The Exploration of Mars:
Crew Surface Activities[1]

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Abstract

Surface activities of the first Mars mission crew, as suggested in phase I of the NASA HEDS reference mission, are discussed in this paper. The HEDS reference mission calls for a two phased approach. In phase I, humans supported by robotic systems will explore the Martian surface, collect and analyze geologic, geophysical, and meteorological data, search for potential permanent base sites, and conduct technology verification experiments. In phase II, a Mars base site will be selected, and the building of a permanent human base will be initiated. In this report two complementary architectures are portrayed. First, a permanent base for 3-6 people consisting of an ISRU unit, two nuclear power systems, a green house, and inflatable habitats and laboratories, built inside adobe structures. Second, a reusable, and resupplyable methane propelled very long range type traverse vehicle capable of collecting and analyzing data, and repairing and deploying scientific payloads during its planned 150 days 4800 km traverse. The very long range traverse vehicle will carry smaller rovers, crawlers, blimps, and an air drill capable of quickly reaching depths beyond 100m. The report presents a global vision of human activities on the surface of Mars at a programmatic level. It consists of several vignettes called "concept architectures" We speculate that these activities will facilitate a phase I Mars exploration architecture.

1. Introduction

With the ongoing construction of the International Space Station, NASA and space agencies around the world are seeking a vision for humanity's next step at the space frontier. It is quite possible that a human mission to Mars might provide a nucleus to align the efforts of the agencies for space activities in the new millennium.

A mission to Mars has many goals, including the study of comparative evolution of Earth and Mars, the assessment of how Mars has changed, and most importantly, determining whether our planet is faced with a similar fate. The answers to these questions hold not only scientific value but when viewed in the larger social context could change the way we view ourselves. The recent discovery of meteorites that might have bacterial fossils gave the initial spark and helped galvanize the need to send explorers and scientists to the Martian surface. By sending these explorers to the Martian surface we may finally be able to answer one of humankind's biggest questions: "Are we the exception or the rule?"

The exploration of Mars has begun in earnest with robotic missions, currently either in orbit, en route, or in production. These missions will establish the skeleton infrastructure that will be needed before human activities can commence. These missions have also begun to provide a picture of the planet that was previously unavailable. Data being returned suggests that Mars is a planet with dynamic geophysical processes and could have harbored life. Geologists are eager to go there and conduct conclusive experiments to find out if life ever evolved there, if certain forms still exist and also if the planet might be able support humanity's ambition to extend a branch of civilization to that planet.

The next step will be to use the gathered data to select potential landing sites for the first human missions. We envision these human missions to be the precursors to the establishment of a permanent settlement on Mars. We imagine that this could happen in the next fifty to seventy five years.

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A human mission to Mars is being studied by NASA and other space agencies. NASA has identified an opportunity for such a mission in the year 2012. Alternative mission architectures, including the nature and duration of activities of the crew during a surface stay of approximately 600 days are currently being discussed by the agency. The USC Mars Exploration Team's preliminary findings of a candidate expedition crew surface mission are presented in this paper.

2. Mission Objectives

Our focus is on the activities of a first human mission to Mars, but we assume that the ultimate goal is a phased, long term human exploration of the planet. Our primary concern is in conducting activities and investigations that will lay the foundation for, enable, or enhance the next several human exploration missions.
The goal is to sustain a six person crew on the surface of Mars for approximately 600 days, and return them safely to Earth. During the surface stay, the crew will perform tasks that are considered impractical or impossible for robotic missions. The proposed crew activities include:

- Demonstrating equipment and techniques to sustain human life on the surface of Mars (e.g., in situ resource use, agricultural experiments, life support technology verification, demonstration of recycling strategies)
- Exploring the feasibility of human settlement on Mars
- Gathering and analyzing data for selection of potential permanent base.
- Providing infrastructure elements for future missions
- Searching for permafrost, ice, or water
- Searching for evidence of past life

The mission system architecture elements for the human exploration of Mars can be divided into two areas of focus; habitation and exploration. Each of these areas is important to determine the feasibility of a human presence and sustainability on Mars. The habitation elements will focus on the development of structures and systems to sustain a human presence, while the exploration elements will examine the Mars environment for natural resources and a permanent base camp for future missions.

The habitation base camp architecture will focus on the survivability and productivity of the human species in a foreign and hostile environment. The crew will experiment and develop habitable structures using materials from Earth and Mars that are capable of providing safe and comfortable working and living spaces. Different types of building technologies and techniques including inflatables, expandable domes and indigenous material structures will be built and tested for safe, long term occupancy. Agricultural experiments will also be carried out to study the effects of the Martian environment on plants. These experiments will be developed in a controlled environment to study the feasibility of human self-sustainability on Mars.

The rover exploration architecture will focus on expanding our knowledge of the Martian environment while searching for natural resources and future permanent base camp locations. Most of the exploration will be performed using the very long range traverse vehicle (VLTV). This vehicle will be capable of traversing the Martian landscape with a crew of three for six months minimum, while providing a comfortable living and working environment. The vehicle will be supplied by cargo landers that will place supply caches at five to seven locations along the VLTV traverse route. Each of the re-supply landers will provide human necessities along with scientific and monitoring equipment to be used for the duration of the traverse. Experiments will be performed to analyze the Martian soil using the Deep Driller which will be capable of drilling down to 100 meters in 3-5 days. Safety is a major issue for the VLTV crew. For this reason an emergency rover concept for rescuing the VLTV crew in an emergency is being studied. This vehicle is capable of carrying a crew of four, (three from the VLTV, one from the base) for up to 3 weeks to return the VLTV crew to the base camp.

A communication system will be implemented to support ground and remote communications for the crew. This system will contain high-gain directional antennas, areostationary relay satellites, and local transmitter/receivers for line-of-sight communications.

Robust power systems are critical to the survival and sustainability of the Martian crew. Different types of power systems deployed will include nuclear systems for the base camp, methane/fuel cell technology for the VLTV, and fuel cell utilization for the emergency rover. In situ resource utilization (ISRU) will be used extensively throughout the architecture. Methane production from the Martian atmosphere is but one example of ISRU that can be implemented for power and propulsion systems.

Tele-operated rovers, both aerial and land based, will be used extensively by the Martian crew to explore terrain that is too dangerous for the human crew, and to study proposed traverse routes. These craft may be operated by the crew from the safety of the habitats/VLTV using haptic systems and virtual reality displays to provide real time data input and acquisition. The mini-rovers can also gather material samples to support the scientific experiments being studied throughout the mission from both the base camp and VLTV.

Whether supporting the base habitation camp, or the VLTV traverse, each system element has a significant impact on the feasibility and success of the human Mars expedition. The following sections in this report will describe in more detail each of these elements, and the significance each has on the proposed mission architecture.

3. Candidate Mission Profile

The first human mission to Mars consists of three phases of operation:

- Precursor Missions
- Cargo Missions
- Crewed Mission

Precursor missions include robotic science and technology verification payloads designed to help us better understand and predict the nature of Mars and its resources. Some examples of robotic mission objectives are to: survey the Martian surface for optimum landing and geo-bio site locations; return data on the exact nature of the Martian radiation environment, the planetary protection provided; obtain meteorological data on Martian weather patterns; and return samples of Martian soil to Earth for agriculture and construction testing. Specific details about these missions are provided in Appendix A.

The second phase of the overall architecture is the multi-staged cargo mission. The cargo mission will provide the human crew with a fully fueled Earth Return Vehicle (ERV) and Mars Ascent Vehicle (MAV) before they leave Earth. Cargo missions will deploy the power plant, ISRU facility, consumable supplies, VLTV, and Earth manufactured construction materials on the surface before they land.

The third phase of the mission architecture is the human mission. The crewed mission objectives are to determine the feasibility of humans living and sustaining themselves on Mars, and to explore the geological, geophysical, meteorological, and biological history of Mars during a long range scientific expedition of the planet's surface.

4. Base Camp

4.1 Site Selection

Using the NASA reference mission as transportation baseline, six crew are landed at a safely accessible site in the low latitude region surrounding the Valles Marineris Canyon system and the Tharsis volcanic region. The site selected was Chasma Perrotin. It was selected because of it being in a safe and temperate equatorial region of Mars, and because of its rich variety of terrain and features in a compact area for geological and geophysical explorations. The site also offers the best choice from a trajectory alignment point of view for landing, orbital support, and ascent and departure.

