N93-26675

158348

p. 19

Propellant Production and Useful Materials:
Hardware Data from Components and the Systems

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Abstract

During the past year significant progress included a major breakthrough in oxygen production through discs (instead of tubes) that resulted in two orders-of-magnitude increase in the yield rates, proving that oxygen production from any iron-bearing silicate (avoiding costly beneficiation) in lunar ISRU; construction of a half-scale robotic soil processor; production of melt-spun fibers in a solar furnace; and the culmination of first-stage research in the construction (and delivery to NASA LeRC) of a self-contained portable oxygen plant that incorporates the first generation ISRU technologies developed at UA SERC. In addition, further reductions in mass and power needs were achieved in two smaller oxygen plants, which, however, have production rates far greater production rates.

SERC continued to attract bright students both at the undergraduate and graduate levels, and several area high school students through the Professional Internship Program (PIP) administered by the local school district. Invited lectures at elementary schools continue to draw enthusiastic response. Another important first was the creation of the Freshman Colloquium, "Space in Our Future, and Our Future in Space," geared toward women and minority students. This course proved to be a success, with more than one-half of the enrollment composed of women. In recognition of these important contributions, the author was appointed to the NRC Committee on Space Science Technologies.

Introduction

The fundamental aim continues to be the education of students in the areas of high-tech innovative space technologies and the actual hardware realization of the more promising concepts. It would be helpful to recognize that unless ISRU is advanced beyond paper studies and isolated laboratory investigations, its extraordinary potentials may never be realized. In fact, it has long been recognized that ISRU is perhaps the only means of achieving significant long-term cost savings in space missions. Unfortunately, much of the work has been at levels that may be described as TRL1 through TRL2, in the usual NASA ITP terminology, so that serious consideration by mission planners could not be assured. At the UA/NASA SERC, we have been fortunate to have support for advancement of technologies through TRL5.

The principal components of this year's work have been the oxygen production plant and its miniaturization; the robotic processing of lunar soils; production of polymers, ceramics, and glasses; development of a valid quantitative Figure-of-Merit to evaluate the overall impact of these on space missions; and the associated controls, simulations, and computations.

The virtues of in-situ resource utilization (ISRU) in introducing significant cost savings in space missions have received extensive attention in recent years.(1-10) Following this general acknowledgment of the potential for cost effectiveness, several studies have examined a theoretical "mission architecture" that could incorporate the ISRU components.(11-15) An interesting, and important, development has been the serious attention paid by industry to these resource utilization missions.(16-19) This interest by industry signifies the recognition of long-term benefits of a tangible nature.

The initial activities and a general summary of the Center's activities have been reported earlier.(20,21) The present chapter is a logical next step in the sequence of technical reports from the Center.(22-24)

The overall "game plan" at the Center is shown in Table 1. At regularly scheduled weekly meetings, innovative ideas are discussed in an open forum consisting of scientists, engineers, undergraduate and graduate students, faculty, and administrators. This free exchange of ideas results in a list of possible candidates for further pursuit. The promising ones are subjected to several reviews: internal reviews by the three Directors, semi-annual reviews by the Center Advisory Committee, and annual reviews by the NASA Technical Representative Committee. In addition, our concepts and results are always subjected to peer review in journals, symposia, and external meetings. Those concepts that survive these reviews are selected for small-scale feasibility demonstrations; this is the first place where hardware experiments are committed. After extensive tests involving several operation scenarios that go beyond the expected boundaries of operation in applications, the more promising ones are selected for table-top units that now produce reasonably realistic quantities of end products. Understandably, only two or three concepts reach this stage because of resource requirements at these larger-scale production stages. Those that continue to prove promising at this stage are selected for breadboard development and testing at the highest level of technology demonstration, or TRL 5 in NASA terminology.

Another important aspect of our activities is our willingness and ability to apply basic knowledge and expertise to important specific national needs. Two such examples are discussed here: one is our design and demonstration of a common lunar lander (Artemis) concept that involves robotic processing of unbeneficiated lunar soils for oxygen (and construction materials) production, and the other is a portable oxygen plant that uses carbon dioxide as its feedstock (with obvious applications to Mars). The latter has already been delivered to NASA Lewis Research Center for demonstration purposes.

The activities at the Center are all aimed at ISRU for introducing significant cost savings and mission simplicity; the specific projects are logically divided into four major categories, or disciplines: (1) lunar, (2) Martian, (3) support, and (4) common technologies. In the lunar category, we are pursuing soil reduction through hydrogen and carbothermal processes, innovative non-equilibrium plasma processing for compact energy efficient reactors, solar processing through direct photon absorption, and some other specific studies that involve soil processing into dishes. In the Martian category, we are processing carbon dioxide to produce oxygen, using the spent (hot) stream to produce hydrocarbons (the hydrogen comes from a water electrolysis unit), and have an overall system design using modern software. A recent study has been started to explore the permafrost and its safe bearing capacity (in support of platforms and structures).

In the support technologies category, we are exploring mechanical properties, general-purpose software development for mission optimization, in-situ mechanical property measurements, and quantitative visualization through CAD.

In the common technologies category, we are developing intelligent semi-autonomous controls with smart sensors, self-contained modular designs, quantitative bill of materials, compatibility testing, and an overall cost-benefit analysis that includes an examination of historical mission data.

This chapter concludes with a brief description of two applications: the common lunar lander and the portable oxygen plant that uses carbon dioxide.

