for the water at the poles comes from the hydrogen signatures that have been recorded there. Investigating the areas where the hydrogen is most concentrated will require careful traverse planning and surface navigation. The difficulties in planning these missions will be similar to the difficulties that will be encountered while planning scientific expeditions on the Martian surface.

Furthermore, although lunar science is low priority for these missions, the South-Pole Aitken basin represents one of the highest priority sites of scientific interest on the Moon. Therefore, it makes sense to land near it. Also, the majority of scientific investigations that could be performed at the equator can also be performed at the pole.

[$] Garrick-Bethell, Ian. Email communication. January 20, 2005.

5.3.2 Lunar Equipment Performance

5.3.2.1 Lunar Mobility Equipment

The ATVs will handle differently on the lunar surface than on the Martian surface. The lunar regolith has different parameters than the Martian surface and the lunar gravity is only half of the gravity on Mars. The performance of the ATVs can be analyzed by using the Mars design and the lunar surface parameters. The different surface parameters are summarized in Table 5-2.

Table 5-2 Lunar and Martian soil parameters

Parameter	Martian Value[29]	Lunar Value[8]
Gravity, g (m/s^2)	3.27	1.63
Cohesive modulus of soil deformation, kc, N/cm^2	1	0.14
Frictional modulus of soil deformation, kphi, N/cm^3	0.85	0.82
Coefficient of soil slip, K, cm	3	1.8
Coefficient of soil/wheel cohesion, cb, N/cm^2	0.1	0.017
Exponent of soil deformation, n	1	1

The main difference in the performance will come about due to the differences in the frictional forces. The frictional forces on the ATV can be calculated using the following equations, as described by Wong in *Theory of Ground Vehicles*.[30] For Mars, the wheel sinkage, z, was estimated to be 1.4% of the wheel diameter. The sinkage on the Moon was then calculated to be 1.5 cm. The wheel slip was estimated to be 0.35. The wheel width, b, of the ATV wheel is 18 cm and the ATV wheel diameter is 157 cm. The camper wheels are 43 cm wide and have a diameter of 163 cm. The sprung mass is the mass of the ATV that is supported by the wheels and is estimated at 550 kg. The coefficient of rolling resistance is estimated at 0.03[31] and the bulldozing resistance is estimated at 140 N. For the camper, the bulldozing resistance is 350 N.[%]

$$F_{Friction} = \# wheels * Rc + \mu_{RollingResistance} * SprungMass * g + BulldozingResistance \tag{5-1}$$

$$Rc = \frac{b * \left(\frac{kc}{b} + kphi\right)}{n+1} * z^{n+1} \tag{5-2}$$

[%] Siddiqi, Afreen. Unpublished work. February, 2005.

$$z = \left(\frac{3 * RoverMass * g}{b * (3-n) * \left(\frac{kc}{b} + kphi \right) * \sqrt{WheelDiameter}} \right)^{2/(2n+1)} \tag{5-3}$$

After the forces are known, the maximum speed, towing capacity, towing speed, and slope capability of the ATV can be determined, using the following equations. The ATV is sized to have 6 kW of power available. The power capacity of the ATV is 49 kW-hr.

$$MaxSpeed = \frac{Power * (1 - slip)}{FrictionForce} \tag{5-4}$$

$$MaxRange = \frac{MaxSpeed * PowerCapacity}{Power} \tag{5-5}$$

The different performance parameters are presented in Table 5-3. The ATV performs better on the lunar surface. This performance increase is mostly due to the lower gravity. The ATV on the lunar surface will be overpowered and thus is capable of higher speeds. However, the speed will still most likely be limited due to the ability to see craters and other obstacles on the surface. Apollo 15 commander David Scott reported that while on the Lunar Roving Vehicle that "In general, 1-m craters were not detectable until the front wheels had approached to within 2 to 3 meters."[8] Therefore, slower speeds will need to be maintained. If the ATV was designed expressly for the lunar surface, it would have a smaller power plant and be less massive. However, the savings in development costs reached by only producing one rover make up for the mass penalty that is incurred. Figure 5-1 shows the increase in the towing capacity of the ATV on the Moon.

Table 5-3 ATV performance changes from Mars to the Moon (all values are approximate)

	Mars	Moon
Max Tow Speed (2000 kg camper) (km/hr)	10	15
Max ATV Speed (km/hr)	40	60
Max range (km)	315	475
Max Tow range (km)	85	115

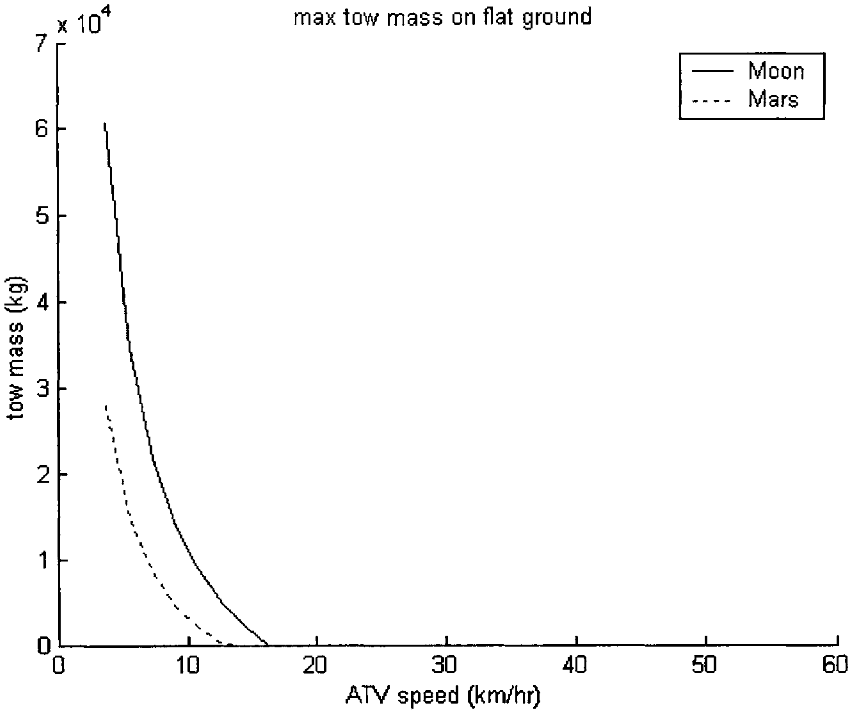

Figure 5-1 Maximum towing capability on flat ground of the ATV on the Moon and Mars

5.3.2.2 Lunar Surface Habitat

The lunar habitat will need to be used for stretches up to the full length of the lunar polar summer, 200 days, which is similar to the time frame that is required for the transfer to Mars. Therefore, the lunar habitat can be the same as the Martian habitat. The lunar habitat will be able to have fewer supplies and some of the subsystems will be able to be reduced in size, since it will not be used for as extended a period of time. The inflatable space will still be needed, since the habitat will not contain the necessary laboratory space. Inflatable structures can also be used to provide a thermal garage in the winter for the mobility equipment. With these considerations in mind, the lunar habitat will be the same size as the Martian habitat, although smaller amounts of consumables will be needed. The lunar habitat parameters are described in Table 5-4. The subsystems in the lunar habitat are shown in Table 5-5.

