Surviving Mars: In-Situ Production of Oxygen and Water

Ryan Belfer, UG

Professor Joseph Miles, PI

Dean Siva Thangam, PI

Goddard Institute for Space Studies

NASA NYCRI

Stevens Institute of Technology

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Abstract

Mars has been a target for manned space exploration for decades, but difficulties such as cost and planetary conditions have made it nearly impossible to send such a mission to Mars. To survive on Mars, astronauts must have a steady supply of oxygen. Transportation of oxygen from Earth would be an incredible detriment to the cost of the mission, so utilizing resources already on Mars would cut the cost greatly. Because evidence of water has been discovered all over Mars, it is possible to use water extraction techniques and hydrolysis to produce oxygen. A mission overview has been created and analyzed to determine appropriate processes and rates for producing enough oxygen for a 1.5-year mission, including the use of the Sabatier methanation reaction and the reverse water gas shift (RWGS), by using existing experimental data of these two processes. By sending a rover connected to a machine running these processes one synodic period in advance, the most cost-efficient method, which frees up space for return fuel if needed, is achieved.

Introduction

For centuries before the advent of telescopes, Mars had been just a red dot wandering the night sky. Observed to contain *canali*, mistranslated to flowing water, interest in Mars increased. With the efforts of NASA's *Mariner* program, a flyby of the red planet showed that no evidence of flowing water, nor any intelligent presence. For the first time, measurements of Mars showed that the planet was radically different from previous notions. Mars had temperatures comparable to winter at the South Pole, and a tenuous atmosphere with a pressure measuring just 1% of Earth's, making a visit to Mars much more difficult.[1] In the late 1970's, the Viking landers showed the dusty and rocky landscape, reminiscent of Earth's deserts. Although the race to a Moon landing encouraged space exploration, the post-Apollo era saw a drop-off in activity. Werner von Braun believed that NASA could send a manned mission to Mars by the late 1980's, but a cut in funding and interest prevented such an undertaking. Multiple rovers, such as *Pathfinder*, *Spirit* and *Opportunity*, and *Curiosity* have delivered pictures, soil analysis, and atmospheric measurements, but a rover does not have human intuition nor freedom of motion.

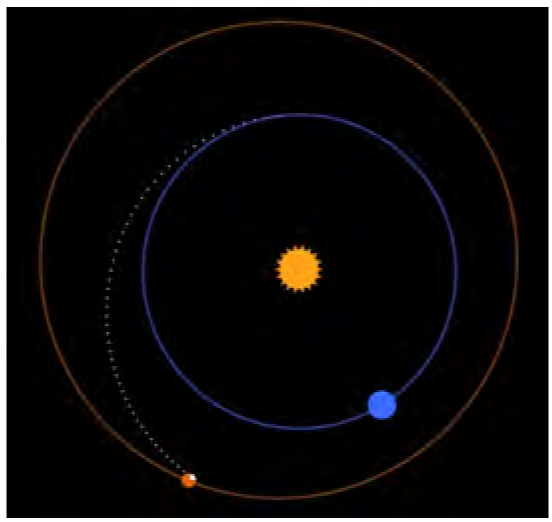

Figure 1 Example of a Hohmann transfer to Mars

Opportunity for a manned mission to Mars opens approximately 26 months due to the Earth-Mars synodic period, or the time it takes for the two bodies to be in the same position relative to each other again.[2] With current propulsion technologies, a rocket launched into a Hohmann transfer orbit would take anywhere between 150 and 300 days, depending on how close the window is to the launch minimum distance due to the eccentricity of Mars' orbit (0.09 compared to Earth's 0.02).[2] It is estimated to cost about $200,000 to send a pound of payload to Mars, so any manned mission to Mars that includes food, air, medical supplies, return fuel, etc., would cost billions of dollars and would not contribute to the long-term colonization of Mars.[3] NASA scientists are working on ways to make such a journey to and stay on Mars more feasible.

The question one must ask is "why?". Taxpayers are reluctant to give funds to a project if it costs billions and there are no returns. However, a manned mission to Mars would give large scientific and social returns. Humans on-site can collect and analyze samples much more efficiently than rovers. Astrobiology would advance from the capability to dig and search for microbes and signs of long-gone life. Humans would become a multi-planet species and advance our reaches, with off-Earth resources from mining Martian soil and space to prevent over-crowding on Earth (though Mars' surface area is 28% of Earth's, the land area is comparable). All of this starts with an expedition to Mars to test how humans might fare and to set up a small base for activity.

Scenario

NASA is prepared to launch a crew of four to Mars using the 2031 launch window. The crew will spend about 540 days on the surface of Mars before heading back to Earth. Their mission is to analyze the soil and atmosphere for organic molecules, while looking around for signs of water and life. The mission will also serve as a stepping stone to colonization efforts. During their stay, the crew will need both oxygen and water to survive, but neither readily exists in usable form on Mars. Therefore, we propose to send an autonomous machine that can create and store oxygen and water for the astronauts until their arrival.

Any such machine may be tested on Earth for an extremely small fraction of the mission cost. As a stepping stone, the system may remain small for the first few trips before scaling up to a colony.

Background

A single conjunction-class mission to Mars would last about 1.5 years, or 540 days, on the surface before being able to return to Earth. A one-way trip would drastically lower costs by not needing return fuel and would allow for a permanent residence on Mars. In both scenarios, the crew needs oxygen, water and food to survive. There is not nearly enough oxygen to breathe in the atmosphere, and too much poisonous carbon dioxide. A human can die from a 2% concentration of carbon dioxide or greater, so the Martian atmosphere absolutely cannot be inhaled.[4]

Atmospheric Component	Mole fraction
Carbon dioxide	0.959
Argon	0.021
Nitrogen gas	0.019
Oxygen gas	0.00145
Carbon monoxide	0.000557

Table 1 Molar atmospheric composition of Mars[5]

Dehydrated food can be brought aboard a spacecraft and plants grown on the surface with the appropriate amount of oxygen and water. These two resources--oxygen and water--would cost billions of dollars to bring along and would require massive enlargements to the Mars flight shuttle, increasing the risk of failure. For a one-way mission, bringing a lifetime supply of oxygen and water is downright impossible. In-situ resource utilization (ISRU) provides an alternative method. ISRU allows us to take materials already present on Mars, extracting and converting them to the desired product. Orbiters around Mars, such as Mars Express and Global Mars Surveyor, have spotted evidence of water in the soil, as well as confirmation of water locked in the polar ice caps.[6] However the water in the soil may be bound to minerals, but even if it is not, the low pressure on Mars (600 Pa) sits below water's triple point, meaning without external forces, liquid water cannot exist, save for a few places at extremely low elevation, where pressure is slightly higher. This means as the polar caps retreat due to warming, the water left at mid-latitudes starts to sublimate into vapor and gets swept into the atmosphere. Yet, this is a slow process and leaves large quantities of water.

The proposed autonomous system would land one synodic period before a manned mission in order to gather water and oxygen by collecting and hydrolyzing the water in the soil. A mission leaving in December 2028 would arrive in July 2029 and have about 740 days before a manned mission would arrive.[7] For a one-synodic period mission, the system would run for 1280 days, while for an indefinite residence, an additional apparatus would be brought that must produce the remaining materials for a constant supply.

A useful conversion is to the Martian sol, which equates to one day on Mars. It is equal to 24.65 hours on Earth, or 1.0275 Earth days.[2] This means that the autonomous device would operate for 1245.7 sols, while astronauts would be on Mars for 525.5 sols.

Life Requirements on Earth and in Space				
Item	On Earth		In Space	
	kg per person per day[1]	gallons per person per day	kg per person per day[2]	gallons per person per day
Oxygen	0.84		0.84	
Drinking Water	10	2.64	1.62	0.43
Dried Food	1.77		1.77	
Water for Food	4	1.06	0.80	0.21

Figure 2 Oxygen and Water requirements for astronauts according to NASA[8]

Total Requirements

According to Figure 1, an astronaut needs 840 g of oxygen and 2.4 kg of water per day. For four astronauts, this comes out to 3.36 kg of oxygen and 9.6 kg of water per day, or 3.447 kg of oxygen and 9.849 kg of water per sol. Since their stay is 540 days long, a total of 1815 kg of oxygen and 5184 kg of water is necessary. Running for 1280 days, the machine would have to produce on average 1.418 kg of oxygen and 4.05 kg of water per day, or 1.455 kg of oxygen and 4.155 kg of water per sol.

