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ONE-MAN, SELF-CONTAINED CO₂ CONCENTRATING SYSTEM

FINAL REPORT

by

R.A. Wynveen, F.H. Schubert
and J.D. Powell

March, 1972

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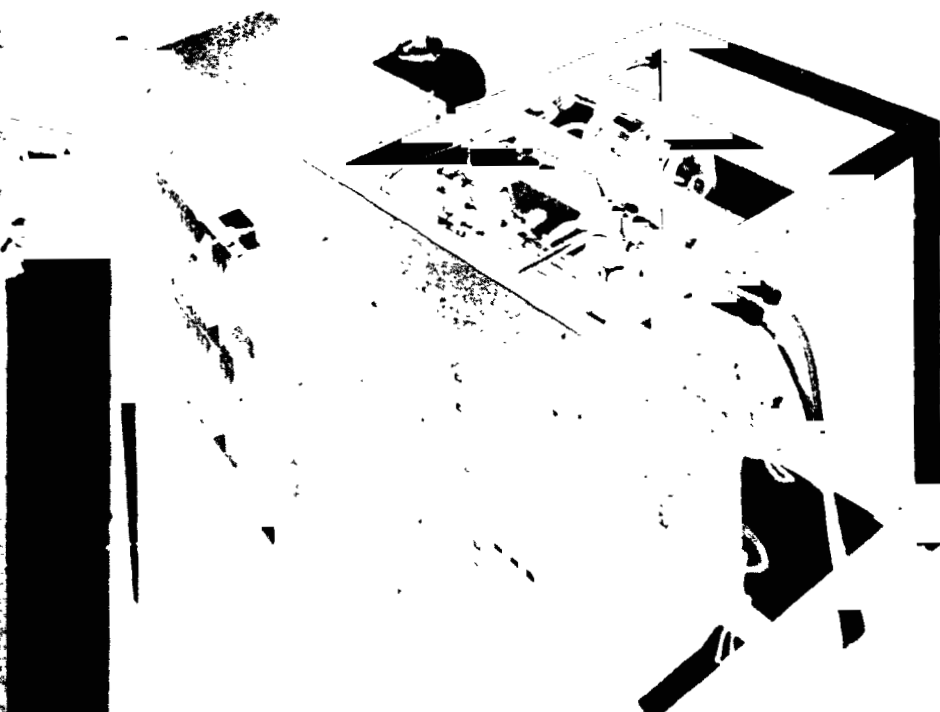
Life Systems, Inc.

Cleveland, Ohio 44122

for

AMES RESEARCH CENTER

National Aeronautics & Space Administration



NASA CR-114426

ER-131-16

ONE-MAN, SELF-CONTAINED
CARBON DIOXIDE CONCENTRATING SYSTEM

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by R. A. Wynveen, F. H. Schubert, and J. D. Powell

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FOREWORD

The development work described herein, conducted by Life Systems, Inc. was performed under NASA Contract NAS2-6118. F. H. Schubert directed the design and fabrication of the CO₂ Removal Unit and the Parametric Test Program. J. D. Powell directed the CO₂ Control Unit development and monitored the 180-day Endurance Test Program. Other engineers that supported the technical effort included W. R. Dineen, D. E. Keck and C. A. Novotny. The program's technicians were R. A. Clark and D. Pry. Clerical work was completed by C. A. Lucas. The overall program was directed by Dr. R. A. Wynveen.

The contract technical monitor was P. D. Quattrone, Chief, Environmental Control Research Branch, NASA Ames Research Center, Moffett Field, California.

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SUMMARY

A program to design, fabricate and test a 1-man, self-contained, electrochemical CO₂ concentrating system was successfully completed. The 1-man system was a pre-prototype engineering model. The system was designed with the capability to remove 4.2 lbs CO₂/day (1.9 kg/day) and to operate nominally at a 2.1 lb CO₂/day (0.95 kg/day) removal rate. It was designed and tested over a range in operating conditions, including air pressures of 5 to 15 psia (3.4×10^4 to 1.0×10^5 Newtons/m²), CO₂ partial pressures from 0.2 to 15 mm Hg, O₂ partial pressures from 3.1 to 15 psia (2.1×10^4 to 1.0×10^5 Newtons/m²), and temperatures from 70 to 100F (21 to 38C). A total of 6,400 hours of operation were accumulated.

The system was designed with electronic controls and instrumentation to regulate performance, to analyze and display performance trends, and to detect and isolate faults.

After the baseline design had been verified experimentally as part of a parallel technology activity, the 1-man system was fabricated and its nominal and off-design performance experimentally characterized as part of a Parametric Test Program. Following this, a variety of minor changes were made to optimize the system. A 180-day endurance test was then carried out to evaluate the effects of operating time on the system's ability to maintain the CO₂ removal function and to sustain its electrical operating efficiency as indicated by the operating cell voltages.

Ground support accessories were included to provide power, fluids, and a Parametric Data Display allowing real time indication of operating status in engineering units.

A Product Assurance Program was included consisting of Quality Assurance, Reliability, Maintainability, and Safety sections.

A parallel technology program was used to verify the baseline design prior to committing the system to fabrication, to evaluate alternate electrodes and electrolytes, to upgrade reliability and maintainability, and to test an O₂ reclamation system that integrated an electrochemical CO₂ concentrating subsystem, a static feed water electrolysis subsystem and a Sabatier reactor for CO₂ reduction.

INTRODUCTION

Technology and equipment are needed by the National Aeronautics and Space Administration to sustain man in space for extended time periods. The objective of this program was to develop a self-contained, 1-man electrochemical carbon dioxide (CO₂) concentrator. The program was divided into six tasks and a program management function. The specific objectives of these tasks were to:

1. Deliver a 1-man, pre-prototype engineering model of the electrochemical CO₂ concentrator. It was to be capable of removing 2.1 lb of CO₂/day (0.95 kg/day). It was to have a designed capability of 4.2 lb/day (1.9 kg/day). It was to include provision for performance trend analysis, fault detection, and fault isolation.

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2. Deliver ground support accessories that allow for parametric and endurance testing of the system.
3. Implement a Quality Assurance Program and to integrate reliability and maintainability concepts into the system design.
4. Conduct parametric and endurance test programs with a goal of six months of operation at normal operating conditions. The purpose was to assess the system's maintainability, reliability and safety.
5. Carry out, in parallel, testing and analytical activities aimed at improving system performance.
6. Develop design recommendations for a multiman system.

The objectives were met. The following sections of the report summarize the program's results.

ELECTROCHEMICAL CO₂ REMOVAL PROCESS

The electrochemical method continuously removes CO₂, eliminating the complexities associated with concentrating systems based on cyclic operation. The CO₂ is removed from a flowing air stream in an electrochemical module consisting of a series of individual electrochemical cells. Each cell consists of two porous electrodes separated by a porous matrix containing an aqueous solution of cesium carbonate (Cs₂CO₃). Plates adjacent to the electrodes provide passageways for distributing the gases over the electrode surface. Specific electrochemical and chemical reactions are detailed in Figure 1.

Moist cabin air containing CO₂, as well as oxygen (O₂), is fed to the cathode where the electrochemical reaction of O₂ and water (H₂O) forms hydroxyl ions (OH⁻). These ions react with the CO₂ forming carbonate ions (CO₃⁼). The output from the cathode compartment is moist air reduced in partial pressure of carbon dioxide (pCO₂).