4.2 Base Camp Architecture

The Mars outpost base camp is designed to test the feasibility of humans sustaining themselves on Mars. The base camp architecture fuses Earth and Mars based resources to allow the crew to grow food, create habitats and a greenhouse, produce their own fuel, H_2O and O_2, and protect themselves from the hazards of the Martian environment. The base camp consists of the crew lander module, central Adobe habitat, agriculture-life science module, MAV, ISRU facility (in addition to the MAV ISRU plant), 2 nuclear reactors, and redundant lander module filled with an emergency 600 day consumable (food, water, air) supply. The Lander module serves as the Command and Control Center of base camp, provides additional living space, a

Solar Particle Event (SPE) storm shelter, and radiation monitoring-testing laboratory space (See Fig. 1). The life science module serves as the camp greenhouse and houses/controls the base camp bio-regenerative CELSS experiment. Additional infrastructuredevelopment over the course of the mission includes a simple road network around base camp, adobe storage houses, adobe lift-off shield, and landing/liftoff pads for the MAV and future landers. With redundant power sources, living spaces, and transportation systems, the base camp tests the potential of ISRU but does not force the crew to rely on it in the case of mission failure. The crew and robotic devices landed in the cargo missions will construct the base camp over the course of the 600-day mission.

4.3 Adobe Habitat Architecture and Construction

The central habitat of base camp as well as the related infrastructure including exposed platforms, roads, aprons, shields, wind breaks and other protected areas and utility channels are envisioned as Adobe structures made with in situ Martian regolith. The Adobe shell/exterior of the habitat houses an inflatable membrane that functions as a self-contained pressure vessel for the crew to live in. Adobe material was chosen to expand on the ISRU for habitat construction and environmental protection objective of the base camp mission. Martian Regolith is a free resource available to us in unlimited quantities on the surface of Mars. The Adobe exterior serves as an excellent Galactic Cosmic Radiation (GCR), Solar Particle Event (SPE), and Ultra Violet (UV) radiation shield, a thermal insulation layer, and provides complete dust storm and micro meteoritic (MM) impact protection. Although the radiation environment of Mars is not expected to be as severe(lower annual dosage) as the moon or interplanetary space, two years of exposure to constant unprotected levels on the surface can pose a considerable radiation risk to the human crew. Using Adobe would dramatically reduce this radiation risk and reduce the overall mission cost in terms of materials development and payload that needs to be sent to Mars [Simonsen 1997]. Adobe construction and use plays a vital role in this base camp mission architecture and in the eventual development and self-sufficiency of humans on the surface of Mars. The Adobe exterior serves as a shell to house the pressurized membrane; not as the structural support to mold and contain the 9 psi environment within the habitat. To compare it with the reference Transhab technology for perspective, using an Adobe shell to house the inflatable membrane dramatically reduces the overall mass of a Transhab type of structure on the surface of Mars. The layers for GCR radiation and MMOD impact protection would no longer be needed, and the insulation layer thickness would be greatly reduced. Water shielding and most typical types (Al) of radiation shielding material are useful against UV and SPE radiation, but have minor reduction against highly energetic galactic cosmic rays. Metal radiation shields can even endanger the crew due to the harmful secondary electron production that results when impacted by GCR's. Galactic Cosmic rays can only be stopped by a large, dense spatial distribution of material; for example Martian Regolith.

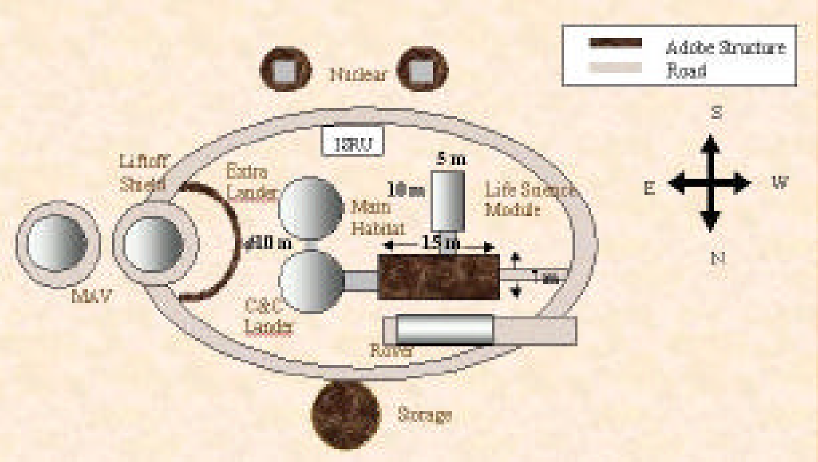

Figure 1: Base Camp Site Plan

The Adobe habitat construction relies on the regolith drill/pump, ISRU brick baker, plastic superadobe bags to hold soil, an inflatable half cylinder membrane (smaller radius of curvature on the bottom), and a Plexiglass sheet supply on the surface. The brick baker is a simple device, which pours Martian regolith into a mild compression mold, bakes it in a small furnace, and produces a brick in the shape of the mold. Molds used in the base camp construction include quarter and half arches, flat square panes, and rectangular bricks. Heat for the furnace is provided by the nuclear reactor. Experiments will also be carried out using solar concentrators to bake the bricks into the desired shapes. The habitat wall structure is created using coil and rectangular bags filled with the free supply of regolith. Each layer is formed directly on top of the other layer and hardened due to compression of the layers above it. A plastic brace is used to support the construction of the walls. Specific spaces (arches) are built into the wall structure for the placement power and gas lines, Plexiglas windows, and airlock junctions. The roof of the habitat is constructed using the "leaning arch" technique. Arches are laid from both ends of the structure in an inclined position gaining support from the previous arch until both sides meet. Quarter and half arches are placed on a movable hard plastic arch track supported by struts and moved on rollers. As each inclined arch is laid in place, the arch track is moved to the next position and the process is repeated from both sides until the roof is complete. Crew involvement in the construction of the habitat includes measuring and triangulation of the site, placement of the empty bags on each successive layer, connecting their open end to the regolith pump, and operating/guiding the servo-operated three pulley system to place the arch fragments on the track. The 1000 kg capacity crane on the VLTV can also be used as a construction aid if needed. The three-pulley system raises the arch segments vertically, horizontally, and laterally over the arch track, with a crew member on a platform guiding each arch segment into place. The pulley is operated by a servo located on the ground. The inflatable, half-cylinder, polymer membrane provides the pressurized environment of the habitat. The inflatable has one main space qualified airlock, and two smaller internal airlocks. It is fitted with built in plumbing and power connections accessed from inside and out for easy checkout and assembly. After the habitat exterior is constructed, the crew will lay down the base floor matting, and then bring in the inflatable to match up its airlocks with the wall openings accordingly (significant margin is built into the wall openings to provide easy match up with the membrane airlock locations). Gas and power line connections are made between the membrane and ISRU facility by the crew. The membrane is then inflated with oxygen and required buffer gases at a regulated 9 psi supply pressure from the ISRU facility. After some initial inflation, the crew will affix the base of the membrane to the Martian surface to line up the permanent airlock junctions. The membrane inflation is completed when the internal pressure reaches 9 psi. Two inflatable tunnel airlocks (IT) are attached to the habitat, with one joining the lander to the habitat (IT 1), and the other joining the habitat to the agriculture-life science (LS) module (IT 2). Each IT has a seal at each end. The inner seal of IT 1 is connected to the habitat and opened to pressurize it and the habitat to 9 psi. The outer seal is then opened and the crew can walk freely out of the lander and into the hab. Due to the automated construction of the habitat, wall construction is expected to take 2 weeks, roof construction 2 weeks, and membrane deployment and integration 1.5 weeks. A margin of two weeks is added to account for any delays. During the construction period, the crew will use the lander coupled with the VLTV to provide additional living space. Internal supplies, furniture, and equipment will be brought in after inflation. Some room partitions are built into the inflatable design, but shelves and hard walls need to be assembled after inflation. The habitat module is divided into two parts: the living/recreation area and the work area. The work area has science laboratories, a workshop, exercise room and a clinic. Equipment in the science laboratories focuses on analyzing the radiation and geological environment of Mars. Laboratory capabilities and equipment includes stereo microscopes, SEM, TEM, EDS machine, X-Ray diffraction, chemical analyzers, small furnace, wet-chem lab, and computer stations for analysis. Radiation monitoring and testing equipment will be housed in the C&C lander module. The clinic will be used to provide crew checkups and to monitor the effects of the low gravity environment on the human body. Some primary care is possible including minor surgery and dentistry The living space has three bedrooms (with two beds per room), toilet / washroom, meeting area, eating area, and pantry to store additional food and supplies. The habitat can house all six crew members, but will be occupied for the majority of the mission, by the base camp crew of three. The ECS system of the habitat sends waste water, food, and CO2 to the LS module where it is processed and recycled as part of the bio-regenerative CELSS experiment. Additional backup recycling units are also found within the habitat and lander modules in case of LS module failure.

