

In Situ Resource ^{p10}
Utilization (ISRU)
Technical Interchange
Meeting

February 4-5, 1997
Lunar and Planetary Institute
Houston, Texas

**IN SITU RESOURCE
UTILIZATION (ISRU) TECHNICAL
INTERCHANGE MEETING**

February 4–5, 1997
Lunar and Planetary Institute
Houston, Texas

Convened by

David Kaplan
NASA Johnson Space Center

Sponsored by

National Aeronautics and Space Administration
Lunar and Planetary Institute

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IN SITU RESOURCE UTILIZATION (ISRU) TECHNICAL INTERCHANGE MEETING

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PREFACE

This volume contains abstracts that have been accepted for presentation at the In Situ Resource Utilization (ISRU) Technical Interchange Meeting, February 4–5, 1997, at the Lunar and Planetary Institute, Houston, Texas. Abstracts are arranged in order of presentation at the meetings, with corresponding page numbers shown in the enclosed agenda.

Logistics, 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.

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LUNAR/MARS IN-SITU PROPELLANT PRODUCTION (ISPP) TECHNOLOGY: DEVELOPMENT ROADMAP.
J. B. Sanders, NASA Johnson Space Center, Mail Code EP4, Houston TX 77058, USA.

Utilizing resources on the Moon, Mars, and other potential sites of human exploration for mission enhancement or for the benefit of Earth has been considered and studied for years. In-Situ Resource Utilization (ISRU) concepts range from making oxygen and fuel for propulsion, power generation, and life support; to making solar arrays from minerals extracted from lunar soil; to running fusion power plants on Earth with lunar supplied Helium-3. Over the years, research has been performed on a number of interesting concepts and chemical processes, and study after study has shown that use of in-situ resources can reduce the cost and risk of human exploration by decreasing Earth launch and logistics requirements while providing life support, propellants, power, and manufacturing capabilities to become more self-sufficient. Over the last few years, ISRU has been viewed more and more as an "enabling technology" for the human exploration and exploitation of our solar system.

Since most of the technologies for ISRU are immature, the mission benefits of using ISRU are based on the research to date as well as estimates of ISRU concept complexity, power demand, and chemical conversion or extraction efficiency. Most of the research being performed by NASA, universities, and industry has been at the concept or experimental proof-of-concept stage with limited component or breadboard development. Also, the research to date has been mostly uncoordinated and unfocused since a clear strategy or mission plan to explore the Moon and Mars in the 21st Century has not been available.

Over the past year, a group within NASA has been attempting to coordinate and focus the development of ISRU technologies in the area of In-Situ Propellant Production (ISPP) to support both robotic and human exploration initiatives to the Moon and Mars. The roadmap currently includes the following:

- 1) a rationale and benefits section on using ISRU for exploration
- 2) an overview of the most promising ISPP concepts for both Lunar and Mars exploration
- 3) an overview of current ISPP development participants and technology activities
- 4) the technology areas and issues that require development for each promising concept
- 5) development schedule with flight demonstrations to support human Moon and Mars exploration
- 6) a preliminary funding profile to develop robotic and human ISPP

The mission strategy used in the ISPP Roadmap for human exploration in the 21st Century is still very preliminary, but covers human exploration of both the Moon and Mars. The mission strategy for lunar exploration begins with a simple, short term lunar surface stay in 2003. The first mission would last only a few days and consist primarily of existing technology; however, long duration landers and habitats, and nuclear transfer stages would be demonstrated on other missions. For missions to Mars, human exploration would begin with the launch of an unmanned habitat and return stage in 2009 to support the first human mission to Mars in 2011. The 2009 return lander would include an ISPP plant to produce the propellant needed for ascent from the Mars surface before the first human crew left Earth in 2011. Robotic orbiters and landers to help define the environment and surface conditions as well as perform engineering demonstrations of key technologies are also an integral part of these mission strategies.

Demonstrating the production of oxygen using lunar resources is a major element of the first human mission to the Moon. Depending on the availability of water on the Moon, the oxygen production demonstration may use either lunar water or regolith. The Lunar Prospector, to be launch this year, will help determine the availability of water on the lunar surface. Should water be found in large quantities at the south pole, a lunar polar explorer could be launched in 2001 to deploy an ISPP demonstration based on lunar water. The first oxygen production demonstration most likely will be constrained by available power and mass, but it is hoped that the oxygen produced could be used to supplement crew life support to extend the first mission by a few days. Once ISPP has been demonstrated, an automated oxygen production pilot plant would be launched in 2005 to refuel small landers for reuse as human or cargo return vehicles. To meet these launch dates, a lunar ISPP chemical process must be selected by 2000 at the latest. Currently, there are five lunar regolith chemical processes being considered: hydrogen reduction, sulfuric acid reduction, methane reduction, molten electrolysis, and vapor phase pyrolysis.

The roadmap for Mars ISPP is centered around making a Go/No Go decision in 2003 or 2004 to support the human exploration of Mars in 2009 and 2011. Four major criteria must be completed to support this Go/No Go decision date: 1) ISPP technologies to be used must be greater than Technology Readiness Level 5 [component prototype demonstrated]; 2) The ISPP chemical process to be used must be selected; 3) an autonomous, long-term system demonstration of the process to be used must be performed; 4) the Mars surface environment and how it impacts ISPP must be characterized. To meet these criteria, the ISPP chemical process to be used in the 2009 mission must be selected in 2000. Also, to meet criteria #4, an ISPP demonstration, called the Mars ISPP Precursor (MIP), is currently under development as a potential payload on the 2001 Surveyor lander. Even though it is not one of the Go/No Go criteria, it is highly desirable to perform an end-to-end demonstration of the ISPP system to be used in 2009 as a verification of the system's performance. Due to Earth/Mars launch opportunity limitations and mission durations, there are only two launch opportunities to perform this type of demonstration and still impact the design of the 2009 vehicle; in 2003 and in 2005. At this time, a Mars sample return mission using ISPP is tentatively planned for launch in 2005 to fulfill this desire.

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ADSORPTION PUMP FOR ACQUISITION AND COMPRESSION OF ATMOSPHERIC CO₂ ON MARS. Donald Rapp¹, Paul Karlmann¹, and David L. Clark², ¹Jet Propulsion Laboratory, Pasadena CA 91109, USA, ²Lockheed Martin Astronautics, Denver CO, USA.

A flight-prototype zeolite adsorption compressor is being developed as a reliable, efficient, cost-effective means of extracting and compressing atmospheric CO₂ on the surface of Mars. Designed as the first stage of a Mars in-situ CO₂ to O₂ chemical conversion process, this work is part of a collaborative effort between Johnson Space Center (JSC), Jet Propulsion Laboratory (JPL), and Lockheed-Martin Astronautics (LMA).

By exposing the sorption compressor to the cold night-time environment of Mars (approx. 6 torr, 200 K), CO₂ is preferentially adsorbed from the Martian atmosphere by the zeolite sorbent material contained within. During the warmer day-time environment, when solar electrical power is available, the adsorbent is heated in a closed volume, thereby releasing CO₂ at significantly higher pressures (600–2000 torr) for use in a CO₂ conversion reactor.

An earlier prototype of this type of system was built and tested by LMA under initial sponsorship of JSC and further development sponsored by JPL. While this prototype adsorption compressor was shown to function very reliably, there are many important issues and challenges remaining in the design of a long-life, highly efficient adsorption compressor with minimum volume, mass, and power requirements. Some of these issues are:

- (1) **Sorbent Material Characteristics.** What quantity of CO₂ can be adsorbed and desorbed by a given amount of sorbent material, which materials are optimal, and what operating pressures and temperatures are required?
- (2) **Removal of Non-CO₂ Gases.** A system must be provided which prevents permanent gases from building up significant concentrations around the adsorbent material, thus creating a diffusive barrier to further adsorption of CO₂.
- (3) **Efficient Day-time Heating.** A system must be provided to allow maximum use of waste heat from an ISRU conversion reactor by the adsorption compressor while also providing for use of electrical power for heating the compressor when waste heat proves inadequate. To minimize input power requirements, the compressor must also be well insulated.
- (4) **Night-time Cooling.** There is a significant challenge in cooling the well insulated adsorption compressor at night. Preliminary modeling shows that internal convection during adsorption is insufficient for cooling the compressor and that an external radiator/convector is necessary. Heat transfer between the sorption compressor and external radiator will require the use of a fluid loop, heat-pipes, or thermal switch device.

The purpose of this paper is to provide insights, analysis, test data and concepts which address each of the issues described above, thereby arriving at a consensus preliminary design of such an adsorption compressor for extraction and compression of atmospheric CO₂ on Mars which provides the most CO₂ for the least volume, mass and power required for the adsorption pump.

CO₂ PUMPING SYSTEM FOR MARS ISRU: ADVANCED ABSORBENT MATERIALS. Mike Reddig and Allen MacKnight, AlliedSignal Aerospace Systems and Equipment, M/S TOR-36-1-93140, 2525 W. 190th Street, Torrance California 90504-6099, USA. (macknia@tormp103.allied.com)

ABSTRACT: A conceptual system design is presented for the CO₂ pumping and pressurization requirements for Mars Propellant Production Facility. The system utilizes CO₂ absorbent materials that are cyclically absorbed and desorbed thermally. The system is designed to use Mars ambient pressure and temperature and deliver 1 kg/day CO₂ at 14.7 psia.

The system consists of 3 beds, inlet valves, a control system, heater and cooler, and a valve module. Each bed is 50 in³ in volume and weighs 1.3 lbs not including the container. The desorption energy requirement is 40–48 W-hr. Valving includes inlet valves to the chemical pumps a delivery regulating valve and a valve module for cycling the desorption process. System operation has one bed absorbing CO₂, one bed Desorbing CO₂ (heating) and one bed cooling. Active temperature control of the beds is considered in order to minimize the bed size and allow for thermal integration with the balance of the system. For example use of waste heat from a Sabatier reactor. System schematic and functional diagrams are presented.

Table 1. Candidate Sorbent Performance Comparison

Sorbent Type	Mass Capacity, g CO ₂ /100 g	Volumetric Capacity, g CO ₂ /100 cu cm
Hydrophobic FCMS	2.55	2.04
Hydrophilic zeolite	1.15	0.92
Solid amine	1.07	0.60

Diffusion analysis at Mars ambient pressure have shown a bed absorption time of only 30 minutes is required for complete saturation. System sizing is dependent upon the specific absorption capacity and temperature coefficients of the sorbent materials. The specific capacities of several candidate sorbents are given in Table 1. The sorbents are Zeolite Molecular Sieve 13X, Solid Amine and AlliedSignal Carbon Molecular Sieve (CMS). A comparison of CO₂ sorbent pumping with these candidates is presented.

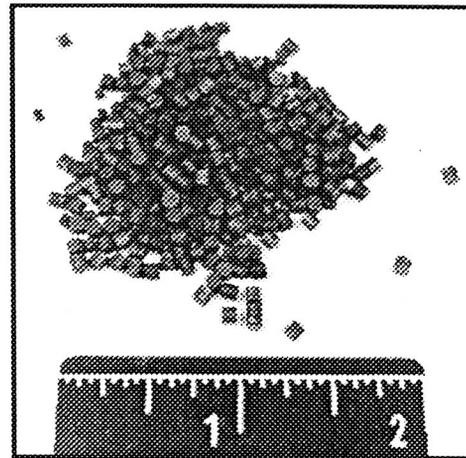


Fig. 1. Pelletized AlliedSignal CMS sorbent.

The AlliedSignal CMS (shown in Fig. 1) is prepared using a patented process and has demonstrated superior carbon dioxide absorption performance. It combines the attractive features of light weight and high capacity. It is currently being developed in support of a NASA research grant studying CO₂ removal from a crewed spacecraft with carbon molecular sieves. The program includes engineering scale tests on a variety of beds which will lead to a flight prototype.

MINING THE MARS ATMOSPHERE. John E. Finn¹ and K. R. Sridhar². ¹Regenerative Life Support Branch, NASA Ames Research Center, Moffett Field CA 94035, USA. (jfinn@mail.arc.nasa.gov), ²Aerospace and Mechanical Engineering, Tucson Arizona 85721, USA, (sridhar@shakti.ame.arizona.edu)

A series of concepts have been developed to mine the atmosphere of Mars and process it to extract or generate compressed carbon dioxide, compressed buffer gas mixtures of nitrogen and argon, water, oxygen, carbon monoxide, and/or carbon. Such products can be of use to science instruments, robotic, and human missions. The products can be for utility purposes, life support, propulsion (both interplanetary and on the planet's surface), and power generation.

The concepts rely on separation, compression, and reaction unit operations. The basic proposed process for separation and compression of Mars gases is based on temperature-swing adsorption. Using the diurnal temperature swing on the surface of Mars as the primary source of energy, the relatively low pressure (6–15 mbar) atmosphere can be compressed to higher pressures (1–2 bar) using an adsorption/ desorption cycle as shown in Figure 1. Higher pressures and mass throughputs are possible if additional heat (such as waste heat from other chemical processes or power plants) is available. Separation of a nitrogen and argon mixture (~4 volume percent of the atmosphere) occurs simultaneously and out of phase with the compression process.

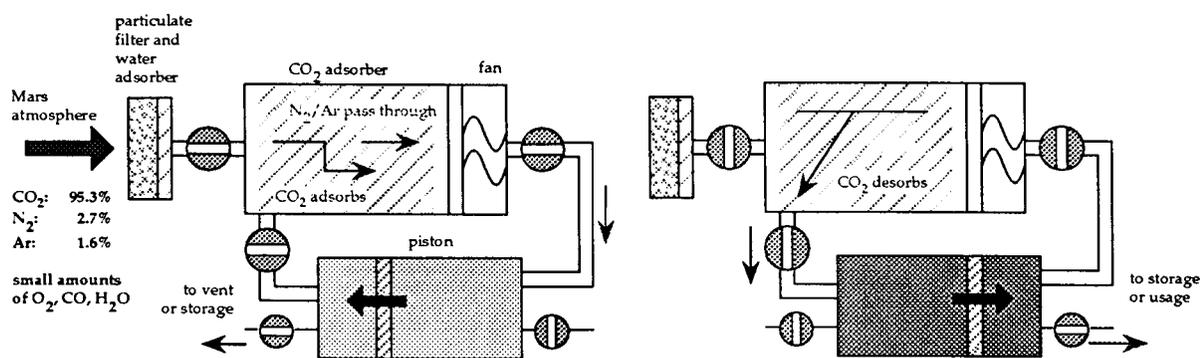


Fig. 1. Simplified schematic of an adsorption-based process for production of compressed pure CO₂ and N₂/Ar gas from the Martian atmosphere. At left, the atmosphere is drawn under cold nighttime conditions through a column that selectively adsorbs CO₂ while N₂/Ar passes through and is collected. At right, the column warms under daytime conditions and desorbs CO₂ at elevated pressure. In this drawing, the CO₂ is used to compress the N₂/Ar mixture.

