Extravehicular Activity Suit Systems Design:
How to Walk, Talk, and Breathe on Mars

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Abstract

Design parameters for a Mars Extravehicular Mobility Unit (EMU) are different from current space shuttle and past Apollo EMU designs. This report derives functional requirements for the life support, communication, and power subsystems of a Mars EMU from the HEDS reference mission and Mars surface conditions and proposes a design that satisfies all of the currently understood functional requirements for each subsystem. Design for the life support system incorporates O_2 storage, possible O_2 production, CO_2 absorption, humidity control, thermal regulation, and radiation protection. The communication system design centers on a reconfigurable wireless network, virtual retinal display, and emergency locator beacons. Portable power options are analyzed, and Direct Methanol Liquid Feed Fuel cells are selected for use in a design that satisfies the power requirements. Mass, cost, and technological readiness are considered for each system. This paper concludes with a recommended combination of subsystem designs that combine to form the primary subsystems of a Mars EMU.

1.0 Introduction

Mankind has the ability to safely send humans into Earth orbit and to the Moon. We have sent telemetry-controlled robots to the far reaches of our solar system as our hands, eyes and ears. We will gain further knowledge about our past and the nature of the universe by sending a human mission to Mars. To accomplish the scientific objectives that help achieve this goal, a human must interact with the Mars surface in real time. This requires an Extravehicular Mobility Unit (EMU) that will ensure the safe and comfortable survival of the human during Extravehicular Activities (EVAs).

Key parameters in designing systems for use on a Mars EMU include the planned length of the mission, the number of EVAs per EMU, and the indigenous resources and physical limitations of Mars. The required EVA duration from the HEDS Reference Mission is 4 hrs, with a goal of 8 hrs. Assuming a 6 person crew, a 500 day max surface stay [1], and that each astronaut performs two EVAs every three days on average (0.66 EVAs per day per person), this leads to 2000 total individual EVAs. If each person has one suit, it will have to withstand use on 333 EVAs. Less exhausting EVA scenarios are outlined below (Table 1).

Table 1: EMU use with respect to # of EVAs

Days surface stay	*Average EVAs per day per person*	*EMUs per person*	*EVAs an EMU with-stands*	*Total Hours for 4hr EVA or 8hr EVA*
500	0.66	1	333	1330 or 2660 hrs
500	0.66	2	167	670 or 1330 hrs
500	0.5 (includes a day off)	1	250	1000 or 2000 hrs
500	0.5 (includes a day off)	2	125	500 or 1000 hrs

Further design constraints are introduced by environmental parameters (see Table 2) that are significantly different on Mars compared to on Earth or in Earth orbit.

Table 2: Comparison of parameters: Mars, Micro-gravity, Earth [2]

Parameter	*Mars*	*Micro-gravity*	*Earth Standard*
Temperature	130K to 300K	Insulated	288K mean
Pressure	.01 atm (1% Earth pressure)	--	1 atm
Gravity	$3.73 ms^{-2}$ (39% Earth)	--	$9.80 ms^{-2}$
Magnetic field	No current field	Missions within Earth field	Magnetic field
Radiation	About 5-15 rems/yr	Same as Earth	About 0.4 rems/yr
Atm. Composition	CO_2, N_2, Ar, O_2	Not applicable	N_2, O_2, H_20, Ar
Solar constant	590 W/m^2 mean	Same as Earth	1371 W/m^2 mean

The mass of the current space shuttle EMU is 113 kg [23], which would translate into a weight of about 44 kg for a Mars EMU. This is an unacceptable amount for a person to carry. An acceptable weight to carry would be about half that, or 22 kg. A martian weight of 22 kg is equivalent to a system mass of about 58 kg, which is the mass limit that we adopt for this design. From the 58kg, 20kg is allocated for upper body EMU structure, 10kg is allocated for the legs/boots and 28kg is allocated for the life support, power, and communications subsystems.

The goal of the design is to meet the following functional requirements while staying within the 28kg mass allocation (Table 3).

Table 3: System Functional Requirements

Life Support System	*Communication System*	*Power System*
Suit pressure 8.3 psi (including N_2 buffer gas)	30km radius range	Provide 150W
O_2 partial pressure 4.1psi O_2 flow rate 0.074kg/hr	Provide biomedical and diagnostic information	Potential 18V
CO_2 flow rate 0.2035kg/hr	Audio and 1-way video	30 minute min. backup power
Temp. 283-317K (9.85-43.85°C)	Scientific information	
Total dose radiation < 10rems	Independent backup 3km radius range	

Most EMU subsystems require modification from those used on current/past EMUs in order to satisfy both the functional requirements and operate under martian conditions (Table 4).

Table 4: Subsystems Affected by Mars Conditions

Subsystem	*Gravity*	*Temp.*	*Press.*	*Atm.*	*B-field*	*Solar*	*Dust*	*Duration*	*# EVAs*
Gas Exchange	✓	✓	✓	✓			✓		
Thermal Regulation	✓	✓	✓	✓			✓		
Radiation Protection	✓			✓	✓	✓		✓	✓
Int. Communication	✓								
Ext. Communication	✓				**c**		✓		
Backup Comm.	✓							✓	
Primary Power	✓	✓				✓	✓	✓	✓
Backup Power	✓							✓	✓

2.0 Design Approach

2.1 Life Support System

The components that require modification from the existing micro-gravity EMU life support system for use on Mars include oxygen storage and production, carbon dioxide removal, humidity and temperature control, and radiation level monitoring.

The primary design constraint for a life support system is EVA duration. The oxygen required for 4 hr to 8 hr EVAs varies from .092 kg to 1.816 kg depending on EVA length and activity level. Here 0.595kg O_2 is used to supply an 8 hr EVA with average exertion. [3] High-pressure oxygen storage parameters are compared with cryogenic oxygen storage.

High-pressure oxygen gas storage on the current space shuttle EMU can be modified for the Martian environment. The current system contains high-pressure canisters for the storage of oxygen in the Primary Life Support System (PLSS). Two rechargeable primary tanks contain all oxygen needed for the astronaut to breathe during an 8 hr EVA at 6.2Mpa (900psia). In the event of primary system failure, two smaller tanks charged to 41.4 MPa (6000 psia) are backup. These provide oxygen to the astronaut at a much higher rate in purge mode for up to 30 minutes. These are not rechargeable, the equipment to re-pressurize them with the necessary amount of oxygen is prohibitively heavy. (For 60-minute backup, the mass would be at 2.38kg and volume at around 5.10L at 6000psia.)

This storage system has limitations. The thick walls necessary to contain the high pressures, while not a concern in micro-gravity, are too massive to use on Mars. The life support system must be physically small, requiring a more volume-efficient method of storing oxygen. Finally, the high pressure for oxygen storage on the current EMU are hazardous if a malfunction occurs. Leakage and bursting are dangers due to the explosiveness of the pressure as well as the flame-enhancing characteristics of oxygen.

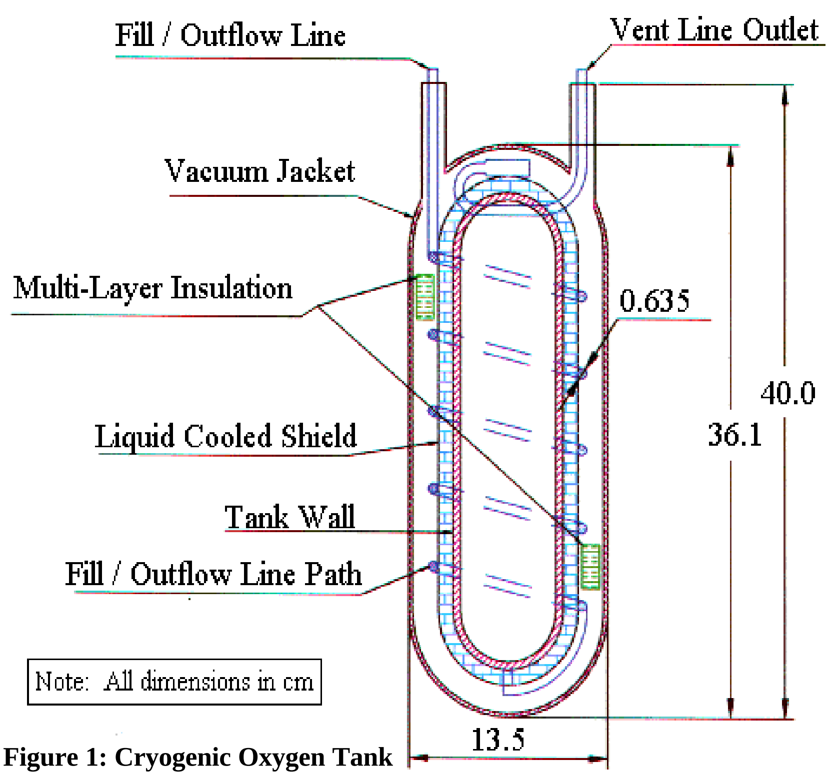

Figure 1: Cryogenic Oxygen Tank

A second proposed method of oxygen storage uses cryogenic tanks to store liquid oxygen. Such a system could use a single oxygen storage device for an 8 hr EVA as well as the 30 minutes of backup. Because it requires too much energy to warm a large quantity of supercritical oxygen passing through the suit during a purge situation, secondary oxygen tanks like those used in current EMUs should provide backup supply. For rechargeability, the secondary canisters may be modified to be filled with liquid oxygen and then warmed to ambient temperature, at which the oxygen will boil, pressurizing the tank.

