ABSTRACTS

IN SITU RESOURCE UTILIZATION (ISRU III) TECHNICAL INTERCHANGE MEETING

February 11–12, 1999

Lockheed Martin Astronautics Waterton Facility
Denver, Colorado

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Convened by
David Kaplan, NASA Johnson Space Center
Larry D. Clark, Lockheed Martin Astronautics

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PREFACE

This volume contains abstracts that have been accepted for presentation at the In Situ Resource Utilization (ISRU III) Technical Interchange Meeting, February 11–12, 1999, hosted by the Lockheed Martin Astronautics Waterton Facility, Denver, Colorado.

Administration and publication support for this meeting were provided by the staff of the Publications and Program Services Department at the Lunar and Planetary Institute.

AGENDA

Thursday, February 11, 1999

7:45 a.m.	REGISTRATION AND CONTINENTAL BREAKFAST
8:45 a.m.	WELCOME AND INTRODUCTION
9:00 a.m.	Hinners N.* *The Strategic Role of In Situ Resource Utilization for Robotic and Human Missions*
9:30 a.m.	Finn J. E.* *Low-Power Temperature-Swing Adsorption for Mars Atmosphere Acquisition*
10:00 a.m.	Clark L. D.* *Mars Atmospheric Acquisition and Compression System — Initial Results*
10:30 a.m.	BREAK
11:00 a.m.	Zubrin R.* Frankie B. Kito T. Muscatello T. *Mars In Situ Propellant Production Utilizing the Reverse Water Gas Shift*
11:30 a.m.	Frankie B. M.* Zubrin R. M. *Production of Higher Hydrocarbon Species on Mars*
12:00 p.m.	Sharma P. K.* Rapp D. Rohatgi N. K. *Methane Pyrolysis and Disposing Off Resulting Carbon*
12:30 p.m.	LUNCH and TOUR OF ATLAS AND TITAN LAUNCH VEHICLE FINAL ASSEMBLY BUILDING (FAB)
2:30 p.m.	Minh N. Q.* Chung B. W. Doshi R. Lear G. R. Montgomery K. Ong E. T. *Fabrication and Performance of Zirconia Electrolysis Cells for Carbon Dioxide Reduction for Mars In Situ Resource Utilization Applications*
3:00 p.m.	Martin J. L.* Corey J. A. Peters T. A. *Low-Cost, High-Performance Cryocoolers for In-Situ Propellant Production*
3:30 p.m.	Mueller P. J.* Durrant T. C. *Cryogenic Propellant Production, Liquefaction, and Storage for a Precursor to a Human Mars Mission*
4:00 p.m.	BREAK
4:15 p.m.	Plachta D.* *NASA's Cyro Working Group*
4:45 p.m.	Wegeng R. S.* Sanders G. B. *Microchemical and Thermal Systems for In Situ Resource Utilization*
5:15 p.m.	WRAP-UP
5:30 p.m.	ADJOURN
6:30 p.m.	DINNER AT A LOCAL RESTAURANT

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* Denotes Speaker

Friday, February 12, 1999

8:00 a m	CONTINENTAL BREAKFAST
8.30 a m	ANNOUNCEMENTS
8:45 a.m.	Blair B R.* *Potential Commercial Uses of Mars ISPP Technology*
9.15 a m	Green S. T * Deffenbaugh D M Miller M. A. *Trade Study of Five In-Situ Propellant Production Systems for a Mars Sample Return Mission*
9:45 a.m	Kuhl C A * Johnson J E *Lunar In-Situ Propellant Production (ISPP) Technology Research*
10:15 a.m.	BREAK
10:45 a.m.	Currier R.* Blacic J. Trkula M *Hydrogen Plasma Reduction of Planetary Materials*
11:15 a.m.	Popovic S.* Ash R. Dinh T. Vuskovic L. *RF-ICP Discharge for a Hybrid Oxygen Production System*
11:45 a.m.	Williams J. D.* Bratkovich T. E. Bussing T. R. A. *Atmospheric Water Vapor Adsorption for Mars In Situ Resource Utilization*
12:15 p.m.	LUNCH and TOUR OF THE ENGINEERING PROPULSION LABORATORY
2:15 p.m.	Kaplan D. 1.* Ratliff J. E. Baird R. S. Sanders G. B. Johnson K. R. Karlmann P. B. Juanero K. J. Baraona C. R. Landis G. A. Jenkins P. P. Scheiman D. A. *Mars In Situ Propellant Production Precursor (MIP) Flight Demonstration Project: Overview and Development Unit Testing Results*
2:45 p.m.	Karlmann P. B.* Johnson K. R. Rapp D. Wu. J. J. *Development Unit Configuration and Current Status of the MIP/MAAC Experiment*
3:15 p.m.	Sridhar K. R.* Gottmann M. Baird R. S. *Oxygen Generator System for Mars In-Situ Propellant Production Precursor Flight*
3:45 p.m.	Juanero K. J.* Johnson K. R. *Development Unit Configuration and Current Status of the MIP/MTERC Experiment*
4.15 p.m.	WRAP-UP
4:30 p.m.	ADJOURN

POTENTIAL COMMERCIAL USES OF MARS ISPP TECHNOLOGY.

B. R. Blair, Division of Economics and Business, Colorado School of Mines, PO Box 841, Golden CO 80402, USA (bblair@mines.edu)

Introduction: Similarities in components and processes between gas to liquid (GTL) technology and proposed systems for Mars in-situ propellant production (ISPP) may point to a commercial market for spinoffs. Recent advances in the conversion of natural gas - primarily methane - to liquid petroleum products are creating optimism for owners of marginal or remote gas fields worldwide. Many commercial players are entering the field of GTL technology, risking significant capital in a bid to compete for market share with traditional oil refineries. The winners in this new field will be equipped with the lowest-cost GTL process using the most advanced technology available. The potential discovery of innovative solutions to problematic or high-cost steps in GTL methane conversion should be considered by ISPP researchers while trying to find solutions that may significantly lower the cost of future Mars missions. This paper will review the current structure of the GTL industry, with a focus on cost elements and proprietary technologies used by the dominant firms.

MARS ATMOSPHERIC ACQUISITION AND COMPRESSION SYSTEM - INITIAL RESULTS.

L. D Clark. Lockheed Martin Astronautics, P O Box 179, Mail Stop H0341, Denver CO 80201, USA (larry d clark@lmco com)

Introduction: Most concepts for In-Situ-Resource Utilization (ISRU) on Mars require the acquisition and compression of atmospheric carbon dioxide One of the most favorable compression methods is the use of an adsorption bed in terms of reliability and power consumption The cold Martian environment can provide enough cooling to adsorb up to 16 percent of the bed mass with CO_2 Heating will then drive off and compress the CO_2 with some of the thermal energy provided by waste heat from the propellant production process A large, flight-like adsorption compressor was designed, built and tested at Lockheed Martin Astronautics in the Engineering Propulsion Laboratory in Denver, Colorado under a contract with NASA-Jet Propulsion Laboratory. The size and performance was designed to provide the quantity of CO_2 expected for a sample return mission. The target value for CO_2 production selected was 3 kg of CO_2 per sol.

Design Considerations: The sorption pump was designed to operate in a diurnal cycle where the acquisition took place during the Martian night when the coldest temperatures could be obtained with radiators. The CO_2 would then be released and compressed during the day during the propellant production period when solar power is available.

The compressor design was intended to include flight-like features yet provide a flexible system. The compressor included an aluminum, vacuum-jacketed
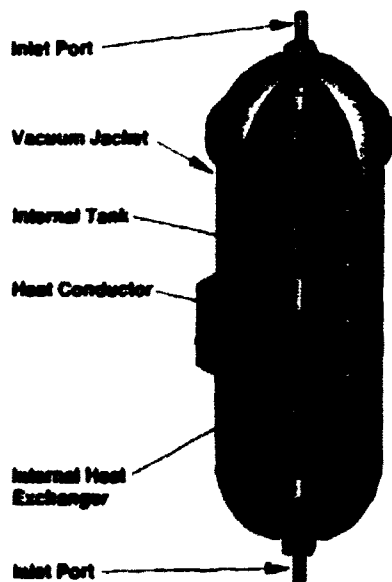
exchanger evenly added and removed heat from the sorbant bed A centrally located heat conductor provided the transfer point for external cooling Flow through the bed was enhanced with an central flow distribution bar and an outer screen plenum to minimize pressure drop.

Total volume of the sorbant bed is 40 liters which held 20 5 kg of Zeolite 13X after reductions from internal hardware Seal on the tanks were made with o-rings to enable removal of the domes and penetrations for later reconfiguration Multi-layer insulation was applied to the inner tank inside the vacuum space

In order to promote purging of the non-condensable gas found in the Martian atmosphere, an external blower was installed in the lower inlet. This centrifugal blower was designed to provide 28 liters per minute through the bed at Martian conditions Solid conduction thermal transfer was used to cool the bed for acquisition. The cooling source must be disconnected during the production period and a large-capacity thermal switch was designed and built to perform this function. The thermal switch was motor driven with large-surface area contacts which closed the thermal connection.

Initial Test Results: Carbon dioxide storage was substantial when operated with pure CO_2 under a temperature swing from -70 C to 150 C. Over 3.3 kg of compressed CO_2 was supplied. This represents over 16% of the sorbant mass. Although testing was limited in this initial study, results with Martian simulant gas reduced the mass storage fraction to less than 8%. It is unclear why the reduction was so severe, even with extensive circulation of fresh atmosphere mix for the entire adsorption cycle. Mass spectrometer data detected significant quantities of the trace gases in the product stream, suggesting that adsorption of the trace gases is taking place.

tank with removable domes. An internal, finned heat

FABRICATION AND PERFORMANCE OF ZIRCONIA ELECTROLYSIS CELLS FOR CARBON DIOXIDE REDUCTION FOR MARS *IN SITU* RESOURCE UTILIZATION APPLICATIONS.

N. Q. Minh, B. W. Chung, R. Doshi, G. R. Lear, K. Montgomery, and E. T. Ong. AlliedSignal Aerospace Equipment Systems. 2525 West 190th Street, Torrance CA 90504-6099, USA (nguyen.minh@alliedsignal.com)

Introduction Use of the Martian atmosphere (95% CO_2) to produce oxygen (for propellant and life support) can significantly lower the required launch mass and dramatically reduce the total cost for Mars missions. Zirconia electrolysis cells are one of the technologies being considered for oxygen generation from carbon dioxide in Mars In Situ Resource Utilization (ISRU) production plants. The attractive features of the zirconia cell for this application include simple operation and lightweight, low volume system

A zirconia electrolysis cell is an all-solid state device, based on oxygen-ion conducting zirconia electrolytes, that electrochemically reduces carbon dioxide to oxygen and carbon monoxide. The cell consists of two porous electrodes (the anode and cathode) separated by a dense zirconia electrolyte. Typical zirconia cells contain an electrolyte layer which is 200 to 400 micrometer thick. The electrical conductivity requirement for the electrolyte necessitates an operating temperature of 900° to 1000°C. Recently, the fabrication of zirconia cells by the tape calendering has been evaluated. This fabrication process provides a simple means of making cells having very thin electrolytes (5 to 30 micrometers). Thin zirconia electrolytes reduce cell ohmic losses, permitting efficient operation at lower temperatures (800°C or below). Thus, tape-calendered cells provides not only the potential of low temperature operation but also the flexibility in operating temperatures. This paper describes the fabrication of zirconia cells by the tape calendering method and discusses the performance results obtained to date.

Fabrication Process: The tape calendering process for making zirconia electrolysis cells is shown in Figure 1. This process involves first mixing electrolyte (zirconia) and cathode (mixture of platinum and zirconia) powders with organic binders in a high-intensity mixer to form plastic masses. Electrolyte and cathode plastic masses are rolled into tapes using a two-roll mill. Electrolyte and cathode tapes of certain thickness ratio are laminated and rolled into a thin bilayer tape. This bilayer tape is then laminated with a cathode tape and rolled again into a thin tape. This process can be repeated until an electrolyte of the desired thickness is obtained. In general, it takes only three rollings to produce micrometer-thick electrolyte layers. The final bilayer tape is cut to size and

fired at elevated temperatures to remove the organics The anode layer (mixture of platinum or strontium-doped lanthanum manganite and zirconia) is then applied on the electrolyte surface to produce a complete cell.

Zirconia cells having thin electrolytes have been successfully fabricated by the tape calendering process described above. Figure 2 shows, as an example, a micrograph of a fracture surface of a zirconia cell produced by tape calendering

Performance of Zirconia Cells: Zirconia cells made by the tape calendering process have been tested for their electrochemical performance. Performance tests mainly involve the determination of cell current/voltage characteristics at different temperatures (700° to 900°C). Figure 3 shows an example of performance curves obtained at 800°C for a 5 cm x 5 cm zirconia cell. High CO_2 utilization (up to 78%) has also been demonstrated. Thermal cycle and thermal shock properties of tape calendered cells have been evaluated. Thermal cycle tests involve repeated heating and cooling of cells between room temperature and 900°C at a ramp rate of 10°C/minute. Thermal shock tests involve exposing room-temperature samples to a 900°C environment and then removing the red hot samples to quench in room temperature. Zirconia cell samples tested to date show no structural damage or degradation after the thermal cycle and thermal shock tests. Multicell (two- and three-cell) stacks were successfully fabricated and operated. Figures 4 and 5 show a photograph of a three-cell stack and its current/voltage curves, respectively. As seen in Figure 5, performance of individual cells in the stack is well matched. The stack is able to sustain multiple (5) thermal cycles from room temperature to 800°C without significant performance degradation (Figure 6).
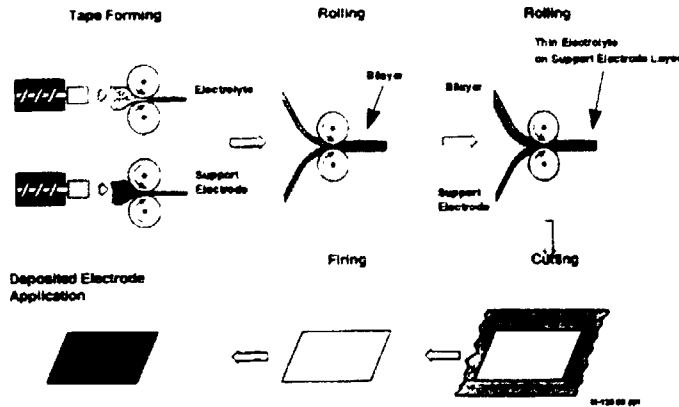
Figure 1. Tape calendering fabrication process.
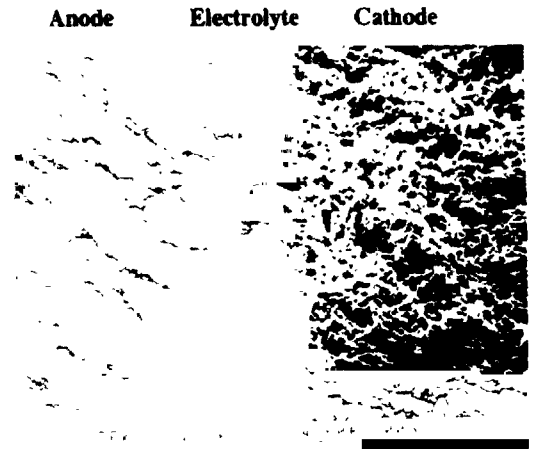
Figure 2. Micrograph of fracture surface of zirco-
nia cell. Anode is a mixture of strontium-
doped lanthanum manganite and zirconia.
Cathode is a mixture of platinum and zir-
conia.
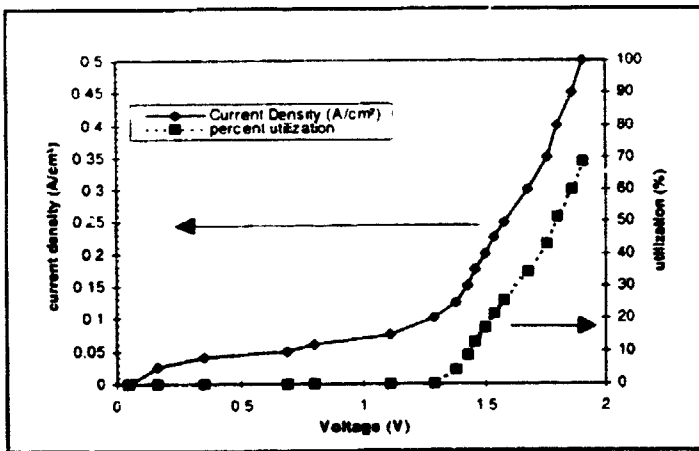
Figure 3. Performance curves of a 5 cm x 5 cm cell at 800°C.

