JOURNAL OF PROPULSION AND POWER
Vol. 11, No. 6, November–December 1995

Mars Sample Return Mission with In-Situ Resource Utilization

K. R. Sridhar*
University of Arizona, Tucson, Arizona 85721

A Mars sample return mission has been proposed where oxygen for the return propellant would be produced using the Martian atmosphere. A mass analysis of an in-situ resource utilization (ISRU) oxygen plant shows that significant reductions in landed mass and mission costs can be attained by using methane carried from Earth and oxygen produced on Mars as propellants for the return trip. The metrics for the mass analysis are based on laboratory data collected from proof-of-concept, scale-up, and long-duration experiments. Using existing technology and current performance levels, it is shown that an ISRU plant capable of producing 7 kg/day of oxygen requires an estimated mass of 108 kg and consumes 2.9 kW of electrical power. A 2.5 kg/day oxygen production facility has a mass of 64 kg and requires 1.1 kW of electrical power.

Introduction

OUR knowledge of Mars was significantly enhanced by the data gathered from the Mariner and Viking missions.[1] Tremendous scientific gains, similar to those garnered from the samples returned from the Moon, could also be made by returning samples of Mars materials to Earth. These samples could then be analyzed in the laboratory with the aid of sophisticated instruments and powerful analytical methods to obtain the fundamental information that would help determine the biology, biochemistry, geochemistry, and petrology of Mars. Several concepts for Mars sample return (MSR) missions have been presented since the early 1970s. A few of the concepts will be discussed in the following section.

The concept of producing the propellant for the return leg of the mission using Martian resources was recommended as a cost-saving measure for MSR missions as early as 1978.[2] This study was followed by many other in-situ propellant production concept studies and they are all in agreement regarding the benefits. In spite of these conclusions, proof-of-concept and breadboard hardware demonstration experiments were not conducted until recently. One reason ISRU is not widely accepted, despite its benefits, is the general perception that the technology is still in its speculative and "view-graph engineering" stage. There is a lack of confidence in the numbers since most were not obtained from actual hardware and are not backed by long-term operating experience.

This study will present a strong case for oxygen production on Mars (for the return propellant) for a MSR mission and will provide the analysis and metrics based on proof-of-concept, scale-up, and long-term test results obtained in the laboratory. It will be shown that such a concept will reduce the mass to be landed on Mars and, hence, the total mission costs. It must be emphasized that all of the data used in this analysis are based on performance levels that have been achieved to date. In instances where future reductions in masses and improvements in performances are projected, they will be stated in this article for completeness, but such projected values will not be used in the analysis.

Received Aug. 31, 1994; revision received Dec. 5, 1994; accepted for publication March 13, 1995.

*Assistant Professor, Department of Aerospace and Mechanical Engineering. Senior Member AIAA.

MSR Missions

There have been several studies and mission concepts proposed for MSR. To illustrate the benefits of ISRU we shall look at two sets of studies. One set is from the 1970s and the other from the 1990s.

In the early 1970s two teams of scientists looked into the possibility of Mars sample return missions. One concept involved a spacecraft with direct entry and landing on the Mars surface, sample acquisition, ascent to a Mars parking orbit, and direct re-entry to Earth.[3] The penalty for this simple concept is the large landed mass of the ascent vehicle. The other concept[4] involved an automated rendezvous between a Mars-orbiting Earth return vehicle and a Mars ascent vehicle. The lightweight Mars ascent vehicle transfers the Mars sample capsule to the orbiting craft, which returns to Earth. This concept has a lighter landed mass, but involves a complex autonomous rendezvous in Mars orbit. After considering the conjunction, opposition, and Venus swing-by trajectories, both teams selected the long-duration conjunction-class missions. The conjunction-class missions require a stay on Mars, or in Mars parking orbit, for over 400 days before returning to Earth. The direct-entry-mode mission was analyzed for 1979 and 1981 launch windows, whereas the Mars orbital rendezvous mode mission was for a 1981 launch window. Since exact launch opportunities repeat themselves every 15 years, these analyses would be valid for the 1994 and 1996 launch windows. The complexity of the autonomous Mars orbit rendezvous in the second mission would tip the scale in favor of the simpler direct-entry-mode mission if the mass to be landed on Mars could be reduced.

In an effort to reduce the landed mass of the direct-entry-mode mission, Ash et al.[2] pioneered the concept of ISRU. Their concept involved carrying a small chemical plant to produce the necessary propellant for the return trip from Martian resources. Due to the long duration of the stay on Mars, the mass of the production plant was much less than the total propellant produced, thereby reducing the landed mass. They proposed extracting water from the soil and carbon dioxide from the atmosphere of Mars to produce methane and oxygen using water electrolysis and a Sabatier reactor. A return sample size of 1 kg was chosen, as opposed to the 0.2-kg sample of Weaver et al.[3] Also, their ISRU-assisted mission did not use a Mars parking orbit on the return. In addition, a single-stage methane-oxygen rocket to accomplish ascent from the Mars surface to a trans-Earth trajectory was proposed. In this scheme, the estimated mass of an ISRU plant (including RTG power) that would produce the required 3330 kg of propellant at 10 kg/day was about 750 kg. The key to mass savings arises from the long stay of 400–500 days on the surface of Mars. The total landed mass of the Mars ascent vehicle (including ISRU plant) was 1600 kg. In comparison, a fully fueled, single-stage ascent vehicle would have a landed mass of over 5000 kg.[2] It should be noted that this concept is based on extracting water from the Martian soil for propellant production. While this may be feasible at certain locations and during certain seasons, the dependence on soil for water restricted the location of the lander and also added a considerable level of risk to the mission. A process to produce oxygen from Martian carbon dioxide using solid oxide electrolysis cells was suggested by Stancati et al.[5] The experiments reported here are based on this process.