The Component Activities

Lunar Resources

Lunar resources include various soils and ores. Initial studies were confined to the (much-studied) ilmenite processes.[23] A major breakthrough in 1992 extended the work to any iron-bearing silicate. The vapor deposition of a monolayer of (imported) carbon enabled the reduction of iron-bearing silicates. One representative result is shown in *Figure 1*. This forms the basis for our Artemis design. In our quest for high-tech efficient reactions, we are exploring cold plasma reactions of lunar ores and direct photon enhancement of chemical reactions. The non-equilibrium plasma enables high electron temperatures to be achieved while maintaining very low translational, rotational, and vibrational (sensible) temperatures; this fact results in good thermal efficiency in reactor design. Besides, the photon-electron interactions have a greater cross section than photon-molecule cross sections; this enables the direct deposition of solar energy into the reaction stream. The results are shown in *Figure 2*. The cold plasma in operation is shown in *Figure 3*. The general nature of the experimental setup for the microbalance investigation of lunar soils is shown in *Figure 4*. Details on the plasma reactor are given in reference 25.

Some of the beams and struts made from (authentically) simulated lunar soils are shown in *Figure 5*. The mechanical properties and their modifications through the use of small (<2% by total mass) quantities of fibers (in this scheme, to be imported from Earth, but in a subsequent scheme to be manufactured on the Moon from glassy silicates) were reported earlier.[23] More recent results have included the production of silicon-based polymers that could be used as the substrates for amorphous photovoltaic cells.

Martian Resources

Our basic work continues to develop newer technologies for oxygen production from carbon dioxide. The 16-cell unit that utilizes yttria-stabilized zirconia is shown in *Figure 6*. The screening matrix and the mass and energy needs are shown in Tables 2 and 3, respectively. A major breakthrough occurred in the alternative disc technology. Compared to the earlier tube geometry, the discs have a far greater effective area. The results are shown in *Figure 7*; a dramatic comparison is shown in *Figure 8*. The effective area in the tube is clearly revealed in the IR thermogram of the tube in *Figure 9*.

A highly sensitive area of importance is the seal between the ceramic (ZrO_2) and the metal (inconel) that houses the overall system. Major advances were made in recent months using shape-memory alloys that improve the seal at higher temperatures. Results are shown in *Figure 10*. Several in-house technologies of solid electrolytes, catalysts, and electrodes were all proven to be superior to what is commercially available. Generous support from JPL, where three of our students were hosted this summer, is acknowledged. This process of Martian CO_2 reduction is also studied in reference 26. Our early work was reported in reference 27.

The spent stream is rich in carbon dioxide and carbon monoxide. If separated, the carbon monoxide can be a valuable fuel on Mars. The separation process has been refined in the last few months. The basic scientific principle involves pressure cycling or temperature cycling. The adsorption/desorption is on a copper-based substrate. The results are shown in *Figure 11*.

Another use of the spent stream could be for the manufacture of hydrocarbons, if hydrogen can be made available. We have a water electrolysis system (WES), loaned to us by United Technologies, Hamilton Standard of Windsor Locks, Connecticut. The WES is shown in *Figure 12*. The principle of the WES is applicable to Martian plants, which could use water from the soil, polar caps, or even from the atmosphere. The hydrogen, so produced, is used in a Sabatier reactor (*Figure 13*). The overall scheme is shown in *Figure 14*, and the principal results are shown in *Figure 15*. Martin-Marietta is expected to fund a small grant at SERC for the study of "higher" chemistry from the hydrocarbons that can be produced starting from methane and hydrogen; it should be acknowledged that the initial construction of the Sabatier reactor was through an earlier MM grant to SERC.

Support Technologies

These include the intelligent controls and smart sensors. The overall view is shown in *Figure 16*. The controls have proven their applicability in several hundred-hour runs that were conducted during severe thunderstorms in Tucson, which resulted in natural (mains) power outages. The full-system operation was reported in reference 23.

Common Technologies

These include ceramics from local soils, mechanical properties of beams and struts made from soils, and quantitative CAD and visualization. The principal results arising from the ceramics research using lunar soil are shown in *Figure 17*.

Specific Applications

The general knowledge base and hardware experience present at The University of Arizona's Space Engineering Research Center have been applied to several national needs, of which two are described here.

Artemis (Lunar Lander)

This project involves the demonstration of a completely self-contained lander that weighs under 65 kg. The basic process is a reduction of any iron-bearing silicate. The reactor, made of a light ceramic, is capable of carbothermal or hydrogen reduction. The overall plant is shown as a scale model in *Figure 18*. A half-scale robotic unit has been built and demonstrated, using solar thermal energy. The full-scale unit's mass and energy balance are shown in Table 4. The sequence of operations is shown in Table 5. The unit is currently undergoing thorough testing and will be developed through TRL 5 in the coming year (*Figure 19*).

Portable Oxygen Plant

A small-scale (1 lb/day class) oxygen plant was designed and constructed using indigenous electrodes, catalysts, and electrodes. The completed unit is shown in *Figures 20* and *21*. The performance characteristics are shown in *Figures 22* and *23*; the unit has been shipped to NASA Lewis Research Center and is expected to be used in demonstrations in conjunction with a rocket motor that will burn the CO and O_2 so produced.

Since this unit is meant for thorough characterization at Lewis Research Center, only the proof-of-working data were obtained at the temperature of 800°.

These medium-temperature data must be interpreted with caution. The high temperatures (1000°C) will yield much higher O_2 production rates.

Summary and Conclusions

At The University of Arizona's Space Engineering Research Center, various activities are carrying novel ISRU concepts through idea generation, scientific screening, feasibility demonstrations, and full-system hardware. Several plants have been built and operated under realistic conditions for extended durations. It is expected that these hardware realizations of scientifically sound ISRU concepts will inspire confidence in mission planners, who could gain substantial cost benefits and acceptability by the general (tax-paying) public, who would then recognize that space ventures need not be costly if we use the local resources "out there."

Acknowledgments

The author thanks Drs. Robert Hayduk and Murray Hirschbein (Code RS, NASA HQ) for their support and the entire team at SERC for the data.