Figure 4 Photograph of a three cell stack.
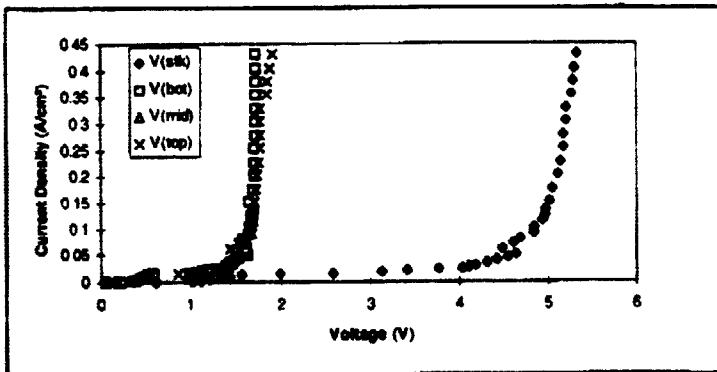
Figure 5. Voltage/current curves at 800°C of three-cell stack
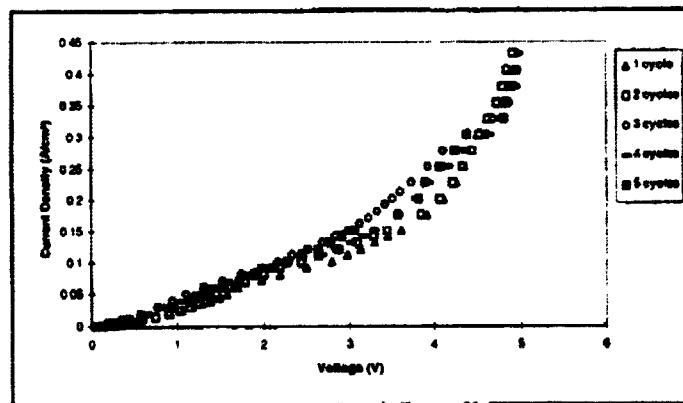
Figure 6. Voltage/current curves at 800°C of three-cell stack
after thermal cycling.

HYDROGEN PLASMA REDUCTION OF PLANETARY MATERIALS. R. Currier, J. Blacic, and M. Trkula,

MailStop J-567, Los Alamos National Laboratory, Los Alamos NM 87545, USA (currier@lanl.gov, jblacic@lanl.gov, mtrkula@lanl.gov)

Large-scale utilization of resources in space exploration and colonization must include the ability to provide oxygen for propulsion and life support. In addition, metals and other structural materials must be produced from locally available planetary resources. We propose to develop a new extractive process for resource utilization in space. This process also has the potential for water extraction from hydrous minerals (water could in turn be used to produce oxygen). Reduction of anhydrous silicate and oxide minerals to produce oxygen and metals will require the importation of hydrogen, which must be recycled with minimal losses. The proposed process uses a microwave or radio frequency produced atomic hydrogen plasma. Electromagnetic energy couples to hydrogen gas to form a non-equilibrium plasma in a reactor configuration that we believe is ideal for low gravity applications. One can form a plasma with high concentrations of atomic hydrogen, at modest bulk temperatures. Thus, we force the system into a standard state where the reductant atomic hydrogen is the key species. This dramatically shifts standard free energies of reaction, for example:

Reaction	ΔG (H$_2$-based)	ΔG (H-based)
$TiO_2 + (2H_2$ or $4H) \rightarrow Ti + 2H_2O$	+104 kcal	-91 kcal
$Al_2O_3 + (3H_2$ or $6H) \rightarrow Al + 3H_2O$	+224 kcal	-81 kcal
$TiF_3 + (3/2\ H_2$ or $3H) \rightarrow Ti + 3HF$	+129 kcal	-18 kcal

Shifting the chemistry from molecular hydrogen to the atomic analogs clearly shifts the equilibrium from one favoring reactants to one favoring products. A conceptual flow sheet for a space-based process using this chemistry might appear as shown in Figure 1:

experiments are being conducted in well-agitated fluidized beds with the plasma maintained above. Gas flow is selected so that particles are constantly carried into the plasma region. We are also examining circulating plasma fluidized bed reactors. Here, solid particles are fed from a conventional fluidized bed (the reservoir) into a "riser" section in which they are transported by high velocity gas through the plasma region. At the exit of the riser, the gas is separated from the solids (e.g. in a cyclone) and the solids fall back into the reservoir bed, where they can be fed through the riser section again. By varying the gas flow velocity in the riser section and pressure differential between the reservoir and riser, one can vary the solids number density in the riser for optimal electromagnetic coupling. For space-based applications, we propose a related process in which the mineral particles are fed from a reservoir fluidized bed or hopper into a "downer" reactor where they simply fall under reduced gravity through the glow discharge region as indicated in Figure 2:
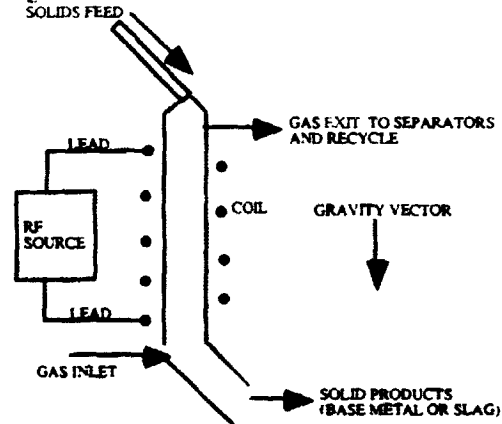
Figure 2. A downer reactor with counter flow of gas. While an inductively coupled plasma configuration is shown here, other means of plasma generation (e.g. with microwave energy) are also possible.

Figure 1. Process flow sheet. When produced as a product stream, the water could then be split to yield oxygen and hydrogen for recycle.

Central to this process is the use of fluidized bed plasma reactors, which permit solid particles to be transported through the glow discharge. We are currently studying hydrogen extraction chemistry in several fluidized bed configurations. Initial screening

Upon separation from the gas stream at the exit of the

downer section, feed particles could be transported back to the reservoir for another pass if needed, or simply disposed of. The unreacted hydrogen gas would be recycled after separation from other products Similarly, upon splitting of water products to produce oxygen, the hydrogen gas would be recycled. The downer reactor offers several advantages which enhance the probability of success. First, by controlling the solids feed rate from the reservoir and the gas flow in the downer section, we could achieve essentially a counter-current reactor with continuous removal of volatile byproducts from the plasma region. This maintains the driving force towards metal production and would help limit back reactions. Second, the downer reactor allows the solids to fall essentially in plug flow (i.e. a delta function residence time). This permits precise control over the extent of reaction. A downer plasma reactor could also be configured with continuous addition and removal of solids. Good gas-solid contact maximizes the desired reactions with atomic hydrogen and aids in uniform conversion of reactants to products Of course, our demonstration experiments involving reduction of mineral surrogates to the base metals and water extraction from minerals must ultimately be correlated to the corresponding operations in low gravity. We will discuss an integrated approach to process development involving demonstration experiments and initial results and concurrent engineering. In particular, we will discuss key issues related to electromagnetic coupling in particle-laden gas streams, the chemical kinetics of metal extraction, plasma-solid interactions, and chemical process design. The importance of the last issue should not be underestimated since an integrated set of unit operations will be necessary. We believe future assessments must continue to include: composition dependencies, temperature and flow requirements for feed and make-up streams, acceptable particle number densities and size distributions, separations in low gravity, and the overall process power requirements.

LOW-POWER TEMPERATURE-SWING ADSORPTION FOR MARS ATMOSPHERE ACQUISITION.

J. E. Finn, Astrobiology Technology Branch, NASA Ames Research Center, Mail Stop 239-15, Moffett Field CA 94035, USA (jfinn@mail.arc.nasa.gov)

The promise of ISRU-based mission architectures for Mars surface exploration will begin to be realized during the next decade as robotic spacecraft sent to Mars carry components and whole chemical plants for producing propellants from the planet's atmosphere These chemical plants will need to perform three primary operations: acquisition of atmospheric carbon dioxide, reactions to transform the gas into oxygen and possibly fuel, and storage of the products. This presentation focuses on development of technologies at NASA Ames Research Center for the first of these operations, carbon dioxide acquisition

The carbon dioxide acquisition component for a propellant production plant has several general, top-level requirements. It has a stringent requirement for minimal power consumption; a critical need for long-term reliability over the period of time the chemical plant must operate (say, 500 days); a production rate requirement for carbon dioxide; and a state point requirement (particularly pressure) for the CO_2 produced. The first two requirements help determine the best technological approach, while the latter two generally define the characteristics (e.g., size and power consumption) of the device. Mass and volume must be minimized, as usual.

Power consumption is likely to be a pivotal factor for selection of the acquisition technology. For illustration, consider a demand for CO_2 at 1 bar obtained from the atmosphere at 7 mbar. Isentropic compression requires about 380 kJ per kilogram of CO_2, or 18 W assuming six hours of production per day, i.e., while photovoltaic electricity is available. While this appears to be a relatively small power demand, mechanical single-stage vacuum pumps have low efficiencies, typically about 7% of isentropic for this 140:1 compression ratio. The energy demand is about 5400 kJ per kilogram CO_2. Ten kilograms of CO_2 per day (an amount that may be required in a near-term mission) produced in six hours would require roughly 2.5 kWe of high-quality electrical power, a high figure for a Mars lander. Furthermore, a number of serious engineering challenges must be overcome to allow such pumps to operate reliably for long periods of time under such stresses as frequent stops and starts, cold nights, large temperature cycles, and dust.

Temperature-swing adsorption is frequently mentioned as a possible candidate for compressing the dilute Martian atmosphere. Perhaps its most important characteristic is its ability to operate with little or no electrical power, as it instead can act as heat engine between the cold Martian night and the warmer day, or between a source of waste heat and the colder Martian environment. Other advantages include the absence of rapidly moving parts and the ease with which it can be scaled in size to a large range of potential applications. It avoids some of the problems associated with cold-trapping, such as the fouling of refrigerated heat-transfer surfaces and potential formation of dry ice in inconvenient locations. Furthermore, it can potentially separate the other constituents of the atmosphere (mostly N_2 and Ar) to form both a purified CO_2 product and a valuable inert gas byproduct.

By taking full advantage of the Mars diurnal temperature cycle, a simple compressor can be constructed that makes minimal use of electrical energy and avoids complicating accessory equipment such as active cooling loops that consume more power, add mass, and reduce reliability. We have proven the concept by building and operating simple adsorption compressors that operate on a Mars-like temperature cycle (see Figure 1).

The energy requirements of a temperature-swing adsorption compressor can be estimated through evaluation of the latent heat of desorption plus the sensible heat of the sorbent and the adsorbed CO_2 it carries. Reaching elevated pressures in the neighborhood of 1 bar requires a relatively high latent heat of desorption of CO_2; for some sorbents half of the required energy goes to supplying this latent heat. For the designs we are presently investigating, the total energy requirement is estimated at 2700 kJ per kilogram CO_2. Again, the important point here is that this energy need not be electrical: the Mars environment can provide most if not all of this heat, and downstream processors or passive solar energy can provide the rest. In applications where low-quality heat is not available, a relatively small amount of electrical energy may be used.

Our devices have been tested in an environmental chamber under simulated Mars atmospheric conditions of gas composition, pressure, and diurnal temperature cycle (Figure 2). We will present results and analyses of this ongoing experimental effort, and discuss some of the technological issues that will be important in building more advanced hardware.

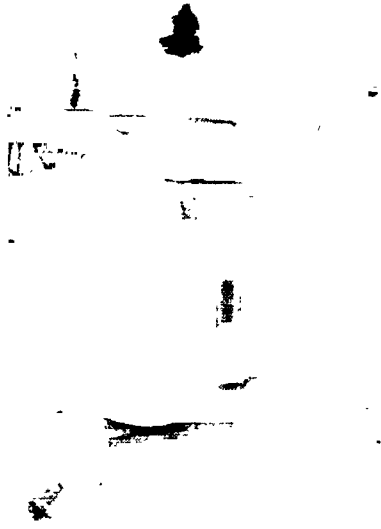Figure 1: An experimental adsorption compressor (supported by a bracket) is mounted on a bell jar's baseplate for testing under simulated Mars conditions of gas composition, temperature, and pressure
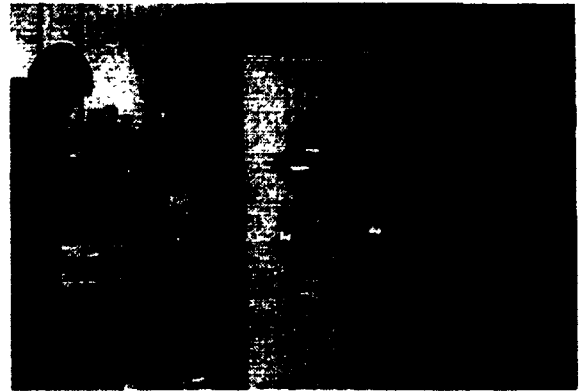

Figure 2: A refrigerated, temperature-programmed environmental simulation chamber is used in these experiments. Gas blending and pressure control is at the left; data acquisition and test control software is on the right.

TRADE STUDY OF FIVE IN-SITU PROPELLANT PRODUCTION SYSTEMS FOR A MARS SAMPLE RETURN MISSION.