Table 5-4 Lunar habitat parameters

Mass (kg)	35000
Pressurized Volume (m^3)	300
Radius (m)	3.7
Length (m)	7
Power (kW)	8.9

Table 5-5 Lunar habitat subsystem mass and power

Subsystem	Mass (kg)	Power (W)
ECLSS	6000	3950
Structure	9000	--
Communication	500	1000
Thermal	2000	1000
Crew Accommodations	5500	2500
EVA/Airlock	2000	--
Radiation Protection*	5800	--
EPS	4500	--
Avionics	200	500

*Additional water mass needed to create the radiation shelter. If regolith is used to shield the habitat, this mass will not be needed

5.3.2.2.1 Lunar Habitat Radiation Protection

The radiation environment on the Moon is much harsher than the radiation environment on Mars, due to the fact that the Moon does not have an atmosphere. The radiation dose absorbed by astronauts on the lunar missions is shown in Table 5-6.

Table 5-6 GCR radiation dose received on lunar missions

	Length (days)	Dose Rate (cSv/day)	Total dose, transit and surface (cSv)
Transit	7 (round trip)	0.1589	
Surface Short Mission	10	0.0795	1.91
Surface Medium Mission	60	0.0795	5.88
Surface Long Mission	180	0.0795	15.42

As can be seen from Table 5-6, the GCR dose is well below the limits established by NASA. Therefore, it is the flares that are of the most concern for the lunar missions.

As mentioned above, the Martian habitat will have a radiation shelter composed of the water that the crew brings along on the trip. The lunar habitat will also be able to have this shelter, even though less drinking water will be needed on the lunar mission. The extra water that needs to be brought, approximately 5800 kg, can be brought as cargo on the mission with the habitat.

Bringing excess water to the Moon can be avoided, since lunar regolith can be piled onto the habitat to act as a shield. Using regolith deviates from the Mars-back approach, but may be necessary due to the harsher radiation environment of the Moon. Regolith is quite effective in reducing the radiation dose received by crew on the surface. The reduction in dose from GCR's as a function of regolith thickness is shown in Figure 5-2. It should be noted that the dose received from protons and neutrons actually increases with regolith thickness, even though the total dose decreases. Figure 5-3 shows the effect of the regolith in reducing the dose received from the three solar flares in 1989. To reduce the effects of solar flares to acceptable levels, Simonsen advocates using a regolith shield that is at least 50 cm thick.[7] Table 5-7 shows the radiation levels that would be present in the center of a cylindrical habitat with the regolith shield.

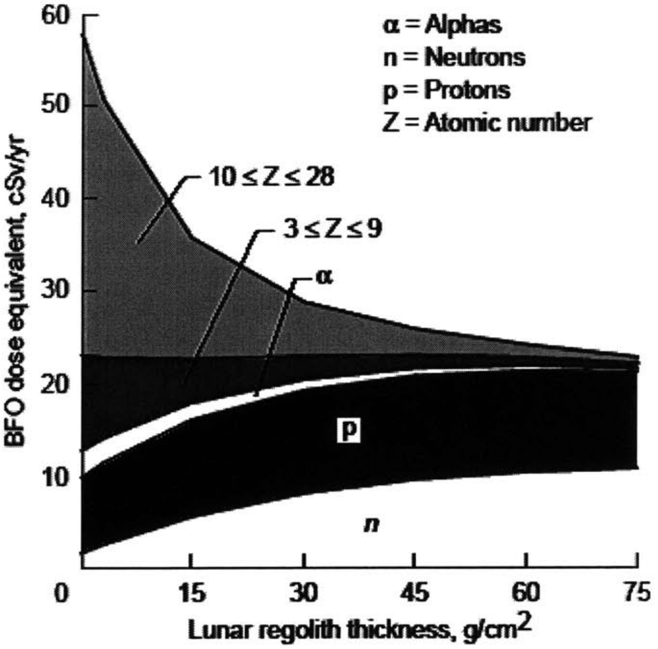

Figure 5-2 BFO annual dose-equivalent contributions from specified particle constituents as a function of lunar regolith thickness for GCR at solar minimum conditions[7]

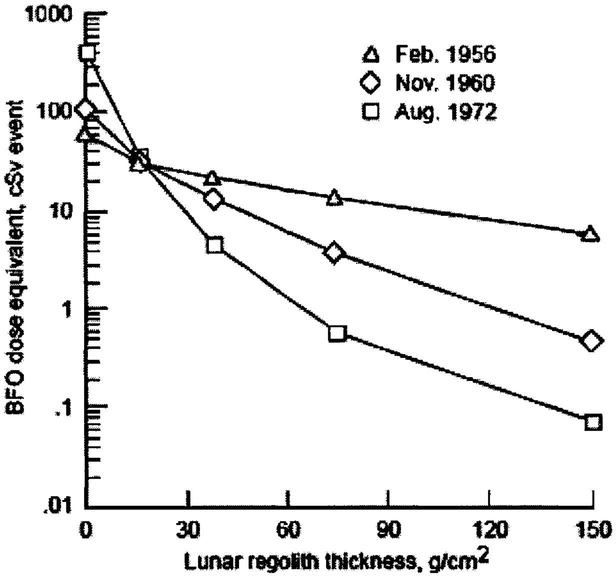

Figure 5-3 Estimated BFO dose equivalent as a function of lunar regolith thickness for three large solar proton events[7]

Table 5-7 Estimated radiation doses inside a cylindrical habitat[7]

Event	Estimated dose in cylinder
GCR	12 cSv/year
Feb. 1956 flare	7.5 cSv
Nov. 1960 flare	1.6 cSv
Aug. 1972 flare	0.3 cSv

Significant amounts of regolith will need to be moved to create this shield. Using the proposed habitat dimensions, approximately 185 metric tons of regolith will need to be moved, assuming a lunar regolith density of 1500 kg/m^3. This calculation assumes that the regolith could be packed perfectly around the habitat. However, it also includes shielding for the bottom of the habitat, which will not be needed.

5.3.2.2.1.1 Excavation Equipment and Time

In order to move this quantity of regolith, excavation equipment is going to be needed. The excavation equipment will consist of attachments to the ATVs, eliminating the need for the development of fully mobile lunar excavation equipment. A backhoe can be attached to one ATV and a trailer to the other. Excavating will occur at a site at least a few hundred meters away from the base to limit possibilities of affect the stability of the ground that the habitat is on.

As was shown in Figure 5-1, the ATV could tow a maximum of 6 mT on the lunar surface. Therefore, a conservative estimate for the tow mass that will be allowed for the ATV would be 3 mT. It would then take 63 trips with the ATV to transit all of the regolith to the habitat. At a 3 mT tow capacity, the ATV could travel at 10 km/hr on the lunar surface, so from a digging site that is 1 km away from the base, it would take 13 hours of driving time to transfer all the regolith.

The amount of time that it takes to excavate the necessary amount of regolith depends on the size of the excavation bucket that is used. The Caterpillar 163-6030 bucket has a mass of 1382 kg and a capacity of 0.76 m^3.[32] Using this bucket, it would take approximately 160 digs with the bucket to excavate the proper amount of regolith, based on the 125 m^3 of regolith that need to be moved. A conservative estimate is 10 minutes for each of the digs, leading to a total time of 28 hours to dig up all the regolith. This time can be tripled for placing it properly around the habitat, leading to a total time of 84 hours, or 11 one-person EVAs.

Simonsen, et al.[9] has estimated that the excavation equipment, consisting of the backhoe and the tow trailer would have a mass of approximately 3000 kg, which is approximately 2800 kg less than the amount of water that would be needed for the shelter, as was shown above.