The proposed tank design is adapted from one suggested by Lockheed Martin for the space shuttle EMU. [3] This consists of an inner tank containing cryogenic liquid surrounded by a liquid-cooled shield (LCS) (Figure 1). This is in turn surrounded by multi-layer insulation (MLI) and a vacuum jacket. This system is designed to minimize heat flow into the liquid so that little vapor venting is required to relieve boiloff pressure. The LCS is key. Outflow liquid oxygen from the bottom of the tank is routed around the LCS to cool it to subcritical temperatures and absorb any heat transferred into the system before it can warm the fluid within. This design reduces heat input to almost zero, and relies on a liquid positioning device (LPD) to keep the cryogenic oxygen over the outlet at the bottom, however, Mars gravity makes this precaution unnecessary. Upon exiting the LCS, the oxygen is warmed to breathing temperature through heat exchange with the power source and liquid cooling ventilation garment (LCVG) explained below.

This cryogenic system addresses the concerns of a portable oxygen supply system in a Martian EVA suit. Using a cryogenic storage method reduces both tank mass and volume over traditional high-pressure systems. This allows for the expansion of the system to carry more oxygen if a longer EVA is desired. Both the cryogenic and high pressure systems can satisfy the life support oxygen flow rate, pressure, and partial pressure requirements, but the cryogenic system can do so with less mass and more oxygen.

Table 5: Comparison Data for two different oxygen storage systems.

	Primary System Mass (empty)	Primary System Volume	Total System Volume	Primary Tank O_2 Mass/Mass	Primary Tank Pressure
High Pressure O_2 System 4 Tanks total	4.4 kg	16.88 L	19.83 L	0.125	6.2 MPa 900 psia
Cryogenic Oxygen System 3 Tanks total	4.0 kg	7.87 L	10.82 L	0.149	< 930 kPa < 135 psia

For subsequent missions, a self-contained oxygen production system that uses the abundant CO_2 in the Mars atmosphere is desirable to produce breathable oxygen dynamically on the EMU. One technology that can achieve this is solid oxide electrolysis. A prototype solid oxide electrolysis unit was demonstrated by University of Arizona Space Technologies Laboratory [4]. Their system heats CO_2 to an operating core temperature of 1023K (750°C), dissociating two molecules of CO_2 into two carbon monoxide molecules and one molecule of oxygen (Figure 2). An electric potential dissociates molecular oxygen into two oxygen ions, which diffuse through an oxygen-permeable yttrium-stabilized zirconia membrane. The ions recombine on the other side of the membrane into molecular oxygen. The prototype mass and volume is 1kg and 3.9L with a steady state power requirement of 9.5W and 15W as the start up power requirement. Reflective ceramic insulation keeps the external surface temperature below 313K (40°C), and oxygen output was 0.5 cm^3/min. [4] The oxygen production is less than the minimum required for human consumption, 0.53 cm^3/min, but of the same order of magnitude. In the future, the production level is expected to rise to provide enough oxygen for dynamic consumption. As a result, suit power will become the only limiting factor for the length of an EVA. Inefficiency from heat exchange with the Mars atmosphere can be decreased through the application of new insulation technologies. For example, silica aerogels

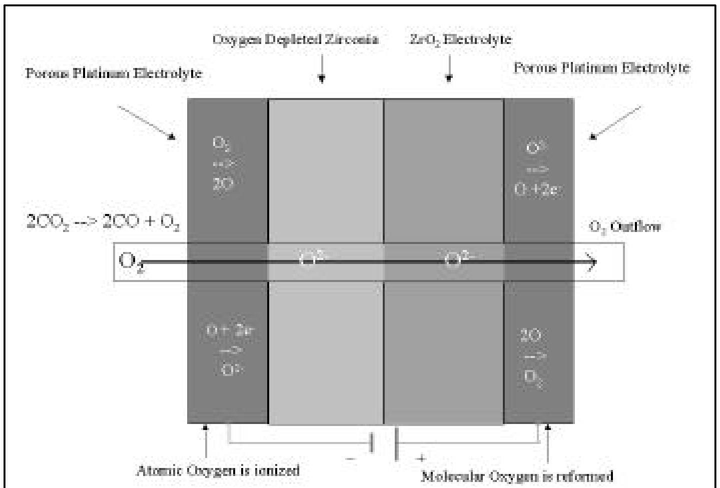

Figure 2: Oxygen Production, Solid Oxide Electrolysis

are extremely lightweight and can be made to be quite strong while possessing an average thermal conductivity of 0.017 W/mK to better insulate the oxygen production cell. [5]

The prototype will be flight tested as part of the MIP (Mars In-Situ Propellant Production Precursor) on the Mars Surveyor Program Lander in 2001[5]. Eventually, further miniaturization and insulation advances may allow the unit to become a standard component in the EMU life support system.

Glow discharge and permeation is another way to produce oxygen from the Mars atmosphere. A reaction chamber heats gas from the Martian atmosphere to 450°C. A glow discharge is generated from a silver electrode that disassociates carbon dioxide into carbon monoxide and atomic oxygen. Oxygen is separated using a silver membrane. A silver lattice structure is selectively permeable to the atomic oxygen, allowing it to pass across the membrane and recombine to molecular oxygen on the other side, where it can be accumulated and used for the astronaut's needs. Carbon monoxide is vented to the atmosphere [6]. The system is at a low level of technological readiness and currently requires 2 kW to produce 1kg of usable oxygen in one day. However, the system does not bring with it any complications involving dust collection and CO_2 pumping, and operates at significantly lower temperatures than solid oxide electrolysis. The system's current status implies that this technology will someday be competitive with other oxygen production techniques for Martian exploration [7].

Several methods exist to remove carbon dioxide. Lithium hydroxide scrubbers have been used extensively on nuclear submarines and past space missions including the Apollo program. Lithium hydroxide (LiOH) spontaneously and exothermically reacts with carbon dioxide (CO_2) to produce solid lithium carbonate (Li_2CO_3).

$$2LiOH_{(s)} + 2H_2O_{(g)} \quad 2\,LiOH\bullet H_2O_{(s)}$$

$$2LiOH\bullet H_2O_{(s)} + CO_{2(g)} \quad Li_2CO_{3(s)} + 3H_2O_{(g)}$$

$$\Delta H° = -25.2 kcal/mol$$

This system has been successfully used to capture exhaled CO_2 and convert it into solid Li_2CO_3 on past space flights. However, the reaction chemistry causes regenerating LiOH to be difficult, making LiOH scrubbers non-reusable. The technique is less than ideal for a prolonged mission where scrubbers for hundreds of EVAs would have to be brought from Earth.

Metal oxides have also been used in past missions. This system relies on the reaction chemistry of metals to take carbon dioxide out of the system. While metal oxide canisters are reusable, the heavy metal substrates cause significant increases in system mass and volume. This problem can be ignored when the system is deployed in micro-gravity, but it makes the system impractical in environments where mass is a limiting factor. [12]

The DARA system, a carbon dioxide removal technique that utilizes solid amines, is the better option. This system, co-developed by the European Space Agency and the German National Space Agency, uses a porous resin as a carrier for series of weak basic amine groups. The mechanism of reaction is:

$$(3)(R\text{-}NH_2) + CO_2 + H_2O \qquad (R\text{-}NH_3^{+} + HCO_3^{-})$$

The solid amine matrix (type DOR-SA-028), produced by Bayer A.G. is composed of a extremely porous polystyrene. Particle size ranges from 0.5 to 1.2 mm, and it is regenerative. When CO_2 load capacity has been reached, 38.1 kg of CO_2 per kilogram of amine at 4kPa partial pressure, the carbon dioxide bonded to the polystyrene matrix can be released by altering the equilibrium of the reaction through a change in pressure or the addition of heat. The high loading capacity allows the total mass of the system to be low enough to make the system practical for EMU CO_2 removal. It is also stable; solid amine active groups and material properties remain intact after 15,000 hours of operation. Even after two years in storage, there is no evidence of material degradation. The reproducibility of the solid amine product is at a replicable quality level. [13] The result of test trials with the system can be used to predict a weight of 2.6 kg for two solid amine canisters. However, power requirements for management and maintenance to the system must be reduced to make the system practical for use on an EMU. [90]

Exhaled water vapor must be removed and recycled. An adult male exhales between 0.15 and 1.5 grams of water per minute [12], so the EMU must remove water vapor at this. NASA currently uses sublimators and lithium hydroxide (LiOH) scrubbers. It may also be possible to use on Mars the same basic methods used in dehumidifiers on Earth: both desiccant- and cooling-based dehumidifier systems might be possibilities.