4.4 Life Science Module Architecture and Construction

The life science (LS) module is a 9 psi pressurized air environment. It is connected to the main habitat via an internal IT airlock. The outer structure of the LS module is a prefabricated polycarbonate honeycomb structure with square shaped openings. The honeycomb is folded out by the crew and fixed into place (in relation to the main habitat) by hammering stakes through tabs at the base of the honeycomb into the ground. Additional Martian soil bags can be added to the base if needed. The LS module will experiment with growing plants in natural and artificial light; therefore, part of the LS module will be transparent and part opaque. 60% of the honeycomb will be filled with Plexiglas squares treated with a Cerous 3 polymethacrylate (CPMA) UV [Yen 1979] resistant coating, and the remaining 40% filled with solar cells mounted on Martian bricks. The crew will be responsible for slotting these pieces into place as part of the construction phase. The inner structure of the LS module is a bi-layered polyethylene inflatable (transparent) similar to the habitat membrane with only one minor airlock. Polyethylene and Adobe materials were chosen for their GCR radiation shielding properties [Wilson 1997]. Polycarbonate and CMPA were chosen for their UV radiation resistance properties.

The inner membrane environment is equivalent to the habitat / lander environment. The second layer of the inflatable is a dense layer of Martian CO2 pumped in from outside. This layer enhances the greenhouse heating and provides additional GCR radiation protection. The greenhouse heating of the LS module is used (in conjunction with electric power heaters) to heat the main habitat using fans and cross flow heat exchanger lines to re-circulate the warm air. After the bi-layer inflation is complete, IT 2 is connected to the LS and main habitat module. When the LS module is pressurized and heated, the seals of the tunnel will be opened allowing full access between all modules. The biomass recycling/production chamber is then brought into the complex to bring the CELSS online. LS module research labs include Martian soil growth experiments with (non)genetically engineered plants in natural and artificial light, hydroponics growth laboratory, and an Extremophile laboratory where plants are genetically engineered to thrive in a low temperature and pressure CO2 environment for eventual growth on the surface. CO2, O2, and H2O recycling units will also be placed in the LS module to accompany the biomass recycling units. The LS module functions as the chemi/bio-regenerative CELSS experiment. Waste water is recycled using filtration for urine, baking of feces, and Zeolite Sieves to recapture water vapor produced by perspiration and plant transpiration. Plant photosynthesis and carbon molecular sieves located in the LS and habitat modules remove the excess CO2. The waste CO2 is then returned to the ISRU facility to be re-entered into the Sabatier reaction for H2O, O2, and CH4 production.

4.5 Site Development

The Mars Base camp development continues beyond the main adobe habitat and LS module construction, over the course of the 600 day stay on the surface. Adobe construction techniques will continue with the base camp crew working with camp robotic devices to develop a simple elliptical road network around base camp. The road network will connect the main airlocks,

habitat ISRU facility, storage locations, and the MAV liftoff pad. The road network development consists of clearing paths and using solar light concentrators (parabolic lenses) to bake the surface of the path. The crew will build Adobe storage houses to store equipment, supplies, and surface mobility vehicles and construct an adobe liftoff shield to protect base camp from debris brought up during liftoff and future landings.

4.6 Communications

High data rate communication between Mars and Earth is accomplished at Ka-band directly from the surface of Mars. This approach allows high rate (20 Mbps) communications by exploiting the mission's nuclear power source, and the presence of astronauts on the surface allows the construction of a relatively large antenna compared to what might be feasible on a Mars-orbiting spacecraft. In addition, unlike a satellite system, the ground-based system can be maintained or repaired by astronauts if necessary. This high rate ground system, however, provides communications for less than half of the Martian day because of line-of-sight obstructions.

The other key elements of the communications plan are a pair of areostationary satellites. These satellites provide a moderate rate (100 kbps each) X-band link between Mars and Earth, and also provide a communications relay between astronauts at the surface base station and those on long-term on exploration expeditions. The use of two areostationary satellites provides redundancy in case of failure. Other backup options were considered, such as the use of surface relay stations, but such stations would be complex, time consuming to assemble, and difficult to power and maintain.

By separating the satellites 19 degrees or more, we can maintain constant contact with Earth (a single satellite would experience daily communication losses of up to 71 minutes per sol due to eclipses when Mars blocks the line-of-sight between the satellite and Earth). The satellites could also provide aerial photographs which could provide advance warning of dust storms. Launching the satellites well in advance of the crewed mission would provide a communication link for preceding robotic missions. Because the satellites are supporting modest data rates compared to the surface-based Ka-band link, the satellites can be powered using solar arrays, avoiding the political objections to additional launches of nuclear power sources.

Planetary geometry has significant impact on communications between Mars and Earth. If the data rate is adjusted to maintain a constant bit-error probability, then the sustainable bit rate varies by approximately a factor of 20 over the mission duration. In addition, communication is disrupted for a brief period from solar scintillation effects when the Sun-Earth-Mars angle becomes sufficiently small. Providing a reliable link during such events might be accomplished by the use of an additional satellite in Solar orbit at about 1 AU (perhaps at the Earth-Sun libration point) which would provide a communications path that didn't require a small Sun-Earth-Mars angle. This solution is deemed unjustifiably expensive.

Under any communications scenario, the value of the Earth-Mars link is significantly augmented by exploiting data compression and buffering. For example, such technologies could allow daily transmission of brief high-definition television (HDTV) clips which could significantly increase public involvement. Further development of optical communications technology could also significantly enhance data return from a human mission to Mars, and provide mass and power savings [Hemmati97, Hall90]. We have not selected such a system as our baseline because, while the development of optical deep space optical links would significantly enhance the mission, communications needs could be supported with currently available technology.

4.7 Power System

An initial source of large-scale power for the base camp will come from the same power source used to fuel the ISRU production of methane and oxygen for the Earth Return Vehicle. A 4 ton, 100kW nuclear reactor manufactured on Earth can provide a continuous source of power for 7 - 10 years which is more than enough power for the base operations of the first human mission. Although compact in size, this unit will require at least 12 tons of shielding in order to be medically safe for the crew. The reactor will most likely be located away from the base camp, preferably in an ancient impact crater whose walls would provide shielding.

Transmission of electrical power will require the use of high voltage power lines buried at least one meter below the soil. Power can be distributed to batteries and electric motors that power the habitat, agricultural, and science modules. This will be the beginning of a power infrastructure whose electric distribution network can be expanded to meet the needs of a growing base camp.

Solar power arrays as a primary source of power for the base camp will be infeasible for the first mission since it would require approximately 25,000 kg of material from Earth to manufacture solar panels that are capable of providing the same power output as the reactor. Smaller solar arrays can be used for the generation of power at a much smaller scale that can be used for various sub-systems. One consideration could be kinetic flywheels that whose electric motors are powered by solar energy. These 2-3m flywheels can then be used to generate electric power. This power source will not be considered as a source of power for the mission, but can be a technology demonstration of future power systems that can be utilized on the surface.

The reference mission also calls for the recycling of water from organic wastes. These same waste products also naturally release methane, which can be used as a source of fuel for space heating and cooking. The process, known as pyrolysis of biomass, occurs when organic wastes are placed under high temperature and pressure to decompose organic material. During this process, several gases are released, including hydrogen, which can be used in fuel cells.

4.8 ISRU/ISRP Technology & Application

ISRU (In-Situ Resource Utilization) and ISRP (In-Situ Resource Processing) are two very important concepts to be used to make human presence on Mars possible. The concept would be to take a raw resource, such as the atmosphere or soil, and then using a sequence of processes, create useful commodities such as Oxygen from the atmosphere or Iron from the soil. In general, there is agreement that ISRU can significantly reduce the cost of exploration, especially for extended duration missions. If the concept ISRU is applied as part of the initial mission design for a human Mars mission, it will provide substantial mass savings and reduce mission risk because the amount of consumables that will need to be taken. This will in turn, have considerable impact on the overall mission size. The ability to automate the production of propellant, consumables and other materials from available resources from Mars will allow a higher level of mission feasibility and reliability. For example, the overall mission robustness of certain surface systems would be increased. This would be because caches of consumables, such as surface vehicle fuels, and Mars Accent Vehicle fuels can be maintained and kept at peak levels.

The sources for ISRU on Mars will come from two primary sources, the Martian atmosphere and soil. The atmosphere of Mars is much thinner than that of Earth, with a surface pressure averaging 1/100th that at the surface of the Earth. Surface temperatures range from -133° C at the winter pole to 23° C on the dayside during summer. The soil and atmosphere composition is shown in the following chart and table and is only based upon previous Mars Mission data.

Mars atmospheric composition (%): (CO2) Carbon Dioxide, 95.32; (N2) Nitrogen, 2.7; (Ar) Argon, 1.6; (O2) Oxygen, 0.13; (CO) Carbon Monoxide, 0.08; (H20) Water, 0.0325; (NO) Nitrogen Oxide, 0.1547; (Ne) Neon, 0.00039; (Kr) Krypton, 0.0000464; (Xe) Xenon, 0.0000124.