5.3.2.2.1.2 Lunar Surface Radiation Protection Outside Habitat

While the habitat shield is being constructed, the crew is still in danger from solar flare events. For short-duration missions, the crew may have to take the risk of being exposed. Fortunately, the Moon is close enough where, if the crew is exposed, they can return to Earth relatively quickly for treatment. For longer missions, if the crew has the use of a camper, the camper can be maneuvered into the shadows on the Moon. The particles of a solar flare emanate radially out from the sun, carrying the magnetic field lines with them. It is unlikely that the particles will be able to gyrate around these field lines. Therefore, it is unlikely that the particles will be able to move around the topography on the Moon, and shadows caused by the topography should be a relatively safe place to be during a solar flare. It is estimated that approximately 1 kW of power will be needed to heat the camper to appropriate levels while in the shadows, which can be provided by a Radio-isotope Thermal Generator (RTG).[§]

5.3.2.2.2 Lunar Habitat Thermal Protection

It has already been mentioned that the temperatures at the lunar pole are colder than the Martian equator, especially during lunar night, where the temperatures can drop as low as 50 K. From a cost perspective, it is highly desirable to have the habitat, rovers, and other surface equipment capable of surviving the lunar night and then be capable of use on future missions. To accomplish this, the habitat will need to be thermally protected during the night.

There are two options for thermally shielding the habitat. Multi-layered insulation (MLI) can be used. Or, if regolith is used for radiation shielding, it will also provide thermal protection. Neither of these methods follow the Mars-back

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[§] Byrne, Shane. Unpublished work. February, 2005.

approach, since the MLI cannot be used on Mars and regolith shielding will not be necessary for radiation purposes. However, the deviation from the Mars-back approach is necessary to survive the significantly colder lunar night. While the crew is in the habitat, it is desirable to maintain the temperature at a comfortable level for the crew, around 20 C (293 K). The MLI works by acting as a radiator with a very low emissivity. The emissivity of the Apollo lunar module was 0.01.[33] Even with the MLI, a heating source will be needed. The steady-state temperature of the habitat can be calculated based on the amount of heat supplied according to the following equation:

$$HabitatTemp = \left(\frac{HeatingPower}{\varepsilon\sigma * SurfaceArea} + OutsideTemp^4 \right)^{1/4} \tag{5-6}$$

where σ is the Stefan-Boltzman constant and ε is the emissivity of the MLI.

The regolith shield, on the other hand, is not purely a radiator. Heat is conducted away from the habitat by the regolith and then is radiated from the surface of the regolith. Using a regolith thickness of 50 cm, as was recommended for the radiation shield, the habitat temperature can be calculated based on the power supply according to the following equations:

$$regolithTemp = \left(\frac{HeatingPower}{\varepsilon\sigma * SurfaceArea} + OutsideTemp^4 \right)^{1/4} \tag{5-7}$$

$$HabTemp = regolithTemp + \frac{HeatingPower * regolithThickness}{k * SurfaceArea} \tag{5-8}$$

where k is the thermal conductivity of the regolith, which is assumed to be 0.025 W/mK and the thickness of the regolith is 50 cm.

The resulting temperatures as a function of the heating power are shown in Figure 5-4. The figure shows that approximately 1.25-2 kW of heating power would be needed to maintain the habitat surface temperature, depending on the time of day and the type of insulation used. This power can be supplied by an RTG like the ones that were used on the Cassini mission. These RTGs generated about 300 W of electric power, but also produce several kW of heat.[\$] The heating power requirement will be lower during the lunar day, since the outside temperature is 150 K. Both the day and night results are shown in Figure 5-4.

[\$] Garrick-Bethell, Ian. Email communication. April 7, 2005.

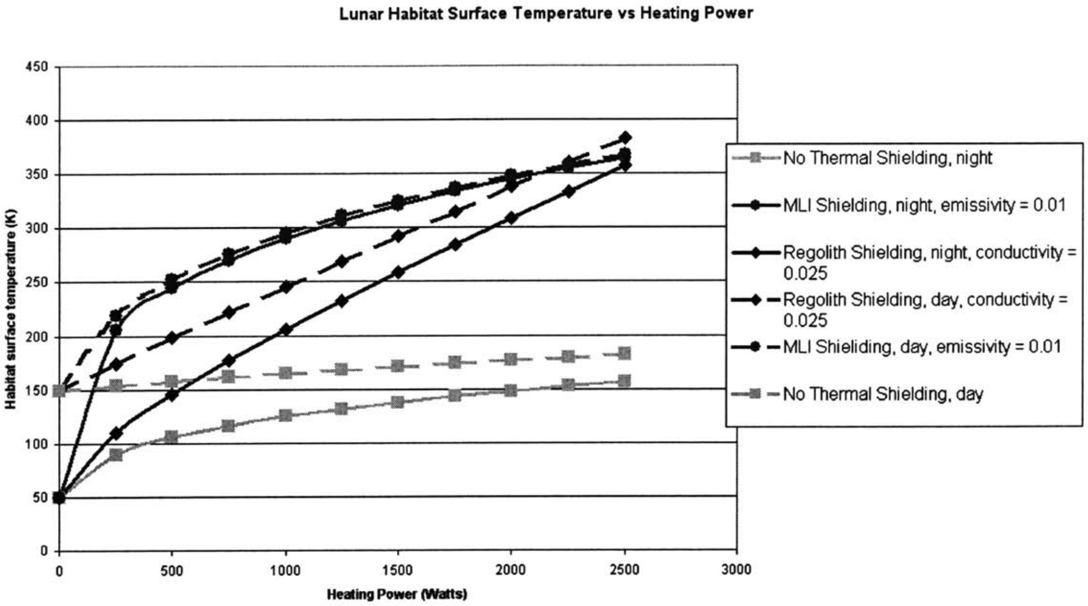

Figure 5-4 Lunar habitat surface temperature, with regolith and MLI insulation. Dashed lines represent daytime thermal conditions, and solid lines represent nighttime conditions.

In either thermal shielding case, it will be necessary to provide thermal shielding for the mobility equipment during the lunar night. There are many ways to accomplish the shielding. In the case of MLI shielding for the habitat, an inflatable garage could be constructed or a thermal blanket could be draped over the equipment. If regolith shielding is used, it should be possible to construct an area under the habitat where the ATVs, campers, and excavation equipment can be stored throughout the lunar night to insure that they will also be able to be reused.

5.3.2.3 Lunar Extra-vehicular Activity Suits

The lunar EVA suits face many similar issues to the Martian EVA suits. Dust abrasion, the ability to walk easily, and the control display are all concerns on the Moon as well as on Mars. The Moon does have several benefits over Mars, however. The reduced gravity will allow the suit to be slightly more massive without a penalty to the astronaut. Furthermore, since the lunar landing will take place on the pole, the temperature will be fairly constant at 150 K throughout the mission life. A sublimator could be used for heat control, as was done during the Apollo missions. However, following the Mars-back approach, sublimators would not be present in the EVA suits, as stated in section 4.4.1.2. Furthermore, on the Moon, water may prove to be even more precious than on Mars, due to the fact that existence of water ice on the Moon has not yet been proven. Hence, sublimators are even less practical on the Moon than they would be on Mars for long term use. A radiator, however, would work the majority of the time, since the outside temperature is so cold. However, similar to Mars, the radiator would be too large to be practical in an EVA suit. The end result for the lunar extra-vehicular mobility units is that the Martian EVA suits should function in much the same way on the Moon. Significant technology development is needs for a suit that will work on both the Moon and Mars.[◆]

5.3.2.4 Lunar Surface Power

Similarly to Mars, there are two options for power supply on the lunar surface – nuclear and solar. The nuclear plant is likely to be of similar design to the one designed for Mars and therefore can be assumed to have the same mass and power output. A solar plant will require a different arrangement on the surface than would be present on Mars.

