Preliminary System Analysis of In Situ Resource Utilization for Mars Human Exploration

Donald Rapp
Jet Propulsion Laboratory
Calif. Inst. of Technology
Pasadena, CA 91109
323-257-7217
drdrapp@earthlink.net

Jason Andringa
Jet Propulsion Laboratory
Calif. Inst. of Technology
Pasadena, CA 91109
818-354-1892
jason.andringa@jpl.nasa.gov

Robert Easter
Jet Propulsion Laboratory
Calif. Inst. of Technology
Pasadena, CA 91109
818-354-3552
robert.w.easter@jpl.nasa.gov

Jeffrey H. Smith
Jet Propulsion Laboratory
Calif. Inst. of Technology
Pasadena, CA 91109
818-354-1236
jeffrey.h.smith@jpl.nasa.gov

Thomas Wilson
Jet Propulsion Laboratory
Calif. Inst. of Technology
Pasadena, CA 91109
818-354-0699
Thomas.j.wilson@jpl.nasa.gov

D. Larry Clark
Lockheed-Martin Space Syst.
P. O. Box 179: P0560
Denver, CO 80201-0179
303-977-3818
larry.d.clark@lmco.com

Kevin Payne
Lockheed-Martin Space Syst.
P. O. Box 179: P0560
Denver, CO 80201-0179
303-977-9010
kevin.s.payne@lmco.com

Abstract

We carried out a system analysis of processes for utilization of Mars resources to support human exploration of Mars by production of propellants from indigenous resources. Seven ISRU processes were analyzed to determine mass, power and propellant storage volume requirements. The major elements of each process include CO_2 acquisition, chemical conversion, and storage of propellants. Based on a figure of merit (the ratio of the mass of propellants that must be brought from Earth in a non-ISRU mission to the mass of the ISRU system, tanks and feedstocks that must be brought from Earth for a ISRU mission) the most attractive process (by far) is one where indigenous Mars water is accessible and this is processed via Sabatier/Electrolysis to methane and oxygen. These processes are technically relatively mature. Other processes with positive leverage involve reverse water gas shift and solid oxide electrolysis. These processes would be appropriate if accessible water is not available on Mars. However the technologies involved are still immature. Processes that require storage of large amounts of hydrogen were deemed infeasible because of power, volume and mass considerations. The critical interfacial issues with Mars are finding accessible sources of water and acquisition of CO_2 from the atmosphere. A technology development and demonstration program is proposed that hinges heavily on the search for accessible water. A roadmap summarizes the future steps needed to implement ISRU in the Human Mission Architecture.

TABLE OF CONTENTS

1. INTRODUCTION

JPL asked our Team to develop a program plan for *In Situ Resource Utilization* (ISRU) development and demonstration for the 2[nd] decade leading to a "commitment to Human Mission Architecture" by the end of the decade. We were requested to include the following subprogram elements in this program:

- Focused technology development work unit descriptions and dates.
- Ground and flight system demonstration descriptions and dates.
- Continuing trade studies.
- Costs profiled by fiscal year.
- Requirements on any flight mission for demonstration accommodation.
- List of relevant contributions from robotic science program per pathways.
- Assume ISRU utility is limited to early human missions (short surface stays) and include the potential for propulsion fuel, heat fuel, breathable air and drinkable water.
- Use launch opportunities 2011, 2013, 2016, 2018.

This paper summarizes our findings.

2. APPROACH

Although previous system analyses have established that ISRU has significant potential for reducing launch mass, there remains a need for a quantitative analysis to quantify the benefits and provide guidance on which ISRU approaches have the greatest merit. Our approach began with a system evaluation of candidate ISRU alternatives, and based on this result, we went on to define a roadmap of focused technology work and flight system demonstrations necessary to enable ISRU. Our approach involved the following elements:

DESIGN REFERENCE MISSION DEFINITION: Define a hypothetical human design reference mission to Mars (without ISRU) as a basis for evaluating potential benefits of utilizing ISRU. In this Study, subsystems are analyzed in terms of a hypothetical scenario in which an ISRU mission lands a combination of a Mars Ascent Vehicle (MAV), an ISRU processing plant, and a power generation system, about 26 months prior to humans landing on Mars. The ISRU system operates for > 600 sols, gradually filling the propellant tanks on the MAV. However, if it were necessary for safety sake to have the propellant tanks filled prior to departure of humans on the second launch, then ISRU operations would have to be completed in about 300 sols rather than ~ 600. This would double the size of the ISRU plant. [14] The humans (crew of 6) stay perhaps 30 sols on Mars and then depart in the MAV. This only one of several possible scenarios for human exploration of Mars but it was chosen because it fits naturally with use of ISRU. Actual calculations were carried out at 1/10 scale. Full scale estimates can be made by multiplying all results by ~ 10.

DETAILED SYSTEM ANALYSIS: We developed a detailed system analysis of ISRU alternatives to determine the leverage of each potential ISRU process on the (1/10 scale) baseline human mission to Mars, in order to identify those ISRU processes worthy of being developed and implemented. Linked spreadsheets were utilized to estimate the parameters of the various ISRU processes based on chemical stoichiometry, publications and reports describing ISRU processes, industrial catalogs, and consultation with technical specialists.

EVALUATION OF PROCESSES: In order to identify the benefit of an ISRU process, and compare the relative merits of alternative ISRU processes, it is useful to develop figures of merit that allow such evaluations. A limited figure of merit is the ratio of the mass of useful propellants produced to the mass of the ISRU system. A better figure of merit is the ratio of the mass of propellants that must be brought from Earth in a non-ISRU mission to the mass of the ISRU system, tanks and feedstocks that must be brought from Earth for a ISRU mission. The best figure of merit is the difference between the total launch mass with ISRU and the total launch mass without ISRU. These figures of merit were estimated for each process. However, it must be admitted that even with the best of figures of merit, the comparison of an ISRU mission with a non-ISRU mission is complicated by the fact that the optimum implementation of the two missions may differ. In particular, for missions without ISPP, it might be best to go into a low Mars orbit to minimize the lander size for descent and ascent to the Earth Return Vehicle (ERV). For missions with ISPP, it might be better to go into a high Mars orbit and thereby increase the ΔV performed by the lander, because it reduces the ΔV required for both Mars capture/orbit and Earth return of the ERV. [14]

MARS DEMONSTRATIONS AND MEASUREMENTS: We identified measurements and technology demonstrations that must be made on Mars to validate ISRU technology and prepare a schedule for carrying these out. Interfaces between potential ISRU processes and the Mars environment were identified and a series of increasingly more ambitious demonstrations was planned to validate the performance of ISRU systems with particular emphasis on Mars environment interfacial issues.

ISRU TECHNOLOGY DEVELOPMENT PROGRAM DEFINITION: We defined technology development programs that must be carried out prior to Mars demonstrations in order to be ready to demonstrate effective technology according to our schedule. The current NASA technology readiness levels of critical Mars ISRU technologies were assessed, and from this, together with the schedules for Mars demonstration, technology development programs were formulated.

COST: We estimated the cost for the entire ISRU venture. Costs were estimated very roughly by utilizing experience in other space endeavors and comparing complexity.

It must be emphasized that this study was limited in scope. For example, a simple propulsion system was modeled using pressure-fed engines and the storage pressures of propellants were selected for convenience. In reality, it is likely that pump-fed engines will be used. In future analysis, storage pressures, mixture ratios and other propulsion characteristics need to be varied so as to maximize overall performance.

3. ISRU PROCESS ANALYSIS

Requirements

Based on previous estimates of propulsion requirements for ascent of a human crew from Mars, a 1/10-scale total impulse requirement for launching the MAV was set at 1.46×10^7 Newton-sec. With the assumed specific impulse of 365 sec for a methane-oxygen the required masses of methane and oxygen were determined, assuming an oxygen/methane mixture ratio of 3.0. These masses are: Methane: 1022 kg and Oxygen: 3066 kg. The mass requirements for other propellant combinations were estimated by scaling according to their specific impulses.

Requirements for life support consumables were based on a 30-sol stay on Mars plus a return flight to Earth of up to 9 months. Water for life support for a crew of 6 over a 10-month period was estimated to be 5,550 kg (full scale), and oxygen for life support was set at 186 kg (full scale). No consideration of the need for buffer gases was included in this preliminary study, but buffer gas requirements for breathing air will be included in a sequel to this study (if there is one).

It is likely that a closed end life support system (CELSS) would be used on a human mission to Mars, in which case the life support consumable requirements would be greatly reduced Because of the uncertainty in bottom-line life support requirements, the primary focus of this study is on propellant production by ISRU.

ISRU Processes

ISRU processes were reviewed in detail. We divided the possibilities into those that are applicable if water is found on Mars and those that might be used if no water is available on Mars. If water is available, there are two potential processes (1 and 2) as shown in Tables 1 and 2. However, we have made now allowance for mass, power and cost requirements for obtaining water on Mars.

Process 1 has the great advantage that it is simple, involving the single step of electrolysis, which is a very mature technology. The primary problem for implementing process 1 is that a considerable amount of hydrogen must be stored. If the hydrogen is stored as liquid H_2, the power required to maintain it at 20-30 K is large and is likely to be prohibitive. If it is stored as a very high-pressure gas at room temperature, the volume will be very large, and would be prohibitive. Storage at a combination of a moderate cryogenic temperature and a high pressure (e.g. something like ~ 113 K and ~ 10,000 psi) would provide a density comparable to that of liquid H_2 and the power requirement for cooling would be similar to that for storing an equivalent volume of CH_4 or O_2. However the mass of such a tank would be prohibitive. Furthermore, because of the low density of hydrogen, the required volume will be very high in all cases. Therefore, storage of hydrogen on Mars does not appear to be practical and that eliminates Process 1 from contention.