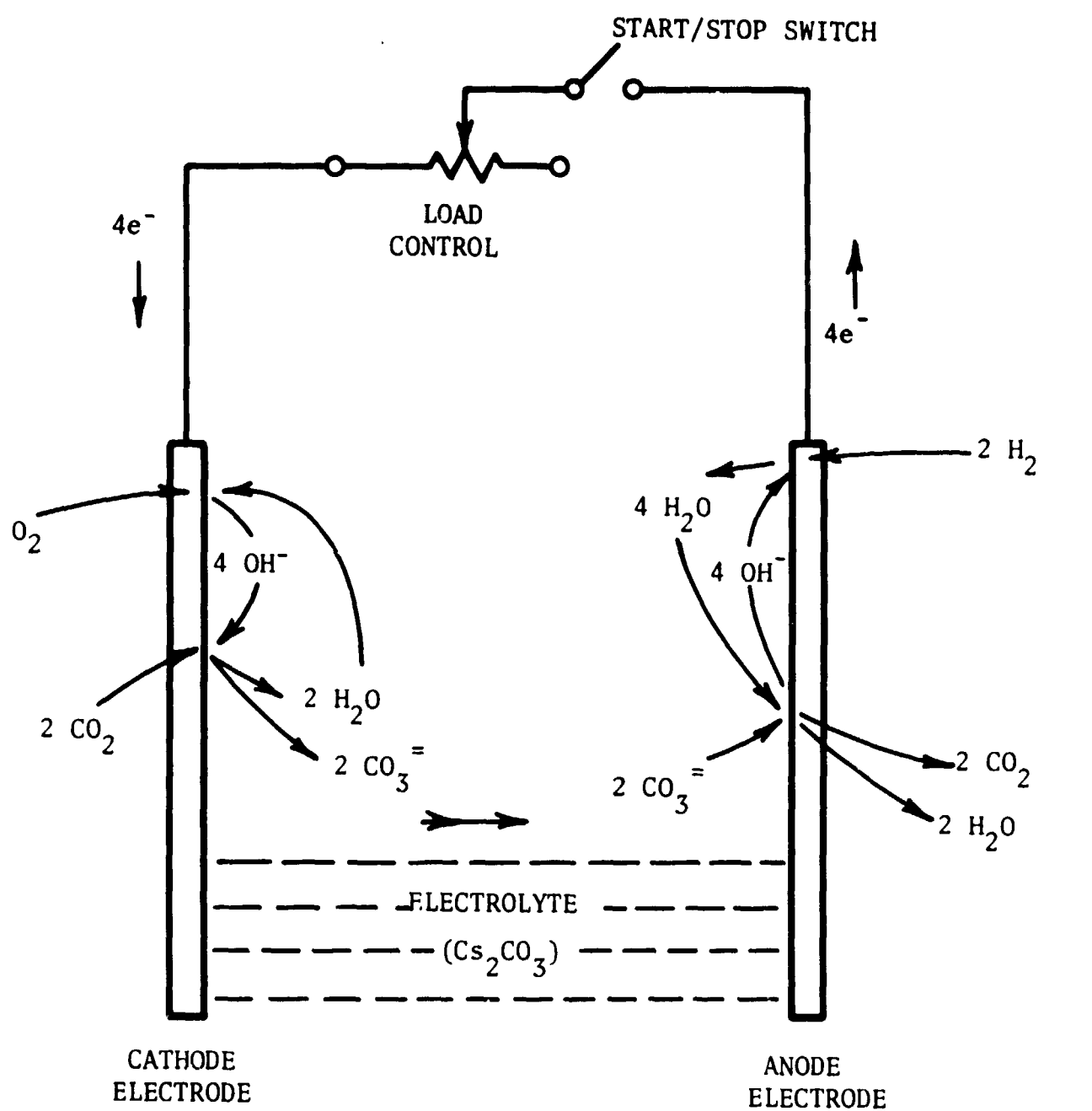
On the anode side, hydrogen (H₂) is fed in. The electrochemical reaction of H₂ and OH⁻ forms H₂O. This decreases the concentration of OH⁻ in the electrolyte. The result is a shift in the equilibrium in such a fashion that CO₂ is given off completing its transfer from the cathode compartment to the anode compartment. The anode effluent contains the CO₂ mixed with any excess H₂ used. The percentage of H₂ in the CO₂ can vary over a wide range, from more than 80% to less than 1%.

System Advantages

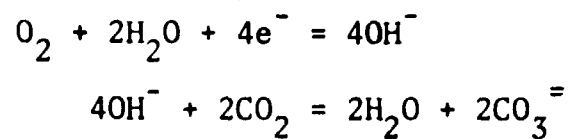
Primary Advantages. The primary advantages are:

1. It can maintain low partial pressures of CO₂ (3 mm Hg to less than 0.2 mm Hg) with a low subsystem equivalent weight including basic component and spare weights and the weight penalty for power and heat rejection. (1)

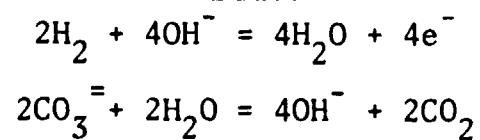
(1) References in parenthesis are cited at the end of the report.



CATHODE REACTIONS:



ANODE REACTIONS:



OVERALL REACTION:

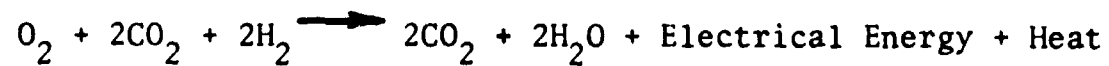


FIGURE 1 ELECTROCHEMICAL AND CHEMICAL REACTIONS

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2. It allows the CO₂ removal rate to be throttled for increased process efficiency, application flexibility, and reliability.
3. It is a continuous process instead of a cyclic operation characteristic of molecular sieves and amine systems. This contributes to higher reliability, less maintenance, and the elimination of a CO₂ accumulator and compressor. (Nothing prevents the system, however, from operating in a cyclic mode.)
4. The concentrated CO₂ cannot be contaminated with cabin air, protecting the CO₂ reduction process catalyst against poisoning from air contaminants.⁽²⁾
5. The system operates more efficiently when emergency pCO₂ levels are reached (>7 mm Hg).

Secondary Advantages. The secondary advantages are:

1. It is a low-temperature process making start and stop easy and avoiding the volume penalty of insulation.
2. The CO₂ is premixed with H₂ to eliminate components (e.g., H₂ and CO₂ accumulators and flow controllers) during integration with a CO₂ reduction subsystem.
3. End item application flexibility exists because only simple modifications are needed for changes in crew size.
4. It is designed for silent operation by using low air flows, low speed blowers, and liquid cooling of electronics.
5. It is independent of process heat for application flexibility.

System Features

In addition to the advantages inherent in the concept, the following features are incorporated:

1. A second generation^(a) of fault isolation and detection instrumentation.
2. A first generation of performance trend analysis instrumentation.
3. A one-button start and stop procedure.
4. A lowered^(a) operating temperature from 100 to 130F (38 to 54C) to 70 to 80F (21 to 27C) minimizing air humidity requirements.
5. Designed for a 2-man, 4.2 lb CO₂/day (1.9 kg/day) removal rate, but derated to be operated at the 1-man, 2.1 lb/day (0.95 kg/day) level for increased reliability.

(a) From those incorporated during the development activities completed under NAS2-4444.⁽³⁾

6. Insitu isolation of any one of the 15 cells avoiding module replacement when only cell maintenance is needed.
7. Internal humidifiers to protect the electrochemical module if the process air is supplied with a dew point below specification.
8. Ready access to all components from front, rear and right side.

CO₂ CONCENTRATING SYSTEM

The 1-man, self-contained CO₂ concentrating system (hereinafter called the CX-1) was divided into two units: CO₂ Removal Unit and CO₂ Control Unit. A block diagram of the system is presented in Figure 2. Design and operating conditions are cited in Table 1. Figure 3 is a photograph of the system. Figure 4 presents three different views indicating component arrangements.

System Operation

Air is pushed through the module by a blower. Part (typically 50% or more) of the CO₂ is stripped from the air and transferred to the H₂ stream. The CO₂ depleted air exits the module and returns to the ambient atmosphere. Depending on the module operating temperature set point, required cooling air is pushed by a fan across the fins located on two sides of the module. Process air flow rate is controlled through blower voltage regulation. The resulting motor current indicates volumetric flow rate.

Air with a pCO₂ of 3 mm Hg must be synthesized for testing. This is done by adding makeup CO₂ through a quick disconnect downstream of the blower when ambient air is circulated through the module. When O₂-enriched air is supplied from a ground support accessory, the CO₂ level is controlled within the auxiliary unit. Hydrogen is supplied and its flow is regulated through a ground support accessory. Static H₂O addition to the internal cell humidifiers is accomplished by reed switch activation of a H₂O feed solenoid valve. The switches are automatically latched or unlatched by magnets positioned on a movable piston. The accumulator is referenced to the module exit air pressure. Distilled H₂O is supplied from a ground support accessory. It is connected to the system with a quick disconnect. The H₂O flow rate is controlled by the evaporative rate within the electrochemical CO₂ concentrating module. The amount of H₂O evaporated depends upon ambient air humidity.