5.3.2.4.1 Lunar Solar Power

The array for the Moon can be sized using the same method that was used to size the Martian array. The main difference is that the solar constant on the Moon is 1368 W/m^2, approximately 6 times the worst-case scenario on Mars. Therefore, a much smaller array can be used to provide the same power. Furthermore, there are no dust storms on the Moon, and it is less likely that dust will coat the lunar array, as there is no wind to stir up the dust in the first place, although possible electrostatic dust suspension needs to be further studied.

However, there are difficulties in using solar power on the Moon, especially with the polar landing site. The first difficulty is the fact that there will be no sun during the winter. Therefore, the array will need to be designed to survive the winter. Secondly, as opposed to the Martian equator, where the sun follows essentially the same path in the sky each day, on the lunar pole, the sun tracks along the entire horizon over the course of a lunar day. Therefore, the sun will move around the array and not always shine on the same side of the panels. A tracking array could be instituted, where the panels would follow the sun as it moves around the horizon. However, the mass of such a system makes it an undesirable solution. Instead, the best way to keep the sun on the panels would be to deploy additional panels, setting up a triangle such that the sun is always shining on enough panels to generate the required panel.[¯] This design is illustrated in Figure 5-5. Figure 5-5 a shows the arrangement of the panels when the sun is directly on one of the legs of the triangle. As the sun moves across the horizon, it's rays will fall on different parts of the panels. However, as can be seen in Figure 5-5 b and c, the panel area that is in contact with the sun's rays will remain the same. It should be noted that some power loss will be seen due to the angle at which the rays strike the panels. Finally, the topography at the lunar pole is much more diverse than on the Martian equator and the low level of the sun will create long shadows. Therefore, the array needs to be placed in an open area that will not be covered by shadows, and will need to be far enough away from the base such that the habitat itself will not shadow the array.

[◆] Hoffman, Jeffrey. Personal communication. March, 2005.

[¯] Catanzaro, Sandro. Personal communication. February, 2005.

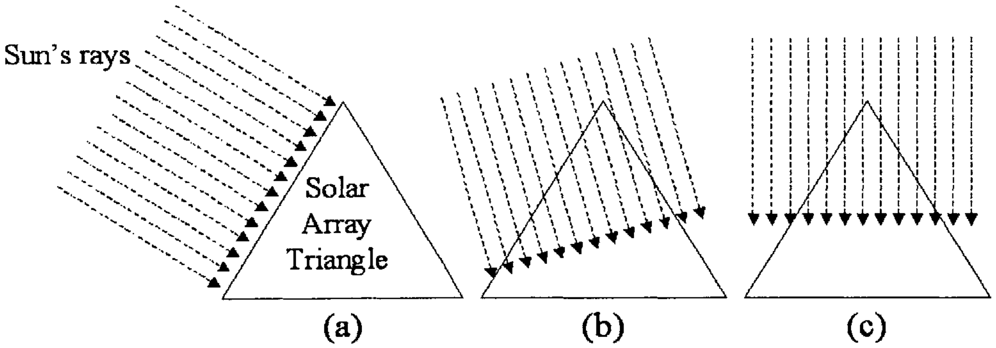

Figure 5-5 Necessary arrangement of lunar solar array at the pole. (a), (b), and (c) show how the array generates power regardless of the angle of the sun on the horizon.

Needing to set up the lunar array in this form requires three times the array area that would normally be required on the lunar surface. However, unlike Martian missions which last for multiple day-night cycles, the lunar missions will only last for portions of a lunar polar day, thereby reducing the need for overnight power storage and allowing for a smaller array area. The required size and mass of the lunar solar array are shown in Figure 5-6. Similar to Mars, the InP array has the lowest mass and will be the cell that is chosen for the array. The effects of the increased solar constant are to lower the necessary area for the array, thereby reducing the required mass. The calculations used to determine the array size were the same as for Mars, except that dust losses are not taken into account due to the lack of wind-blown dust on the Moon. For the three power conditions cited in section 4.5.5, recharging the ATVs, powering the habitat, and running an ISRU plant, the solar array turns out to be 1/3 as massive on the Moon as it would need to be on Mars.

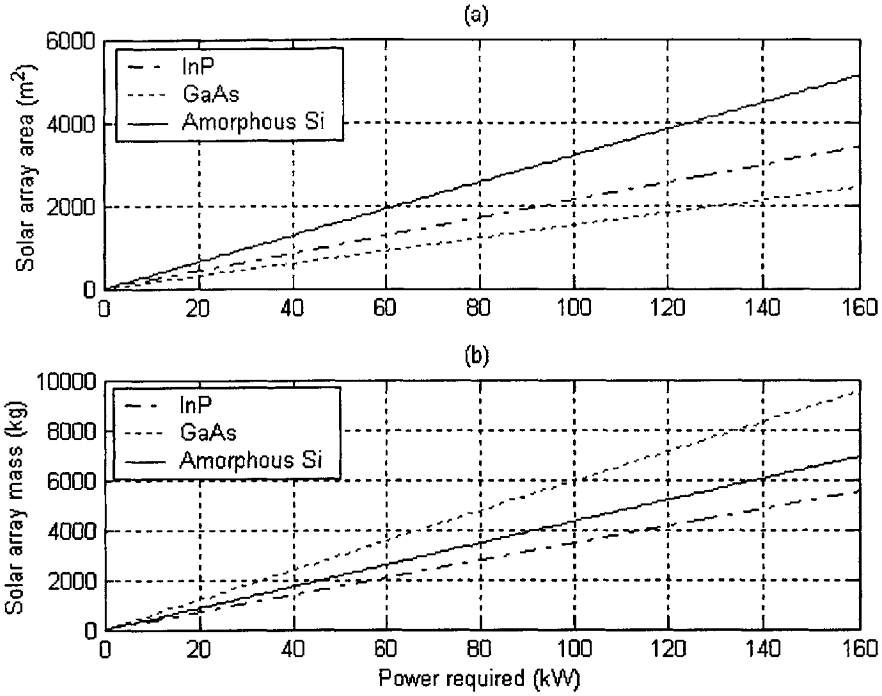

Figure 5-6 Lunar solar power array size (a) and mass (b).

5.3.2.5 Lunar Navigation and Communications System

The lunar navigation and communication system will face similar requirements to the Martian system. The lunar architecture will require the communications satellite to be in a Molniya orbit around the lunar South Pole. Since the Molniya orbit does not allow the satellite to continuously be over the South Pole, the communications gap time will be larger, reaching times of up to 6 hours. Adding additional satellites in Molniya orbits can lessen the communications gap. All the other requirements are satisfied.[~]

5.4 Lunar Science

It has already been stated that science is not going to be a top priority on the lunar missions. However, there will be time, especially during the Martian simulation phase, to perform science activities. Much like the exploration activities already described, the lunar science activities that will be performed will be those that best prepare for performing science on the Martian surface.