Process 2 avoids the H_2 storage problem but it involves a more complicated chemical engineering process that includes CO_2 acquisition and compression, electrolysis of water, and Sabatier conversion.

If water is not available, there are two main options. In one option (Process 3 in Tables 3-1 and 2) we bring the required H_2 from Earth and use it in a Sabatier/ Electrolysis process. This process has disadvantages because not only must a large amount of H_2 be brought to Mars, but the process produces only one oxygen molecule per methane molecule. Since rockets require typically 1.5 oxygen molecules per methane molecule, there is a large excess of methane produced and there is no defined use for this methane. Not only do we have the very challenging task of transporting H_2 to Mars and storing it there, but part of it is wasted as excess methane.

The other option if water is not available on Mars, is to bring a space-storable propellant such as hydrazine to Mars and be content with systems that only produce O_2 from Martian CO_2. We have used hydrazine for purposes of illustration but a less-toxic propellant may be preferred. These are shown as processes 4 and 5 in Tables 1 and 2. Since O_2 accounts for 75% of the mass in a stoichiometric hydrazine-oxygen propellant mixture, one would produce a significant fraction of the needed propellant mass from ISRU in these cases. Furthermore, because of the higher density of hydrazine than hydrogen, the total propellant volume would be much smaller when hydrazine is used than when hydrogen is used. Processes 2, 4 and 5 have similar volume requirements. However, processes 4 and 5 would not produce consumable water; that would have to be brought from Earth. The problem with process 4 is that it has only been demonstrated in a simple breadboard and it is a complex process. Considerable further work is required to determine its efficiency and power requirements, and to determine its longevity and reliability. The problem with process 5 is that only simple single-disk breadboards have been tested, and no one has ever demonstrated that a robust zirconia stack can be manufactured and operated. Further, the solid oxide electrolysis system requires many seals to remain robust at 900 - 1000°C - a demand that may never prove feasible. However, current developments on solid oxide fuel cells for terrestrial applications may provide important technical solutions.

In addition to the basic processes listed in Tables 1 and 2, we define composite processes that utilize two ISRU processes in tandem when no water is available on Mars. Process 3 produces an excess of methane (or equivalently a shortage of oxygen). This excess methane requires a considerable amount of hydrogen to be transported from Earth to Mars. If a RWGS or SOE system was transported to Mars to produce enough oxygen so that the combination of Sabatier/Electrolysis from Earth-brought hydrogen plus either RWGS or SOE to produce extra oxygen, a modification of Process 3 would result in which no excess methane is produced.

We therefore define Processes 6 and 7 that are similar to Process 3 except that the RWGS or SOE process is used to augment the oxygen so that the proper mixture ratio (MR) is achieved with no excess hydrogen.

Although these processes reduce the requirement to bring hydrogen from Earth and reduce the required volume, they add complexity to the ISRU system.

Table 1. ISRU Process Characteristics

	PROCESSES	Is water available on Mars?	Resources brought from Earth for ISRU	Resources brought from Earth as propellants	propellant mass % provided by ISRU	Resources brought from Earth for consumables	ISRU products
1	Electrolyze Mars Water	Yes	None	None	100	None	$2H_2 + O_2$
2	Sabatier/Electrolysis/ Mars Water	Yes	None	None	100	None	CH_4+2O_2
3	Sabatier/Electrolysis/ H_2 from Earth	No	H_2	None	100	water	$CH_4+(1)O_2$
4	Reverse Water Gas Shift	No	Small amount of H_2	Hydrazine	75	water	O_2
5	Solid Oxide Electrolysis	No		Hydrazine	75	water	O_2
6	Combine 3 and 4	No	H_2	None	100	water	$CH_4+(MR)O_2$
7	Combine 3 and 5	No	H_2	None	100	water	$CH_4+(MR)O_2$

Table 2. ISRU Processes Comments and Issues

	PROCESS	Comments and Issues
1	Electrolyze Water	Simplest system. Does not require CO_2 acquisition. Only process step is electrolysis. Requires H_2 storage which is impractical.
2	S/E Mars Water	Requires multiple steps: (1) Electrolysis of water, (2) Sabatier conversion, (3) electrolysis of product water. More complex than process 1. Requires CO_2 acquisition, electrolysis and Sabatier. Storage volume considerably lower than for process 1 despite higher Isp of process 1.
3	S/E/ H_2 from Earth	Requires H_2 storage during cruise to Mars and on Mars. Volume is very large and is probably impractical. Produces only 1 O_2 per CH_4, so that some excess CH_4 would be produced.
4	RWGS	Does not produce consumable water. Produces 75% of required propellants for MAV. Very compact system due to high hydrazine density. RWGS has uncertain performance & reliability.
5	SOE	Does not produce consumable water. Produces 75% of required propellants for MAV. Very compact system due to high hydrazine density. Not clear SOE system is technically feasible.
6	Combine 3 and 4	Modification of Process 3 in which RWGS is used to produce additional oxygen to balance mixture ratio. Reduces need for hydrogen from Earth if only propellants are produced by ISRU.
7	Combine 3 and 5	Modification of Process 3 in which SOE is used to produce additional oxygen to balance mixture ratio. Reduces need for hydrogen from Earth if only propellants are produced by ISRU.

Propellant Masses and Volumes

The dominant factor that determines the mass and volume of the *Mars Ascent Vehicle* (MAV) is propellant storage. Propellant volumes depend upon the conditions (pressure, temperature) under which propellants are stored. It turns out that over the pressure range 15 to 300 psi, the saturated temperature and density of liquid hydrogen, oxygen and methane vary considerably, and therefore the storage conditions need to be defined carefully to mesh with the ISRU process requirements and also to maintain the storage volume as minimally as is practical.

The estimated propellant masses for processes are shown in Table 3 under "needed for propulsion." The propellants produced by the previously defined seven ISRU processes are quantified in Table 4. The masses produced by ISRU are also entered back into Table 3 and compared with the propellant masses needed for propulsion.

There can be some mismatch between the oxygen/fuel ratio produced by ISRU and the oxygen/fuel ratio required for propulsion. Processes 1 and 2 produce a stoichiometric ratio of oxygen to fuel. However, because ascent rockets usually run fuel-rich, ISRU Processes 1 and 2 produce an excess of oxygen. Much of this might be useful for life support. Process 3 produces an excess of methane. Processes 4 and 5 can be scaled to produce the required amounts of oxygen with no venting. This is illustrated in Table 4. We have chosen the mixture ratio to maximize the specific impulse. This is an over simplification. Because oxygen has a much higher density than hydrogen or methane, the storage tanks for hydrogen or methane are considerably larger per unit mass, and a minimum propulsion system mass is likely to be reached with a higher mixture ratio than optimum for Isp [1].

The conditions (temperature and pressure) under which propellants are stored have a major impact on the required volumes of the propellant storage tanks. If a propellant is stored as a saturated liquid in contact with its vapor, then in general, the storage temperature increases and the density decreases as the pressure is increased.

The increase in storage temperature is beneficial because it reduces the power load for cryogenic cooling. However the decrease in density will increase the storage volume which is detrimental.

The ISRU chemical reactor system will be more compact if it operates at higher pressures. For processing purposes, it is likely that operating pressures will be desired at or above 100 psi. In the unlikely case that the propulsion system is pressure-fed, storage at ~ 300 psi might be desirable. If the propulsion system is pump-fed, storage of propellants at lower pressures would be allowable. Any mis-matches between appropriate pressures for storage and appropriate pressures for processing might lead to a requirement for compressors, which adds complexity to the system. Ultimately, more detailed system trade studies need to lead to optimal choices for ISRU operational pressures and propellant storage pressures.

The storage pressures have a significant influence on propellant volumes. For our purposes here, we will assume that liquid oxygen is stored at 100 psi (T = 113 K, density = 1.01) and liquid methane is stored at 100 psi (T = 141 K, density = 0.374). We will further assume that hydrogen is stored as a dense gas in the range near T ~ 113 K and p ~10,000 psi where the density is 0.07. Based on these assumptions, Table 5 provides a summary of tank volumes.

Table 3. Comparison of propellants needed for propulsion with propellants produced by ISRU.

	Process	Needed for Propulsion			Produced by ISRU			Excess Produced by ISRU		
		H_2	O_2	CH_4	H_2	O_2	CH_4	H_2	O_2	CH_4
1	Electrolyze Water	508	2,792		508	4,064			1,272	
2	S/E Mars Water		3,065	1,022		4,088	1,022		1,023	
3	S/E/ H_2 from Earth		3,065	1,022		3,065	1,532			510
4	RWGS		3,394			3,394				
5	SOE		3,394			3,394				
6	Combine 3 and 4		3,065	1,022		3,065	1,022			
7	Combine 3 and 5		3,065	1,022		3,065	1,022			

Table 4. Summary of propellant and feedstock masses in kg (does not include tank masses) scaled for assumed values of Isp. No allowance is made for producing consumables.

	Process	Isp (sec)	O_2/ Fuel ratio	Propellants	Brought from Earth	Mars CO_2	Water from Mars	Produced by ISRU on Mars		
								H_2	O_2	CH_4
1	Electrolyze Water	452	5.5	O_2 and H_2	nothing		4,572	508	4,064	
2	S/E Mars Water	365	3.0	O_2 and CH_4	nothing	2810	2,300		4,088	1,022
3	S/E/H_2 from Earth	365	3.0	O_2 and CH_4	383 kg H_2	4213			3,065	1,532
4	RWGS	310	2.4	O_2 and hydrazine	1415 kg hydrazine + small amt. H_2	9333			3,394	
5	SOE	310	2.4	O_2 and hydrazine	1415 kg hydrazine	9333			3,394	
6	Combine 3 and 4	365	3.0	O_2 and CH_4	256 kg H_2	5612			3,065	1,022
7	Combine 3 and 5	365	3.0	O_2 and CH_4	256 kg H_2	5612			3,065	1,022

Table 5. Summary of tank volumes (cubic meters) to hold propellants required for propulsion.

