POWER GENERATION AND ENERGY USAGE IN A PRESSURIZED MARS ROVER

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Long distance Mars surface exploration by human crews requires pressurized rovers. Rover power generation and energy storage are major logistical issues since fuel storage capacity limits maximum travel range, and fuel is the single largest component by volume in a rover. This study estimates power and energy requirements for a 3-person, 1000 km round-trip vehicle, and compares power and energy source options based on current and near-future technology. Fuel cells are selected as the optimal power source based on durability, flexibility, maintainability, scalability, redundancy, and size. Hydrocarbon fuels are chosen over hydrogen, based on storage volume limitations.

INTRODUCTION

The power and energy sources in a rover greatly affect the rover design, capabilities, and mission architecture. Because of the significant size, the power system will drive layout, overall volume, and mobility.

A rover will be designed around the chosen power system because it is the largest and most massive component on the rover. Systems that require large blocks of space will take living area away from the crew and could lead to an uncomfortable rover. If a nuclear power plant is used, the rover will need to pull a trailer to house the plant. A solar array would require large structures above the rover to support the cells and keep them directed towards the sun. Every feature of the rover will be designed to allow space for the power system.

Mobility is optimized by trading power plant size with vehicle agility. Science, computing, and recreation capabilities will be limited by available power.

The mission architecture is completely dependent on the chosen power system for the rover. Solar and nuclear power will allow the rover almost unlimited time away from the habitat and the ability to explore a much larger surface area on Mars. If a rover needs fuel to run, then a fuel production and processing plant must be available at the habitat. This plant will need power and raw materials to operate.

To choose the proper power generation system, we first estimate energy requirements of a single rover mission. We then evaluate nuclear fission, solar cells, batteries, internal combustion engines, and fuel cells for the criteria discussed above and on their durability and safety. Finally, we discuss our chosen power system and how it will affect a Mars rover.

POWER AND ENERGY REQUIREMENTS FOR A MARS ROVER

The power and energy requirements of a pressurized rover can be broken down into three categories: internal, external, and mobility. The purpose of this section is to break down each of these categories into separate components and estimate the energy usage on a Mars rover over a two-week (14 day) mission. This is an important first step because it provides a benchmark that can be used to determine the required output of the power generation system.

Internal Energy Requirements

Internal systems include life support, science instrumentation, computing systems, and crew comfort. These numbers are based on an assumed crew size of three people. The following table outlines the energy requirements[1].

Table 1
INTERNAL ENERGY USAGE

Internal Component	Energy per Day
Kitchen equipment and food prep	3.0 kW-hr
Climate Control & Life Support	25 kW-hr
Glove Box, Instruments	10 kW-hr
Computer Workstations	2.0 kW-hr
Hygiene/Plumbing	3.0 kW-hr
Airlock (1 EVA/day)	1.0 kW-hr
Cockpit Station	2.0 kW-hr
Lighting	1.2 kW-hr
Equipment (writing/photo/science)	0.3 kW-hr
Recreation	1.0 kW-hr
AV/Communication	2.5 kW-hr
Daily Total	**51 kW-hr**

Using these numbers, the total internal energy requirements can be estimated at about 714 kW-hr per two-week mission.

External Energy Requirements

Mars rovers will be equipped with a wide range of exterior equipment to be used for crew safety and sample gathering. Exterior equipment includes a winch, manipulator arm, drill, and small companion rover. Swales Aerospace, under NASA funding, recently demonstrated a low-energy, dry planetary drill system for use on Mars that can drill 10 m through solid rock using only 90 W of power[2]. This drill concept could be used for sample gathering or drilling for water at low power cost

A companion rover will also be an important piece of equipment on a rover to compliment or even replace the robotic arm. The smaller rover will be used to gather samples or explore areas out of reach for the pressurized rover, without risking the safety of the astronauts. The total external energy requirements are estimated at 15 kW-hr per day or 210 kW-hr for the entire mission.