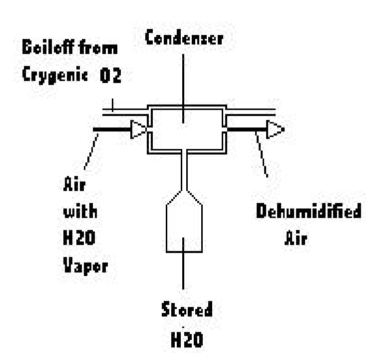

Figure 3: Sample Humidity Removal System

Lithium hydroxide scrubbers are efficient, but not recyclable. The mission would need to bring enough scrubbers for over two years worth of EVAs. Finally, desiccant dehumidifier materials have a high affinity for water vapor such as lithium chloride that combines with water to form a liquid solution and continues to absorb water after solution has formed [15]. After use, the solution can be heated to regenerate the LiCl and water vapor. However, this process requires a fan and volume to hold the solution.

The cooling-based dehumidifier is the most practical because it requires no regeneration of expendables and no extra volumes, and can be used to supplement other parts of the EMU: liquid oxygen tubes may be used as coolant, and oxygen could be heated also in this process, for breathing. This would satisfy the life support requirement to filter out humidity.

A critical life support consideration is maintaining a thermal balance within the Mars EMU. Current space suits are designed to function in a vacuum. However, for the Mars EMU, convective heat loss through the atmosphere must be considered. The range of temperatures comfortably tolerated by humans is about 18°C to 27°C [18].

Current EMU's consist of a Liquid Cooling and Ventilation Garment (LCVG) and insulating materials [19]. Cold water, fed through the LCVG tubes, picks up heat as it circulates throughout the body [87]. The LCVG then separates into two streams, one directed to a sublimator and the other directed to a contaminant control system [24]. The sublimator convects heat and water vapor to the atmosphere [87]. The insulating materials consist of aluminized Mylar plastic, unwoven Dacron, and Orthofabric; these synthetics can protect from a temperature range of -129°C to 148°C, which is sufficient for the Mars temperatures.

Challenges in developing a Mars EMU include heat convection to the Mars atmosphere and EMU thermal accumulation [18]. The EMU heat sources and heat sinks are listed as follows.

Table 6: EMU Heat Sources and Sinks

Heat Sources		**Heat Losses**	
Body Heat	0 – 560 W	Wind	300 –730 W
Fuel Cell	0 – 150 W	Cryogenics	7-15 W
Solar Heat	0 – 120 Wm^{-2} ± 20%	Boots	Minimized
Total Range	**0 – 850 W**	**Total Range**	**300 – 750 W**

Solar heat on Mars is nominally 590 Wm^{-2} with ±20% variation due to the perihelion-aphelion positions. The white exterior of the suit will absorb only an estimated 25% of the heat, reducing the solar effect. The EMU power supply (here a fuel cell) generates excess heat that must be relieved for efficient operation. Convection heat losses due to atmosphere through the EMU surface can range from 300 W to 725 W [23]. Oxygen from cryogenic storage must be heated to breathe. In response to the cold martian temperatures, the solution proposed by Hamilton Standard is the creation of an external thermal garment. However, for thermal insulation to be effective on Mars, layering up to four inches thick will be required [23].

According to Hamilton Standard, the solution to thermal regulation in the suit is passive heat rejection. EMU insulation is minimized and allows heat to escape to the Mars atmosphere. If heat loss is too great, a thermal overgarment, stored on the EMU support cart, can be donned. Hamilton Standard conducted tests demonstrating the ease of donning and doffing the external thermal garments [23] but thick garments hamper mobility. If the LCVG unit is to be used as needed on the Mars EMU, a sublimator cannot be used as there is a problem with its heat exchange mechanics on Mars. [87] Wind speed may not dissipate sufficient heat, requiring an auxiliary cooling device. The sublimator successfully dissipated heat for current EMUs, but it is impractical for use on Mars. The porous plate on the sublimator would get clogged by dust. It is designed for a vacuum and the atmospheric pressure on Mars, 1% of Earth pressure, will inhibit sublimation [87]. A sublimator also vents valuable water, preventing the Mars EMU from remaining a closed system. A convection radiator is another alternative, warm water from the LCVG circulates through a finned radiator on the EMU backpack. The radiator convects heat to the Mars atmosphere but requires a large finned radiator array.

Table 7: Sample Metal Hydride Heat Pump System (MHHP)

	HCI Tests	**Mars Mission Requirements**
Dimensions	0.305 m × 0.610 m × 0.914 m	0.305 m × 0.457 m × 0.080 m
Radiative Surface Area	1.49 m^2	0.261 m^2
Mass	112.2 kg	7.35 kg
Radiator Temperature	56°C	80°C
Heat Radiation	440 W	125 W
Duration	4hrs	4hrs, replacement in cart
Power required (approx.)	20 W with ~10% efficiency	20 W with ~10% efficiency

A Regenerable Nonventing Thermal Sink (RNTS) as proposed by Hydrogen Consultants, Inc (HCI) is a practical option. The system uses Metal Hydride Heat Pumps (MHHP) and a blackbody-type radiator [89]. The low temperatures on Mars would facilitate heat radiation to the ambient atmosphere.

Mars heat radiation requirements are lower because the bulk of EMU cooling is from atmospheric convection. The amount of heat that the MHHP can dissipate varies with the ambient temperature on Mars and the temperature of the radiator surface. The following figure illustrates different radiator temperatures with corresponding heat dissipation. The MHHP can replace sublimator as the cooling mechanism for the LCVG. The MHHP consists of an aluminum radiator lined with tubes of hydride A ($La_{1.1}Ni_{4.6}Sn_{0.4}$) [89]. Tubes of hyrdride B (MM $Ni_{4.5}Al_{0.5}$) are placed in the radiator cavity. Warm water from the LCVG runs over the hydride B tubes and heats the metal hydrides, causing the release of hydrogen. This hydrogen is fed into the hydride A tubes and is deposited onto hydride A, increasing radiator surface temperature which dissipates heat to the Mars atmosphere [89]. Hydride B is the cooling source and hence its temperature be kept just above 273 K to prevent the cooling water from freezing. Using two containers with hydrides A and B eliminates venting; the containers can also be recharged at the base [89]. Compared to the current EMU, the LCVG configuration will remain unchanged. The only major change is using the MHHP in place of the water-fed sublimator.

Thus a solution to thermal regulation to stay well within the required temperature range of 9.85ºC to 43.85ºC involves utilizing the environment as well as implementing an active auxiliary thermal control system. Areas of continued research include other sources of heat loss, MHHP power requirements, and effectiveness of multiple insulative layers.

The radiation environment on the surface of Mars is more difficult to deal with than for previous manned missions for two reasons. First, the radiation that astronauts will be exposed to will be of a different variety than was previously encountered. Also, the energies and fluxes of the radiation will be much higher than designers have had to previously consider. Complicating this fact is the extended duration of the mission. Missions to Low Earth Orbit (LEO) or to the surface of the moon were of short enough duration that weight savings on radiation insulation could be justified by the brevity of the mission. [2] There are three kinds of radiation on Mars:

- Ultraviolet radiation consists of high frequency electromagnetic waves traveling through space at the speed of light. The fact that this type of radiation is composed entirely of energy (and therefore has no mass) makes it relatively easy to counteract. This type of radiation is a familiar concern on Earth, and significant research has been done into inexpensive and effective methods of blocking it.

- Another type of radiation is solar particles, mostly protons, and due to their particulate nature these particles will be inherently more difficult to block. On Earth, much of this radiation is deflected by the magnetic field – protons have a charge, and are deflected by the large field produced by the Earth. Mars does not have any appreciable magnetic field. Solar Particle Events (SPEs), when the sun periodically releases high concentrations of high-energy particles in the form of solar flares and solar storms. are the real danger.

- Very high-energy heavy particles coming from neighboring galaxies are commonly referred to as Galactic Cosmic Radiation (GCR). Although this radiation spreads throughout the universe at a constant rate, surface doses fluctuate in response to solar activity, solar minimums corresponding to the highest levels of GCR and vice versa. These particles will not be detected in large quantities when compared to the normal flux of solar radiation; however, their extremely high velocity and larger mass make them a serious consideration. Again, these particles are not a concern on Earth, as the magnetic field and thick atmosphere deflect most dangerous levels.