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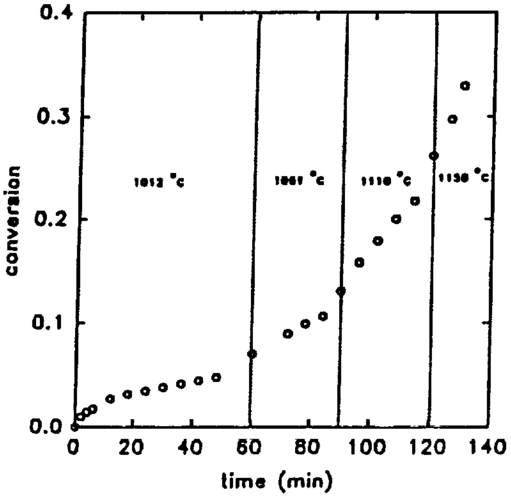
FIGURE 1

PROVEN OXYGEN PRODUCTION

solid carbon mixed with (simulated) lunar soil



UA SERC, KNRR

Reduction of Fayalite (Fo_{93}) with deposited carbon

FIGURE 2

Graduate Students: Dan Bullard & Gary Thomas

Intent

Recovery Of Oxygen From Lunar Resources Using A Hydrogen Plasma

Major Achievements

- Improved Efficiency In Hydrogen Utilization Over Conventional Heating
- Recovery of 1.5 atoms Of Oxygen Per Molecule Of $FeTiO_3$ Possible
- Evaluation Of Plasma Variables On extent Of Reaction

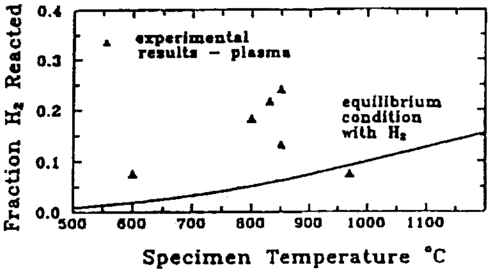
Comments

- Energy Efficiency For Production Of Plasma Can Approach 85 To 90%
- Particles 10 μm In Diameter & Smaller Can Be Reacted - Also Possibly Larger Particles
- Plasma - Solid Reaction Complete Within 2 Minutes At 700 °C And Below

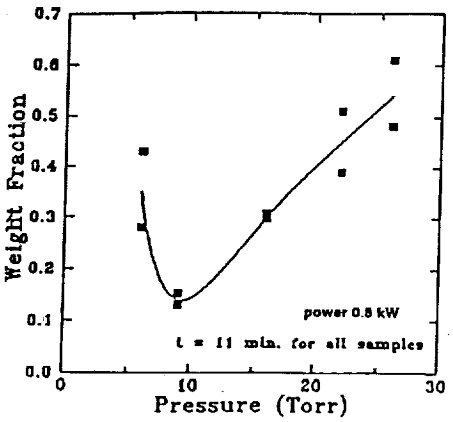
Future Work / Work In Progress

- Design Of Fluidized Bed Plasma Reactor (50 To 100 g) To Improve Plasma - Solid Contact And Achieve Greater Efficiency In Hydrogen Utilization
- Evaluation Of Fundamental Kinetic Parameters
- Scale up

Reduction Of Ilmenite



Weight Fraction Ti_2O_3 Produced From TiO_2



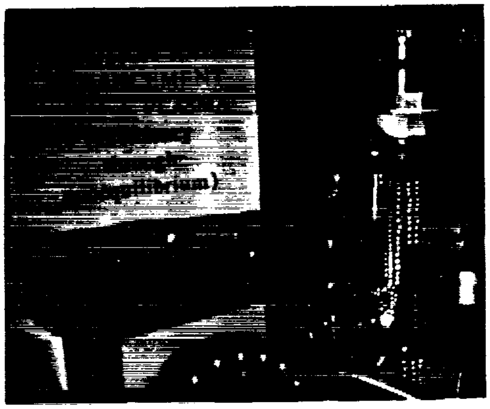


FIGURE 3. COLD PLASMA OPERATION.

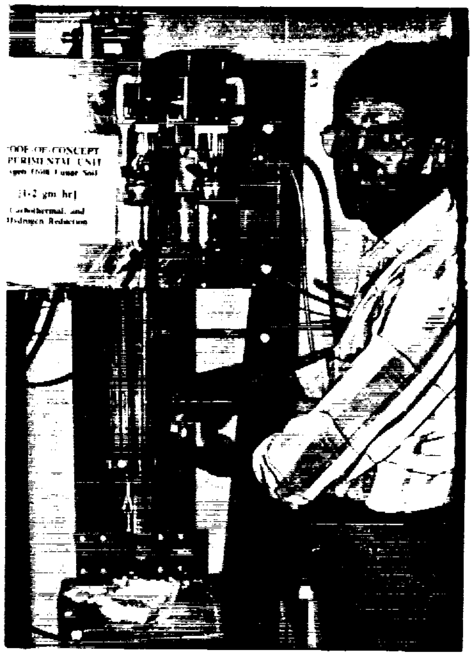


FIGURE 4. SETUP USED FOR MICROBALANCE INVESTIGATION.

FIGURE 5. BEAMS AND STRUTS MADE FROM SIMULATED LUNAR SOILS.