After a hiatus in the early and mid-1980s, there has been renewed interest in the MSR missions. In early 1990, Gamber and Adams[6] looked at system concepts for MSR missions for the 2001–2007 launch opportunities for the conjunction-class missions. Nine concepts were explored and three were presented at an AAS/AIAA astrodynamics conference.[6] They all involved a rover for soil sample acquisition. One concept, called the "low complexity" concept, was developed that involved a single Titan IV launch. It involved direct entry to Mars and ascent to a parking orbit around Mars before return to Earth. The ascent vehicle was a 2-1/2 stage vehicle. For a 5-kg sample return, the mass of the Mars ascent vehicle in this concept was 1996 kg and the propellant wet mass was 1812 kg. It was designed for the 2001 launch opportunity. The engine was an advanced pump-fed XLR-132 with high expansion ratios.

The MSR mission proposed in this article will be analyzed using the mission requirements proposed by Ash et al.[2] and Gamber and Adams.[6] The former mission had a total propellant need of 3330 kg for a single-stage methane–oxygen rocket with an oxygen-to-fuel ratio of 3.4 and an assumed specific impulse of 342 s. The oxygen requirement for this case is 2573 kg. If 7 kg of oxygen are produced per day, this amount can be produced in 368 days. For the latter mission, based on the specific impulse requirements and 2-1/2 stages for the Mars ascent vehicle, a methane–oxygen vehicle operating at an oxygen-to-fuel ratio of 3.5 and specific impulse of 350 s would require 307 kg of methane and 1075 kg of oxygen. It is important to note that, since the propellants and specific impulses for the original mission are different from the methane–oxygen system being considered here, the dry and wet masses recommended originally have been recalculated. An ISRU plant producing 2.5 kg of oxygen a day would generate the required amount in 430 days (total stay on Mars = 490 days). Therefore, two ISRU oxygen plants will be designed: one for the production of 7 kg/day of oxygen and the other for 2.5 kg/day.

ISRU Technologies for Mars

Numerous studies have outlined various technologies available for propellant production and life support on Mars. A few of them are referenced here for the interested reader.[7–18] The most common and widely studied of the many technologies that have been proposed for propellant production involve oxygen and methane. One approach involves the production of oxygen and methane from Martian water and atmosphere using the Sabatier process and water electrolysis, as mentioned previously.[2] Another involves their production using hydrogen carried from Earth and carbon dioxide from the Martian atmosphere.[19] Some approaches involve the production of oxygen from the Martian atmosphere using solid oxide electrochemical cells[18] or glow-discharge and permeation.[17]

Mars Sample Return with ISRU (MSRI)

ISRU Process Selection and Philosophy

In the proposed mission, oxygen will be produced from carbon dioxide in the Martian atmosphere using solid oxide electrochemical cells (SOEC). The locally produced oxygen and Earth-carried methane will be used as the propellants for the return leg of the mission.

The production of methane using Earth-carried liquid hydrogen involves the storage of liquid hydrogen at 20 K during the long transit to Mars and its storage for a significant portion of the long wait on the surface of Mars. It requires the operation of two separate chemical plants, viz., the Sabatier and water electrolysis. In addition, methane and oxygen are produced in a 1:2 mass ratio, as opposed to the 1:3.5 ratio required for optimum rocket specific impulse. Production of the required amount of oxygen results in excess methane being produced. This, in turn, translates to a heavier ISRU plant being built for greater capacity. The other fuel option that merits serious consideration is carbon monoxide. The SOEC produces carbon monoxide and oxygen in the mass ratio of 1:0.57, which is very close to the optimum specific impulse mass ratio of 1:0.55. The specific impulse of the carbon monoxide–oxygen rocket is low, 260–300 s, but since both fuel and oxidant are produced by the same device (SOEC) and no resources are carried from Earth, it is definitely worth considering. However, due to the low technology readiness level of the carbon monoxide–oxygen engine and the need for its development, this technology is not considered in the present concept. The carbon monoxide–oxygen engine technology is currently under development[20] and this concept should be revisited when it attains maturity.

ISRU Process Plant Architecture

A schematic of the simplified oxygen production plant is illustrated in Fig. 1. The Martian atmospheric gas is filtered to remove dust and particulates and is compressed from its ambient pressure to about 0.1 MPa. The gases are then heated from the ambient temperature to about 1223 K by means of a waste-heat-recovery heat exchanger and make-up heater. Following this, the hot gases enter the SOEC. In practice, the make-up heater and the SOEC are integrated into a single unit. In the SOEC, carbon dioxide dissociates into carbon monoxide and oxygen due to electrocatalysis and thermal dissociation. A dc potential is applied across the SOEC to separate the oxygen from the gas mixture. The oxygen produced is compressed, liquefied, and stored. The high-quality heat of the gas mixture exhausting from the SOEC is extracted in the recovery heat exchanger before it is rejected out of the system. Only a fraction of the carbon dioxide entering the SOEC dissociates to produce oxygen. At the present time,

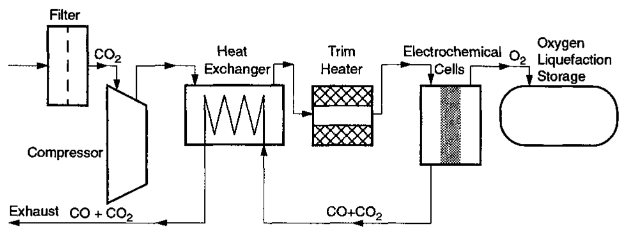

Fig. 1 Schematic of a simple Mars oxygen plant.

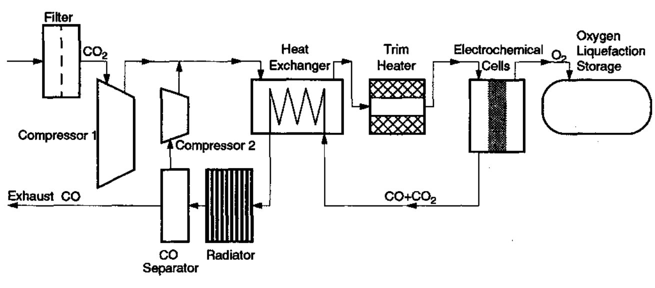

Fig. 2 Schematic of a Mars oxygen plant with CO_2 recycling.