Table 8: NASA radiation exposure limits for LEO missions [5]

Exposure Interval	Blood Forming Organs	Ocular Lens	Skin
30 Days	25	100	150
1 Year	50	200	300
Career	100-400	400	600

The normal background radiation exposure on Earth is about 0.4 rem/yr. The occupational limit for high risk jobs is 5 rem/yr. A once in a lifetime emergency exposure of 25 rem is not fatal, but 500 rem over the course of a human lifetime will be lethal (this figure is dependent on many physical characteristics and could vary by as much as a factor of two). [3] NASA has also set limits for radiation exposure for missions into low earth orbit (LEO).

Although no limits have been set for a Mars mission, reasonable estimates can be derived, assuming an overall dosage maximum of 100 rem for the entire mission, of which, 5-10 rem will come from exposure during EVAs. Technology for blocking ultraviolet radiation already has been developed to a relatively high degree. Quality plastics are good enough to stop even the high levels of UV radiation on Mars, and protective coatings can be applied to almost any surface.

Background solar radiation, although dangerous if unshielded, is well blocked by relatively thin layers of shield material. Taking SPEs into account complicates the situation. It would not be practical to provide the astronauts with enough shielding to withstand SPEs at all times. Fortunately, SPEs can currently be predicted up to a day in advance. After one is detected from Earth, an alert to Mars will give the astronauts about 15 minutes to retire to a designated “storm shelter” set up to shield them from radiation storms.

GCR requires the most innovative thought. Unlike SPE radiation that causes damage simply by colliding with molecules in its way, GCR arrives with such momentum that it breaks apart atoms of the shield materials producing secondary radiation particles. In this scenario, small quantities of shielding are worse than no shielding at all. The GCR component of the background radiation on Mars is too energetic to be shielded against without unacceptable quantities of material [7]. Moreover, these fluxes are low enough to justify the omission of this extra mass. Solar particle events can be protected against through the use of a storm shelter. By shielding against UV and background solar radiation, predicting SPEs, and calculating that the GCR radiation is not enough to be harmful, the requirement to protect the astronauts from radiation is satisfied.

2.2 Communications

In the design of this external-to-EMU communications system, the assumption was made that there would be no existing infrastructure for communications (such as a satellite network or local area network) for the first manned mission. This “starting from scratch” approach led to the evaluation of the following system possibilities in selecting a suitable communications network for an EMU and its data interface to interact with.

Table 9: Communications System Comparison

Communications Network	**Infrared**	**Fiber Optic**	**Satellite**	**Reconfigurable Wireless Network**
Supports navigation	✓	--	✓	✓
Mobile/Flexible	✓	--	✓	✓
Robust	✓	--	✓	✓
Allows easy repair	✓	--	--	✓
Practical setup	--	--	--	✓
Upgrade/Extendable	--	--	✓	✓
Flight Tested	--	Not large scale	✓	--
Max. Range	--	4km*	3900km	30km
Network Mass	--	175kg/km	About 8000 kg	About 180kg
Power Requirement	--	--	Solar/battery	10W (EMU)
Mars Dust Factor	Not good	Not good	--	Good

*100 fiber single mode loose tube cable without splicing

Assuming that the first manned Mars mission will have EVA range limited by either the distance the astronaut can travel on foot or by a small rover during a 4 hr (or a goal of 8 hr) EVA, a range of 30km for a surface communication system is adequate. If the astronaut is traveling at a quick clip of 5mph for 4 hrs (this is, for the goal 8hr EVA = 4 hr out and 4hr back), that is only a distance of 20 miles or about 32km. It is only necessary then, to have a ground-based communication system with a range of 30km for the first mission. This saves cost and mass on satellites.

A wireless radio system was selected from the options (Table 9) as being the most mass and cost efficient for a primary mission. In this RF system, the loss experienced by the carrier signal and the range to which it can be detected is dependent on the surrounding terrain. [37] The frequency at which the system operates is in the VHF band (100MHz to 450MHz). A non-mountainous terrain strewn with boulders is assumed. [38] The wavelengths corresponding to the 100 MHz to 450 MHz range are 3 m to 0.66 m. The signal power must never fall to less than 3 dB within the mobile receiver area regardless of the terrain. [34, 39]

Table 10: Revised Communication Design

Current EMU Design		Revised Design for Mars EMU	
External System	*Internal System*	*External System*	*Internal System*
No ground network	"Snoopy Cap"	Local Wireless Network	Virtual Retinal Display
Backup tethering system	Extravehicular Comm.	Mobile base/repeaters	Component relocation
	System control box with data interface display	Remote emergency locators	

The Reconfigurable Wireless Network (RWN) developed by Cornell Professor Zygmunt Haas and collaborator Siamak Tabrizi satisfies the requirements for a ground network. [36] This network is expandable for the increased demands that future missions may have. In addition, it minimizes the power required for transmissions, allowing for hand-held systems (or EMU systems) of a practical size and weight. There is no single point of failure since the RWN is organized in a flat configuration, all users with the same equipment rather than certain transmitters acting as centralized relay points.

Cellular phones on Earth rely on being within range of a base station at all times. Because Mars is not yet populated with base stations at regular intervals, cellular networks cannot be used. RWN can adapt to a changing network topology. This involves adapting to roaming base stations as well as compensating if one or more of them should fail. Haas and Tabrizi [2] propose having each mobile unit function also as a base station, negating the need for mobiles to remain within a certain radius of a fixed base station. [35]

The use of mobile base stations presents another challenge. On Mars, this allows the astronauts to communicate around obstacles and even out of line-of-sight of the lander base. Because of this mobility, a more sophisticated routing protocol that accounts for a changing network topology is required.

There are two general alternatives for routing a protocol. Proactive protocols continuously evaluate the network topology and update this information so that whenever a call needs to be made, the correct route can be immediately determined. Reactive protocols do a global search for the correct route at the time the call is requested. Clearly proactive protocols have a faster response time for calls that are made, yet require a constant flurry of information being sent to update the routes even when no calls are being made. Reactive protocols, because of their idleness, do not tie up the transmission medium until a call is required, yet may cause a significant delay in the establishment of a call.

For RWN purposes, Haas and Tabrizi propose a hybrid of these two extremes - Zone Routing Protocol (ZRP). This protocol performs proactive routing in the local neighborhood of a transmitter, but uses reactive methods for any long-distance communications. This limits the high traffic demands because the continual updates only occur in a limited area (relative to each transmitter), and also avoids the big delays associated with a purely reactive protocol.

Haas [38] has tested this protocol in simulation by using a 10 by 10 mile grid. With randomly distributed 'dark territories' that block communication, he simulated 51 mobile units. When each mobile unit was allowed to move at up to 50 mph, and given a communication radius of 5 miles, the percentage of calls blocked was nearly 0%. For Mars EMU communication, it is unlikely that more than 5 mobile units will be active at a time. Top speed will also be far under 50 mph. Using 10 Watts of power for communication purposes on the EMU is enough to provide a range of at least 10 km at a transmission frequency of 100 MHz.

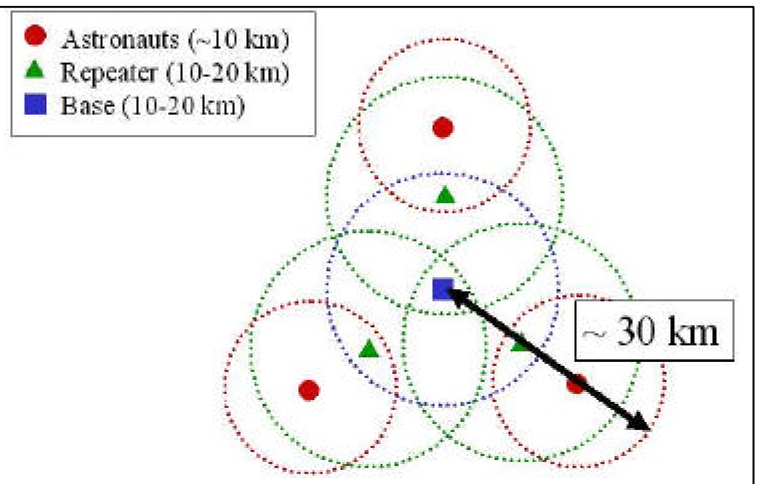

Figure 5: Triangular Ranging using repeater stations

While accommodation for mobility is a very attractive feature of ZRP, it naturally is not restricted to mobile units and can also take advantage of fixed stations. To this end, ZRP can also make use of deployable repeater stations that could be included to lengthen transmission range. A RWN is designed to handle more than our current mission needs and can easily be extended to handle the greater demands of a larger crew.