Mobility Energy Requirements

The power required to move the rover is directly dependent on the mass and expected range of the rover. A recent report by our team[3] estimated the optimal range of a Mars rover based on landing site possibilities and their distances to interesting features on Mars. We found that a rover with the ability to travel 500 km out (1000 km round trip) would be the most efficient at visiting interesting sites. To gain a proportional increase in number of accessible sites, the range would need to be increased to 3000 km roundtrip.

Our team performed a study using the Mars Rover Mass and Volume Estimator[4] to predict the operating mass of the rover. Called the Massenator for short, the spreadsheet-based program uses a set of interrelated parameters to describe the mass, volume, and power requirements of a rover designed by the user. The program inputs include crew size, range, use of a trailer, and pressurized or unpressurized cabin. The rover that we have designed is larger than some other designs to incorporate an airlock, increased scientific instrumentation, increased crew comfort, and increased rover mobility. Our current design is approximately 5,000 kg fully loaded (wet mass).

Our most recent estimate for off-road mobility power requirements on Mars is 0.25 W-hr / km-kg. We calculate 1,000 kW-hr will be required per 1000 km sortie for mobility, based on our expected vehicle weight, and a decreasing fuel load through the mission.

An added issue is whether to save all of the water generated through energy use within the vehicle. Since the total amount generated far exceeds the amount required for the crewmembers, jettisoning water would reduce weight and increase mobility. However, water may be difficult to locate and separate on Mars, so there is an incentive to retain it. The above calculations are based on retaining the water, but releasing the carbon dioxide. This can be done because the majority of the atmosphere on Mars is carbon dioxide, and therefore does not pose the same environmental concerns as it does on Earth. Releasing the carbon dioxide will also help to expel some of the extra heat generated by the power system and save the rover from the difficulties that come with storing CO_2.

Total Power and Energy Requirements

Based on the above analysis, the rover will need to produce approximately 2000 kW-hr of energy over a 14-day mission to run all of the systems. Peak power loads will occur when the rover is running life-support, computers, communications, and driving uphill over rocks, which requires 90 kW of power.

POWER GENERATION OPTIONS

This section will discuss the possible options for power generation on a Mars rover. Using the mission design and power requirements outlined in the above sections, we will evaluate the pros and cons of each option using the parameters discussed in the main considerations section below. All of the options that are considered will be based on currently available technology or technology that will be available in the next few years.

Main Considerations

Durability. A major concern for a power generating system is its durability. Due to the rover's expected 2-week missions and multi-year lifespan, components will have to withstand the repeated abuse of the dusty Martian landscape, vibrations and shocks from the terrain, fuel impurities, and astronaut handling. They will have to be recharged, re-used, and repaired after use.

Flexibility. The scenarios encountered by a rover are many and varied. From climbing mountains to drilling, from scouting to utility work around the habitat, the power generation system and ancillary components must be capable of high power output and long duration operation with a minimum of modifications.

Maintainability. Breakdowns are to be expected and planned for. Replacement or repair of any damaged components must be easily accomplished with a minimum amount of tools and agility. Periodic maintenance of the equipment should be kept to a minimum to leave time for other tasks.

Scalability. The various tasks a rover will be expected to perform will demand different power fluxes and total energy. The ability to reconfigure the power generation to accomplish these tasks is tantamount to successful mission operation.

Redundancy. The ability of the rover to function through system failures and breakdowns is the single most important factor in guaranteeing crew safety. Power systems should be fully redundant. Ease of incorporating parallel systems will drive this consideration.

Mass. One of the critical factors in selecting any aerospace component is mass. Total mass must take into account the engine itself, backup engines, fuel for various missions, tankage for that fuel, and safety factors.

Volume. While lowering mass is a driving priority, the volume required for various fuels and power generation components directly impacts rover structure and design. Large volumes required for fuel storage are a cause for design concern.

Nuclear Fission

The SP-100 reactor (United States), was a 100 kW reactor developed for aerospace applications[5]. This reactor weighs about 5,400 kg and operates near 1400 C[6]. The shielding needed to allow nearby human activity would require a lightweight neutron shield of lithium hydride and a heavier gamma shield of tungsten or lead that is 20 cm thick. Large radiators would also be needed to disperse the megawatts of heat generated by the system. Overall, this system is too large and heavy for a Mars rover.