SOEC operating in our Space Technologies Laboratory convert up to 32% of the carbon dioxide. At such conversion rates (as will be seen in a following section), the compressor mass and required power are high. However, by incorporating a separator that recycles the unspent carbon dioxide back into the system, the mass and power requirements of the compressor unit can be greatly reduced. A schematic of this plant, with carbon dioxide recycling, is shown in Fig. 2.

It must be noted that research will be underway shortly to study the performance of the SOEC at pressures well below 0.1 MPa. Should the SOEC perform satisfactorily at pressures close to the Martian ambient, the recycling of carbon dioxide may not be necessary. The performance data presently available are for 0.1 MPa only; hence, the design of the system at 0.1 MPa pressure. The Martian atmosphere and each of the components of the system are described in the following sections.

Martian Atmosphere

The Martian atmosphere is composed of 95.3% carbon dioxide, 2.7% nitrogen, 1.6% argon, 0.13% oxygen, and trace amounts of water vapor, neon, krypton, xenon, ozone, and other gases.[21] The average total atmospheric pressure is about 800 Pa, and it varies from 600 to 1000 Pa as a function of the season. This variation is due to condensation and evaporation of carbon dioxide at the polar caps. The atmospheric pressure also varies with surface altitude, as is to be expected. The atmospheric pressure data from the two Viking landers showed the variations of pressure with season and altitude.[22] The total pressure at the Viking I site varied from 680 to 900 Pa and at the lower elevation Viking II site it varied from 750 to 1020 Pa.[22] From the viewpoint of the oxygen production plant, it would be advantageous to land at lower elevation sites in order to exploit the higher atmospheric pressures and thereby reduce the workload of the compressor. The bottom of Hellas Basin in the southern hemisphere is more than 4 km below the planetary reference level, the atmospheric pressure can reach 1500 Pa,[23] and it has the most water,[24] making it biologically and biochemically very interesting.

Martian Dust and Filters

One of the concerns about use of the Martian atmosphere is Martian dust. The Martian atmosphere has to be filtered of dust and particulates before it is compressed. The Viking missions have provided useful information about the dust and dust storms that prevail on Mars. The value of the dust loading under clear sky conditions is 10 ppm.[16] During a dust storm, the dust loading is typically 10^{-2} kg/m^2, and the total estimated mass of the Mars atmosphere is 200 kg/m^2.[16] During the present epoch, great dust storms have not occurred during the northern spring and summer due to the reduced insolation. In the period between 1909–1982, 16 global dust storms were observed and recorded from Earth and/or by spacecraft. Typically, a local dust storm expands slowly for about 4 days and then expands rapidly for the next 4. Within the next 5–10 days, the dust has encircled the planet. The time constant for settling of the dust (decay by a factor of e) is about 60 days.[25] The composition of the dust is thought to be magnetite and basalt.

Based on the Viking lander data and a model for optical parameters, Pollack et al.[26] deduced the cross-sectional, area-weighted, mean particle diameter to be 0.4–2.5 μm. They also calculated that the wind speed at the top of the planetary boundary layer would have to exceed 50–100 m/s in order for the dust particles to get suspended. The typical wind speed on Mars is only about 10 m/s. Hence, unusual local or global conditions are needed to put dust particles into suspension. Ash et al.[8] considered the dust analyses performed by various investigators using the Viking Lander data, including that of Pollack et al.[26] They assumed a continuous dust load of one 5-μm particle/cm^3 of Martian atmosphere. It is also important to note that the high winds associated with the dust storms occur only in the region of the dust storms and, although the dust is carried globally, intense surface winds do not accompany it.[16]

In summary, it is possible to select the location and timing of the mission such that the need to protect the ISRU plant from high winds and large amounts of dust can be virtually eliminated. For clear sky conditions, the 10-ppm dust can be easily filtered with present-day technology. A filter mass of 0.05 kg/kg of Martian atmosphere is chosen for a 400-day operation. The dust filter mass would scale linearly with flow rate for the range that is of interest.

Solid Oxide Electrochemical Cell

The key component of the Mars oxygen production plant is the SOEC, which separates the oxygen from the gas mixture of carbon dioxide, carbon monoxide, and oxygen. The principle of operation of the SOEC is shown schematically in Fig. 3. At the temperatures of operation of the SOEC (1073–1273 K) carbon dioxide partially decomposes into oxygen and carbon monoxide by thermal dissociation and electrocatalysis. The cell consists of an electrolyte sandwiched between electrically conductive porous electrodes. The separation of oxygen in the cell occurs due to the oxygen ion conductivity of the electrolyte material (zirconia that is partially stabilized with yttria). Oxygen vacancies exist in the crystal lattice of the electrolyte. These vacancies provide conduction sites for the transport of oxygen ions through the electrolyte. A dc potential applied across the electrolyte provides the driving force for oxygen transport. At the cathode electrode/electrolyte interface, oxygen molecules decompose into oxygen ions with a negative charge of two. The oxygen ions then move from vacancy-to-vacancy, until they arrive at the anode electrode/electrolyte interface, where they lose the excess electrons and reform into molecular oxygen. The molecular oxygen then diffuses out of the porous electrode.

At our laboratories, extensive testing of the SOEC has been conducted for the past three years and the effort is ongoing. Commercially available tubular cells were tested for proof-of-concept, scalability, and endurance. A schematic of a cluster of four tubes is shown in Fig. 4. Figure 5 is a photograph of a fully packaged, compact unit of a four-tube cluster with overall dimensions of 62 × 51 × 35 cm^3. Four such clusters were plumbed together to obtain an oxygen production of 120 l/day.

