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Oxygen Plant Breadboard Design, and Techniques For Improving Mission Figure-of-Merit

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ORIGINAL CONTAINS COLOR ILLUSTRATIONS

Abstract

A breadboard oxygen plant to process anaerobic carbon dioxide is designed and constructed; the objective is not only to produce a key propellant component extraterrestrially, but also to develop the important technologies that are necessary for a successful operation of In-Situ Materials Utilization hardware. The solid electrolytic cells are supplied to our specifications by an established vendor. The cell thermal control, electrical control and flow control are installed after detailed designs. Extensive data are obtained that characterize the operation of the plant as the input parameters are varied. The initial mass, energy and volume needs provide the input to a figure-of-merit software program to calculate the impact of various candidate technologies upon the overall mission. The desirability of studies on storage and high-density propellants is brought out. This task dovetails into other tasks that are evaluating alternative cell materials, catalysis for compactness, and smart sensors for effective control. The breadboard design and operation of the complete system are believed to represent engineering "firsts".

Introduction

Various studies have indicated the desirability of in-situ resource utilization, or in-space materials utilization (ISRU/ISMU) for significantly reducing the costs of space missions. Since a large fraction of any mission cost is associated with space transportation (access to space), it has been recognized that reducing our dependence upon earth-transported propellants would be a valuable first step. Since a large fraction of the chemical propellants consists of oxidizers, oxidizer production at extraterrestrial sites should receive primary attention. The actual plant design and testing will depend upon various factors such as consistency with our Center mission, available resources, synergism with current tasks, scientific merit and appropriateness for university research; another important factor is the likelyhood of impact and transferability of results to inductry.

After a very careful consideration of all of these factors, it was the unanimous decision of the center Advisory Committee that a plant designed to extract oxygen from gaseous carbon dioxide meets most, if not all, of the above criteria. Aside from its obvious application to Mars missions (MSR, MO, MR and MMM), the plant can also be used in lunar missions that utilize the popular carbothermal reduction of lunar materials (ilmnite), where carbon dioxide is one of the byproducts. More important is the opportunity that such a plant provides to study and execute innovative designs in electrochemistry, thermal controls, flow controls, autonomous operations, packaging and a test-bed for obtaining long-term engineering data. Simplicity and the absence of major unknowns were also factors.

The next section describes the basic oxygen plant, the components and the overall design. The operation and preliminary results follow. The summary section outlines the future work on the plant. At the time of this reporting, the plant has been successfully designed and operated. The oxygen production rate has been shown to be consistent with electrochemical considerations. The cell thermal control has been proven through moden IR diagnostics. The product gases have been unambiguously identified through gas chromatography on site (and mass spectroscopy at a local laboratory). The important plant characteristics of long-term operation, possible cell contamination, scaleability and a host of related issues, including exhaust products utilization, will be the subject of future research.

The Plant Design

The heart of the plant consists of a solid electrolytic cell maintained at a temperature sufficient to dissociate the incoming carbon dioxide, while the potential difference across the cell separates the oxygen from the other gases. The cell geometry was chosen to be cylindrical, 14" long and approximately 1" O.D. The cell wall is coated with platinum for conductivity. The cell is wrapped by resistance heater coils of nichrome. The entire assembly is contained inside a stainless steel tube. The tube is then packaged into a thermal box that is insulated with a non-asbestos type fiber cloth.

The flow into the cell is from a specially ordered anaerobic carbon dioxide bottle, regulated down to one bar pressure. The question of the optimum operating pressure is being studied at the present time; factors include the plant mass, terrestrial testing operations, plant volume and the ease of compressing the extraterrestrial gases (Martian carbon dioxide is at 6-8 mbar) to the operating design pressure. The output flow from the oxygen side is led into a collection jar, which is through the downward displacement of water, at the present time for clear visual demonstration of gas evolution. The exhaust gases (carbon dioxide and carbon monoxide) are carefully vented out, although plans are underway for using this stream both thermally and chemically. The electric potential is maintained across the cell through a simple power supply unit. The overall plant is schematically shown in figure 1 and an external view of the assembled hardware is shown in figure 2.