For decades, the U.S. military, federal agencies and scientific research groups have utilized repeater stations for their receiver-transmitter communication needs. Their scientific uses have proven especially viable in harsh conditions such as those found in Antarctica, where the ruggedness and isolation of the region make a robust communication network necessary. [40] There are two general varieties of repeater stations: active and passive. For use on Mars, an active station is best since passive stations tend to have high attenuation because it only reflects the signal received instead of amplifying it before transmitting, as an active repeater does. Also, a repeater station with duplexing capabilities will be useful, as it will allow the station to receive and transmit signals at the same time. [41] The ideal repeater station will be lightweight and capable of being used for navigation. Examples of commerical and military navigation systems include VHF Omni Range (VOR), Distance Measuring Equipment, (DME), or the common global positioning system (GPS). With the range restriction of 10km, three repeater stations can be deployed to create a triangular ranging area. During EVAs, astronauts will be able to relay signals between the repeater station via their transceivers. Figure 5 shows a sample network scenario with triangular ranging. The astronauts are out of range of the base but within range of the repeater stations, allowing relay to the base

Commercial repeater models like the Motorola GR900 typically have a range of 3-4km [42]. However, at free space attenuation, the reliability of such models is decreased because of their small design. [43] On Mars, a more robust and reliable system is needed such as the MastrIII repeater station designed by General Electric.[44] Such models are frequently used by military agencies because they guarantee not only a range of at least 10 km but are also able to withstand harsh and unusual conditions. [43] Most commercial repeater stations offer a variety of frequency ranges, in both UHF and VHF range. For the purposes of mobile communication on Mars, a range of 150 Mhz in VHF will suffice, as this is the range standard repeater stations operate on. [44]

Table 12: Repeater Stations

Commercial Models	Frequency Range (VHF)	Mass	Duplexer	Transmission Range
GE MastrIII	150 – 174 Mhz	50 - 60 kg	Yes	> 10 km
Motorola GR 300/900	136 – 174 Mhz	10 - 20 kg	Yes	< 5 km

The RF power output of average repeater stations is about 100 watts. [44] This can vary however, depending on the size of the station; the smaller, desktop models output 10 - 25 watts of power. [44] Through the use of a simple high-mounted antenna, this power output can be almost doubled. [43]

The drawback in using repeater stations is simply a matter of mass. Reliable models used in scientific fieldwork and government operations are about 60 kg each. [43] Setting up repeater stations can be the first step to creating an entire relay network on Mars. This approach should be considered first-generation and only necessary because of the reliable backup it offers. The primary alternative, satellites, are much more massive and not easily repaired. They cover a lot more area, but that may not be necessary on a first manned mission.

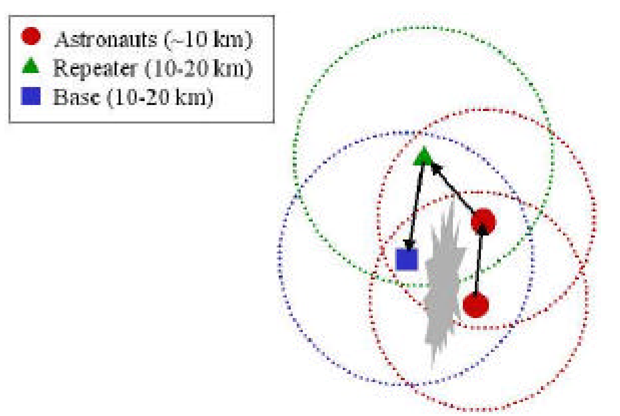

Figure 6: Sample Network Scenario with large obstacle

While the ground-based system we have proposed is ideal for initia l mission constraints, a satellite infrastructure would extend the range of communications and navigation functions to the level required for the significant scientific exploration proposed for future missions. Assuming the habitat delivery vehicle [1] provides a satellite in geostationary Mars orbit (GMO) for a continuous link to Earth, a single GMO satellite could provide reliable communications for a range of approximately one third the total surface area of Mars[70].

Extending the range of expeditions allowed by a ground-based infrastructure requires the addition of many perimeter stations as well as many active intermediate repeater stations to amplify communications and navigation signals. In addition, the presence of surface obstacles requires the redirection of ground-based communication and navigation signals with even more repeater stations. In the long run, repeater stations add considerably to the mission payload, the necessary power support (since each station must be individually powered), and the groundwork required to establish the network.

The current terrestrial GPS satellites weigh 1667 kg each and employ Delta II rockets for launch support into geosynchronous Earth orbit [68]. Adding three LPS technology satellites (the orbiter can act as the fourth) would increase the total mission payload by nearly 5000 kg. For the initial mission, with “roaming” expeditions probably limited to within 10 km, this payload mass greatly exceeds the mass associated with the repeater stations and navigational beacons of the ground-based architecture proposed.

One solution is a radical downsizing of the satellite components in order to provide navigation and satellite communications from GMO orbital altitudes without exceeding the practical payload mass limits. This is the most technologically demanding system proposed for Mars communications and navigation, requiring the most research and development for realization. A mass-based classification scheme has been established for small satellites:

Large Satellite: >1000kg
Small Satellite: 500-1000kg
Mini-satellite: 100-500kg
Micro-satellite: 10-100kg
Nano-satellite: <10kg

In order to match and compete with the payload of the initial ground-based communications network, the small satellites combined with their receiving/transmitting ground support equipment should be limited to a total on the order of 400-500kg.

Another design criterion for communication on Mars is a viable EMU data interface system for use during EVAs. The current space shuttle EVA suits used by NASA implement a communications system which consists of five parts: a headpiece, or "Snoopy Cap," a helmet-mounted video camera, a biomedical monitoring system, a control pad, and an extravehicular communicator that sits on top of the primary life-support system (PLSS). [45]

The Snoopy Cap is a fabric hood that can fit over the head of the astronaut during an EVA. The hood contains an earpiece and microphone as well as a link to an external video camera mounted on the helmet for one-way video transmission from astronaut to base. The earpiece, microphone, and video camera are connected through the suit's hard upper torso (HUT) to the extravehicular communicator via a pass-through. [45] The biomedical monitoring system functions so that both the astronaut and the base may monitor the astronaut's physical status. Electrocardiographic (EKG) information is transmitted in the same manner as audio and visual information: through the extravehicular communicator mounted atop the suit's PLSS. [45] Current designs for the extravehicular communicator used on space shuttle EVA suits are 30.4 cm long, 10.9 cm high, and 8.8 cm wide, with a mass of 3.9 kg. [45] The communicator utilizes two single-channel UHF transmitters and three single-channel UHF receivers for radio communications. In addition, the controls for the communications system are located on the front of the HUT in the suit's display and control module.

Hamilton Standard Space Systems International, Inc., the company responsible for the designs of the current space shuttle EVA suits, recommends base-lining a communications system that is similar to the current space shuttle EVA suit communications system, but with the radio communications components integrated into the HUT of the suit. [23]

The current communication system consisting of an audio transmitter/receiver, a video transmitter, and an EKG monitor operating under the current specifications would probably be sufficient for short-range use on the surface of Mars. But to do better long-range exploring, a more current communications support system, including networking, long-range capabilities, and navigation is needed. A visual "heads-up" display, much like the helmet-mounted displays (HMDs) used by military fighter pilots, would also be useful and keep the astronaut’s hands free.[47]

Figure 7: Sample VRD View of Mars

Microvision Inc. has developed a specific application heads-up display for military aviators and ground troop commanders which uses a laser, monocle-size optical and tiny scanners to “paint” an image on the eye by moving the laser beam across and down the retina. Their screenless device, called a Virtual Retinal Display (VRD), allows the pilot or commander to see the surrounding environment while also accessing digital navigation cues and images that appear to float several feet away, even in bright sunlight. A single electronically encoded, low-power laser beam projects rows of pixels directly on the user’s eye, creating a high-resolution, full motion image directly on the retina. [46]

VRD components are tiny and lightweight, allowing the device to integrate into small, highly portable packaging configurations, such as a helmet or hard upper torso of the suit. The light sources and scanners use very little power to project images on the retina. VRD is able to achieve a wider range of the color palette than any other display technology, modulating light sources to vary the intensity of red, green and blue light. It is capable of interfacing with head tracking systems, video sensor, and display controls which would enhance interaction in the Martian environment. Figure 7 shows a sample VRD display as seen by the astronaut. This includes a basic time and sol number count in the upper right-hand corner. In the lower right-hand corner is a biomedical monitoring table with heart rate and blood pressure data, as well as a distance marking from the nearest repeater or base station. The map allows for navigational tracking, with features such as the base, repeater stations and other astronauts clearly displayed. Navigation parameters are also marked. The left side of the screen includes gas level, temperature and pressure readings. At pr sent, new innovations in miniaturization are shrinking the hardware needed to generate the VRD. Tiny laser diodes will replace larger conventional lasers and handheld displays are being produced in microscopic size.