S T. Green, D M. Deffenbaugh, M A Miller, Southwest Research Institute, 6220 Culebra Rd., San Antonio, Texas 78238, USA (sgreen@swri.org)

Introduction: One of the goals of NASA's HEDS enterprise is to establish a long-term human presence on Mars at a fraction of the cost of employing today's technology. The most direct method of reducing mission cost is to reduce the launch mass of the spacecraft. If the propellants for the return phase of the mission are produced on Mars, the total spacecraft mass could be reduced significantly. An interim goal is a Mars Sample Return (MSR) mission, which is proposed to demonstrate the feasibility of in-situ propellant production (ISPP) Five candidate ISPP systems for producing two fuels and oxygen from the Martian atmosphere are considered in this design trade-off study:

1) Zirconia cell with methanol synthesis,

2) Reverse water gas shift with water electrolysis and methanol synthesis,

3) Sabatier process for methane production with water electrolysis,

4) Sabatier process with water electrolysis and partial methane pyrolysis, and

5) Sabatier/RWGS combination with water electrolysis.

These systems have been the subject of numerous previous analytical studies and laboratory demonstrations. In this investigation, the systems are objectively compared on the basis of thermochemical performance models using a commonly used chemical plant analysis software package. The realistic effects of incomplete chemical conversion and gas phase separator performance are included in these models. This study focuses on the chemical processing and product separation subsystems. The CO_2 compression upstream of the chemical plane and the liquefaction/storage components are not included here.

For the purposes of this study, the return vehicle dry mass was assumed to be about 150 kg and the total ΔV required for returning to Earth is assumed to be 9 km/sec (launch plus Mars-Earth trajectory insertion). Fuel choices are limited to methane and methanol. For the methane option, 270 kg of fuel and 1000 kg of oxygen are required for the return trip. In a methanol engine, 660 kg of fuel and 930 kg of oxygen are needed. To provide a basis for the chemical process flow rates, it was stipulated that the ISPP plant would operate on Mars over a 500-day period while preparing for the Earth-return launch window.

Two of the chemical plants produce methanol and oxygen, and three plants produce methane and oxygen. An example of one of these systems is depicted in the simplified process flow diagram shown here. In all of the systems, CO_2 is taken from the Mars atmosphere by a sorption compressor and fed to the chemical plant. The CO_2 is combined with hydrogen, which is transported from Earth and chemically converted into a fuel and oxygen.

Analysis: The ISPP plants were analyzed with a commercial chemical plant software package, CHEMCAD™ (Chemstations. Inc., Houston, Texas). This approach provides a uniform methodology for computing the plant thermal and chemical performance so that the different ISPP options can be objectively compared on a power and mass basis. This package, like many others on the market, is intended for use in the petroleum refining and hydrocarbon processing industry. Some ISPP components (*e.g.*, water condensers) do not have exactly analogous CHEMCAD™ models, however, by combining two or more simpler models, these components are simulated.

The CHEMCAD™ software was used to compute the thermo-chemical performance and flow distribution for each ISPP system This detailed

RWGS w/ Methanol Reactor
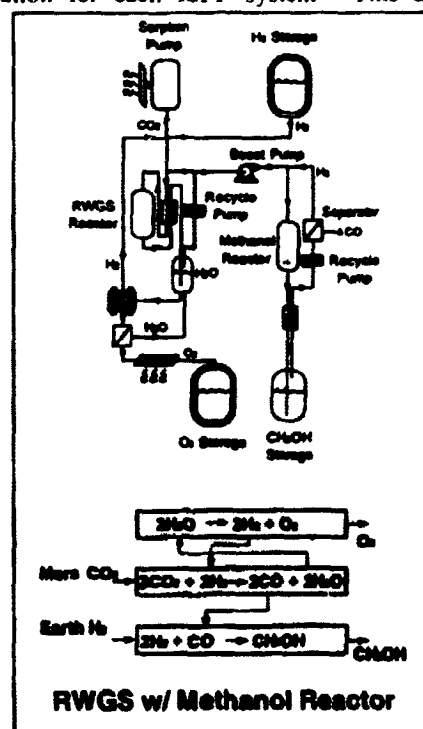
ISPP System Resource Requirements

	Zirconia Cell/ Methanol TRL=4	RWGS/ Methanol TRL=4	Simple Sabatier TRL=5	Sabatier/CH4 Pyrolysis TRl=5	Sabatier/ RWGS TRL=4
Electrical Power (watt)	1395	4100	1333	1617	2686
Cooling Load (watt)	359	3000	560	621	1603
Mass (kg)	42.31	75.53	20.55	30.09	40.02

analysis was used as a basis for estimating the electrical power requirements, heat rejection requirements, and mass of each system component. The results of the analysis and an assessment of the technology readiness level are summarized for each ISPP system in the above table.

The relative merits of the five ISPP systems were evaluated using a commercially available decision analysis package, DecideRight™. Essentially, a decision table is formed with alternative choices listed as rows of the table and the evaluation criteria as columns of the table. Evaluation criteria are sorted from left to right in order of importance (i.e., the factor considered to be most significant in meeting overall needs ends up in the leftmost position). Similarly, as choices are evaluated according to effectiveness in meeting the different criteria, the best choices migrate to the top of the list. When the process is complete, the best choice should emerge at the top of the list of alternatives.

The factors considered in this design trade study are system reliability, cost to produce flight hardware, system mass and volume, power consumption, production rate, ancillary equipment needs, fuel choice, and system scalability. System reliability, cost, mass, and power were all weighted

as high importance. Production rate was considered to be of medium importance since all the systems could easily meet the required production rates. The remaining criteria were given low importance.

Results: Within each evaluation category, each ISPP system is ranked according to the quantitative model results and current state of the system's development. The results of the decision analysis are presented in the table below. The Sabatier systems are more highly rated mainly because of their advanced development in military non-space applications. The low rating for the RWGS system was due primarily to the high power consumption in the main reactor as a result of its high reflux flow requirement

Decision Matrix Results for ISPP Systems

A CONTINUED FEASIBILITY STUDY OF WATER VAPOR EXTRACTION FROM THE ATMOSPHERE OF MARS.

M.R Grover, M.O Hilstad, M A Schneider, and A.P. Bruckner, Department of Aeronautics and Astronautics, University of Washington, Box 352400, Seattle WA 98195-2400, USA.

Key to a successful ongoing Mars exploration program is the identification of an indigenous source of water on Mars, both for propellant production, and in the long term, for support of human explorers. At the University of Washington, a process called WAVAR, or Water Vapor Adsorption Reactor, has been the focus of ongoing studies [1,2]. A relatively simple process, WAVAR extracts water vapor distributed in the Martian atmosphere by adsorbing it in zeolite 3A, a strongly hydrophilic crystalline alumino-silicate molecular sieve adsorbent commonly used in industrial dehumidifiers.

As shown in Fig. 1, WAVAR in its most basic form passes Martian atmosphere through a bed of zeolite 3A pellets. Once saturated, the bed is isolated and the adsorbed water is driven off by heating through microwave irradiation. The water is then condensed and collected for storage.
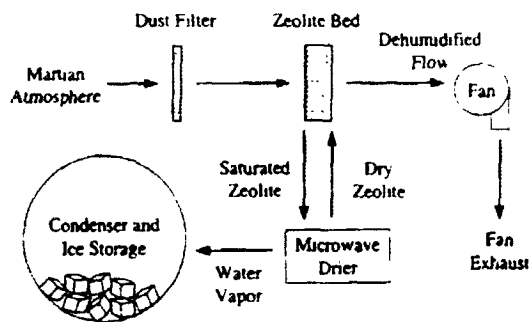

Fig. 1 The WAVAR process.

While a simple process, the challenge in engineering WAVAR lies in the volumetric processing requirements brought about by the very low water vapor content in the Martian atmosphere. The seasonal variation of local humidity at the two Viking Lander sites was found to be in the range of $\sim1.8\times10^{-7}$ – 2×10^{-6} kg/m^3 at VL-1 and $\sim4\times10^{-10}$ – 3×10^{-6} kg/m^3 at VL-2 [3]. The global average as measured by the Viking orbiters was found to be $\sim2\times10^{-6}$ kg/m^3 [4]. Assuming 100% extraction, the global average concentration requires the processing of $\sim5\times10^5$ m^3 of atmosphere to obtain 1 kg of water. Although certainly feasible, the engineering challenge lies in carrying out extraction while maintaining a power level that is a reasonable percentage of typical space mission power budgets, and at the same time minimizing the physical size of WAVAR.

In this study a WAVAR design is examined that uses an active technique for generating air flow. The

design requirements for the unit are based upon the restrictive design parameters of a robotic Mars mission powered by solar energy. Under such conditions it is assumed that the average power available for WAVAR operation is no more than 400 W during a ten-hour period of usable solar flux. The physical size of the unit is limited to that which fits on a Mars lander platform, having a footprint less than 2 m^2 and volume less than 1 m^3. To evaluate the performance of the design, this study simulates WAVAR operation under various Mars ambient conditions, both real and hypothetical.

Key to the WAVAR concept is the use of a molecular sieve adsorbent called zeolite, a strongly hydrophilic crystalline alumino-silicate commonly used in industrial dehumidifiers. For WAVAR, a zeolite must be chosen that adsorbs water molecules but not other species in the Martian atmosphere. The major constituent of the Martian atmosphere is CO_2 (95% by volume) and is the primary species to be excluded. The only zeolite that can exclude CO_2 is the K type (type 3A), which is a zeolite with most of the naturally occurring smaller sodium cations replaced by larger potassium cations. This reduces its average pore size to 3 Å which excludes the 3.3 Å size of CO_2 but accepts the 2.65 Å size of water [5].

An important parameter of zeolite 3A is its capacity for water, defined as the mass of water adsorbed per unit mass of dry zeolite. As can be seen in Fig. 2, the capacity of zeolite 3A varies strongly with both the ambient vapor pressure of water and the temperature. These data were obtained from a chart published by W.R. Grace Davison Molecular Sieves [6], having isotherms down to 253 K. The isotherms down to 170 K, represented by dashed lines, were obtained by logarithmically extrapolating the available data. These isotherms are important indicators of zeolite performance in Martian ambient conditions.

The specific WAVAR design used in this study is based upon the geometry of a previous WAVAR design [2]. The adsorption bed parameters in this study, critical in determining WAVAR performance, are as follows: bed area = 0.8 m^2, bed thickness = 0.006 m, bed mass = 2.9 kg, filter area = 0.8 m^2.

In previous WAVAR studies as well as in this study, simulations were carried out using Mars ambient conditions at the Viking Lander I & II sites, the Martian North Pole, and at a hypothetical site termed New Houston, which has the global average water vapor concentration.
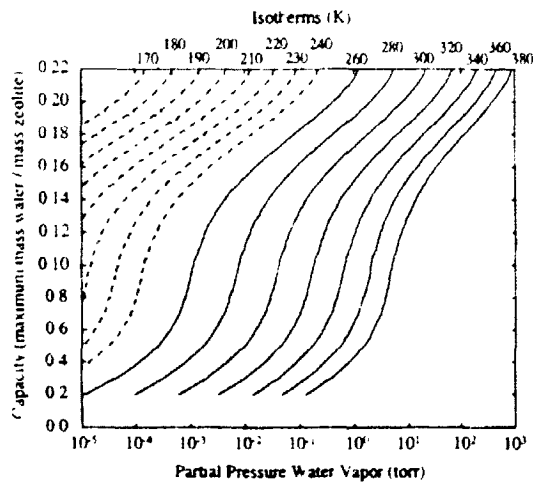
Fig. 2   Isotherms for capacity as a function of water partial pressure. The curves are from W.R. Grace Davison Molecular Sieves [6]. Dashed curves represent logarithmic extrapolations.

bed was also reduced from 3 mm to 2 mm to ensure adequate interception of flow by the zeolite.

Preliminary results indicate that the thinner bed will make possible better yield while reducing the power requirements Initial results show a 40% increase in water collected while reducing the power requirement by at least 10%, compared to the equivalent area thicker bed.

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Fig. 3   Seasonal variation of vapor concentration as used in the simulations. Solid lines are actual data, dashed lines are estimated.

The seasonal water vapor concentration variations at these sites can be seen in Fig 3. In addition to seasonal variations, during a typical Martian sol the temperature varies significantly and thus so does the water capacity of the zeolite. This variation, combined with daily cycles in available solar energy, dictate the adsorption/desorption cycling of the WAVAR.

Previous studies assumed a 4 cm bed thickness. The current study used a bed thickness of 6 mm which analysis indicates will provide adequate adsorption performance. Reducing the thickness of the zeolite bed gives significant benefits to the pressure drop across the bed and therefore the power required of the fan. In changing the bed thickness, zeolite pellet size within the

DEVELOPMENT UNIT CONFIGURATION AND CURRENT STATUS OF THE MIP/MTERC

EXPERIMENT. K J Juanero and K R Johnson, California Institute of Technology, Jet Propulsion Laboratory, 4800 Oak Grove Drive. Pasadena CA 91109. USA (kenneth.j.juanero@jpl.nasa.gov, kenneth.r.johnson@jpl.nasa.gov)

Abstract: The Mars In-Situ Propellant Production (ISPP) Precursor (MIP) experiment package is planned for inclusion on the Mars 2001 Lander. This experiment package consists of five experiments whose purpose is to demonstrate the performance of various ISPP processes in-situ on Mars. The demonstrated ability to produce propellant for Mars Return Vehicles (MRV) is considered to be a necessary precursor to any future manned mission to Mars. The Mars Thermal Environment/Radiator Characterization (MTFRC) experiment is part of the MIP package and is intended to determine the Mars night sky temperature as well as to characterize the performance degradation of radiators caused by environmental exposure on Mars over time. Radiators are needed as part of the ISPP process to remove heat from the Mars Atmosphere Acquisition and Compression (MAAC) CO_2 sorption compressor. MTERC will provide the data needed to optimize the design of radiators for ISPP and other processes.

A MTERC Development Unit (DU) has been fabricated and tested at JPL. The MTERC DU consists of 1) a radiator subassembly, 2) a motor/cover subassembly, 3) a differential temperature control circuit and motor control electronics circuit board, and 4) a command and data handling electronics circuit board. This paper will describe the operational theory and the configuration of the MTERC DU and will discuss the current status of the MTERC experiment development including some selected results of performance testing that has been completed prior to the ISRU III meeting.

MARS IN-SITU PROPELLANT PRODUCTION PRECURSOR (MIP) FLIGHT DEMONSTRATION PROJECT: OVERVIEW.

D. I. Kaplan[1], J. E. Ratliff[1], R. S. Baird[1], G. B. Sanders[1], K. R. Johnson[2], P. B. Karlmann[2], K. J. Juanero[2], C. R. Baraona[3], G. A. Landis[3], P. P. Jenkins[3], and D. A. Scheiman[3]. [1]NASA Johnson Space Center, Houston, Texas, 77058; [2]Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena, California 91109, [3]NASA Lewis Research Center, 21000 Brookpark Road, Cleveland, Ohio 441.

Introduction: Strategic planning for human missions of exploration to Mars has conclusively identified in-situ propellant production (ISPP) as an enabling technology [1]. A team of scientists and engineers from NASA's Johnson Space Center, Jet Propulsion Laboratory, and Lewis Research Center is preparing the MARS ISPP PRECURSOR (MIP) Flight Demonstration The objectives of MIP are to characterize the performance of processes and hardware which are important to ISPP concepts and to demonstrate how these processes and hardware interact with the Mars environment. Operating this hardware in the actual Mars environment is extremely important due to both uncertainties in our knowledge of the Mars environment as well as because of conditions that cannot be adequately simulated on Earth.