The feasibility of both separation and compression processes have been demonstrated in the laboratory under simulated Mars temperatures, pressures, and composition (1). Candidate materials (Figure 2) have been identified and their compression performance has been studied in the laboratory (2).

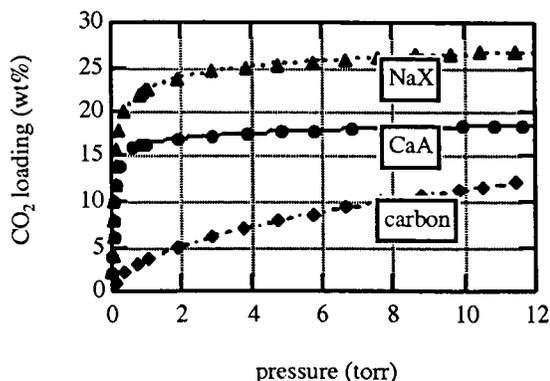


Fig. 2. A series of isotherms obtained at NASA Ames Research Center for CO₂ adsorption on various materials at 200K at Mars surface pressures. Loading data at low and high temperature ranges are used to design adsorption compressors (from ref. 2).

Separation and compression steps can be combined with reaction steps, such as solid oxide electrolysis of CO₂, to form plant designs which are capable of producing a range of useful products from Martian atmospheric raw material. These include the following:

Compressed carbon dioxide: There are several uses for the compressed CO₂ utility gas. In science instruments they can be used to blow dust off optics and instrument interiors, clean specimens, etc. In robotic missions they can be used, among other things, to blow dust off solar panels, inflate panels and structures, give propulsive thrusts to unjam stuck mechanisms, and provide the "feed stock" for propulsion generation plants. In manned missions, the gas can be used for the above applications as well as oxygen generation for life support, and for plant growth chambers. They can also be used as a means of providing the "green-house gas" for an enclosed Mars dome.

Nitrogen and argon mixtures: The gases can be used as a carrier gas in instruments, buffer gas for life support, and as a source of nitrogen for other chemical processes (production of ammonia for example).

Oxygen generation: Oxygen can be produced from the predominantly carbon dioxide atmosphere by a process called solid oxide electrolysis. In this solid state process oxygen and carbon monoxide are produced from the feed gas of carbon dioxide. Oxygen thus produced can be used for propulsion and/ or life support.

Carbon monoxide: Carbon monoxide is the byproduct of the CO₂ electrolysis process. This "fuel" can be used to advantage for Mars surface propulsion, and as a fuel to operate a regenerative fuel cell in the night, if the electrolysis is performed during the day with photovoltaic cells. In this manner, the same CO₂ electrolyzer stack hardware will perform as a fuel cell during the night (an energy storage device with high efficiency).

Carbon: Carbon can be produced by disproportionating the carbon monoxide to produce solid carbon and CO₂. If this process is added to the electrolyzer, the end products of the combined process would be solid carbon and oxygen. Carbon can be used as a fuel, or as valuable carbon fiber that will be used to build reinforced fiber composites.

Water: The small amounts of water present in the atmosphere can be mined using a temperature swing adsorption process. The volume of air that needs to be processed to obtain significant amounts of water is quite high in most locations.

Since the planetary materials required for the above processes come from the atmosphere that is relatively homogeneous, this concept can be site independent as long as it is on the surface of Mars. Most of the processes described here require very little, if any, electrical energy. The primary source of energy for most of the processes comes from the diurnal temperature swing on the surface. Most of the components involved in these processes are solid state, i.e., they have very few moving parts and hence, inherently more reliable. The solid oxide electrolysis technology can be used to extract oxygen in the carbothermal or hydrogen reduction process used for LUNOX from regolith (commonality of technology for Moon and Mars ISRU).

References: (1) Finn, J. E., Sridhar, K. R., and McKay, C. P., "Utilisation of Martian atmosphere constituents by temperature-swing adsorption," *Journal of the British Interplanetary Society*, 49 (11), p.423-430 (1996). (2) Finn, J. E., Sridhar, K. R., and McKay, C. P., "Martian atmosphere utilization by temperature swing adsorption", Paper No. 961597, presented at the 26th International Conference on Environmental Systems, Monterey, California, July 1996.

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MARS IN SITU PROPELLANT PRODUCTION: NEEDS AND TECHNOLOGIES. Michael L. Stancati, Darla J. German, Mark K. Jacobs, John C. Niehoff, Science Applications International Corporation, 1501 Woodfield Road, Suite 202N, Schaumburg Illinois 60173, USA.

The renaissance of Mars exploration that will commence with the arrivals next year of Mars Global Surveyor and Mars Pathfinder, coupled with the discovery of evidence of past microbial life, has created renewed interest in launching a Mars Sample Return (MSR) mission shortly after the turn of the century. Many flight modes and advanced technologies have been proposed to enhance the science return and performance, or to reduce the overall cost of MSR. One of these is In Situ Propellant Production (ISPP): making some or all of the propellant for the return journey at Mars, thus eliminating the need to carry it as dead weight on the outbound Earth-to-Mars leg. Several competing technologies have been proposed for recovering usable propellant constituents at Mars. Because each ISPP alternative requires significant funding and lead-time for technology development, including a possible flight demonstration, the NASA Space Science Enterprise must answer key questions:

- What is the need for ISPP in robotic science missions at Mars?
- What benefit would early development of ISPP have for the Human Exploration and Development of Space (HEDS) Enterprise?
- What ISPP technology approach(es) best suit the Enterprise's need?

Many previous studies have attempted to address one or more of these questions, analyzing and documenting the benefits of ISPP in various mission design and planning contexts. For example, an early study¹ suggested potential performance benefits for several robotic sample return missions to Mars and other targets, and a more recent investigation² highlighted the cost-reducing potential of ISPP for the Space Exploration Initiative's human missions to Mars. Why, then, do the basic questions about ISPP remain under discussion? Why are planners of robotic missions unwilling to baseline ISPP as the technology of choice to enable an affordable sample return from Mars? Because no evaluation has produced an unequivocal statement of the benefits of proceeding in a particular direction.

The Director of Advanced Technology and Mission Studies, Office of Space Science, has charged SAIC to perform an independent assessment (now in progress) that will assist the Space Science Enterprise in answering the questions above. Our approach is to define an evaluation methodology that will enable full and fair comparison of conventional and ISPP-based mission concepts and ISPP technology alternatives, using performance measures of immediate significance to the Enterprise. Recognizing that some of these metrics are quantitative and others are qualitative, we have selected a tool based on the Analytic Hierarchy Process that readily combines numerical and subjective responses to an organized "breakdown structure" view of the elements of the decision. This approach also readily supports collection of expert opinions and group decision-making.

We will describe the approach, the Expert Choice decision-making tool, and the mission set which has been chosen from the Roadmap³. The complete set of evaluation criteria will also be described, and sample cases will be presented. An important aspect of this presentation is to solicit comments and feedback from the attendees of the Technical Interchange Meeting to ensure that the final methodology and criteria are robust and completely represent the ISPP technology alternatives under evaluation.

¹Stancati, M. L., J. C. Niehoff, W. C. Wells, H. Feingold, and R. L. Ash. "In Situ Propellant Production for Improved Sample Return Mission Performance," *Astrodynamic* 1979, Vol. 40, *Advances in the Astronautical Sciences*, American Astronautical Society, 1980, pp. 909-921.

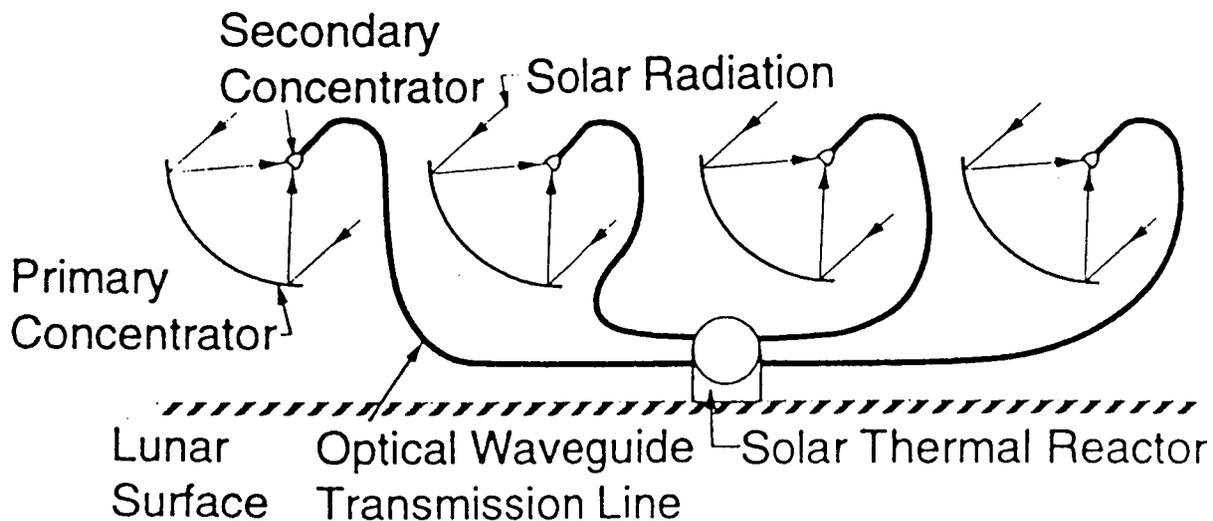
²Jacobs, M. K., J. T. Collins, and M. L. Stancati, "Assessment of potential Benefits from Lunar/Mars Propellant Production for Support of Human Exploration of the Moon and Mars," paper IAA-91-658, 42nd Congress of the International Astronautical Federation, Montreal, Canada, October 5-11, 1991.

³"Mission to the Solar System: Exploration and Discovery," A Mission and Technology Roadmap, Version B, September 27, 1996.

OPTICAL WAVEGUIDE SOLAR ENERGY SYSTEM FOR LUNAR MATERIALS

PROCESSING. T. Nakamura*, J. A. Case, and C. L. Senior, Physical Sciences Inc., 2110 Omega Rd. #D, San Ramon, CA 94583, USA, 510-743-1110, Fax 510-743-1117, (*E-mail: nakamura@psicorp.com).

Abstract. This paper discusses results of our work on development of the Optical Waveguide (OW) Solar Energy System for Lunar Materials Processing. In the OW system as shown in Figure 1, solar radiation is collected by the concentrator which transfers the concentrated solar radiation to the OW transmission line consisting of low-loss optical fibers. The OW line transmits the solar radiation to the thermal reactor of the lunar materials processing plant. The feature of the OW system are: (1) Highly concentrated solar radiation (up to 10^4 suns) can be transmitted via flexible OW lines directly into the thermal reactor for materials processing; (2) Solar radiation intensity or spectra can be tailored to specific materials processing steps; (3) Provide solar energy to locations or inside of enclosures that would not otherwise have an access to solar energy; and (4) The system can be modularized and can be easily transported to and deployed at the lunar base.



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Fig. 1. Optical Waveguide Solar Energy System for Lunar Materials Processing

This work was an SBIR Phase-II program supported by NASA/JSC with the following main objectives: (i) design and fabricate a subscale ground test model of the OW solar energy system; (ii) conduct tests to characterize performance of the OW solar energy system; and (iii) demonstrate lunar material processing. Since its inception in March 1994, the ground test model of the OW solar energy system was constructed and series of performance characterization tests have been conducted. Figure 2 shows the subscale ground test model of the OW solar energy system. As shown in the figure there are two parabolic concentrators mounted on a single axis tracking system. Optical fiber cables placed at the focal points of the concentrator transmits the solar energy inside of the laboratory where the concentrated solar radiation enters the thermal reactor for a high temperature material processing.

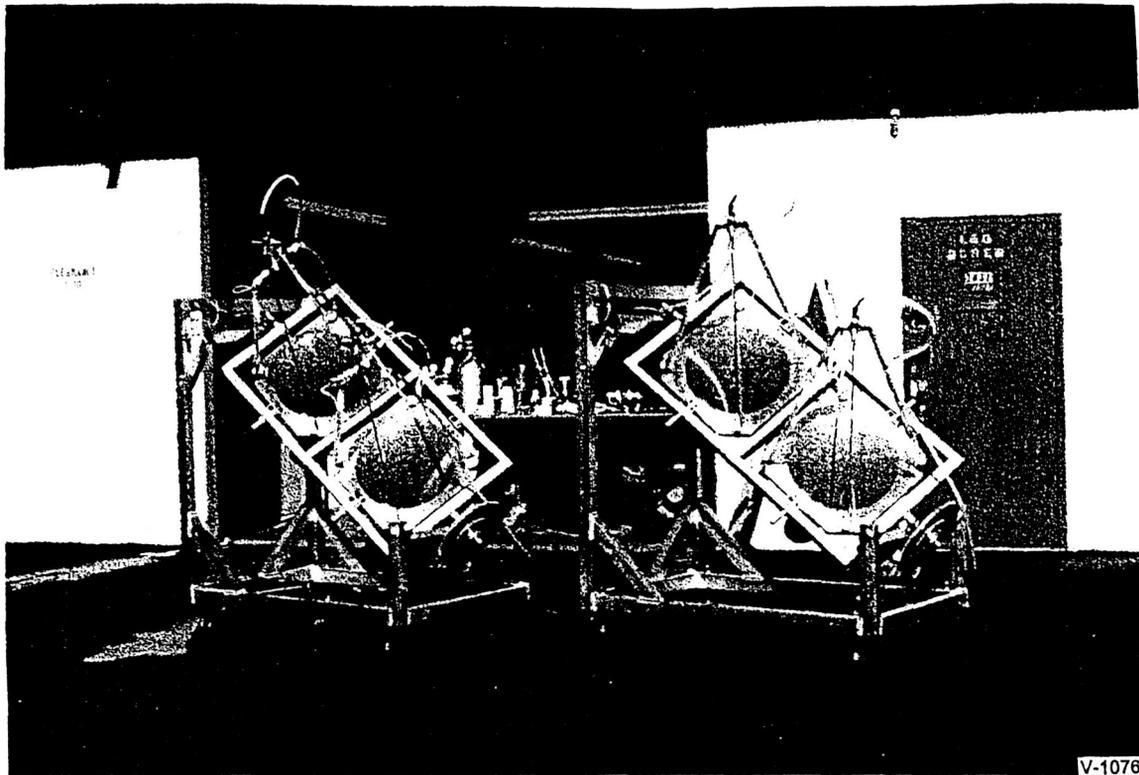


Fig. 2. Subscale ground test model of the OW solar energy system

We have successfully completed a series of materials processing demonstration experiments using ilmenite and the simulated lunar soil (JSC-1) with hydrogen to reduce the oxides at 830°C. The thermal reactor used for the process demonstration has four light injection ports, each of which incorporates 37 optical fibers, inject solar radiation through a narrow slit on a multi-layer radiation shields at the material processing container which will be heated to the processing temperature. In addition to material processing experiments, we have conducted a series of photovoltaic power generation test using the high concentration solar power delivered by the optical fibers. In this experiment, high concentration GaAs cell made by Research Triangle Institute (RTI) was used to generate power. Results obtained to date show that the GaAs cell generated power at 300 sun intensity without performance deterioration. Detailed discussion of the whole program will be presented in the conference paper.