Startup/Shutdown. Start and stop only require the pushing of one switch. No other adjustments or sequence of steps are required. The CO₂ concentrating process begins immediately. No time delay is needed for warm-up.

CO₂ Removal Unit

This unit contains all the mechanical and electrochemical hardware needed to continuously remove 2.1 lb CO₂/day (0.95 kg/day) from an atmosphere having a pCO₂

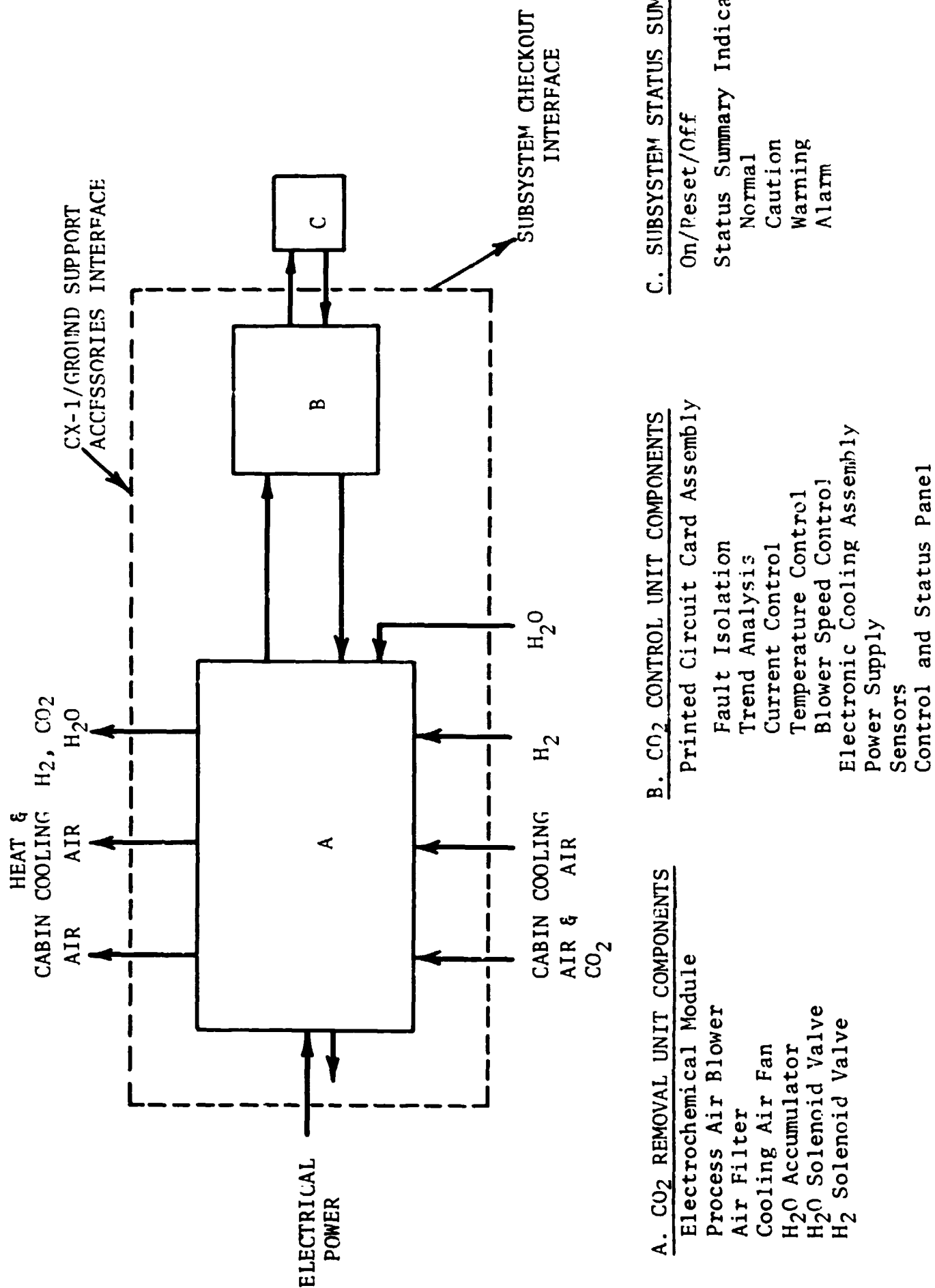


FIGURE 2 CX-1 BLOCK DIAGRAM

TABLE 1 DESIGN AND OPERATING CONDITIONS

Total Pressure, psia	
Baseline	14.7 (1.0×10^5 Newtons/m ²)
Range	5 to 15 (3.4×10^4 to 1.0×10^5 Newtons/m ²)
C ₂ Partial Pressure, psia	
Baseline	3.1 (2.1×10^4 Newtons/m ²)
Range	3.1 to 14.7 (2.1×10^4 to 1.0×10^5 Newtons/m ²)
Diluent	Air Constituents
CO ₂ Partial Pressure, mm Hg	
Baseline	3.0
Nominal Maximum	7.6
Emergency Maximum	15
Range	0.2 to 15
Air Temperature, F	
Baseline	72 (22C)
Range	66 to 75 (19C to 24C)
Air Dew Point	
Maximum, F	73 (23C)
Minimum, F	64 (18C)