The Moon-Mars Science Linkage Steering Group (MMSSG) produced a report of the scientific activities that could be performed on the Moon and would directly benefit the Martian science objectives laid out by the MEPAG and discussed in section 4.8. The MMSSG report identified 10 science investigations and 10 demonstrations of technologies relevant to scientific activities and identified

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[~] Information sub-team of the MIT/Draper CER team. Unpublished work. February, 2005.

linkages between lunar and Martian science. These 20 science themes can be found in Table 5-8. The report also sorted the themes into three categories. Category A consists of the science themes, Category B of the resource themes, and Category C of the technology themes. The themes could then be prioritized within each category.[34]

5.4.1 Prioritization of Lunar Science Themes

Following the Mars-back approach, the science themes on the Moon should be prioritized based on their importance to Martian science themes. The MMSSG report performed this ranking and the results are summarized in Table 5-8. The rankings for Category A were based on the capability of the theme to advance the understanding of Mars if it was first performed on the Moon, the alignment with the MEPAG report on the Mars exploration priorities, the capability of the theme to answer major scientific questions, and the necessity of performing the lunar activity to future Mars missions. The rankings for Category B and C were based on the capability of the activity to add to the ability to be ready to explore Mars, the importance that the activity be performed by a lunar robotic explorer prior to the first human lunar landing, the affordability of the activity, and the level of technology required to carry out the activity.

Table 5-8 MMSSG ranking of the lunar science and technology themes[34]

Rank	Overall Science Priority (Category A)	Overall Lunar Technology Priority (Categories B and C)
High Priority	Impactor Flux vs Time	
	Exogenous Volatiles	
High-Medium Priority	Thermal and Magmatic Evolution	In-situ sample selection and analysis
	Interpreting Geologic Environments	Sample return
		Drilling technologies
Medium Priority	Endogenous Volatiles	Seismic technologies/studies
	Interior Planetary Structure	Water as a resource
	Early Planetary Differentation	In-situ fuel resources
	Regolith History	Assess bio-organic contamination
Low Priority	Planetary Asymmetry	ISRU technology demonstrations
	Energetic Particle History	Communication and ranging systems
		Exploration and processing of planetary materials

5.4.2 Relationship of Lunar Science Themes to Martian Science Goals

Of the four Martian science goals identified in the MEPAG report and cited in section 4.8, only the goal of studying the surface and interior of Mars has a close link on the Moon. The Moon will serve as the main area of preparing for the human exploration of Mars. The Moon is not thought to have ever harbored life, therefore there will not be a need to search for life. The Moon is also not thought to have had a significant atmosphere, so there are not many investigations into the Martian climate that can be performed. Hence, the main connection is in the geological investigations. However, techniques used in the performing of lunar science may still be useful in performing the other areas of Martian science investigations. There are still many linkages between Moon and Mars science that were identified by the MMSSG and that relate to the science themes identified above. These linkages are presented in the sections below.

The accomplishment of the lunar science themes and objectives will be done using the same set of equipment as will be used on Mars, enabling the testing of that equipment.

5.4.2.1 Early Planetary Evolution and Planetary Structure[34]

Unlike Mars and Earth, the Moon still preserves a significant amount of the geologic record of its early evolution, including such features as a magma ocean that have been proposed to have once existed on Earth and on Mars. Mars, like the Moon, is asymmetrical, and isotopic studies of basalts in both locations suggest a similarity in the early development of both bodies. While the size of Mars most likely affected its development compared with the Moon, the Moon provides a model for what the Martian development process may have been like. This science linkage includes the Moon-Mars themes of composition and structure of planetary interiors, early planetary differentiation, planetary thermal and magmatic evolution, and planetary asymmetry.

5.4.2.2 Evolution of the Planetary Surface[34]

The bombardment history, which would have had a significant on the planetary development, of the Moon and Mars may be quite similar. This history, if the Martian cratering record can be calibrated to match the Moon's record, could prove an invaluable tool in dating the surface processes on Mars. This science linkage includes the Moon-Mars themes of impactor flux versus time, interpreting geologic environments, and structure and composition of planetary regoliths.

5.4.2.3 Record of Volatile Evolution and Behavior[34]

The Moon and Mars actually differ significantly in the history of their volatiles, due mostly to the lack of a lunar atmosphere. However, there exist certain cases where the history of lunar volatiles will be useful in understanding their history on Mars. The study of energetic particles has been well documented for the Moon. These particles have had a strong influence in the shaping of the atmosphere on Mars. Another case that will be useful is the study of the nature of volatile reservoirs in early planetary mantles that can be used to understand some of the subsurface volatile collections on Mars. This science linkage includes the Moon-Mars themes of energetic particle history, origin and history of endogenic volatiles, and the origin and history of exogenous volatiles.

5.4.2.4 Human Resource Issues[34]

The Moon, with its low-gravity environment, will provide a valuable testing ground to understand the effects of long-term low-g exposure on humans before sending a crew to Mars. Currently, the only long-term studies have been in zero-g on the International Space Station. The Moon will provide a valuable middle point between zero and 1-g studies. The Moon also contains resources that can be useful to crews on the surface. The most useful of these will be water, which can be used for drinking or converted into fuel. Extracting water from the lunar poles may be a similar process used to extract subsurface water on Mars. This science linkage includes the Moon-Mars themes of water as a resource, in-situ fuel sources, and exploration and processing of planetary materials.

5.4.2.5 Science-Based Technological Demonstrations on the Moon[34]

As mentioned earlier, the science techniques used on the Moon will be similar to those used on Mars. Techniques that may be of critical importance include drilling, resource extraction, and communication systems. Testing these techniques on the lunar surface will help to reduce the risks that would occur with first deploying them on Mars. The Moon-Mars themes in this linkage include communication and ranging systems, in-situ resource utilization technology demonstrations, drilling technologies, seismic net technologies, assess bio-organic contamination, sample selection and characterization technologies and strategies, and sample return technologies.

5.5 Lunar Campaign

As mentioned before, the lunar campaign will start before all of the equipment that will be used on Mars and the Moon is completed. The progression of missions needs to be designed such that the maximum use is made of the equipment that is ready at the time of each mission. Furthermore, the missions should be designed to deliver maximum value. One of the indicators of value will be the high visibility events that occur on each mission. Finally, the main objective of the lunar missions will be to prepare for Martian exploration, which can be measured in terms of the MERL for each mission. This progression will be another large indicator of the value of the campaign. It is assumed that the ATVs, campers, and habitat will not be able to survive the lunar night unless they are properly thermally shielded.

This campaign was designed to give a minimum number of lunar missions phases that would be required for the exploration system to be ready to go to Mars. The individual mission phases are flexible and can be changed based on the equipment that is available at the desired launch time for the mission.

5.5.1 Earth Development

It is estimated that development and testing on Earth will raise the MERL to 50%. Many of the Martian systems can be raised to a level of 3 before they are even launched. The completion level for each of the objectives contained in the MERL is shown in Figure 5-7.