Plant Operation and Preliminary Results

The plant has been operated at different cell temperatures, different flow rates and different voltages. The principal results are shown in figures 3 and 4. Figure 3 shows that the oxygen production rate varies nearly linearly with the applied cell voltage. The manufacturer suggested a production rate of 4 ml per minute at 2 volts, whereas we have consistently obtained 5-6 ml per minute at this voltage. The basic Nerst potential equation suggests production rates closer to values reported here. The flow rate of the carbon dioxide is a parameter, but not a strong one, suggesting electrochemical control of production rather than fluid dynamic control. However, there is a flow rate at which fluid dynamic control does become perceptible, as seen in figure 4. Beyond a flow rate of 300 ml per minute of carbon dioxide, the oxygen production rate reaches "saturation" at 5.6 ml per minute. Beyond 700 ml per minute of carbon dioxide flow rate, the oxygen production rate actually decreases, suggesting that the residence time is not sufficient for the production/separation of oxygen. The cell voltage and temperature were held constant during these tests.

Detailed theoretical (equilibrium) calculations were made to determine the minimum operating temperature both from the point of view of production rates and from the point of view of minimizing solid carbon formation on the cell walls and within the cell. These calculations were performed using the NASA CET86 program, and are reported elsewhere in this report. It was shown that at temperatures above 650 C, the carbon formation was minimal. This brings us to the important aspect of the cell thermal environment. The mean cell temperature is hardly as important as the local cold/hot spots that can promote carbon depositions, or, destroy the cell. Hence, a good overall thermal scanner was needed. This is provided through a color coded infrared video monitor. Preliminary results are shown in figure 5, that shows that the temperature of the dell is maintained reasonably uniform in the present design. More work is underway.

Summary

The oxygen plant design has been completed with a single cell. The eventual design calls for a bank of 175 cells in order to produce 2 kg of oxygen per (24 hr) day; this assumes cell operation slightly below the full capacity of 6 ml/min. The overall geometry of the cell banks may have to be considerably different from the simple cylindrical geometry used here. Alternative disk geometries and alternative materials (other than Zirconia), and catalysis for compactness are all being studied. The thermal control, the electrical control and the eventual automation all need more study. The high-temperature seals at the ends are particulaly vunerable to attack by oxygen,

and are being separately studied.

This project is providing input to various other tasks and is receiving inputs from several other tasks, indicating a true engineering design principle in action. The eventual breadboard is expected to consist of the compact packaging of components shown in several figures in the report by professor Nikravesh (elsewhere in this report).

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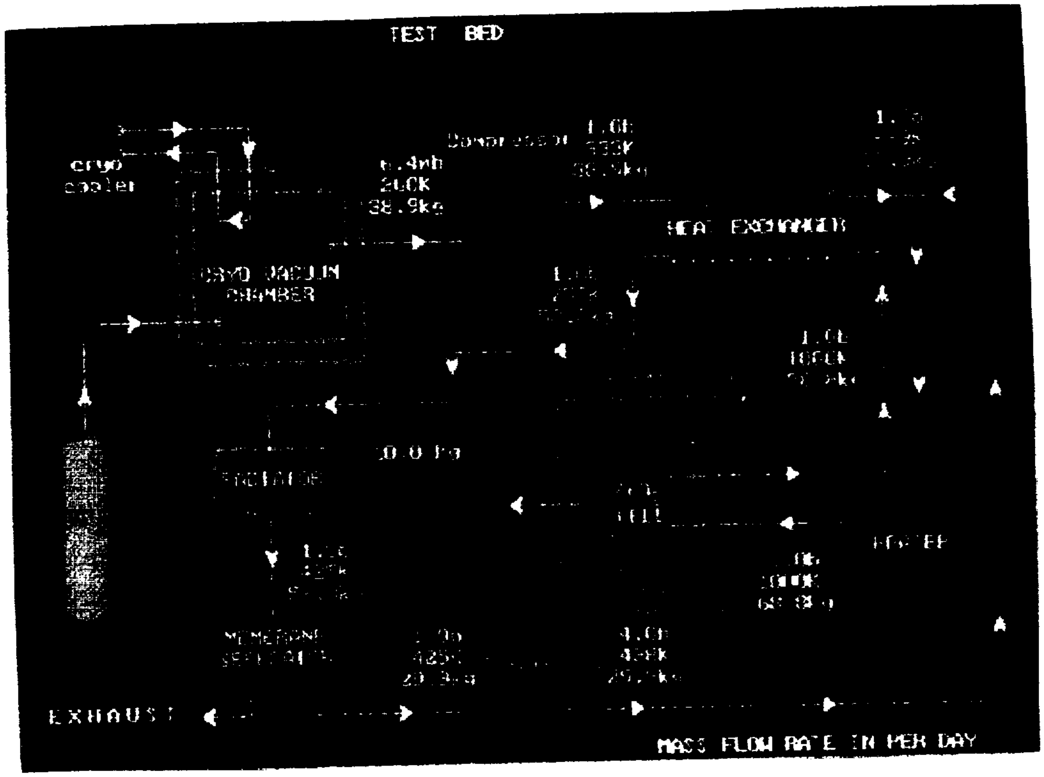