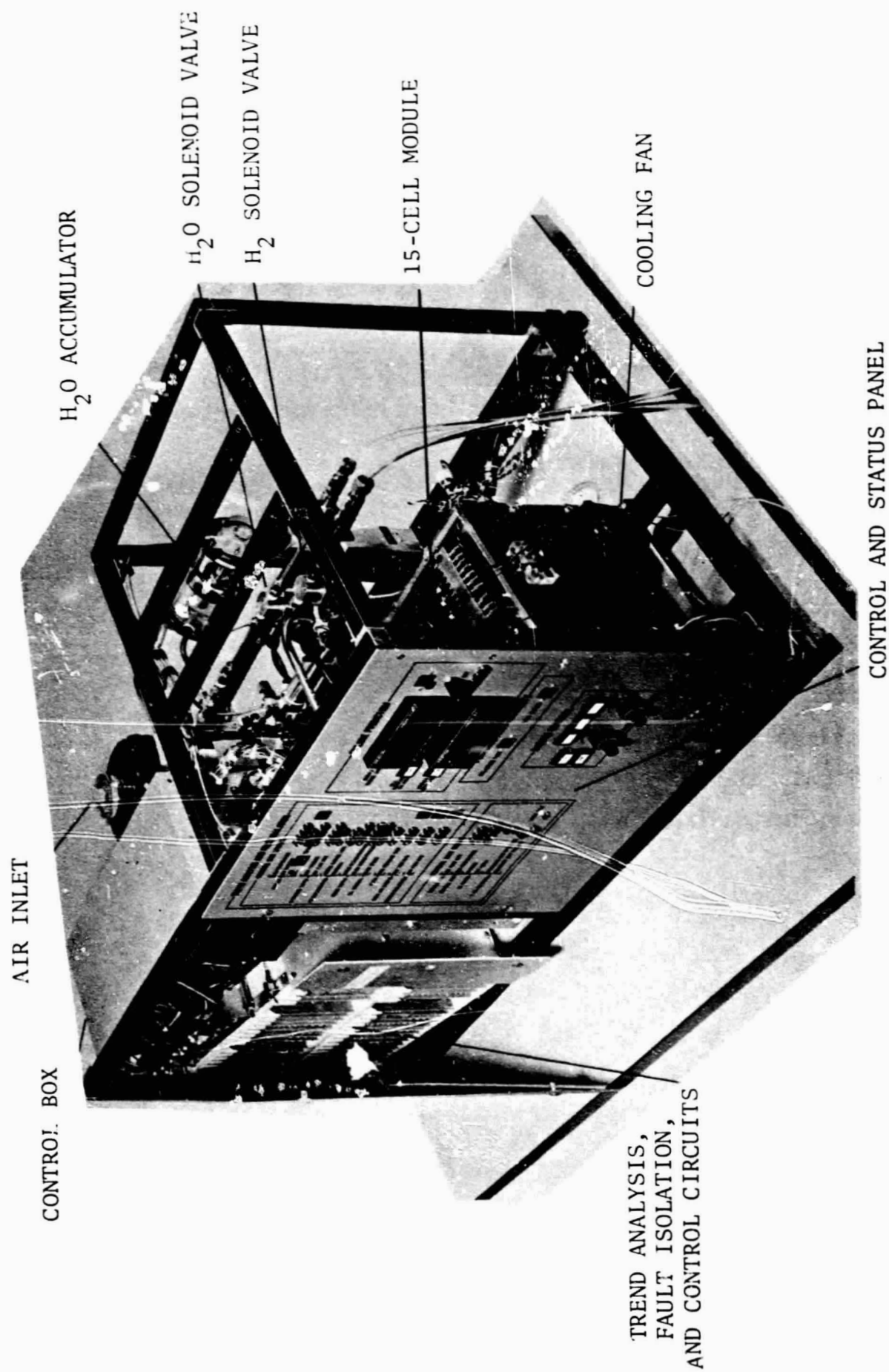
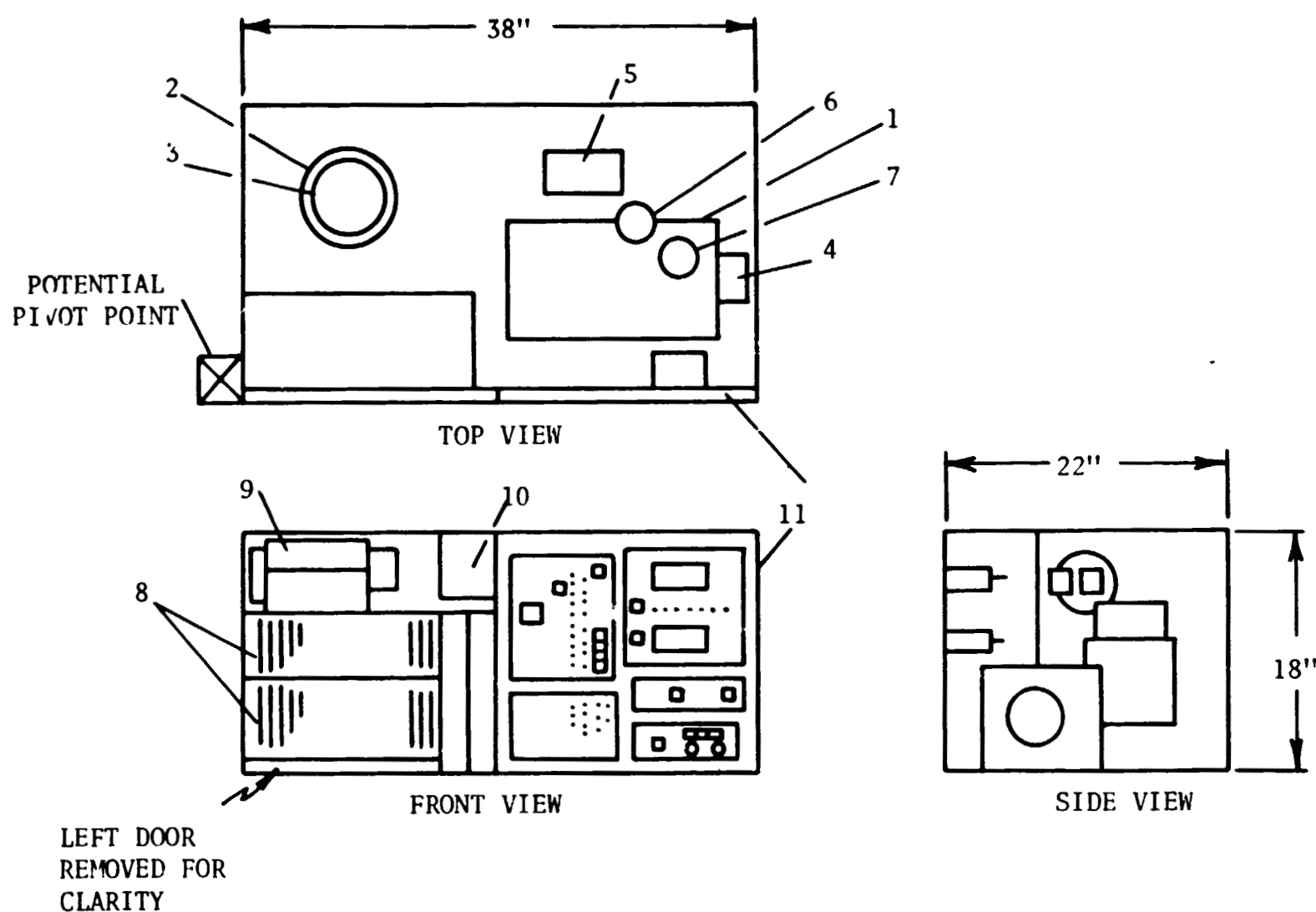


FIGURE 3 SELF-CONTAINED, ONE-MAN CO₂ CONCENTRATING SYSTEM



CO₂ REMOVAL UNIT

1. Electrochemical Module
2. Process Air Blower
3. Air Filter
4. Cooling Air Fan
5. H₂O Accumulator
6. H₂O Solenoid Valve
7. H₂ Solenoid Valve

CO₂ CONTROL UNIT

8. Printed Circuit Card Assembly
9. Electronic Cooling Assembly
10. Power Supply
11. Control and Status Panel

FIGURE 4 THREE VIEWS SHOWING CX-1 COMPONENT LOCATIONS

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range 3 to 5 mm Hg. The plumbing schematic is shown in Figure 5. A schematic of a single cell of the module is presented in Figure 6 to show the humidifier location relative to the electrochemical cell where the CO₂ is concentrated.

Electrochemical Module. The module shown in Figure 7 has a design similar to the 15-cell module developed under NAS2-4444.⁽³⁾ It used the same electrodes and titanium-clad copper current collector/fin composites, Figure 8. This was done for two reasons. First, to allow measurement of CO₂ concentrator performance with electrodes that had already accumulated 2,000 hours of operation. (Typically, electrochemical devices perform better when new electrodes are used. This can lead to a false level of capability when the ECO₂CS is being developed for a 5-year operating life.) The second reason was the desire to devote the program's resources to developing a maintainable, self-contained system. Thus, its electrical performance was given secondary emphasis.^(a)

Module improvements resulted from incorporating internal humidification to simplify humidity control, change in cavity design for improved gas distribution, and a reduction in flow restriction to enable handling larger air flow rates with lower pressure drops. The cell plates, humidifier plates and compression frames, shown in Figure 9, were made from injection-molded polysulfone. Internal gas manifolding was used.

The internal humidifier concept works as follows: the humidifier cavity, humidifier membrane and the cell's electrode-cell matrix-electrode sandwich are initially charged with electrolyte at the same concentration, hence a specific dew point. The dew point equivalent to the charge concentration is the highest allowable for the incoming process air for long-term cell operation. When process air enters the cathode compartment having a dew point lower than that of the original charge concentration, H₂O is transferred from the electrolyte in the humidifier and the cell matrix to the air. As H₂O is lost to the process air, the concentration of electrolyte increases and its volume decreases. Only the humidifier cavities are connected to an external supply of H₂O which, therefore, becomes the source of H₂O used for internal humidification. The decrease in liquid volume in the humidifier cavities causes H₂O to be drawn into the cavities from an external H₂O accumulator. The accumulator is cyclically and automatically refilled, as its H₂O is used in humidification.

Process Air Blower. This device forces air through the cathode compartments of the module. The blower selected was a multistage Rotron Model No. MRDU, Type K8-6502, Series 329AS. It is capable of delivering 0 to 13 scfm (0 to 368 slpm) of air at a minimum static pressure of 10 inches of H₂O (1×10^4 Newtons/m²). It was also designed for limited use with O₂, as needed on the Parametric Test Program. The blower motor was of the induction type permitting current-versus-air flow rate calibration and to allow for manual flow adjustments.

Process Air Filter. The function of this device was to remove solids and, through the incorporation of active carbon, a limited range of gaseous contaminants from the air. This was done to prevent blower wear and module contamination. It is located upstream of the cabin air blower. The activated carbon was sandwiched between two layers of 1/2 inch (1.3 cm) thick filterdown. The latter retains the carbon and traps dust and dirt particles. The filter has a Rotron part number of 10017-7.