		Transport					Power				Mobility					Mars Analog Environment Creation										Scientific Activities									auto	
		Precision martian unmanned landing	precision lunar unmanned landing	precision lunar manned landing	aerocapture demonstration	Ascend from surface	new solar cell development	nuke plant development	power system deployment	ISRU development	EVA suit functional test	ATV functional test	crater traversal capability	camper thermal survival	Camper functional test	Habitat functional test	habitat thermal survival	excavation possible	excavation equipment	radiation mitigation procedures	full martian mobility	similar communication system deployed	working beacons	Dust mitigation strategies tested	Forward contamination procedures tested	reconnoiter	observe	measure	lab analysis	sample retrieval	drilling	coring	station placement	robotic tele-operation	autonmous scouting	autonomous science
Mission:	Location																																			
Development	Earth	0	0	0	5	3	3	3	0	3	3	3	3	3	3	3	3	3	3	5	0	0	4	3	3	3	3	3	3	3	3	3	3	5	0	0
1 Lunar Return	Moon	0	0	5	0	5	0	0	0	0	5	5	0	5	4	0	0	0	0	0	0	0	0	4	0	5	5	0	0	5	0	0	0	0	0	0
2 Robotic	Moon	0	5	0	0	0	5	5	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5	5
3a Hab Deployment	Moon	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
3b Mars Analog	Moon	0	0	5	0	5	0	0	0	0	0	5	0	5	5	5	4	5	5	5	0	3	5	4	4	5	5	4	4	5	0	4	4	4	0	0
4a Cargo Delivery	Moon	0	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
4b Mars Sim	Moon	0	0	5	0	5	0	0	0	0	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	5	0

Figure 5-7 Completion levels for MERL objectives during the lunar campaign

5.5.2 First Lunar Mission Phase– Short Lunar Return

The first mission to the moon will be a short stay return mission. The habitat module will not be developed by the time that this mission launches. Therefore, the crew will be dependent on the CEV for their surface habitation. The design of the CEV places limits on the duration that it can be used for habitation. For a crew of three people, the CEV can be used on the surface for 10 days. Therefore, the first mission is sized to be a 10-day mission. Three crewmembers were chosen because three people allows for greater flexibility on the surface. A three-member crew can perform more EVAs than a two-member crew. During EVA activity, one crewmember will be able to remain in the CEV. While this requirement will most likely not be in place on Mars, it will be helpful to have supervisory capability on the surface for the first return mission.

This first mission in the proposed campaign will land at the South Pole and utilize ATVs to explore the terrain around the landing site. If the ATV development has not been completed prior to this mission, the astronauts can walk on the surface, adding to the flexibility of the system. The goal of the exploration will be to scout the area for potential landing sites for the equipment, such as the habitat and power plant, which will arrive on future missions. The crew will also scout for sites of scientific interest and for a location to place the solar array. This mission has a higher risk due to radiation than future missions will. On future missions, there will be a radiation shelter on the surface of the Moon. On this mission however, since the habitat will not have arrived yet, there will not be a set radiation shelter. However, since this mission is short, the chance of a significant solar flare is small.

The mission will demonstrate the ability to perform precision landing on the lunar surface and to ascend from the surface. It will also test the ATVs, if available, and the EVA suits. The high visibility events for the mission include the landing, the use of the ATVs and EVA suits, and the ascent from the surface. The first mission will raise the MERL to 62%. The mission is summarized in Table 5-9.

Table 5-9 Lunar campaign summary table

Mission	1	2	3a	3b	4a	4b
Objective	Short stay lunar return	Robotic exploration communications and power	Habitat deployment	Mars analog environment creation	Cargo delivery	Mars mission simulation
Crew	3 Human	Robotic	Robotic	3 Human	Robotic	5 Human
Surface stay time	10	600	--	60	--	180
Mission tasks	Demonstrate return, scout habitat landing sites	Site scouting, solar (or nuclear) power activation	Habitat landing	Habitat and mobility equipment shielding, preparation for Mars simulation	Supply delivery for Mars simulation mission	Accurately simulate Mars mission
Additional working surface assets at end of mission	None	Communications satellite, solar power array (or nuclear power plant)	Habitat, excavation equipment (if needed)	2 ATVs, camper	3 ATVs, camper	Full Martian capability
Required hardware development	ATV, Camper, EVA suit	Communications satellite, solar power array (or nuclear power plant)	Habitat, excavation equipment	--	--	--
MERL	62%	--	--	76%	86%	97%

5.5.3 Second Lunar Mission Phase– Robotic Exploration

The second lunar mission will be a robotic mission, sending robotic rovers to the poles. The robotic mission allows more time for the development of the large amount of hardware required for the second human mission, including the habitat and the excavation equipment. The mission will also serve to keep up interest in the Moon while this equipment is being finalized. The robotic mission will also serve to make the next human mission more productive, by identifying sites of interest ahead of time. Robotic precursors will also be sent to Mars, so this mission helps to set up a Mars-like environment for lunar exploration.

The robots will further explore the area for sites of scientific interest and will perform science experiments. The robots will also be able to precisely determine the thermal and radiation environment that will exist at the pole over time. The power plant, whether it is solar or nuclear, will also be sent on this mission. There are two reasons for sending the power plant at this point. First, mass considerations would make the third mission too heavy if the power plant was included on that mission along with the crew. Second, the power plant can be tested on the Moon before it is to be used, so that the habitat can be guaranteed to have power when it lands. The power plant will be designed to survive the lunar night. The lunar communications satellite will also be deployed on this mission. This mission will raise the MERL to 76% and is summarized in Table 5-9.

5.5.4 Third Lunar Mission Phase- Mars Analog Environment Creation

The third lunar mission will be split into two parts. The first part, mission 3a, will be an unmanned mission that lands the habitat and excavation equipment, if needed, at the south pole. The second part, mission 3b, will bring the crew along with two ATVs and a camper. The split has two reasons. First, mass restrictions require the two separate missions. Second, the habitat can be landed first and checked out to make sure that it works before the crew arrives.

The purpose of this mission is to prepare the assets on the lunar surface for the Mars Mission Simulation mission. Due to launch constraints, the habitat as well as one camper and two ATVs will need to be sent to the lunar surface separately from the remaining camper and ATVs that will be used on the final mission. These assets will not be able to survive the lunar night unprotected. The way in which the vehicles and the habitat are thermally protected depends on the strategy that will be used. If the habitat will be shielded with MLI, the crew on the surface will need to shield the ATVs and camper, most likely through the use of a thermal blanket attached to the habitat. If the habitat is to be shielded with regolith, this mission will perform the excavation necessary to shield the habitat. A garage could also be constructed out of regolith to shield the ATVs and the camper. The crew on this mission will also test out the habitat, powering it up for the first time on the lunar surface and making sure that it works. Hopefully, the majority of the problems can be worked out on this mission before the longer stay of mission 4. Given time, the crew can scout sites of potential interest for the next mission. The crew will also use the camper for the first time. Radiation protection on this mission will be in the form of the shelter in the habitat.

Three crewmembers were chosen for this mission due to the CEV constraints. The habitat will have landed by the time that the crew lands on the surface. However, problems may be encountered in activating and moving into the habitat. If these problems are encountered, three crewmembers will have the longest time, in days, to live out of the CEV and try and fix the problem. Therefore, a three-crewmember mission is the most robust to problems with the habitat. The crew will live in the habitat while it is being shielded. This mission provides an excellent opportunity to test out dust contamination procedures.

This mission will test the excavation equipment, if necessary, and use it to pile regolith on the habitat. The habitat will be tested and the power system will be connected to the habitat. The camper will be tested out. At the end of the mission, there will be a working habitat, power system, excavation equipment, 2 ATVs, and a camper on the surface that can be used on the next mission. The high visibility events for this mission include the landing, the start-up of the habitat, the usage of the camper, and the excavation process. This mission will raise the MERL to 86% and is summarized in Table 5-9.