THIN FILM SOLAR CELL GROWTH ON THE SURFACE OF THE MOON BY VACUUM EVAPORATION. A. Ignatiev, A. Freundlich, and T. Kubricht, Space Vacuum Epitaxy Center, University of Houston, Houston TX 77204-5507, USA.

The need for significant electrical power on the surface of the Moon, and the unique ultra-high vacuum environment of the Moon can allow for the direct fabrication of solar cells on the lunar surface by vacuum evaporation. The availability of significant electric power at the surface of the Moon will be principal driver defining the complexity of a future lunar base. Proposals to generate power on the Moon include both nuclear and solar (photovoltaic) systems. The main drawback to all of the approaches to date is that all of the mass for the power system must be transported from the Earth to the Moon. For the lunar base this could amount to over 40 metric tons to the Moon for the utilization phase.

A more efficient and synergistic approach is to attempt to utilize existing lunar resources to generate the electric power system. The synergism occurs from the fact that there is an ultra-high vacuum environment on the surface of the Moon, and that there are materials present on the Moon from which thin film solar cells could be made within this vacuum environment. The vacuum environment is directly applicable to the vacuum deposition growth of thin film solar cells, and there have already been lunar regolith processing techniques proposed that would have as by-products elemental materials that could be specifically used to generate thin film solar cells. As a result, thin film solar cell production on the lunar surface with *in situ* resource utilization is a viable approach for electric power generation on the Moon.

Lunar resource utilization has focused principally on the extraction of oxygen from the lunar regolith. These processes have as their by-products (or more directly as their "waste products") materials such as iron, silicon, and magnesium, and these materials are the ones specifically needed for the fabrication of silicon solar cells. Pressures on the surface of the Moon are generally in the 1×10^{-10} Torr range or better, thus representing a near-ideal environment for direct vacuum deposition of thin film silicon solar cells using the "waste" silicon present on the Moon.

The quality of the "waste" materials may be poor as the impurity levels will probably be beyond those acceptable for "solar cell-grade" materials. As a result, a reduction of efficiency is to be expected unless additional purification is undertaken. However, since an aim of the lunar initiative is to use *in situ* lunar resources, a decrease of efficiency can be tolerated and compensated for by simply growing more net cell area.

The proof-of-concept direct lunar vacuum evaporation of solar cells promises to be a major impact to lunar utilization. Not only will major amounts of mass-to-orbit be reduced by this technique, but it will also clearly demonstrate full utilization of lunar resources for power generation. The extent of this process and application of this philosophy to future planetary explorations is unlimited.

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**IN SITU RESOURCE UTILIZATION (ISRU) TECHNICAL INTERCHANGE MEETING:
OVERVIEW OF RESEARCH FOR LUNAR OXYGEN PROCESSING AT CARBOTEK
DEVELOPMENT LABORATORIES.** J. D. Ortego, Jr., L. L. Sorge, M. Guo-Murray, M. A. Gibson, and
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Abstract: Oxygen production from indigenous lunar material is considered an enabling technology for future solar system exploration. Lunar derived oxygen provides many lunar base program enhancements. A great mass benefit can be derived when Earth return propellant oxidizer is not manifested for transit vehicles traveling to the moon. This results in substantial cost savings to the overall space transportation infrastructure. In addition, lunar produced oxygen can be used to supplement life support systems. Finally, many of the lunar oxygen processes under development produce by-products which are excellent construction materials, rich in iron and titanium, for shielding habitats and lunar surface equipment from cosmic radiation and more lethal solar flares. As a result of the apparent benefits of lunar derived oxygen, NASA has funded research for the development of promising techniques since the mid-1980's in order for the technology to be available for lunar return missions. Carbotek, with funding and technical assistance from NASA Johnson Space Center and the Shimizu Corporation, Space Systems Division, has been developing oxygen producing technology since 1984. This paper describes past and future work by Carbotek on two processes, hydrogen reduction of ilmenite and magma electrolysis.

Carbotek began developing a process for oxygen production from ilmenite-rich lunar deposits in 1984 to support NASA's lunar base operations and large-volume propulsion needs under the technical guidance of Dr. David McKay of JSC. Carbotek proposed the reduction of iron oxide in ilmenite by hydrogen at elevated temperatures in a three-stage fluidized bed reactor. Water vapor formed by the reduction reaction is electrolyzed to produce product oxygen, which is liquefied and stored, and hydrogen, which is recycled to the reactor. Reaction rate, thermodynamic equilibrium, and lunar-gravity fluidization behavior are key factors which have been considered in the development activity. NASA awarded Carbotek two Phase I and one Phase II SBIR contracts, which provided approximately \$800,000 for this development work from late 1984 through early 1989. Shimizu Corporation provided approximately \$700,000 for the fluidized-bed reactor process development plus the technical support of several of their engineers from 1991 through the present. Two U.S. Patents were granted in 1990, one for the oxygen process and another for a lunar hydrogen production process.

A Plexiglas two-dimensional bed was constructed to measure bubble sizes at lunar gravity on NASA's KC-135 aircraft to develop fluidized bed reactor design criteria. Four lunar simulants were filmed while fluidizing at lunar gravity for digital analysis of the video data. Analysis revealed that a linear relationship clearly exists between the bubble size and vertical bed position. A key observation was the size of the bubbles is inversely proportional to the particle density of the test solids. Solids with low particle density such as glass beads form larger bubbles than the more dense MLS-1 and Florida ilmenite fractions. Also, a theoretical correlation relating bubble rise velocity as a function of bubble diameter and gravity was verified by these tests. A comprehensive data set now exists making it possible to predict the bubble size and rise velocity of numerous lunar starting materials for fluidized bed lunar oxygen processes.

Another objective has been the understanding of standpipe behavior in fluidized beds at lunar gravity and to provide solids friction factors at 1/6 g for predictive design. A total of 10 flights have been conducted aboard NASA's KC-135 variable gravity airplane to aid in the understanding of this behavior. A variety of materials were tested during these flights including glass beads with air, and Florida ilmenite, and JSC-1 and SMZ-1 lunar soil simulants with helium. The flights proved to be successful and the information obtained was used to improve the test hardware and procedures for successive flights. An empirical formula for solids velocity versus friction factor was determined for the glass beads and air. Since the necessary equations contain the gravity term explicitly, this relationship can be combined with existing 1-g data to properly size standpipes for a lunar multi-stage fluidized bed reactor system.

In addition to mechanical design issues, Carbotek has studied the chemistry and kinetics of terrestrial ilmenite and lunar ilmenite. For the first time, water/oxygen production from Apollo program lunar samples has been experimentally demonstrated. A 10 gram sample of lunar basalt designated 70035/96 was obtained from NASA and used in seven separate reactivity experiments varying temperature and pressure. The experiments gave extremely encouraging results as all ilmenite was reduced in every

experiment. Water production was followed continuously during reduction, and these data were analyzed kinetically. Quantitatively, the data were best represented by a shrinking core process in which both chemical reaction and diffusion play significant roles. Reaction rate showed only a 0.15 order dependence on hydrogen concentration, and rate and diffusion constants were such that lunar ilmenites were initially about twice as reactive as terrestrial ilmenites.

With funding provided by NASA Johnson Space Center, Small Business Innovation Research (SBIR) program, and under the technical guidance of Dr. Thomas Sullivan of JSC, Carbotek initiated an aggressive scale-up of the magma electrolysis process invented by Drs. Haskin and Colson. In this process, lunar feedstock is heated to high temperature (1400°C+) to transform the material into a molten state (magma). Using a platinum/rhodium anode, and an iron cathode, the molten feedstock is electrolyzed in a process similar to that of alumina electrolysis. Oxygen trapped in the mineral phase is liberated and forms as gaseous bubbles on the surface of the anode, proceeding to rise through the melt and burst on the surface. The oxygen is carried out of the electrolysis cell by a stream of inert gas where it is separated and collected as a direct product of the process.

Carbotek's scale-up was approximately one thousand, which was a substantial leap in the technology. Key areas of the design included a large high temperature furnace system with material feed and extraction systems; large Pt/Rh anode ring systems capable of variable position; and an electrolysis power and gas analysis system. These challenges alone proved very difficult, but satisfactory design solutions were achieved.

The major obstacle proved to be melt containment. Due to these unforeseen melt containment problems, actual electrolysis runs were not possible. During this work, it was discovered that spinel (in its current form) is not suitable for containing the synthetic oxide melts. Tests performed at Carbotek and JSC suggest that the melt infiltrates the spinel pore space and grain boundaries. Liquid diffuses into the crucible, grain recrystallization and growth occurs and the spinel loses mechanical strength. As a result the spinel becomes more permeable and does not contain the melt. In order to answer the many questions of long duration melt containment, a new research program should be implemented to research materials problems alone. The basis of this work could then lead to further magma electrolysis tests using the equipment and system designed and confirmed by Carbotek.

Carbotek's current work involves funding from NASA, through SAIC, for the design and operation of a 3 in. single-stage batch fluidized bed system. This will be Carbotek's first kg-scale demonstration of the hydrogen reduction fluidized-bed process. In addition, Carbotek has recently been awarded, with Physical Sciences Inc. (PSI) serving as a subcontractor, a NASA SBIR Phase I contract to couple PSI's solar optical waveguide system with Carbotek's fluidized bed reactor.

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PROSPECTIVE ROLES OF LUNAR/MARTIAN CONCRETE IN SPACE PROGRAMS. T. D. Lin, Lintek International, Inc.

The recent discoveries of possible life on Mars and a huge ice lake in the lunar south pole region have had great impacts on our thinking toward the Mars exploration and lunar development. The 21st century appears to be an exciting era in which mankind may build bases on the Moon and conduct manned missions to Mars.

Data on the returned lunar materials, Martian soil collected by the Viking landers, and a Martian meteorite (ALH 84001) reveal a wide range of engineering applicability for these extraterrestrial materials. A substantial number of papers presented during recent space symposia and seminars advocate the utilization of space resources for productions of noble and common metals, oxygen and water, Helium-3 for fusion power generation, and construction materials. Construction on the Moon and possibly on Mars will be the logical goals for the next major national space programs.

Solar system resources will undoubtedly offer tremendous commercial opportunities to space entrepreneurs. Space tourism, space industrialization, oxygen and He³ storage facilities, lunar landing/launching ports, and surface transportation support systems all require major construction involving the use of enormous volumes of building materials. The concept of transporting needed construction materials from Earth is economically impossible due to the high transportation cost (\$10,000/kg to the Moon). The only viable alternative is to beneficiate or process local lunar materials with simple operation procedures to make high performance structural elements. One such alternative is to use concrete since virtually all needed materials are readily available on the Moon.

Substantial studies on the production of cement, water, reinforcing bars, and aggregates from lunar materials have been carried out in the last decade, including a lunar concrete cube made with forty grams of actual lunar soil used as aggregate. The measured strength of the tested lunar concrete cube exceeds 700 kgf/cm² (10,000 psi), twice the minimum strength required by the ACI Building Codes in designing concrete columns. This is a convincing evidence that supports the validity of the lunar concrete concept.

The hydrogen reduction process has been successfully demonstrated in producing oxygen and water from lunar ilmenite by other researchers. The residue of the process is a combination of iron and titanium oxide that can be extruded to form reinforcing bars or fibers. The availability of ice on the Moon will eliminate the need for water production and further reduce the production cost of concrete on the Moon.

Concrete, the most widely used construction material since the invention of Portland cement in 1824, is a versatile material capable of withstanding solar radiation, lunar temperature extremes, high compressive stresses, and moderate tensile stresses if reinforced with fibers. The engineering properties of concrete have been well documented. The profound concrete technology developed in the last 170 years can be applied to the envisioned planetary construction with slight modification to accommodate the effect of the vacuum on concrete casting.

In 1990-91, an innovative Dry-Mix/Steam-Injection (DMSI) procedure was developed solely for the purpose of casting concrete in space. The procedure is rather simple and straightforward. It involves mixing cement and aggregate in a dry state and exposing the mixture to a 180 C steam in a confined chamber for 18 hours. Surprisingly, concrete thus made develops a strength of 700 kgf/cm², two and half times that of companion cubes made with the same mix proportion, using the conventional wet-mix procedure which requires 28 days to develop the desired design strength. The rapid hydration shortens the manufacture time while the high strength development increases the product quality of concrete. The DMSI method will be an added spin-off benefit of space technology to the terrestrial precast concrete industry.

Conceivably, the existing solar energy, robotic, and remote control technologies can be integrated to form a remote-control lunar cement/concrete production system. A remote-control semi-autonomous manipulation system (Skaar, University of Notre Dame) with a human supervisor unit stationed on Earth will minimize the need for a human presence at the lunar sites. The proposed remote-control concrete production system can be designed, assembled, and thoroughly tested here on Earth prior to transporting to and installing on the Moon. Once established, the system can be repeatedly used to produce concrete without astronauts attending the job sites on the Moon.

At the Fifth International Conference on Engineering, Construction, and Operation in Space held in Albuquerque, New Mexico, June 1996, David McKay and Carlton Allen presented a paper, "Concrete - A Practical Construction Material for Mars." The paper reveals that key materials including water (polar ice) required for the manufacture of concrete are much more readily available on Mars than on the lunar surface. A hardened concrete, however, may be attacked (carbonation) by the Martian atmosphere that consists mainly of carbon dioxide. The carbonation reaction is of a long term process, it may take a few years of direct exposure to carbon dioxide for concrete to disintegrate. A preliminary test program to determine such effect is in progress. Partial test data will be available for discussion during the forthcoming In-Situ Resource Utilization (ISRU) Technical Interchange Meeting.

REGOLITH EVOLVED GAS ANALYZER (REGA). Carlton C. Allen¹ and David S. McKay²,¹Lockheed Martin Engineering and Sciences, Houston, TX 77058, USA, (allen@snmail.jsc.nasa.gov), ²NASA Johnson Space Center, Houston, TX 77058, USA, (mckay@snmail.jsc.nasa.gov).