(a) The Contractor has subsequently developed a new electrode structure that increases process efficiency and has designed a cell avoiding titanium as a structural material because of NASA's reluctance to approve the use of titanium for spacecraft.

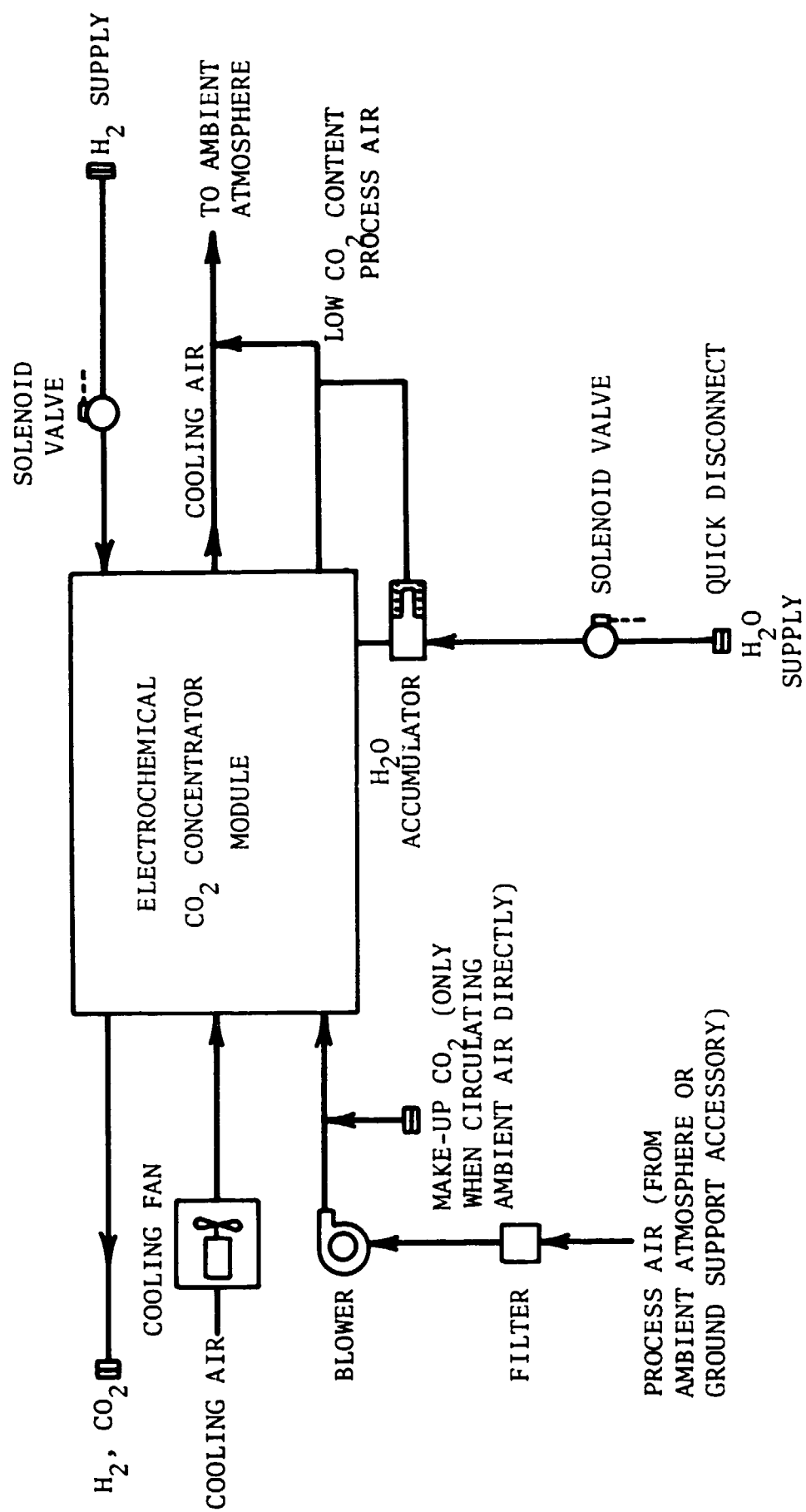


FIGURE 5 CX-1 PLUMBING SCHEMATIC

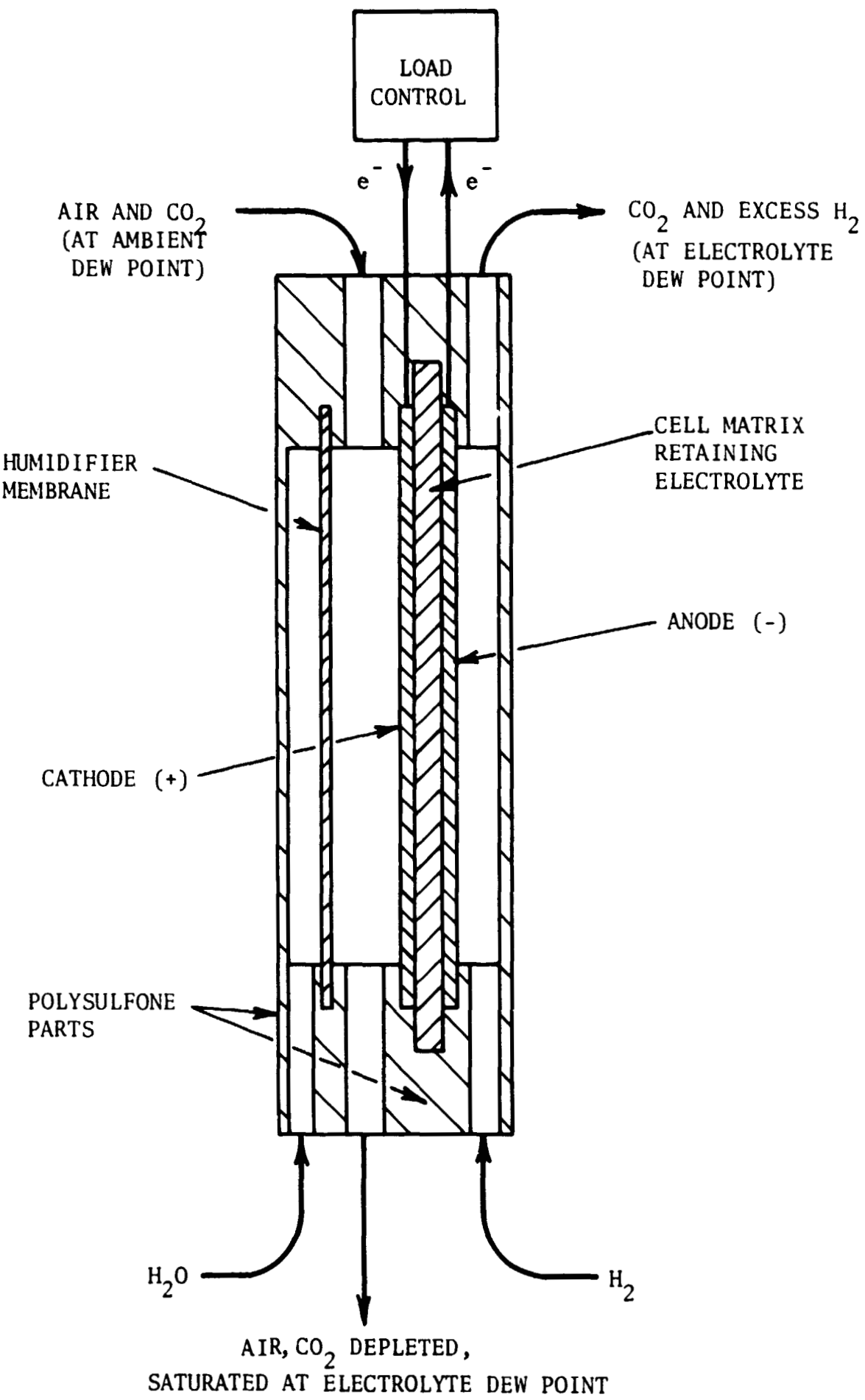


FIGURE 6 SINGLE CELL SCHEMATIC

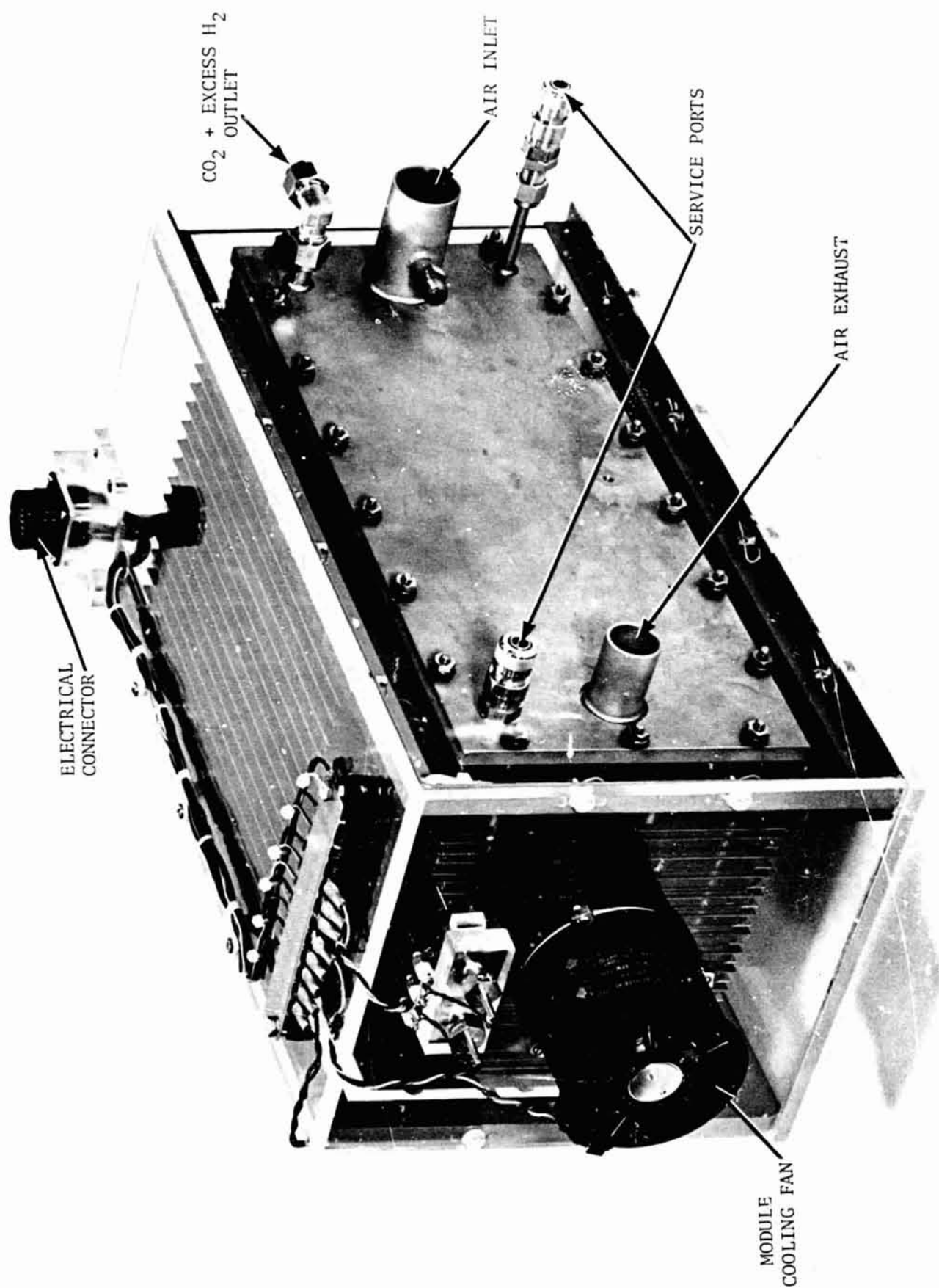


FIGURE 7 15-CELL ELECTROCHEMICAL MODULE

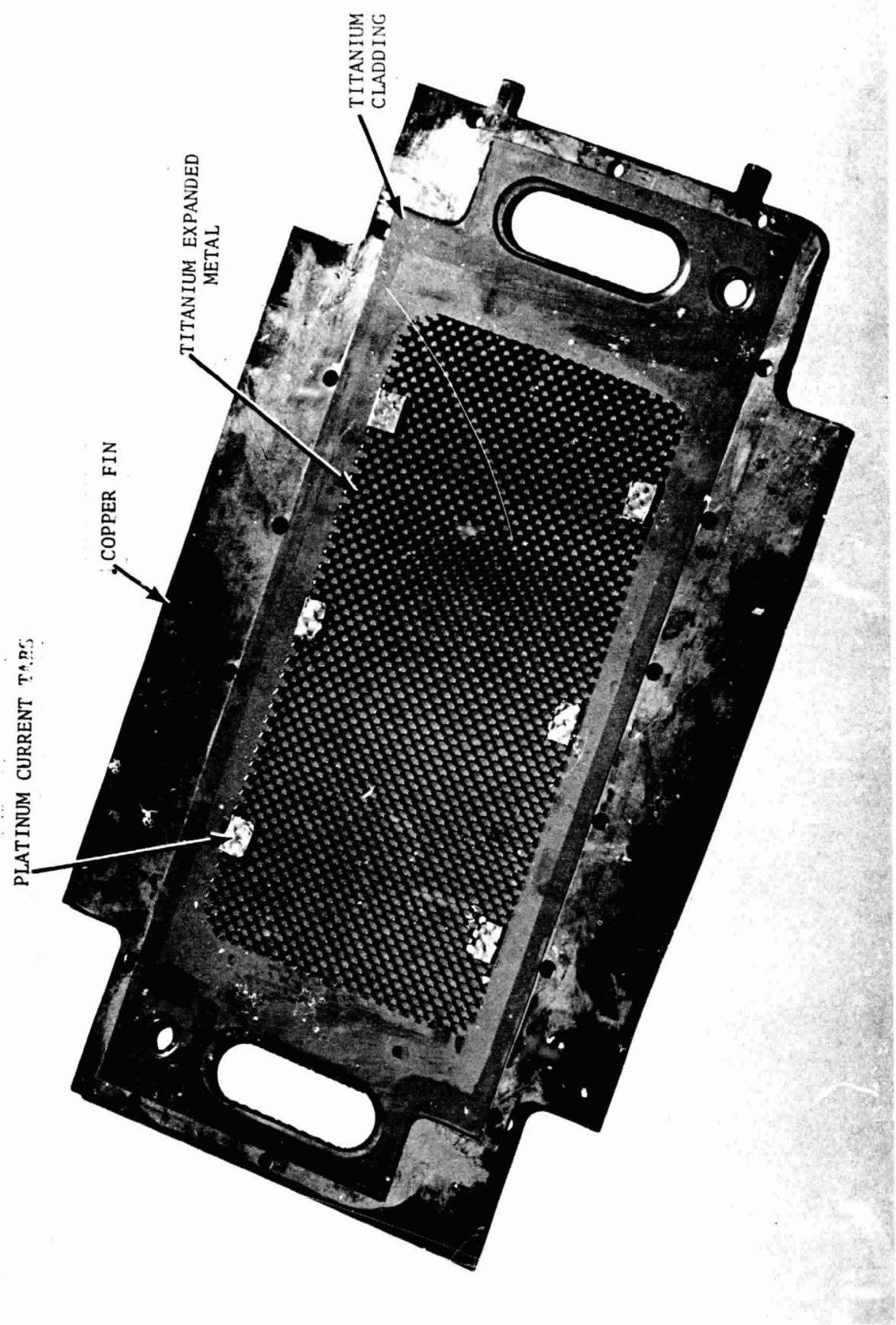


FIGURE 8 TITANIUM CLAD COPPER CURRENT COLLECTOR

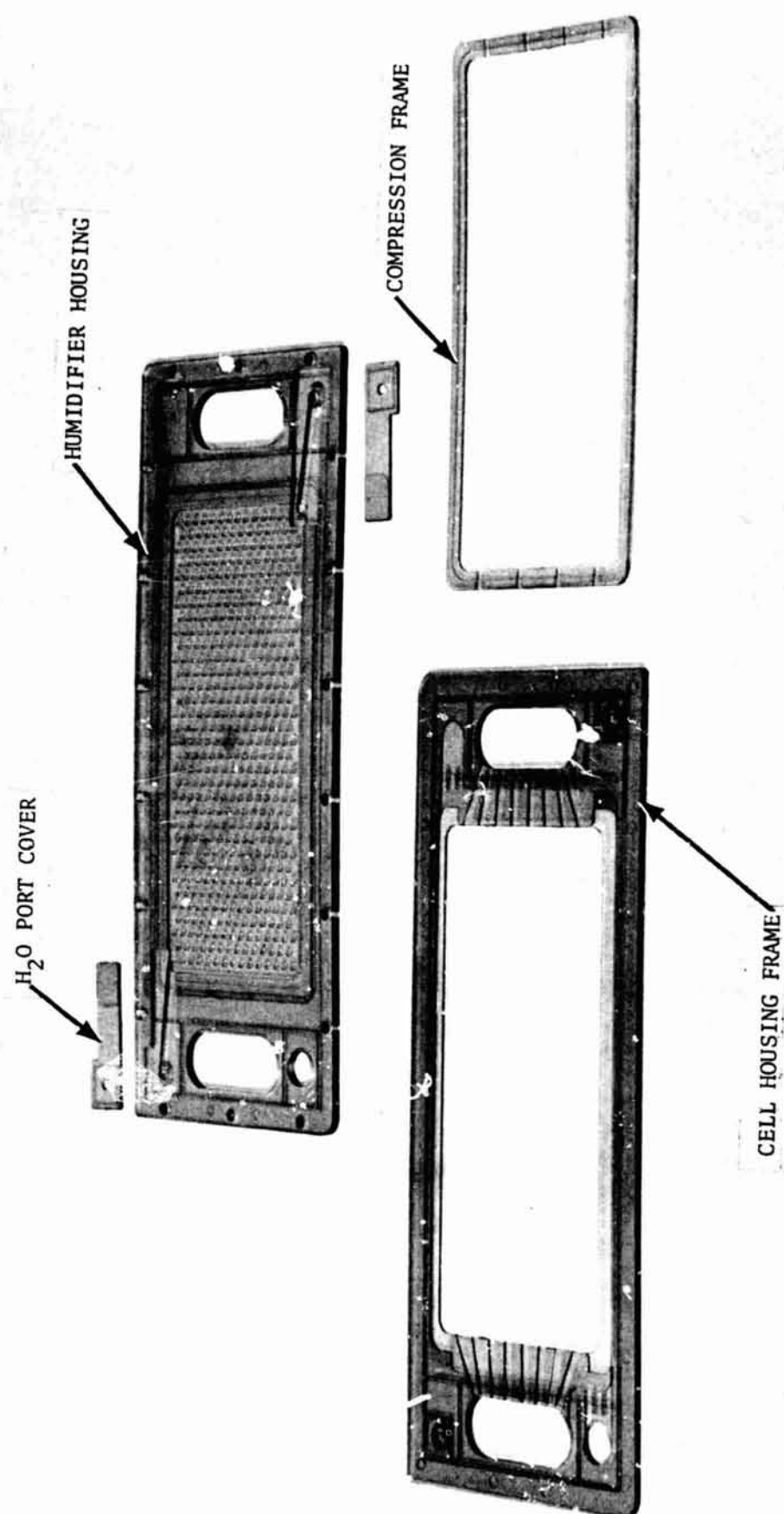


FIGURE 9 INJECTION MOLDED CELL PARTS

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Cooling Air Fan. This unit forces ambient air over the external fins of the module. It is a Rotron Aximax 3, Series 422 DS. It was sized to deliver up to 60 scfm (1700 slpm) at a static pressure of 0.75 inches of H₂O (1.9×10^2 Newtons/m²). At that flow rate, 65 BTU/hr (19 watts) of generated waste heat can be removed per degree rise in the cooling air. At nominal design conditions, the module generates 202 BTU/hr (59.2 watts). The fan only operated intermittently to maintain the module at a temperature less than an adjustable preset level.

