A solid oxide electrolyzer is manifested to fly on a Mars spacecraft that NASA will launch in April 2001. The electrolyzer experiment, called the Oxygen Generator System (OGS) will electrolyze the predominantly CO₂ atmosphere of Mars to produce oxygen. The OGS is intended to be a proof-of-concept experiment for NASA’s plan to use Mars atmosphere as a resource for producing propellants and life support consumables on future Mars missions. It will be the first time that nonterrestrial resources are used to produce consumables of use to humans, thereby making OGS a landmark experiment. A solid oxide electrolyzer with a yttria stabilized zirconia electrolyte will dissociate CO₂ to CO and O on the cathode side of the cell and provide a pure O₂ stream on the anode side through ionic pumping. The primary focus of this paper is to describe the design methodologies used to make the electrolyzer flight worthy.

INTRODUCTION

A solid oxide electrolyzer that can produce oxygen from the mainly CO₂ atmosphere of Mars will fly on the 2001 NASA mission to Mars. The electrolyzer experiment, called the OGS (Oxygen Generating System), is one of the experiments on a payload called MIP (Mars In-situ propellant production Precursor) that will be flown by NASA Johnson Space Center. The MIP payload will demonstrate technologies that are critical to NASA’s goal of using Mars atmospheric resources to produce propellants and life support consumables for future robotic and human missions to Mars. The Space Technologies Laboratory of the University of Arizona has been contracted by NASA to develop the OGS experiment.

The concept of producing consumables using planetary resources, or “living off the land,” is called In-Situ Resource Utilization (ISRU). NASA has identified ISRU as a key technology that needs to be developed and demonstrated to facilitate human missions to Mars (1). In most space missions the launch costs from Earth surface to Low Earth Orbit (LEO) account for a significant fraction of the total mission costs. Current costs are in the range of U.S. $20,000 for every kilogram that is launched to LEO. Also, for every kilogram that is returned to Earth from Mars, about 40 kilograms needs to be launched from LEO to Mars. It is quite clear from these numbers that reducing the total mass that needs to be landed on Mars can significantly reduce the cost of a Mars mission. Several
studies have shown that the cost of a human mission to Mars can be reduced by 20 to 40 percent if the fuel and oxygen needed for the rocket to return to Earth are produced on Mars from Mars resources (1-5). The risk of a human mission to Mars is also significantly reduced if safety caches of life support consumables and return propellant are manufactured and stored through robotic cargo missions that precede a human mission. The ability to produce necessary consumables from planetary resources is also an essential step for permanent settlements outside of Earth.

The Martian atmosphere is composed mainly of CO$_2$ (95.3 volume percent) with significant amounts of nitrogen (2.7 volume percent) and argon (1.6 percent). Several other gases are also present in trace quantities. The average pressure of the Mars atmosphere is about 8 hecta Pascals and varies from 6 to 10 hecta Pascals with seasons as the major constituent, CO$_2$, condenses to form the seasonal polar caps. The average temperature on Mars is a function of the season and latitude. The diurnal temperature swings can be as high as 60 Celsius. Temperatures in the range of -100 to 0 Celsius can be expected.

The Mars atmosphere is a valuable resource for producing propellants and life support consumables. However, since the atmospheric pressure is rather low, the gases have to be compressed to higher pressures before they are processed. A zeolite based temperature swing adsorption compressor will be used on MIP to provide compressed CO$_2$ at about 1 bar to the OGS. The interface between the Mars atmosphere, the compressor and the OGS is shown schematically in Figure 1.

Figure 1. OGS Flow Schematic in the Mars Payload.

This paper will focus on the OGS experiment and the special challenges that had to be overcome to meet the mission constraints and requirements. Design details, and performance data will be presented.

**OBJECTIVE AND SIGNIFICANCE OF OGS**

The primary objective of the OGS is to demonstrate the production of oxygen from Mars atmospheric gases using solid oxide electrolysis. A successful demonstration on Mars will provide mission planners with the confidence to incorporate this technology in future missions. Solid oxide electrolyzers can be used in Mars missions for several applications, for instance:

- Oxygen generation for use as a return propellant with Earth carried fuel (5).
- Make-up oxygen for a Sabatier and water electrolysis plant that produces fuel and oxygen in a fuel rich proportion for use in a rocket.
- Compression of the oxygen for liquefaction and/or storage (6).
- Production of both oxygen and CO for use in a CO/O₂ rocket or surface mobility (rovers, hoppers, planes, etc.).
- Regenerative fuel cell to provide power during the night from the excess CO and O₂ generated during the Martian day with solar power (7).
- Centralized and portable life support oxygen generators (6).

The specific technical objectives of the OGS are to characterize its performance and demonstrate the reliability of the hardware for space missions. For performance characterization, it is necessary to verify the production of oxygen both qualitatively and quantitatively. It is also necessary to determine the CO₂ conversion efficiency and the long-term changes in performance due to operation in a Mars environment. The reliability of the device has to be established under the severe launch, entry, and landing environments as well as thermal cycling between Mars ambient and electrolyzer operating temperatures.