Table 13: Comparing Virtual Retinal Display to other visual display components

Display Source	Resolution (Pixel Size)	Luminance	Color	Weight	Power Consumption
VRD	.5 Micron	Unlimited brightness	Full color with no loss in resolution	Low	Low
CRT (Cathode Ray Tube)	25 Micron	Up to 1,000 fL	Only with sequential	High (with cabling)	High
AMLCD	12 Micron	Poor – backlight dependent	Yes in 6 VGA resolution	Low	High with backlight
Ferro-Electric LCD	13 Micron	Poor - 20fL	Yes with field sequential LEDs	Low	Low
Thin Film Electro-Luminescent	24 Micron	Poor - 60fL	Yes with field sequential shutters, small color depth	Low	High
Field Emission Display (FED)	16 Micron	300 fL	Yes with low resolution	Low	High
AMLCD on CMOS	12 Micron	Poor - 30fL	Yes	Low	Low

During planetary exploration, there are considerable risks because of the unfamiliarity of the terrain. Simple navigation and emergency-alert systems can be deployed for backup. There are many available methods on Earth, from the Cospas-Sarsat Personal Locator Beacon (PLB) [48,49] system to the avalanche beacons [50] which have been recommended by the International Commission for Alpine Rescue (ICAR). [51] Because it is impractical to assume immediate satellite coverage on Mars due to mass and cost restrictions, a light, simple, low-power homing beacon would be ideal. To achieve the best blend of beacon characteristics, a combination of the Cospas-Sarsat and avalanche beacons should be used.

PLBs have a 406MHz digital or 121.5MHz analog satellite signal as well as a homing beacon. Although their efficiency would increase through satellite use, 121.5MHz homing beacons are viable alone. They have a range of 3-5km, and, if necessary, can be sent in Morse code to include more information. [52] Avalanche beacons are light (230 grams), small (130 x 80 x 25 mm), and have a working life of about 250 hours on 3V batteries. They have high-impact strength and shock resistant casing, can operate between -30ºC and 50ºC, and can be connected to an earphone, allowing for audio transmission. However, avalanche beacons only have a range of 80m. [50]

An ideal beacon would combine the PLB homing beacon with an avalanche beacon. With this combination, a 3-5 km radius could be covered to locate an astronaut. In an emergency, a rescue team would need to come within 45m of the astronaut and then the avalanche beacon could pinpoint his location with an accuracy of 70cm. [53] This simple beacon could be triggered either manually or automatically (by shock), and would send a signal out which could be received by both other astronauts and the base station. All EVA suites should have both a transmitter and a receiver to allow the fastest possible astronaut rescue. An accompanying rover/cart should also have a receiver like the Cospas-Sarsat Repeater Unit to relay the message back to the base. [54]

2.3 Power

The power section compares the practicality of current portable power options and focuses on a direct methanol liquid feed fuel cell (DMLFFC) as the main power source for a Mars EMU with a small battery as backup. Reactant production, reactant storage, fuel cell materials and thermal distribution are analyzed.

The power system for the Mars EMU will be required to satisfy the maximum possible power demand over the duration of a 4 hour EVA (goal of 8 hours). While the Ag-Zn battery currently used to power the shuttle EMU is capable of supplying approximately 70 watts at 17 volts [1], the design proposed here requires ~150 Watts. A new portable, reusable power source is needed to satisfy functional requirements for a Mars EMU:

- 150 W (at 18V)
- Low mass
- Sealed from µm dust
- 4 hr supply (8 hr goal)
- Maximum 333 EVAs use for a 500 day surface stay

The values below break down the total power draw of a Mars EMU as estimated by engineers at Hamilton Standard [2]. Note that these values are only rough estimates that use as a baseline the current shuttle EMU subsystem power requirements.

Table 14: Mars EMU Subsystem Power Breakdown (estimates by Hamilton Standard)

Subsystem	Power required (estimated)
Communications	10 W
Cooling fluid (LCVG) circulation	30 W
Life support	5 W
Lighting / Ventilation	30 W
Instrumentation	5 W
Active Control Valves	5 W
Control / Monitoring System	5 W
Dynamic H_2O separation	10 W
Heaters	35 W
Information Display	10 W
Total Power	145 W

Portable power technology candidates for use on a Mars EVA suit are numerous. However, many are not desirable because they have low power/mass ratios, cannot be reused over many cycles, or are potentially toxic to the astronaut. Nuclear power is quickly ruled out as a portable power candidate, as is solar power because to meet the power requirement, more surface area of solar array would be needed than there is surface area of an EMU.

Table 15: Portable primary power options

Type	Power Profile	Advantages	Disadvantages
Solar	~ 50 W/m^2 (Mars)	Power density Unlimited power	~ 3 m^2 for 150 W Fragile Dust accumulation
Battery Nickel Metal Hydride Lithium-Ion Silver-Zinc	 ~ 55 Wh/kg ~ 250 Wh/kg ~ 90 Wh/kg	 ~ 3000 recharges ~ 2.4 kg for primary ~ Flight qualified	 ~ 10.9 kg Not flight qual. for EMU ~ 6.7 kg, ~100 recharges
Nuclear	High	Power density	Not flight qual. for EMU
Fuel Cell H_2-O_2 CH_3OH	 ~ 300-600 Wh/kg (achieved) ~ 500-1000 Wh/kg (expected)	 Power density Low mass Power density ~ 1kg mass Mars resources	 H_2 storage Still being developed

The most reasonable portable power options are of the battery or fuel cell type. With fuel cells, the logistics that are involved with using a hydrogen-oxygen fuel cell, namely the difficult provision and storage of the hydrogen, prohibit its use as an on-back portable power supply for this application. Batteries seem like a viable solution, with lithium-polymer or lithium-ion batteries as practical choices. These would require electrical recharging, and if they are used as primary on-back power supplies, it would be difficult to get NASA approval for them because lithium is volatile should it come in contact with water, and the cells would be in close contact with a water-based human. It would be easier to get approval for a smaller lithium ion battery to be used as backup. The current silver-zinc (Ag-Zn) battery is practical for use in a micro-gravity EMU, but to provide the additional primary power that would be needed on a Mars EMU would significantly increase its mass (at 283 A h/kg).

The HEDS reference mission mentions batteries as a possible power supply for the EMU. Batteries can be recharged a limited number of times while a fuel cell may produce electricity as long as fuel is supplied. Extra batteries would need to be brought to meet mission duration and backup requirements. A silver-zinc battery powers shuttle EMUs and must be stored dry, filled, sealed and charged prior to flight. Ag-Zn batteries are dense and impractical due to mass constraints. Fuel cells are lightweight compared to the required number of Ag-Zn batteries.

It is desirable to use indigenous resources. Mars has an atmospheric pressure that is 1% of Earth's and consists of 95% carbon dioxide. [60] The HEDS reference mission outlines the use of this carbon dioxide to produce methane for the Earth return vehicle (ERV) propellant using the Sabatier reaction. [1] Robert Zubrin has developed a working model in Mars-like conditions. [61] In order for methane production to be practical, hydrogen must be sent to Mars since no significant source of hydrogen is known to exist on Mars. Conceptual missions have a methane production plant and an earth return vehicle sent to Mars a year before any crew is sent. The plant produces methane from the transported hydrogen and carbon dioxide in the Mars' atmosphere. Once enough fuel is confirmed to be available for a crew to return to Earth from Mars, a crew may be sent. Once methane is available, methanol may be produced by modified standard-industry processes [61] or new processes developed for the automobile industry. This small amount of methanol can then be used as fuel for DMLFFCs. It is possible to synthesize methanol directly from CO_2 and water as shown in Figure 8. [1]

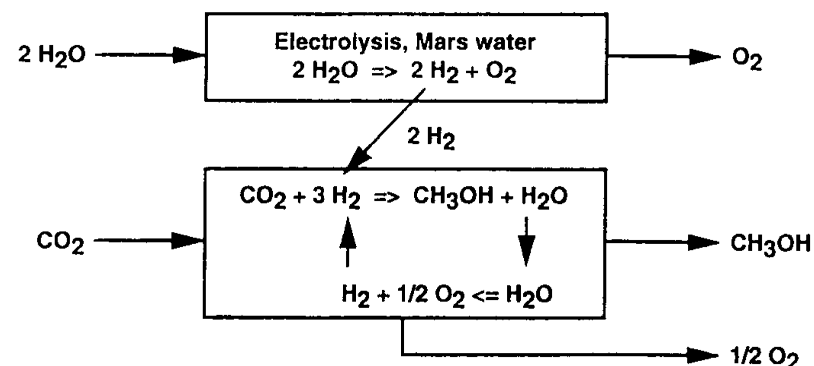

Figure 8: Methanol synthesis from CO_2

A fuel cell stack is built from a number of cells arranged in series. Each cell works as follows: oxygen is pumped into the cathode side, and a methanol/water solution is fed into the anode side, where the anode catalyst strips hydrogen from the methanol. The catalyst atomizes and then dissociates the hydrogen into protons and electrons. The electrons become the generated electricity. This anode reaction produces carbon dioxide, which can be collected or vented out of the system. The protons are then conducted through the membrane-electrode assembly (MEA), made of the anode, Proton Exchange Membrane, (PEM) and cathode, to the cathode side, where they react with the atomized oxygen and incoming electrons to form water. The water can then be recycled or stored for later use. Each cell is separated by a bipolar plate that acts as both the anode for one cell and as the cathode for the neighboring cell. These plates have channels in their surface which distribute the reactants across the membrane assembly. [62]

The anode partial reaction is: CH3OH + H2O à CO2 + 6H+ + 6e-.