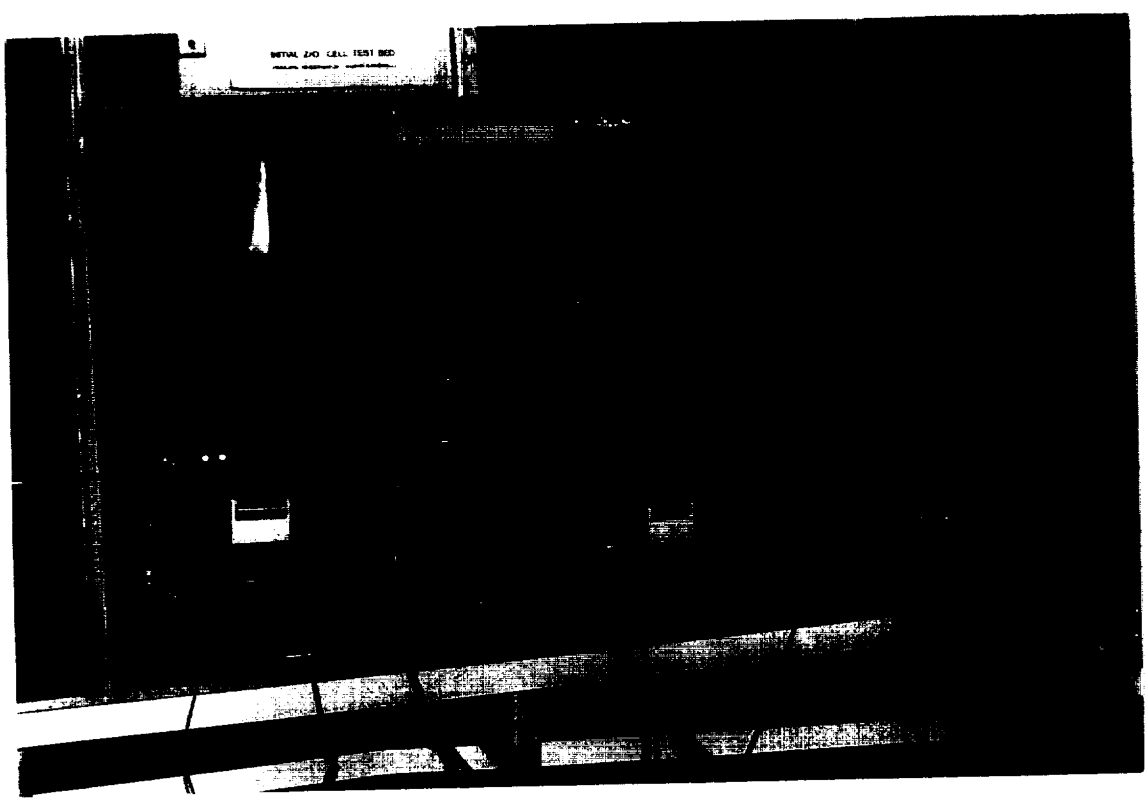

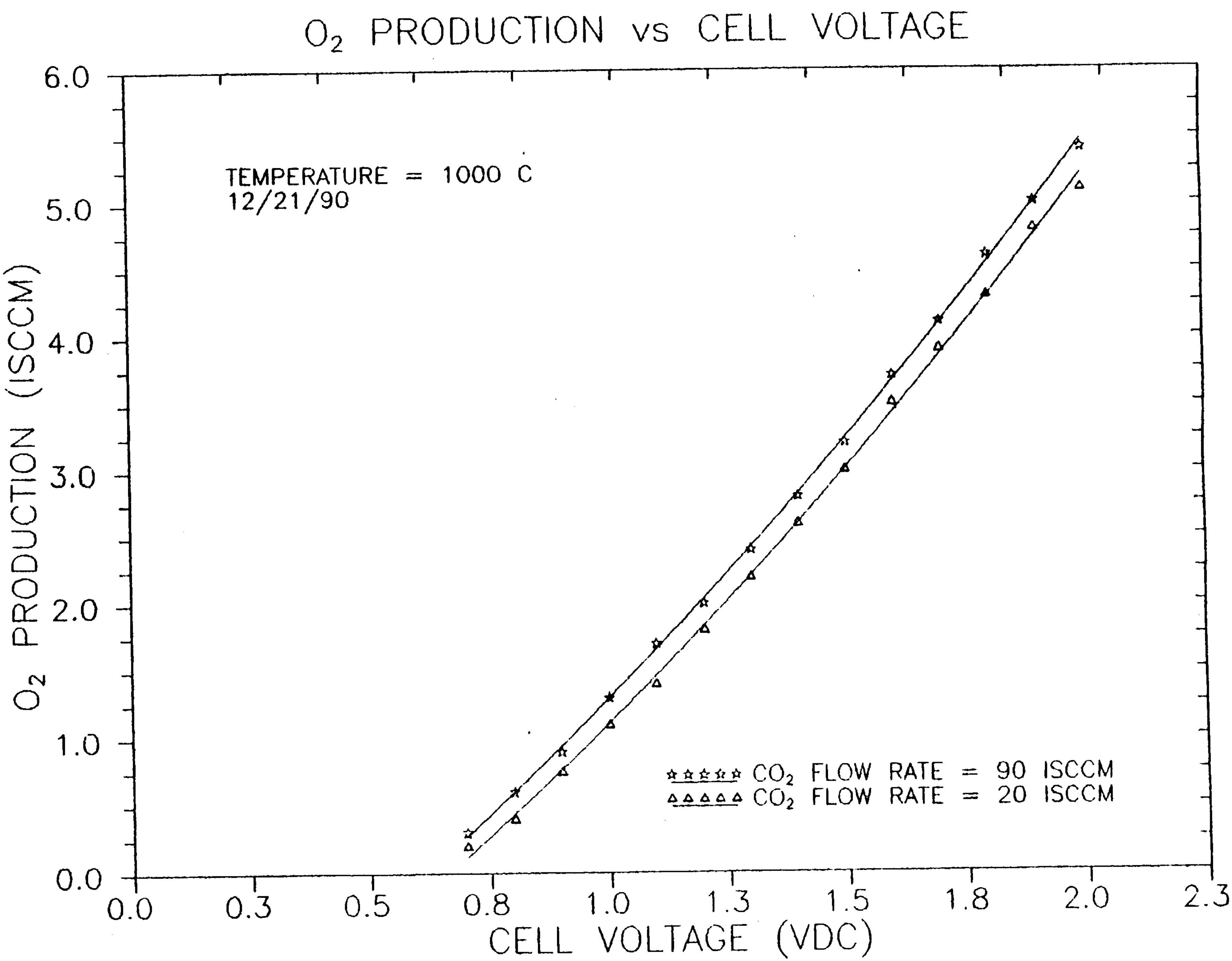
O2 PRODUCTION vs CELL VOLTAGE
TEMPERATURE = 1000 C
12/21/90
O2 PRODUCTION (ISCCM)
6.0
5.0
4.0
3.0
2.0
1.0
0.0
0.3
0.5
0.8
1.0
1.3
1.5
1.8
2.0
2.3
CELL VOLTAGE (VDC)
CO2 FLOW RATE = 90 ISCCM
CO2 FLOW RATE = 20 ISCCM