To reduce the massive shielding and heat-dispersion requirements, the power plant can be towed behind the rover on a trailer. However, this approach greatly limits the off-road capabilities of the rover that will be necessary for Mars exploration. Pulling a trailer will increase the mass of the rover by approximately 1000 kilograms because it must duplicate systems such as wheels, suspension, and structure that already exist on the rover. Due to these limitations, nuclear fission is not considered a viable option for a pressurized Mars rover.

Solar

Silicon is the most well developed solar cell technology, and has been used on all but a tiny fraction of space solar arrays. The conversion efficiency of standard-technology silicon cells currently flown is about 14.5%, with 20% efficiencies demonstrated in the laboratory[7]. Advantages of silicon cells are that large area cells are available (8 by 8 cm cells are being manufactured for the International Space Station), the array manufacturing technology is well developed, and the technology is well characterized for vibration, thermal-cycling, and other environmental loads of the space environment.

Recent advances in thin-film solar cells have allowed them to reach conversion efficiencies rivaling that of silicon cells. The benefits of these cells are that they are created on a flexible plastic and therefore are not as likely to be damaged on a Mars rover compared to standard solar cells.

The main benefit of photovoltaic power is that its a reliable energy source as long as there is sunlight on the cell. There is no mission length limitation and no requirement for fuel. These features open up a lot of possibilities in mission design and rover design. By removing the size and weight of the fuel, the rover can be much smaller and nimbler for off road travel. It will also allow for increased space on the interior of the rover for crew comfort.

However, even with a solar cell efficiency of 18%, a mean Martian solar flux value of 0.7, and the panels pointed at the sun, the output would only be about 126 W/sq m. Taking dust and pointing into account and the output might be only 110 W/sq m. This means that close to 800 sq m, about two basketball courts worth, of cells would be needed to produce enough power for normal operation and additional cells would be needed to store up power for continued operation at night. The problems with a large array bouncing above the rover quickly overshadow any benefits of not having to carry fuel.

Although solar cells are not a logical choice for the main power generation system because of their required surface area, a small array on the roof of the rover may be a design consideration to provide life support for the crew in the event of an emergency.

Batteries

Batteries feature many of the characteristics that we are looking for in a Mars rover power system because of their modular nature and simple structure. If a battery goes bad or a connection breaks, it is a simple matter to change out the battery or repair the connection. There is also little worry about Martian dust and wear and tear because batteries have no moving parts that can get worn out and ruined. These features provide the rover with a high level of maintainability.

Most importantly, however, the rover will be very reliable. If sets of batteries are wired in parallel, redundancy and backup power can be easily built into the power system. This design will also allow the rover to quickly scale its power output to meet the needs for driving or science work.

Ultralife Batteries, Inc., Eagle-Picher Technologies, and Lockheed Martin Missiles & Space worked together in a joint venture funded by the U.S. Department of Commerce National Institute of Standards and Technology in 1998[8]. Their goal was to develop and market a new generation Li-ion polymer battery pack for aerospace applications with a specific energy greater than 200 Wh/kg and an energy density greater than 475 Wh/l. As of 2002 they were producing batteries with a specific energy and energy density of 160 Wh/kg and 305 Wh/l respectively. If they achieve their goal specific energy, the rover will still need to carry 10,000 kg of batteries to store all of the power needed on a mission. This is not a reasonable mass for the rover to carry and so batteries have been abandoned as a possible power source.

Internal Combustion Engines

Internal combustion engines have over 100 years of automotive research and development behind them making them one of the most well understood propulsion systems of our time. They are capable of quickly varying their power output and are able to run off of methane/oxygen fuel[9]. This means that the same high-energy propellant produced for the Earth Return Vehicle can be used in the rover, thereby simplifying fuel production at the habitat and the amount of fuel that needs to be carried on the rover.