The maximum storage needed would be for the first day that the astronauts arrive, as the rate of use is greater than the rate of production for this system. This means 1049.3 kg of oxygen and 2997 kg of water should be available at the beginning of the manned mission.

The astronauts will use a habitat under 1 atm of pressure consisting of air that is 80% nitrogen and 20% oxygen.

Launch Specifications and Economic Justification

Whatever apparatus is chosen to do the job, it must be launched to Mars on a rocket powerful enough to get it there. Many rockets are designed to achieve Low Earth Orbit (LEO), that is, get the cargo to the International Space Station. A rocket to Mars must be able to achieve Heliocentric Orbit (HCO), which greatly reduces payload-carrying capabilities. Rockets that can get to HCO include Boeing's Delta II rocket and SpaceX's Falcon Heavy rocket. Both rockets cost approximately $100 million to launch.[9,10] The actual cost depends on the amount of payload, however. The cost to send one kilogram of payload to Mars is $440,000.

The three options of sending oxygen and water are the following: (1) take everything from Earth and send it to Mars, (2) load an ISRU device with the manned mission, and (3) send the ISRU device ahead of the manned mission to have materials ready to use upon human arrival. The first option ensures that enough oxygen and water are available for use, but greatly increases the payload mass. For 540 days at 840 g of oxygen and 2.4 kg of water per person, an extra 7000 kg would be added to the payload, costing an extra $3.08 billion. This method is not recommended due to cost and volume constraints. The second option and third option are similar except an extra rocket launch is not needed for the second option. However, the $100 million cost of an extra launch costs the same as loading an additional 230 kg into the manned rocket. We must determine if losing the 740 days of preparation time would result in the apparatus increasing in mass by 230 kg or greater.

Figure 3 Delta IV Heavy rocket, also with enough thrust to send a payload to Mars

Any storage tank and high pressure pump would not be used for oxygen and water, reducing mass. A high-pressure 1000 L tank has a mass of about 15 kg when empty, while a high-pressure 10000 L tank has a mass of about 110 kg. If we assume a middle range for storage, say 3000 L tanks, then the mass should be about 90 kg total; adding pumps should not exceed 120 kg total. Now we have a 350 kg discrepancy. Assuming the apparatus that is sent ahead has a mass of 300 kg which includes a mobile component, and has 2.4 times as much time to produce oxygen and water, the mass addition becomes 300 x 2.4 - 300 = 420 kg. Now there is a 70 kg difference that favors sending two launches. But what if the mass is not that large and the one-launch option is actually better? Then power requirements must be considered. Human-powered generators waste precious energy for the astronauts, so additional power supplies must be used. Even for efficient batteries such as lithium-ion batteries, which produce up to 120 watt-hours per kilogram currently, an additional 30 kg of battery would have to be added for a one-flight option.[11] In short, there are additional hidden costs that make the two-launch option more cost-effective.

Choosing a landing site

Although the environment of Mars is similar planet-wide, there are differences that make certain sites more habitable than others. Temperatures play a large role: the poles can drop to -150°C at night, far too cold for any human or robot activity. The equator can get as warm as 20°C at midday, but much of the planet averages around -50°C to -60°C, with 80°C of daily temperature swings.[12] Not only can this damage metals in autonomous systems, but it can present challenges in event of a power failure. Dust and wind must also be taken into account. Dust particulates are very fine on Mars, and while they may not cause severe damage to the internal components, they can cover solar panels and reduce power output dramatically, similar to the power reductions on the Mars Explorer Rovers after a planet-wide dust storm. Winds can gust up to 100 km/h, but due to the thin atmosphere have a lessened effect on equipment than they would on Earth.[12]

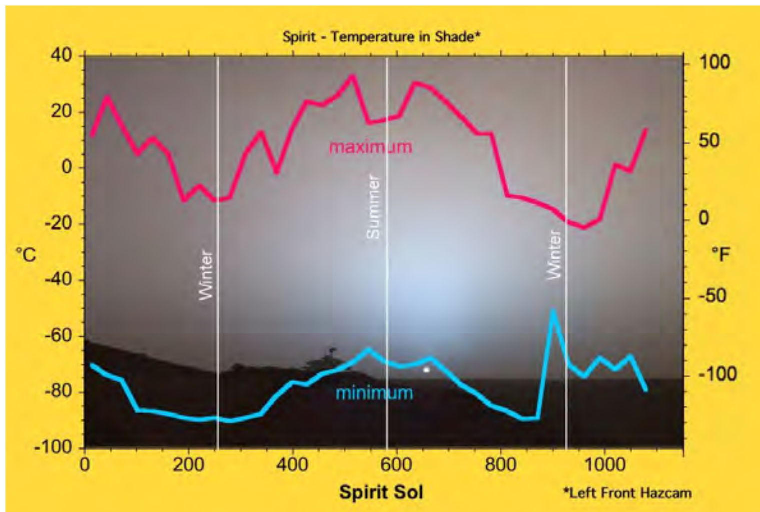

Figure 4 Temperature at Spirit Rover site[13]

The southern and northern hemisphere are quite different. Foremost, the seasons have different lengths unlike on Earth. A Martian spring in the northern hemisphere is 50 days longer than the spring in the southern hemisphere. The north is thus warmer and with more daylight for a significantly longer time. Furthermore, the north is flatter than the south, with fewer craters and more plains. The south has a permanent layer of dry ice in its ice cap, which makes any sort of attempt at extraction much more difficult than necessary.

In deciding to land in the northern hemisphere, sites are divided into into three categories: polar region, mid-latitudes, and equatorial region. From Figure 5, it appears that large amounts of water exist in the polar region, but it is locked up in ice that must be drilled. The polar region is more inhospitable than lower latitudes. The mid-latitude region suffers from large swings in daylight times due to Mars' 25° axial tilt and is more cratered than the equator. As for the equator, the region has lower water density but is warmer and days are more suited for human and robot activity.

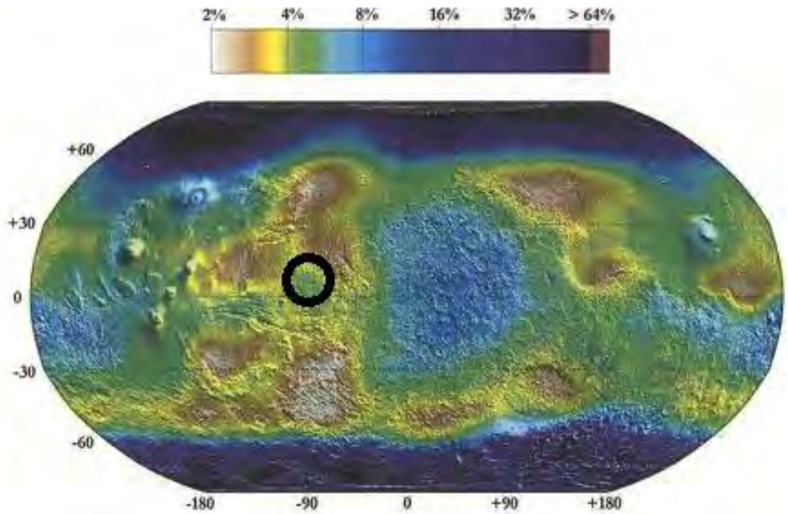

Figure 5 A map of soil by percent weight that is water with an example of 5% water near Chryse Planitia[14]

We choose a region near Chryse Planitia that satisfies safety conditions: it is flat, at a low altitude with pressure above the triple point, and has a daily high temperature of -10°C in spring and summer. The coordinates of the landing site are approximately 15°N 50°W.