The MIP Flight Demonstration is a payload onboard the MARS SURVEYOR Lander and will be launched in April 2001. MIP will be the first hardware to utilize the indigenous resources of a planet or moon. Its successful operation will pave the way for future robotic and human missions to rely on propellants produced using Martian resources as feedstock.

MIP Overview and Objectives: MIP is comprised of five distinct experiments; their names and key objectives are:

- Mars Atmospheric Acquisition and Compression (MAAC): to selectively absorb and compress carbon dioxide from the Martian atmosphere;
- Oxygen Generator Subsystem (OGS): to produce propellant-grade, pure oxygen;
- Mars Array Technology Experiment (MATE): to measure the spectrum at the Mars surface and to test several advanced photovoltaic solar cells;
- Dust Accumulation and Repulsion Test (DART): to investigate the properties of dust and to test techniques to mitigate the settling of airborne dust onto solar arrays; and
- Mars Thermal Environment & Radiator Characterization (MTERC): to measure the night sky temperature and to demonstrate the performance of radiators.

The MIP package will be small and light weight. Its overall external envelope is approximately 40 x 24 x 25 cm (15.7 x 9.4 x 9.8 inches), and its mass is 8.5 kg (18.7 lbm).

The long-term effects of operating in the Martian environment is key information being sought by MIP. There-fore, MIP would like to operate for a lifetime of 90 sols or more on Mars.
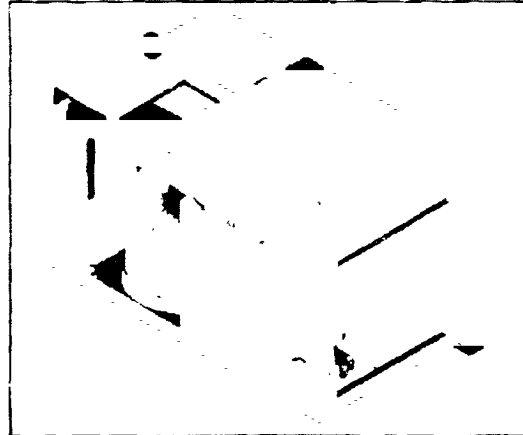
Mars ISPP Precursor (MIP) Flight Demonstration

Mars Atmospheric Acquisition and Compression (MAAC): The most readily available resource on Mars is the atmosphere. Hence, carbon dioxide, which makes up more than 95% of the atmosphere, is the primary resource being considered for ISPP missions. However, the Mars atmospheric pressure is only 6 to 10 torr (0.1 to .15 psi), while most ISPP processes operate at approximately 760 to 3800 torr (1 to 5 atm.). Therefore, a CO_2 collection and compression device is required that is relatively small, light-weight, power efficient, tolerant to dust contamination, rugged and reliable enough to operate for long periods under the severe daily and seasonal temperature variations.

The primary objective of the MAAC experiment is to demonstrate and characterize the performance of a sorption compressor. A sorption compressor contains virtually no moving parts and achieves its compression by alternately cooling and heating a sorbent bed comprised of materials which absorb low pressure gas at low temperatures and desorb high pressure gas at higher temperatures. The characteristics of the material in the sorption pump define how much gas can be absorbed and which species are more readily absorbed over others. Due to the lack of rotating/moving parts, it has significant potential for high lifetime, reliability, and robustness.

MAAC acquires CO_2 during the cold Mars night when temperatures are typically 200°K. To facilitate cooling, the sorbent bed is attached to a horizontal radiator facing the night sky. Once an adequate amount of CO_2 has been

absorbed (~12.5 g), the sorbent bed is heated and pressure in the sorption pump rises until 815 torr of pressure is reached. At this point, CO_2 can now be feed to the OGS experiment.

Oxygen Generator Subsystem (OGS): The ultimate objective of any ISPP demonstration is the production of oxygen and/or fuel from in-situ resources. The primary objectives of the OGS experiment are to demonstrate the production of oxygen from Martian atmospheric carbon dioxide (CO_2) as well as to investigate the basic performance of zirconia solid-oxide oxygen generator hardware in the Mars environment. The zirconia solid-oxide oxygen generator produces oxygen by electrolyzing CO_2 at elevated temperatures (750°C) to strip off an oxygen ion from the molecule. Once the oxygen ion has been removed from the CO_2 molecule, the zirconia material acts as an oxygen pump and separator by allowing only the oxygen to pass through it's crystal lattice when a voltage is applied across the zirconia material. The OGS is sized to produce 0.5 standard cubic centimeters of O_2 per minu (sccm) while operating. We desire to run the OGS about ten times on the Martian surface

Mars Array Technology Experiment (MATE): Until Mars PATHFINDER landed in July 1997, no solar array had ever been used on the surface of Mars. PATHFINDER was designed for a relatively short duration mission compared to a 500 sol surface stay for a Mars sample return mission that would incorporate ISPP. Since making propellants and storing them cryogenically requires significant power, power generation over a long period of time is critical for mission success.

MATE will incorporate five different individual solar cell types, two different solar cell strings, and temperature sensors to characterize promising solar cell materials and designs. MATE will also incorporate two radiometers and a dual spectrometer. The dual spectrometer will measure the global solar spectrum from 300 to 1700 nm by incorporating two separate photodiode arrays each with its own fiber optic feed and grating. Besides measuring the solar spectra on Mars, the dual spectrometer will also identify dust absorption and reflection bands, quantify daily variations in spectra and intensity, and improve atmospheric modeling.

Dust Accumulation and Repulsion Test (DART): Measurements from the PATHFINDER mission showed a dust deposition rate of 0.3% per day during a relatively clear (no dust storms) season. This accumulation could be catastrophic for a 500 sol lifetime mission.

DART will utilize a microscope, a dust accumulation monitor, and a sun position sensor package. The microscope will measure the amount and the properties of set-

tled dust, and determine the rate of dust deposition, the particle size distribution, the particle opacity, the particle shapes, and possibly information about the particle composition through measurements of the optical properties.

DART will also incorporate tilted solar cells and an electrostatic dust repulsion device. Instead of attempting to remove settled dust, the DART experiment will use high-voltage to attempt to repel the dust before it settles

Mars Thermal Environment & Radiator Characterization (MTERC): Thermal management is critical for efficient operation of an ISPP plant. Heat removal radiators will be required for such operations as cooling down a sorption pump sorbent bed, and cooling oxygen and fuel before liquefaction and storage.

The MTERC experiment will include four radiator plates: two with high emissivity and two with low emissivity. One high and one low emissivity plate will be protected by a movable cover and will serve as the experiment control radiators. These control radiators will experience the least degraded measurement of the effective Mars night sky temperature and will serve as comparisons for the two continuously exposed radiators in order to examine the impact of dust accumulation, wind abrasion, etc. on long-term radiator performance.

Conclusion: The successful performance of the five individual demonstrations of MIP will provide both knowledge of and confidence in the reliability of this technology. At the completion of this flight demonstration, the MIP Team will be able to:

• recommend preferred hardware configurations for the intake and adsorption of carbon dioxide from the Martian atmosphere;
• understand the performance characteristics of zirconia cells to generate propellant-grade oxygen;
• understand long-term performance degradation characteristics of advanced solar array and radiator concepts operated in the actual Mars environment;
• evaluate the functionality of electrostatically repelling airborne dust from landing on a solar array; and
• recommend preferred hardware designs for innovative thermal management including the radiation of heat to the outside environment.

References:
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DEVELOPMENT UNIT CONFIGURATION AND CURRENT STATUS OF THE MIP/MAAC

EXPERIMENT. P. B. K Imann, K. R. Johnson, D Rapp, and [1] J Wu, California Institute of Technology, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 9110*), USA (paul b karlmann@jpl.nasa.gov, kenneth.r.johnson@jpl.nasa.gov).

Abstract: The Mars In-Situ Propellant Production (ISPP) Precursor (MIP) experiment package is planned for inclusion on the Mars 2001 Lander. This experiment package consists of five experiments whose purpose is to demonstrate the performance of various ISPP processes in-situ on Mars. The demonstrated ability to produce propellant for Mars Return Vehicles (MRV) is considered to be a necessary precursor to any future manned mission to Mars. The Mars Atmosphere Acquisition and Compression (MAAC) experiment is part of the MIP package and is intended to demonstrate that, by using a sorption compressor, CO_2 can be preferentially adsorbed at about 6 torr from the Mars atmosphere during the night when the bed is cold then subsequently compressed to about 800 torr by heating the bed and desorbing CO_2 during the day. The compressed CO_2 produced by MAAC is to be fed to the Oxygen Generator Subsystem (OGS) where pure oxygen is to be produced. Pure oxygen is considered to be one of the primary constituents of a future manned MRV propellant system.

A MAAC Development Unit (DU) has been fabricated and tested at JPL. The MAAC DU consists of 1) a sorption bed filled with a CO_2 selective sorbent material, 2) a purge system to be used to periodicly backflush non-CO_2 gases from the sorbent bed during adsorption, 3) a JPL-developed gas-gap heat switch that allows heat transfer to a radiator for heat removal from the bed during the night time adsorption period and that impedes heat transfer during the day time desorption period, 4) a radiator to radiate heat to the night sky during the adsorption period, 5) a set of three isolation valves and connecting tubing, 6) two pressure transducers and several thermocouples for monitoring the MAAC operating conditions, and command and data handling electronics. This paper will describe the operational theory and the configuration of the MAAC DU and will discuss the current status of the MAAC experiment development including some selected results of performance testing that has been completed prior to the ISRU III meeting.

LUNAR IN-SITU PROPELLANT PRODUCTION (ISPP) TECHNOLOGY RESEARCH Christopher A. Kuhl, James E. Johnson. Southwest Research Institute.

Future long duration missions for robotic and human exploration of the solar system will require systems that can utilize in-situ materials during the mission in place of bringing consumable resources from Earth. Oxygen, used as a propellant and required for human habitat, is found abundantly in lunar soil in the form of oxides. Considerable gains in mission performance are possible by utilizing lunar oxygen, alleviating the need for spacecraft to transport it and reducing the mass fraction of the vehicle system at lift-off. Four in-situ lunar oxygen extraction and production methods are addressed to help significantly reduce the mass fraction attributed to the transportation of oxygen during a mission. Production methods addressed are Hydrogen Reduction of Illmenite, Carbothermal Reduction with Methane, Sulfuric Acid Reduction, and Molten Silicate Electrolysis.

Near term needs for manned missions to the lunar surface will require oxygen production rates in the range of 10 to 30 mt/yr (metric tons per year). To provide a means for mission planning in terms of required mass and volume for a particular production plant, a software package entitled Lunar Oxygen Plant Sizing (LOPS) was developed to support plant scaling analysis. This software has been used to show comparative sizing needs for lunar oxygen plants over a production range of 2 to 100 mt/yr. Computed results compare favorably with values found in the literature, in terms of specific energy and mass for given types of lunar oxygen plants. Conclusions from the computations show Hydrogen Reduction of Ilmenite being the most massive and having the largest energy requirement, and Sulfuric Acid Reduction the least in both aspects. For all processes, the photovoltaic power plant comprises over 78% of the total mass of the processing plant, and the liquefaction subsystem contributes negligibly to the overall mass and energy requirements of a production plant.

The Hydrogen Reduction process requires a great deal more energy and mass than others, but the process is at a higher level of development or TRL. A determination of which process would be best suited among the other three processes considered will rely heavily on the technological feasibility rather than small differences in mass and energy. The results of these comparisons can aid in identifying areas of each process that need further research involvement, to ultimately determine if the use of a specific process is attainable. Taken on the whole, Hydrogen Reduction appears to be the most developed process, but it is massive and needs

considerable energy. Alternatively, Sulfuric Acid Reduction presents some challenges to bring it to a viable lunar process, but it is potentially the lowest power and mass option.

The Technology Readiness Level for the Hydrogen Reduction and Sulfuric Acid Reduction methods has been assessed at level four mainly because these systems as a whole or all of the major components will perform in a laboratory environment. In the case of Hydrogen Reduction, critical elements of the process have been verified by laboratory tests using lunar regolith simulant. Also, low gravity flight tests in NASA's KC-135 show that the basic fluidization process needed for proper operation of the fluidized-bed reactor will occur. The Sulfuric Acid process is based on modifications of one of the oldest and most successful processes used by industry to produce white paint pigment. While this process has not been tested in low gravity conditions, it is well known that pumping of slurries and liquids used in the process will work in low gravity environments.

The Technology Readiness Level for Molten Silicate (Magma) Electrolysis and Carbothermal Reduction with Methane has been assessed at level three mainly due to the lack of complete validation of the processes in a laboratory environment. In the case of Magma Electrolysis, only limited experimental work in small crucibles is reported in the literature. Carbothermal Reduction, as applied to lunar applications, has had parts of the process demonstrated, but questions still remain on how to recycle carbon in an effective manner.

By comparing the Hydrogen Reduction method with the Sulfuric Acid Reduction Method, differences in potential payoff and challenges in plant setup, or risk, become apparent. Both processes provide about the same oxygen yield, but the potential gain by using Sulfuric Acid Reduction comes in the form of considerably lower plant mass and energy requirements. Attaining high payoff of the Sulfuric Acid process must be traded off with the perceived lower risk in setting up a Hydrogen Reduction plant. This lower risk comes about because certain elements of the Hydrogen Reduction process have been tested in low gravity environments. However, there appears to be no convincing arguments to preclude the Sulfuric Acid process from working in the lunar environment. In addition, Sulfuric Acid Reduction operates at a pressure of 1 atmosphere whereas the Hydrogen Reduction Process typically operates at a pressure of 10 atmospheres. This further amplifies the

attractiveness of the Sulfuric Acid Process
Theretore. high payoffs (lower mass, less energy,
smaller volume, and no feedstock benefication)
appear reasonable with further developments ot the
Sulfuric Acid process.

Processes like Hydrogen Reduction,
Carbothermal Reduction, and Magma Electrolysis
must maintain their heat once started or go into a "hot
standby" or idle mode when production is stopped.
A fluidized-bed reactor, for example, generally
contains firebrick, and if thermally cycled, the
firebrick will crack and the reactor will eventually
fail. In the case of Magma Electrolysis, the magma
can solidify in places where damage can be done to
the process equipment. These issues magnify the
concerns regarding reliability and soundness of
process controls for these processes

The use of photovoltaics coupl. with
regenerative fuel cells as a means of generating
power, especially for continuous daylight and night
cycles, comes with significant weight penalty. The
mass of a photovoltaic power system for any of the
plant options producing 20 mt/yr of oxygen will be
about 80% of the total mass of the plant. This
implies using a process during daylight hours only
and save the weight of the regenerative fuel cells or
look for other sources of energy, perhaps nuclear
power. If only daylight operation is used, the
processes must be able to startup and shutdown
easily.

Summaries of the processes in terms of
mass, energy, and volume for 20 mt/yr plants are
provided below.