**PRINCIPLE OF OPERATION**

The oxygen generator works on the principle of solid oxide electrolysis. At elevated temperatures, solid oxide electrolytes such as yttria stabilized zirconia become oxygen ion conductors. The basic configuration of the electrolysis cell is shown in Figure 2. At the cathode, CO₂ dissociates to form CO and O. The oxygen atom reacts with the incoming electrons from the external circuit to form an oxygen ion. The oxygen ion is conducted through the vacancies in the crystal structure of the electrolyte to the anode. At the anode, the oxygen ion donates the electrons to the external circuit to form an oxygen atom. Two oxygen atoms combine to form an oxygen molecule at the anode side of the cell.

Figure 2. Principle of Operation of a Solid Oxide Electrolyzer.
DESIGN CHALLENGES AND SOLUTIONS

The payloads on the Mars spacecraft are provided with electric power during daylight from onboard photovoltaic arrays. The total continuous power consumption of the experiment is limited to 15 Watts or less during daylight. Nighttime power is not available to the experiment from the lander spacecraft. The fact that Mars ambient temperature during daytime is expected to be in the range of −70 to −30 Celsius posed significant thermal challenges. These challenges are further complicated by the requirement that the OGS should not exceed 1 kg in mass and not exceed a volume envelope of 3 liters. The first challenge was to design an electrolyzer package that could reach a high enough operating temperature (>700 Celsius) and maintain that steady state temperature within the power budget that was provided. The second challenge was to make sure that the electrolyzer could ramp up to the operating temperature at a fast enough rate to provide a few hours of operation while the daytime power is available. The third was to ensure that the electrolyzer package would survive the thermal stresses induced by a sudden loss of power. These challenges were handled by clever thermal packaging. A customized composition of yttria stabilized zirconia with some additives that allowed the operation at 750 Celsius and provided the same performance as 8 mole percent yttria stabilized zirconia at 950 Celsius was used. The conduction paths in the electrolyzer package were greatly reduced by the choice of materials, geometry, and thickness. A new high performance insulation was used to reduce thermal losses. In-house fabricated thick film ceramic heaters that were lightweight, capable of 10 Celsius per minute or higher ramp rates and operate to a high temperature limit of 900 Celsius were used to heat the electrolyzer. The ramp rate of the electrolyzer was set to 10 Celsius per minute. In order to reduce thermal stresses, the manifolds were made of thermal expansion matched Plansee chrome alloys.

The OGS is required to operate for at least 10 sols (Martian days). Since nighttime power is not available, this requirement translated to the need for an electrolyzer with a seal that can thermally cycles several tens of times. A custom, multi-layer, metal braze seal between the electrolyte and the metal manifolds was developed for this application by United Technologies Corporation.

The OGS is also required to withstand the shock and vibration loads that will be encountered during launch, entry, and landing. The maximum loads were specified to be 35 Gs. Clever mechanical packaging, such as the special rib support to the electrolyte, the suspension of the electrolyzer with support guy wires and the secondary protection, offered by the densely packed insulation, provide the needed support.

DESCRIPTION OF THE ELECTROLYZER PACKAGE

The electrolyzer cell is a single planar zirconia electrolyte with platinum electrodes on both the anode and cathode sides. The zirconia electrolyte has a diameter of 32 millimeters and a thickness of about 300 microns. The cell is sandwiched between chrome alloy metal manifolds that are supplied by Plansee. The electrolyzer package is expected to have a leakage rate that is lower than 2.7 * 10^{-3} standard cubic centimeters per second. A multi-layer custom metal braze developed by United Technologies Corporation is used between the zirconia electrolyte and Plansee manifolds.
The electrolyzer cell with the manifolds is in turn sandwiched between two thick film ceramic heaters that were fabricated in-house. These ceramic heaters have a platinum heating element and reach temperatures of up to 900 Celsius at ramp rates that far exceed the 10 Celsius per minute required by OGS. Each of the heaters can individually handle over 15 Watts of electrical power. Figure 3 is a photograph of one such heater. Under nominal operation, the two heaters share the heating load, but each is designed to operate alone in the event that one of them should fail. The platinum heating elements also serve as Resistive Thermal Devices (RTDs) that provide a temperature measurement. The heater and the electrolyzer are held together by clamps that also serve to provide a mechanical compression seal to the electrolyzer. The upper clamp also has four guy wires that are used to suspend the electrolyzer cell in the housing that encloses it. The upper manifold (cathode side) has a CO₂ inlet tube and an exhaust gas outlet tube brazed to the manifold. The two tubes are bonded externally together to allow for heat exchange between the inlet cold gas and the outlet hot gas. An oxygen outlet tube is brazed to the lower manifold (anode side). The tubes are spiraled to reduce conduction losses. Figure 4 shows an exploded view of the electrolyzer cell assembly.