Of the power generation options that have been considered so far, the internal combustion engine is the only option that is a reasonable size and mass. An internal combustion engine capable of producing 90 kW of power weighs about 100 kg and is about 0.05 cubic meters in size. This is very reasonable for a Mars rover. One drawback is the amount of fuel that then engine must carry to operate. Current internal combustion engines burn fuel with about 25% efficiency. Since such a large portion of the rover's weight is fuel and oxidizer, any options that can improve on this efficiency must be closely considered.

Some of the main problems with internal combustion engines are that not only does the simplest design incorporate at least forty moving parts, but that there is only one engine. This means that if one of these forty parts wears out or breaks, then the rover cannot produce any more power. The only way to build redundancy, and therefore safety, into the system is to have more than one engine. Having a single engine also means that if even a small amount of power is needed, the entire engine must be operating to produce the power. There is no way to scale back and save the engine from extra use. If two smaller engines are used to ensure redundancy, there will be a loss in the power to mass ratio because of the many duplicate systems between the two engines. Although internal combustion engines are feasible, they are not recommended from an efficiency and, most importantly, safety standpoint.

Fuel Cells

Fuel cells combine all of the benefits of batteries and the internal combustion engine into one system. Like batteries, fuel cells are a simple device with no moving parts that can get worn out in a Mars rover. It will also be easy to make a fuel cell system redundant by setting up two or three smaller cells in parallel with each other instead of using one large cell. When a fuel cell does fail, it will be relatively simple to replace because there are no mechanical connections between the fuel cell and the wheels. The only connections will be for mounting, for electrical connections, and for fuel lines.

In the past, the main drawback of fuel cells was large size compared to internal combustion engines. Now common fuel cell technology includes cells capable of generating 100 kW that are only 100 kg and 0.062 cubic meters. Although this is larger than a comparable engine, fuel cells are capable of 40-60% efficiencies and can therefore make up for larger engine size by carrying less fuel. Like combustion engines, fuel cells can run off of the high-energy methane and oxygen fuel being used in the Earth Return Vehicle if they include a reformer to break down the methane into hydrogen. Reformers have also shrunken considerably in recent years and have the potential to become much smaller if new micro-channel reforming technology can be used.

Automotive fuel cells have been produced with 5,000-hour lifetimes, which equal that of current combustion engines[10]. This is only about 200 days of constant use on the Martian surface. With parallel fuel cells, not all of the fuel cell system needs to be running the whole time. If only a small amount of power is needed, only one of the fuel cells needs to be running. This feature could allow the fuel cell system to have a lifetime more than double that of an internal combustion system. There is also hope that the base lifetime of the fuel cells can be increased since some stationary fuel cells have been demonstrated with a lifetime of over 40,000 hours.

There are many benefits of going with a fuel cell system that are independent of the basic design characteristics that are discussed above. Since fuel cells can be manufactured into almost any shape, the entire system could be packed into the floor of the rover. This would allow the interior to be designed into any configuration imaginable and would also lower the center of gravity of the rover to increase stability. Since the entire system is electrical, in-hub motors can be used in all of the wheels to create an excellent level of redundancy should one of the motors breakdown. An all-electrical system also means that it is possible to implement a drive-by-wire system in the rover. This would allow the rover to be tele-operated from anywhere in the rover and even from Earth if the crew experiences problems. If these features are desired in a combustion engine system, the mechanical energy will have to be converted to electrical energy, causing the fuel efficiency drop further to about 21%.

Because of the many advantages fuel cells offer in terms of durability, flexibility, maintainability, scalability, redundancy, and size over the other available options, we have chosen them as the optimal power generation system for a pressurized Mars rover.

THE FUEL CELL SYSTEM

This section will describe the overall design of the fuel cell system in terms of fuel, the fuel cell, reforming the fuel, and storing the fuel. This section will also raise a number of design questions that should be considered when developing the overall system.

Choice of Fuel

Choosing the proper fuel for a Mars rover is important because it is one of the biggest factors in the overall size and mass of the rover. If the wrong fuel is chosen, the rover may be too large, have limited range, or have insufficient power to be used effectively as an exploration tool on Mars.