	Process	Propellants	H_2 tank*	O_2 tank	CH_4 tank	Hydrazine tank	Total volume
1	Electrolyze Mars Water	O_2 and H_2	9.0	2.8			11.8
2	Sabatier/ Electrolysis/ Mars Water	O_2 and CH_4		3	2.8		5.8
3	Sabatier /Electrolysis/ H2 from Earth	O_2 and CH_4	6.8**	3	2.8		12.6
4	Reverse Water Gas Shift	O_2 and hydrazine	small	3.4		1.4	4.8
5	Solid Oxide Electrolysis	O_2 and hydrazine		3.4		1.4	4.8
6	Combination of Processes 3 and 4	O_2 and CH_4	4.5**	3	2.8		10.3
7	Combination of Processes 3 and 5	O_2 and CH_4	4.5**	3	2.8		10.3

* Assuming storage at 29 K and 100 psi where density is 0.057.

** This assumes that the H_2 tanks are distinct from the CH_4 tanks. If it is possible to gradually replace H_2 by CH_4 in storage tanks as the process proceeds, the H_2 tank requirement would be greatly reduced.

Table 6. Amount of CO_2 required over 600 sols for various processes, and mass and power of acquisition system.

		CO_2 requirement				CO_2 Acquisition	
	Process	Total kg CO_2 for: $2CO_2 \Rightarrow 2CO + O_2$	Total kg CO_2 for: Sabatier reactor	Total kg CO_2	Total CO_2 flow rate (kg/hr)	Mass (kg)	Power (W)
1	Electrolyze Water					0	0
2	S/E Mars Water		2810	2810	0.19	10	234
3	S/E/H_2 from Earth		4213	4213	0.28	15	345
4	RWGS	9333		9333	0.63	34	776
5	SOE	9333		9333	0.63	34	776
6	Combine 3 and 4	2796	2816	5612	0.38	21	468
7	Combine 3 and 5	2796	2816	5612	0.38	21	468

4. SUBSYSTEMS

Mass and power estimates for ISRU systems are provided in the sections that follow. However, no allowance was made for the mass, power and cost requirements of obtaining water on Mars.

Mars CO_2 Acquisition

The requirements for Mars atmosphere acquisition are to produce essentially pure CO_2 at appropriate flow rates for the various processes over 600 sols. Table 6 summarizes total requirements for carbon dioxide from the atmosphere.

Three approaches for Mars atmosphere acquisition were considered: (1) sorption compressor, (2) mechanical compressor, and (3) cryo-compressor. A preliminary evaluation indicated that the sorption compressor was relatively massive and power-hungry compared to the other two choices, so it was eliminated from contention. The performance of a mechanical compressor was estimated by taking the known characteristics of an existing commercially available mechanical compressor that fitted the requirements.

The mechanical compressor, and cryo-compressor approaches were compared for a system that produces 0.5 kg/hr of CO_2. The cryo-compressor approach requires ~ 616 W and the mass is estimated to be ~ 27 kg. This can be compared to a mechanical compressor with membrane CO_2 purification, that had an estimated requirement of ~ 1790 W and 240 kg. The cryo-compressor approach is a clear winner. These values were scaled to the requirements in Table 6.

Chemical Conversion System

Mass and power requirements for each of the chemical conversion systems were estimated by modeling all components and making rough estimates based on engineering experience.

Water Electrolysis:

Electrolysis mass and power requirements are based on commercial units running at 1.64 V [3]:

Mass = 11.2 kg per kg/hr of water feed rate

Power requirement = 2,440 W per kg/hr of water feed rate

Sabatier conversion of $CO_2 + H_2$ to $CH_4 + H_2O$

Sabatier conversion includes the reactor, heat exchanger, water condenser, hydrogen recovery unit, valves and tubing, and sorption dryers. Mass and power for each unit was estimated based on previous prototype Sabatier plants [3]:

Mass = 12.5 kg per kg/hr of CO_2 feed

Power = 163 W per kg/hr of CO_2 feed

Solid Oxide Electrolysis

The solid oxide electrolysis (SOE) estimates were based on the following typical parameters:

Cell Voltage	1.6	volts
Current Density	0.5	amps/cm^2
Max cell size	60	cm^2
No. cells/stack	30	
Cell Thickness	0.25	cm
Stack length	7.5	cm
Stack diameter	8.74	cm
Stack Volume	450	cm^3
Stack density	3	g/cm^3
Stack mass	1350	g
Plant mass ratio	0.0565	kg/cell

This was enclosed by a 0.076 cm thick stainless steel pressure vessel. The resultant mass and power estimates were:

Mass = 2.1 kg per kg/hr of CO_2 feed

Power = 1,806 W per kg/hr of CO_2 feed (note: this is based on an assumed voltage requirement of 1.6 V. If lower voltages prove to be feasible, this could be reduced)

Reverse Water Gas Shift

RWGS conversion includes: the reactor, inlet and outlet heat exchangers, water condenser, recirculation compressor, hydrogen recovery unit, valves and tubing, and sorption dryers. Mass and power for each unit was estimated based on previous prototypes [4]:

Mass = 15.7 kg per kg/hr of CO_2 feed

Power = 657 W per kg/hr of CO_2 feed (note: requirements for recirculation need further study)

The feedstocks needed for each process are provided in Table 7. If these values are divided by (600 sols x 24.67 hours/sol) flow rates can be calculated and the above-tabulated mass and power requirements can be used to infer requirements for each process. The results are provided in Table 8.

Propellant Storage

The mass and volume of an ISRU system are dominated by the requirements for propellant storage, and propellant storage also makes a significant contribution to power requirements as well. We have only made rough estimates of mass and power requirements for propellant storage, and these estimates need to be refined in future work.

The volumes of tanks are simple to estimate based on known propellant densities. The masses of conventional tanks were estimated by sizing the thickness of the walls required for allowable stress with a safety factor of 1.5. However, ultra-light tank (ULT) technology offers the promise of lower tank masses in the future.

Tank masses and cryocooler powers were estimated as follows:

Oxygen and Methane Storage:

We assumed that the oxygen was stored at at 100 psi (T = 113 K). Oxygen and methane storage tank masses were estimated from:

Mass = 25 V (kg)

where V is the volume in m^3. The cryocooler requirements for oxygen and methane differ because of their different heats of liquefaction. Based on a cryocooler specific power of 6, we found:

CH_4 cryo power (W) = flow rate (kg/hr) * 2980

O_2 cryo power (W) = flow rate (kg/hr) * 1050

CH_4 cryo mass = flow rate (kg/hr) * 93

O_2 cryo mass = flow rate (kg/hr) * 33

Flow rates were calculated by dividing the total amount of propellant by (600*24.67) hours for 600 sols of operation.

Hydrogen Storage:

For hydrogen storage, we found that the power requirement for cooling to liquid hydrogen temperature was over 20 kW for this subscale system. For a full-scale system, this equates to > 200 kW of power merely to liquefy hydrogen. The alternative is to treat hydrogen storage in terms of hydrogen at around 10,000 psi at a temperature of about 113 K where the density is 0.07. At this temperature, cryocooling requirements are similar to those of methane and oxygen but the tank mass increases considerably. To store hydrogen as a liquid at 100 psi (T = 29 K) requires a tank that weighs about 0.15 kg per kg of hydrogen [2]. The cryocooler requirements for this hydrogen storage were estimated to be:

H_2 cryo power @ 29 K = flow rate (kg/hr) * 603,000

H_2 cryo mass @ 29 K = flow rate (kg/hr) * 28,400

The hydrogen flowrate for process 1 is around 0.035 kg/hr, so the power and mass of the cryocooler are: 21 kW and 1000 kg. The mass of the storage is around 75 kg.

Storage of hydrogen as a dense gas at 10,000 psi and T = 113 K would allow the same type of cryocooler to be used that was used on the oxygen tank at 100 psi and 113 K. The mass of a conventional tank to operate at 7,000 psi was estimated to be 10 kg per kg of hydrogen [2]. At 10,000 psi it will be even higher. The cryocooler requirements for high-pressure hydrogen storage were estimated to be:

H_2 cryo power @113 K = flow rate (kg/hr) * 62400

H_2 cryo mass @113 K = flow rate (kg/hr) * 2600

The mass of storage at 7000 psi would be ~ 5000 kg [2], and at 10,000 psi would be greater. The cryocooler would weigh about 90 kg and would require about 2.2 kW.

Thus hydrogen storage for process 1 presents a conundrum. Whereas storage at low-pressure results in a very manageable tank mass, the cryocooler mass and power are very high. On the other hand, for storage at high pressure, the cryocooler requirements are reduced by a factor of ten but the storage mass increases to prohibitive levels. We therefore conclude that hydrogen storage is not feasible in either regime, and processes that require significant amounts (thousands of kg) of hydrogen storage do not appear to be feasible. However, for purposes of illustration we have used the low-mass high-power hydrogen storage option in the tables that follow. In doing this, we have added to the cryocooler mass the mass of the power system for hydrogen cryocooling. This mass is estimated to be 100 kg per kW based on a full-scale reactor.

For processes 3, 6 and 7, the hydrogen is already stored under the assumed conditions when sent from Earth, and therefore the power requirement is not to compress and cool a continuously produced stream, but rather to merely keep a tank cold. This power requirement is likely to be considerably less than the power requirement to compress and cool, although the cryocooler must operate throughout the cruise period when conditions are not optimal. There is considerable uncertainty about the cryocooler requirements for these processes. This will be refined in future studies. The resultant estimates for tank masses and cryogenic cooling requirements for propellant storage are given in Table 9.