Landing Mechanism

NASA has already sent four rovers to Mars, as well as additional landers. The landing mechanism will not change from past missions. First, a large parachute is deployed. This parachute must have a large surface area because the pressure on Mars is 1% of what it is on Earth, so according to the equation $\text{Pressure} = \text{Force} * \text{Area}$, the radius of the parachute must be ten times larger than what it would be on Earth. After, the heat shield is discarded and then the shell is also discarded. Thrusters on the capsule activate to slow the payload to a soft landing. Because the capsule


Figure 6 Airbags used by *Spirit* and *Opportunity* to land

keeps horizontal velocity, a tetrahedral "pyramid" of airbags is deployed to prevent damage. Once stopped, the airbags deflate and are dragged to the bottom of the capsule. The capsule opens whichever side of the pyramid will allow for the payload to stand upright.[15]

Past landings have shown that NASA has the capability to land within 2 miles of the desired drop-off spot for unmanned payloads, while precision landing was invented for the Apollo missions to land astronauts within a fraction of a mile of the desired drop-off point. With this certainty, landing the astronauts near the autonomous device is not considered a problem.

Chemical Methods

Oxygen can be produced on Mars through water electrolysis. The following chemical formula shows that for every two moles of water, one mole of oxygen can be made.

$$\mathbf{H_2O \rightarrow H_2 + \frac{1}{2}\, O_2}$$

This reaction takes 1.23 V of electricity in the water to work, but is reliably efficient and can be assumed to be 100% efficient.[16]

Water must be available for both storage and electrolysis. In order to store as much material as needed each day, using only extraction may not be efficient enough. We can create additional water and/or oxygen through other mechanisms. Three such mechanisms are the solid oxide hydrolysis, the Sabatier reaction, and the Reverse Water Gas Shift (RWGS). The first mechanism uses solid wafer stacks to absorb carbon dioxide from the atmosphere and then electrolyzes it into carbon monoxide and oxygen, with the reaction:

$$\mathbf{CO_2 \rightarrow CO + \frac{1}{2}\, O_2}$$

This process takes electricity and is not very efficient compared to electrolysis. The stack is solid and weighs more than other mechanisms' devices would.

The second mechanism, the Sabatier reaction, was discovered in the early 20th century and has been used in refinery processes ever since. The reaction occurs at high temperatures, is effective in a 300-400°C range centered around 400°C, and is highly exothermic.[17] The reaction is as follows:

$$\mathbf{CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O,}\ \Delta H = -165\ \text{kJ/mol}$$

This reaction takes the carbon dioxide in the atmosphere and mixes it with hydrogen to produce methane and water. The water can then be electrolyzed to reform 2 moles of hydrogen. This leaves a 2-mole deficit, meaning that hydrogen must be supplied.

The last mechanism is the RWGS, which takes atmospheric carbon dioxide and mixes it with hydrogen like the Sabatier, but produces carbon monoxide and water. The reaction is endothermic, meaning it would need an extra heat supply. The reaction is as follows:

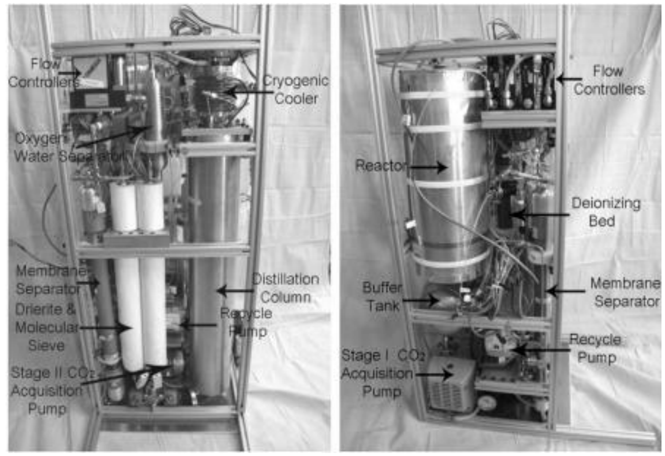

Figure 7 Lab-scale Sabatier reactor

$$\mathbf{CO_2 + H_2 \rightarrow CO + H_2O,}\ \Delta H = 41\ \text{kJ/mol}$$

The RWGS uses one mole of hydrogen, meaning no extra hydrogen needs to be provided. This reaction proceeds at higher temperatures of around 600-700°C.[18]

A decision matrix was created to decide which reaction to use. Before creating the matrix, we considered combining the Sabatier reaction, which gives off heat, with the RWGS, which needs heat to operate, assuming that this would be power-efficient.

Mechanism Decision Matrix

		Solid Oxide		**Sabatier**		**Sabatier/RWGS**		**RWGS**	
Criteria	Weight	Score	Weighted	Score	Weighted	Score	Weighted	Score	Weighted
Efficiency	35	9	315	8	280	9	315	5	175
Cost	25	5	125	7	175	6	150	4	100
Power	20	3	60	7	140	7	140	4	80
Supplies	10	9	90	4	40	6	60	9	90
Practicality	10	2	20	8	80	9	90	5	50
Total	100	27	610	34	715	**37**	**755**	27	495

After deciding to combine the two reactions to increase output and save power, we can add yet another reaction. Because there is still a deficit of hydrogen, we can gain some back with the syngas reaction, which takes the methane produced by the Sabatier reaction and reacts it with atmospheric carbon dioxide, as follows:[19]

$$\mathbf{CH_4 + CO_2 \rightarrow 2CO + 2H_2}$$

Assuming 100% efficiency of all reactions, the overall net reaction should come out as:

$$\mathbf{3CO_2 \rightarrow 3CO + 1.5\ O_2}$$

This means that outside of the system, the virtually unlimited atmospheric carbon dioxide can be converted into oxygen at a 2:1 ratio. This process cannot be used for large-scale terraforming because a mostly carbon monoxide atmosphere is poisonous for humans.

Efficiencies

The process system cannot realistically have 100% efficiency, meaning that the overall net reaction does not hold true. Because not all reactions run to completion and there are byproducts, hydrogen will have to be supplied from Earth and extra water must be supplied. Using experimental data, we can estimate the greatest efficiencies of each process:[19,20]

Process	Efficiency
Sabatier	95%
RWGS	80%
Electrolysis	100%
Syngas	75%

The most efficient temperature for the Sabatier-RWGS system is 500-600°C. In order to get an overall reaction, we can multiply each stoichiometric coefficient by the percentage, additionally accounting for the reactant methane in syngas starting at 95% since it is a Sabatier reaction product. We also scale up the hydrolysis reaction so that enough hydrogen is produced. The overall non-simplified reaction becomes:

$$\mathbf{2.95\ CO_2 + 5H_2 + 3H_2O + 0.95\ CH_4 \rightarrow 0.95\ CH_4 + 2.225\ CO + 2.7\ H_2O + 4.425\ H_2 + 1.5\ O_2}$$

Because hydrogen is easily separated from other byproducts, the unreacted hydrogen from the Sabatier and RWGS reactors can be recycled back into the system using membrane separators. Taking this into account, we find the final reaction to be:

$$\mathbf{2.95\ CO_2 + 0.3\ H_2O + 0.175\ H_2 \rightarrow 2.225\ CO + 1.5\ O_2}$$

This reaction is unbalanced. The carbon dioxide is taken from the atmosphere, so any amount of carbon dioxide needed is possible to attain. However, additional water must be provided from the soil. For every 5 moles (160 g) of oxygen, 1 mole (18 g) of water must be extracted. Because we must produce 1815 kg of oxygen, an additional 204.2 kg of water will be extracted, but will not have to be held in a tank. The hydrogen must be brought from Earth or created as a product from electrolyzing water. For every mole (32 g) of oxygen produced, 0.1167 moles (0.2333 g) of hydrogen must be supplied. Thus, we must supply 13.24 kg of hydrogen. The cost to send this hydrogen from Earth is about $5.82 million, a small fraction of the total cost. By performing hydrolysis, we would have to extract an extra 119.2 kg of water, an additional 93 g per day. If supplying extra power for this extraction costs more than transporting the hydrogen from Earth, then we will choose to transport it.