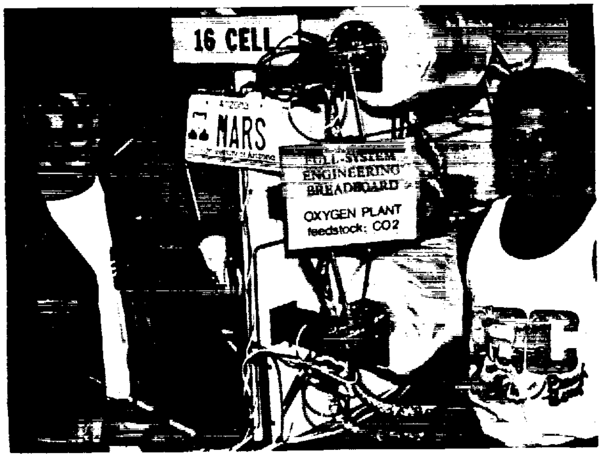
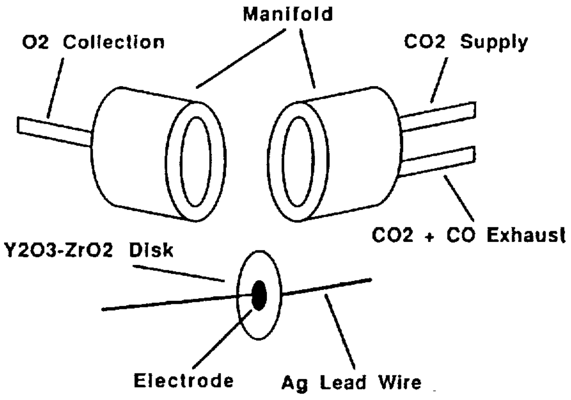


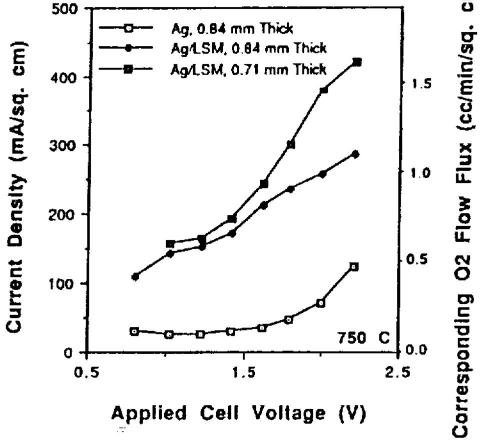
FIGURE 6. SIXTEEN-CELL UNIT USED TO PRODUCE OXYGEN FROM YTTRIA-STABILIZED ZIRCONIA.

IN-HOUSE DISK RESULTS

Disk Geometry



Current Density and Flow Flux vs. Voltage for Ag and Ag/LSM Electrodes



	Oxygen Flow Flux cc/min/sq. cm
Best Performance Tube	0.23
Best Performance Disk	1.65

FIGURE 7

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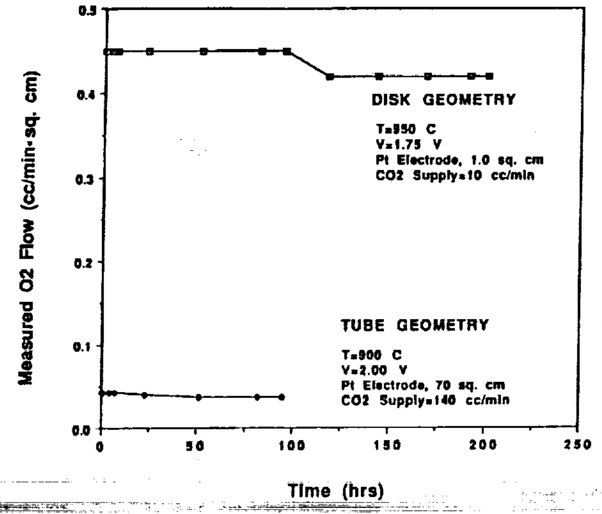
FIGURE 8

Measured Oxygen Flow vs Time



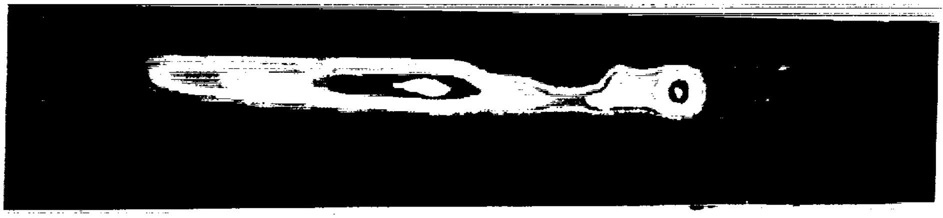
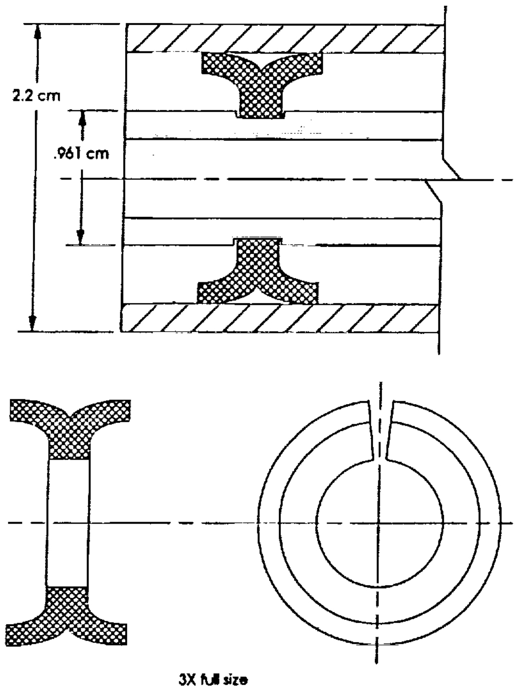
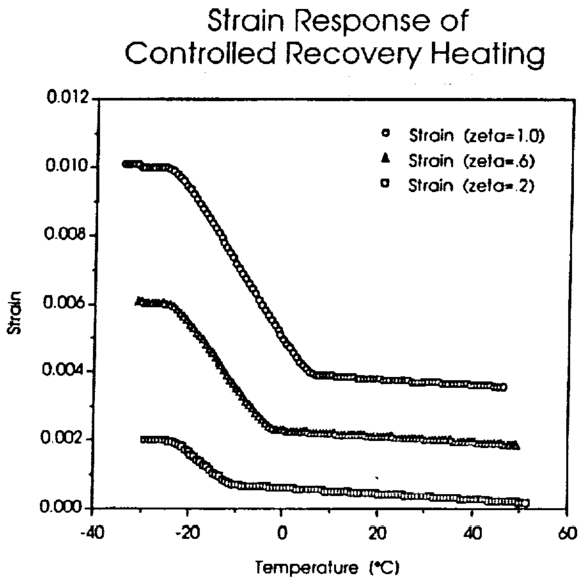