Balance of System

In addition to CO_2 acquisition, chemical conversion and propellant storage, ISRU systems will need a control system, support structure, additional plumbing, thermal control, etc. These have been simply lumped into a single term and crudely estimated as 20% of the mass and 10% of the power required for CO_2 acquisition, chemical conversion and propellant storage.

The mass requirements of all subsystems for each process are summed up in Table 10. The power requirements are summed in Table 11.

Table 7. Feedstocks for processes

	Process	kg of CO_2 for: $2CO_2 \Rightarrow 2CO + O_2$	kg of reagents for: $2H_2 + CO_2 \Rightarrow CH_4 + O_2$		
		CO_2	H_2O	H_2	CO_2
1	Electrolyze Water		4572		
2	S/E Mars Water		2300		2810
3	S/E/ H_2 from Earth			383	4213
4	RWGS	9333			
5	SOE	9333			
6	Combine 3 and 4	2796		256	2816
7	Combine 3 and 5	2796		256	2816

Table 8. Mass and power requirements for chemical conversion systems.

		$2CO_2 \Rightarrow 2CO + O_2$		$2H_2 + CO_2 \Rightarrow CH_4 + O_2$		Total	
	Process	Mass (kg)	Power (W)	Mass (kg)	Power (W)	M (kg)	P (W)
1	Electrolyze Water			3.5	753.7	3.5	753.7
2	S/E Mars Water			5.9	789.2	5.9	789.2
3	S/E/ H_2 from Earth			2.6	614.6	2.6	614.6
4	RWGS	9.9	414.3			9.9	414.3
5	SOE	1.3	1138.7			1.3	1138.7
6	Combine 3 and 4	3.0	124.1	4.1	410.8	7.1	534.9
7	Combine 3 and 5	0.4	341.1	4.1	410.8	4.5	751.9

Table 9. Total storage requirements. Includes ullage but does not include hydrazine tank. Masses for processes 1, 3, 6 and 7 are driven by the requirements of storing hydrogen.

	Process	total tank mass (kg)	total tank volume (m^3)	total cryo power (W)	cryo power sys mass (kg)	total cryo mass (kg)	Total tank+ cryo mass
1	Electrolyze Water	160	11.8	21199	2100	1006	3266
2	S/E Mars Water	164	5.8	424		13	177
3	S/E/ H_2 from Earth	221	12.6	16384	1596	773	2590
4	RWGS	103	4.8	241		8	111
5	SOE	103	4.8	241		8	111
6	Combine 3 and 4	202	10.3	10924	1050	513	1765
7	Combine 3 and 5	202	10.3	10924	1050	513	1765

Table 10. Mass requirements for processes (kg). Processes 1, 3, 6 and 7 are driven by the requirements of storing hydrogen.

	Process	CO_2 Acquisition	Chemical Conversion	Propellant Storage	Balance of System	Total Mass
1	Electrolyze Water	0	3.5	3266	654	3923
2	S/E Mars Water	10	5.9	177	39	231
3	S/E/ H_2 from Earth	15	2.6	2590	522	3129
4	RWGS	34	9.9	111	31	186
5	SOE	34	1.3	111	29	176
6	Combine 3 and 4	21	7.1	1765	359	2151
7	Combine 3 and 5	21	4.5	1765	358	2148

Table 11. Power requirements for processes (W). (Mass is in kg).

	Process	CO_2 Acquisition	Chemical Conversion	Propellant Storage	Balance of System	Total Power	Mass of Power System
1	Electrolyze Water	0	754	21398	2215	24367	2437
2	S/E Mars Water	234	789	848	187	2058	206
3	S/E/ H_2 from Earth	345	615	16808	1777	19545	1954
4	RWGS	776	414	482	167	1839	184
5	SOE	776	1139	482	240	2637	264
6	Combine 3 and 4	468	535	11348	1235	13586	1359
7	Combine 3 and 5	468	752	11348	1257	13825	1382

5. PROCESS COMPARISONS

The requirements for the reference mission were given at the beginning of Sec. 3. A full evaluation of an ISRU process for propellant production requires that we compare the masses and costs of carrying out the reference mission in two ways:

1. **Conventional** (without ISRU): Bring hydrazine and nitrogen tetroxide propellants (for example) from Earth in a single launch or multiple launches if required.

2. **ISRU-enabled**: Send the ISRU system (and MAV) to Mars at the previous opportunity (~ 26 months earlier) and allow it to produce propellants for the return trip to Earth. Then send the human expedition without the MAV.

A limited figure of merit **(FOM-1)** is the ratio of the mass of useful propellants produced to the mass of the ISRU system. This figure of merit is a necessary (but not necessarily sufficient) indicator of the effectiveness of an ISRU system. Clearly, if the ISRU system does not produce a good deal more mass of propellants than the mass of the ISRU system, it has little merit. Unfortunately, FOM-1 does not provide a comparison of the ISRU propulsion system with the non-ISRU propulsion system. If the ISRU propulsion system is inefficient, producing large amounts of ISRU propellants may not be as rewarding as FOM-1 indicates. Estimates of FOM-1 are given in Table 12.

A better figure of merit **(FOM-2)** is the ratio of the mass of propellants that must be brought from Earth in a non-ISRU mission to the mass of the ISRU system, tanks and feedstocks that must be brought from Earth for a ISRU mission. This is a much better measure of the effectiveness of ISRU because it compares a significant part of the propulsion systems with and without ISRU.

The best figure of merit **(FOM-3)** is the difference between the total launch mass with ISRU and the total launch mass without ISRU. This is a more rigorous figure of merit because the combination of two launches spaced by ~ 26 months leads to many complexities and this is the ultimate bottom line. These figures of merit are presently being estimated for each process and will be available by December, 2004.

The propulsion system for the conventional mission utilizes hydrazine-nitrogen tetroxide (N_2H_4-N_2O_4) with an estimated Isp of about 330 sec at a mixture ratio of 1.2. (This Isp is optimistic, but so are the values we used for methane and hydrogen with oxygen). To achieve the required total impulse for launching the (1/10 scale) MAV (1.46 x 10^7 Newton-sec), we require 4,520 kg of propellant (330/365 x methane-oxygen propellant mass) divided as 2465 kg of NTO and 2055 kg of hydrazine. Using the known average density of these propellants, at ~ 1.2, the total volume of the propellant tanks is 3.8 m^3. These propellant tanks are estimated to weigh about 100 kg. Thus, in summary, the (1/10 scale) reference mission requires transporting 4,520 kg of propellants to Mars in tanks that weigh about 100 kg and occupy a volume of 3.8 m^3.

We may now generate FOM-2 by comparing the propellant mass requirements for the reference mission with the total mass brought from Earth for the ISRU system together with any feedstocks, for each ISRU mission. Table 13 shows such a comparison with the mass of the power system neglected. A strong argument can be made that (except for hydrogen storage) a nuclear power system (either RTG or reactor) will be available "for free" during the 26-month period that the ISRU system is operating prior to arrival of humans because (1) RTG and reactors have relatively long life, and (2) the power system would have to be available to humans after they arrive, so why not deliver it with the ISRU system, 26 months early? As long as the power requirement for ISRU is less that the power requirement for the human stay, this argument appears to be reasonable. Nevertheless, the power required for hydrogen storage is greater than that required to support humans, so its mass was included in the hydrogen storage mass. Masses of the relevant power systems (at an assumed ~ 0.1 kg/W) are given in Table 11. It can be seen that Process 2 is a clear winner, although processes 4 and 5 also have positive leverage.

A comparison of the volumetric requirements of the ISRU missions with the volume requirement of the reference mission was provided in Table 5.

It may be concluded that Process 2 is the most attractive process because it has the highest mass leverage (by far), a moderate volume requirement that is probably acceptable, and low power requirements. However, if the mass of water acquisition were taken into account for process 2, its figure of merit would decrease. Process 1 is much simpler than Process 2 but the volume requirement is much larger and the mass leverage (driven by the high hydrogen storage mass) is much lower. Processes 4 and 5 are appropriate if water is not accessible on Mars. They offer moderate mass leverage with low volume, but they utilize low TRL technologies. These processes could be useful for life support independent of propellant production. Processes 6 and 7 are more complex improvements on Process 3, but all three have high volume requirements and moderate mass leverage.

Table 12. Mass and power requirements for processes vs. usable propellants produced. FOM-1 is the simple figure of merit = (total mass of usable propellants produced/mass of ISRU system). The low figures of merit of processes 1, 3, 6 and 7 are due to the high mass required for hydrogen storage.

	Process	ISRU Mass (kg)	ISRU Power (W)	H_2 produced (kg)	O_4 produced (kg)	CH_4 produced (kg)	FOM-1
1	Electrolyze Mars Water	3923	24367	508	2,792		0.8
2	Sabatier/ Electrolysis/ Mars Water	231	2058		3,065	1,022	17.7
3	Sabatier /Electrolysis/ H_2 from Earth	3129	19545		3,065	1,022	1.3
4	Reverse Water Gas Shift	186	1839		2,669		14.4
5	Solid Oxide Electrolysis	176	2637		2,669		15.2
6	Combination of Processes 3 and 4	2151	13586		3,065	1,022	1.9
7	Combination of Processes 3 and 5	2148	13825		3,065	1,022	1.9

Table 13. Comparison of mass requirements for ISRU missions with mass requirements for reference mission. (All masses in kg.) FOM-2 is the figure of merit = (Reference Mission Propellant and tank Mass from Earth) / (ISRU and feedstock mass brought from Earth).