Marner et al.[27] demonstrated the importance of selecting the optimal electrolyte and electrode materials for the efficient operation of the cell. Proper selection of the electrode and electrolyte materials can significantly reduce the mass of the SOEC and the plant, as well as the power requirements. Extensive testing in our Space Technologies Laboratory has confirmed this to be the case for the carbon dioxide reduction reaction.[28] These tests have been performed using disk cells

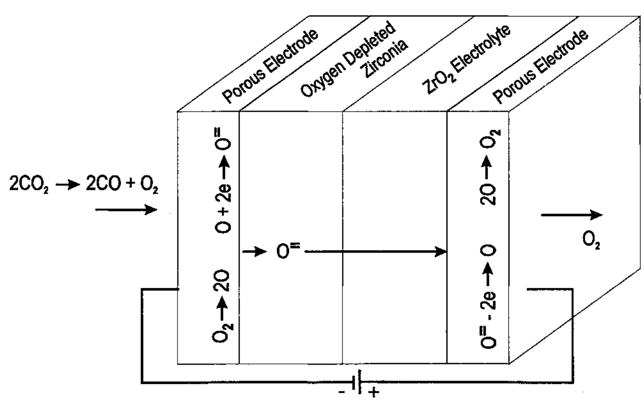

Fig. 3 Solid oxide electrochemical cell operation.

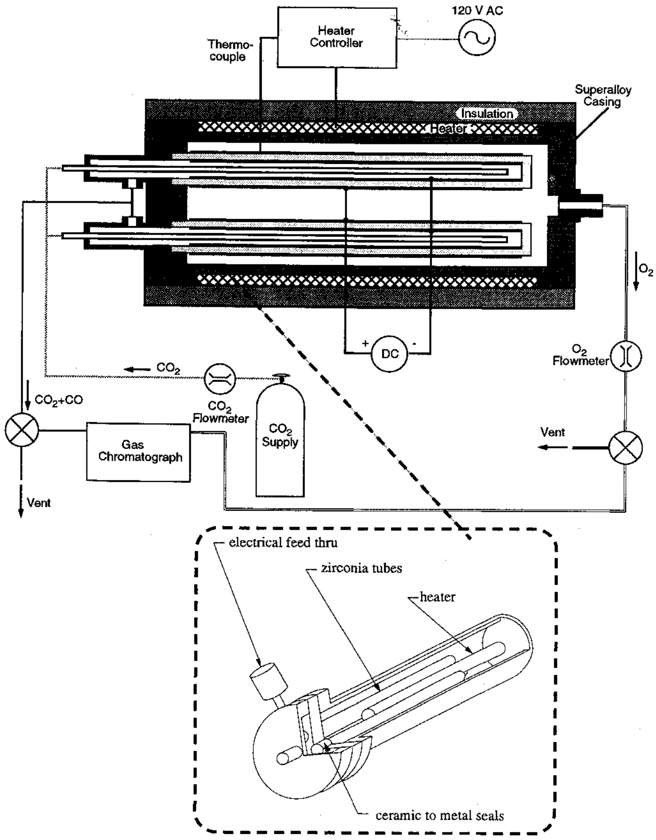

Fig. 4 Schematic of a SOEC tube-cell cluster test bed.

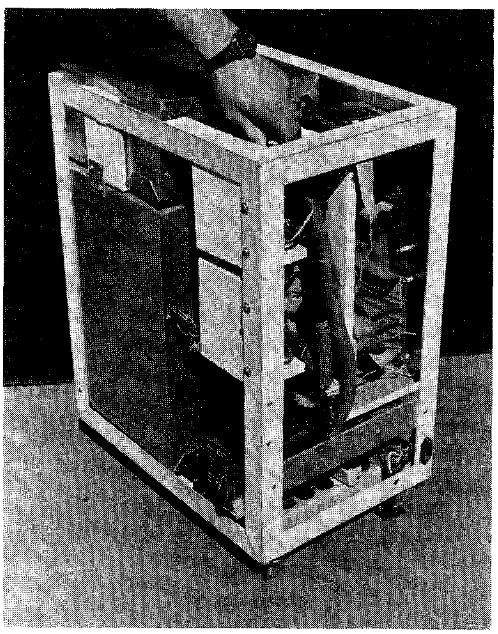

Fig. 5 Packaged four-tube cluster with built-in controls and instrumentation.

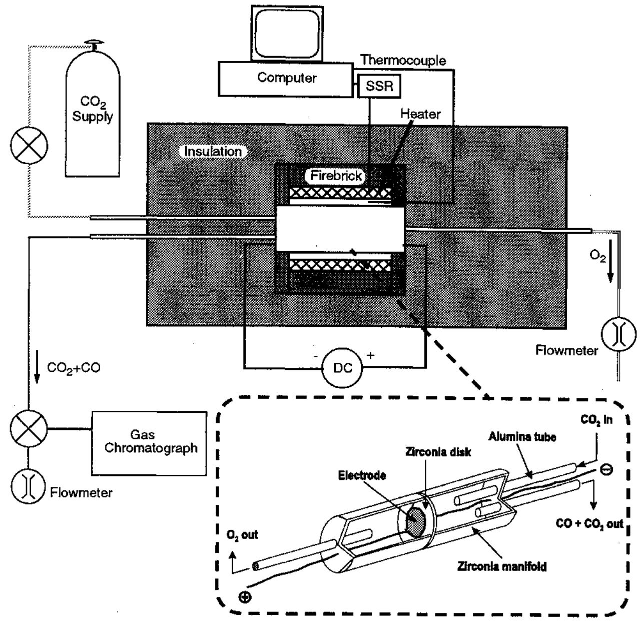

Fig. 6 Schematic of a SOEC disk-cell test bed.