5.5.5 Fourth Lunar Mission Phase– Mars Mission Simulation

The fourth lunar mission is the last Mars preparatory mission in the lunar campaign. It will consist of both manned and unmanned missions. The unmanned mission, mission 4a, will deliver cargo to the surface. The cargo will consist of supplies for a 180-day stay in the habitat for a crew of 5 and 3 ATVs and one camper. Once these vehicles reach the surface, the mobility will be the same as the mobility on the Martian surface, namely 5 ATVs and 2 campers.

The manned mission is planned to be a 5-crew, 180-day mission. The 180 day mission length was chosen to take full advantage of the lunar summer. It is not desirable or necessary to run a full 600 day lunar mission to be prepared for a mission of 600 days on Mars. 180 days should suffice. The crew of 5 was chosen to mimic the Martian crew size.

The goal of this mission is to simulate, as accurately as possible, the Martian mission. The campers will be used for long distance traverses and multi-day stays away from the base. Scientific experiments will be performed. The lunar science and how it relates to the Martian science was discussed in detail in section 5.4. The crew will have more direct control over its actions than on previous missions, to simulate the conditions on Mars, where the time lag in communications will require more decision-making on the part of the crew as opposed to mission control. This mission will help to gain the necessary procedural experience to run a Martian mission. After completion of this mission, the MERL will be at 97% and the mission is summarized in Table 5-9.

The MERL is not at 100% after the end of the lunar campaign. The reason for the gap is that certain Mars necessary objectives, such as precision landing on the Martian surface, can only be accomplished on test missions to Mars itself, and these missions are not accounted for in the lunar campaign. Since all the objectives are weighted equally, and without regard to cost or difficulty, the objectives that need to occur on Mars only contribute a small amount to the MERL, since there are substantially fewer of them. However, these objectives are just as important as the objectives that will occur on the Moon and should not be ignored in the preparation for Martian exploration.

6 Future Work

This thesis presented a Mars-back approach to lunar surface operations, culminating in the design of a lunar campaign to achieve Mars readiness. There is still significant room to improve on the data presented here. The effects of both the lunar and Martian environment on surface equipment and the crew needs to be better understood. Robotic missions to Mars are currently planned to study the surface environment. The results of these missions will help to understand the environment, especially the effects of dust storms on equipment and the radiation at the surface. Similar missions to the Moon are also being planned. A second iteration of the designs presented in this thesis can be conducted once the new information is gathered.

The habitat design presented herein is also preliminary. The interior design can be better defined by laying out the rooms in more detail. The actual amount of open space can then be calculated and it can be made certain that there is enough room for the crew. Once the radiation environment on the surface is known the radiation shielding of the habitat can be better designed. The feasibility of using regolith to shield the habitat needs to be investigated further to determine if the benefits of the shielding are worth the effort required to construct the shield.

The EVA suits and the mobility equipment both need to go through a more detailed design process to fully understand their capabilities on Mars and on the Moon. Significant development is required for the EVA suits in order to find a scheme that will work on both the Moon and on Mars.

Finally, the MERL can be improved. The objectives can be specified to a larger extent and the completion levels can be better defined. A weighting scheme should be applied to the objectives to take into account the cost and difficulty of completing the objectives. The MERL can be extended to other aspects of the exploration system to provide a better evaluation of the readiness for Martian exploration.

While this work is performed, the Mars-back approach needs to be forefront in the minds of the mission planners. It is the way to keep a sustainable space exploration system, since it keeps the focus on Mars and drives down cost by only developing one equipment suite. The Mars-back approach can and should be applied to other aspects of the mission, such as the transportation elements.

7 Conclusion

A Mars-back approach has been identified as the preferred way to perform lunar exploration. This approach will lead to a more sustainable exploration system. For surface operations, the Mars-back approach entails using the same suite of surface equipment, including mobility equipment, habitats, and power systems, on the lunar and Martian surfaces.

To determine the proper suite of equipment for the Moon and to plan a lunar campaign to prepare for Martian exploration required a detailed design of the Mars baseline surface architecture. This architecture will consist of 5 crewmembers on a 600-day surface stay. They will have the use of 5 ATVs and 2 campers to aid in exploring and performing science activities. The habitat will consist of a vertically oriented cylinder with the volume available to the crew increased by the use of inflatable structures.

With this architecture, a Mars-back approach to lunar surface operations can be defined. The equipment will be tested on the lunar surface to gain experience in using it and to make sure that it works before sending it to Mars. The Moon provides a cheaper testing ground than Mars, so using it as a testing ground will help to keep costs down. Knowing the equipment that will be needed on the surface allows for the development of a lunar campaign that can be evaluated through the use of the Mars Exploration Readiness Level. The campaign will consist of four mission phases. The first phase will send humans back to the Moon for the first time since 1972. It is designed to be similar in extent to the Apollo missions, with short surface stays and limited excursions from the lander. The second phase consists of robotic exploration and power and communications system deployment. The purpose of this mission is to deploy the power plant and communications satellite and to keep up interest in the Moon while the equipment needed for the third mission phase is developed. The third phase consists of creating a Mars analog environment on the Moon and testing out the habitat before a long-duration mission is attempted. The fourth mission phase is a full Martian simulation mission, lasting for the entirety of the lunar summer. After this mission, the exploration system should be ready to head to Mars.

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APPENDIX A - Determination of Maximum Range of Mobility Options

The following equaitions were used to determine the maximum range for each mobility option. The mobility options can be found in Table 4-2. The maximum range was set to be the range at which the crew on the excursion could be safely returned to base, assuming the number of failures specified in the breakdown tolerance of the mobility option. For example, a mobility option with a breakdown tolerance of 2 is limited in range to the distance that the crew can be returned from if two vehicles breakdown.

Variables:
R_n = range for mobility option n
t_EVA = max EVA time
V_w = walking speed
V_ASR = Apollo-style rover speed
V_ATV = ATV speed
V_prov = prover speed
T_prov = max prov time
N_camper = number of campers

Equation	Description
$R_1 = \frac{v_w * t_{EVA}}{2}$	Half-day's walk
$R_2 = \frac{v_{ASR} * t_{EVA}}{2}$	Half-day's ASR drive
$R_3 = \frac{v_{ASR} * t_{EVA}}{1 + \frac{v_{ASR}}{v_w}}$	The range is equal to the speed of the ASR times the max EVA time minus the time it would take to walk back to base. That equation is then solved for the range to get the equation on the left.
$R_4 = \frac{v_{ASR} * t_{EVA}}{2}$	Half-day's ASR drive
$R_5 = \frac{v_{ASR} * t_{EVA}}{3}$	One-third-day's ASR drive. It takes twice as long for the second rover to rescue the first, so three trips in total are needed, limiting the range to one-third-day's drive.
$R_6 = \frac{v_{ASR} * t_{EVA}}{1 + \frac{v_{ASR}}{v_w}}$	See R3
$R_7 = \frac{v_{ATV} * t_{EVA}}{2}$	Half-day's ATV drive
$R_8 = \frac{v_{ATV} * t_{EVA}}{2}$	Half-day's ATV drive