		ISRU-enabled Mission				Reference Mission	FOM-2
	Process	ISRU System Mass #	H_2 brought from Earth	Hydrazine brought from Earth*	Total brought from Earth	NTO and Hydrazine from Earth	
1	Electrolyze Mars Water	3923			3923	4620	1.2
2	Sabatier/ Electrolysis/ Mars Water	231			231	4620	20.0
3	Sabatier /Electrolysis/ H_2 from Earth	3129	383		3512	4620	1.3
4	Reverse Water Gas Shift	186		1445	1631	4620	2.8
5	Solid Oxide Electrolysis	176		1445	1621	4620	2.9
6	Combination of Processes 3 and 4	2151	256		2407	4620	1.9
7	Combination of Processes 3 and 5	2148	256		2404	4620	1.9

* Includes about 30 kg for hydrazine tank

Includes all propellant and feed stock tanks including the hydrogen tank when hydrogen is brought from Earth, except it does not include the 30 kg hydrazine tank when hydrazine is brought from Earth

6. FOCUSED TECHNOLOGY DEVELOPMENT

ISRU Technologies

Each process in the foregoing tables utilizes one or more process steps (technologies) in fulfilling its requirements. Table 14 lists the various process steps (technologies) needed to carry out the processes in the tables in Sec. 3. The NASA technology readiness levels are given in the TRL column.

The various technologies needed for each of the processes in the tables in Sec. 3 are identified in Table 15. It can be seen that oxygen storage and cryocooling are needed for all five processes, and electrolysis of water and acquisition of CO_2 are needed by 4 of the processes. Until we can resolve whether water is accessible and recoverable on Mars, all the technologies need to be developed further. If water is found to be accessible on Mars, development of technologies I and K can be terminated

Technology C is only listed for completeness. Hydrogen storage in any form appears to be impractical.

Validation of Technologies on Mars

ISRU flight demonstrations are needed to validate Earth-based development and testing. Flying progressively more complex ISRU demonstration missions will minimize the risk and increase the confidence in use of ISRU for Mars human missions.

The specific needs for validation of technologies on Mars are summarized in Table 16.

Table 14. Process Steps (Technologies)

	Process or Technology	Present TRL	Description
A	Find water	**3-6**	Global search for water-likely areas probably from orbit, followed by ground-truth with rover-mounted instruments and eventually, recovery of water.
B	Extract water	**3-4**	Drills and possibly heaters to recover water, depending on its physical state and depth and dispersion.
C	H_2 Storage	**3**	Hydrogen tank. If liquid H_2 is used, the power for cryocoolers is likely to be prohibitive. If H_2 is stored at high pressure, the tank mass becomes prohibitive.
D	O_2 Storage	**4+**	Store liquid O_2 at ~ 113 K in minimum weight tanks.
E	CH_4 Storage	**4+**	Store liquid CH_4 at ~ 113 K in minimum weight tanks.
F	Cryocoolers	**4+**	Develop cryocoolers to maintain O_2 and CH_4 tanks in the Mars environment with minimum power usage and acceptable reliability.
G	Acquire, compress and purify CO_2	**2/3**	Acquire, purify and compress CO_2. Alternate technologies are valued depending on their power requirements, mass and volume, reliability, purity of CO_2 and pressure of CO_2 (higher the better). Also, buffer gas for breathing would be a valuable byproduct.
H	Electrolyze water	**5/6**	Adapt mature electrolyzer technology to be capable of transport to Mars and operating in the Mars environment.
I	RWGS Converter	**2/3**	An end-to-end system that takes pure compressed CO_2 and converts it to $CO + O_2$, separating the O_2 and venting the CO. A small amount of hydrogen is used as a facilitating chemical, and is recirculated from products to reagents.
J	Sabatier Converter	**4+**	An end-to-end system that takes pure compressed CO_2 and H_2 converts it to $CH_4 + H_2O$, separating the CH_4, and electrolyzing the H_2O. The overall process is $CO_2 + 2H_2 \rightarrow CH_4 + O_2$.
K	Solid Oxide Converter	**2/3**	An end-to-end system that takes pure compressed CO_2 and converts it to $CO + O_2$, separating the O_2 and venting the CO.
L	Thrusters for MAV	**4**	Optimized thrusters for ISRU propellants (methane and oxygen for process 2)
M	Ascent vehicle configuration	**4**	Analysis of requirements, constraints, and interfaces of the MAV with the ISRU system and its propellant tanks

Table 15. Technologies Needed for Each Process

	Technologies ⇓/ Processes ⇒	1. Electrolyze Mars Water	2. Sabatier/ Electrolysis/ Mars Water	3. Sabatier /Electrolysis/ H_2 from Earth	4. Reverse Water Gas Shift	5. Solid Oxide Electrolysis
A	Find water	Yes	Yes			
B	Extract water	Yes	Yes			
C	H_2 Storage	Yes		Yes		
D	O_2 Storage	Yes	Yes	Yes	Yes	Yes
E	CH_4 Storage		Yes	Yes		
F	Cryocoolers	Yes	Yes	Yes	Yes	Yes
G	Acquire, compress & purify CO_2		Yes	Yes	Yes	Yes
H	Electrolyze water	Yes	Yes	Yes	Yes	
I	RWGS Converter				Yes	
J	Sabatier Converter		Yes	Yes		
K	Solid Oxide Converter					Yes
L	Thrusters for MAV					
M	MAV configuration					

Table 16. Need for Validation of Technologies on Mars

	Technology	Validation
A	Find water	Must be done on Mars. High priority.
B	Extract water	Must be done on Mars. High priority.
C	H_2 Storage (113 K, 10,000 psi)	One test will suffice for all three. A Mars validation is suggested but is lower priority than validation of CO_2 acquisition.
D	O_2 Storage	
E	CH_4 Storage	

	Technology	Validation
F	Cryocoolers	Must be done on Mars to assure heat sinks are understood as well as dust effects on radiators.
G	Acquire, compress, purify CO_2	Must be done on Mars. High priority.
H	Electrolyze water	Eventually, it should be tested in lower gravity of Mars but this is low priority.
I	RWGS Converter	Eventually, it should be tested in lower gravity of Mars but this is low priority.
J	Sabatier Converter	Eventually, it should be tested in lower gravity of Mars but this is low priority.
K	Solid Oxide Converter	Probably not necessary to test on Mars.
L	Thrusters for MAV	Probably not necessary to test on Mars.
M	MAV configuration	Probably not necessary to test on Mars.

Table 17. Summary of needs for recommended technology tasks

Technology Task	If water is available on Mars	If water is not available on Mars
(1) O_2 and CH_4 storage	Needed	Only O_2 storage needed
(2) Cryocoolers	Needed	Needed
(3) Acquire, compress, purify CO_2 and buffer gases	Needed	Needed
(4) Electrolysis of Water	Needed	May be needed, depending on process used
(5) Sabatier Conversion System	Needed	May be needed, depending on process used
(6) RWGS Conversion System	Not needed	May be needed, depending on process used
(7) Solid Oxide Electrolysis System	Not needed	May be needed, depending on process used
(8) Ascent Vehicle Thruster Development	Needed, but details are process-dependent	Needed, but details are process-dependent
(9) Ascent Vehicle Configuration Analysis	Needed, but details are process-dependent	Needed, but details are process-dependent

Suggested Technology Tasks

(1) O_2 and CH_4 storage

Develop concepts for optimized storage of CH_4 and O_2 on Mars and develop and demonstrate storage tanks under simulated Mars conditions using adaptations of commercial cryocoolers.

(2) Cryocoolers

Prepare a detailed review of available cryocoolers and estimate the required power to maintain propellants on Mars. Assess the lifetimes and reliabilities of cryocoolers. Determine if there is a need and if there is a technical basis for improving the state of the art to optimize performance and/or assure reliability. If appropriate, develop an optimized cryocooler and demonstrate with storage tanks under simulated Mars conditions.

(3) CO_2 Acquisition, Compression and Purification

This activity has two parts.

(a) Develop a prototype CO_2 Acquisition, Compression and Purification System based on cryogenic freezing out of CO_2 from the atmosphere and advance this technology from its present state of TRL 2/3 to TRL 6.

(b) Evaluate the potential for mechanical compressors to acquire CO_2. If, as seems likely, the cryo-compressor approach eventually proves to be feasible and distinctly superior, the mechanical compressor approach can be eliminated.

(4) Electrolysis of Water

This requirement starts with a relatively mature technology that should be adapted so it can withstand launch, cruise and EDL loads, as well as operate in reduced gravity of Mars.

(5) Sabatier Conversion System

The Sabatier Conversion System [3] needs to be matured by developing a compact, optimized engineering model and validating its performance, longevity and robustness by long-term testing in a simulated Mars environment.

(6) RWGS Conversion System

The RWGS Conversion System [4] needs to be matured by developing a compact, optimized engineering model and validating its performance, longevity and robustness by long-term testing in a simulated Mars environment. *If water is available on Mars and the Sabatier/electrolysis process is chosen, this Task can be eliminated.*

(7) Solid Oxide Electrolysis System [5,6]

The ability to build and operate robust SOE Conversion System stacks needs to be demonstrated. Then it needs to be matured by developing a compact, optimized engineering model and validating its performance, longevity and robustness by long-term testing in a simulated Mars environment. *If water is available on Mars and the Sabatier/electrolysis process is chosen, this Task can be eliminated.*

(8) Ascent Vehicle Thruster Development [7]

Ascent vehicle thrusters that can utilize ISRU-produced propellants need to be developed and validated. Of critical importance is determining the performance as a function of oxygen/fuel mixture ratio.