The obvious choice of fuel would be pure hydrogen because it can be fed directly into the cell without reforming. However, to satisfy the energy requirements of the vehicle even liquid hydrogen would require immense storage requirements (several tens of cubic meters). A hydrocarbon fuel that can be reformed, or used directly by a fuel cell, is needed. Since both the fuel cell and the reformer are based on *power* vs. *total energy* needs, there is a better tradeoff in weight and volume if a denser fuel can be employed. Candidate fuels would be methane (CH_4), methanol (CH_3OH), or a higher hydrocarbon such as ethane (C_2H_6) or propane (C_3H_8)[11]. Although the higher hydrocarbons are easier to store and less oxidizer is needed, creating larger hydrocarbons on the Martian surface is much more difficult. Larger hydrocarbons also may not reform as efficiently or be used as effectively in the fuel cell of choice and so are not considered a good choice for a rover.

We have little choice in oxidizer: we must use oxygen. Depending on the fuel, different amounts of oxygen are needed for the raw energy output. To release 1 kilowatt-hour of raw energy, the fuels mentioned above have fuel requirements listed in Table 2.

Table 2
FUEL TO OXIDIZER RATIOS

Fuel	Oxidizer
Methanol (179 grams)	268 grams Oxygen needed
Methane (75 grams)	298 grams Oxygen needed
Ethane (77 grams)	285 grams Oxygen needed
Propane (79 grams)	282 grams Oxygen needed

In addition to the oxygen needed for power generation, about 1000 grams of oxygen is needed per person, per day of the sortie. For a 3-person crew on a two-week sortie, this is about 52 kg. We could provide a 2x margin of safety by allocating 100 kg for this purpose, but there will be no shortage of oxygen because of the large amounts consumed by the power generation system. For example, more oxygen is needed to power climate control than is actually used by the astronauts themselves.

Choosing between methane and methanol requires a close look at storage requirements and thermal characteristics. For a given amount of energy storage, methanol requires 2.4 times more mass and 1.3 times more volume than methane[9]. The benefit is that methanol tanks need only hold a liquid (similar to terrestrial vehicles) and will therefore lead to a simpler system. To receive the storage benefits of liquid methane, the storage tanks will have to be actively cooled. However, since we will have to liquefy the oxygen anyway, and since Mars has a much lower average temperature than Earth, the burden of dealing with liquid methane will not be as unreasonable. Due to the extra size and mass requirements of methanol, we will assume a liquid methane / liquid oxygen fuel system in the rover.

Types of Fuel Cells

Much has been discussed recently on the potential for proton exchange membrane (PEM) fuel cells to replace internal combustion engines[12]. The choice of PEM fuel cells for terrestrial land vehicles is based in part on criteria that are not necessarily important for a Mars rover. These include a low operating temperature (20-60 C), a fast startup time, a quick response rate, and the desire to not exhaust CO_2. This means that a rover is not limited to a PEM fuel cell, but can consider other options such as solid oxide or molten carbonate fuel cells.

Because a Mars rover must carry its own oxidizer, we feel that overall efficiency is one of the most important criteria. PEM fuel cells are typically 40% efficient with a pure hydrogen fuel, and solid oxide fuel cells (SOFC) can be as much as 60% efficient with a methane fuel source[13,14]. The drawbacks to SOFCs are that they are heavier than PEMs and that they run much hotter. A typical SOFC runs between 700-1000 C, whereas PEM fuel cells are capable of operating around 80 C. This is a concern because of the thin atmosphere on Mars and the need to radiate extra heat away from the rover.

Current development efforts such as NEXCAP (NASA) are working to make SOFCs suitable for aircraft APU applications. An SOFC producing 90 kilowatts is expected to weigh about 200 kilograms within the next five years. This weight is mostly offset by the removal of the reformer, which is not needed. The overall improved efficiency and the ability to use hydrocarbon fuels directly are a great advantage. Other fuel cell types such as direct methane or methanol fuel cells are also promising, but since they are geared for small applications (cell phones, etc.) it appears their efficiency is not as favorable. Molten Carbonate fuel cells are another possibility and can also use hydrocarbons directly as fuel.