$R_9 = \frac{v_{ATV} * t_{EVA}}{1 + \frac{v_{ATV}}{v_w}}$	See R3.
$R_{10} = \frac{v_{ATV} * t_{EVA}}{2}$	Half-day's ATV drive
$R_{11} = \frac{v_{ATV} * t_{EVA}}{2}$	Half-day's ATV drive
$R_{12} = \frac{v_{ATV} * t_{EVA}}{3}$	See R3.
$R_{13} = \frac{v_{prov} * t_{prov}}{2}$	Half of the total distance the pressurized rover can travel.
$R_{14} = t_{EVA} * v_{ASR}$	Full-day's drive on the ASR. Assumes that the pressurized rover breaks down and the crew then drives back to base on the ASR.
$R_{15} = \frac{v_{prov} * t_{prov}}{2}$	Half of the total distance the pressurized rover can travel.
$R_{16} = \frac{t_{EVA} * v_{ASR}}{2}$	Half-day's ASR drive. Since the ASR is at the base in this configuration, it drives out to rescue the crew and then back, so it can only go a half-day's drive.
$R_{17} = v_w * t_{EVA}$	Full-day's walk. This equation assumes that both the pressurized rover and the ASR have broken down, so the crew needs to walk back from the pressurized rover.
$R_{18} = \frac{v_{prov} * t_{prov}}{2}$	Half of the total distance the pressurized rover can travel.
$R_{19} = \frac{v_{prov} * t_{prov}}{3}$	One-third of the total distance the pressurized rover can travel. The second pressurized rover is used to rescue the crew from the first. This equation assumes that it is the drive system that has failed on the pressurized rover, not the life support system.
$R_{20} = t_{EVA} * v_{ATV}$	Full-day's ATV drive.
$R_{21} = t_{EVA} * v_{ATV} * n_{camper}$	Mulit-day ATV drive. Assumes that the other campers can be used as stopover points on the way to rescue the crew from the first camper. Also assumes that the life support system in the first camper has not failed.

APPENDIX B – Function Listing for Major Programs

This appendix contains descriptions of the functions used to create the major programs used in the development of this thesis. The programs can be found on the CD attached as Appendix C. All code was written in MATLAB.

Activities Model

The actual code used for the activities model is contained on the CD attached as Appendix C. What follows is a brief description of the functions used in the model. The functions are listed in alphabetical order.

ability_to_visit_site
This function inputs a mobility option and the speeds of the mobility equipment and calculates whether or not the mobility option can reach a specified site of interest, by comparing the distance of the site to the maximum distance that can be reached by the mobility equipment based on the maximum time that can be spent on an EVA.

Activities
This function creates a sorted list of the different activities that can be performed at a site. The list is sorted by the importance rank given to each activity. Each activity contains a reference to the Equipment List that specifies the equipment that is needed to perform each activity. Each activity also contains an estimate of the time, in person-hours, that the activity will take to perform.

Activities_Model
This function inputs the number of crew, the mission length, and the mobility option and calculates how many sites can be visited, how many activities are performed across all sites, the total mass of science equipment that will be needed, the total time that is needed for all the activities, the order in which the sites of interest are visited, and the amount of extra time that is available to the crew in the schedule. This function is the main function in the program as it calls all the other functions to perform calculations. This function also creates the timelines of exploration.

Activities_scouting
This function is a version of Activities that is used if the user turns on the scouting option. The scouting option is used to let the crew scout many sites ahead of time, before choosing which sites to explore in more detail. It is assumed more detailed exploration will occur at 20% of the sites scouted.

calccrewtime
This function was written by Sandro Catanzaro and was based on the First Lunar Outpost Study done by Lockheed Martin.[15] The function calculates the crew time parameters for use in other parts of the model.

calc_open_rover_time
This function calculates the amount of time that an open rover can spend at a site based on the maximum allowable EVA time, the open rover speed, and the distance of the site.

calc_prov_time
This function calculates the amount of time that a pressurized rover can spend at a site based on the maximum amount of time that pressurized rover can be used before it needs to be resupplied, the speed of the pressurized rover, and the distance of the site from the base.

calc_walking_time
This function calculates the amount of time that an EVA crew can spend at a site that they walk to, based on the walking speed, the maximum allowable EVA time, and the distance of the site.

Equipment
This function creates a list of all the equipment that will be needed to perform the desired activities at the sites of interest. Each piece of equipment has a mass estimate associated with it.

Exploration_Selection
This function lessens the time spent at sites when the exploration approach is chosen. This approach desires to visit as many sites as possible, so if performing all the activities at all the sites requires too much time, the lowest-ranked activity is removed from the lowest-ranked site. The process is repeated until enough activities have been removed so that the required mission length fits within the specified mission duration.

fill_Crewtime
This function was written by Sandro Catanzaro and based on the Lockheed Martin First Lunar Outpost Study.[15] This function sets up the input parameters that will be used in calccrewtime.

Science_Selection
This function lessens the number of sites visited when the science approach is chosen. This approach desires to perform as much science at a site as possible, so if performing all the activities at all the sites requires too much time, the lowest-ranked site is not visited. The process is repeated until enough sites have been removed so that the required mission length fits within the specified mission duration.

set_mobility
This function sets the number of surface vehicles based on the mobility option.

set_up_crew_timeline
This function established a timeline for the activities of the crew. The crew is split into EVA teams of 2 crewmembers each and the location (either at the base or at a site) of the teams are tracked. The results can be plotted and are used in determining how many sites can be reached, as the availability of the crewmembers may not track directly with the availability of the vehicles.

set_up_timeline
This function sets up a timeline for the mobility equipment. Each vehicle's location is tracked, and time is set aside for the recharging of the equipment. The results can be plotted and are used in determining how many sites can be reached, as sites requiring the same mobility equipment cannot be visited at the same time.

Sites
This function creates a ranked list of all the sites of interest that are specified. The site specification consists of its distance from the base, the activities to be done at the site, a categorization and ranking of the site, and the number of times that the activities done at the site are to be repeated. The sites are sorted based on rank within categories, but not across category. Therefore, the order of visited sites will be the top ranked site from each category, then the second ranked site from each category, and so on.

Sites_scouting
This function is used when the scouting option is turned on. Scouting is performed by using only the scouting activity at each of the sites, thereby establishing extra time spent there. It is assumed that only 20% of the scouted sites will want to be explored in more depth.

timeline_calc
This function performs the actual calculations needed in set_up_timeline to create the timeline for the vehicles.

Habitat Sizing Model

The code used to create the habitat model is contained on the CD attached as Appendix C. What follows is a brief description of the functions used in the model. The functions are listed in alphabetical order.

hab_size
This function calculates the usable floor area of the habitat, given a diameter, length, level height, and orientation of the habitat. The area is calculated by determining the number of levels, which sets the absolute floor area of the habitat. The area for the radiation shelter and walkways is then subtracted. It is assumed that the equipment will take up 2/3 of the available area[17]. This fraction is modified based on the amount of space available inside the habitat that is not used by the crew – for example, if the height of a vertically-oriented cylinder is not a multiple of the level height, the extra height can be used for equipment storage. The extra volume is taken into account and the fraction of the area taken up by the equipment is adjusted.

horizontal_vertical_hab_compare
This function compares the available interior area of vertical and horizontal habitats across various volumes. The volumes are determined by the user-specified maximum diameter and length of the habitat. Combinations of these two parameters are used to determine the volume and then the interior area.

optimal_hab_size
This function determines the optimal habitat size and orientation for a given total volume. It calls hab_size to determine the orientation and dimensions that give the most usable floor area, which is the parameter used to define the optimal size. That orientation and dimensions are then reported to the user.

APPENDIX C – CD WITH CODE FOR MAJOR PROGRAMS

The code for the Activities Model and the Habitat Model can be found on the CD accompanying this thesis.