(9) Ascent Vehicle Configuration Analysis [8]

A significant analysis is needed to evaluate alternatives for configuring ascent vehicles to accommodate ISRU-generated propellants, with particular emphasis on practical limits to propellant tank volumes.

A summary of recommended technology tasks is provided in Table 17.

7. Continuing Trade Studies

Additional analysis is needed for the following reasons:

- To improve the accuracy and credibility of estimates of various figures used in the estimates of mass and power requirements of various processes by further research and analysis.
- To estimate the uncertainties in the various figures used, so as to lead to an estimate of the overall uncertainties in the comparison of ISRU missions with non-ISRU missions.
- To refine our preliminary estimates of storage pressures and temperatures, tank masses, mixture ratios, realistic specific impulses and other aspects of propulsion systems, including the trade between pump-fed and pressure-fed engines.
- To include in the analysis, production of buffer gases for life dilution of oxygen for life support.
- To greatly increase the extent of our analysis of the comparison of overall mission scenarios with and without ISRU.
- To develop a cohesive strategic long-range NASA plan for reducing uncertainty about Mars water, building upon analysis by Mars scientists, observations made in upcoming Mars missions, and opportunities for Human Precursor missions.

We also need to clarify the role of power in ISRU applications. The assumption made herein is that the power system is available "for free" because it is needed a priori for human support once humans arrive on the second flight. This needs to be examined thoroughly.

Future work leading toward Human Precursor demonstrations should follow four parallel paths:

- Continuing trade studies
- Search for water on Mars
- Advance ISRU technologies
- Plan critical measurements and demonstrations relevant to ISRU on Mars

As plans for Human Precursor missions begin to gel in the years ahead, continuing trade studies will be needed to assure that we fully understand the value associated with ISRU, and that we have appropriate roadmaps leading to readiness for these missions. Until basic questions on the feasibility of acquiring water on Mars, ISRU technologies based on water or no water must be pursued in parallel, and it is difficult to schedule specific details on ISRU demonstrations on Mars.

8. Flight Demonstrations

Measurements to Reduce Risk

The purpose of flight demonstrations is to build confidence in the viability of ISRU systems and to reduce the risk of unknown failure modes by testing representative systems in a real environment. The potential risks and impacts are shown in Table 18. Measurements that can be made to reduce risk are summarized in Table 19.

To "buy down" risk, we need to perform measurements, primarily related to acquisition of water and characterizing Mars dust, and validate ISRU processes by testing them on Mars. If water is available on Mars a significant improvement in ISRU would be enabled. However, there are major uncertainties about the availability of water. Therefore the #1 risk item is the question: Can we obtain water in a practical matter on Mars for ISRU?

Need for Mars Water Resources

Issues for acquiring indigenous Mars water include:

- Distribution of water (depth, latitude, etc), especially relative to candidate sites for human landing.

- Form (near-surface hydrated regolith, ice, permafrost, etc.)

- Extent (concentration, deposits, extended layers, etc)

- Predictability--How can we reliably find and predict the ISRU-relevant characteristics of water deposits?

- Does Mars water constitute a biohazard? Conversely, can we avoid contaminating Martian water with Earth microbes?

- Recoverability, as a function of form and extent (e.g., what is better/easier to utilize--a small ice deposit or a large regolith deposit?)

The prevailing view of at least some Mars scientists [9] seems to be that porous subsoil is filled with ice at higher latitudes to the extent of 18% by weight, below some critical depth (the "ice table") that decreases as we approach the poles. This depth might be hundreds or more meters in equatorial regions. A conjectural concept of the ice table is shown in Figure 1. The curve is pinned by the physical observation from orbit of ice at the surface at the polar cap. It is anticipated that the Phoenix mission will add a data point in the latitude range 65-75°N that is likely to show an ice table depth under 1 m. The remainder of the ice table curve is unknown and one guess is shown in Figure 1. The upper-mid latitude region where the ice table may be accessible to surface acquisition is outlined.

In equatorial regions, Odyssey data indicate that there may be a few % water tied up in some way (water of hydration of rocks?) near the surface but this will require acquiring very large amounts of regolith and heating it to high temperatures to drive off water. While it may be possible to process large amounts of regolith to acquire a small percentage of water, it seems inherently much more attractive to search for the ice table at upper-middle latitudes if human exploration plans allow landing at higher latitudes.

The MARSIS and SHARAD instruments can only probe at depths >100 m with low resolution. These instruments may provide important geological information at depth but are not expected to provide much information relevant to near-surface water content.

Table 18. ISRU Risks and Potential Impacts

RISK	IMPACT
Water is not available	Loss of opportunity to minimize mission mass, cost, and/or risk
Water is not available at landing site	Mission failure if resource processing is critical
Water and atmosphere is present BUT - Form is different than expected (concentration, state, composition) - Location is different than expected (depth, distribution) - Unexpected impurities	Processing failure or reduced production rate: May lead to loss of mission if processing is critical
Interaction of ISRU system with Mars environment (dust, temperature, pressure, …) leads to unforeseen problems	

Table 19. Measurements that will reduce ISRU Risks and Potential Impacts. Critical measurements shown in **bold** font.

General Area	Specific Measurement
Water Acquisition, Processing and Purification	Ice distribution (depth and lateral inhomogeneity)
	Ice/soil fractions and textures (permafrost?)
	Bound water forms and availability
	Availability of vapor (humidity)
Atmosphere Acquisition, Processing and Purification	**Dust properties (physical) for filters**: During development of ISRU systems that utilize gas intake from the Mars atmosphere, it will be necessary to simulate Mars dust on Earth in order to test gas intake systems prior to validating them in situ on Mars. By measuring dust properties on Mars early, most of the testing of Mars ISRU processes that require atmospheric intake can be done on Earth in a less costly fashion, and only a final validation test will be required on Mars.
	Dust properties (chemical / mineral) for catalysts
	Composition: including oxygen and water vapor content at several locations as a function of day/night, season, and other parameters. The purposes of these measurements are (1) to identify and quantify any insidious trace gases that might exist, (2) to provide an inventory of oxygen and water vapor levels, and (3) to provide data essential to ISRU processes for recovering buffer gases from the non-CO2 part of the Mars atmosphere.
Environment	Toxins
	Wind
	Thermal environment: with particular emphasis on the performance of radiators as a function of orientation and exposure, as well as the effects of dust accumulation. Determine the effective radiator sink temperature of Mars under various conditions (day, night, wind, …). Oxygen storage on Mars for life support will likely utilize cryocoolers. If ISRU is used on Mars there will be a need for much larger cryocoolers for propellant storage. The performance on Mars depends upon the effective heat sink provided by the Mars environment for heat rejection, and dust accumulation is likely to affect performance of heat radiators. Power systems and other units that reject heat will also benefit from these measurements.

Search for Accessible Water

Pervasive uncertainty regarding availability and accessibility of near-surface ice on Mars remains as a "wild card" that will affect the strategy for ISRU development and demonstration. Until we know more about the form, extent, concentration and purity of water deposits, it will be difficult to define effective flight demonstrations of flight test articles that require Mars water. An effective strategy for searching for Mars water resources will depend to a great extent upon what constraints are imposed by human mission planners on allowable landing sites. It is possible that initial human exploration would be constrained to near-equatorial sites. Certainly, the Valles Marineris at 10°S would be an attractive venue. If there are strong reasons for believing that human exploration will have to be equatorial, then Phoenix, the poles, and a search for the ice table in 45-65°N near-surface exploration would become irrelevant. There almost surely is no near-surface ice table in equatorial regions. The thrust of the search for water in equatorial regions would then revolve about two points:

(1) System modeling to estimate what minimum percentage of stored water in the equatorial regolith is worth processing by gathering regolith and heating it to high T to drive off the water. (e.g. If there is 2% water by weight, it will take 1.2 x 10^6 kg of regolith to deliver 24,000 kg of water for ISRU).

(2) Ground truth in local areas in equatorial regions where Odyssey predicts higher percentages of water 4-8% vs. mostly 2% over much of the equatorial region.

If, however, the range of possible sites for human exploration is not confined to equatorial regions, and if the human venture has a strong preference to use ISRU to avoid bringing ~ 40,000 kg of propellant and life support resources from Earth to [illegible] thrust of the search for w[illegible] of expanding the range [illegible] within reach of the su[illegible] much latitude (no pun i[illegible] landing site in as tempe[illegible] seem obvious that proces[illegible] or 2 m deep, in situ b[illegible] more fruitful than collect[illegible] heating it. The thrust [illegible] near-surface ice table would then revolve about two points:

No pun intended (footnote) 3rd paragraph pg. 16 1st column

(3) System modeling to define the methods and evaluate the feasibility of processing near-surface ice below the ice table at shallow depths to deliver the water needed for ISRU.

(4) Ground truth in the latitude range 45-65°N to further define the curve of ice table depth vs. latitude as you proceed southward from Phoenix.

If human site selection is unrestricted, it appears more appropriate to use the first test-bed missions to attempt to confirm availability of accessible ice in preference to testing ISRU demonstrations on Mars. If these missions are unable to acquire water, a decision has to be made whether to concentrate on ISRU without water, or continue to search for recoverable water beyond 2013, depending on available evidence.