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REGA, the Regolith Evolved Gas Analyzer, is a flight instrument under development at the NASA Johnson Space Center (1). REGA is designed to measure volatiles and their interactions with the regolith on a variety of solar system objects. For bodies such as the Moon or asteroids, the *Evolved Gas Analysis* mode of operation will provide identification and quantitative data on volatile species evolved from the sample at various programmed temperature steps (2). Priority lunar targets include samples from permanently shadowed craters and the regolith of volcanic terrain containing volatiles from outgassing. The *Regolith Reactivity Analysis* mode will provide quantitative data on the interactions of planetary surface materials with a variety of gases. In the lunar application, regolith samples can be heated and reacted with hydrogen to liberate oxygen (3). REGA's *Atmospheric Composition Analysis* mode employs the mass spectrometer run in a configuration open to the atmosphere. Assuming that the spacecraft outgassing background can be overcome, this analysis will provide quantitative compositional data, including isotopic abundances (4). The mass spectrometer will monitor the atmosphere over time and may detect transient gas events (5).

The instrument consists of five subsystems: (I) a programmable furnace which can be loaded with samples of regolith, (II) a mass spectrometer which detects and measures atmospheric gases or gases evolved during heating, (III) a tank of pressurized gas which can be introduced to the regolith material while detecting and measuring volatile reaction products, (IV) a mechanism for dumping the regolith sample and repeating the experiment on a fresh sample, and (V) a data system which controls and monitors the furnace, gas system, and mass spectrometer. A schematic of the REGA instrument components is shown in Figure 1.

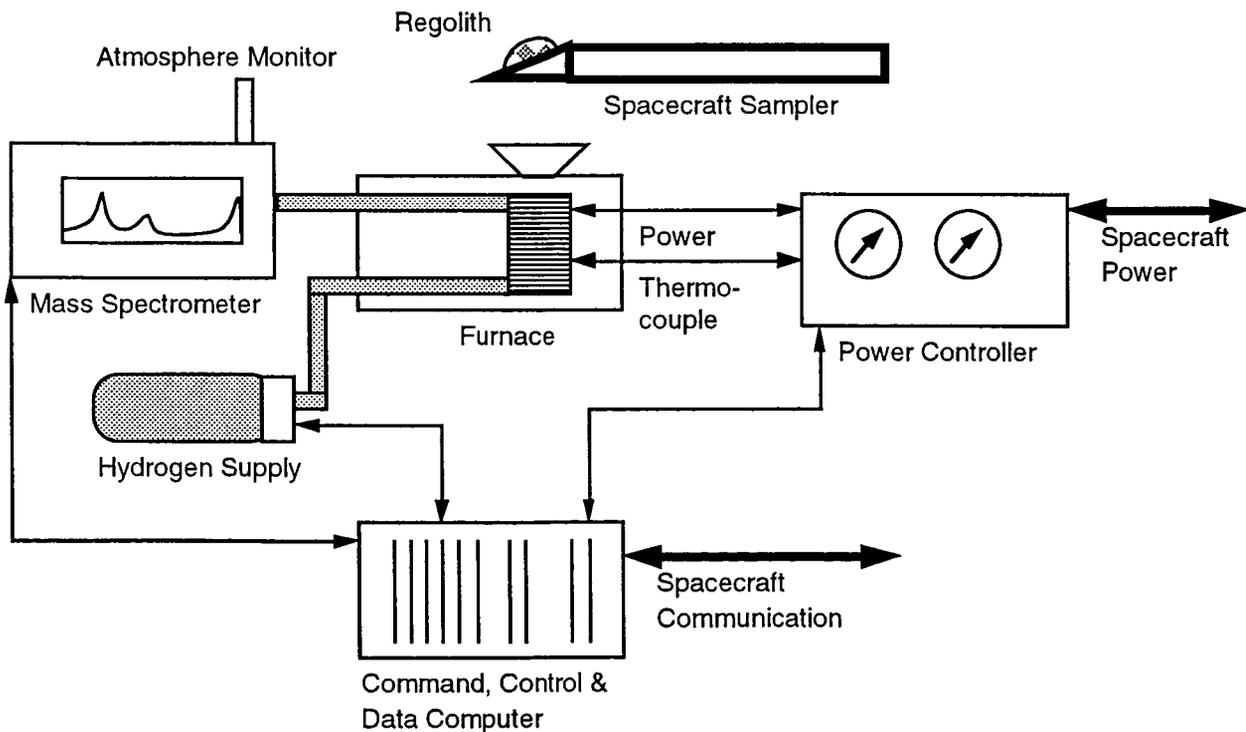


Fig. 1. REGA schematic (lunar configuration).

REGA is currently in the final year of development. The project includes design and prototyping of the furnace unit, sample load/dump system, gas plumbing, mass spectrometer, and data system, followed by integration of the various subsystems into a single functional instrument. To date we have:

- Fabricated four prototype furnaces and two heater models for full scale testing
- Fabricated a gas delivery system
- Integrated the REGA furnace prototype with a mass spectrometer
- Demonstrated that the prototype furnace can repeatedly heat 1 g of lunar soil simulant to 900°C in a hydrogen atmosphere to produce water
- Quantified the effects of composition, temperature, and hydrogen flow rate on oxygen yield from 19 lunar soil and glass samples

During FY97 we plan to construct and test a complete initial REGA prototype, optimize the design in a second instrument, and fabricate and program the control system. A parallel effort will complete a small dedicated mass spectrometer for integration into the REGA instrument. Specific tasks planned for FY97 include:

Prototype Construction

- Purchase materials and components for prototype construction
- Have custom mechanical parts machined
- Breadboard electrical circuitry
- Assemble REGA Alpha prototype instrument
- Test REGA Alpha prototype instrument
- Detail any mechanical and/or electrical design changes required

Prototype Optimization

- Purchase additional materials or components required
- Have any new parts machined or existing parts altered
- Complete any required alterations of the breadboard electronics
- Assemble REGA Beta prototype instrument
- Test REGA Beta prototype instrument

Programming and Evaluation

- Design algorithm and program visual control and monitor software
- Debug control and monitor software
- Evaluate complete REGA prototype system

Mass Spectrometer Fabrication and Testing

- Fabricate mass spectrometer
- Integrate mass spectrometer with REGA Beta prototype
- Test and optimize performance of integrated unit

The final product of our three year effort will be a fully operational breadboard instrument. All REGA subsystems will be designed such that they can be upgraded for space qualification. We intend to produce an instrument with sufficient maturity that it can be successfully proposed for a variety of lunar and planetary missions.

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A QUANTITATIVE METHODOLOGY FOR MISSION ARCHITECTURE AND FIGURE-OF-MERIT WITH ISRU AND COMPARISONS WITH A BASELINE. Kumar Ramohalli and Massimiliano Marcozzi, Space Engineering Research Center, 4717 East Fort Lowell Road, Tucson Arizona 85712, USA. Sponsor: NASA Headquarters

The purpose of this paper is to present a quantitative methodology for comparisons of various mission architectures in the specific context of Mars Sample Return; there have arisen several doubts lately regarding the meaningful comparisons of missions that use widely diverse architectures.

The fundamental advance made here is in the incorporation of the Technology Readiness Levels of various components into the systematic evaluation of the overall mission impact. Quoting from several recent papers (mostly in the area of space economics) it is recognized that the TRL's do affect the mission cost, while the probability of success(failure) is not that readily amenable to the TRL approach. Several simple techniques for introducing the TRL value into the spreadsheet are presented.

As a first example, nine different options are considered for the return vehicle. Using well proven numbers for the performance (specific impulse, structural factors,...), the landed mass on Mars is calculated. The ISRU options are: Sabatier and Solid Oxide technologies.

The paper also includes a detailed analysis of the Mars Ascent Vehicle performance in the Martian atmosphere, including the aerodynamic aspects.

The output is presented in the form of bar charts for the mass. It is a flexible approach and can be changed with technology advances.

PRODUCTION OF OXYGEN FROM CARBON DIOXIDE USING ZIRCONIA ELECTROLYSIS CELLS.

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The generation of oxygen from carbon dioxide has been identified as one of the key In Situ Resource Utilization (ISRU) processes for future Mars missions. One promising method for oxygen generation is to electrolyze carbon dioxide taken from the Martian atmosphere with zirconia electrolysis cells. A zirconia electrolysis cell consists of two electrodes (the anode and cathode) separated by a zirconia electrolyte. Carbon dioxide is fed to the cathode, accepts electrons from the external circuit, and undergoes a reduction reaction to form carbon monoxide and oxide ions. Oxide ions are conducted through the zirconia electrolyte to the anode. At the anode, oxygen ions combine (undergo an oxidation reaction) to produce oxygen and release electrons to the external circuit. A direct-current power source provides the electron flow from the anode to the cathode in the external circuit. Zirconia cells operate in the temperature range of 600° to 1000°C. The overall reactions are as follows:



Zirconia cells have been developed as fuel cells (commonly referred to as solid oxide fuel cells or SOFCs) for terrestrial electric power generation using either hydrogen or hydrocarbon as fuel. This type of cell has also been considered for oxygen separation and oxygen compression. AlliedSignal has developed SOFC technology for military and commercial applications and has demonstrated an innovative and simple process based on tape calendering for making thin (1 to 10 micrometer) zirconia electrolyte cells. This process is equally well suited for the fabrication of lightweight, high-performance zirconia electrolysis cells for oxygen production from carbon dioxide. A schematic diagram of the tape calendering process for SOFCs is shown in Figure 1. In this process,

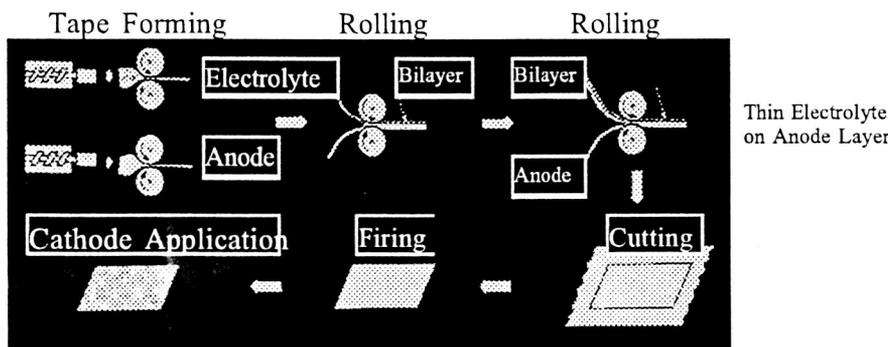


Fig. 1. Schematic for SOFC tape calendering process electrolyte and anode powders are first mixed with organic binders to form green (unfired) ceramic masses. The masses, having a doughy consistency with many of the characteristics of a plastic, are rolled into tapes using a two-roll mill. Electrolyte and anode tapes of prescribed thickness ratios are laminated and rolled into a bilayer. This thin bilayer is then laminated with another thick anode tape, and the laminate is rolled again into a thin bilayer tape. The process can be repeated with different tape thickness ratios until a desired electrolyte film thickness is obtained. In general, the process requires only three rollings to achieve a bilayer with micrometer-thick electrolytes. The bilayer is fired at elevated temperatures to remove the binders and sinter the ceramics. A cathode layer is applied on the electrolyte surface of the sintered bilayer to produce a complete cell. The microstructure of a typical SOFC cell fabricated by this process is shown in Figure 2. SOFC cells up to 400 cm2 area have been produced.

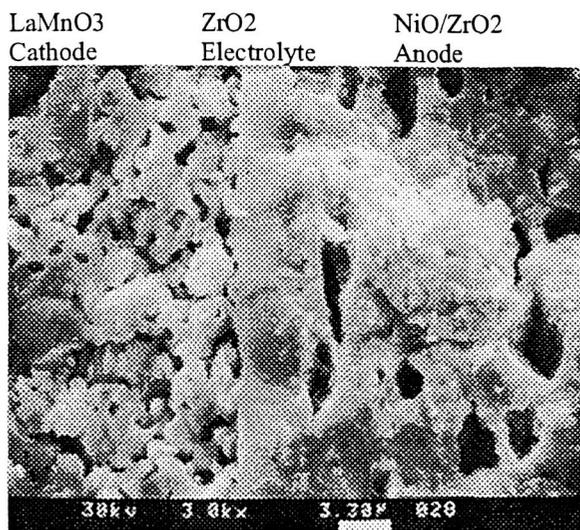


Fig. 2. Thin Electrolyte Cell

Using the AlliedSignal fabrication process, extraordinarily high power densities at lower temperatures (1.03 kW/kg and 0.9 kW/L at 800°C) have been achieved. For carbon dioxide electrolysis, the high power density and relatively low temperature mean lighter weight, smaller volume, and reduced power are needed to produce the required amount of oxygen. For ISRU missions, these performance advantages translate directly into reduced cost and reduced weight and volume, both for the system and for associated power generation equipment.

This paper discusses the tape calendering process and its potential application in fabrication of lightweight, high-performance ISRU zirconia cells for oxygen production from Martian carbon dioxide.

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OXYGEN PRODUCTION ON MARS USING SOLID OXIDE ELECTROLYSIS. K. R. Sridhar,
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Introduction: If oxygen for propulsion and life support needs were to be extracted from martian resources, significant savings in launch mass and costs could be attained for both manned and unmanned missions. In addition to reduced cost the ability to produce oxygen from martian resources would decrease the risks associated with long duration stays on the surface of Mars. One method of producing the oxygen from the carbon dioxide rich atmosphere of Mars involves solid oxide electrolysis. A brief summary of the theory of operation will be presented followed by a schematic description of a Mars oxygen production plant and a discussion of its power consumption characteristics.

There are many ways in which solid oxide electrolyzers can be used on Mars missions. Some of them are:

- oxygen generation for use as a propellant with Earth-carried fuel,
- make-up oxygen generation for a Sabatier and water electrolysis system,
- compression of the oxygen generated for liquefaction and/or storage,
- production of both carbon monoxide and oxygen for use as propellant for intra-planetary and inter planetary travel, and
- as a regenerative fuel cell to provide power during the night from the excess carbon monoxide and oxygen generated during the martian day using solar power.

Principle of Operation: A solid oxide electrolysis cell works on the principle that, at elevated temperatures, certain ceramic oxides, such as yttria-stabilized zirconia (YSZ) and doped ceria, become oxygen ion conductors. The basic configuration of an electrochemical cell is shown in figure 1. A thin nonporous disk of YSZ (solid electrolyte) is sandwiched between two porous electrodes. For oxygen generation from carbon dioxide, CO₂ diffuses through the porous electrode (cathode) and reaches the vicinity of the electrode-electrolyte boundary. Through a combination of thermal dissociation and electrocatalysis, an oxygen atom is liberated from the CO₂ molecule and picks up two electrons from the cathode to become an oxygen ion. Via oxygen ion vacancies in the crystal lattice of the electrolyte, the oxygen ion is transported to the electrolyte-anode interface due to the applied d.c. potential. At this interface the oxygen ion transfers its charge to the anode, combines with another oxygen atom to form O₂, and diffuses out of the anode.