FIGURE 9. INFRARED THERMOGRAM SHOWING EFFECTIVE AREA OF THE TUBE ELECTROLYTE (ZrO_2).

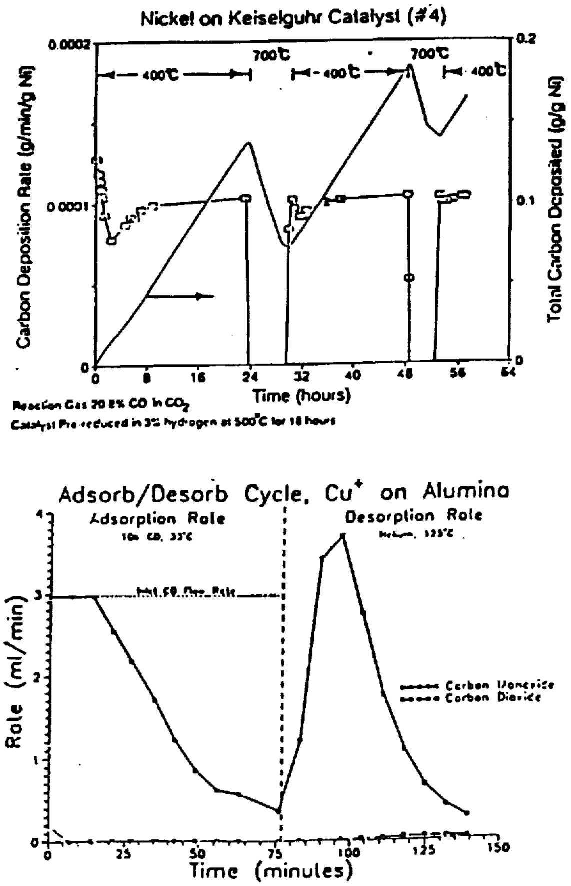
FIGURE 10

High Temperature Seal using a Shape Memory Alloy





The shape memory alloy that will be used is Ni-Ti.

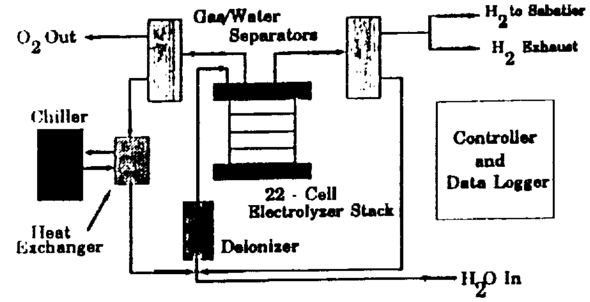


Reaction Gas 20.8% CO in CO_2
Catalyst Pre-reduced in 3% hydrogen at 500°C for 18 hours

Fig. 11. Carbon monoxide removal from electrochemical cell discharge gas.

FIGURE 12

WATER ELECTROLYSIS SYSTEM



Experimental Mass and Flow Rates as a function of Electrolysis Current

Stack Amps	Oxygen Out		Hydrogen Out	
	kg/day	cc/min	kg/day	cc/min
8	0.72	375	0.09	750
15	1.85	970	0.24	1940
30	4.34	2275	0.55	4550

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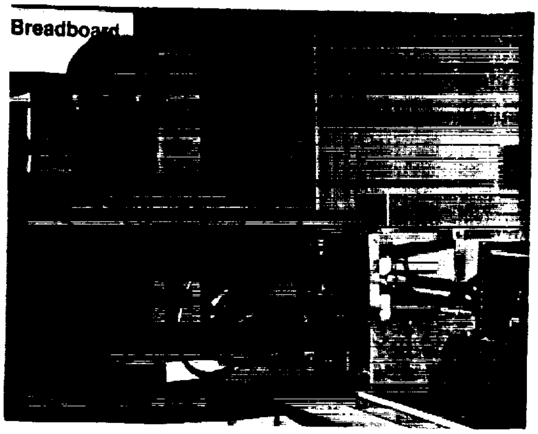


FIGURE 13. SABATIER REACTOR SETUP.