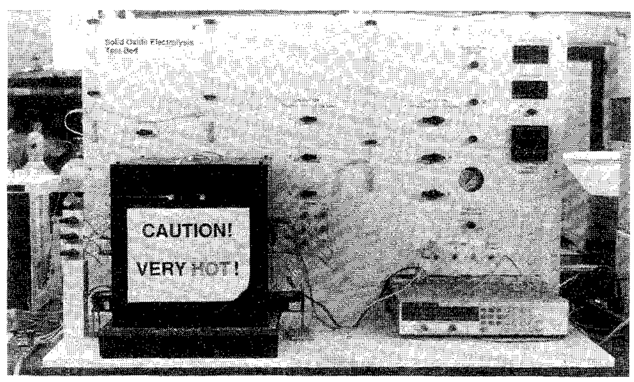

Fig. 7 Test bed for characterization of disk cells.

that are fabricated in-house. It has been found that an 8-mole% yttria-stabilized zirconia electrolyte sandwiched between porous platinum electrodes provides optimum and stable production levels of oxygen. A simple schematic of the disk cell is shown in Fig. 6. Figure 7 is a photograph of the laboratory test bed for characterization of disk cells. The nominal electroded area of each disk is 100 mm^2.

The performance of the disk cells at various operating temperatures and dc potentials is shown in Fig. 8. It is seen that the oxygen production rate (which is related directly to the cell current), increases with increasing temperature and increasing dc potential. The data points in the figure are the experimental data and the solid lines are best-fit curves. Figure 9 illustrates the variation of oxygen production with carbon dioxide feed rate. At a fixed cell operating temperature and dc potential the mass of the feed gas is a limiting condition. At carbon dioxide flow rates below the knee the rate of oxygen transport across the cell is limited by a lack of oxygen at the cathode surface. Increasing the carbon dioxide flow rate above the limiting value will not result in increased oxygen production, as evidenced by the flat portion of the curve. It is seen that carbon dioxide conversions of up to 32% (efficiency) have been achieved. This graph is for a cell operating temperature of 1223 K. The SOEC efficiencies are expected to be even higher at 1273 K, but the laboratory-demonstrated value of 32% is used as the SOEC efficiency for the present analysis. The disk cells have been subjected to over 1800 h of continuous testing and no degradation in performance has been observed. Figure 10 depicts the results of an endurance test on one of the disk cells. In addition, the cells have been tested with simulated Martian gas, with no noticeable change in oxygen production.

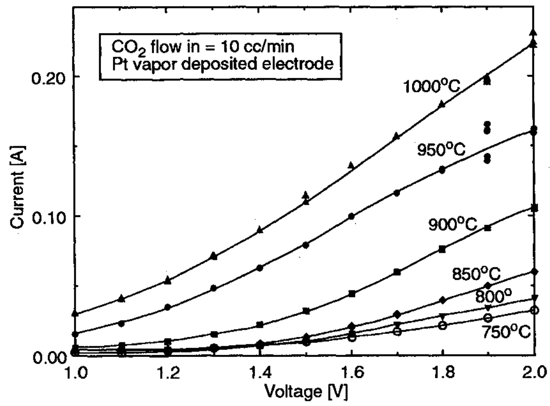

Fig. 8 SOEC disk characterization tests.

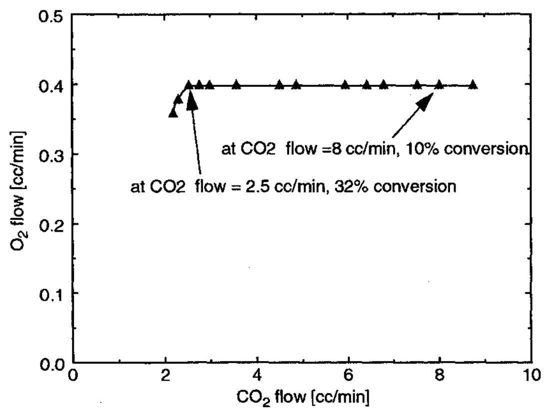

Fig. 9 Effect of CO_2 feed rate on oxygen production.

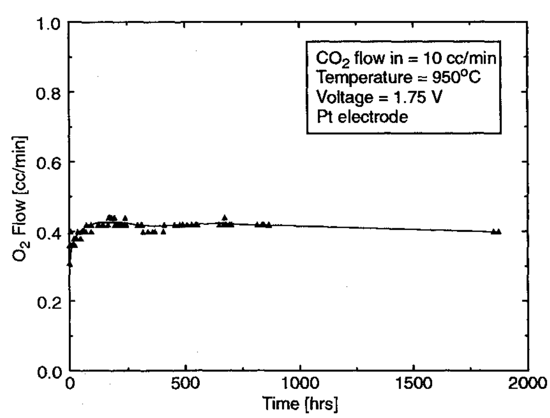

Fig. 10 Endurance test results for a SOEC disk.

The disk cells can be manifolded and stacked into compact units, as described by Marner et al.[27] The masses of the SOEC for the production of 7.0 and 2.5 kg of oxygen/day are 10 kg and 4 kg, respectively. The mass estimates are based on recent experiments in our laboratory on disk cells of varying electroded areas. These experiments have shown that, with proper design of the manifolds and electrical interconnects, a 32% efficiency can be attained for disks with electroded areas larger than 1 cm^2. The oxygen production rate of 1 $cm^3/min/cm^2$ of electroded area can be sustained for much larger electroded areas at a dc potential of 1.7 V and cell temperature of 1273 K. The masses of the SOEC required to produce 7.0 and 2.5 kg of oxygen are now calculated based on these observations. Zirconia disks, 76.2 mm in diameter and 0.7 mm in thickness with an electroded area of 34.42 cm^2, are used for both systems. The 7.0-kg unit requires 98 disks, for a total mass of 1.78 kg, and the 2.5-kg unit needs 35 disks, for a mass of 0.64 kg. While the former are assembled in three stacks, the latter are assembled in one. The interconnects, which deliver the electrical potential to the electrodes and form the flow channels for the gases, are made of perovskites, such as lanthanum manganite or lanthanum chromate. The masses of the interconnect plates for the two systems are 6.91 and 2.46 kg, respectively. The seals, electrical wires, and plumbing constitute the rest of the SOEC's mass. The masses of the insulation and thermal control mechanisms for the SOEC are 1.5 and 0.7 kg. The dc powers required for the production of 7.0 and 2.5 kg of oxygen/day are 1.73 and 0.62 kW, respectively, at 1.7 V.