A simple schematic of the production of CO and CO₂ from solid oxide electrolyzers is presented in figure 2. A blower moves the martian atmosphere through a dust filter to a zeolite temperature-swing adsorption compressor. The compressor utilizes the diurnal cycle of Mars for the temperature swing. The compressed CO₂ is dissociated in an electrolyzer and collected for storage/liquefaction. The CO and CO₂ stream from the electrolyzer stack is separated into CO and CO₂ in a molecular sieve bed.

The start-up and steady state operating characteristics of the electrolyzer are shown in figure 3. The power characteristics are based on current experimental data that have been extrapolated based on reasonable advances in the future. A schematic for the storage and liquefaction of oxygen using solid oxide electrolyzers is shown in figure 4.

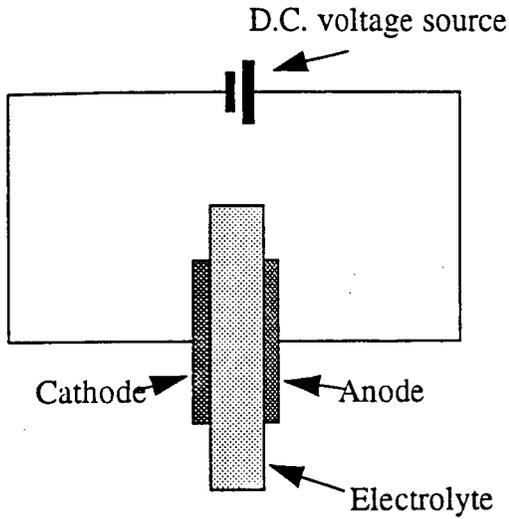


Figure 1. Electrochemical Cell Schematic

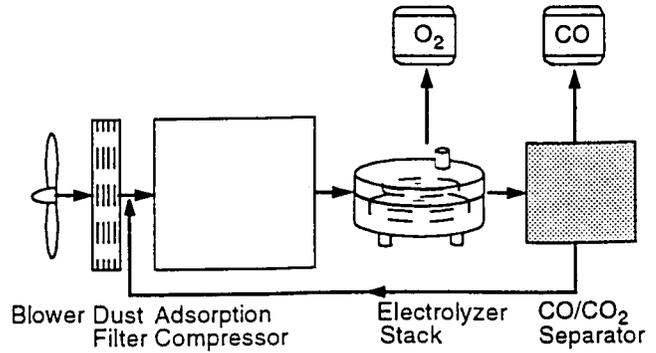


Figure 2. Oxygen plant Schematic

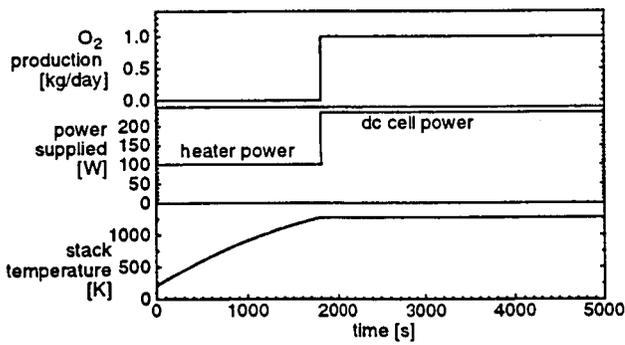


Figure 3. Operating Characteristics of Stack

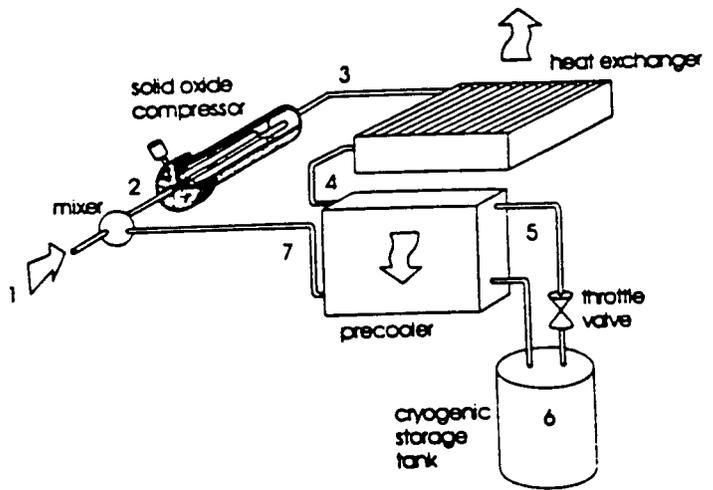


Figure 4. Oxygen Liquefaction and Storage

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A CHEMICAL APPROACH TO CARBON DIOXIDE UTILIZATION ON MARS. Aloysius F. Hepp, National Aeronautics and Space Administration, Lewis Research Center, Cleveland OH 44135, Geoffrey A. Landis, Ohio Aerospace Institute, 22800 Cedar Point Road, Brook Park OH 44142, and Clifford P. Kubiak, Department of Chemistry, Purdue University, West Lafayette, IN 47907

We describe several novel proposals for CO₂ reduction through chemical, photochemical, and photoelectrochemical means. The approach involves coupled catalytic cycles to simultaneously produce oxygen and carbon monoxide. Efficient metal catalysts and photocatalysts are to be used for both half-reactions: i) the reduction of CO₂ to CO; and ii) the evolution of O₂. Photolytic reduction of CO₂ to CO and oxygen can occur under mild conditions using a series of recently synthesized trinuclear nickel catalysts. Nickel cluster catalysts hold great promise because of the proven ability of nickel cluster materials to catalyze the reduction of CO₂ to CO. This can be coupled with photocatalytic or photoelectrochemical systems for oxygen evolution to accomplish the overall "splitting" of CO₂ to CO and O₂. A newly-synthesized copper dimer provides an alternative catalyst for the electrochemical "splitting" of CO₂ (solar cells could provide energy). In another concept, p-GaP, which has nearly ideal band placement for photocathodic reduction of Ni₃ cluster electrocatalysts for CO production, coupled with anodic oxygen evolution produces a photoelectrochemical device (see scheme). Finally, a purely photochemical system could employ Pt co-catalysts with the nickel catalysts to result in the "splitting" of CO₂. One goal of our effort is to design photochemical and photoelectrochemical systems for the extraterrestrial manufacturing of products required to sustain a human presence on Mars from atmospheric carbon dioxide. Another goal of our work is to design simple proof-of-concept experiments to demonstrate the use of these technologies on Mars. Our overall goal with a chemical approach is to point out the vast amount of chemistry and photochemistry that is known for CO₂ and CO with metals and metal compounds. Our hope is to reinvigorate the debate over the technologies to be used to exploit in-situ resources. With an enhanced arsenal of technologies available to combat the challenges of distance, time, and hostile environment, the dream of human exploration of the solar system may become a reality

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INVESTIGATION OF THE REVERSE WATER GAS SHIFT REACTION FOR PRODUCTION OF OXYGEN FROM MARS ATMOSPHERIC CARBON DIOXIDE. Tom Meyer¹ and Robert Zubrin², ¹Boulder Center for Science and Policy, P.O. Box 4877, Boulder Colorado 80306, (303) 494-8144, -8446 FAX meyertr@colorado.edu, ²Pioneer Astronautics, 445 Union Blvd., Suite 125, Lakewood CO 80228, USA.

This presentation will report on progress of the first phase of the project titled Mars In-situ Resource Utilization Research (MIRUR) being performed under a NASA ACRP grant, Robert Zubrin, PI and Tom Meyer co-investigator. The MIRUR proposal is a plan to undertake a study of Mars in-situ resource utilization strategy and applications centered upon exploiting the unique potential of the reverse water gas shift (RWGS) reaction as a means of producing oxygen, water, storable fuel, and other hydrocarbon materials on the surface of Mars out of Mars atmospheric carbon dioxide and other readily available indigenous materials.

The first phase of the research includes a comprehensive analytical study examining the potential applications for engineering subsystems and mission strategies made possible by such RWGS based subsystems, and will include an actual experimental demonstration and performance characterization of a full-scale brassboard RWGS working unit. By the time of this presentation the laboratory demonstration unit will not yet be operational but we will present the results of our analytical studies to date and plans for the ongoing work.

The reverse water gas shift (RWGS) reaction has been known to chemistry since the mid 1800's. While it has been discussed as a potential technique for Mars life support and propellant manufacture in the literature, there has been no experimental work done to demonstrate its viability for such applications to-date. The RWGS reaction is given by equation,



This reaction is mildly endothermic and will occur rapidly in the presence of an iron-chrome catalyst at temperatures of 400°C or greater. Unfortunately at 400°C the equilibrium constant Kp driving it to the right is only about 0.1, and even at much higher temperatures Kp remains of order unity. Thus there is a significant problem in driving the RWGS reaction to completion.

However, assuming that reaction can be driven as written, an oxygen production system can be created by coupling the above reaction with a water electrolysis reaction. That is, the CO produced by the above reaction is discarded while the water is electrolyzed to produce oxygen (the net product), and the hydrogen can be recycled to reduce more carbon dioxide. Barring leakage losses, if all of the hydrogen is recycled, this process can go on indefinitely. The only reagent needed is a small amount of water which may be imported or obtained from indigenous sources.

Since the RWGS reaction is mildly endothermic and does not go to completion, ways must be found to shift it further toward the right, that is further toward completion. There are a number of ways that this could be accomplished. These are:

- a) Overload the reactor with CO₂ to force the complete consumption of H₂, and then recycle the excess CO₂ in the exhaust stream back into the reactor.
- b) Overload the reactor with H₂ to force the complete consumption of the CO₂, and then recycle the excess H₂ in the exhaust stream back into the reactor.
- c) Operate a system that removes water vapor from the reactor, thereby driving the reaction to the right. Such a system could either be a desiccant bed or condensing apparatus.

d) A combination of approaches (a) and (c).

e) A combination of approaches (b) and (c).

This presentation will discuss the anticipated results from applying these strategies including estimates of the yields and energy costs and review the practical problems. We will also review the overall goals of the project, compare the advantages and disadvantages of other systems for the production for oxygen, and discuss the possible mission strategies made possible by RWGS.

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RADIO-FREQUENCY-BASED GLOW-DISCHARGE EXTRACTION OF OXYGEN FROM MARTIAN ATMOSPHERE: EXPERIMENTAL RESULTS AND SYSTEM VALIDATION STRATEGIES. L. Vuskovic, Z. Shi, R. L. Ash, S. Popovic, and T. Dinh, Physics Department, Old Dominion University, Norfolk Virginia 23529, USA.

Abstract: Extraction of oxygen from Mars atmosphere was identified very early as a near-term opportunity for in situ resource utilization (ISRU) which could enable round-trip missions to Mars using existing space launch capabilities [1]. Since 1979, stabilized zirconia electrochemical cells have been studied as elements of oxygen production systems that operate using thermal dissociation of CO₂ (which constitutes 95.32% of the Mars surface atmosphere [2]) while separating and compressing the resulting oxygen product. Research at the University of Arizona has demonstrated long lifetime operation of the stabilized zirconia cells when operated at elevated temperatures and at terrestrial pressures [3].

On the other hand, the interface between Mars atmosphere and the zirconia cells has not yet been fully defined. Mars surface barometric pressure is nominally 6.6 mb (5 torr), but varies significantly due to the seasonal migration of carbon dioxide between the poles [4]. In addition, significant dust storms have been observed which occur at regular intervals [5]. Unfortunately, the instruments on board the Viking Lander spacecraft were unable to determine the composition of Mars dust and to date it has only been possible to infer its composition from terrestrial measurements [6]. It is desirable to filter the dust from Mars atmospheric feedstock, but because of the very low surface pressures, a generic filtration system must be designed which removes micron size particles without producing large pressure losses across the filter system [7]. To date, experiments have shown that the stabilized zirconia electrochemical cells are able to extract oxygen efficiently from pressurized Mars atmosphere, but the process of collecting and compressing Mars atmosphere prior to electrochemical separation represents a possible technology limit. In order to bypass that potential technology barrier, researchers at Old Dominion University and NASA Langley Research Center started to explore systems that could eliminate the need for filtration and compression of Mars atmosphere by uncoupling the oxygen production process from the electrochemical pumping process. Building from Outlaw's research on atomic oxygen production systems [8], we were able to determine that glow-discharge systems could be used to liberate oxygen from Mars atmosphere and that the oxygen could be collected through a silver permeation membrane [9]. Since the permeation membrane could be used as one electrode on a stabilized zirconia membrane, the resulting glow-discharge oxygen production system could either be separated from or integrated with the electrochemical cells.

The early experiments utilized direct current, glow-discharge techniques to increase oxygen yield from carbon dioxide at temperatures in the 300°C to 600°C range [10]. The objective was to show that it was possible to separate the oxygen production and collection processes from the oxygen compression process. Subsequently, stabilized zirconia cells could either be replaced by other types of vacuum pumping systems or they could be used as pumps, operating directly on the oxygen which passed through the silver permeation membrane/electrode. Hence, our research has shown that it was possible to extract oxygen from uncompressed Mars atmosphere at reduced temperatures, compared with the original zirconia-based designs. By utilizing a silver electrode/permeation membrane as the interface between the feedstock and the electrochemical cell, we were able to show experimentally that a glow-discharge could be sustained in the Mars atmosphere which resulted in significantly higher oxygen yields at lower temperatures [11]. That approach can eliminate the requirements for Mars atmospheric filtration and compression prior to oxygen extraction. However, too much electrical power was consumed via the DC glow-discharge to justify near-term ISRU system development studies based upon that technology. Even though the DC glow-discharge experiments demonstrated that an order of magnitude increase in oxygen yield, with no additional power, could be achieved by simply reducing the thickness of the silver permeation membrane by an order of magnitude, further reductions in power consumption were required. Since the ultra-thin silver permeation membranes could be used as the electrode surfaces on the stabilized zirconia cells—eliminating fabrication problems associated with leaks in the silver membranes—our research demonstrated how the glow-discharge system and the zirconia systems could be completely complementary if the power requirements could be reduced further. The DC glow-discharge power consumption was still considered to

be approximately one order of magnitude higher than levels that would be acceptable for ISRU systems for Mars surface applications.