Figure 3

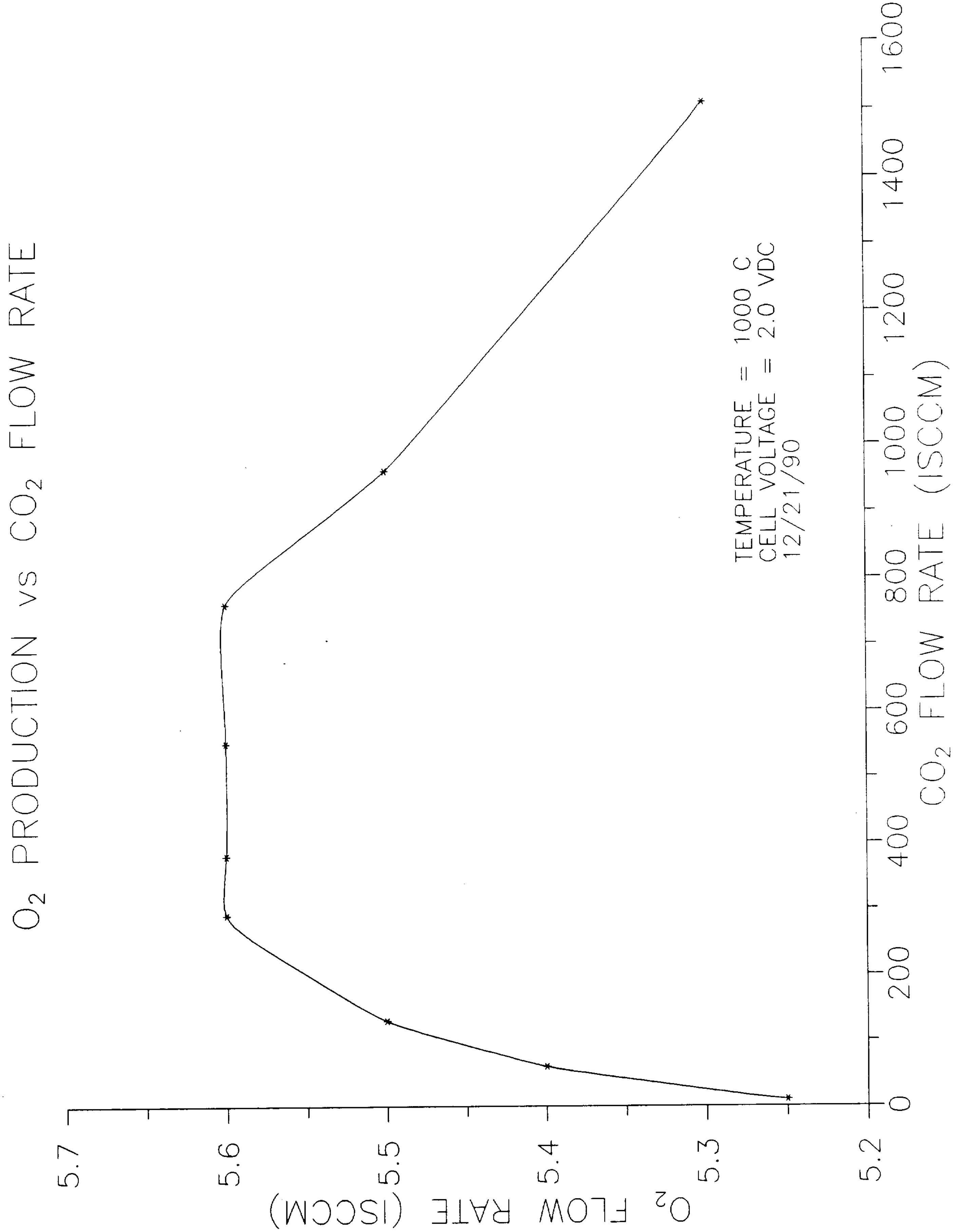
O_2 PRODUCTION vs CO_2 FLOW RATE
TEMPERATURE = 1000 C
CELL VOLTAGE = 2.0 VDC
12/21/90
O_2 FLOW RATE (ISCCM)
5.7
5.6
5.5
5.4
5.3
5.2
0
200
400
600
800
1000
1200
1400
1600
CO_2 FLOW RATE (ISCCM)