During the course of the Endurance Test Program the Aximax 3 fan was replaced by a low speed, squirrel cage blower. This was done to avoid the noise pollution characteristic of high RPM fans. Simultaneously, and in anticipation of the warmer summer weather, provisions were made to cool ambient air below the ambient room temperature level.

Water Accumulator. The function of this device is to absorb volume-pressure fluctuations occurring within the humidifier cavities. It has also been designed to dampen the flow and the pressure overshoots that are characteristic of H₂O pressure regulators. The device was manufactured from acrylic plastic. It is cylindrical in shape. Figure 10 is a photograph of the accumulator following 6,400 hours of testing and, shown on its right, a second generation unit made of stainless steel.

A spring-loaded diaphragm separates the internal volume into a H₂O and atmospheric air compartment. The spring is on the atmospheric side and exerts a negative pressure on the H₂O compartment. The unit was designed and developed at Life Systems.

Initially, a H₂O vacuum regulator was included in the feed line. The purpose was to maintain the H₂O pressure constant at a pre-set (and adjustable) level. The regulator was a Kendall Model 16 from Fairchild-Hiller. It had a downstream, pressure-referenced, spring-loaded diaphragm. The allowable input range was from atmospheric to 60 psig (5.1×10^5 Newtons/m²) with the downstream pressure maintained between -5 inches H₂O (1.3×10^3 Newtons/m²) and -2 psig (8.8×10^4 Newtons/m²). During the Parametric Test Program it was removed from the system as part of a concept simplification effort. Its function was replaced by two reed switches resulting in a more reliable mode of periodic H₂O addition.

Water Solenoid Valve. The function of this device is to shut off H₂O flow during maintenance or under emergency conditions. It is a 2-way, subminiature Series C from Skinner Precision Industries.

Hydrogen Solenoid Valve. The function of this device is to shut off H₂ flow during maintenance or emergency situations. It is a 2-way, subminiature Series C from Skinner Precision Industries.

CO₂ Control Unit

This grouping of hardware contains all the electronic and electrical instrumentation necessary to control the CO₂ removal process, to allow for manual variation of the operation as required during the Parametric Test Program, to allow readout of the trends in system performance, to detect all faults, and to isolate some of them.