Recently, radio frequency (RF) glow-discharge systems have been identified and tested which have the potential to reduce the glow-discharge power consumption levels sufficiently to justify experimental evaluation for possible use as the front end of an optimized ISRU Mars oxygen production system [12]. The experiments which will be reported here represent the current status of RF-based glow-discharge production of oxygen from Martian atmosphere. The experiments have been performed using an 0.32 mm thick silver (Ag_{0.05}Zr) permeation membrane over a porous substrate. The discharge has been maintained at temperatures in the 300°C to 600°C range, with RF frequencies between 10 MHz and 100 MHz. Power consumption levels between 0.1 W/cm² and 4.0 W/cm² were maintained and the RF glow-discharge was operated in the pressure range between 1 torr and 10 torr. Pure carbon dioxide has been used as the feedstock gas thus far, but a three species approximation of Mars atmosphere (95.7% CO₂, 2.7% N₂, and 1.6% Ar) has been obtained and we expect to report preliminary results from those experiments as well.

Several encouraging results have been obtained to date. First, the RF glow-discharge appears to be optimized at 5 torr, which corresponds with nominal Mars ambient pressure. In addition, the temperature at which oxygen yield appears to approach maximum levels is approximately 400°C. These characteristics, coupled with the determination that oxygen permeation rates scale with the thickness of the permeation membrane, means that an RF-glow discharge system can be designed which consumes electric power at reasonable levels. That approach represents an attractive alternative to filtration, compression and elevated temperature operation of the stabilized zirconia cells that have been studied as the Mars oxygen production system of choice. The RF-system is both compatible with the earlier zirconia systems and capable of interfacing with other types of evacuation/compression systems that could be used for the oxygen compression and storage steps.

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CHEMICAL PROCESS SYSTEM MINIATURIZATION. Robert S. Wegeng, Charles J. Call, M. Kevin Drost, Annalee Y. Tonkovich, P.O. Box 999, Pacific Northwest National Laboratory¹, Richland Washington, USA.

Abstract: The purpose of this presentation will be to describe the potential for the realization of compact chemical processing systems, exhibiting high process rates, using precision engineering techniques, originally developed for the electronics industry.

Researchers at the Pacific Northwest National Laboratory (PNNL) have successfully fabricated and tested a variety of microcomponents that perform many of the standard unit operations of interest for chemical processing systems. Microcomponents currently in various stages of development at PNNL include chemical reactors, heat exchangers, gas absorbers, liquid-liquid extractors, and microactuators for pumps, valves and compressors. In some cases, prototypes show the potential for high performance and capacity (throughput).

If successfully developed, microchemical systems may represent a new class of chemical process systems. As Figure 1 suggests, these systems will be more compact than conventional, "macro" chemical processing systems, and can exploit microscale phenomena, such as heat and/or mass transport, to significant advantage. In addition, systems composed of multiple units have the potential of providing high degrees of redundancy. Finally, their small size and weight should make them available for distributed/portable/mobile applications.

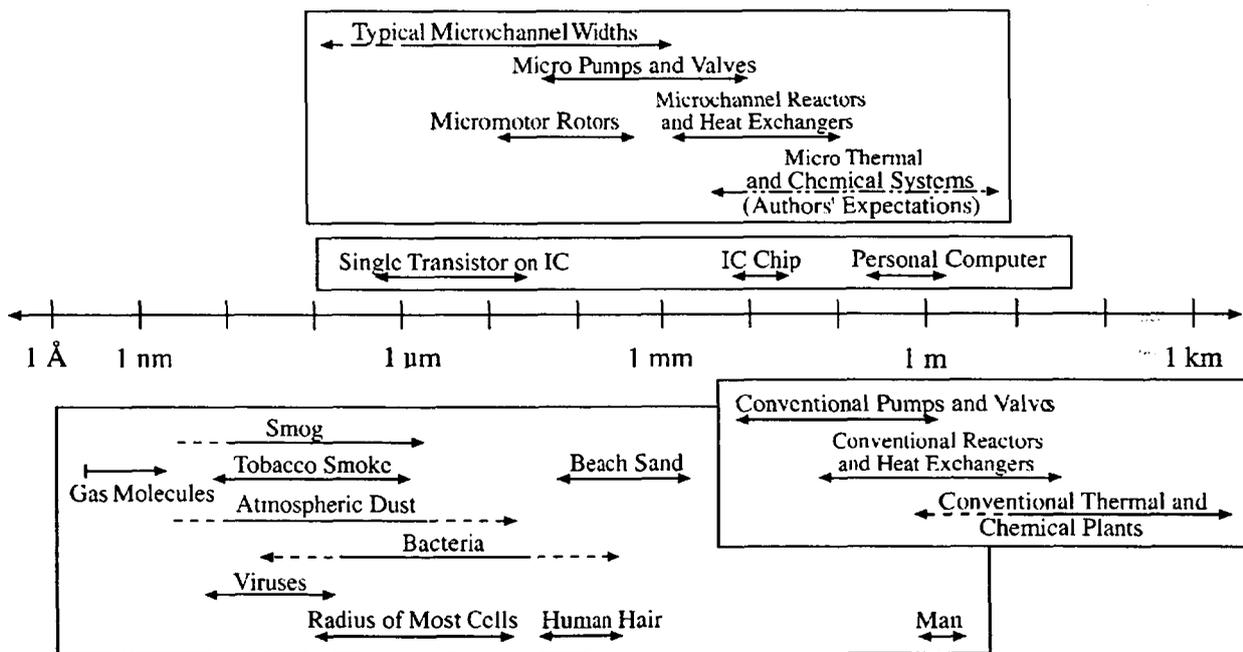


Fig. 1. Sizes/Characteristics of Microcomponents.

¹The Pacific Northwest National Laboratory is operated by Battelle Memorial Institute for the Department of Energy (DOE). Work described in this presentation was funded by DOE and the Defense Advanced Research Projects Agency.

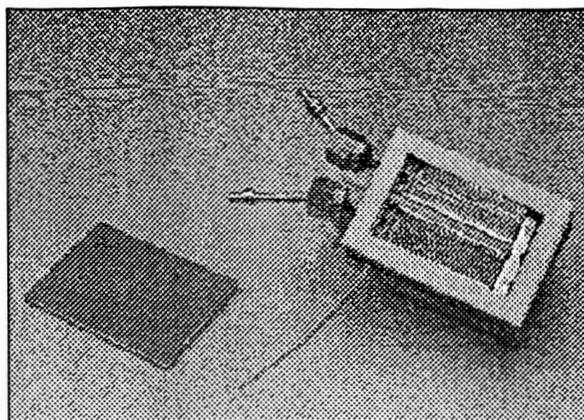
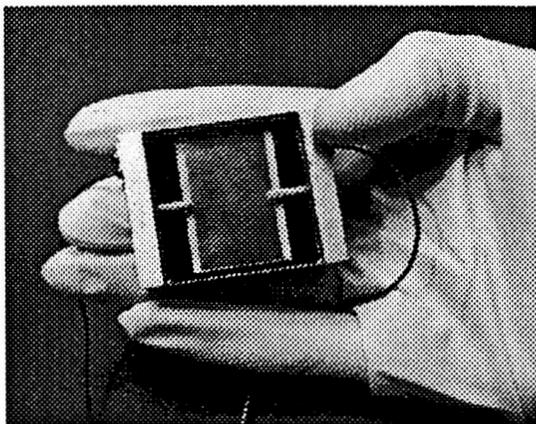


Fig. 2 and Fig. 3. Microchannel Heat Exchanger (left) and Microchannel Chemical Reactor (right).

Microchannel heat exchangers have exhibited high performance potential. In experimental investigations at PNNL, microchannel heat exchangers have provided high overall heat flux (e.g., 100 watts/cm²) coincident with high heat transfer coefficients (10,000 - 13,000 watts/m²-C for liquid flow, and 30,000 - 35,000 watts/m²-C for evaporating flow) and low pressure drops (less than a few pounds per square inch). Similar results have been observed for mass transport in microchannels.

Experiments have also included the integration of exothermic and endothermic microchannel chemical reactors with microchannel heat exchangers. Gas phase, catalytic, and plasma reactors have been investigated, with favorable results. For example, the reactor shown in Figure 3 and subsequent versions have been demonstrated as an integrated combustor/evaporator (boiler), successfully demonstrating high heat flux (e.g., greater than 50 watts/cm² with an overall energy conversion efficiency exceeding that of conventional, large-scale boilers (e.g., greater than 82%).

In another example, the catalytic, partial oxidation of methanol and butane has been successfully demonstrated in a proof-of-principle microchannel reactor system, with moderate to high syngas (CO + H₂) production rates. The interest here is to produce a hydrogen fuel stream for lightweight fuel cells, for man-portable and vehicular power generation. Compact chemical processing systems for environmental remediation and small heat pumps for portable and commercial/residential use are additional targeted applications.

Scaleup is intended to be provided through the incorporation of system architectures that accommodate large numbers of microcomponents working in parallel and in series. Such configurations should provide additional novel operating characteristics, such as enhanced reliability (through redundancy) and high turndown ratios with individual components continuing to operate at or near ideal operating conditions.

References: [1] Call, C. J., M.K. Drost, and R.S. Wegeng, "Combustion and Partial Oxidation in Compact Microchannel Reactors", *A.I.Ch.E. 1996 Spring National Meeting*, New Orleans, Louisiana, February, 1996. [2] Cuta, J., W. Bennett, and C.E. McDonald, "Fabrication and Testing of Microchannel Heat Exchangers", *SPIE Micromachining and Microfabrication '95 Conference Proceedings*, 1995. [3] Tonkovich, A.Y., C.J. Call, D. Jimenez, R.S. Wegeng, R., and M.K. Drost, "Microchannel Heat Exchangers for Chemical Reactors", published in the *Proceedings of the 1996 National Heat Transfer Conference*, session on Heat Transfer Issues in Chemical Reactor Design and Operation, *AICHE*, August 1996. [4] Wegeng, R.S., C.J. Call, and M.K. Drost, "Chemical System Miniaturization," presented at the Spring National Meeting of the *AICHE*, February 1996. Available on the World Wide Web at <http://w3.pnl.gov:2080/transfer/tech/fliers/microfly.html>.

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ASSESSMENT OF LIQUEFACTION/REFRIGERATION OF MARS IN SITU PROPELLANT PRODUCTION. Allen Mac Knight and Leon Schipper, AlliedSignal Aerospace Systems & Equipment Torrance California 90504-6099, USA.

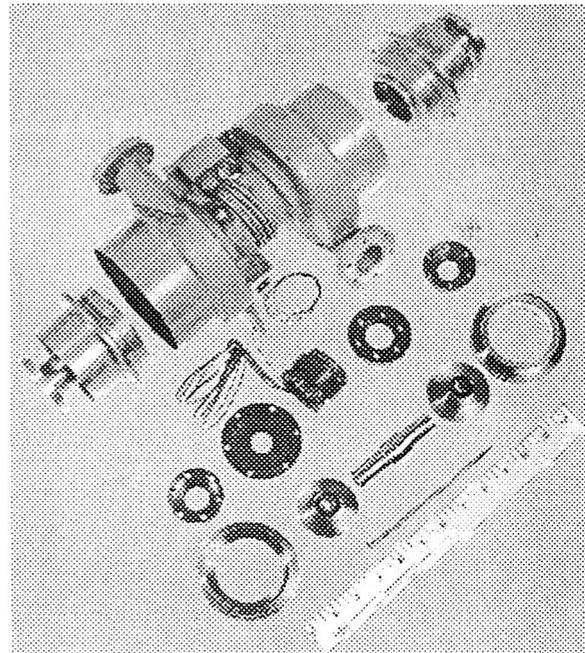
Abstract: This paper presents an assessment of various means of liquid storage of potential propellants manufactured in situ from the Martian atmosphere applicable to rover and/or return to earth mission. In situ potential production of two types of bipropellants, namely the use of either methane and carbon monoxide (obtained through different processes), and oxygen as oxidizer are considered. Design considerations and implications for both direct prototype liquefaction and application of refrigeration to condense, pump if required, the specific propellant prior to storage are reviewed. In the present assessment efforts were primarily associated with the liquefaction or refrigeration of oxygen.

In a typical liquefaction cycle the oxygen is compressed, cooled in a series of heat exchangers, and partially liquefied through a Joule-Thompson expansion. The high operating pressure is best obtained via the application of CO₂ adsorption pressure beds located at the inlet of the supplied CO₂ stream and augmented pressurization, if required, through the use of multi-stage compressor assembly. Sensible heat sink removal capability is provided by the separated oxygen vapor stream augmented by thermal radiation to the Mars environment. Additional cooling can be obtained from hydrogen supplied if methane is formed, turbo expansion, or augmented refrigeration. This concept is rather complex and requires excessive input power.

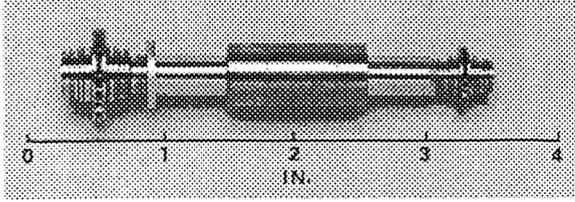
The present required cooling load (sensible and phase change) is such that the use of a reversed Brayton refrigeration cycle, of single expander, is most competitive, in terms of power requirement, associated weight, and potential long operation. Accordingly, evaluation emphasis was placed on this concept to provide the required liquefaction. In a reversed Brayton single expander cycle a gaseous working fluid is compressed and then cooled by rejecting heat to the surroundings; further cooling is obtained by recuperative heat exchange with gas returning to the compressor. The cooled high-pressure gas is expanded through a turbine producing cold, low pressure gas that provides the required refrigeration. Refrigerator performance characterization were determined including variation in operational pressure of the gaseous

oxygen stream, and change in molecular weight to achieve desired performance potentials of the involved turbine and compressor assemblies.

The long term operation is provided via the application of self reliant gas bearing (requiring no external lubrication or coolant of the rotating assembly). Under the development of a dual expander, known as the Mini-Halo Turborefrigerator, 9291 hrs of testing were accomplished inclusive of the completion of 7400 hr of endurance system testing. Subsequently a three stage expansion, capable of cooling further lower temperature loads was developed. Use of self reliant fluid bearing, in addition to assembly simplicity, allows high speed rotation such that desirable turbomachinery performance are realized. Prototype hardware of the Mini-Halo, used in the endurance test is shown in the Figures below.



Motor-Compressor
125,000 RPM/1.8 in Dia.



Turboalternator
200,000 RPM/0.4 in Dia.