Future missions and exploration will expand this list of resources, and could provide even more options for future mission planning. One such option would be the significant presence of water that could be easily obtained and utilized. This resource would be the most valuable to any type of human presence. Until such future resources are determined and verified, mining and then processing the Martian atmosphere and soil for known substances, will provide several key materials for Manned mission success. Future mining and processing of the surface materials listed here will require equipment, which will probably not be included in early Mars missions. With processing “Air mining” could yield Water, Oxygen, Nitrogen, Carbon Monoxide, Methane, and Ammonia, while “surface mining” could yield Water, Sulfur, Iron, Titanium, Aluminum, magnesium, ceramics, glass, and other building materials

For the first series of Manned Mars Missions, the primary needs from ISRU will be the manufacture of consumables. Such manufacturing will be Oxygen and propellant in the form of Methane (CH_4). Other important resources that can be extracted from the Mars atmosphere are buffer gases. Nitrogen and Argon make up a significant volume percent of the Martian atmosphere. When they are separated from the predominantly carbon dioxide atmosphere, these gases have a variety of applications ranging from their use as carrier and sweep gases for scientific instruments to buffer gas for human life support. Other applications include using compressed gases to deploy inflatable structures and drive pneumatic tools. Such tooling could be designed to be powered by several different modes of power input (electric, combustion, or gas pressure) using dual-use techniques.

The process for the production of Oxygen and propellant will make use of the chemical processes as shown in the figure. The production of Oxygen will either be by the electrolysis of Water, or the extraction from the Martian atmosphere using a Solid Oxide Electrolysis Cell, which involves the direct dissociation of carbon di oxide into Carbon Monoxide and Oxygen gas. The other, known as "Sabatier-Electrolysis”, by combining hydrogen with Martian carbon dioxide in the presence of a nickel or ruthenium catalyst yields methane and water. The methane is stored and the water electrolyzed to produce hydrogen and oxygen. The oxygen is stored, and the hydrogen reacted with Martian carbon dioxide to produce more methane and water. There are also several other approaches and that could be used to create a form of a Martian produced energy economy. Each approach has it’s own advantages and disadvantages. Currently the Solid Oxide Electrolysis Cell technology has been a proven process on Earth, and at this time it is currently going to be flown and tested on the Mars 2001 lander. Methane/Oxygen combustion has about 80 percent of hydrogen/oxygen’s specific impulse, yet it is easier to store than hydrogen. Thus it is a more attractive choice for the Mars Ascent Vehicle fuel since the long time period that will be spent on the Martian surface. Another process to make Water and Carbon Monoxide is from a reverse water gas shift process as well as an output from the Solid Oxide Electrolysis. The Carbon Monoxide that is processed in these reactions could also be used as a fuel, but since it has low specific-impulse (30 percent of hydrogen/oxygen) and high burning temperatures, it would be better suited for other operations such as in ground and surface equipment than rocket engine propellant. A potential system to make use of all of these systems in a reaction would be as shown in the figure to the figure to the right. Oxygen would be produced by this system along with Carbon Monoxide. Other types of ISRU methods that could be used on the first human Mars missions would involve a more low tech approach. They would entail using the Martian soil for construction purposes. The manufacture of bricks or other building construction materials as described in an earlier section.

4.9 System and Equipment Reuse

Much of the systems and equipment mass that has been used on previous Manned Missions (Apollo), and much of the same mass represented in the designs of future projected human Mars missions all have used a similar design approach. This approach has the systems equipment only performing one function and then becoming inert mass with only a limited role as a structural function. For instance using an Apollo example, the LM had a decent engine, stage hardware, system equipment and structure. On this mission it was only used once for the primary function of landing safely on the Lunar surface. After it performed that function it became just inert structure, only providing a base or platform for the return launch and some of the surface operations. The current philosophy is to approach a human Mars mission in the same manner. The design philosophy has expanded somewhat by trying to make use of ISRU techniques for the production of propellants and consumables, but with equipment and mass that we bring to the surface we are still using the previous philosophy. This gives us a tremendous opportunity. With the ISRU philosophy we are trying to make some changes in the design to obtain mission advantages and benefits by using some very raw materials that we hope to find there. However, we seem to not consider much of the “resources” that we have brought to the surface with us and then are not using after their one time use. If we used the same type of creative design methods and philosophy as we do for ISRU and apply it to the design of our own equipment. Lets call this philosophy DRU (Design Resource Utilization). If we applied DRU, to the design of for instance the same type of example as the Apollo mission. The LM could possibly have used the same stage to land and then take off again after shedding some of the landing structure. This would have been a mass savings of a considerable margin, especially if you backtrack it all the way back the initial launch. There would have been some trade-offs that would have to be considered but it would have been an option. More options would have been with for instance with structural components on the LM. They were only used once for the landing and then had little secondary use. If DRU was applied you could come up with a number of design scenarios. Such as if you designed a structural member on the leg of the LM to then be used for a structural member on the lunar rover giving it a second life. This would have reduced the mass that you would have had to bring as primary equipment. Another example would be to use part of the foot pad, if it was designed with this in mind, to detach and then connect to a structural member from another part of the vehicle, and thus creating a shovel, one of the most basic of tools. This number of feasible dual-use designs is significant, and is a function of time of construction. The Apollo type mission is limited, because of the time scales involved. But for a human Mars mission, with a much longer duration time, the complexity of systems and number of potential dual-use systems would be enormous an only limited by our creativity. Such designs could also be applied to secondary or back up systems, increasing mission safety and reducing risk. The type and number of systems that could be devised, and the potential benefits in safety, mass savings, mission reliability, it would be a favorable to apply DRU techniques for the future planning of Mars and other human missions.

4.10 Astronaut Surface Mobility Systems

The objective of the Astronaut Surface Mobility System (ASMS) is to provide transportation of one or two space suited astronauts (one pilot and one passenger) within short range (5 km radius of operation) from base camp or main rover in a

short and effective manner. The system will be simple, lightweight, and quite frugal in power consumption. Because the astronauts will spend only a short period of time to conduct a mission within this short range, the system will be totally unpressurized. In this short mission duration, the EVA spacesuits will be expected to handle all of the hazards of the Mars environment.

The following are the candidates for ASMS:

1. Mars Stilts - Due to rough and dusty terrain on Mars, it may prove difficult for astronauts to walk around and conduct geological exploration in certain interesting regions. The lightweight, collapsible, telescopic stilts that operate using compressed gas will occupy only a very small footprint on the surface. They may be carried along with the geology backpack kit and deployed as needed. On difficult terrain, it may be possible for the astronaut to take much larger strides wearing this system (and hence cover larger exploration areas) and because astronauts will be at a higher elevation from the surface, they could also appreciate the surface topography from a better vantage point.
2. Jet Pack - The acceleration due to gravity on Mars’s surface is about 40% of that on Earth. A jet pack with a simple, cold gas pressure vessel gas tank will provide a good lifting force on Mars. Astronauts will be able to travel relatively fast in an emergency situation. The gas tank can be re-pressurized at the base camp or main rover with the abundant CO2 from Mars’s atmosphere (See Fig. 2).