Process Methods

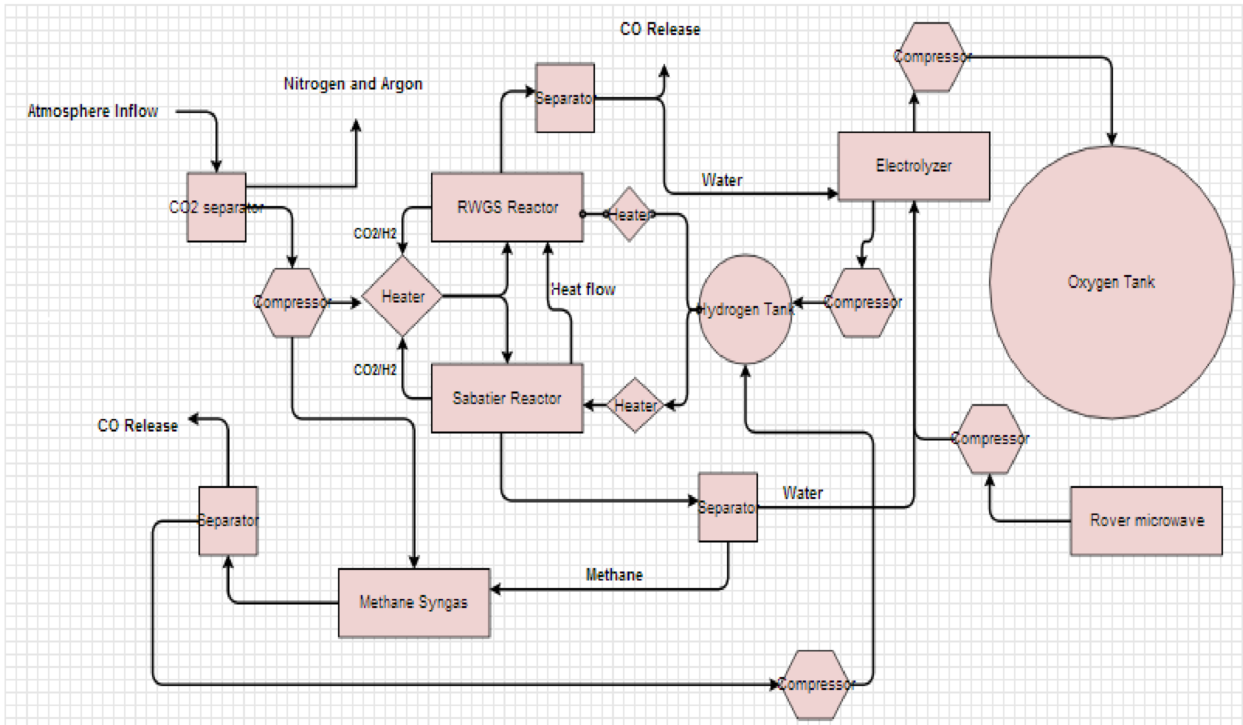

Figure 8 Simplified process diagram of the full Sabatier/RWGS/Syngas mechanism

The process starts with atmospheric intake of carbon dioxide, which is then delivered to the three reactor chambers after being compressed and heated. A movable microwave is used to extract water from the soil, which is then sent to the electrolysis chamber. The Sabatier reactor transfers heat to the RWGS reactor, then both reactors send water to the electrolysis chamber after separating products, while the syngas reactor sends hydrogen to the hydrogen tank for recycling. The oxygen and hydrogen are compressed and sent to their respective tanks.

Setting Up

The process cannot start as soon as the landing finishes; power must be started and the rover has to roll out. The capsule that lands must be able to contain everything sent. Nothing should be stacked to save room because components may damage each other. Assuming that the lab-scale Sabatier reactor shown previously in Figure 7 is a proper size, the process system should measure about 2 m^2 base and 2 m tall, for 4 m^3 total volume. The storage tanks will be about 4 m^3 total. The final component, the rover, does not need to be very large, only needing to support a sensor and microwave. Including a power supply, It may be about half the base of *Spirit* or *Opportunity*, or about 2 m^3 in size. The power supply for the process system should be no larger than 1 m^3. The total size is for a capsule is thus 10 m^3.

The process system will stay where it lands and will have a thermal covering made of a material such as Mylar to protect it from low temperatures and dust. Any atmospheric intake will have to be an exception so that it can be exposed. To prevent dust from building up inside, a cover grating is added where the holes are small enough that dust cannot get stuck.

To get the system and rover upright, a similar mechanism to *Spirit* and *Opportunity* landings is used, where accelerometers are used to detect which side of the landing container is down. The *egress* phase consists of moving the rover off of the landing platform. It will not take as long as other rover egress phases, which take about 3 sols, because it does not have as many instruments; it needs to be able to navigate around rocks and move a small distance. A smaller rover using a proportional power supply to the Mars Exploration rovers will move at about 1 cm per second using a similar hazard avoidance system. To get the rover about 15 m out from the lander, about 25 minutes are needed, which should not shift the operating time.

The process can start up as soon as the landing stage is over. Assuming that it does not run on solar power (see Power Requirements), there is no reason for the system to delay starting after sensors are checked.

Microwaving Rover

Although once the processes get started, no net water is needed theoretically, the process efficiencies realistically cannot be 100%, so extra water is needed. A movable microwave must be used because once all of the water is extracted out of an area of soil, it must move to a new area to extract more. Previous university research has gone into design and construction of a working microwave that uses magnetrons to heat the soil, while NASA has done lunar soil heating experiments.[21,22]

We assume that 5% of the soil is water by mass, and that the penetration limit of the microwave is 0.1 meters. The density of Martian soil is about 1.52 g/cm^3, or 1520 kg/m^3.[23] So for every square meter down to a depth of 0.1 m, there are about $1520 * 1 * 1 * 0.1 * 0.05 = 7.6$ kg. If we assume that oxygen production takes no net water, then we must extract 5184 kg, which means that the rover must traverse 682.1 m^2, or a 26.1 m by 26.1 m patch of soil. Taking into account the process efficiencies previously calculated, the rover would cover 709 m^2 assuming an Earth-based hydrogen supply. Without bringing any additional hydrogen, the rover would cover 724.7 m^2.

The rover needs to analyze the soil for traces of water ice, but does not need any other scientific instruments. Assuming a flat landscape, the wheel radius does not need to be large; it only needs to support the mass of the rover. The power to drive the rover can be borrowed from the power to run the microwave, as it would be difficult to have both functions occur simultaneously. The tubing connecting to the compressor should be able to stretch as far as the rover goes. If the rover makes a circle around the landing site, the radius would be at least 16-17 meters, meaning the tubing should cover this length. The tubing would be wound up during flight and unwound on Mars.

Atmospheric Intake

In addition to providing water from the environment, also carbon dioxide must be provided. The air on Mars can be approximated as 96% carbon dioxide, 2.1% argon, and 1.9% nitrogen. Although argon is an unreactive noble gas, nitrogen may pose a problem by creating unwanted byproducts. To purify the carbon dioxide, we can use a membrane separator (sieve) or a carbon scrubber that traps and holds only carbon dioxide. Because the sieve readily sends carbon dioxide to the next part of the process, we choose to use a molecular sieve. The nitrogen and argon are then put back into the atmosphere.

For every mole of oxygen (32 g), 1.97 moles of carbon dioxide must be introduced into the system. Assuming a small loss of 1-2% from leakage and imperfections in the sieve, we can round this number to 2 moles (88 g) of carbon dioxide per mole of oxygen. Since 1815 kg of oxygen are needed, approximately 4992 kg of carbon dioxide must be input. This amounts to 3.9 kg of carbon dioxide input on average per Earth day.