FIGURE 4

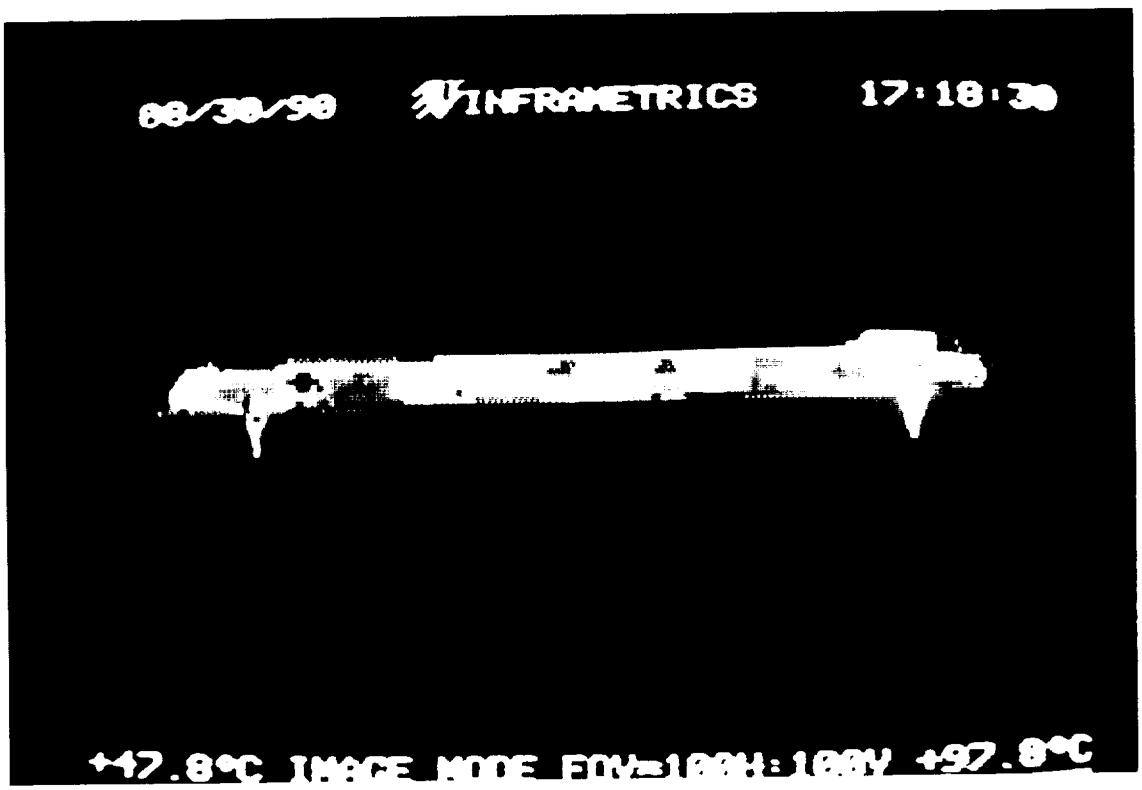

FIGURE 5. INFRARED IMAGE OF THE OXYGEN CELL