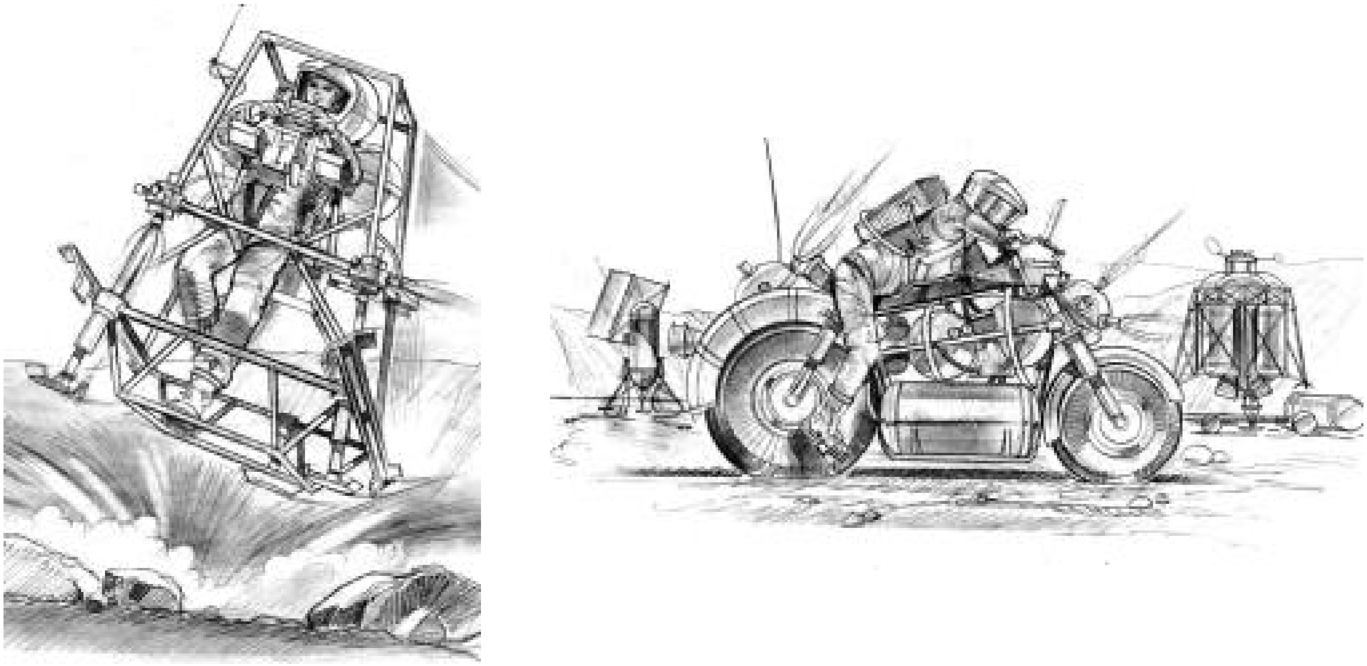

Figure 2: Surface Mobility Concepts

3. Hang Glider - Astronauts could ride the hang glider after they are lifted up by the jet pack. They will remain in the air for a while before approaching surface again and then they can re-fire the jet pack to lift themselves to the air again. However, since the atmospheric density is only one hundredth that of Earth's at sea level, very large wingspans/surface areas that need to be effectively deployed during this mission still need more investigation.
4. Blimp - An aerodynamically shaped blimp with large aspect ratio and a small engine could fly an astronaut pretty fast with little fuel. The blimp could be equipped with solar arrays to generate some power. The engine could be a regular gasoline/methane engine with Oxygen/CO2. The Methane could be from in situ resource utilization. The radiation heat generated during operation will keep the engine warm enough to operate and the water by product could be collected and used.
5. Hot Air Balloon - The hot air balloon could be easily deployed by heating up the gas in Mars atmosphere. It could attach solar arrays and turbines, which run by solar power to help generate lift and thrust.
6. Cable Cars - The temporary cable car could be use to transport astronauts just like at the ski resort. It could run by man power or solar power. This system could transport crew and cargo between chasms, gorges and large gullies that are hard to get across using conventional means.
7. Parachute - In Mars canyon surveying, particularly in the shallow sloped hills, Astronauts could use controlled parachutes/parafoils to speed down hill with their feet only 2-3 feet above the surface. The parachute will slow them down and they will be able to control their movement in the air.
8. Ski - In some parts of Mars canyon and surface, the soil may be mainly composed of sand and dust accumulation due to the vigorous aeolic activity presenting a very smooth topography akin to sand dunes and quick sand pits. Astronauts could use skis and gravity to move around in this environment.
9. Small Helicopter/Gyrocopter - A small, lightweight helicopter/gyrocopter with counter-rotating turbines to diminish residual angular momentum, small engine, and open structure could be an alternative to the blimp. These piloted vehicles could hover over areas of interest and fly in and out of tight spaces such as would be encountered in canyon and valley floor exploration.
10. Two Wheeled Rover - Due to the rough terrain on Mars, four wheeled vehicles would experience a lot of vibration because it would be difficult to maneuver through the rocky terrain. A two wheeled rover or motorcycle could easily maneuver itself over this kind of terrain and hold its track to the smoother surface (See Fig. 2).

5. The Very Long Range Traverse Vehicle

5.1 Landing Sites & Traverse

The landing site selected for this mission was chosen for its closeness to equator, and for its proximity to the geologically interesting regions of Valles Marineris and the Tharsis regions. As stated earlier, the main objective of the mission is to explore geological and geophysical features for determining suitable areas for future permanent bases. The landing site selected, Chasma Perrotin, which is located in a safe distance for eastward approaches from the tall volcanoes of the Tharsis region, fulfilled this main criteria. Additionally, all the Martian region types are easily within reach of this site. These regions are defined as Equatorial Plains (EP), Northern Plains (NP), Lava Flow (LF), Channel Terrain (CT).

For effectively exploring these vast regions, a very long range traverse vehicle (VLTV) concept (See Fig. 3) was developed. Comparable to NASA's earlier designs, the VLTV was designed to be able to operate independently of a base, to sustain a crew of three for durations of more than 150 days, over traverses of more than 5000 km. The VLTV, therefore, includes a well-equipped laboratory for detailed sample analyses, a separate workshop area for repairs and preparation of scientific payloads that is soft landed from an equatorial orbiting cargo bus, and a number of systems for exploring and sampling the immediate areas around the VLTV during its planned 3-5 day stops, including blimps, small unmanned rovers, and crawlers, and a drilling system (See Fig. 4).

The VLTV is a large (13m long with a diameter of 5m) and heavy vehicle (25-30 MT). Therefore, detailed visual and sounding information regarding the traverse path giving surface structure, and surface and subsurface conditions are required. A blimp sized at 10x20 m deployed and some $<1m^3$ stowed would be able to carry a payload of 10 kg, including an air pressure operated harpoon for sample collection, camera, sounder (1-1000 MHz), and an IR spectrometer. It would be used both for sample and data gathering, as well as for flying ahead of the VLTV for checking and assuring stability of the unimproved terrain along its planned track. For the detailed planning of the VLTV traverse, MGS high resolution images (down to 1.5m) in combination with sounding information from the Mars Express will be utilized. The VLTV will also carry Athena derived rovers, with instrumentation similar to that of the blimp. However, instead of the harpoon, the rover will have robotic arms for scooping and picking up surface material. Crawlers will also be included on the VLTV. Supported by an "active" umbilical, that serves as structural tether, power cord and communications link, these vehicles will be designed for controlled descent down steep slopes and cliffs of the canyon system for reaching otherwise hard to get to rock surfaces. Instruments will be similar to those on the rover.

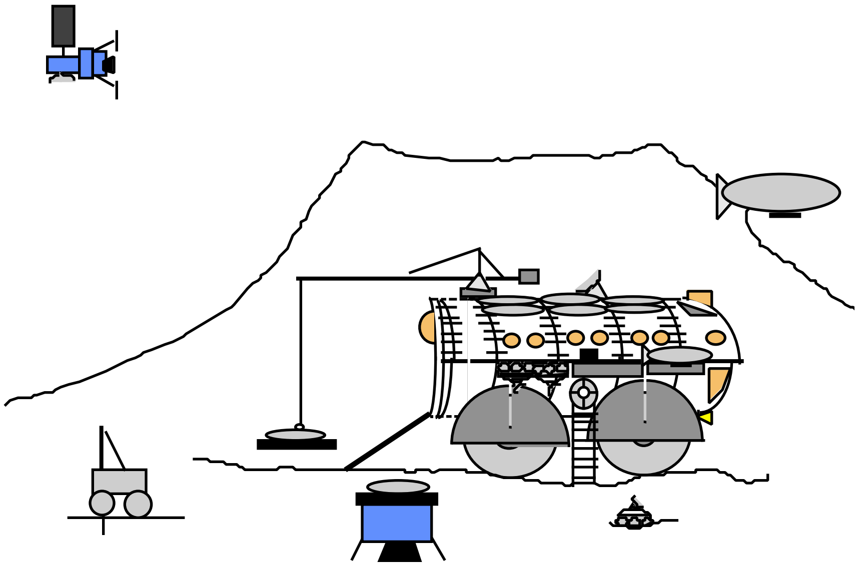

Figure 3: VLTV and Related Support Systems

The VLTV will carry basic geological field tools such as a rock drill for coring down to 15 cm, rock hammer, chisel, rake, shovel, scoops, tongs, long extension handle, sample scale, sample collection bags, and sealable containers, binocular microscope. These tools will be used by the VLTV crew during EVA.

An extensive suite of geophysical instruments will also be available to the VLTV crew. Some of these instruments are, electromagnetic sounder for detecting water and volatiles, and for measuring the variation in the dielectric constant and bulk densities of the soil. Frequencies 1 to 1000 MHz; Active seismic experiments for determining the structure of the upper Martian crust (2 km depth) through the use of geophones and possible detonation of explosives; Traverse gravimeter for determining gravity variation over the Martian surface; Electrical properties experiment for determining subsurface structure and water down to 1 - 2 km; Profiling magnetometer for measuring local variations in the Martian magnetic field.