Process	Mass [kg]	Energy [kW]	Vol [m³]
Hydrogen Reduction	93332	109	184
Magma Electrolysis	46365	59	89
Carbothermal Reduction	55482	70	92
Sulfuric Acid Reduction	44474	55	86

Important observations and conclusions with
regard to the distribution of mass and energy
requirement within the subsystems of the four
processes are as follows:

•Energy requirements for mining and
benefication range from one-third to two-thirds of
the total energy required for the processing options
studied. Hydrogen Reduction requires two-thirds of
its energy for resource processing whereas the
Carbothermal method requires one-third of its energy
for resource processing. For all processes studied, the
mass of the mining and benefication subsystems
contributed a mass fraction of 8% to 19% of the total
mass of a production plant. Clearly, the resource
subsystem requirements for the Hydrogen Reduction
process greatly penalize this option to the point that it
may be excluded as a viable near term processing
option for lunar oxygen.

•In terms of energy required for chemical
processing, the Carbothermal method requires nearly
two-thirds of its energy for the chemical process due
to the requirement to operate at 1625°C whereas the
Hydrogen Reduction method requires slightly less
than one-third of its total energy for the chemical
process. Sulfuric Acid and Carbothermal require 52%
and 65%, respectively of its total energy for chemical
processing although in terms of total kilowatts, the
Sulfuric Acid proces is clearly the lowest.

•For all processes studied, the energy and
mass requirements for the liquefaction and storage
plant were a small fraction of the total ranging in the
2% to 5% region. This implies that not much would
be gained in reducing total energy and mass of the
processing options by reducing mass and energy
demands of the liquefaction plant and associated
storage.

As a final conclusion, the software
developed in the present work appears to provide
valid results. The computed results in terms of plant
specific energy versus plant specific mass covering a
wide range of oxygen production rates agree well
with values reported in the literature. This was true
even when it was necessary to account for the
differences in nuclear power options versus
photovoltaic power options. This indicates that the
scaling process used in the software is providing
good estimates of mass and energy for the four
processing options.

LOW-COST, HIGH-PERFORMANCE CRYOCOOLERS FOR *IN-SITU* PROPRELLANT PRODUCTION.

J. L. Martin[1], J.A. Corey[2], and T.A. Peters[3], [1]Mesoscopic Devices, LLC. 350 Hills St Suite 106, Richland, WA 99352 (jmartin@mesoscopic.com) [2]CFIC, Inc. 302 Tenth St. Troy, NY 12180, (jcorey@mindspring.com), [3]NASA Johnson Space Center, mail code EP4, 2101 NASA Road One, Houston, TX 77058 (todd.peters@jsc.nasa.gov).

Introduction: A key feature of many In-Situ Resource Utilization (ISRU) schemes is the production of rocket fuel and oxidizer from the Martian atmosphere. Many of the fuels under consideration will require cryogenic cooling for efficient long-term storage. Although significant research has been focused on the techniques for producing the fuels from Martian resources, little effort has been expended on the development of cryocoolers to efficiently liquefy these fuels. This paper describes the design of a pulse tube liquefier optimized for liquefying oxygen produced by an In-Situ Propellant Production (ISPP) plant on Mars.

Requirements for ISPP cryocoolers: A recent NASA paper outlined the requirements for cryocoolers to support an ISPP plant.[1] Cryocoolers are required in several of the mission phases. If hydrogen is transported from earth, cryocoolers will likely be required to minimize boiloff during the trip to Mars. All ISPP concepts require cryocoolers to liquefy the oxygen If methane is used as a fuel, the cryocooler must also liquefy the methane stream. Cryocoolers are also required to minimize boiloff from the tanks while they are being filled.

Depending on the mission of interest, the required cooling loads range from 2.4 to nearly 20 W at 90 K for robotic missions, and up to 100 W for manned missions. Of the various cryocoolers required by the ISPP missions, the most challenging case appears to be the liquefier for the oxygen and methane. Based on current projections for the 2007 mission, this liquefier will be required to liquefy 0.1 kg/hr of oxygen (at 90K) and 0.025 kg/hr of methane (at 112K). The total cooling load for this case is approximately 18 W. The liquefier will be required to operate for up to 500 days, on ~8 hrs/day, and off ~16 hrs/day.

A pulse tube oxygen liquefier: As part of our NASA Phase I Small Business Innovation Research (SBIR) program, we developed a design for a pulse tube oxygen liquefier sized to the ISPP application. Pulse tube cryocoolers appear to be a good choice for the ISPP liquefiers. Pulse tube cryocoolers can operate very efficiently at the temperatures and power levels of interest, and can be made to operate reliably for long periods without maintenance.

Our cryocooler design is illustrated in figure 1. The liquefier consists of three subsystems: a compressor, a coldhead, and a condenser.
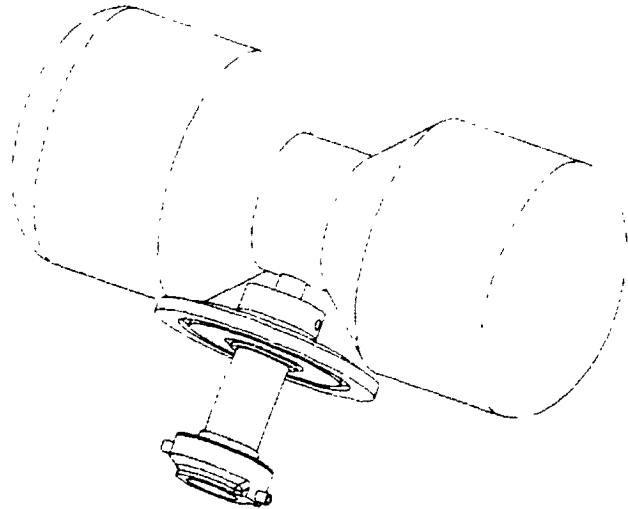
Fig. 1. Pulse tube oxygen liquefier

The compressor. The compressor is a linear resonant compressor. The linear design eliminates the need for rotary-to-linear conversion, leading to a more compact and efficient compressor. The compressor piston is supported by thin metal flexures, which provide high radial and low axial stiffness. The high radial stiffness allows the piston to be accurately centered in the cylinder, maintaining a small gap that eliminates the need for piston rings. The resulting compressor has no rubbing or sliding parts and is lubricated only by the helium working gas. While such designs have been used before in Stirling cycle cryocoolers, our design has a number of unique features that allow it to obtain a unique combination of high efficiency, low weight and low cost.

Our cryocooler uses a STAR moving magnet linear motor. Developed by CFIC, the STAR motor utilizes cost-effective block magnets and a single-air-gap design that minimizes the mass and cost of the moving magnets. STAR motors have been used in compressors ranging from 300 to 15,000 W of power input. In this work, we extended these designs to 100 W. Using two compressors operating nose-to-nose on a common compression space yields a balanced 200 W compressor.

The coldhead. Pulse tube cryocoolers have a significant advantage over Stirling cycle coolers in that they have no moving parts in the cold head. Our base-

line design utilizes a compact coaxial design where the regenerator is arranged as an annulus around the pulse tube. This simplifies the heat rejection from the warm end of the pulse tube and integration with the storage tank.

The condenser. Liquefiers are distinguished from cryocoolers in that they must use a condenser to condense a superheated vapor. To minimize the system mass, a compact condenser is required that can efficiently condense the oxygen stream In this project, we developed and tested a compact condenser that appears to have a number advantages, including reduced sensitivity to gravity, low pressure drop and high heat transfer coefficient. Based on our preliminary performance measurements, we expect that this condenser will operate at less than 150 Pa pressure drop and less than 0.5 K wall subcooling at heat fluxes as high as 3 W/cm^2.

Predicted system performance: We used Los Alamos' DELTAE thermoacoustic modeling code to design the coldhead. Based on these results and our experience with similar machines designed for the terrestrial telecommunications market [2], we predict that our cooler will produce 20 W of cooling at 90 K with 175 W input power to the inverter while rejecting to a heat sink at 245 K. The mass of the liquefier (exclusive of electronics) is predicted to be 8.3 kg. The compressor is approximately 150 mm in diameter and 350 mm long. We expect to produce the first prototype of the cryocooler in 1999.

References: [1] Kittel, P., Salerno, L.J., Plachta. D.W., Cryocoolers 10, 1998. [2] Martin, J.L., Corey, J.A., Martin, C.M., Cryocoolers 10, 1998.

ROBOT IDENTIFICATION AND EXTRACTION OF NATURAL GLASS.

S. E. Moskowitz, The Hebrew University of Jerusalem, P. O. Box 7843, Jerusalem 91078, Israel (mosk@cc.huji.ac.il)

Introduction: The quality of natural glass is established by temperature and chemical composition of the original melt, rate of cooling, presence of wa- ter and other volatiles, and crystallization kinetics. Glass preservation over millions of years depends on whether the processes of chemical decomposition and devitrification remain secondary. As a resource material, natural glass can be utilized in the construction of extraterrestrial outposts [1]. Possible landing sites containing natural glasses can be identified by means of a global surveyor spacecraft equipped with high resolution imaging sensors.

Landing Sites: Fulgurites are glasses resulting from lightning strikes. Fusion followed by super- cooling freezes the melt within long and bifurcating tubular structures [2].

Another type of glass is created during meteoritic impact. Below a certain level of impact, the shock wave crushes minerals such as quartz and plagioclase feldspar into low porosity diaplectic glass and maskelynite [2]. Higher levels, >60 GPa, produce flow and entrapped heat. In the wake of the passing shock wave, silica polymorphs convert to normal glasses. Vesiculation occurs while releasing volatiles.

Volcanic glasses are formed by rapid cooling of lava and fusion of ash. At the lower end of the silica scale, < 45% SiO_2, basaltic magmas have low viscos- ity and the resulting tachylites are heavily crystallized. Particles of ash are fibrous and oblong in shape. At the upper end, >70% SiO_2, the viscous rhyolitic lava yields thick layers of obsidian. Rock fragments and shards of solidified vitric foam comprise the tuff. Lunar formations appear as homogeneous spherules. Volcanic natural glasses are located on the surfaces of lava flows or along selvages of dikes.

Tektites are marked by strain birefringence and organized schlieren bands. They possess siliceous glass inclusions, but lack microlites. There is a linear relationship between bulk specific gravity and bulk index of refraction. The index varies inversely with silica content and directly with ferrous oxide, an indicator of magnetic susceptibility [3]. Pure glass is an amorphous aggregate; hence, it lacks crystalline structure. Specific gravity and magnetic susceptibility as well as index of refraction can be measured by a teleoperated robot.

Prospecting: For the purpose of verifying the ex- istence of natural glass, the robot will drill boreholes into rock formations at the landing site. Within these cavities, the teleoperated machine will emplace instrument packages containing sensors, electronics for sensor control, power delivery and output signal processing, and a data link to the human operator. The suite of sensors may include a magnetometer to detect magnetic forces, a gravimeter to discern dif- ferences in density, and an ellipsometer to determine index of refraction [4].

Index of Refraction: Ellipsometry is an experi- mental procedure to evaluate optical properties of a material by observing the polarization of reflected light. Interacting with in situ material, the electromag- netic radiation is reflected, refracted, dispersed, and absorbed.

Two parameters are measured b an ellipsometer. The remaining parameter is calculated from a con- straint which relates rectangular coordinates of a point on the unit sphere. Alternatively, two ellipsometric angles can be monitored. One set of observations, whether parameters or angles, can be uniquely deter- mined from the other.

Ellipsometric angles give the complex ratio of Fresnel reflection coefficients for light polarized paral- lel and perpendicular to the plane of incidence.

The complex dielectric constant can be found from an expression involving the angle of incidence and the three ellipsometric parameters. A nonlinear opera- tion on the complex dielectric constant defines the real val- ued indices of refraction and attenuation. As a complex conjugate, these indices form a complex index of re- fraction. The attenuation index at the wavelength of light employed in the experiment char- acterizes ab- sorption per unit length of path propagat- ing in the material.

Regarding measurement sensitivity, instru- ment re- quirements are more stringent for a distinction between types of glass than for a differentiation be- tween glass and nonvitreous substances.

Mining: Rock drilling and detonating, loading and transporting glass bearing materials to the lander craft, and deploying of waste are key activities of the mining operation. In opencut, the height of bank that can be safely built is determined by the thickness and physical

properties of the deposit, size of bucket used by the robot, and climatic conditions.

Rock fragmentation will be accomplished in four steps. First, holes are electrically drilled at assigned locations. These openings are then enlarged. Second, main charge and detonator are placed in each hole. Third, the explosive is compacted and holes filled with loose regolith material. Fourth, the charge is au- tomatically detonated. Although compressive failure can occur, fragmentation most often results when the rocks are sub-

jected to tensile waves reflected from a free surface. Effectiveness of fragmentation also depends on the geometric arrangement of holes and the delayed sequence of firings controlled by caps

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CRYOGENIC PROPELLANT PRODUCTION, LIQUEFACTION, AND STORAGE FOR A PRECURSOR TO A HUMAN MARS MISSION.

P. J. Mueller[1] and T. C. Durrant[2]. [1]Space Dynamics Laboratory/Utah State University, 1695 North Research Park Way, North Logan, UT 84341-1947. e-mail: paul.mueller@sdl.usu.edu. [2]Lockheed Martin Space Mission Systems & Services, 2400 NASA Road 1, P. O. Box 58561, Houston, TX 77258-8561, e-mail: tom.durrant@lmco com.

The current mission plan for the first human mission to Mars is based on an in-situ resource utilization (ISRU) approach to reduce the amount of propellants needed to be taken to Mars and ultimately to reduce mission cost. The current Mars Robotic Exploration Program does not include ISRU on the early sample return missions. A need exists to demonstrate ISRU technologies on one or more robotic missions prior to the first human mission.

This presentation outlines a concept for an ISRU-based precursor mission as a technology demonstration prior to the first human mission. It will also return Martian soil samples to Earth for analysis. The mission will primarily demonstrate cryogenic oxygen and fuel production, liquefaction, and storage for use as propellants for the return trip. The fuel will be hydrocarbon: either methane, methanol, or ethylene. Hydrogen feedstock will be brought from Earth.

The analysis used to develop the mission concept includes several different thermal control and liquefaction options for the cryogens. Active cooling and liquefaction devices include Stirling, pulse tube, and Brayton-cycle cryocoolers. Insulation options include multilayer insulation, evacuated microspheres, aerogel blankets, and foam insulation. The cooling and insulation are traded off against each other for a minimum-mass system. In the case of hydrogen feedstock, the amount of hydrogen boiloff allowed during the trip to Mars is also included in the tradeoff. Passive cooling using external radiators is also considered for reducing the heat leak to the hydrogen during cruise.

The spacecraft concept includes a Lander (including the propellant production plant) with a Mars Ascent Vehicle (MAV) mounted atop it. An option is explored where the engines on the MAV are also used for descent and landing on the Martian surface. So the propellant tanks would contain descent propellant during the trip from Earth. This propellant would be consumed in descent to the Martian surface, resulting in the nearly-empty MAV tanks to be filled by the ISRU plant.

The presentation includes conceptual layout drawings of the proposed Lander/MAV combination, including propellant tanks and ISRU components. Mass estimates of the various components are also included.

RF-ICP DISCHARGE FOR A HYBRID OXYGEN PRODUCTION SYSTEM.