FIGURE 14

Sabatier "Test Tube" Reactor

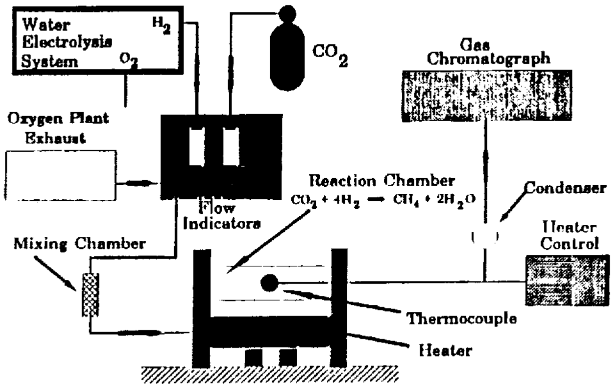
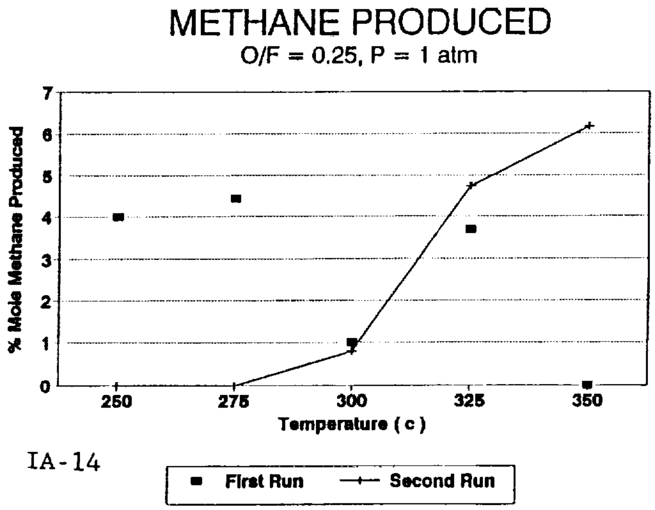


FIGURE 15



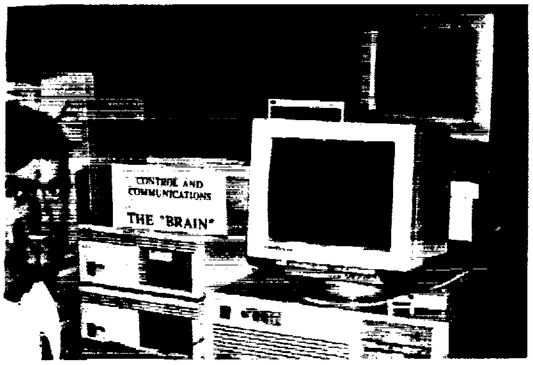
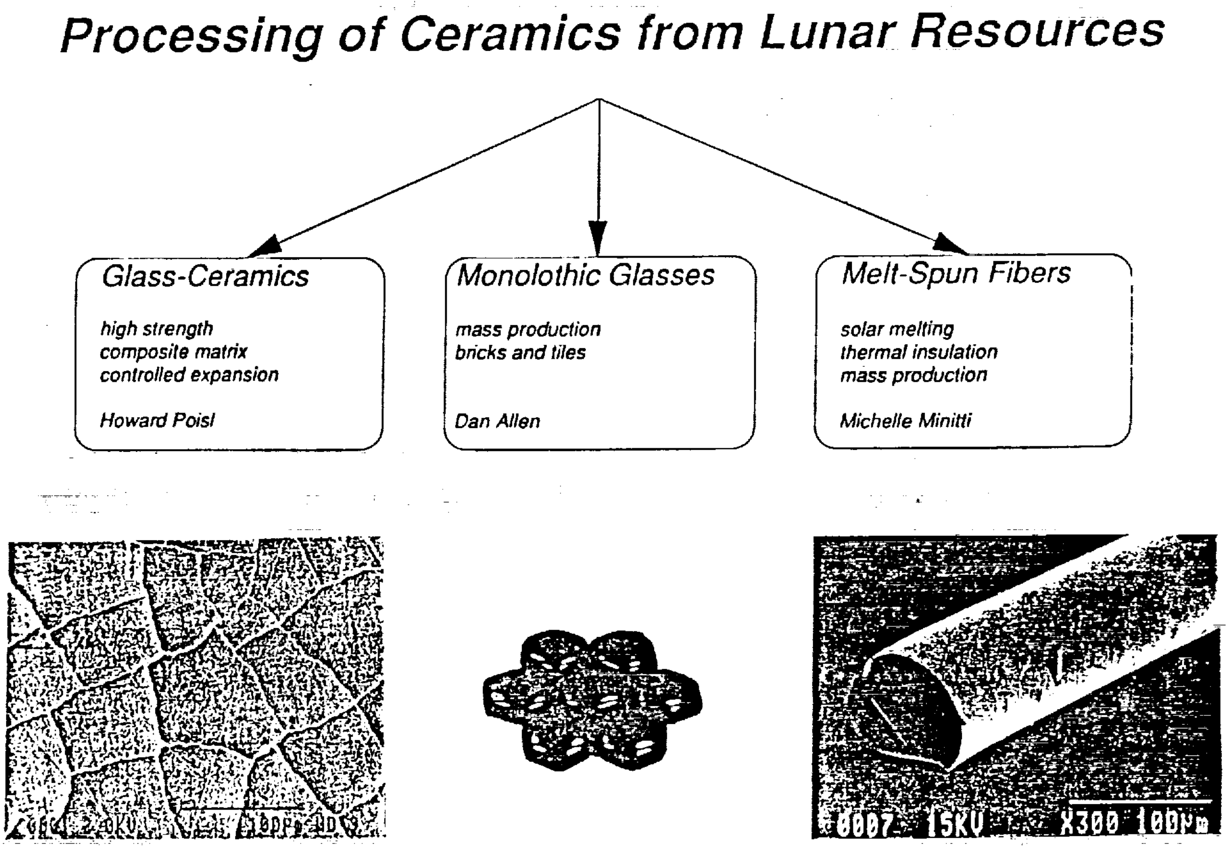


FIGURE 16. SUPPORT TECHNOLOGY SETUP, WITH SMART SENSORS AND DEDICATED ADAPTIVE CONTROLS.