The VLTV internal laboratory would be fitted to make it possible for the rover crew to analyze the collected samples for possibly changing or modifying a planned traverse without going back to a base. The laboratory should therefore include equipment such as mass Spectrometers for determining molecular level particles, optical, electron, and atomic force microscope for high magnification sample analysis, crystal growth experiments, X-ray spectrometer for accurate elemental analysis, neutron spectrometer, analysis and detection of organic materials, IR Laser Spectrometer for detecting trace gases indicative of biological activity, UV laser spectrometer for detecting Nicotinamide Adenine Dinucleotide (NADH) which plays a central role in the oxidative metabolism process, centrifuge spinning up to 30,000rpm for molecular level separation, possibly a vacuum chamber, and an oven with mass spectrometer.

In addition to these systems carried on the VLTV, a logistics lander in an equatorial orbit will place geophysical /meteorological monitoring packages at selected spots along the traverse. This package may include a magnetometer for measuring magnetic field strength and direction; passive seismometer for measuring seismic events; heat flow probes for measuring heat flow in the near Martian interior; meteorology sensors for measuring temperature, atmospheric pressure, wind velocity, humidity and atmospheric opacity and dust transport, mass 100 kg. The VLTV work shop area will used for testing and setting up these packages. The actual deployment of the instruments will require some EVA. It is assumed that the mass of this package will be around 100 kg. Micro and nano technologies are expected to reduce this mass estimate by 2006, which

Figure 4: View From the VLTV Cockpit

is the defined technology cut-off time for this mission. The package will be left by the VLTV crew and set to transmit data back to base camp, and possibly directly to Earth via an orbiter. The lander will also be able to carry fuel tanks, water, and oxygen making it possible to extend a traverse, if needed.

Based on preliminary findings, a geologically diverse traverse covering the areas of Tithonia Chasma (CT), Ius Chasma (CT), Noctis Fossae (CT), Noctis Labyrinthus (CT), Tharsis Montes (LF), Pavonis Mons (LF), Ascraeus Mons (LF), Fortuna Fosse (EP), Tharsis Tholus (LF), Echus Chasma (CT), and Hebos Mensa is proposed (See Fig 5). Later high resolution image, spectral, sounding, and altimeter data may change the route of this suggested traverse.

The VLTV will first head for the Tithonia Chasma/Ius Chasma region. In some places the Tithonia Chasma is about 6 km deep. Overlapping landslide lobes cover the canyon floor and scarps that bound a rift valley within the canyon. On the south canyon wall, distinct bright and dark horizontal stripes can be seen. New imagery indicate possible layering of nearly the entire depth of the canyon. This type of extensive layering has not been seen before in Valles Marineris. It calls into question common views about the upper crust of Mars, that there is a deep layer of rubble underlying most of the Martian surface, and points to possibly a much more complex early history for the planet. Landslide deposits and windblown drifts are other typical features of the Tithonia Chasma.

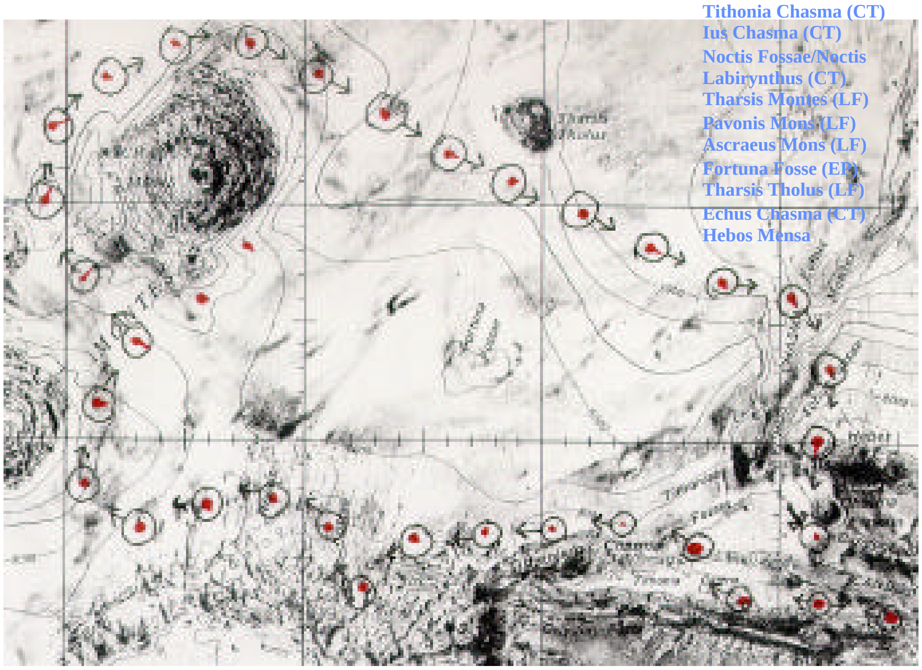

Figure 5: VLTV Traverse Route

Next the VLTV moves into the areas of Noctis Labyrinthus and Noctis Fossae. This appears to be very difficult terrain, and more high resolution images are required before the final route can be set. The origin of the Valles Marineris by faulting is very apparent in these regions. Most canyons have a classic “graben” form. Other canyons are more irregular in form and have rough floor terrains, possibly the consequence of landsliding and the puzzling process of pit formation. In some areas it seems as if surface materials have sifted downward into large subsurface cavities. Noctis Labyrinthus is near the crest of a several thousand km updoming of the Martian crust.

After having explored canyons and cliffs, the VLTV heads towards the large shield volcanoes of Pavonis Mons and Ascraeus Mons in the Lava Flow region of the Tharsis Montes. The VLTV will first drive towards the east side of Pavonis Mons, then turn north west, a route between Pavonis Mons and Ascraeus Mons, then turn north and east to encircle Ascraeus Mons.

Pavonis Mons with a base diameter of some 500 km features a single circular caldera, possibly the result of the last eruption having eliminated all trace of earlier event collapses. On the west side of the caldera small white features, interpreted as dust clouds generated by strong downslope winds, can be seen. The Ascraeus Mons (base diameter 300 km) caldera, stretching to 11 km above the surrounding plains, shows a high number of event collapses.

The VLTV leaves the Tharsis Tholis region and heads over the Equatorial Plains in the Fortuna Fossae area to the south of Tharsis Tholis. This is a smaller volcano with a base diameter of 150 km, and height of 8 km. Approaching the volcano, the indented western flanks can be seen. Similar indentations appears on the east flank. These indentations might have been caused by the center of the volcano collapsing when the lava supply drained away.

From Tharsis Tholus, the traverse continues over equatorial plain type of terrain east towards Echus Chasma. The initial plan calls for a crossing of the chasma. However, more accurate altimeter data, and high resolution images are required before making that decision. The same type of data is required for selecting the route from the Echus Chasma, through Hebos Mensa back to base camp at Chasma Perrotin.

If the first traverse is completed successfully, and time permits, another traverse might also be attempted eastwards starting at day 350-400. Such a traverse will be discussed in a later paper.

5.2 Power and Drivetrain Systems for the VLTV

For any mobile mission architecture to be successful, propulsion systems for mobility must be able to provide sufficient power and reliability for an extended stay on the surface of Mars. The various surface mission elements require a significant amount of work in terms of horsepower (drilling for surface water, traction for a 30 - ton surface VLTV, digging of soil, etc.) and the question of power becomes more apparent. Nuclear power for the base camp architecture is a definite first choice but does not meet the needs for the mobile mission presented in this paper. The amount of shielding required and the risks of moving a reactor over unimproved terrain in a trailer quickly leads to the need for an alternate source of power. Since methane/oxygen ISRU production is already providing the propellant for the ERV proposed in the NASA reference mission, internal combustion of methane and oxygen in piston engines provides an attractive option for surface mobility. The greater power density of combustion engines provides for enhanced mobility, which enables a year-round, cost-effective mobile exploration program on the surface of Mars.