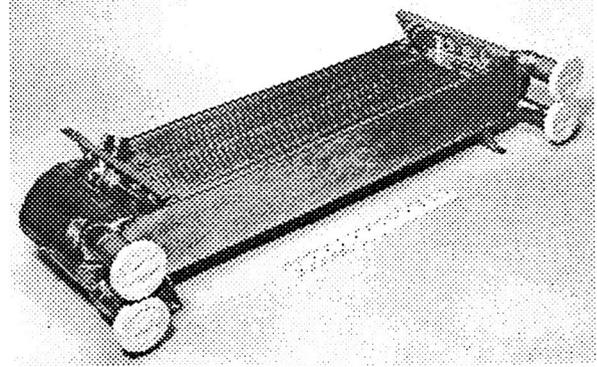


Plate-fin Recuperator
0.98 Effectiveness

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QUALIFICATION, SAMPLING, REMOVAL & EXCAVATION OF MINERALS & ELEMENTS FROM THE SURFACE OF PLANETARY BODIES. Stephen Gorevan, Thomas Myrick, Roopnarine, Shaheed Rafeek, Kin Yeun Kong, Honeybee Robotics, 204 Elizabeth Street, New York NY 10012, USA.

Abstract: Numerous automated discrimination, sampling and excavation tools, in varying states of development, may evolve to enable significant portions of ISRU goals. These discrimination, sampling and excavation tools are described as follows:

A) Discriminating Sniffer — a porous-gas permeable ceramic plug with a heating element is connected to a flexible tube that is continuously evacuated by a pump associated with a mass spectrometer. This discriminating mass spectrometer and drill apparatus may be mounted on small rovers (Fig. 1).

B) Borehole Fiber Transport — a protected IR spectra fiber (or other types of fiber) may be mounted to the non-rotating drill shaft to assist in the identification and cataloging of subsurface minerals (Fig. 2).

C) Sample Extraction & Transfer — the rover-mountable double auger design and its variants allow for the acquisition of samples (after qualification by the above techniques) from below the surface of rock and regolith. Samples are sealed at depth and transferred to other qualification instruments or to a storage container (Fig. 3).

D) High Resolution Rock & Regolith Discrimination — acquired samples may be positioned within 100 microns or less repeatability to allow for high-resolution microscopic evaluation of samples (Fig. 4).

E) Mobile Excavator — robotic system facilitates large regolith structure mapping with miniature instruments and sensors. The system will allow sensor/instrument access to a 1-meter deep excavated wall of virtually unlimited length. The system may also be employed for civil engineering excavation purposes or element and mineral removal (Fig. 5).

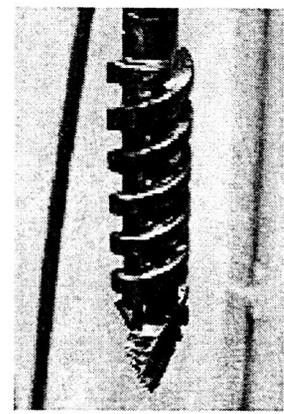
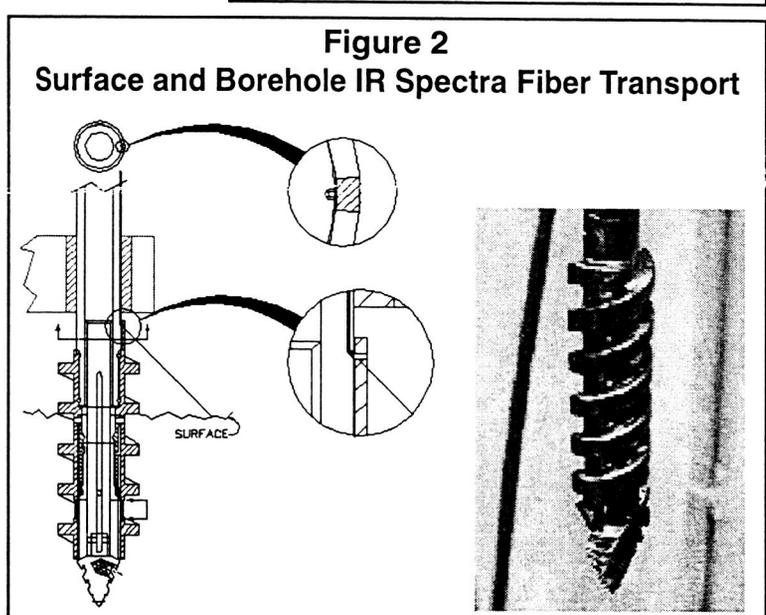
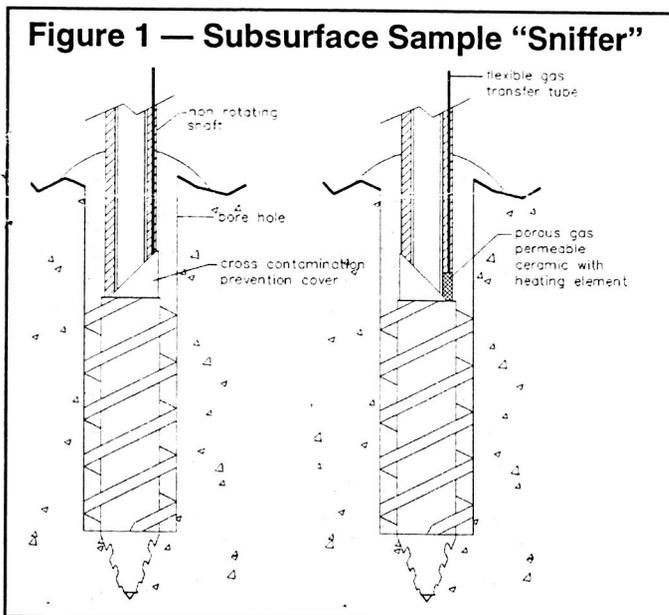
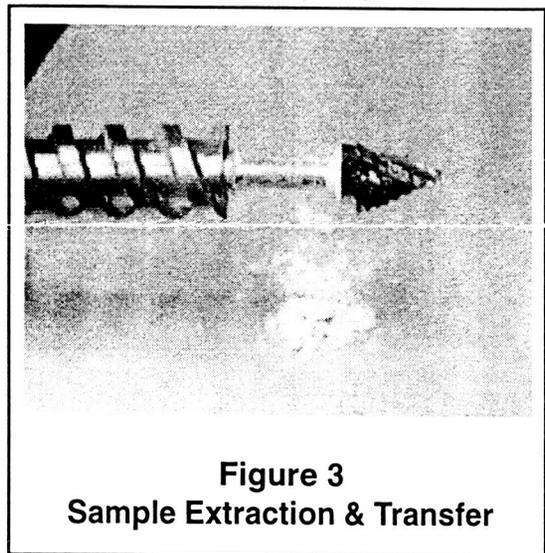


Figure 4 — Microscope Image of Sample

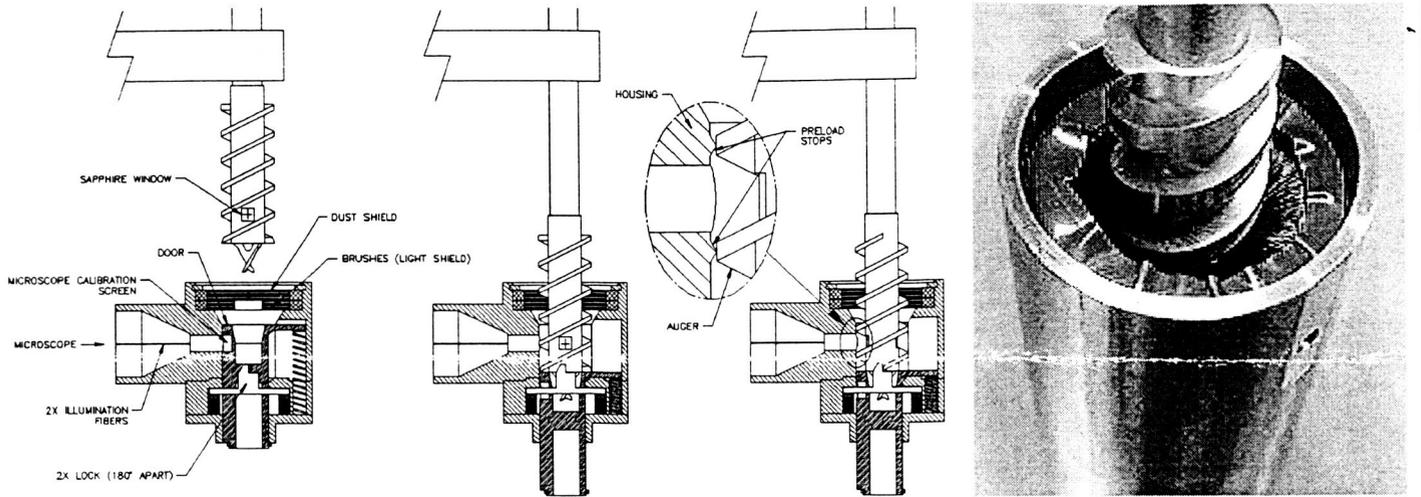
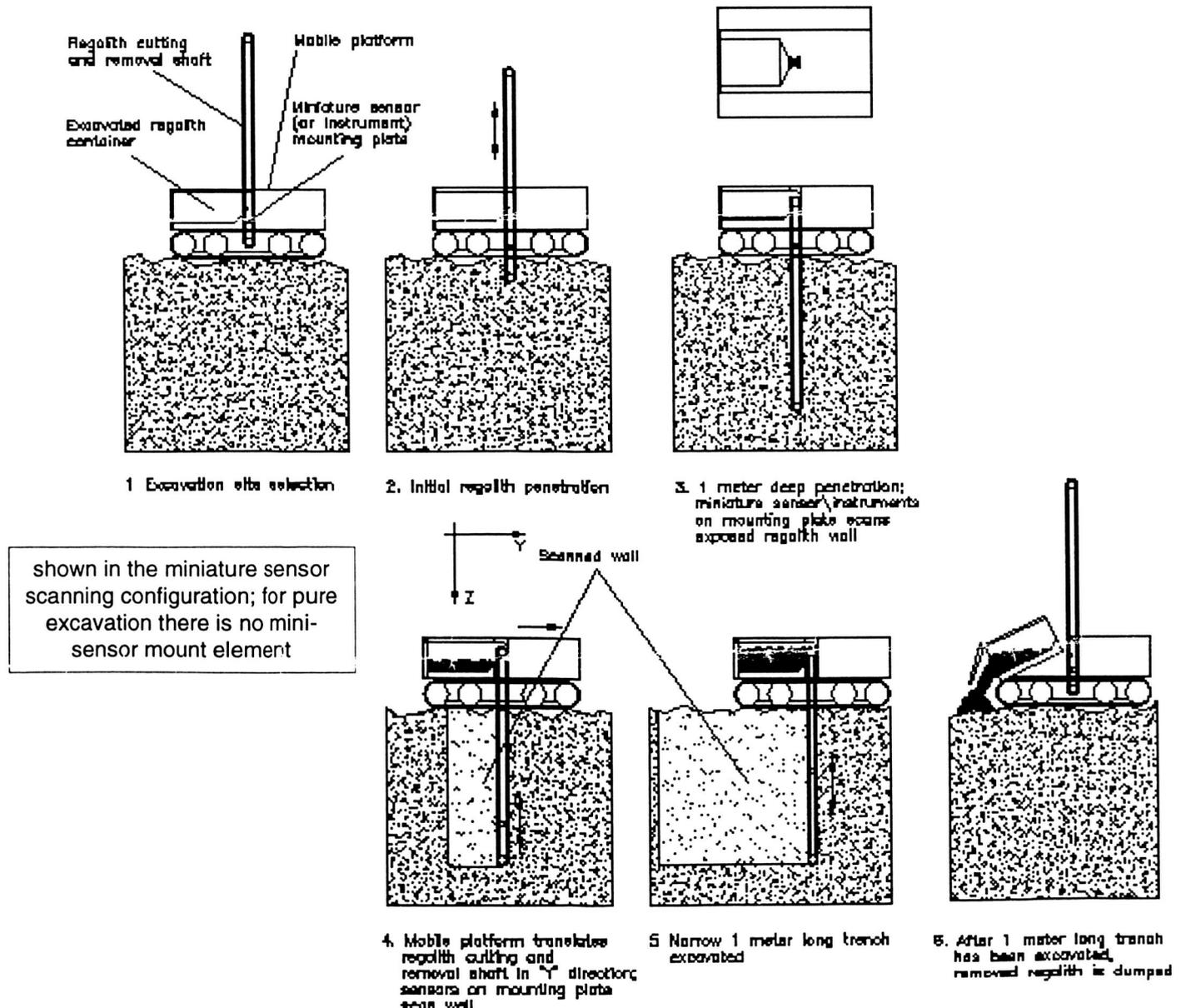


Figure 5 — Miniature Planetary 'Excavator' Operational Sequence



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EXPERIMENTAL STUDY OF A WATER VAPOR ADSORPTION REACTOR FOR MARS IN SITU RESOURCE UTILIZATION. Steven C. Coons, John D. Williams, Adam P. Bruckner, Department of Aeronautics and Astronautics, University of Washington, Box 352250, Seattle WA 98195-2250, USA.

The future of cost-effective exploration of Mars, and indeed the solar system, depends strongly on the development of a strategy known as *in situ* resource utilization, or ISRU. *In situ* resource utilization is defined as the use of indigenous resources at the site of an interplanetary mission for the production of propellant and/or life support consumables. For the past five years, University of Washington design teams have conducted Mars mission analyses for both piloted and robotic exploration. All of these missions have used ISRU propellant production plants and all have shown the significant merit of the ISRU approach over more conventional designs in which the return propellants are brought from Earth.

The UW designs have primarily incorporated some form of the Sabatier/electrolysis (S/E) cycle for production of methane/oxygen propellant. These designs (as well as other Mars ISRU mission designs using S/E propellant plants) have required hydrogen feedstock which must be transported from Earth. The problems associated with long-term cryogenic hydrogen storage prompted the search for alternative methods for getting hydrogen to Mars, including the transport of water. While the mass penalty for taking water from Earth to Mars turned out to be too great, it was thought that if a reliable source of water on Mars were accessible, a completely ISRU mission using an S/E propellant plant could be undertaken.

Water is present on Mars as ice in the polar caps, adsorbed in the regolith, and possibly in subsurface deposits, but the atmosphere of Mars is the most highly characterized and globally distributed water source on the planet. The desire to utilize this atmospheric water led to the development of the Water Vapor Adsorption Reactor (WAVAR) concept by the authors.¹ Past designs for extracting atmospheric water have used a compression-cooling process, which requires a high power input.² Water vapor separation by adsorption has fewer moving parts, and is both

less massive and less energy intensive. Adsorption is a separation process utilizing molecular sieves, which selectively attract molecules of a fluid as the fluid passes through a stationary bed. Adsorption itself is an exothermic process requiring no energy input other than that required to move the fluid. Removal of the adsorbed molecules from the bed, however, does require energy.