Because nitrogen exists in the atmosphere already, it may be used to lower costs of transporting a nitrogen atmosphere. The manned flight vehicle carries nitrogen with it, so unless the habitat is larger, no extra nitrogen is needed. Assuming that the habitat is indeed larger than the flight vehicle by at most double, the astronauts will need at most 100% more nitrogen. All of the nitrogen provided for a habitat atmosphere must be created before human arrival, allotting 740 days for possible nitrogen production. For every mole of carbon dioxide extracted, we can extract 0.0198 moles of nitrogen. In 740 days, we extract 65,600 moles of carbon dioxide, meaning we can get 1,299 moles of nitrogen, or 36.4 kg. At 1 atm and 25°C, this quantity of nitrogen takes up 31.8 m^3, which is much less than 80% of proposed habitat volumes. This number is closer to 5-10% of the proposed volume. The cost to transport this is $16 million. Sending up an extra storage tank, along with another compressor and cooler, does not make nitrogen extraction at all efficient.

Compressors

Compressors are important to the system because they increase the system pressure, which allows for the Sabatier, RWGS, and syngas reactions to take place. At higher pressures and lower volumes, molecules have a lower mean free path, meaning they will "bump" into each other more frequently. A higher pressure therefore increases reaction rate. There are four jobs of compressors: (1) to compress carbon dioxide for the reactions, (2) to compress any water in vapor phase for electrolyzing, (3) to compress hydrogen into its tank and for reactions, and (4) to compress oxygen and water for storage purposes. The carbon dioxide and electrolyzer compressors have the atmospheric pressure to overcome. Around the proposed landing site, the elevation is around 2,600 m below zero Mars elevation. This makes the atmospheric pressure about 793 pascals, or 0.00793 bar, or 0.00783 atm. Because the reaction must be carried out at more than 1 bar, the compressor must compress the gases by approximately the reaction pressure. If we assume reactions are carried out at 5 bar, then the compressor must compress the carbon dioxide and water vapor by 5 bar.

For the hydrogen already in the system, it should already be under system pressure and unexposed to the atmosphere, so it does not need to be compressed multiple times.

The oxygen storage compressor must be powerful. At its peak, the tank must contain 1,049.3 kg of oxygen. Unless the volume were as large as an entire rocket, the pressure gradient would be extremely large. Assuming a 2,000 L tank, the oxygen would be under 350 atm of pressure at higher temperatures, and 250 atm at lower temperatures. At this pressure, the oxygen would be liquid.[24] This means that the compressor will have to compress the oxygen to its liquid form, but not further. A positive displacement pump is able to keep constant flow regardless of pressure and can be used before compression and then after to send the oxygen to storage and keep it there.

Heaters and Coolers

Heaters and coolers will take up most of the power to the system. Heaters are used to heat the gases to reaction temperatures. A heated gas will expand at constant pressure and pressurize at constant volume. Using constant volume, the heaters work in conjunction with the compressors to heat and pressurize the gases. The syngas reaction must be heated the most, so some heat from the Sabatier reaction can be used to catalyze it. Otherwise, the RWGS reaction can run without any heat from a heater, but rather from Sabatier-produced heat.

Coolers are used to cool down water and oxygen so that they can become liquefied. A cooler (cold sink) will be attached to the rover to cool the sublimated vapor back into water. Although the atmosphere is cold enough to cause deposition, no air should mix with the water vapor, so the cold sink, along with a compressor, is responsible for turning the vapor into water.

At 1 atm, oxygen has a boiling point of -183°C, even colder than the Martian atmosphere. Even using piping with a low heat capacity, the oxygen would cool to -90°C, still too warm. This means that to store the oxygen, a cryocooler must be used.

Electrolysis

Electrolysis splits water into hydrogen gas and oxygen gas. The process is largely endothermic because the reverse process is spontaneous, but electrolysis can also be accomplished by running a current through the water, using 1.23 V of power. Because water is not a conductor, many times a salt such as sodium hydroxide is added to conduct the electricity. Once the water is electrolyzed, the hydrogen and oxygen are separated. A Hofmann voltammeter can separate the gases into different tubes by hooking up a battery to the anode and cathode.

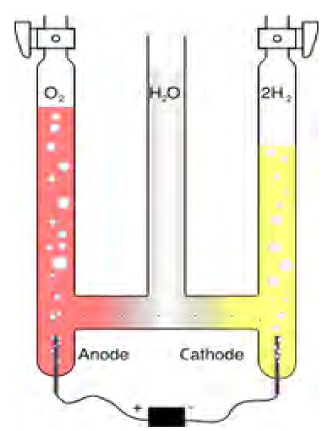

Figure 9 Hofmann voltammeter

Storage

Storage of the oxygen and water is crucial to the mission. The storage containers must be rigid so as to not puncture from the conditions on Mars nor from the landing. They cannot be too small because the build-up of pressure would be too great, but they also cannot be too large because there would not be enough room on the rocket for other parts of the payload. There needs to be 2997 kg of water and 1049.3 kg of oxygen available for the astronauts upon arrival; afterwards the rate of consumption outdoes the rate of storage.

Water

To store water as a liquid , it must be kept under an appropriate temperature. Because the container is sealed, atmospheric pressure is not a concern. The container must also be able to link directly to the piping in the habitation module, so there must be at least one valve on the container, though more valves should be added for drinking, food hydration, plant-growing, and hygiene. At 1 atm, water has a density of 1 kg/L. Because liquid water has a small compressibility factor, the density can be considered as not pressure-dependent. We can therefore assume that the density will stay constant and a small compressor may be needed for the last few weeks when the filled volume is low and the water may have a high vapor quality. This makes the volume of the container approximately equal to the volume of the water, or 3000 L, which is equal to 3 m^3. The tank is relatively large for a space mission but is necessary. In comparison, a box that would fit the *Curiosity* rover measures 17 m^3. Curiosity is by far the largest rover sent to Mars.

Oxygen

Storing oxygen is more complicated than storing water. The critical temperature for oxygen is -119°C, so even on a cold winter night, the oxygen would probably still be gas at atmospheric conditions. The previously discussed cryocooler would be necessary. At maximum capacity, the 1049.3 kg of oxygen would exist in liquid form. Oxygen is over 800 times as dense in liquid form than in gaseous form. Because the density of liquid oxygen is 1.141 kg/L, a 920 L, or 0.92 m^3, a tank would be needed.[25] This is smaller than the water tank. However, before the oxygen tank is full, the oxygen would be a gas and build up pressure. If the temperature in the tank is the critical temperature, then the critical pressure is 51 atm, which would be achieved about 60 days after the system starts operation. A 1000 L tank made from steel has a pressure limit of thousands of psi, where 1000 psi is already 68 atm, more than enough. The total volume between these two tanks would be 4 m^3, comparable to a box that would fit one of the *Spirit* or *Opportunity* rovers.

Delivery

Upon arrival, astronauts would connect the habitat to the storage tanks using piping. Gravity and a pressure gradient would take care of any force needed to move the materials to the habitat. Water may be stored at 25°C and may not have to be heated, but a turbine would have to be used for the oxygen. Because liquid oxygen will expand to 850 times its stored volume to mix into the air, either the radius of the pipe would have to expand by a factor of 29.2, or the velocity of the flow would increase by a factor of 850. An increase in radius by a factor of 10.6 and velocity by a factor of 8 is possible, since the gas should enter the habitation module at a higher speed so that it may mix with the nitrogen.

Oxygen input should come from more than one pipe to ensure homogenous mixing. An astronaut on the other side of the habitat from the input pipe may not have as high an oxygen concentration as someone closer to the pipe. If two pipes are used on opposite sides of the habitat, the pipe length would be at least tens of meters to set the two apart, which is not practical. Two pipes can be placed toward the middle a few meters apart, which will prevent problems if one pipe breaks or malfunctions. The pressure gradient between the tank and habitat will carry the oxygen toward the habitat, even on the last day of habitation, considering that there will be backup oxygen in case there are takeoff delays. Because the pressure difference is so great, the oxygen will naturally flow at a high velocity from tank to habitat. To accommodate this, a high-pressure valve is installed to control the flow to the appropriate mass flow rate.