5.2.1 Current and Future Alternative Fuels Technology

Methane combustion and hydrogen fuels cells have not received much consideration in past space exploration mission for obvious reasons. But for a manned mission to Mars, these technologies become increasingly feasible as ISRU methane and

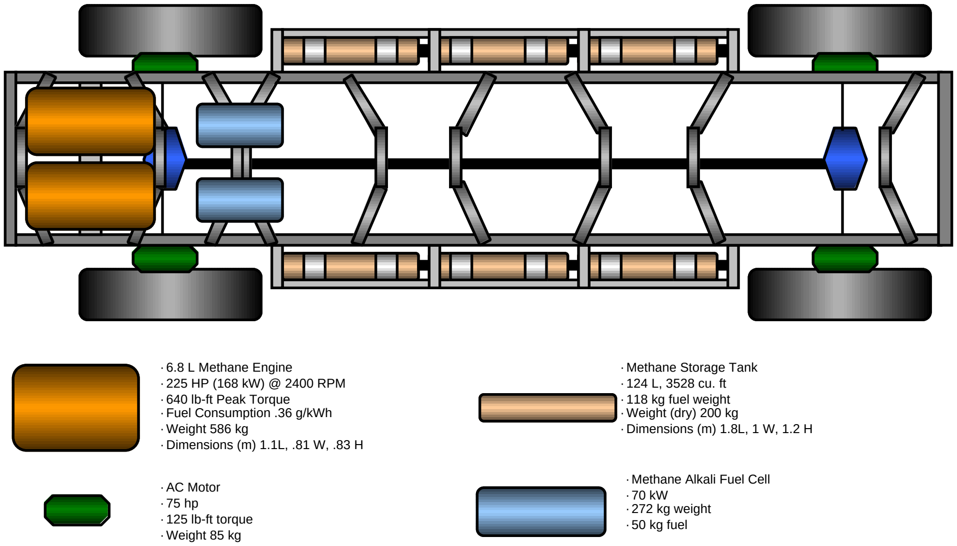

Figure 6: VLTV Drive Train and Power System

oxygen production on the surface becomes practical. On Earth, the amount of research dollars pouring into alternative fuels technology for transportation is being driven by the onslaught of deregulation in the natural gas and electric industry. State politicians wishing to provide alternative electricity suppliers with a fair chance in the new competitive US energy market while addressing the needs of environmental lobbyists are encouraging the advancement of green power generating technologies through legislation and government subsidies. For example, California State Senate Bill 90, enacted on October 12, 1997 placed the $540 million of the renewable energies program, the aim of which is to subsidize the cost of alternative fuel research. Advances in natural gas (methane) and hydrogen fuel cells for vehicle transportation are offering viable alternatives to enable surface mobility of crewed vehicles on Mars.

5.2.2 Methane Combustion on Mars

The current reference mission calls for the on-site production of methane and oxygen to fuel the Earth Return Vehicle. Six tons of liquid hydrogen brought from Earth will react with the carbon dioxide rich atmosphere of Mars to produce water and methane (methanation). Electrolysis will strip the hydrogen atoms from the water molecules to be re-used in the chemical process. The result in 10 months of production will be 108 tons of methane-oxygen propellant. Assuming that the ERV will require 96 tons for the trip back home, this leaves 12 tons for the VLTV [Exploration99, p. 47].

The VLTV's primary power source will be two 6.8L dedicated methane engines, one operational and the other standby (See Fig. 6). An internal combustion of 10% methane, 70% oxygen, and 20% carbon dioxide (replaces nitrogen as expander gas in Earth-based combustion engines) will provide 225 HP (168 kW) of power per unit. A turbocharger will be needed to compress the Martian atmosphere prior to induction into the engine cylinders given that the outside atmospheric pressure is only 1% that of Earth. Assuming the VLTV travels an average speed of 24 km/hr, this engine will consume approximately .37 kg of methane/oxygen fuel for every kilometer traveled. Given that one liter of methane/oxygen fuel weighs .95 kg and the engine is able to push the VLTV 2.55 km per liter of fuel consumed, a 4800 km trip will require approximately two tons of fuel. Liquid methane and oxygen produced by the ISRU plant can be transferred to storage tanks on-board the VLTV. The fuel storage capacity with 6 methane tanks and two oxygen tanks can give the VLTV a range (before refueling) of 1800 km. The following drawing shows the VLTV chassis with the engine and storage tank configuration.

5.2.3 Regenerative Hydrogen Fuel Cells and Electric Motors

Since the methane engine will provide electric power through a belt driven alternator when the VLTV is in transit, the need for power arises during the times when the VLTV is at rest. Also, a back up propulsion system will be needed in the event of engine failure. An alkali cell, fueled by 50 kg of liquid methane can provide 70 kW of power at 70% efficiency. Two of these power plants with a combined weight of 544 kg would provide sufficient electric generating capability to run independent AC motors on each of the wheels, enough power would remain for on-board VLTV systems. The alkali cell also produces water vapor as part of the reaction, which can either be condensed for crew consumption or stripped of hydrogen to be used in the cell (remaining oxygen to be pumped into the oxygen tanks).

One major drawback of this technology is that the potassium hydroxide electrolyte reacts with carbon dioxide to form potassium carbonate, which not only gradually degrades the electrolyte, but also precipitates out and clogs up the pores of the electrodes. Since carbon dioxide is abundant in Mars's atmosphere, this is a major problem, though one European company (Zevco) claims to have overcome this limitation, and is producing alkali fuel cells for vehicles on Earth [Fuel00]. If this technical problem has already been solved today, given the rapid advances in fuel cell technology, the alkali cell will be a practical power source in five years time.

5.2.4 Risks/Benefits of Methane Technology for Mars Exploration

Methane combustion engines and fuel cells provide an efficient, cost-effective source of power. The health concerns of the power systems are non-existent when compared to nuclear power as an alternative to powering a mobile system. Methane combustion engines have been tested and are currently in use in Arctic environments whose operating conditions differ from that of Mars only slightly. These engines can be tested in a vacuum chamber simulating the atmospheric pressure of Mars in order to verify the feasibility of this power source.

Any vehicle powered by internal combustion will contain numerous moving parts. Lubricants and other fluids will need to be developed that can be effective on the Mars surface environment. Spare parts such as hoses, filters, and drive belts will have to be brought along also. The power systems presented here are also entirely dependent on the success of ISRU methane/oxygen production, as is the successful return to Earth. Given 5 years of further research, the size, weight, and power output of methane combustion engines and fuel cells will be more than sufficient to meet the power needs of any mobile mission architecture for the surface exploration of Mars.

5.3 Science On Mars

Does Mars have the necessary geophysical, geological, and meteorological characteristics and resources to support humanity's ambition to settle there? Several scientific experiments may be done by the first crew to arrive and move about the Mars surface. The crew may be instrumental in setting up experiments and monitoring activity and evolving and changing out science payloads during the course of their 619 day stay. These include exobiology experiments to detect if life could have or continues to exist there, a variety of geological and geophysical experiments covering areas such as plate tectonics, volcanism and mineralogy, and magnetotelluric experiments to find out more about the dynamics of the planetary core and present activity.

Science payloads include equipment to detect and monitor water content in the atmosphere and on the surface as well as probes to look for it in subsurface strata (the deep drill is explained in a separate section); Biological and palentological payloads to explore for signs of life, past and present; Stations to continually monitor aeolic activity, dust transport mechanisms and seasonal changes over long durations, possibly in the order of 15-20 Martian years; Seismic stations operating over similar periods, enabling us to build up better models of tectonics or other local phenomena; and Solar studies and interaction with Mars environment including insulation, radiation and effects in the thin CO2 atmosphere. Potentially, one might also consider placing more exotic payloads such as gravity wave detectors, and very long base interferometry systems on the Martian surface.

Some of the unique physical features on Mars lend themselves to conducting unusual experiments. One such experiment is the Long Term Mars Atmospheric Profiler (MAP). The MAP could make it possible to profile the atmospheric environment of Mars over the long term, from surface level all the way to the top of a 28 km high volcano such as Olympus Mons, the tallest volcano in the solar system.

The MAP suggests a conceptual method for gathering data on atmospheric characteristics and environmental interactions through the use of a very long "active" tether. This tether has built in nanotechnology sensors that can detect and monitor variables including pressure, temperature, wind direction and speed, moisture, vibration, magnetic measurements, dust, and Solar radiation.

These nanotechnology sensors connected to a fiber optic data cable are integrated with the tether. The tether system may be deployed by a spacecraft lander on the top of a volcano, or by using a tow missile from the surface. Once deployed, the sensors will relay data to the lander/tow missile launcher. From there the data may be transmitted to a Mars orbiting satellite. Over a period of several years, it might be possible to build up a model of the Mars atmospheric profile.

5.4 Mars Drilling Operations

The Mars Deep Driller. (See Fig 7) is a drilling system that will initially reach depths of 100 meters using an air dust drilling method (schematic shown below). With this method, compressed air (CO_2) will travel down the shaft of the drill rod, blowing the dust and debris out of the wellbore. The compressed air also serves as a lubricant. Most types of Terrestrial deep drilling systems use water saturated mud as lubricant instead.

The deep drill system consists of compressor components and drill components. The proposed Compressor system has the following specifications: 2500 CFM (cubic feet per minute) average while filling, 2500 cm^3 tank capable of holding liquid CO_2, valves will release gaseous CO_2 at 100 CFM, heaters to keep tank/valves above –60º F, and a 30 HP (22.4 kW) pump. The drill system can be characterized as follows. It includes drill rods and bits, a air/dust deflection plumbing & wellbore chute, and a drill holding structure with momentum wheel & hammering system. Overall dimensions stowed are 3 meters long, 3 meters wide, and 3 meters high, and overall dimensions deployed are 3 meters long, 3 meters wide, and 7 meters high. Power Requirements: 50 kW minimum continuous, 22.4 kW while roving. Mass excluding drill rods for the system is 1300 kg, and the mass of the required liquid CO_2 150 kg. The system is capable of drilling to depths of 3 km.