S. Popovic, R. Ash, T. Dinh, and L. Vuskovic. Old Dominion University, Norfolk VA 23529, USA.

The purpose of this presentation is to demonstrate feasibility of a radio-frequency inductively-coupled discharge (RF-ICP) to be integrated into a hybrid system from two complementary, already demonstrated, technologies for the efficient production of oxygen from Martian atmosphere. The two technologies involved are (a) radio-frequency discharge method for dissociation of carbon dioxide. and (b) oxygen separation using a ceramic honeycomb technology. This approach will ensure the optimal utilization of the advantages of the both subsystems, the RF-ICP reactor and ceramic honeycomb separator.

Radio frequency discharge proved efficient in oxygen production by dissociating carbon dioxide [1]. Currently used oxygen separation through silver membrane-electrode is still under development. The honeycomb technology proved efficient in extracting oxygen [2].

Operation scheme of the hybrid system is given in Fig.1. Martian atmospheric gas mixture containing predominantly carbon dioxide is introduced to the radio frequency discharge region where it is decomposed into carbon monoxide, molecular, and atomic oxygen. The mixture flows through the RF reactor forced by convection due to gas heating by RF discharge and by the heat from the recombination of atomic into molecular oxygen. Free convection is anticipated in the initial experiments. However, if necessary to meet the target performance, a forced-flow generating unit could be introduced. Molecules of the recombined oxygen, unreacted carbon dioxide, and carbon monoxide, move through the duct .o the ceramic honeycomb. The honeycomb is heated by the gas and. if necessary, by additional electric heaters to the optimal operating temperature. Oxygen is separated through the walls of the honeycomb structure. and residual gas is removed from the system.

The proposed reaction cell is based on the radio-frequency, inductively coupled plasma mode (RF-ICP) to allow for the enhanced oxygen production in gas flow and increase the gas throughput through the reactor and ceramic honeycomb separator. Thus, it is anticipated that the hybrid system has the potential to (1) increase reliability of an ISRU system, (2) operate at optimal power efficiency, and (3) operate strictly on the resources from the Martian environment.

Comparative analysis of the two plasma modes currently used for oxygen production, RF-CCP and RF-ICP for the hybrid system will be given. RF-CCP is used in combination with the silver extraction membrane, and RF-ICP is designed to be used for the hybrid system. Complementary aspects of the two techniques with respect to the effective oxygen production and extraction will be demonstrated. Status of development of the techniques will be presented.

References: [1] L. Vuskovic, R. L. Ash, S. Popovic, T. Dinh, and A. Van Orden, "Oxygen Production and Separation from Martian Atmosphere by the Radio-Frequency Discharge", p. 33, Book of Abstracts, ISRU II Technical Interchange Meeting, Houston, Nov. 18-19, 1997. [2] W. N. Lawless, "Oxygen Extraction using a Ceramic honeycomb Technology", p. 23, Book of Abstracts, ISRU II Technical Interchange Meeting, Houston, Nov. 18-19, 1997.

Metal Enclosure

Pump

Thermometer

Residual gas out

Honeycomb

O_2

Oxygen Tank

DC Power Suppl,

DC Powermeter

Duct

RF Power Supply

Matching Circuit

RF Discharge Reactor

RF Powermeter

RF Antenna

Martian air in

Pressure Gauge

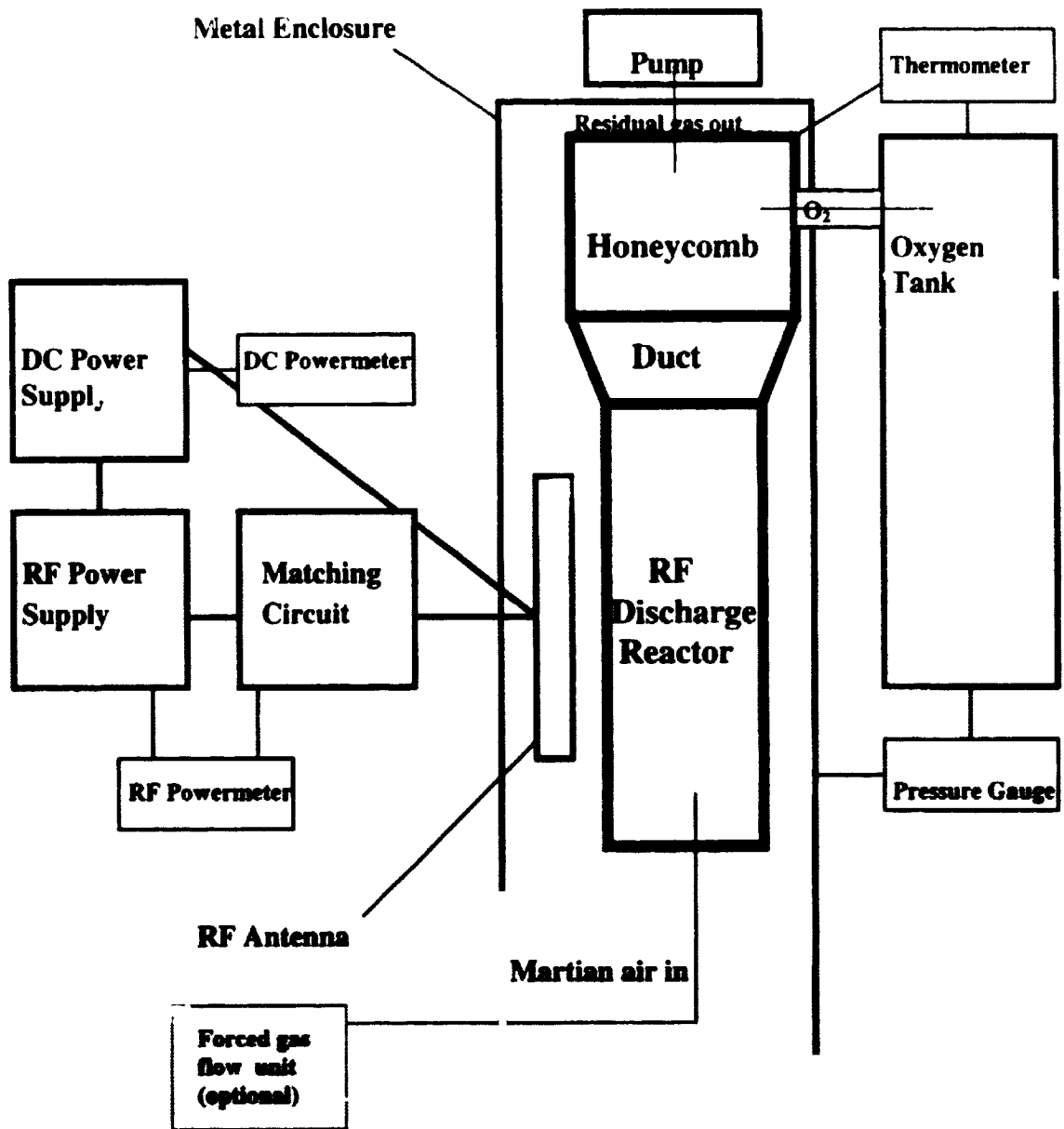**Forced gas flow unit (optional)**

Fig. 1. Scheme of the hybrid system for oxygen production

METHANE PYROLYSIS AND DISPOSING OFF RESULTING CARBON.

P. K. Sharma[1], D. Rapp[2], and N. K. Rahotgi[3], [1]Mail Stop 183-401, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 91109, USA (pramod.k.sharma@jpl.nasa.gov), [2]Mail Stop 157-205, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 91109, USA (drapp@jpl.nasa.gov), [3]Mail Stop 125-224, Jet Propulsion Laboratory, 4800 Oak Grove Drive, Pasadena CA 91109, USA (naresh.k.rohatgi@jpl.nasa.gov)

Introduction: Sabatier/Electrolysis (S/E) is a leading process for producing methane and oxygen for application to Mars ISPP. One significant problem with this process is that it produces an excess of methane for combustion with the amount of oxygen that is produced. Therefore, one must discard roughly half of the methane to obtain the proper stoichiometric methane/oxygen mixture for ascent from Mars. This is wasteful of hydrogen, which must be brought from Earth and is difficult to transport to Mars and store on Mars.

To reduce the problem of transporting hydrogen to Mars, the S/E process can be augmented by another process which reduces overall hydrogen requirement. Three conceptual approaches for doing this are (i) recover hydrogen from the excess methane produced by the S/E process, (ii) convert the methane to a higher hydrocarbon or other organic with a lower H/C ratio than methane, and (iii) use a separate process (such as zirconia or reverse water gas shift reaction) to produce additional oxygen, thus utilizing all the methane produced by the Sabatier process. We report our results here on recovering hydrogen from the excess methane using pyrolysis of methane. Pyrolysis has the advantage that it produces almost pure hydrogen, and any unreacted methane can pass through the S/E process reactor. It has the disadvantage that disposing of the carbon produced by pyrolysis presents difficulties.

Hydrogen may be obtained from methane by pyrolysis in the temperature range 1000°–1200°C. The main reaction products are hydrogen and carbon, though very small amounts of higher hydrocarbons, including aromatic hydrocarbons are formed. The conversion efficiency is about 95% at 1200°C. One needs to distinguish between thermodynamic equilibrium conversion and conversion limited by kinetics in a finite reactor.

The main reaction is

$$CH_4(g) \Rightarrow C(s) + 2H_2 \quad \Delta H = 74.9 \text{ kJ/mole} \quad [1]$$

The solid carbon formed in the above reaction can be burned off with carbon dioxide at elevated temperatures (with an associated energy penalty) according to

$$C(s) + CO_2 \Rightarrow 2CO \quad \Delta H = 172.6 \text{ kJ/mole} [2]$$

The energy requirement for reaction [1] is moderate. Therefore, if a process can be devised where the carbon formed by pyrolysis is physically removed or stored without the burnoff reaction [2], pyrolysis could be a

strong contender to augment the S/E process. If, however, the burnoff reaction is required, the energetics are less favorable. Nevertheless, despite the less favorable energetics, it is useful to know whether process (2) can be made viable

The goals of a research program on recovery of hydrogen from methane are (in descending priority order):

1. Study the kinetics of pyrolysis to arrive at a pyrolysis reactor design that produces high yields in a confined volume at the lowest possible operating temperature.

2. Study the kinetics of carbon burnoff to determine whether high yields can be obtained in a confined volume at acceptable operating temperatures.

3. Investigate catalytic techniques for depositing carbon as a fine soot which can be physically separated from the reactor.

In the JPL program, we have made significant measurements in regard to goal 1, cursory measurements in regard to goal 2, and would plan to pursue goal 3 if additional resources are secured.

Measurements and Results *Pyrolysis.* A tubular quartz reactor was used to study pyrolysis in the temperature range 1000°–1200°C. The reactor was coupled to a mass spectrometer sampling system for analysis of gaseous products. The reactor could be opened up after one or several pyrolysis runs and total carbon deposited could be obtained. This experimental set up allowed the monitoring of both the solid carbon product as well as the reaction gas products.

The reactor was a 1.5" ID by 2-ft. long quartz tube which had a 6" long preheater zone and an 8" long quartz wool packed main reaction zone. A quartz wool trap was used to catch the small amounts of room temperature condensables formed and the reaction gas products were routed to the mass spectrometer sampling system. The pyrolysis was carried out in a series of 5 runs at flow rates of 50 to 200 ml/min of methane. For each run, a nearly constant temperature for the reaction zone was attempted. The gas phase product composition was monitored at 15 minute intervals. Thus, a near continuous monitoring of the reaction gas products was obtained for each run. At the end of the five pyrolysis runs, the reactor was opened and the quartz wool with deposited carbon was removed and weighed. Carbon deposited from the cumulative reaction in the five runs was obtained and compared with the theoretical value deduced from the product gas analysis and flow rate. The agreement was within 15%, and the error was expected due to

certain simplifying assumptions made in the analysis. These results clearly show that one can achieve >95% conversion of methane to hydrogen at 1200°C in a moderately sized reactor at appropriate flow rates. Further experiments are planned to refine the trade relationship between temperature and conversion at various flow rates.

Carbon burn off. To be able to test the burnoff of carbon from the pyrolysis reaction, the quartz wool with the deposited carbon was packed back into the reactor. The reactor was set up again and pure carbon dioxide was made to flow through it. The main reaction zone was maintained in the temperature range 1130° to 1150°C, though a part of the reaction zone cooled off to 850°C due to an electrical problem in the furnace. The flow rate of carbon dioxide was 200 ml/min. The reaction gas products (CO plus unreacted CO_2) were analyzed by the mass spectrometer at 15 min intervals. The regeneration run was continued for a total of 24 hrs. At the end of the run, the reactor was opened and examined visually. The quartz wool was taken out and weighed to determine the carbon that did not burn off. A major part of the quartz wool that was packed in the reaction zone that was at 1130°–1140°C was relatively close to the original color of the quartz wool, but the part of the zone that was at 850°C was quite black and did not appear to be well regenerated. The mass of the unburned carbon was compared to its predicted value based on the product gas analysis. The agreement was again within 15% error which can be explained due to some carbon lost in manual operations, as well as certain approximations that had to be made in making the calculations. In a limited set of runs, the reactor bed temperature was varied in the range 1000° to 1200°C and reaction product gas composition was determined. The kinetic rate constant can be obtained from this set of runs and used to carry out modeling in order to design and optimize a reactor which can achieve a high carbon burnoff with a high CO_2 utilization.

In order to examine the surface morphology on the quartz fibers before and after carbon burn off, small samples of quartz wool after pyrolysis (with deposited carbon) and after burn off with CO_2 were examined with Scanning Electron Microscopy (SEM). The SEM photographs illustrate that during pyrolysis, carbon builds up around the quartz fiber, apparently in a porous form. Subsequent reaction with carbon dioxide gradually removes the carbon deposit. In order to have a viable process, it may not be essential to remove the entire carbon deposit as long as the unreacted carbon does not continue to build up.

The work completed so far indicates that most of the carbon produced in pyrolysis can be burned off with CO_2 at a temperature of 1150°C. However, the energy penalty associated with the carbon burn off is substantial, and another problem is that excess CO_2 may have to go out

the stack, requiring a larger compressor.

Pyrolysis without carbon burnoff. To make the process of hydrogen recovery from methane energy efficient, a process that mechanically removes the carbon (and does not need to burn it off) will be considerably more attractive.

Some recent advances in methane cracking over a Ni/silica catalyst have shown that carbon can be produced in filament form which create light hollow structures. This type of carbon can be elutriated out of the reactor bed and separated using a cyclone. In a scheme based on this concept, carbon burnoff is not essential and considerable energy could be saved, but questions of catalyst regeneration still have to be answered.

Summary: The JPL methane research program is one year old. At its completion, we will have measured the kinetics of pyrolysis and carbon burnoff. If future resources become available, we would like to pursue pyrolysis concepts that allow physical removal of the carbon, so that the energy intensive step (reaction [2]) can be avoided.