Because a habitat module cannot be moved easily once it lands, it either must land with the process system, or the landing accuracy of two separate landings must be on the tens of meters scale. Such an accurate landing is unlikely on Mars, so if NASA sends the habitat with the astronauts, they must spend extra money on a precision landing system that would guide the habitat to the process system. Sending the habitat module along with the process system may be beneficial and cost-effective, but when it is sent is irrelevant as long as it lands in proximity to the system. An increased volume would allow for more oxygen storage, but because the partial pressure maximizes at 0.2 atm, the vast majority of the oxygen would still have to be held in a tank.

Sending the habitat with the process system may pose problems. If there is no power or upkeep, it may be damaged by the environment. If the astronauts do not travel in the habitat and land a few kilometers away, then they will be in danger of oxygen starvation. To rectify the problem, the astronauts will travel with emergency suits for a walk on Mars. Because the gravity on Mars is 38% of Earth's, the energy exerted will be less than if the same suited walk was made on Earth.[2]

Carbon Dioxide Disposal

Carbon dioxide will start to build up in the habitat, which both increases CO_2 concentration and lowers O_2 concentration. A human cannot function normally in an atmosphere that contains a >2% concentration of carbon dioxide or <19% concentration of oxygen.[26,27] Because oxygen will constantly be pumped into the habitat, a lower concentration of oxygen will not occur. If oxygen is pumped in at the same rate it is consumed, the concentration would be 19.6% when carbon dioxide levels reach 2%. A person produces approximately 1.043 kg of carbon dioxide per day, or 1.07 kg per sol.[28] This becomes 4.28 kg per sol for the habitat. A small habitat with 300 m^3 of living space would mean that after one sol, the carbon dioxide concentration would be 0.781%. In comparison, Earth's atmospheric carbon dioxide level is 0.04%. Although it would be possible to spend two sols without disposing the carbon dioxide, it is safer to dispose the carbon dioxide once per sol.

Carbon dioxide cannot be simply vented without losing oxygen and pressure. A solid adsorbent, over which carbon dioxide passes, will capture and hold the carbon dioxide until it can be released into the atmosphere. Common carbon dioxide scrubbers include limestone, amines, hydroxides, and charcoal. Some of these substances are known as zeolites and are laid down as a bed of material. NASA has tested and used an amine swingbed system, which takes out carbon dioxide and moisture from the air.[29] The chemical reaction of respiration is:

$$C_6H_{12}O_6 + 6\ O_2 \rightarrow 6\ CO_2 + 6\ H_2O$$

Water vapor is also produced and can be removed along with the carbon dioxide by using this system. On a spacecraft, the swingbed takes the gases that it absorbs, swings to the outside, and vents the gases into space. It would be dangerous to allow the swingbed to be exposed to the

Martian atmosphere because of the large concentration of carbon dioxide. Instead, the swingbed will swing into an airlock vacuum, release the gases, swing back into the habitat, and then the airlock will be purged to release the gases.

As of 2013, the amine swingbed had completed all troubleshooting, and was being tested for 1000 hours. A 15-year window until a habitat launch allows for enough time to drastically improve efficiencies.

Figure 10 Swingbed used on ISS

Operating Schedule

Just like the Mars rovers, the system cannot operate continuously for the duration it is there. There will not be enough power to do so, especially if solar power is used. The cold nights will hamper system efficiency, and any radio contact with Earth will be suspended. All operations will therefore be done during Mars' daytime.

Because Mars has a more eccentric orbit than Earth, the seasons have a largely different numbers of days.

Length of Martian Seasons[30]

Season in Northern Hemisphere	Number of Sols (days)
Spring	194 (199.3)
Summer	178 (182.9)
Autumn	142 (145.9)
Winter	154 (158.2)
Total	668 (686.3)

The spring and summer have similar conditions, while autumn and winter also have similar conditions. The northern hemisphere advantageously has 76 more days of more sunlight and higher temperatures than the southern hemisphere.

Using data from daylight duration on Earth, Mars daylight times can be extrapolated. At the analogous coordinates on Earth, after taking into account the 2° addition in tilt, the average daylights were the following: spring and summer had 12.52 hours of daylight per day, while autumn and winter had 11.61 hours.[31] These values become 12.86 and 11.93 hours per sol, respectively.

The 2028 and 2031 launch missions will have the payloads arrive around July 29, 2029 and then around August 8, 2031 (740 days). For the process system, the landing occurs 144 sols into Martian summer[32]. Running for 1246 sols, the seasonal breakdown is the following: 388 sols in spring, 266 sols in summer, 284 sols in autumn, and 308 sols in winter, where the last day it needs to run is 54 sols into summer.

The heaters and coolers of the system, as well as any solar power, take time to start working at full potential. It can be estimated that it takes about 45 minutes for all systems to start completely. This allows a maximum runtime of 12.1 hours in spring and summer and 11.2 hours in autumn and winter. However, dust storms and other local weather phenomena hamper production, so we must account for time lost. At the Viking 1 site, three "great dust storms" over a two-year period were recorded.[33] Each storm can make any water extraction impossible for approximately 10 days. Assuming the same frequency in storms, 30 days are lost, though a large fraction of the storms occur during northern winter. After all things considered, the systems can run an average of 11.5 hours per sol in spring and summer and 10.5 hours per sol in autumn and winter, though if solar power is used this may be reduced to as few as 8 hours in the winter.

Flow Rates

Flow rates help to determine how much mass and power must be given to the system to allow it to run; a feasible flow rate for all parts must be used for the system to work. All flow rates will be given at a per hour basis. We split the flow rates into two timeframes: the first is the 740 days during which the process system must run before astronauts arrive, while the second is the last 540 days during which both the process system and the delivery system must run.

First Stage

The first 740 days lasts for 720 sols, consisting of one Martian year plus an extra 52 sols, which will extend to around the third week of autumn, which will be counted as summer in order to run more efficiently and because the amount of daylight at the autumnal equinox is similar to that of the vernal equinox. The breakdown is 424 sols of spring/summer and 296 sols of autumn/winter. Multiplying by daylight operation hours, the total operating time for the first part is 7984 hours.

To obtain the 1049.3 kg of oxygen, 131.42 g of oxygen per hour must be produced. For the 3115 kg of water that must be microwaved out of the soil, 390.12 g of water per hour must be produced.

The electrolysis of water which produces the 131.42 g per hour of oxygen will also produce hydrogen at a rate of 16.428 g per hour.

For the carbon dioxide intake, 2886 kg of carbon dioxide need to be purified and put into the reactors, of which 2837.5 kg will be used. This equates to 355.4 g of carbon dioxide per hour, coming from 373.07 g of total air intake per hour, assuming 1-2% is lost by the sieve.

Assuming that the three reactors have the same reaction rate (i.e. some thermal equilibrium has been reached), each of the Sabatier and RWGS reactors has an intake of 961.86 kg during the first stage of the mission, while the syngas reactor has 913.77 kg. This is an inflow of 120.47 g per hour for Sabatier and RWGS, while the syngas reactor takes 116.4 g per hour. Using the stoichiometry of the reactions, we then find the input and output rates.

Sabatier (g/h)			**RWGS (g/h)**			**Syngas (g/h)**		
H_2	CH_4	H_2O	H_2	CO	H_2O	CH_4	CO	H_2
21.90	41.62	93.64	5.476	61.33	39.43	41.62	109.25	7.936

Table 2 First stage flow rates in grams per hour of closed-system compounds. Compounds in red are inputs, those in blue are outputs.

The net flow out of the hydrogen tank is thus 3.012 g/h, giving a total outflow of hydrogen of 24.05 kg for the first stage. This is more than what is brought in the tank because we assume that the hydrogen is recycled. After subtracting the recycled hydrogen from the Sabatier and RWGS processes, the net flow out is 0.822 g/h, or 6.561 kg for the first stage, which is reasonable given that 13.24 kg are supplied.

Second Stage

The second stage consists of the final 540 days, or 525.5 sols, in which the astronauts will have arrived and will be completing their mission. During this stage, the delivery system and carbon dioxide disposal system will be implemented. The seasonal breakdown of the second stage is: 124 sols in autumn, 154 sols in winter, 194 sols in spring, and 53.5 sols in summer, totaling 278 sols in autumn/winter and 247.5 sols in spring/summer. This second part is considerably colder overall, but the astronauts will be able to leave in summer when conditions on the ground and in the atmosphere are fairer and warmer. The process system will run for 5765 hours, while the delivery system will be running constantly.