The cathode partial reaction is: (3/2)O2 + 6H+ + 6e- à 3H2O.

The overall cell reaction is: CH3OH + (3/2)O2 à CO2 + 2H2O. [63]

The PEM is a polymer film that blocks the passage of gases and electrons but allows hydrogen ions (protons) to pass. [64] Current DMLFFC technology uses DuPont's commercial Nafion, a perfluorinated ionomer with thechemical composition below:

$$-O-CF_2-CF(CF_3)-O-CF_2-CF_2-S0_3H.$$ [65]

Nafion exhibits relatively good proton conductivity but also allows some methanol to cross over from the anode to the cathode side. Researchers are learning about PEMs. Sen, et al. compared Nafion-115 to Dow's membrane material, PFSA-800, to learn in what way water content affects membrane conductivity. They found that resistivity of the membranes decreases sharply with temperature up to 60ºC, reaches a minimum near 80ºC and then increases up to 100ºC. The Dow membrane has a lower resistivity than Nafion-115 over the entire range. They also found that water content has a significant impact on membrane resistance. The resistivity decreases by approximately two orders of magnitude between 0 and 100% [relative humidity] at room temperature. [65]

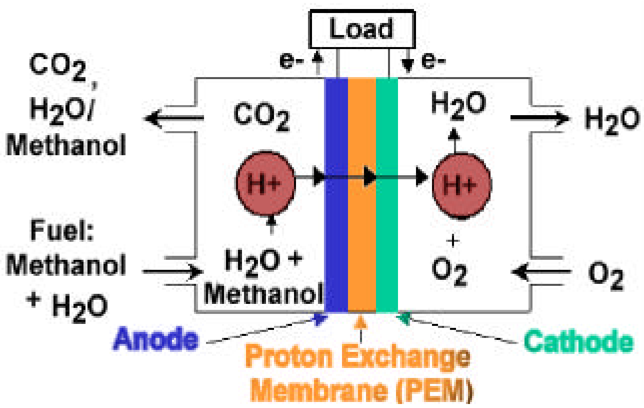

Figure 9. DMLFFC Schematic

The anode catalyst is responsible for stripping hydrogen from methanol, and the cathode catalyst reduces oxygen. The highest performing anode material is the one that demonstrates the highest activity for methanol electro-oxidation. Anode and cathode catalysts may be supported or unsupported. A support is a structural backing such as porous carbon which is transparent to the conduction of protons. Chu et al. tested unsupported alloys of platinum (Pt) and ruthenium (Ru) of different compositions and at different temperatures for use as an anode catalyst. They found that Ru was inactive below 25ºC but became active from 40 to 80ºC, and that for a voltage of 0.3V, a 50:50 composition provides the best results on an electrode [geometric] area basis. [65] Subsequent research by other groups using various methanol concentrations has confirmed a 1:1 ratio for Pt-Ru as optimal.

Bipolar plates separate individual fuel cells and distribute fuel or oxygen to their active surface areas. Individual fuel cells must be arranged in stacks to achieve a usable voltage and current. The plates function as anode to one cell and the cathode to the neighboring cell, allowing efficient packing of cells. Borup and Vanderborgy outline design criteria for plate materials. The design constraints they consider include electronic conductivity, gas diffusivity, chemical compatibility, cost, weight, volume, strength, and thermal control. [66]

Table 16. System mass design

Stack Size (# cells)	30	Mass of PEM (g)	12.75
Cell Length (cm)	9	Mass of Anode (g)	9.22
Cell Width (cm)	5.25	Mass of Cathode (g)	9.22
Stack Pwr (W)	153	Mass of Plates (g)	790.97
Stack Vltg (V)	18	Sys. Mass (g)	822.16
Pwr Density (mW/cm^2)	150		
Voltage per cell	0.6	Sys. thickness (cm)	6.60
Pwr rqmnts (W)	*150*	Sys. volume (cm^3)	311.85
Voltage rqmnts (V)	*18*		

Fuel cells in a series stack add their voltages and power outputs. Stack output power is a function of stack voltage and current density, but stack output voltage depends on the sum of individual cell voltages. Hence, minimizing the number of fuel cells in the stack can be accomplished only by maximizing the voltage output of each cell. There are three main ways to accomplish this: (1) increasing cell operating temperature, (2) using pure oxygen at the cell cathode, and (3) careful construction of the cell's membrane and electrode assemblies.

Table 17: Fuel Cell Specifications vs. EMU Needs

Fuel Cell Specs:*		EMU Needs:	
Output Voltage:	0.6 V	Power Req'd:	150 W
Current Density:	150 mA/cm^2	Voltage Req'd:	18 V
Power Density:	90 mW/cm^2	Required Duration:	4 hours
Overall Efficiency:	35 %	Goal Duration:	8 hours

* At 60 °C, operating on Earth air at 20 psig and a flow rate 3 to 5 times stoichiometric. [80

]Increasing the cell operating temperature from 60°C to 90°C can increase cell output voltage by almost 50% over the data given above. However, there are three problems with this approach. First, a higher operating temperature increases the rate of reactant crossover in the fuel cell, resulting in a loss of output current and a drop in fuel cell efficiency. [80] The cold environment on Mars will make it difficult to insulate a cell and guarantee an operating temperature of 90°C. The most significant concern is that a high operating temperature increases the thermal stress on fuel cell systems. This leads to early dehydration of each cell's PEM, rendering the cells inoperative and useless. [79] Such failure compromises crew safety and also requires a large reserve stock of replacement fuel cells.

Using pure oxygen at the cell cathode to react with methanol at the anode can increase cell voltage by 15% to 20%. [84] On an EMU, pure oxygen would be used anyway. This method of increasing cell voltage is probably the easiest and presents no major problems. The DMLFFC was originally designed to react liquid methanol and pure gaseous oxygen directly, but scientists at JPL used a high-flow air supply to provide oxygen for fuel cell testing since oxygen is present in Earth's atmosphere in significant quantities. Careful preparation of the membrane-electrode assemblies with catalyst material can also contribute another 15% to 20% increase in fuel cell performance. [84] This is a fairly time-consuming process and increases fuel cell cost, but it need only be done once, before the cell is brought into operation for the first time.

A combination of pure oxygen usage and catalyst preparation can thus provide an overall increase in cell output voltage of 30% to 40% to about 0.63 V, which leads to a proportional decrease in the number of cells required for the EMU's power stack. In addition, increasing cell output voltage also leads to an increase in cell output power. To satisfy the EMU power requirements, fuel cells are rated at 0.6V each at a power density of 150mW/cm

In addition to providing on-back power for the EMU, a fuel cell stack can generate a significant amount of waste heat. With current DMLFFC efficiency, approximately two-thirds of the energy potential of the methanol is unused. Half of this lost energy is dissipated in the form of electrochemical efficiencies and heat energy needed to maintain cell stack temperature. The other half of the unused energy is dissipated as waste heat to prevent undesirable increases in stack temperature and power fluctuations. [78, 86] The waste heat generation of the stack is thus roughly equal to its electrical power generation, or 150 W.

The fuel cell stack will be insulated against the Mars environment to maintain its temperature and the waste heat must be actively transferred out of the stack to prevent a heat buildup. Because the EMU will operate in a cold environment, the DMLFFC waste heat can be recycled inside the EMU to provide an auxiliary heat source for the astronaut. A heat exchanger may be used to transfer the waste heat to the liquid cooling/heating ventilation garment. This heat exchanger can be made of aluminum and will conduct heat to feedwater from the LCVG, thus increasing the water temperature and adding heat to the astronaut's body. Having an in-suit active heat source will reduce the need to don and doff thermal insulative overgarments intended to reduce heat loss. This will give astronauts greater mobility in surface activities since these garments are very bulky, reaching up to four inches thick. [23]

DMLFFC reactions will consume methanol and oxygen to produce usable electric power. The amount of the reactants consumed is dependent on the duration of the EVA and the average power produced on the EVA. These two factors can be combined and expressed in terms of energy with units of watt-hours. In general, an average EVA duration of four hours will require 600-800Whr, with an eight hour EVA requiring 1200-1600Whr.