![Figure 3. Photograph of a Thick Film Ceramic Heater.](image)

![Figure 4. Exploded View of a Electrolyzer Cell Assembly.](image)
A new silica and fibrous glass high performance insulation from Thermal Ceramics was characterized and used in the OGS packaging to attain the energy efficiency required. The dome shaped enclosure is filled with insulation, in the form of crushed powder. A solid model rendering with a cutaway of the dome is shown in Figure 5. This image also shows the guy wires that suspend the cell assembly in the dome.

![Figure 5. A Cutaway Solid Model of the OGS Showing the Support Guy Wires.](image)

**BALANCE OF PLANT**

A base plate that holds the dome enclosure and the cell assembly also supports the flow control and instrumentation needed for the balance of plant. Figure 6 is a schematic of the balance of plant. Due to the severe constraint on the total mass of the system, a calibrated combination metal frit and flow orifice assembly is used to regulate the pressure and flow rate of the gases in the cathode side and monitor the flow rate on the oxygen side. The coarse metal frit primarily filters the dust and other particulates from the flow and the orifice meters the flow across it. The upstream orifice on the cathode side steps down the pressure of the gas flowing from the compressor. The downstream orifice chokes the flow of gases venting to the Mars atmosphere. Through a proper choice of orifice sizes that was established by testing, the flow rate of CO₂ to the electrolyzer is regulated at 3 standard cubic centimeters per minute. A solenoid valve downstream of the electrolyzer, on the cathode side, is periodically shut off to monitor the increase in pressure. This is a secondary method of verifying flow rate of CO₂.

During operation, the dc voltage across the electrolyzer is adjusted to attain 0.5 standard cubic centimeters per second of oxygen flow. The primary method of measuring oxygen production is by measuring the ionic current. The oxygen thus produced is vented to the Mars atmosphere through the frit assembly on the anode side. Monitoring the pressure in the plumbing provides a secondary method of the verifying the oxygen production rate. A solenoid valve on the anode side is shut off periodically and the increase in the line pressure monitored to attain a tertiary method of verifying oxygen production.
Figure 6. Flow Diagram for the OGS.

Figure 7 is a solid model of the OGS with the base plate and Figure 8 is a photograph of the actual hardware in a development unit configuration.

Figure 7. Solid Model of the OGS with the Base Plate and Flow Control.

The development unit of the OGS was operated at the University of Arizona using a custom-built electronics box called the Ground Support Equipment (GSE). The GSE was controlled by National Instruments LabView software, which also acquired the data. In addition, the LabView software is used for failure detection and failure correction algorithms. The failure detection algorithm will detect and flag system anomalies and categorize them in a hierarchical order. Failure modes that are easily confirmable and correctable on board will be handled by the failure correction algorithm during the operational cycle. Other, more difficult failure modes will be handled by performing a controlled shut down and dump of the data by telemetry to the ground for analyses and corrective actions. For the flight unit, the software and hardware for controlling the experiment are being built by NASA.
EXPERIMENTAL RESULTS

The power profile obtained by analysis was verified on the OGS development unit using a Mars simulation chamber. The temperature, pressure, and the gas composition of Mars are simulated in the chamber. The results showed that OGS takes about 90 minutes for start-up mode, a mode where the electrolyzer is heated to the operating temperature but not pumping oxygen. The maximum power consumption during this period is restricted to 15 Watts. During steady-state operation, the unit requires 9.5 Watts to maintain the cell temperature. Figure 9 depicts the power and temperature profile of the unit in the Mars simulation chamber. It should also be noted that when the pressure of the chamber is increased to Earth ambient temperature, the power required to maintain the electrolyzer goes up due to increased convective heat transfer. The oxygen pumping characteristics of the OGS is shown in Figure 10. The unit produces 0.5 standard cubic centimeter per minute of oxygen and a dc potential of 1.7 Volts.
Figure 9. Power and Temperature and Profile of OGS.

Figure 10. The OGS Electrolyzer Cell Operating Characteristics.
SUMMARY

A solid oxide electrolyzer will be flown on a 2001 robotic Mars mission to generate oxygen from the atmospheric carbon dioxide on the planet. This proof of concept experiment is intended to instill confidence in using the process to generate oxygen for propulsion and life support on future Mars missions. The oxygen generator system weighs less than 1 kilograms and fits in an envelope that is less than 3 liters. It has a single planar solid oxide electrochemical cell that is made of yttria stabilized zirconia electrolyte and platinum electrodes. The system consumes 15 Watts of electrical power to heat up to its operating temperature of 750 Celsius and 9.5 Watts at steady state to maintain the temperature. The unit can withstand shock and vibration environments of up to 35 G and also cold soak temperatures of up to -100 Celsius. The unit will also thermally cycle between the Mars ambient and operating temperature at least 10 times. The autonomous operation of the unit on Mars will also include simple failure detection and correction algorithms. A development unit configuration of the experiment has been successfully tested at the University of Arizona. The flight unit will be delivered to NASA by the end of the year. The unit will be launched on a mission to Mars in April 2001, and will begin operations on Mars in January 2002.

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