The remaining 765.7 kg of oxygen will be produced at 132.8 g per hour and the remaining 2155.1 kg of water will be produced at 373.8 g per hour. The electrolysis of water will also produce hydrogen at a rate of 16.6 g per hour.

For the carbon dioxide intake, 2105.7 kg of carbon dioxide need to be purified and put into the reactors, where 2070.6 kg of it is used, still assuming the 1-2% loss. This equates to 359.2 g of carbon dioxide input per hour, coming from a total 377.1 g of air intake per hour.

Each of the Sabatier and RWGS reactors has an intake of 701.9 kg during the second stage of the mission, while the syngas reactor has 666.8 kg. This is an inflow of 121.75 g per hour for Sabatier and RWGS, while the syngas reactor takes 115.66 g per hour.

Sabatier (g/h)			RWGS (g/h)			Syngas (g/h)		
H_2	CH_4	H_2O	H_2	CO	H_2O	CH_4	CO	H_2
22.14	42.06	94.63	5.534	61.98	39.85	42.06	110.4	7.886

Table 3 Second stage flow rates in grams per hour of closed-system compounds. Compounds in red are inputs, those in blue are outputs.

The net flow out of the hydrogen tank is 3.188 g per hour, but after correcting for recycled hydrogen, it is 0.974 g per hour, which accounts for much of the rest of the remaining hydrogen originating from Earth. The last remaining hydrogen is used to change molar ratios to shift chemical equilibrium toward the products.

For the delivery system, water must be delivered on demand, so there is no constant flow rate. A valve would be used to control flow. For oxygen, we assume there are two pipes. There is no consensus on how large the volume of a Mars habitat would be, so we may assume one of three sizes: 300 m^3 (small), 600 m^3 (medium), and 900 m^3 (large). By calculating for the lower bound, we simply multiply to scale to the larger habitats. To mimic conditions on Earth, the habitat is kept at 1 atm and 25°C, where 0.2 atm consists of oxygen. Using the ideal gas law, which is a fair approximation for a relatively low-mass gas like oxygen, we find that a 300 m^3 habitat would use 78.48 kg of oxygen, whereas the medium would use 156.95 kg, and the large would use 235.43 kg. Although there would be enough oxygen to create such an atmosphere, there would have to be this much oxygen left on the last day of the mission to sustain the atmosphere, meaning at least an extra 78.48 kg would have to be produced; otherwise the astronauts would run out of oxygen about 29 days before the end of the mission.

There are three solutions to this problem: produce oxygen at a faster rate for the first stage, bring the oxygen from the shuttle, or bring an additional smaller system to create oxygen. An extra 78.48 kg of oxygen would mean an extra 9.82 g per hour of oxygen production, which raises production rates by about 7%, while the large habitat would raise production rates by around 21%. Because astronauts would already have oxygen in the shuttle, an atmospheric transfer to an equalization pressure--which can be roughly estimated as total transfer--can take place. Assuming that the shuttle carries enough oxygen for 50 m^3, there still needs to be 13 kg oxygen produced at minimum. Bringing an additional system would increase costs and be pointless if a more powerful system can be sent in the first place.

By extracting more water, there will be enough hydrogen so that extra is not needed, and there will be enough oxygen to sustain this environment. An additional 88.3 kg of water would have to be extracted to provide the appropriate level of oxygen for the small habitat, while for the large habitat, an additional 264.9 kg of water is needed. However, if a water recycling system is put into place, none of this would be necessary because some of the existing water could be hydrolyzed. Water used for food and plants cannot be recycled, so about 0.164 kg of waste water for the small habitat or 0.5 kg of waste water per day for the large habitat would have to be recycled. The system to accomplish this would be small compared to everything else and could be brought with the manned mission, eliminating the need for any changes to the process system.

Once the atmosphere is piped into the habitat, the oxygen flow will be constant. The astronauts will be using 3.452 kg of oxygen per sol, or 140 g per hour of oxygen, which must be the flow rate to replace the oxygen. This leads to a loss of about 2 kg per sol on average from the tank, which will deplete the tank on the last day. Astronauts will have enough oxygen from the habitat to have sufficient backup.

Using two pipes, the oxygen flows at 70 g per hour through each pipe to the habitat. The density of oxygen is about 1.43 g/L, so it flows out of the pipe at 13.6 mL/s. On the tank side, the liquid oxygen density is 1.141 kg/L, flowing in at 0.017 mL/s. For this flow, the pipe diameter can be relatively small, but still must be large enough so as not to break. Because the temperatures and pressures of the pipe are different from the oxygen tank, the liquid will quickly expand into gas, so if the pipes are 10 m long with a radius of 5 cm, the volume is 0.0785 m^3. The daily maximum temperature can be -20°C, so if the oxygen has enough time to become this temperature, 1 g will exert 0.008 atm on the pipe, so there is no danger of internal breakage.

Power Requirements

The largest limitation the mission will face is power supply. An autonomous device cannot be connected to a generator, so it must travel to Mars with its own power supply. The cold temperatures there may damage some power supplies, while dust may affect others. Although setting up small wind turbines using a rover is a possibility, and the winds on Mars can average a velocity of 10-15 m/s, the thin atmosphere means at the same velocity, the winds are much weaker than those on Earth[12].

Currently operating rovers such as *Opportunity* run on solar power while others such as *Curiosity* run on plutonium. Plutonium is radioactive and gives off most of its energy as heat, which would be good for heating up the reactors, but does not work well for the components that run on electricity. There are three system groupings that use power: (1) the process reactors and their respective components, including heaters, compressors, and pumps, (2) the microwave and transfer system on the rover, including pumps, and (3) the rover itself. Each system can use a different source, but we will assume the rover uses solar power and the process system uses batteries.

For the process system, previous research has been conducted to determine how much power is needed. In one such study, it was determined that to produce 5 kg per day of an oxygen-methane fuel mixture, 2830 W was needed over a 12-hour period. In terms of mass, the oxygen makes up two thirds of the mixture, meaning a similar amount of power would be used to produce 3.33 kg of oxygen per day.

Scaling Relations for Mars ISRU Systems
(mass in kg, no redundancy. 12 hr daytime power in Watts -night power=0)

	0.5 kg/day		5 kg/day		50 kg/day		500 kg/day	
S/E-RWGS								
sorption pumps	5	24	20	240	80	2400	320	24,000
chemical synthesis	4	150	8	1500	44	15000	404	150,000
controls	2	20	4	40	8	80	12	160
lines, valves, misc	3	0	9	0	27	0	84	0
refrigerator	2.5	105	10	1050	40	10,500	160	105,000
Total	*16.5*	*299*	$\boxed{51}$	$\boxed{2830}$	*199*	*27,980*	*980*	*279,160*

Figure 11 Scaled numbers of a working process system from a Zubrin paper about RWGS[20]

This system does not include the syngas reactor, which takes more power to consume the methane than to store it. However because much of the power goes into refrigerant, about one third of that power, or 350 W is no longer needed. The additional requirements for a third reactor is about 2000 W for the 12-hour period, but because the reaction is exothermic overall and can produce power for another reactor, we assume an addition of about 1500 W instead, bringing the total to approximately 3800 W. An increase in electrolysis rate occurs if more ions are used, so a power increase is unnecessary to cover the slight increase in water electrolyzed.

Scaling to 10.5 and 11.5 hours of work to make a minimum of 1380 g of oxygen and maximum of 1511.33 g of oxygen during the autonomous phase, the maximum power needed is 1969 W during the autumn/winter period. To cover any slight increase in power requirements, astronauts may be able to create additional power during the second phase.

The microwave part of the rover has been conceived and the calculated power consumption is 2.4 kW for 12 hours to produce 400 g per hour of water, meaning a maximum power of 2.7 kW for the 10.5-hour days of operation[21].