Carbon Dioxide Compression

To date, all the laboratory data obtained for oxygen production from carbon dioxide using SOEC are for operating pressures of 0.1 MPa. Testing of the SOEC at lower pressures is about to begin. For this reason, the Martian atmosphere is assumed to be compressed to 0.1 MPa. Oil-sealed pumps were not used at this time due to the low temperature of the intake gases and the potential contamination of the SOEC downstream. Nonmechanical compressors, such as adsorption pumps, have been recommended elsewhere for this application.[10–12] Due to their level of technology readiness, mechanical pumps are preferred over the nonmechanical ones in this article.

Several off-the-shelf pumps were evaluated for their applicability in terms of life, mass, and power. It was also seen that the recycling of unspent carbon dioxide significantly reduced the compressor mass and power. The mass savings are depicted in Table 1 for an oxygen production rate of 10 kg/day.[29] The results show that recycling is very beneficial at lower SOEC efficiencies. For the production of 7 kg of oxygen/day at an SOEC efficiency of 32% and separator efficiency of 90%, 23.3 kg of carbon dioxide/day is needed as input gas; this corresponds to roughly 24.3 kg/day of Martian atmospheric gas. The mass of a compressor that can deliver this amount of oxygen at 0.1 MPa by taking in Martian atmosphere is 30 kg. The power required by this unit is 0.75 kW. For the production of 2.5 kg of oxygen/day, the mass and power requirements of the compression unit are 20 kg and 0.375 kW, respectively. The mass and power estimates for the compression units for both systems are based on dual-stage rotary vane pumps. Such pumps are used in terrestrial applications as a backing pump for Roots pumps, diffusion pumps, and cryopumps. With some modifications, these pumps can be used for the Mars application. Both the mass and power needs can be reduced substantially for space applications with minimal effort. Details of the various options considered for mechanical compression, as well as the mass models for the compressors, can be found in Sridhar and Iyer.[29]

It should be noted that the waste heat from radioisotope thermoelectric generator (RTG) power units could be used to keep the compressor warm (300 K). This would enable the use of pumps with oil seals and lubrication. The possibility of downstream oil contamination could be avoided by using an oil-trap filter.

Waste-Heat-Recovery Heat Exchanger

This piece of apparatus extracts heat from the gases being exhausted from the SOEC at 1273 K and imparts that heat to the cooler gases entering the SOEC. This counterflow tube-in-tube heat exchanger is designed to produce exhaust gases to temperatures of 873 K. The mass of the heat exchanger for the production of 7.5 kg of oxygen/day is 1.0 kg and that for the 2.5-kg plant is 0.4 kg.

Make-Up Heater

The make-up heater heats the gases to the temperature of the SOEC (1273 K). In this design, it is integrated with the SOEC. Ground testing is being conducted with resistive heaters. It is proposed that plutonium-238 bricks, which have been used in past missions as part of the RTG units, be used as a

Table 1 Total mass savings due to CO_2 recycling for 10 kg/day O_2 production

	No carbon dioxide recycling			Carbon dioxide recycling			Savings	
η_{cell}	CO_2 intake, kg/day	Pump mass, kg	Pump power, kW	CO_2 intake, kg/day	Pump mass, kg	Pump power, kW	Mass, kg	Power, kW
0.2	137.50	239	9.1	38.50	73	1.8	166	7.3
0.3	91.67	157	6.3	33.92	59	1.6	98	4.7
0.4	68.75	141	5.5	31.63	55	1.5	86	4.0
0.5	55.00	120	4.4	30.25	51	1.5	69	2.9
0.6	45.83	91	3.6	29.33	50	1.4	41	2.2
0.7	39.29	82	3.2	26.68	50	1.4	32	1.8
0.8	34.35	59	1.6	28.17	50	1.3	9	0.3

Table 2 ISRU oxygen plant masses

	Oxygen production			
	7.0 kg/day		2.5 kg/day	
Component	Mass, kg	Electric power, W	Mass, kg	Electric power, W
SOEC	10.0	1730	4.0	620
SOEC insulation and thermal control	2.5	—	1.7	—
Intake compressor	30.0	750	20.0	375
Heat exchanger	1.0	—	0.4	—
Heater	5.8	—	2.9	—
Liquefaction and storage				
Oxygen	20.0	350	10.0	70
Methane	10.0	40	6.0	30
Dust filter	1.6	—	0.6	—
Recycling subunit	4.0	15	2.2	8
Other[a]	23.0	—	16.0	—
Total system	107.9	2885	63.8	1103

[a]Plumbing, structure, controls, and microprocessor.

heat source. The half-life of the plutonium is 189 years. These bricks have a mass of 2.89 kg and a thermal output of 250 W. Temperatures of up to 1573 K can be attained with these bricks, which are 93.2 × 97 × 53.3 mm in size.[30] The larger plant (7.5 kg) would require two bricks and the smaller plant would require one brick.

Liquefaction and Storage

The methane carried from Earth is liquefied, but it needs refrigeration to remain liquid at 110 K. The oxygen produced by the SOEC is cooled to Martian ambient temperature easily, but requires liquefaction and refrigeration to remain liquid at 90 K. The 200 K Martian temperature provides a good sink, which improves the efficiency of the refrigeration cycles compared to those on Earth. A reverse Brayton cycle turbo cooler, or a Stirling cooler, can be used to perform the liquefaction and cooling. They are both available commercially and are capable of long-duration performance with no maintenance.[31] For the plant producing 7.0 kg of oxygen, a 20-kg cooler requiring 350 W of electric power is required for oxygen, and a 10-kg cooler requiring 40 W of power is required for methane. The corresponding numbers for the 2.5-kg plant are 10 kg and 70 W for oxygen and 6 kg and 30 W for methane.