Acquisition of CO_2 from the Atmosphere

A necessary component of all practical Mars ISRU processes is acquisition and compression of CO_2 from the atmosphere. A very promising approach is based on solidification of CO_2 from the atmosphere using an efficient cryocooler [10]. This system must generate about 25,000 kg of CO_2 in a human mission, which implies processing over 100,000 cubic meters of atmosphere. Based on a model originally generated by G. Landis [11], it can be estimated that at an optical depth of 0.5 (average clear conditions on Mars) there are about 5 x 10^6 micron-size dust particles suspended in a cubic meter of atmosphere [12]. This implies that in the course of processing about 1.1 x 10^6 cubic meters of atmosphere, we will have to dispose of more than 5 x 10^{12} dust particles. The average volume of a dust particle is calculated by using a radius characteristic of the average of the $r^3N(r)$ distribution, which turns out to be roughly ~ 2.5 microns [12]. Thus the volume of a dust particle is estimated to be 64 x 10^{-12} cm^3. Hence the total volume of dust that must be rejected from 1.1 x 10^6 cubic meters of atmosphere is about 320 cm^3. It will be important to demonstrate a Mars acquisition system on Mars that can reject prevalent dust in amounts such as these. This should be done early in the program because it is a critical step needed for all practical ISRU processes.

Mars Thermal Environment

There are two issues of concern to ISRU in regard to the Mars thermal environment. One is the effective thermal environment as a heat sink for radiators connected to cryocoolers. The other is the effect of dust accumulation on radiator performance.

At present, we do not have accurate measurements of the effective night sky temperature although there are models for this. Radiator performance during the daytime when the sun is shining is difficult to estimate. The long-term performance of radiators will change with dust accumulation. It will be very helpful to make measurements on Mars to clarify these unknowns.

The rate of settling of dust is simply estimated [11,12] by dividing the number of dust particles in a vertical column by the settling time (time it takes for a vertical distribution of dust particles to settle out). The number of dust particles in a vertical column of area 1 cm^2 for an optical depth = 0.5 is estimated by using the definition of optical depth. The settling time (as measured by the rate of decay of optical depth after a dust storm) is something of the order of 80 sols. Therefore the settling rate is about

30,000 particles per cm^2 sol. The optical obscuration produced by these dust particles is about 0.15%, resulting in a loss of power from solar arrays of about 0.15% per sol - which has recently been confirmed by MER measurements. The effective area of a dust particle for covering thermal surfaces may differ from that for optical surfaces, but this is a good rough approximation.

The MTERC experiment [13] was a sophisticated instrument for measuring the thermal environment on Mars. It was scheduled to fly on the Mars 2001 Lander but that mission as cancelled. An updated version of this experiment would be very valuable for providing important data to Mars ISRU planners.

Roadmap

As we discussed previously, the strategy for ISRU precursors hinges heavily on the need for accessible Mars water, which greatly enhances prospects for ISRU in human missions. Furthermore, the strategy for the search for accessible water hinges on whether NASA will permit human landings at upper-middle latitudes or whether NASA will restrict the landings to near-equatorial sites. Simple logic dictates that with limited resources, we should seek the sources of water that are most easily discovered and processed. Evidence and models suggest that there may be a shallow subterranean ice table at upper-middle latitudes (45-65°N) and this is the region of preference to search for accessible water if landings in such areas are permitted. If landings are not permitted at such high latitudes, then the search at equatorial latitudes should be for locally higher concentrations of bound water in regolith. We therefore derive two roadmaps, one for the case where upper-middle latitude landings are permitted, and one for the case where only near-equatorial landings are permitted.

We conjecture two phases of precursor missions to pave the way for use of ISRU on Mars. Phase I comprises the 2011 and 2013 Mars missions. Phase I has the primary goals of

- Searching for accessible water in an appropriate area, and characterizing the resource if it is found.
- Demonstrating the capability to acquire significant amounts of high-pressure CO_2 from the Mars atmosphere with suitable dust mitigation on the intake system and the cryocooler radiator surfaces.

An additional goal (if resources permit) is to demonstrate ISRU systems with production and storage of ISRU-produced propellants.

The location and method of searching for water on the 2011 and 2013 missions will depend on NASA guidance on restrictions on the first human landing site. If NASA restricts this site to a near-equatorial region, then the search for water should be confined to areas where Odyssey data indicate local maxima in the amount of water tied up in the regolith. Such a mission would need to have the capability to dig or drill down to perhaps 1 m, collect regolith, and heat it to drive off water in a closed system.

If NASA will allow landing sites in the 45-65°N region of latitude, then the high priority goals that absolutely need to be accomplished in 2011 and 2013 are:

- Determine one point on the curve in Figure 1 for each landing opportunity to bracket the curve on the vertical scale. This will require a capability to probe down to at least one meter below the surface and locate and characterize ice deposits.
- Demonstrate the capability to acquire Mars atmosphere and produce adequate flowrates of pure CO_2 and possibly buffer gas over at least 80 sols.
- Demonstrate the capability to process in situ Mars ice and produce a representative flowrate of liquid water. This will require some means (perhaps in situ melting and pumping out liquid water) if significant near-surface ice deposits are found.

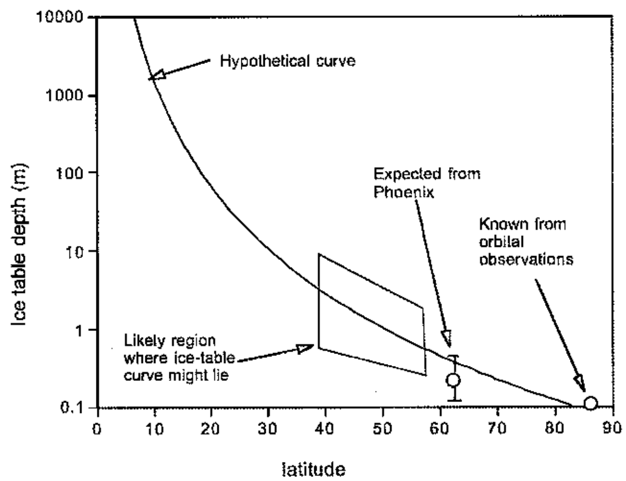

Figure 1. Hypothetical curve showing a possible dependence of ice table depth on latitude.

We therefore propose the strategy for Phase I (2011 and 2013 Mars demonstrations) described in Table 20.

The most difficult thing about planning a sequence of Mars missions beyond 2013 is the time delay in receiving data and feedback from previous missions. Figure 2 illustrates the relationship between the schedules for various precursor missions from Phoenix through the 2020 precursor mission. The main intent of Phase II is to reduce risk by operating complete end-to-end ISRU systems culminating in a significant application at increasing scales from 2016 to 2020. However, there is a difficulty in planning the 2016 Precursor mission because:

The 2013 Precursor results will not be available until about the mid-point of Phase C/D of the 2016 spacecraft development. Therefore, the concept and design for the 2016 mission will rest almost entirely on 2011 Precursor (and previous mission) data. Data from the 2013 Precursor mission will begin to accumulate during phase C/D of the 2016 mission, which might suggest some "mid-course corrections" to the 2016 mission, particularly in regard to landing site. We would like to use the 2016 Precursor mission to demonstrate a small-scale end-to-end ISRU system representative of the technology that will ultimately be used for Mars ISRU. However, at the time that the 2016 Precursor is designed, we may not have assurance that we can count on accessible water, and therefore it may not be clear whether the ISRU system should be based on Sabatier/Electrolysis or one of: RWGS or SOE. Taking an optimistic view, we can hope that enough data are available to establish that water can be successfully acquired on Mars and that the Sabatier/Electrolysis process is the one chosen for demonstration.

This needs further study. It might well be that the 2016 mission should be delayed until 2018. With this assumption, the Phase II Mars demonstration strategy involves the following:

2016 Lander: This mission would operate a complete end-to-end ISRU system (1/20 scale, duration 80 sols) culminating in a significant application such as operation of a Mars Hopper.

2020 Lander: The primary purpose is to demonstrate at large scale (~ 1/5 scale) and moderate duration (~150 sols) an end-to-end ISRU system culminating in a significant application such as providing propellants for an ascent vehicle to rendezvous in Mars orbit. This demonstration will validate robust water and atmosphere acquisition and processing leading to significant quantities of ISRU products, and utilization of these products in an ascent vehicle.

COST

Cost estimates will be developed by December, 2004.

Table 20. Suggested Plan for 2011 and 2013 Landers

Capability	If NASA restricts landing sites to near-equatorial regions	If NASA allows landing sites from 45° N to 60°N
2011 Mission		
Landing site	Areas such as the orange region in Figure 7-2 near a longitude of ~ 22°, a few degrees south of the equator.	About 10-15° southward of Phoenix, assuming that Phoenix finds a near-surface ice table.
Water-search capability on board rover	Capability to probe down to ~ 1-m, collect regolith down to 1-m, and heat samples in closed systems to drive off water and thereby measure water content.	Capability to probe down to ~ 1-m, characterize the ice table if one is found, and recover water by some process such as in situ melting and pumping.
Atmosphere acquisition	Demonstrate a significant scale Mars CO_2 acquisition system that includes dust mitigation and operate it for at least 80 sols.	
Thermal environment	Implement an instrument similar to MTERC to characterize the thermal environment, and operate a cryocooler with an exposed radiator for at least 80 sols.	
ISRU demonstration	If resources permit, demonstrate oxygen production on the 2011 Lander.	
2013 Mission		
Landing site	An area distinct from that used in 2011, but with similar possibilities for higher-than-average water content in regolith.	About 10-15° southward of the 2011 mission, assuming that Phoenix finds a near-surface ice table.
Water-search capability on board rover	Capability to probe down to ~ 1-m, collect regolith down to 1-m, and heat samples in closed systems to drive off water and thereby measure water content.	Capability to probe down to ~ 1-m, characterize the ice table if one is found, and recover water by some process such as in situ melting and pumping.
Atmosphere acquisition	Demonstrate a significant scale Mars CO_2 acquisition system that includes dust mitigation as part of an end-to-end ISRU demonstration.	
Thermal environment	Operate a cryocooler with an exposed radiator for at least 80 sols as part of an end-to-end ISRU demonstration.	
ISRU demonstration	If resources permit, demonstrate methane and oxygen production on the 2013 Lander.	