Detail of carbon wrapping on silica fiber
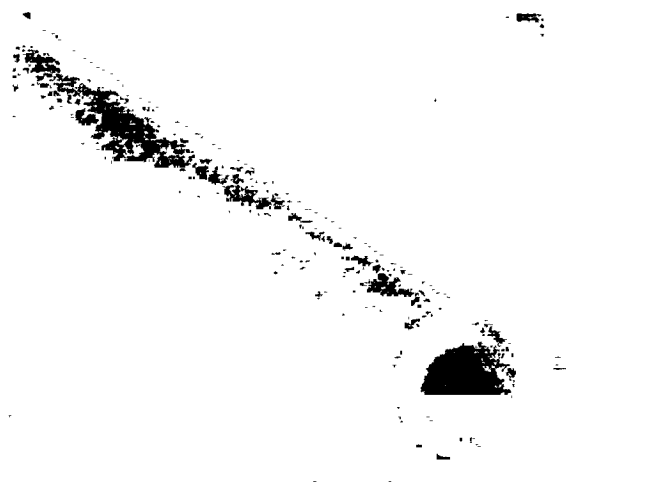
Silica fibers after carbon burnoff

OXYGEN GENERATOR SYSTEM MARS IN-SITU PROPELLANT PRODUCTION PRECURSOR FLIGHT.

K. R. Sridhar[1], M. Gottmann[1] and R. S. Baird[2]. [1]The University of Arizona (Aerospace and Mechanical Engineering Department, Tucson, Arizona 85721. Sridhar@shaku.ame.arizona.edu, matthias@ares.ame.arizona.edu) [2]NASA Lyndon B Johnson Space Center Johnson Space (Houston, Texas 77058-3696, r.s.baird1@jsc.nasa.gov)

The 2001 Lander to Mars will carry the first ever ISRU payload to Mars. This payload, the Mars In-situ Propellant production Precursor (MIP), will demonstrate a variety of technologies that will be required for future ISRU Mars indigenous material processing plant designs. One of those technologies is that of extracting oxygen from the predominantly carbon dioxide atmosphere of Mars, a prerequisite for future sample return and human missions to Mars. The Oxygen Generator Subsystem (OGS) portion of the MIP will demonstrate this and is the focus of this paper.

The primary objective of the OGS is to demonstrate the production of oxygen from Mars atmospheric gases. Secondary objectives are to measure the performance and reliability of oxygen generation hardware in actual mission environments over an extended time. Major constraints on the OGS design came from several sources. The Lander provides power to the system from solar power that is harnessed by photovoltaic arrays. This limited OGS to daytime only operations (six to eight hours) and a maximum power of 15W. The reliance on solar power necessitated thermal cycling of the OGS between Mars ambient and OGS operating temperatures. The Lander also limited the total mass of the MIP payload to 7.5 kg with a correspondingly small volume, and the OGS was one of six experiments in the MIP. Mass and volume were to be minimized. Another constraint was cost. Mission funding, as always, was tight. Cost was to be minimized. In short the OGS design had to be low power (<15 Watts), low mass (1 kg), low volume, low cost, and be capable of cyclical operations for an extended stay on Mars. After extensive research, a zirconia based solid oxide electrolyzer design was selected.

Several technology challenges had to be addressed with the detailed design of the OGS. First, the ceramic zirconia electrolyte of the electrolyzer had to be packaged to survive the vibration and shock environments of launch and landing (up to 35G in the x, y, and z axes). Second, the seals had to survive multiple thermal cycles from Mars ambient conditions to the operating temperature of the cell, 750°C. Third, a low mass thermal insulation material had to be found and a low heat loss thermal packaging of the electrolyzer had to be designed such that the electrolyzer cell could be heated up to 750°C and maintained at that temperature with the 15 Watts that are available. Fourth, a long-life miniature heater was required for heating the electrolyzer cell.

Figure 1 is a solid model of the OGS development hardware. The suspension of the electrolyzer cell with 4 support wires and the cushioning provided by the crushed insulation ensure the survivability of the cell elements when they are subjected shock and vibration. Custom metal manifolds that have the same coefficient of thermal expansion as zirconia and custom seals that were developed for us by United Technologies facilitate the thermal cycling of the electrolyzer, while maintaining the integrity of the gas tight seals between the manifolds and the cell. The third challenge was solved in part with a modified version of a new commercially available insulation material that was characterized and tested at both the University of Arizona and in independent thermal testing labs. The conduction paths were reduced to minimize heat leakage, by the choice of materials, their dimensions and placement. The fourth challenge was solved with a custom designed ceramic heater. This ceramic heater is capable of ramping up at up to 30°C/minute for several hundred cycles without failure.

Aside from these technology challenges, practical aspects of the design, ranging from low mass and power gas flow control hardware to sensors, were addressed. Each of these technology challenge solutions, the overall OGS design, and operation of the OGS will be discussed in further detail as part of this paper.

The OGS design was put into practice in a development unit that was tested extensively. Figure 2 is a photograph of the OGS DU hardware. Physically, the OGS Development Unit (DU) mass was measured to be 0.96kg with a volume of less than $2540cm^3$ ($155in^3$). The electrolyzer generated 0.5sccm O_2 at 131.5mA cell current and a CO_2 feed rate of 2.5sccm. The electrolyzer generated higher O_2 flow rates with correspondingly higher input voltages and CO_2 feed rates. The heater and insulation package is capable of raising the cell temperature from -100°C to 750°C in approximately 105 minutes in Mars external environmental conditions using a maximum of 15W. The cell temperature was then maintained at 750°C with approximately 9.5W of power. A power and temperature curve for the OGS DU is shown in figure 3. Dome surface temperatures did not rise above 15°C over the ambient environment temperature during steady state oxygen production operations. The electrolyzer cell assembly also survived a sudden power loss shutdown test without damage and restarted without incident. Figure 4 shows the oxygen production characteristics of the DU. While the requirement was 0.5 sccm of oxygen, the unit produced well over twice that amount and still remained within the power budget.

A few development test problems were encountered. The initial electrolyzer assembly seal supported multiple thermal and pressure cycle operations at the 55.15 kPa (8 psi) level but began to leak when exposed to 137.8 kPa (20 psi) gas. Seal manufacturing process and electrolyzer assembly mechanical modifications have been devised and incorporated into the development hardware. A second

problem was encountered during vibration testing   An
internal guy wire broke loose   This was traced to the use of
incorrect wire material   Proper wire material and a modified
wire attachment design have been incorporated into the
development hardware   The OGS DU has been   finished
and delivered to the Johnson Space Center for   grated
MIP development testing   Details of the OGS dev opment
testing results and implications will be discussed as part of
this paper

Overall, the OGS development hardware more than
meets it's objectives. Fabrication and qualification testing of
the OGS flight design are scheduled to be completed by the
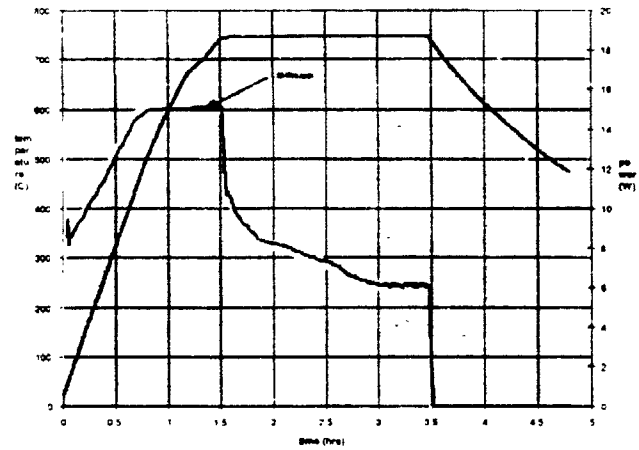end of this summer.

Figure 3

Figure 1
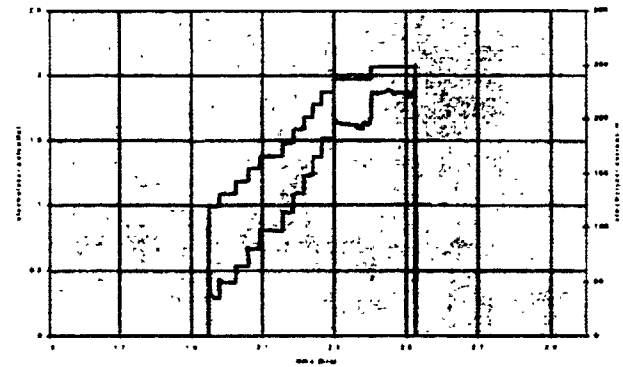

Figure 4

Figure 2

MICROCHEMICAL AND THERMAL SYSTEMS FOR IN SITU RESOURCE UTILIZATION.

Robert S Wegeng[1] and Gerald B Sanders[2], [1]Pacific Northwest National Laboratory. Mail Stop K2-14, P.O. Box 999, Richland, WA 99352, robert.wegeng@pnl.gov, [2]NASA Johnson Space Center Mail Code EP4, Houston, TX 77058. gerald.sanders@jsc.nasa.gov

Introduction: *Process Intensification* and *Process Miniaturization* an simultaneously be achieved through the application of microfabricated chemical process systems, based on the rapid heat and mass transport in engineered microchannels. Researchers at NASA's Johnson Space Center (JSC) and the Department of Energy's Pacific Northwest National Laboratory (PNNL) are collaboratively developing micro thermal and chemical systems for NASA's Mission to Mars program.

Preliminary results show that many standard chemical process components (e.g., heat exchangers, chemical reactors and chemical separations units) can be reduced in hardware volume without a corresponding reduction in chemical production rates. Low pressure drops and improved thermal integration are also accomplished when appropriate scaling rules are applied and when individual microchemical components are packaged together into integral systems.

Background: Robotic sample return missions and postulated human missions to Mars and other bodies can be greatly aided through the development and utilization of compact chemical processing systems that process atmospheric gases and other indigenous resources to produce hydrocarbon propellants/fuels, oxygen, and other needed chemicals. When used to reduce earth launch mass, substantial cost savings can result.

Microchannel Heat Exchangers: The use of engineered microstructures offers the potential to reduce conventional resistances for heat and mass transport. Single-phase flow in microchannels is typically laminar, with heat and mass being dominated by diffusion processes. According to diffusion theory, the timescale (t) necessary to approach complete thermal mixing across the width of a fluid channel is on the order of

$$t \sim d^2/\alpha$$

(for heat transport, where d is the width of the channel and α is the thermal diffusivity of the fluid) or

$$t \sim d^2/D$$

(for mass transport, where D is the mass diffusivity of the fluid)

Microfabrication techniques, allowing for the engineering of microchannels that are substantially less

than 1 millimeter wide, can therefore be used to construct microcomponents that require very short residence times.

At PNNL, researchers have demonstrated microchannel heat exchangers in a planar, sheet architecture, that exhibit relatively high heat fluxes (100 watts/cm^2 perpendicular to the sheet) and convective heat transfer coefficients (10,000 to 35,000 watts/m^2- C), with low pressure drops (2 to 3 psi). For these test articles, channel dimensions included widths typically ranging from ten to hundreds of microns, depths ranging from tens of microns to several millimeters, and lengths of a few centimeters. See Figures 1 and 2 below.
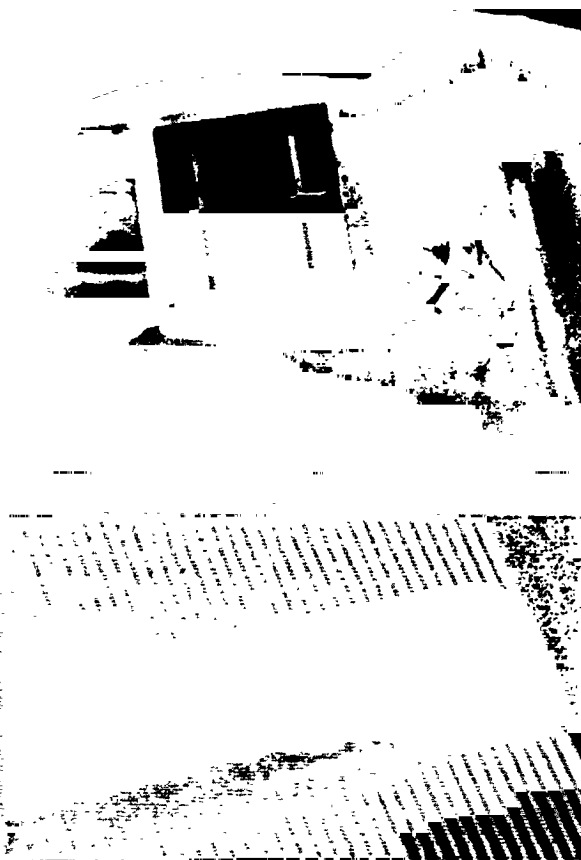
Figures 1 and 2
PNNL Microchannel Heat Exchanger (above)
Typical Engineered Microchannels (below)

Microchannel Reactors: Engineered microstructures offer a number of potential advantages for the manipulation of chemical reactions. The advantages

include the ability to achieve uniform velocity fields within precise microstructures; improved temperature control through enhanced heat transport properties; short residence times (through heat and mass transport enhancements), therefore leading to high processing rates per unit hardware volume; and the potential to incorporate other features that influence chemical interaction (e.g., electric fields).

Microchannel reactors and heat exchangers can additionally be assembled into single, integral hardware units, with individual components operating in parallel or in series or an appropriate combination. Figure 3 shows a representative unit, with four microchannel reactor cells and four microchannel heat exchanger cells. This unit is capable of processing gases at the rate of 1250 Liters/min, therefore demonstrating the high processing rates that can be achieved in micro chemical and thermal systems.

Microchannel Separations Units: Microchannel gas absorbers and adsorbers are also in development, with preliminary results showing similar enhanced processing rates due to the heat and mass transport advantages in engineered microchannels. The incorporation of microchannel heat exchangers provides an opportunity for rapid thermal cycling and therefore offers a very compact sorption pump for the collection and compression of CO_2 from the Martian atmosphere. Pictures of microchannel absorption and adsorption currently in design and testing are not presented here due to space limitations but will be shown at the ISRU-III Technical Interchange Meeting.

Integral Micro Chemical System for the Insitu Production of Propellants and Oxygen: Currently, a conceptual design is being produced for an integral micro chemical system that includes CO_2 acquisition and compression using microchannel adsorbers and heat exchangers, followed by reaction with H_2 in microchannel reactors. Microchannel phase separators may additionally be included within this integral unit for the removal of water from the product stream.

This system, which is contemplated for robotic missions, would produce methane as the propellant using the Sebatier Process:

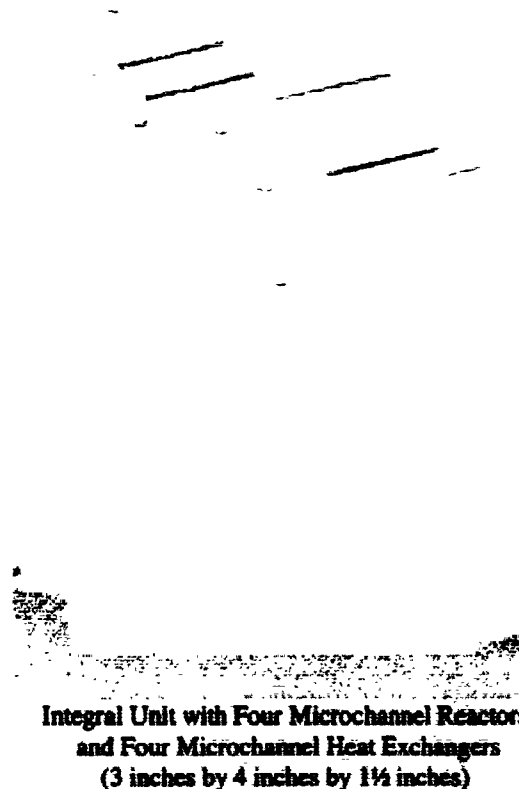$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$
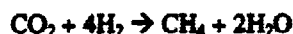
Oxygen would then be produced from the water, using an electrolyzer, with the hydrogen being recirculated to the reactor. However, this reaction does not produce methane and water/oxygen in the correct proportion propellants and oxidizer. A second microchannel reactor, providing the Reverse Water Gas Shift reaction, is therefore contemplated. This reaction creates water for the electrolyzer via the reaction:

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

Operating the Sebatier Process microchannel reactor in parallel with the Reverse Water Gas Shift microchannel reactor, with appropriate flow rates to each, should provide the correct product mix.