The rover's power requirement for driving will not be as high as that for the rovers. The *Opportunity* rover needs about 100 W to drive, but this rover would be lighter and thus require less power[34]. A standard solar panel like the ones on *Opportunity* put onto the rover would cover the power requirements of about 40 W. The 40 W is a justified value because the size should be in between the *Sojourner* and *Opportunity* rovers to support a microwave and refrigerator-compressor mass.

Solar Power

Solar power is a growing industry that has many applications. It is currently used to power the ISS as well as other spacecraft. Solar power depends on the incident flux from the Sun, meaning that Mars will have less solar energy available than Earth does. Mars receives about 600 W/m^2 at its distance from the Sun[35]. Due to the dusty atmosphere, the surface of Mars receives much less than this amount, instead receiving around 300 W/m^2. This number is highly variable depending on the weather.

Various types of solar cells exist, each with a different efficiency. One of the lesser-efficient but fastest-growing types of solar cell is the thin-film solar cell (TFSC). TFSC currently have a maximum efficiency of 28%, but by 2028, the efficiencies may reach around 35% efficiency, if not higher. The rover *Sojourner* was able to produce 68 W/m^2 at 18% efficiency meaning with similar conditions, a 35% efficient cell could produce 132 W/m^2, but because of varying conditions, especially dust storms, we can assume an average of 90 W/m^2 based on data about *Opportunity*'s dust factor.[36,37] There are "cleaning events" that occur periodically, about every 20 sols on average, that prevent the dust factor from increasing too much, so the efficiency should not deviate for long periods.

Slightly less than 0.5 m^2 of TFSC, which can be put on the rover, is needed to drive. In order to power the microwave, which takes 2.7 kW, 30 m^2 of TFSC is needed. Although TFSCs can be rolled up and fit into a rocket, the

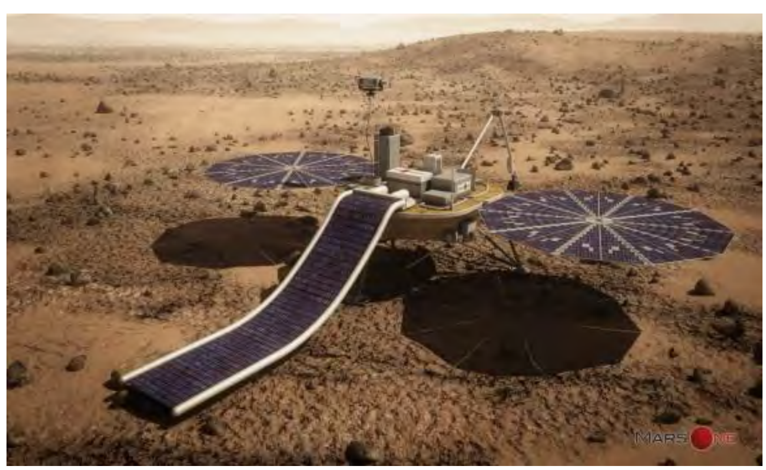

Figure 12 TFSC attached to a Mars One Lander

challenge is to lay it on Mars without human intervention. For cleaning events to be effective, the film must be off the ground so the dust can fall off. A TFSC with inflatable sides, as shown in Figure 12 will stay off of the ground and can be unwound as the rover travels. Due to its light weight, 30 m^2 of TFSC would add about 8 kg to the rover[38]. It can be rolled into a 30 m x 1 m sheet and unrolled during the first sol of the process running, meaning penetration will suffer until all of it is rolled out.

Battery Power

Another, more reliable source of energy, battery power supply depends on the mass of the batteries available. The current most efficient and rechargeable battery is the lithium-ion battery (LIB). A LIB can run during the day and recharge during the night, allowing little-to-no power loss. Currently, the very upper limit of LIB efficiency is about 250 Wh/kg.[11] By 2028, this may be a normal efficiency to use. Assuming this efficiency, it would still take 82.7 kg of batteries to run. Because the mass of batteries needed is greater than the actual process reactors, it is not efficient. If LIB technology were to produce 500 Wh/kg by 2028, this may then be efficient enough to use.

Nuclear Power

Nuclear power uses a radioactive isotope generator such as a plutonium rod to generate heat. This heat would remove much of the power requirement for heating the reactors, but little electricity is generated for cooling. Nuclear power will not decrease in efficiency in the 4 years it is expected to run, and it has been tested in numerous missions dating back to the Apollo program. These radioisotope thermoelectric generators (RTG) generate heat even when the process reactors are not running, which allows the components to survive the colder Martian nights. The heat can be converted to electricity using a thermoelectric generator or a Stirling engine. The generator has a current maximum efficiency of 10%, while the Stirling engine efficiency is 20%.[39] Although the plutonium itself produces about 500 W thermally per kg, the generator itself has a mass of about 45 kg. Thus, a 5 kg plutonium pellet can produce 2500 W of heat and 120 W electricity.[40] According to Zubrin's study, about half the power required by the process system is due to chemical synthesis, which requires heat to work.[20] This halves the power requirements, but because the generator is massive, the efficiency is lower than battery efficiency.

The mass required for a combination of nuclear and battery power would be about equal to all battery power, but also will ensure that the components stay heated and keep their efficiencies. So, the currently most efficient method would be to use an RTG to heat the reactors and components and to use LIB to power the coolers. The additional 85 kg would cost an extra $37.5 million, but ensures that the system can survive the temperature swings on Mars.

Troubleshooting

Because the process system has to run for 720 sols without direct human intervention, any problems have to be solved remotely or autonomously. Problems include: (1) power failure, (2) broken tubes or pipes, and (3) complete system failure.

Power failure does not occur in RTG and rarely occurs in LIB. Because LIB fail due to heat, as long as the RTG is shielded from the LIB supply (i.e. opposite sides of the system), no failures should occur, as spontaneous failure rate for LIB is one in ten million.[41] Solar panels may lose efficiency but these results take into account any power lossiness. The power connections themselves may short, so to fix this, extra connections can be used that can be switched to by a remote switch if the main wiring fails.

Pipes should not break due to pressure, but if they corrode, melt, or fracture due to temperature changes, system flow is disrupted. To combat this, extra bypasses need to be installed that are by default in a closed valve position, but will be remotely opened if the other pipes are damaged. Because no repairs can be made on-site for 720 sols, an extra piping for each connection should be implemented to allow for one break to each part. *Opportunity* has been running for ten years as of 2014, so it is possible for a system to survive harsh Martian conditions.

If a complete system failure occurs due to parts becoming unattached or damaged in any way, then the system can no longer produce oxygen or water. The mission may be delayed by one launch window while parts are retested to solve whatever problem occurred. If a more efficient fuel is invented, an opposition-class mission or a direct injection can be used to send a new system to Mars before astronauts arrive.

For fixable problems that require a system diagnostic, simple valves are installed along the pipes to close or open flows. If a valve is closed for more than an hour, the system will have to be manually shut off to prevent pressure build-up.

Conclusion

A manned mission to Mars brings with it many challenges to overcome. The challenges have to be met economically and efficiently. The first generation of Mars astronauts will be a test to see how well-suited we are to exploring celestial bodies. Securing oxygen and water off of Earth is a problem that can be solved with *in-situ* utilization of the atmosphere and soil. This particular ISRU cannot be done on any other planet besides possibly Venus, which has too great of an atmospheric pressure to work with the soil. Because the Moon has no tenuous atmosphere and low concentration of water in its regolith, Mars is the closest habitable body. Although more advanced systems must be incorporated to create a permanent Mars habitat, this Sabatier-RWGS-Syngas system is a starting point and can be scaled up for larger settlements.

The space age has brought with it great advances in science, and sending astronauts to Mars would be invaluable to resource utilization efficiency technologies, as well as astrochemistry and possibly astrobiology. A renewed interest in space would help to bolster NASA's funding, which could be used for extended missions to the outer planets' moons, such as Titan or Ganymede. The next era of human exploration has to start with a reach to other planets, and the tenacity to survive.

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