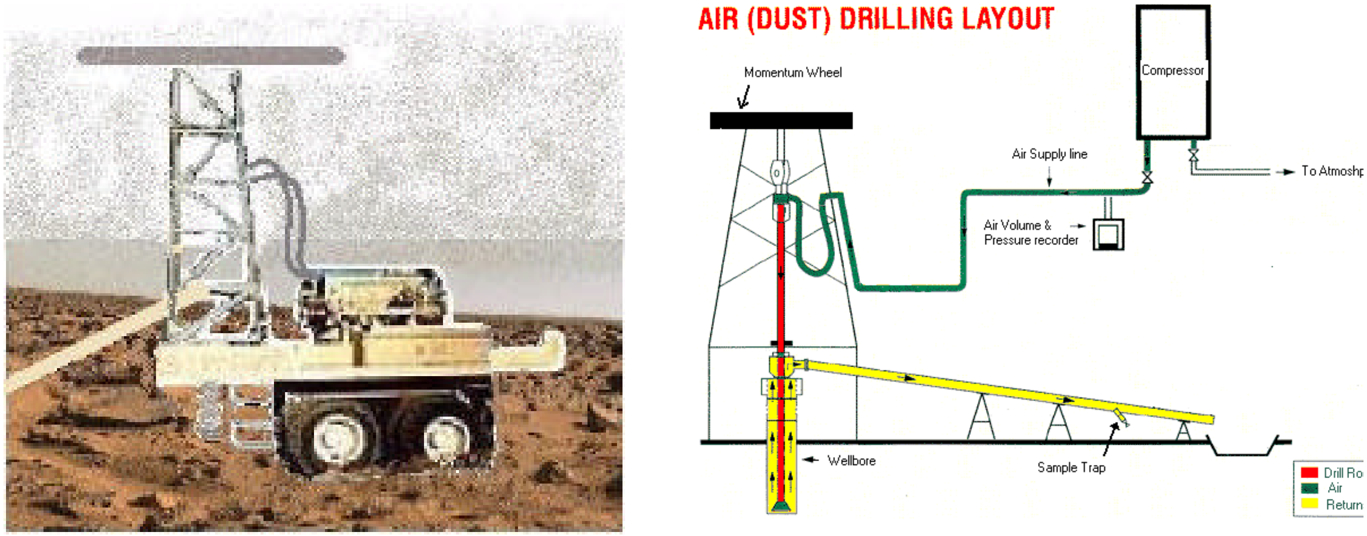

Figure 7: The Mars Deep Driller

Since the probing depth of the Deep Driller will only be 100 meters for the first roving mission, the best spots to drill will be at the low lying terrains for finding water or ice. The bottom of any river channel such as the bottom of Valles Marineris, or any dried up lake bed will be a prime spot. However, it will also be useful to drill to smaller depths of only 10 meters along the route to map out the characteristics of the soil over the entire general regions. Using software to monitor and record the composition of the dust in the various areas will aid further in determining the best possible sites to drill.

The Deep Driller is mounted on a 4-wheeled trailer for maximum portability. The drill can be used in conjunction with the VLTV, or at various sites around the habitat area.

The Deep Driller will have its trailer connected to the VLTV for towing along the route. When the VLTV has stopped at a drilling site, the drill can be automatically disconnected from the VLTV (except for the power and data cables) and guided to a drill spot at maximum 500 feet away. There will be a connecting power/data line to the drill to perform the initial set-up sequence.

There are two different scenarios in which the Deep Driller will operate. The first is at the base camp. Before and after roving missions, there will be ample time to perform drilling operations. The second is along with the VLTV while exploring the surface. When the VLTV begins its operation, the compressor will also be running to fill the CO_2 tank. Power is limited with the Driller; therefore it will drill in bursts. Once there is enough CO_2, a momentum wheel will power up to assist with the torque required for drilling. Once the drill rig is operating, EVA may be required to assist the robotics in adding the drill rods at which time core samples can also be gathered for analysis within the VLTV. All information will be recorded including the amount of ice and the mineral composition at the depth it was drilled. Drill rates of up to 12.5 meters per hour are achievable. This is much better than most conventional drill methods used currently on Earth.

Continuous air drilling can get to substantial depths in a short period of time. The limitation for the first mission is the weight and volume of the drill rods. The thin air on the surface also requires more time to fill up the compressor. Future missions will continue to bring additional drill rods increasing probe depths to 3 km, depending on subsurface layer content. For the first few missions, it will take about 30 days to pump enough CO_2 to drill for 12 hrs (up to 150m). The Driller will be working intermittently, taking up to five days to deplete the 30-day supply. The system is electrically driven which works well given the VLTV and base camp will be providing electricity. However it restricts the distance at which the Driller can be from its electrical power source. A total autonomous system would be the most desirable, however complexity becomes inevitable. EVA may therefore be required if component mechanisms becomes stuck or jammed.

5.5 Emergency/Rescue System

Crew Safety is of the highest priority in human space missions. Therefore, the Emergency Rescue System is an integral part of this mission plan and architecture. There are various alternatives to emergency or rescue operations, and each one of them are specific to possible failure modes and effects that we envision. Our Mission Plan focuses on the VLTV for terrain exploration. This VLTV would cover long distances and any one traverse would take 150 days. On such long duration traverse crew safety would be essential in the event that the VLTV systems fail. For such failures we have a rescue rover that would be positioned at Base Camp and would set on the rescue mission when summoned. This rover might take as long as 6 days to get to the VLTV and depending on the type of emergency this may not always be a viable solution. Another alternative is to have a "rocket hopper" which would be a sub orbital vehicle stationed at the base camp. The rocket would be loaded with the necessary supplies to sustain the crew and then launched to the location of the VLTV. Landing would take place by parachute and the ISRU station would supply the fuel. This would be a one-time use vehicle and would provide immediate assistance to the stranded VLTV crew until the rescue team gets there.

6. Further Studies

All of the sections above require more detailed investigation. Also, these concept architectures could be better coordinated with NASA studies in progress. In particular, experiments need to conducted in the following areas.

ISRU Structures: The USC Mars team would like to build and test ISRU structures for extraterrestrial infrastructure development and derive metrics as well as study human robot interaction and synergy and develop tools for improving the efficiency and rate of build up activity. Land and facilities are available to construct and test simulations of extraterrestrial habitats and infrastructure.

The VLTV: More research on similar vehicles and their capabilities on Earth need assessment. It may be possible to adapt existing systems and mechanisms for the Mars missions. Simulations need be conducted on Earth that prove the validity of using large vehicles in harsh conditions over unimproved terrain. It is possible to imagine that a full up simulation may be undertaken on the lunar surface in advance of the Mars Surface Expedition.

Interplanetary communications: The potential of using NASA reference mission elements for enhancing both local and interplanetary communications needs further study. For example, it may be possible to use the Transhab or the Earth Return Vehicle (ERV) communications platforms to augment the Mars orbital communications infrastructure. Also, during predicted communication blackout periods, it may be possible to use other spacecraft operating in the inner solar system as missions of opportunity at the time to relay data.

Multipurpose Systems and Equipment Reuse**:** This whole area needs detailed investigation so that uses can be built in very early in the design of systems rather than seize opportunities as and when they occur. It should be possible to coordinate this approach with the NASA reference mission activity and explore alternative uses for expendables.

7. Conclusion

A human mission to Mars in the new millennium could be the next major program for the space agencies of the world as the construction of the International Space Station is completed. International in scope, employing a highly synergetic human - robot complementary architecture, the first crew would set about exploring Mars to find out if life ever existed there and if humanity can settle there. An aggressive first mission architecture employing a base camp and long range traverse vehicle may provide all the data needed for future long term settlement missions. Such a mission would provide a coherent vision and nucleus for humanity’s next step at the space frontier.

Such an interplanetary mission requires extended and complex preparation. End to end simulations of the mission on Earth, in orbit and the moon are proposed as a way to evolve a robust mission architecture. As humans are perceived to be the most fragile part of this system chain, particular attention needs to be paid to sustain their psyche and health and overall well being.

The human Mars missions offer the opportunity for mankind to continue exploration and ask questions that are open-ended in our quest to understand the world and universe that we live in. The technical issues are not the hardest ones to answer as they are usually black and white. It is the policy questions that will be the gray areas that we will have to provide the answers to. The development of our space faring capabilities are a natural extension of the seafaring development that took place prior to the great exploration period and will allow us to continue to grow in the future. We have to be willing to take risks in the quest for knowledge, information and opportunities for economic improvement.

8. Acknowledgments

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