Since fuel cells have only recently become a commercial product, there are many different types of fuel cells in development that may be useful for a Mars rover. If the rover were built today, it would probably use a PEM fuel cell and reformer because of the demonstrated reliability in mobile applications. As other fuel cell technologies become more mature they will offer the benefit of higher fuel efficiencies and removing the reformer. For the remainder of this paper, we will assume a combination of current and near-term technologies that provide us with a fuel cell capable of 50% efficiency and the ability to run directly from hydrocarbon fuels.

Reforming Methane or Methanol

If the fuel cell technology capable of using hydrocarbons directly does not develop as we expect, than a reformer will be used. A reformer can be used with both

PEM and solid oxide fuel cells. However, the heat generated by a solid-oxide cell could be used to make the reforming process more efficient[12]. A reformer should be avoided because it would lower the overall efficiency to about 40%, increase our fuel/oxygen weight by about 1000 kilograms, and add complexity to the system.

The traditional approach to using hydrocarbon fuel with fuel cells is through steam reforming that usually requires a large, complicated device. Steam reforming consists of heating methane and water to a high enough temperature such that they dissociate, and then tipping the reaction to produce hydrogen and carbon monoxide products. This is performed in a reaction vessel with nickel catalysts.

$$CH_4 + H_2O \rightarrow CO + 3H_2$$

Since PEM fuel cells cannot tolerate carbon monoxide and hydrogen can still be extracted from the fuel, another reaction is performed in a different reactor with an iron catalyst. This is known as the "Reverse Water Gas Shift" (RWGS) reaction:

$$CO + H_2O \rightarrow CO_2 + H_2$$

This extracts the last pair of hydrogen molecules available. The highest achievable efficiency of the reforming process is about 90% and requires a carefully tuned system that produces significant amounts of hydrogen. Mobile reactors will have a lower (80%) energy efficiency.

A more recent approach to reforming is through the use of microchannel technology[15]. Microchannel reformers use similar processes to the macro reactor described above, except the vessels are tiny channels as small as 10-100 microns in diameter. A reactor may consist of thousands of these channels that are coated with the needed catalysts to support the reactions. Efficiency is typically low (20-30%) and power output only tens of watts, but some researchers are working to produce 5-10 kilowatt models that have efficiencies comparable to traditional reforming technologies.

Storing Methane

Liquid Natural Gas (LNG) vehicles have been in use for many years. They are typically used for large vehicles, which have need for dense fuel storage. A double-walled tank with a vacuum insulator allows vehicles to remain fueled for several days[16]. Although such vacuum technology may not be precisely usable on Mars, the lower ambient temperatures should make liquid methane a very reasonable fuel strategy.

For our application, we will need to store approximately 300 kilograms of liquid methane, occupying a volume of 700 liters, or .7 m^3. The methane will be cooled to 109K to take liquid form, and then enclosed in .15 m of insulation. This brings the tank volume to a total of 1 m^3. Further analysis of power usage and thermal cycles on Mars could indicate that a thinner insulation be employed because the resulting boil off would be used immediately by the fuel cells. A slightly pressurized version of the tank (100-200 psi) could also sustain average Martian temperatures without insulation at all.

Storing Oxygen

Liquid oxygen is similar to methane because it needs cooling to about 90K to become liquid. Similar characteristics would allow the tanks to be near each other, and share insulating coverings. About 1200 kilograms of oxygen is needed by the rover. This is a volume of 1200 liters (LOX is about the same density as water.) Accounting for insulation, about 1.7 m^3 of tank volume is needed. As with the methane tanks, a careful analysis of fuel/oxygen use rates, weight of pressurized tanks, and choice of insulation is needed to get the best volume and mass tradeoffs for the tanks.

Tank Location

The majority of the fuel and the fuel cell will be stored in a compartment under the crew cabin of the rover. This is done to lower the center of gravity and increase the safety of the crew. Since methane has favorable solar radiation shielding properties, it may be beneficial to store some of the fuel on the roof[17]. As the tanks empty, they may be filled with exhaust water to further maintain the shielding capability. Since oxygen outweighs the methane by 4 to 1, the center of gravity will remain favorable.