Oxygen compression and liquefaction can also be accomplished by using the solid oxide tubular cells followed by a Joule–Thomson process. The oxygen produced at 0.1 MPa in the SOEC is compressed to about 15 MPa in the tubular cells in a single stage. The high-temperature oxygen is then cooled to the Martian ambient temperature and is expanded in an orifice to produce liquid oxygen. This process is in the developmental stages in our laboratories and it holds promise as an advanced concept. Details of this scheme can be found elsewhere.[32]

Recycling Subunit

The carbon monoxide separator, the radiator that cools the exhaust gases from the SOEC to 300 K, and the make-up compressor are part of the recycling subunit. Polymeric membranes are commercially available to separate the carbon dioxide from the exhaust gases of the SOEC. In addition, researchers at the University of Arizona have been successful in developing carbon monoxide separators using supported nickel and cobalt catalysts.[33] The mass and power requirements of the make-up compressor are very small (0.1 kg and 10 W). The total masses of the recycling units for the 7.0- and 2.5-kg systems are 4.0 and 2.2 kg, respectively.

Total System Mass and Power

The total system masses and electrical power needs for the 7.0- and 2.5-kg oxygen production units are tabulated in Table 2, along with the component power and mass data. The electrical power is not converted into a mass penalty in the table due to the wide variation of mass penalties used in the literature. Until recently, it was common to assume a mass penalty of 30–40 kg/kW electric, the projected value for the SP-100 class reactors. With the cancellation of this program, the only existing technology that seems viable for the current application is RTG. The RTGs that have been flown and are flight qualified have a mass of 55 kg and produce 300 W of electric power.[30] The 523–573 K waste heat from the RTG can be used for process heat. It is estimated that a 1-kW electric RTG can be made for a mass of 140 kg. The power penalty used in this analysis will be 140 kg/kW electric.

Results and Conclusions

The total system mass of an ISRU oxygen plant that can produce 7 kg of oxygen/day is 107.9 kg and its electrical power consumption is 2.9 kW. The 2.5-kg oxygen plant has a mass of 63.8 kg, and it requires 1.1 kW of electric power. At a power penalty of 140 kg/kW, the total masses of the 7.0- and 2.5-kg oxygen plants are 512 and 218 kg, respectively. These masses are based on existing technology and performance levels.

Should such an ISRU plant be incorporated into the modified direct-entry-mode mission of Ash et al.,[2] the mass of the ISRU plant and fuel would be 1269 kg (757 kg of methane and 512 kg for the ISRU plant), instead of the 3330 kg of propellant needed for a non-ISRU mission. This would be a significant reduction of the total landed mass of the Mars lander. It is higher than the 750-kg ISRU plant proposed by Ash et al., but it does not depend on a Martian water supply.

The mass of the ISRU plant and Earth-carried methane that can replace the 1382 kg of propellant on the Gamber et al.[6] mission is 525 kg (218 kg for the ISRU unit and 307 kg of methane). This will significantly reduce the landed mass on Mars and, therefore, the cost of the mission.

The use of oxygen produced from the Martian atmosphere with ISRU technology and Earth-carried methane as the propellants for the return leg of a MSR mission has been proposed. This concept has been developed using existing technology and currently attainable performance metrics. This analysis shows that significant reductions in the landed mass and cost can be achieved with this relatively low-risk, low-complexity concept. Thus, the use of ISRU technologies can make unmanned sample return and manned missions to Mars economically viable.

Acknowledgments

This work was sponsored by NASA through Grant NAGW-1332. The author would like to thank the UA/NASA Space Engineering Research Center for their support. Thanks are extended to K. N. Ramohalli for the many discussions and to Brian Vaniman and Scott Miller for obtaining much of the data on the oxygen plant. The author would also like to thank Jim French for his suggestions. Thanks are also extended to Matthias Gottmann for some of the figures.

References

[1]Flinn, E. A., Csanady, G., and Siscoe, G. L. (eds.), "Scientific Results of the Viking Project," *Journal of Geophysical Research*, Vol. 82, No. 28, 1977, pp. 3959–4681 (special issue).

[2]Ash, R. L., Dowler, W. L., and Varsi, G., "Feasibility of Rocket Propellant Production on Mars," *Acta Astronautica*, Vol. 5, No. 9, 1978, pp. 705–724.

[3]Weaver, W. L., Darnell, W. L., Norton, H. N., and Jaffe, L. D., "Mars Sample Return Through Parking Orbit," *Astronautics and Aeronautics*, Vol. 13, Jan. 1975, pp. 42–51.

[4]Moore, J. W., and Scofield, W. T., "Mars Sample Return by Orbital Rendezvous," *Astronautics and Aeronautics*, Vol. 13, Jan. 1975, pp. 52–62.

[5]Stancati, M. L., Niehoff, J. C., Wells, W. C., and Ash, R. L., "Remote Automated Propellant Production: A New Potential for Round Trip Spacecraft," AIAA Paper 79-0906, May 1979.

[6]Gamber, R. T., and Adams, G. L., "A Low Cost/Low Complexity Concept for the Mars Sample Return Mission," *Astrodynamics 1991, Proceedings of the AAS/AIAA Astrodynamics Conference*, edited by B. Kaufman, K. T. Alfriend, R. L. Roehrich, and R. R. Dasenbrock, Vol. 76, Pt. 2, American Astronautical Society, New York, 1991, pp. 1495–1512.

[7]French, J. R., Norton, H. N., and Klein, G. A., "Mars Sample Return Options," *Aerospace America*, Vol. 23, Nov. 1985, pp. 50–53.

[8]Ash, R. L., Richter, R., Dowler, W. L., Hanson, J. A., and Uphoff, C. W., "Autonomous Oxygen Production for a Mars Return Vehicle," International Astronautical Federation Paper IAF-82-210, Oct. 1982.