Processing of Ceramics from Lunar Resources

Glass-Ceramics

high strength
composite matrix
controlled expansion

Howard Poisl

Monolothic Glasses

mass production
bricks and tiles

Dan Allen

Melt-Spun Fibers

solar melting
thermal insulation
mass production

Michelle Minitti

FIGURE 17

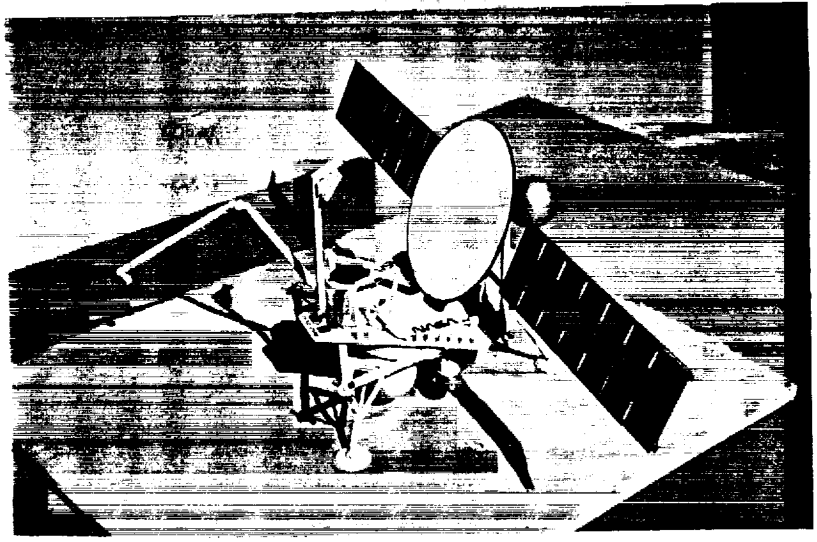


FIGURE 18

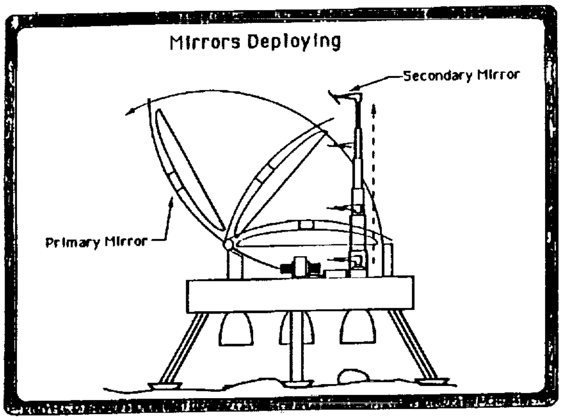


FIGURE 19

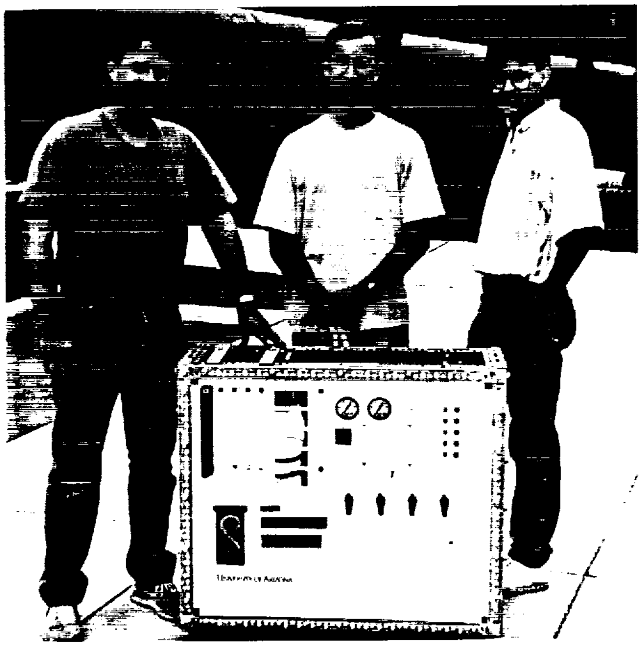


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Figure 20. Portable oxygen plant ($CO_2 \rightarrow O_2$).

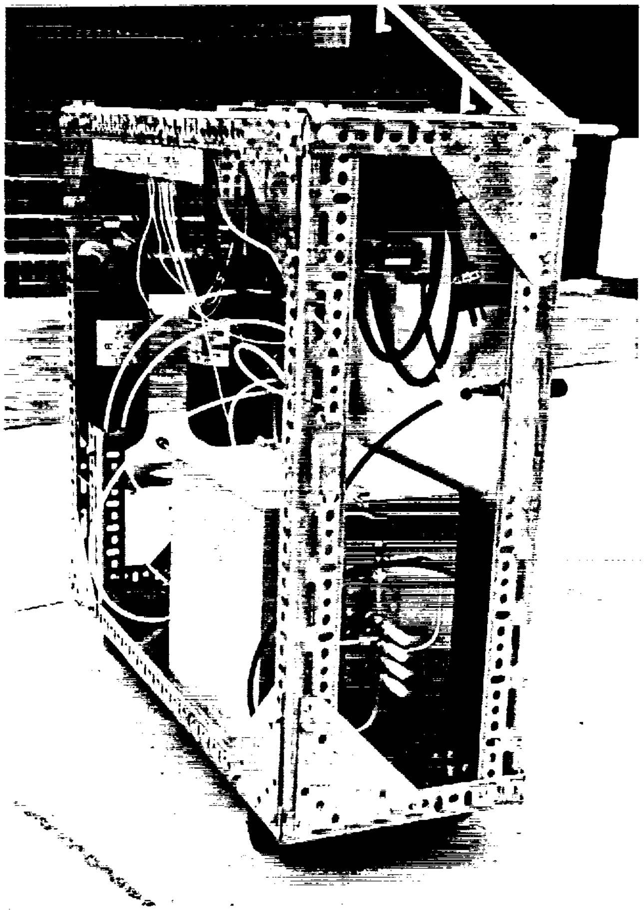

Fig. 21. Portable oxygen plant (cover removed).