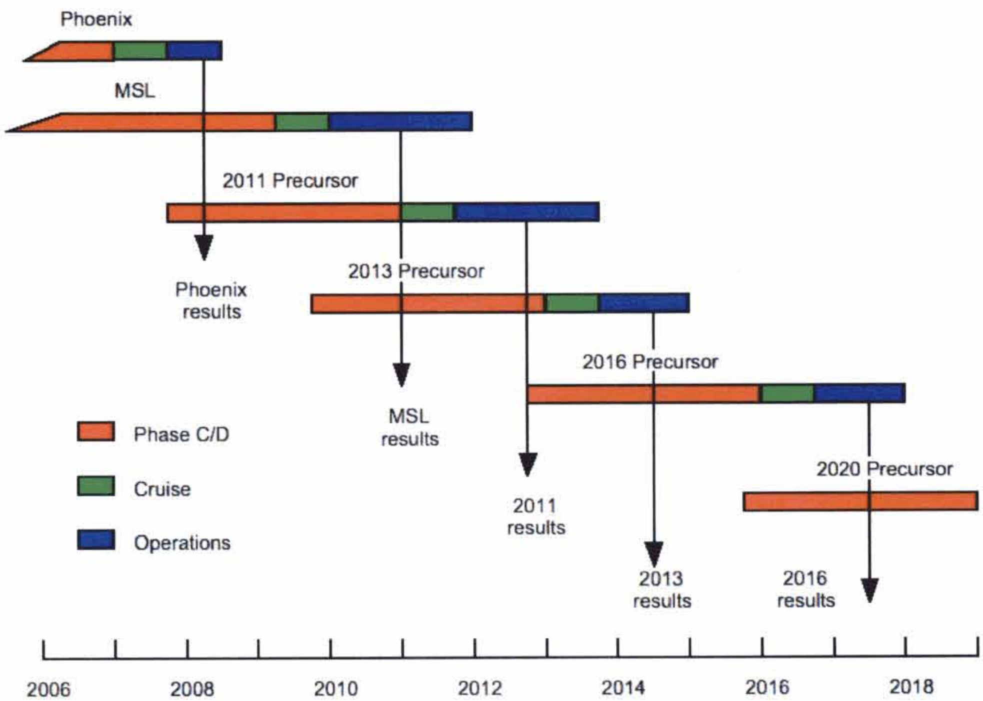

Figure 2. Sequence and probable schedule of planned and potential missions.

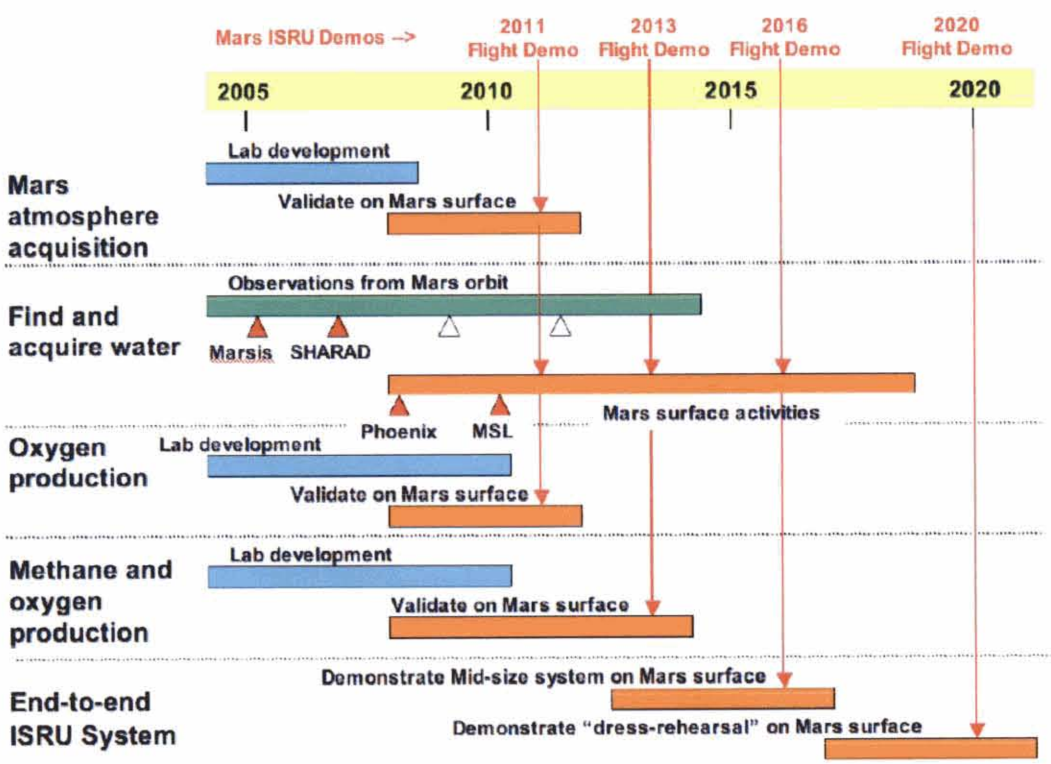

Figure 3. Roadmap for development and demonstration of ISRU technology.

REFERENCES

[1]. Daniel P Thunnissen, Donald Rapp, Christopher J. Voorhees, Stephen F. Dawson, and Carl S. Guernsey, "A 2007 Mars Sample Return Mission Utilizing In-Situ Propellant Production," AIAA 99-0851, 1999.

[2] Private communication from Joe Lewis, JPL.

[3] D. Larry Clark, "In-Situ Propellant Production On Mars: A Sabatier/Electrolysis Demonstration Plant," AIAA 97-2764, July, 1997.

[4] Robert Zubrin, B. Frankie, and T. Kito, "Mars In-Situ Resource Utilization Based on the Reverse Water Gas Shift," AIAA-97-2767, 33rd AIAA/ASME Joint Propulsion Conference, Seattle, WA July 6 - 9, 1997; *ibid*, "Report on the Construction and Operation Of a Mars in-situ propellant Production Unit Utilizing the Reverse Water Gas Shift," AIAA-98-3303, 34th AIAA/ASEE Joint Propulsion Conference, Cleveland Ohio, July 13-15, 1998.

[5] S. C. Crow, "The MOXCE Project: New Cells for Producing Oxygen on Mars," AIAA 97-2766, July, 1997.

[6] K. R. Sridhar, M. Gottmann and R. S. Baird, 2001 Mars In-Situ Oxygen Production Flight Demonstration, AIAA 99-2413, (1999); K. R. Sridhar, and B. T. Vaniman, "Oxygen Production on Mars Using Solid Oxide Electrolysis," 25th Intl Conf on Environmental Systems, Paper 951737, San Diego, July 10-13, 1995.

[7] Daniel P. Thunnissen, Carl S. Guernsey, Raymond S. Baker, and Robert N. Miyake, Advanced Space Storable Propellants for Outer Planet Exploration, AIAA-2004-3488, 2004.

[8] David Stephenson, "Mars Ascent Vehicle – Concept Development," AIAA 2002-4318, IAA/ASME/SAE/ ASEE Joint Propulsion Conference & Exhibit, Indianapolis, Indiana, 7-10 July 2002.

[9] Michael T. Mellon, William C. Feldman, and Thomas H. Prettyman, "The presence and stability of ground ice in the southern hemisphere of Mars," Icarus 169, 324–340, 2004.

[10] Clark, D.L. and Payne, K., "Evaluation of Mars CO_2 Acquisition Using CO_2 Solidification," Lockheed-Martin Space Systems Contract Report to JSC, 2000.

[11] G. A. Landis, "Dust Obscuration of Mars Solar Arrays," Acta Astronautica 38, 885-891 (1996).

[12] D. Rapp, D., S. Dawson, and N. Mardesich, "Solar Energy on Mars," JPL Report, May, 2003.

[13] Kenneth R. Johnson and David E. Brinza, "The Mars Thermal Environment and Radiator Characterization (MTERC) Experiment," SAE Paper 00ICES-178, 2000.

[14] Jerry Sanders, NASA-JSC, private communication, 2004.

ACKNOWLEDGEMENT

The authors are indebted to Kenneth Johnson, Carl Guernsey, Daniel Thunnissen and Joe Lewis of JPL for many valuable inputs. We are also indebted to Jerry Sanders of JSC for reviewing the manuscript and providing valuable guidance on many issues.

BIOGRAPHY

Donald Rapp is a contractor to JPL who has 45 years experience in chemical, engineering and space systems. He was a full professor at the University of Texas and served as Chief Technologist for the JPL Mechanical and Chemical Systems Division for 15 years. He published three textbooks and over 80 articles. His JPL Report D-15223, "A Review of Mars In Situ Propellant Production Technology, provides a detailed description of ISRU technology circa 1998, most of which is still germane today.

Robert Easter is a senior system engineer at JPL who has a very broad experience in system engineering of space systems. He is currently leading JPL's ongoing system analysis of requirements and implementation of Human Precursor missions including the potential impact of ISRU.

Jeffrey H. Smith, Jason Andringa and Tom Wilson are JPL system engineers who support Robert Easter in the ongoing analysis of Human Precursor missions.

D. Larry Clark is the Manager of the Lockheed-Martin Spacecraft Technology Development Laboratory. Among his many accomplishments are key developments in ISRU including a Sabatier/Electrolysis demonstration plant, and a proof-of-concept for cryo-acquisition of CO_2 on Mars.

Kevin Payne is an engineer at Lockheed-Martin who has carried out important engineering development of cryo-acquisition of CO_2 and he has provided important elements of the present study as detailed spreadsheets.