In order to determine the amount of reactants consumed in producing these amounts of power, the baseline of a current DMLFFC developed at Giner, Inc is used as reference. At Giner, with the stack operating conditions of 0.45V/cell, 100 mA/cm^2 and 60°C, a 0.5 M methanol solution has been shown to maximize efficiency. Under these conditions, DMLFFCs will consume methanol at a rate of 1.4x10^{-2} moles per watt-hour and oxygen at a rate of 2.1x10^{-2} moles per watt-hour [57]. In addition, the stack inefficiency known as "cross-over" will consume additional methanol and oxygen at rates approximately 30% of those listed above. Finally, due to imperfect reactant utilization, increased oxygen flow rates oxygen will require quantities on the order of two times those given below.

To maintain maximum reactant utilization and efficiency with a 0.5 M methanol solution while meeting the power requirements of the EMU (including cross-over), EVAs will require the amounts of methanol listed below introduced to the closed loop anode supply evenly over the duration of the EVA.

Table 18: Reactant Consumption Amounts

EVA Duration	Methanol Consumed	O_2 Consumed
4 hr	0.40-0.54 L	0.61-0.81 L
8 hr	0.81-1.08 L	1.22-1.62 L

Note that while the stack operating conditions may vary between those listed above and those used on Mars, the interdependence between the reactant consumption rates and the operating conditions is stable enough that the rates given above would not change radically. The goal here is instead to show that only moderate amounts of methanol and oxygen are required in producing the required power.

In addition to making sure that the fuel cell is reusable and can meet average power needs, it is necessary to make sure that the fuel cell design does not continuously tax the fuel cell at maximum – this creates great stress on the system to be continuously providing peak power. A small, nontoxic battery used in parallel with the fuel cell will help get the cell heated up to start as well as provide peak power requirements so that the fuel cell is not operating at max stress.

A stack of 30 cells with area 9.00 x 5.25 cm^2 is required to achieve the 150W and 18V requirement. System mass and volume was estimated given densities of DuPont's Nafion for PEM, platinum-ruthenium for the anode catalyst and platinum for the cathode catalyst. Aluminum is used for the plates. The total volume is less than 3.5 L and mass is less than 4kg, which are reasonable values for a power system, compared to the current EMU Ag-Zn batteries, which would require 21.8 kg to achieve 150 W for an 8 hour EVA.

Table 19: Current best estimates (CBE) volume and mass for a sample design

(margin = 25%)	**CBE volume + margin (L)**	**CBE mass + margin (kg)**
FC dry	**0**	**1.03**
methanol	**1.25**	**1.08**
water		
-PEM uptake	**0.06**	**0.06**
-storage	**0.31**	**0.31**
cables, tubes, pumps, storage	**1.25**	**1.25**
Total	**3.28**	**3.72**

Power options include solar, nuclear, battery, and fuel cells. A fuel cell system was chosen as the best candidate after disqualifying the other options. Solar power requires ~340m^2 to produce 150 Watts on Mars and is highly variable. Nuclear power has many political and flight qualification problems. Battery technology is another practical option and is used in current EMU systems where Ag-Zn mass is not a limitation in micro-gravity, but it is on Mars. Lithium-ion batteries are the best performing battery systems with low weight, high reliability and long lifetime, but flight qualification will be difficult due to the chemical nature of lithium. For the near term, fuel cells, direct methanol liquid feed fuel cells in particular, are chosen as the most practical as the portable power source for the Mars EMU.

3.0 Conclusions from above discussions

3.1 Life Support

Modifications upon the life support component of the EMU for use on the Mars surface include cryogenic oxygen storage, solid amine carbon dioxide removal, a modified dehumidifier, and a regenerable nonventing thermal sink. Further development should focus around refinement of a small scale cryogenic oxygen system, and mass and power reduction in the carbon dioxide, humidity absorption, and thermal system.

3.2 Communications

Through the use of a reconfigurable wireless network using repeater stations, the astronauts will have a dependable communication system within a reasonable range of the base. Emergency locator beacons, with independent navigation capabilities, will provide back up should the primary communication system fail. An advanced communication display, the virtual retinal display, improves audio and video transmissions during EVAs. In the future, satellite networks can provide room for growth and expansion.

3.3 Power

A DMLFFC adequately meets all of the portable power needs of a Mars EMU, and should be used in parallel with a battery for peak loads to avoid overloading and stressing the system. The "waste" heat generated by the fuel cell can be harnessed to perform the functional task of warming the EMU. The use of methanol, a non-toxic easily generated mission resource in small amounts as power makes use of Mars resources and reduces the amount of mass to be transported from Earth.

Future research in designing an electrical power system for an EMU with application on Mars, many of which are funded by the drive to utilize DMLFFCs in the automotive industry, would include developing the following:

- An efficient means of producing methanol from methane at lower temperatures on Mars.
- Improved membranes (JPL & USC) in an effort to improve both reactant utilization and efficiency while reducing cross-over within the DMLFFC.
- Even lighter and cheaper materials for use in the DMLFFC by optimizing the fabrication process of the PEM, MEA and plates.
- A method for maintaining the correct CH_3OH concentration at the anode.

- An improved heat exchanger for transfer of heat from DMLFFC.
- A complete model of the DMLFFC and power distribution system.
- A prototype for field testing under simulated Martian conditions.

3.4 Meeting Functional Requirements

Table 20: System functional requirements checklist and mass tally

EMU System Component	**Proposed Solution**	**Meets Functional Requirements**	**CBE Mass**
Gas Exchange	Cryogenic Oxygen Storage System Back Up Oxygen Tanks Solid Amine Desorbed System	✓ ✓ ✓	4.6 kg 6.4 kg 2.9 kg
Thermal Regulation	Heat Exchanger	✓	7.35 kg
Radiation Protection	No additional mass necessary	✓	--
External Communications System	Reconfigurable Wireless Network	✓	2 kg
Internal Communications System	Virtual Retinal Display	✓	3 kg
Backup Communications System	Hybrid Beacon	✓	0.25 kg
Primary Power System	Direct Methanol Liquid Feed Fuel Cell	✓	3.75 kg
Backup Power System	Lithium-ion battery	✓	0.3 kg
		TOTAL MASS	**30.55 kg**

Combining the system components analyzed above with their current best estimate masses (margin included) puts us only 2.55kg over the allocated mass. This difference will probably be balanced out as the newer technologies improve and CBE margins decrease.

The proposed system components for use in a Mars take the NASA HEDS Reference Mission requirements and also the physical characteristics of Mars into account. The range of technological readiness levels for these components is large, some have been flight-tested or are on their way to be, and some are just making their first commercial debut. Development and prototyping of all of these components to integrate on a Mars EMU will, as with any space mission, take years. However, the time scale for the development and testing of most of the above technologies is in step with the desire to send humans to Mars within the next 10-20 years. In order for humans to reach yet another once-impossible goal, true planetary exploration, research and development for a Mars EMU must begin promptly and proceed unhindered.

4.0 Outreach

The Cornell 1999 HEDS-UP Team committed to two kinds of outreach, through the media and also community service/educational outreach. Due to the cohesiveness of the team and the general interest sparked by the topic of Mars Exploration, both efforts were a great success.

4.1. Media

After our proposal to participate in the 1999 HEDS-UP competition was accepted, the Cornell and local media responded with great interest. The following articles were generated that we are aware of, plus one pending article in the next biannual issue of the Cornell Engineering (Alumni) Magazine.

- The Cornell Daily Sun, 12/4/98, p. 9
- Cornell Chronicle, 12/10/98, p. 1
- The Times-Independent (Moab, Utah), 12/24/98 p. A5
- The Ithaca Journal, 12/24/98

4.2. Educational Outreach: Kaboom! Mars Volcanoes, Expanding Your Horizons, April 10, 1999

(Workshop modified from NASA's Destination: Mars Teacher Activity Packet, printed by the Earth Science and Solar System Exploration Division, Johnson Space Center).

The team hosted a workshop for the Expanding Your Horizions program to help renew the interest of middle school girls in math and science. We hosted two sessions of ten middle-school girls each, plus parents. Each session began with a brief history on Mars and volcanic action before moving quickly into the fun stuff – modeling volcanoes using layers of playdough and eruptions of vinegar and baking soda. Multiple eruptions were "fired" off and the flow mapped with a layer of playdough. Once the mapping was complete, groups traded volcanoes and dissected them by small parts in to try to figure out what the mapping looked like. More than 14 team members came during the day to interact with the girls.

One member of the team was a guest lecturer at Lawrence Middle School in Lawrenceville, New Jersey. The lecture covered a brief history of Mars, the current climatic conditions, and prominent geological features on Mars. The lecture concluded with a small project where groups of students were given a mission objective and had to design an instrument to accomplish the task.

Over the past few months the Cornell HEDS-UP team has enjoyed researching missions and learning about Mars and sharing what we have discovered with others.

Digital Collage Photograph of the Kaboom! Mars Volcanoes Workshop

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