The design of the integral system is nontrivial, as it must take into account less than complete conversions on the part of the reactors, differences in ideal operating temperatures and heating/cooling requirements for the reactors as well as the adsorption units, and phase separations and recycle. Experiments are being conducted on individual "cells" at this time, and it is anticipated that a conceptual design will be available by the time of the ISRU-III Technical Interchange Meeting.

Figure 3

**Integral Unit with Four Microchannel Reactors and Four Microchannel Heat Exchangers
(3 inches by 4 inches by 1½ inches)**

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ATMOSPHERIC WATER VAPOR ADSORPTION FOR MARS IN SITU RESOURCE UTILIZATION.

J. D. Williams, T. E. Bratkovich and T. R. A. Bussing. Adroit Systems, Inc., 411 108th Ave NE, Ste 1080, Bellevue, WA 98004, (425) 450-3930

Introduction: ASI has successfully completed a Phase I SBIR contract to develop a method for extracting water vapor from the atmosphere of Mars in an efficient, lightweight, and reliable manner. Through the use of molecular sieve technology, the Water Vapor Adsorption Reactor (WAVAR) would provide a dependable source of water to future exploration missions from sources indigenous to the red planet. This water can be used as feedstock for propellant production, for direct human consumption, or as the basis for a multitude of industrial, agricultural and biological processes. Using locally available materials at the site of an interplanetary mission is known as in situ resource utilization (ISRU). Missions employing ISRU techniques can attain dramatic cost savings, while improving mission robustness, by reducing the amount of raw materials transported from Earth. The most important of these materials is water. WAVAR would meet this need, providing a crucial technology for future missions.

Water on Mars: The availability of water on Mars is undisputed. As illustrated in Figure 1, it is present in the polar caps, the regolith, the permafrost (speculative), and the atmosphere. Extraction of water from the regolith is technically feasible provided sufficient availability is demonstrated. Utilization of water from the polar caps would involve minimal processing and mining, but would entail landing on the polar ice sheet, which precludes effective solar power generation. Additionally, the polar regions are less likely to harbor signs of past or present life.

However, it is the Martian atmosphere that is currently the most highly characterized and globally distributed water source on the planet. Carbon dioxide makes up the bulk of the atmosphere on Mars, while water vapor makes up only a small fraction [1]. However, though the absolute humidity is low, the atmosphere is, for most times and locations, completely saturated (100% relative humidity) with respect to the nightly temperature minimum [2].
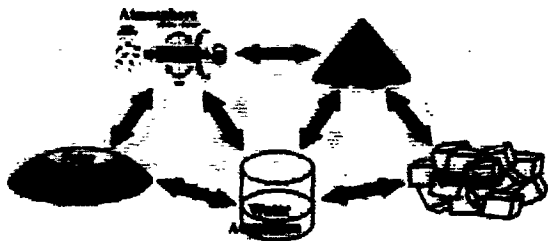

Figure 1. Martian water reservoirs.

The total water content of the Martian atmosphere is between 1 and 2 cubic kilometers [3]. However, con-

centration is strongly dependent on the season, latitude, and local topography. This was clearly demonstrated by column abundance data gathered from the Viking orbiters' Mars Atmospheric Water Detectors (MAWD), as shown in Figure 2. Unfortunately, column abundance data does not translate directly into available concentrations at ground level. For ground level concentrations, atmospheric scientists typically rely on two sources of data. The first is direct measurements of temperature (from which water vapor concentration can be inferred), like those taken by the Viking landers and Mars Pathfinder. The second source of data is generated by sophisticated computer simulations such as those run at NASA Ames Research Center by the Mars Atmosphere Global Circulation Modeling Group.

To operate WAVAR in as efficient a manner as possible, landing sites with water concentrations at or above the global average are desirable. If such landing sites are chosen, then WAVAR has the potential to become a critical technology for advanced robotic exploration, and an enabling technology for a sustained human presence on the red planet. Humid sites have the added advantage that they are attractive to exobiologists. In searching for signs of past or present life, the warmest, wettest spot on the planet is a likely candidate for initial exploration.
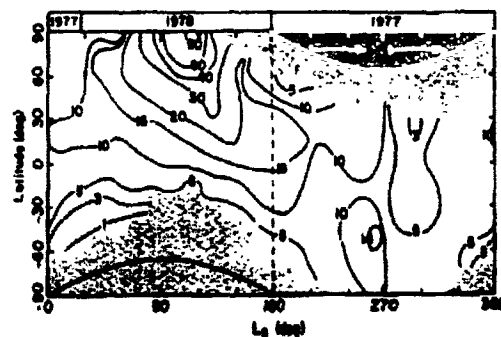

Figure 2: Column abundance of water vapor from Viking MAWD.

Adsorption: The water vapor adsorption reactor is a separation device. Water vapor must be extracted from the other constituents of the Martian atmosphere before it can be utilized. A particularly effective way for separating trace amounts water vapor from other gases is temperature-swing adsorption. This process involves two distinct steps operating in batch mode: 1) Adsorption, in which the water is separated from the other constituents at the surface of the adsorbent, and 2) Desorption, in which heat is used to drive the water off of the sorbent, after which it is collected. Temperature-swing adsorption is used in many applications, including large-scale dehumidification, and is a well-understood indus-

trial process

Adsorption techniques have been used in the chemical and petroleum industries for over 100 years, because it is a low-energy solution to the problem of separating mixed fluid species. Adsorption utilizes molecular sieves (the adsorbent) to selectively attract molecules of a fluid (the adsorbate) as it passes through a fixed bed The molecular sieves are synthetically formulated crystalline structures of metal alumino-silicates (typically zeolites) that have been activated by removing the water of hydration. The result is a crystalline cage containing uniform micropores.

Free gaseous or liquid molecules are attracted to the surface of the adsorbent by Van der Waals forces [5]. These molecules are adsorbed selectively as a result of two microscopic phenomena: 1) molecular size-exclusivity of the adsorbent's micropore structure, and 2) the difference in sorption rates between the flow constituents. Adsorption itself is an exothermic process requiring no energy input other than that required to move the fluid. Removing the water from the bed (desorption), however, does require energy.

By tailoring the ion content (in this case, by introducing potassium ions) of an adsorbent, larger gas species can be excluded from capture. For water vapor adsorption on Mars, a logical choice of adsorbent is limited to those with an aperture of 3 Å (slightly larger than a water molecule), such as UOP (formerly Union Carbide) Molecular Sieve 3A. This adsorbent is highly specific to water, and will exclude other Martian atmospheric constituents such as CO_2, N_2, Ar, O_2 and CO. The pelletized form allows it to be packed easily into a bed to provide a large surface area while imposing an acceptable pressure drop; fine powders, gels, and pure thin-film crystals are also available.

Research Program: The primary goal of the Phase I program was to show WAVAR proof-of-concept through test and analysis. Four technical tasks were completed. The first of these tasks was the design and construction of a low-cost test rig, shown in Figure 3, to simulate the Martian atmosphere. The simulation included fidelity of pressure, temperature, humidity and gas composition. The test rig consisted of a vacuum, thermal control and data acquisition systems. The second task was to use this apparatus to conduct the first known proof-of-concept of water vapor adsorption by zeolite 3A in a Martian atmospheric environment. Further tests were run to collect adsorption data and to validate analytical models for the performance of zeolite 3A under these conditions.
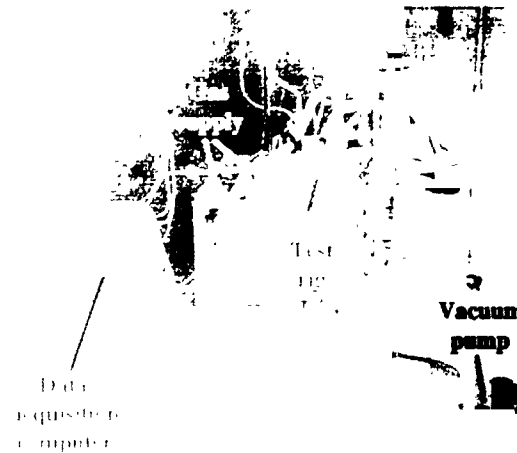

Figure 3: Water vapor adsorption experimental apparatus.

Task 3 of the Phase I program involved the formulation of a new, low-specific power WAVAR design which employs ambient wind patterns to eliminate blowers or fans. Atmospheric data was generated using the time and location accurate computational tools of the Mars Atmosphere Global Circulation Modeling Group. These data were supplied to a performance model, which was then integrated with mission analysis tools at Lockheed Martin Astronautics. An analysis was conducted of WAVAR-based Mars sample return mission. This showed significant benefits over conventional, imported hydrogen- and imported methane-based propellant production scenarios. The fourth task included a detailed test/analysis plan for future work.

The results of the Phase I effort clearly demonstrate the potential of WAVAR technology to dramatically reduce the costs of Mars sample return, robotic, and human exploration missions in the coming decades. With the attainment of proof-of-concept, and therefore Technology Readiness Level 3, WAVAR has been shown to be technologically feasible.

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MARS *IN SITU* PROPELLANT PRODUCTION UTILIZING THE REVERSE WATER GAS SHIFT.

R. Zubrin, B. Frankie, T. Kito, and T. Muscatello, Pioneer Astronautics, 445 Union Boulevard, Suite 125, Lakewood CO 80228 (Phone: 303-980-0890).

This report describes recent work accomplished on a Mars in situ propellant production project utilizing the reverse water gas shift (RWGS) reaction. This project began with a NASA Phase I SBIR in 1997 and has been continued as a Phase II program in 1998. John Connolly is the JSC program manager and Robert Zubrin is the principal investigator at Pioneer Astronautics.

During the project, Pioneer has successfully built and operated two chemical synthesis units representing the cores of machines capable of manufacturing oxidizer and a variety of fuels out of primarily indigenous Martian material. The units include a Reverse Water Gas Shift (RWGS) unit and a Methanol Synthesis (MEOH) or Fischer Tropsch (FT) unit.

The RWGS unit works in the following manner: Liquid hydrogen is transported from Earth to Mars, where it is combined with carbon dioxide acquired from the Martian atmosphere in a catalytic reactor to produce carbon monoxide and water. Water is condensed and separated from the gas phase. Unreacted feed components are compressed, recovered from the gas phase in a membrane unit separator, and recycled to the catalytic reactor. Effluent from the membrane unit ("retentate") is sent to the MEOH or FT units.

At H2/CO2 mixture ratios of 1:1 nearly all the hydrogen is reacted to make water, which can then be electrolyzed to produce oxygen and hydrogen, which can be recycled. Used in this way, the hydrogen brought to Mars can be recycled many times to produce an enormous amount of oxygen and CO. Alternatively, the feedstock to the

RWGS can be run with an excess of hydrogen, in which case the effluent from the RWGS will contain both CO and H2. Such a mixture is known as synthesis gas and is the ideal feedstock for making methanol, dimethyl ether, paraffins, olefins, or aromatics

The MEOH unit works in the following manner: Effluent from the RWGS unit, consisting primarily of carbon monoxide with some residual unreacted hydrogen, is combined with fresh hydrogen feed, if required, and sent to a catalytic methanol synthesis reactor. The synthesis reactor combines one carbon monoxide molecule with two hydrogen molecules to produce methanol. Production from the methanol synthesis reactor is condensed and separated from the gas phase. Unreacted feed components are separated in a second membrane separator and recycled to the RWGS reactor feed. The second membrane retentate, consisting primarily of excess carbon monoxide, is vented from the system.

The MEOH unit was designed in a generic fashion so that different varieties of catalytic reactors could be tested without changing the process configuration. In addition to the methanol synthesis reactor, Pioneer experimented with a hybrid methanol/DME reactor and a Fischer-Tropsch hydrocarbon synthesis reactor.

Accomplishments to date:

Pioneer has recorded a number of significant accomplishments during the project. Highlights include:

1) Development, manufacture, and demonstration of a catalyst which is 100% selective for the RWGS reaction at a wide range of conditions.

2) Design, construction and operation of an ISPP machine including a RWGS unit and either a methanol synthesis unit or Fischer Tropsch unit.

3) Operation of the RWGS machine in oxygen production mode and attained mass leverages in excess of 1600.

4) Discovery that by altering the reactor temperature, pressure, and feed ratio, the RWGS unit could be run in combined Sabatier/RWGS mode with potential mass leverage of 20. Achieved an actual mass leverage during operation of 16.5, which compares to a 10.3 leverage for the S/E unit.

5) Operation of the machine in a mode to produce a combined 50/50 molar CH4/CO ratio fuel with a stoichiometric oxygen ratio. In this mode, the system demonstrated a mass leverage of 31 with a 23 excess oxygen mass leverage.

6) Demonstration of production of synthesis gas (syngas) feed for methanol, dimethyl ether (DME, =CH3OCH3), Sabatier, or Fischer-Tropsch reactors. The quality of syngas produced was sufficient to allow a methanol/O2 leverage of 16.3 or a Fischer-Tropsch/O2 leverage of 22.4.

7) Demonstration of production of a 89% methanol/ 11% water fuel product with no other detectable contaminants.

8) Demonstration of conversion of 8% of the feed carbon dioxide to dimethyl ether (DME) in a one pass (no recycle) hybrid reactor.

9) Demonstration of conversion of at least 44% of the feed carbon dioxide to ethane or higher hydrocarbon species in a one pass Fischer-Tropsch reactor.

10) Demonstration of complete recovery of gaseous hydrogen in a two membrane loop system, with no gaseous hydrogen detected in the system vent.

11) Use of the RWGS system as a first stage of a Fischer Tropsch system incorporating a recycle loop and a combination Fe-K/ZSM5 catalyst to produce an olefin mixture predominantly composed of propylene (C3H8), with significant admixtures of methane, ethylene (C2H4), and C4 and C5 olefins, for an average H/C ratio of about 2.3.

12) Use of the RWGS system as a first stage of a Fischer Tropsch system incorporating a recycle loop and a combination Fe-K/ZSM5 catalyst to produce a liquid hydrocarbon fuel consisting predominantly of toluene (C7H8), with significant admixtures of benzene and xylenes, for an average H/C ratio of 1.2.

In conclusion, we find that based on the work done to date, that the RWGS offers a feasible and potentially attractive method of performing in-situ propellant production on Mars and should be researched further.