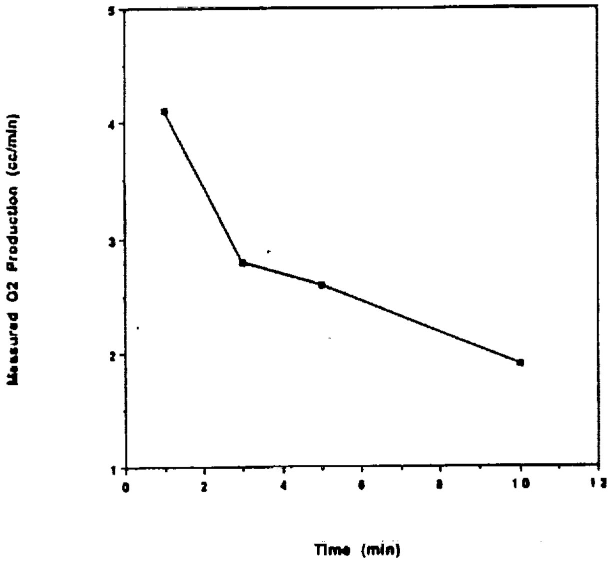

Fig. 22. Oxygen production versus time (T = 800°C, V = 2.00 V, LSM/Pt electrode).

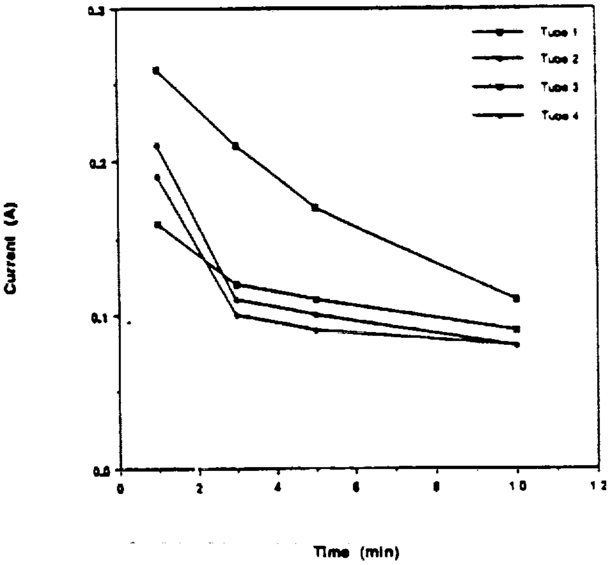

Fig. 23. Current versus time for Lewis unit tubes (T = 800°C, V = 2.00 V, LSM/Pt electrode).

Table 1. The basic game plan for in-situ resource utilization.

NOVEL CONCEPTS IN HIGH TECHNOLOGY:	"Anything Goes"
FEASIBILITY STUDIES:	"Back-of-the-Envelope Calculations and "Test-Tube" Evaluations
SMALL-SCALE PROOF-OF-CONCEPT:	Mathematical Models, Computer Simulations, First Hardware
BREADBOARD ENGINEERING DEMONSTRATIONS:	Realistic Full-Size System at Realistic Production Rates
HIGHEST TECHNOLOGY READINESS LEVEL:	Plans and Software Delivered to NASA and Industry

Table 2. Screening matrix for yttria-stabilized zirconia.

Tube	Electrode	Temperature (°C)	Applied Voltage	Oxygen Yield (cc/min)
C-4	Proprietary	825	2.40	11.75
C-6	Proprietary	825	2.98	12.90
C-7	Proprietary	825	2.37	7.0
SERC1	Ag/LSM	800	2.62	5.0
SERC2	Pt/LSM	1000	2.00	3.8
SERC3	Pd/LSM	850	2.00	2.9
SPECIAL	Undisclosed	900	2.00	22.4

Table 3. Mass and energy needs for oxygen production utilizing yttria-stabilized zirconia.[a]

	Single-Cell Unit	4-Cell Unit 0.1 kg/day	16-Cell Unit 0.4 kg/day	Full-Scale Prototype 1-2 kg/day
Mass (kg)	4.08	13.15	52.16	113.0
Dimensions[b] (cm)	20×20×28	30×30×46	120×120×46	30×46×36
Power Needs: Thermal (kw)	0.37	0.50	2.00	4.80
Electrical (w)	3.0	12.5	50.0	150.0

[a] Immediate Applications: portable 0.1 kg/day demo unit for LeRC; prove ability to engineer; package and operate at sites other than SERC.

[b] ZrO_2 subsystem only.

Table 4. Summary of mass and power needed for integrated oxygen production.

	Mass (kg)	Power (w)
Communications	3.5	10/120
Computer	4.25	16
Sensors/Acutators		
Servo motors (8)	6.4	480.0
Flow meters (2)	0.8	7.5
Pressure sensors (2)	0.1	0.2
Force/torque sensors (2)	1.0	*
Proximity sensors; strain gauge	*	*
Flow control valves (2)	1.2	2.4
Thermocouples (2)	*	*
CCD camera (1)	0.2	3.0
Mass spectrometer (1)	0.5	2.0
	10.2	495.1

*Negligible.

Table 5. Integrated oxygen production: task decomposition.

Soil Sample Acquisition

- Move arm and gather soil
- Deposit in crucible through sieve

Reactor Operation

- Mix solid carbon powder with soil
- Insert crucible at the focus
- Control heating (mirror adjustment)
- Measure/identify gases
- Remove and store residue (tiles from slag)

Data Management

- Obtain measurements and store data

Telemetry and Upload

- Adjust antenna/transmit data
- Upload code and data