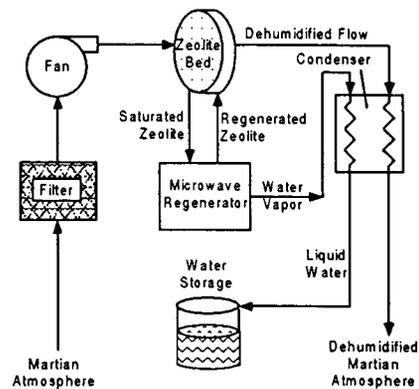


Fig. 1. Process schematic of WAVAR, the Water Vapor Adsorption Reactor.

WAVAR is conceptually very simple, as can be seen from Fig. 1. Martian atmosphere is brought into the system through a filter by an axial-flow fan. The filtered atmosphere is passed over the adsorbent bed where the water vapor is removed from the flow by the zeolite 3A molecular sieve. The disk-shaped bed is divided into sectors by insulative separators. Once a sector has reached saturation, it is rotated into a chamber and sealed off from the outside. A microwave emitter is engaged, heating the adsorbent bed sector and driving off the water vapor. The desorbed water vapor is condensed and piped to storage, where it is available for utilization by a S/E propellant production plant or for use by a manned Mars base. The WAVAR design has only six components: a filter, a pump, an adsorption bed, a regeneration unit, a condenser and a control system. These subsystems are shown in Fig. 2.

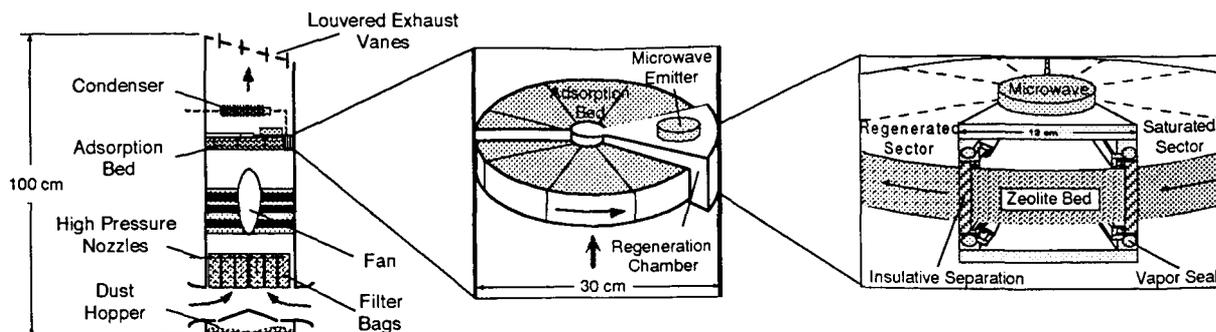


Fig. 2. Water Vapor Adsorption Reactor.

The Water Vapor Adsorption Reactor is an energy efficient method of extracting water from the Martian atmosphere. For the assumed conditions, (253K, 800 Pa, 0.06% humidity)² WAVAR uses 4.9 kW-hr for every kilogram of water it extracts. In comparison, an optimized compression-refrigeration cycle operating under the same conditions requires 70 kW-hr per kilogram water.²

The possible uses of a WAVAR unit on Mars are as numerous as the number of ways water is used here on Earth, but one of the most important uses will be for propellant production. With a reliable water source, an S/E propellant plant would be able to produce methane/oxygen propellant entirely from indigenous resources. WAVAR would extract water vapor from the Martian atmosphere and the water would be electrolyzed, with the O₂ stored for oxidizer and the H₂ processed with ambient CO₂ in a Sabatier reactor to produce CH₄, more O₂, and additional water which is recycled.

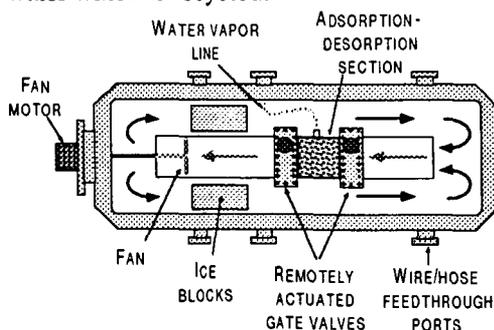


Fig. 3. WAVAR experimental test chamber.

The current status of WAVAR is that of the initial design and theoretical calculations

described above.¹ A recently updated description is also available electronically on the World Wide Web.³ However, initial proof-of-concept experiments are needed and are currently in the planning stage at the University of Washington. To obtain experimental data, a low pressure, low temperature, CO₂-rich environment must be produced in which some level of humidity control can be attained. Simulation of the Martian atmosphere will be conducted by using a vacuum chamber that will be placed in a Scientemp Low-temperature Cabinet (model #85-6.8) which will provide the required refrigeration down to 188 K. The vacuum chamber (Fig. 3) will be filled with CO₂ and pumped down to the required pressure (~6 Torr) using a vacuum pump. Within the vacuum chamber will be a duct with an adsorption/desorption test section between two gate valves. Low pressure CO₂ will be drawn into the duct and across the test bed by a fan. Constant humidity will be maintained via the sublimation of water vapor from blocks of ice placed in the bottom of the chamber. This will ensure a saturated level of humidity commensurate with the temperature, very nearly approximating conditions on the surface of Mars. Once the test section has been saturated, the gate valves will isolate the test section and resistive heating tape around the test section will desorb the sample and the water vapor will be piped off for measurement. These proof-of-concept experiments validating water vapor adsorption under simulated Martian conditions are expected to be under way by Spring 1997.

¹Williams, J.D., Coons, S.C., Bruckner, A.P., "Design of a Water Vapor Adsorption Reactor for Martian *In Situ* Resource Utilization," *J. Brit. Interplanet. Soc.*, 48, No. 8, August, 1995, pp. 347-354. ²Clapp, W.M., "Water Supply for a Manned Mars Base," *The Case for Mars II*, McKay, C.P., ed., AAS Publications, 1985, pp. 557-566. ³WAVAR on the Web, <http://weber.u.washington.edu/~stevenc/wavar/>

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IN-SITU PROPELLANT PRODUCTION ON MARS: A SABATIER/ELECTROLYSIS DEMONSTRATION PLANT. David L. Clark, Lockheed Martin Astronautics, Denver Colorado 80201, USA.

An efficient, reliable propellant production plant has been developed for use on Mars. Using a Sabatier reactor in conjunction with a water electrolysis system, a complete demonstration plant has produced methane and liquid oxygen from simulated Martian atmosphere. The production plant has demonstrated high efficiency, extended duration production and autonomous operations. This paper presents the results and conclusions relating to eventual use in a Mars sample return mission. This work was funded by the Jet Propulsion Laboratory (JPL). The production plant was built and tested at the Propulsion Center of Lockheed Martin at the Denver Colorado facility.

In order to reduce launch mass for missions where a Mars ascent vehicle is required, a system has been proposed where the propellants are manufactured from Mars atmospheric carbon dioxide and hydrogen brought from earth. The resulting propellant mass produced can be over eighteen times the mass of the supplied hydrogen.

Carbon dioxide is acquired from a simulated Martian atmosphere with a sorption pump using the low Martian night temperatures to drive the adsorption process. The CO₂ is pressurized with the addition of heat from electrical heaters and waste heat from the reactor. The production plant acquired a gas mixture similar to the Martian atmosphere, demonstrating selective adsorption to provide nearly pure CO₂.

Methane and water are produced in a high-efficiency Sabatier reactor where reaction efficiencies higher than 98 percent are routinely achieved. The effective efficiency was boosted to nearly 100 percent with the addition of a novel hydrogen recovery pump which scavenges the residual hydrogen gas from the exhaust stream using well-developed solid-polymer electrolyte technology. The reaction is exothermic and self-sustained operation was achieved with waste heat recovered for driving the sorption compressor.

Water is separated into the constituent hydrogen and oxygen with a solid-polymer electrolyzer. This extremely efficient device also pressurizes the hydrogen for recycling into the reactor, eliminating a mechanical device. The oxygen product is dried and scrubbed of residual CO₂, resulting in nearly pure oxygen suitable for liquefaction.

Production rates for this demonstration plant exceeded 125 grams of liquid oxygen for a six-hour production day. The methane was vented to an analyzer for residual gas measurements. The entire propellant production plant has no moving parts except for valves, suggesting a long operational lifetime. None of the components or subsystems require new technologies or breakthroughs, just further engineering development.

In order to efficiently store the propellants they must be liquefied. The pilot production plant uses a readily available cryocooler to liquefy the entire oxygen output as well as control pressure and eliminate boil-off during non-production periods. Using a precooler to lower the incoming gas to Martian ambient temperatures, the Stirling-cycle cryocooler operated under closed-loop control to maintain Dewar pressure during production and hold periods.

The system was operated with automatic controls which started, stopped and maintained the system. Time-based commands started and stopped the production cycle while conditional sequences controlled the transition modes. Closed-loop controls provide simple, reliable steady-state operation. The system was operated autonomously for four diurnal production cycles, in addition to over twenty five days of developmental test operations with the system.

This in-situ propellant production plant has demonstrated the feasibility of the Sabatier/water electrolysis concept for use on Mars. The simple design, minimal number of moving parts and use of well-developed technologies makes this concept a viable option for Mars sample return missions as well as future manned missions. The system is easily scaleable and realistic mass and power estimates can be generated for any production requirement.

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MARS ISPP PRECURSOR [MIP]: THE FIRST FLIGHT DEMONSTRATION OF IN-SITU PROPELLANT PRODUCTION. David Kaplan, Code EX, NASA/Johnson Space Center, Houston Texas 77058, USA.

Strategic planning for human missions of exploration to Mars has conclusively identified in-situ propellant production (ISPP) as an enabling technology¹. The Mars reference mission concept predeploys a robotic propellant production plant to the planet two years before the planned departure of the crew from Earth. The successful operation of this plant is necessary for the human journey to begin.

In response to a solicitation for flight demonstration projects from NASA Headquarters in June 1996, a team of engineers from the Johnson Space Center, Jet Propulsion Laboratory, and Lewis Research Center proposed — and subsequently was selected to fly — the Mars ISPP Precursor (MIP) Flight Demonstration. The objective of MIP is to characterize the performance of processes and hardware which are important to ISPP concepts and which interact with the Mars environment during operation. Because of uncertainties associated with the Mars environment and conditions that cannot be adequately simulated on Earth, operating this hardware in the actual Mars environment is extremely important. Failure to perform testing of this hardware in the actual Mars environment could lead to propellant production degradation or failure, and/or the need for overly-conservative designs which would increase system mass and cost.

The MIP Flight Demonstration will be the first ISRU² hardware ever deployed to a planet or moon. Its successful operation will pave the way for future robotic and human missions to use and rely on propellants produced using the Martian atmosphere as feedstock.

The MIP is comprised of seven distinctive demonstrations:

- Mars entry and landing environment characterization;
- Atmospheric dust filtration;
- Atmospheric carbon dioxide collection and conditioning;
- Radiator/thermal management demonstration;
- Advanced photovoltaic cell/array demonstration;
- Dust accumulation and removal tests; and
- Production of oxygen.

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;
- recommend preferred hardware configurations for innovative thermal management concepts of heat transfer between the components of the ISPP plant as well as to the outside environment;
- understand long-term performance degradation characteristics of advanced solar array concepts operated in the actual Mars environment;
- evaluate the functionality of electrostatically removing accumulated dust off the solar array; and
- understand the characteristics of zirconia cells to generate propellant-grade oxygen.

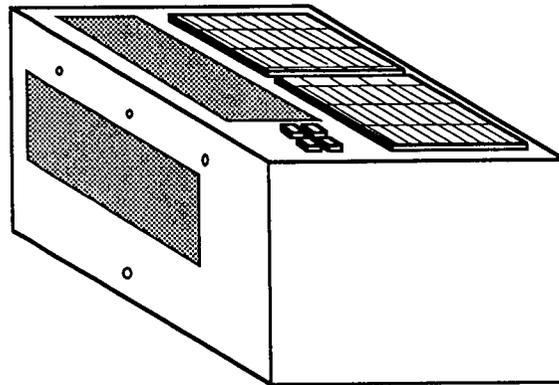
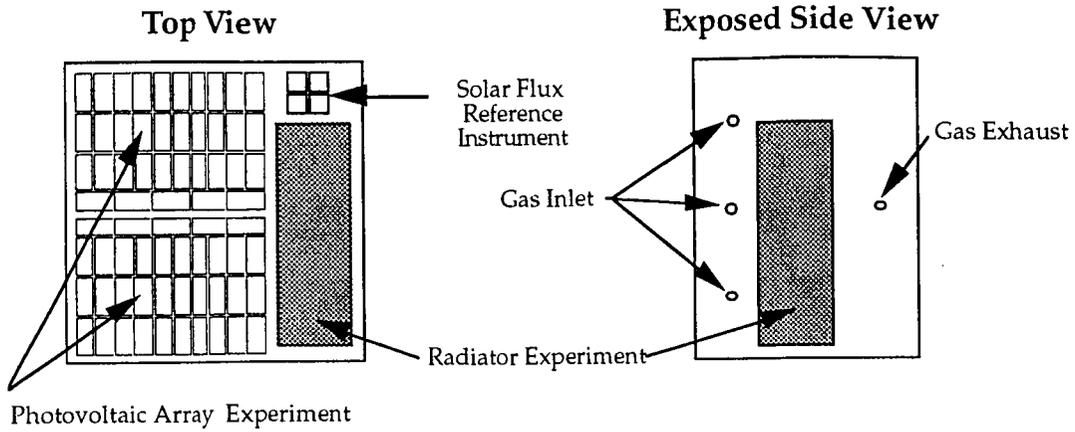
The MIP Flight Demonstration unit is to be flown as a payload on the MARS SURVEYOR 2001 Lander. Therefore, it will be designed to meet SURVEYOR Lander instrument and mission specifications. Standard vehicle power, data/communications, and mechanical interfaces will be used to integrate the MIP unit onto the SURVEYOR 2001 Lander.

As a MARS SURVEYOR payload, the MIP unit will be only one of several instruments competing for power, volume, and mass allocations. Therefore, the MIP package will be designed to be small and light weight. Initial design goals are for an overall maximum external envelope of 30.5 x 30.5 x 30.5 cm (12 x 12 x 12 inches) and a package mass of 3 to 5 kg (6.6 to 11 lbm). The actual package design limits will depend upon SURVEYOR Lander hardware limitations that will be defined as the 2001 mission matures. MIP power requirements have not yet been determined; however, preliminary analysis shows a power level in the 15 to 30 watts range.

¹ "Mars Reference Mission," NASA SP-6107, February 1997.

² In-Situ Resource Utilization

The MIP unit will be designed to operate up to 500 days on the surface of Mars. This duration is comparable to the operation requirement for an ISPP plant incorporated into a robotic Mars Sample Return mission.



Preliminary Mars ISPP Precursor (MIP) Flight Demonstration design concept