[9]Ramohalli, K. N., Dowler, W., French, J., and Ash, R., "Some Aspects of Space Propulsion with Extraterrestrial Processing," *Journal of Spacecraft and Rockets*, Vol. 24, No. 3, 1987, pp. 236–244.

[10]Ramohalli, K. N., Lawton, E., and Ash, R., "Recent Concepts in Missions to Mars—Extraterrestrial Processing," *Journal of Propulsion and Power*, Vol. 5, No. 2, 1989, pp. 181–187.

[11]Ramohalli, K. N., Dowler, W., French, J., and Ash, R., "Novel Extraterrestrial Processing for Space Propulsion," *Acta Astronautica*, Vol. 15, No. 5, 1987, pp. 259–273.

[12]Frisbee, R. H., and Jones, R. M., "An Analysis of Alternate Hydrogen Sources for Lunar Materials to Earth Orbit," AIAA Paper 83-1344, Jan. 1983.

[13]Carroll, W. F., Steurer, W. H., Frisbee, R. H., and Jones, R. M., "Should We Make Products on the Moon?" *Astronautics and Aeronautics*, Vol. 21, June 1983, pp. 80–85.

[14]Ash, R. L., and Cuda, V., Jr., "Technology Status Report for In-Situ Propellant Production," Jet Propulsion Lab., Pasadena, CA, May 1984.

[15]Ramohalli, K., Kirsch, T., and Preiss, B., "Figure-of-Merit Approach to Extraterrestrial Resource Utilization," *Journal of Propulsion and Power*, Vol. 8, No. 1, 1992, pp. 240–246.

[16]Meyer, T. R., and McKay, C. P., "The Resources of Mars for Human Settlement," *Journal of the British Interplanetary Society*, Vol. 42, No. 4, 1989, pp. 147–160.

[17]Ash, R. L., Wu, D., and Outlaw, R. A., "A Study of Glow-Discharge and Permeation Techniques to Separate Oxygen from Martian Atmosphere," Paper E.4-S.4.05X, World Space Congress, Washington, DC, Aug.–Sept. 1992.

[18]Ramohalli, K. N. R., and Sridhar, K. R., "Extraterrestrial Materials Processing and Related Transport Phenomena," *Journal of Propulsion and Power*, Vol. 8, No. 3, 1992, pp. 687–696.

[19]Zubrin, R. M., Baker, D. A., and Gwynee, O., "Mars Direct: A Coherent Architecture for the Space Exploration Initiative," AIAA Paper 91-2333, June 1991.

[20]Linne, D. L., and Meyer, M. L., "A Compilation of Lunar and Mars Exploration Strategies Utilizing Indigenous Propellants," NASA TM 105262, Jan. 1992.

[21]Owen, T., Biemann, K., Rushnek, D. R., Biller, J. E., Howarth, D. W., and Lafleur, A. L., "The Composition of the Atmosphere at the Surface of Mars," *Journal of Geophysical Research*, Vol. 82, No. 28, 1977, pp. 4635–4639.

[22]Haberle, R. M., "The Climate of Mars," *Scientific American*, Vol. 254, No. 5, 1986, pp. 54–62.

[23]McKay, C. P., Meyer, T. R., Boston, P. J., Nelson, M., MacCallum, T., and Gwynne, O., "Utilizing Martian Resources for Life Support," *Resources of Near-Earth Space*, edited by J. S. Lewis, M. S. Matthews, and M. Guerrieri, Univ. of Arizona Press, Tucson, AZ, 1993, pp. 819–843.

[24]Jakosky, B. M., and Farmer, C. B., "The Seasonal and Global Behavior of Water Vapor in the Mars Atmosphere: Complete Global Results of the Viking Atmospheric Water Detector Experiment," *Journal of Geophysical Research*, Vol. 87, No. B4, 1982, pp. 2999–3019.

[25]Zurek, R. W., "Martian Great Dust Storms: An Update," *Icarus*, Vol. 50, Nos. 2/3, 1982, pp. 288–310.

[26]Pollack, J. B., Colburn, D. S., Flaser, F. M., Khan, R., Carlston, C. E., and Pidek, D., "Properties and Effects of Dust Particles Suspended in the Martian Atmosphere," *Journal of Geophysical Research*, Vol. 84, No. B6, 1979, pp. 2929–2945.

[27]Marner, W. J., Suitor, J. W., and Glazer, C. R., "A Model to Predict the Removal of Oxygen from Air Using a Zirconia Solid Electrolyte Membrane," 20th Intersociety Energy Conversion and Engineering Conf., Denver, CO, Aug. 1988.

[28]Sridhar, K. R., Vaniman, B., Nanjundan, A., and Miller, S., *Solid Oxide Electrolysis*, Univ. of Arizona, SERC Rept. APR-94, Tucson, AZ, Sept. 1994, pp. 20–73.

[29]Sridhar, K. R., and Iyer, V. A., "Thermal Analysis of a Mars Oxygen Production Plant," International Astronautical Federation Paper IAA-91-671, Oct. 1991.

[30]Shirbacheh, M., "Power System Options for Mars Environmental Survey Mission (MESUR)," *NTSE-92, Nuclear Technologies for Space Exploration*, Vol. I, ANS, Lagrange Park, IL, 1992, pp. 163–172.

[31]Wade, L., private communication, Jet Propulsion Lab., Pasadena, CA, 1993.

[32]Sridhar, K. R., and Miller, S. A., "Solid Oxide Electrolysis Technology for ISRU and Life Support," Society of Automotive Engineers TP 941255, June 1994.

[33]Nolan, P. E., Cutler, A. H., and Lynch, D. V., "Carbon Formation Theory for Space Oxygen Processes," *Engineering, Construction, and Operations in Space IV*, edited by R. G. Galloway and S. Lokaj, Vol. 2, American Society of Civil Engineers, New York, 1994, pp. 1199–1209.