As the fuel is depleted, about 55% of the beginning fuel weight would be removed if all the carbon dioxide is vented, and all of the water is retained. The oxygen tanks alone will have enough volume to hold all of the exhaust water.

CONCLUSION: Overall System

The Mars rover power generation system was designed to supply 2,000 kW-hr of energy with a maximum power output of 90 kW. This energy should last a crew through their 14-day mission and allow them to explore a round trip of 1000 km. Mobility is provided from in-hub electric motors that are controlled with a drive-by-wire interface in the rover cockpit.

While the majority of the fuel for the mission is stored in insulated tanks below the crew cabin floor in the form of liquid methane and liquid oxygen, some of the methane is stored in the roof to provide solar radiation protection from the crew. Three 30 kW (total of 90 kW) solid oxide fuel cell stacks are used to convert the methane and oxygen into energy. Solid oxide cells were chosen because of their ability to run directly from methane without a reformer, and for their 50% fuel efficiency. The rover will use three parallel fuel stacks so that the power system is redundant, scalable, and ensures safety for the crew. The entire wet mass of the power generation system is 2500 kg and requires 3 m^3.

The system will vent the waste CO_2 to the atmosphere to save space on the rover and to help eliminate excess heat. The water generated through the chemical reaction in the fuel cell will be recaptured and stored in the oxygen tanks as they are emptied. After purification this water will be used by the crew as potable drinking water.

EXAMPLE CALCULATION

Assuming we that need 2000 kW-hr of total electrical energy:

At 50% FC efficiency, 4000 kW-hr (raw total) energy needs to be stored.

Methane stores 13.44 kW-hr/kg, which implies that we need:

4000 / 13.44 = 297 kg of Methane

The chemical reaction in the fuel cell is:

CH4 + 2O2 -> CO2 + 2H2O

16 64 -> 44 36 (grams*moles per reactant)

This reaction shows that 4 times more O2 is needed than methane so:

4 * 297 = 1190 kg of O2 is needed

Liquid O2 density is about same as water (actually 1.15) so about 1200 liters of O2 is needed (tanks are bigger).

Liquid methane density is 0.4256, so about 700 liters are needed. Again, the overall tanks are bigger.

The total weight of fuel and tanks is 2500 kg, which includes extra weight (100 kg) budgeted for SOFC (over PEM) or for a reformer if PEM fuel cells are used.

REFERENCES

1. "Analog Rover Design Paper", Michigan Mars Rover Team, 2000
http://www.umrover.org/olympus/Analog-rover.doc/file_view

2. http://www.swales.com/news/drydrilling_instrument.html

3. "Range and Terrain Report", Michigan Mars Rover Team, 2002
http://www.umrover.org/olympus/Range-and-terrain/file_view

4. "Mass/Volume Estimator", Michigan Mars Rover Team, 2003
http://www.umrover.org/olympus/Volume_Mass_Estimation.xls/file_view

5. “Space Reactor Arms Control”, Primack, Abrams, et al, Science and Global Security, 1999, Vol. 1, p 59-82.

6. http://www.uic.com.au/nip82.htm

7. “Power Generation Report”, Michigan Mars Rover Team, 2002 http://www.umrover.org/olympus/Power-generation/file_view

8. http://www.ulbi.com/whitepapers/Power_Sources_ATP_2002.pdf

9. “The Case for Mars”, R. Zubrin, 1996

10. Personal correspondence, Moshen Shabana, General Motors

11. Handbook of Chemistry & Physics , 45th Edition, 1964, Published by The Chemical Rubber Company

12. http://www.sae.org/automag/features/fuelcells/fuelcell2.htm, http://www.sae.org/automag/features/fuelcells/fuelcell6.htm

13. http://www.fe.doe.gov/coal_power/fuelcells/fuelcells_sofc.shtml

14. http://www.eva.wsr.ac.at/publ/pdf/fuelcell_hydro1.pdf

15. http://www.tekkie.com/innovagen.htm

16. http://www.nexgenfueling.com

17. “Radiation Shielding Report”, Michigan Mars Rover Team, 2003 http://www.umrover.org/olympus/RadiationEffects.pdf/file_view