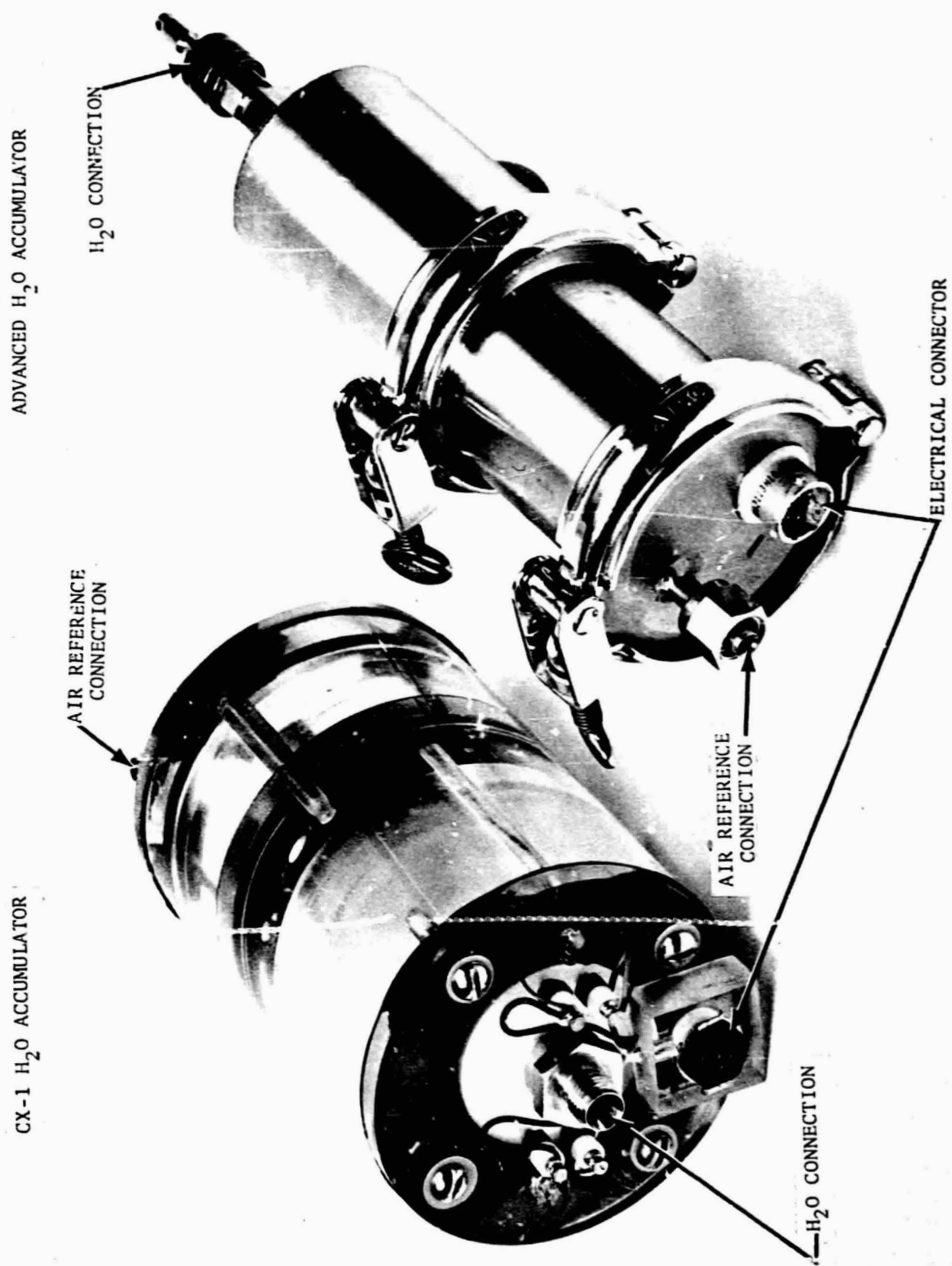


FIGURE 10 WATER ACCUMULATORS

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Printed Circuit Card Assembly. This assembly, shown in Figure 11, contains the printed circuit (PC) cards in a swing-out, card mounting system for ease of maintenance. It also contains the heat generating transformer-rectifier used to power the electronics and the power portions of the 15-volt regulator, the electrochemical module load control, the module's thermal control, and the shutdown control. Removing the heat generating items from the PC cards enabled mounting all heat-generating devices on a single cooling assembly.

Electronic Cooling Assembly. The function of the device is to remove the heat generated by the electronic components. A Wakefield Engineering, Inc. Series FCA-700, confined air flow cooling package was used. The design eliminated the necessity for ducting and baffles, while insuring full utilization of the air passed through the effective fin area. The design provided excellent accessibility to the semiconductors and resistors, facilitating installation and maintenance. A total of 12 semiconductors and 14 resistors are located on the exterior of the cooling module.

Initially, the package incorporated a Rotron Aximax 3 cooling fan. This unit was selected to be identical to that used for cooling the module and, thereby, increase subsystem component interchangeability. Prior to the Endurance Test Program, the fan was removed and water-cooled copper tubes added. This avoided the noise associated with the high speed cooling fan.

Printed Circuit Card Mounting. A Scanbe Manufacturing Corp. card mounting unit was designed and sized to hold the 40 printed circuit cards used to mount the electronic components (Figure 12).^(a) The unit employs injection-molded, vibration and shock damping nylon for all components that come in contact with the card itself. The card guides have a small profile to reduce air flow impedance, helping promote convective system cooling.

A one-piece, T-series card guide is used. All cards are symmetrical and have a dimension of 5.16 x 6.26 inches (13.1 x 15.9 cm). Each card is spaced 0.60-inch (1.52 cm) center to center except four cards which are located 0.69-inch (1.75 cm) center to center.

Circuit card ejectors are included as part of the card support system. The ejectors operate by leverage action against the card guide which disengages the card from its connector. The use of card ejectors not only provides for quick and convenient removal of an individual card from the file, but they add to system reliability by preventing damage to the card components or connectors from improper card removal. The individual handle also eliminated special extraction tools.

Each circuit card position and function is numerically coded with a marking bonded to the base material.

The card mounting unit contains two rows of 20 card positions each, held together with flanged endplates. Each card has the connector mounted "off the centerline" of the card to key the card to insert only one way. The two-row file of vertically oriented cards is mounted in a swing-out enclosure for ease in assembly and maintenance. Aluminum bars are used to support the guides and spacers.

(a) A total of 36 PC cards were used in the CX-1 with four card positions reserved for later incorporation of performance fault prediction features.

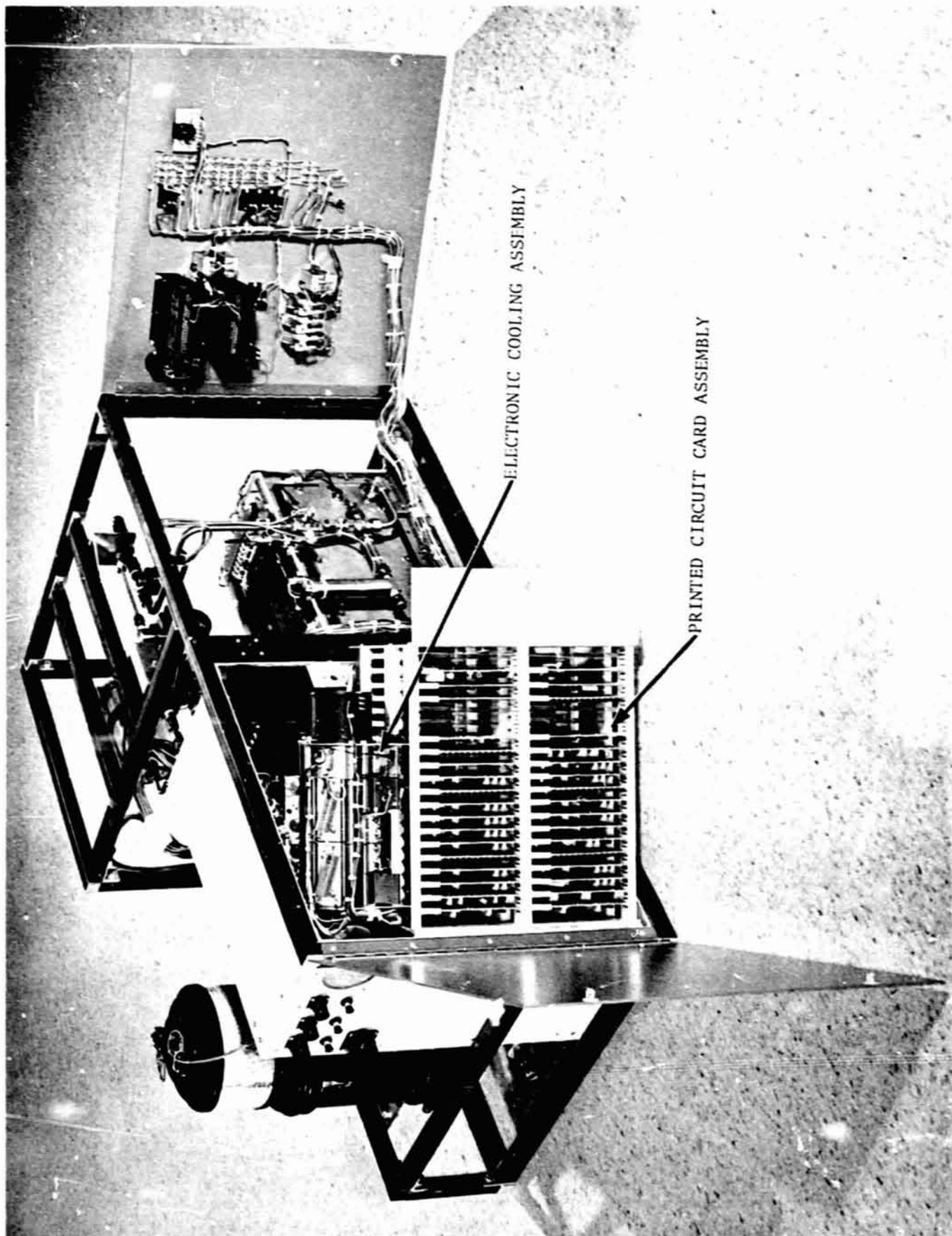


FIGURE 11 PRINTED CIRCUIT AND ELECTRONIC COOLING ASSEMBLIES

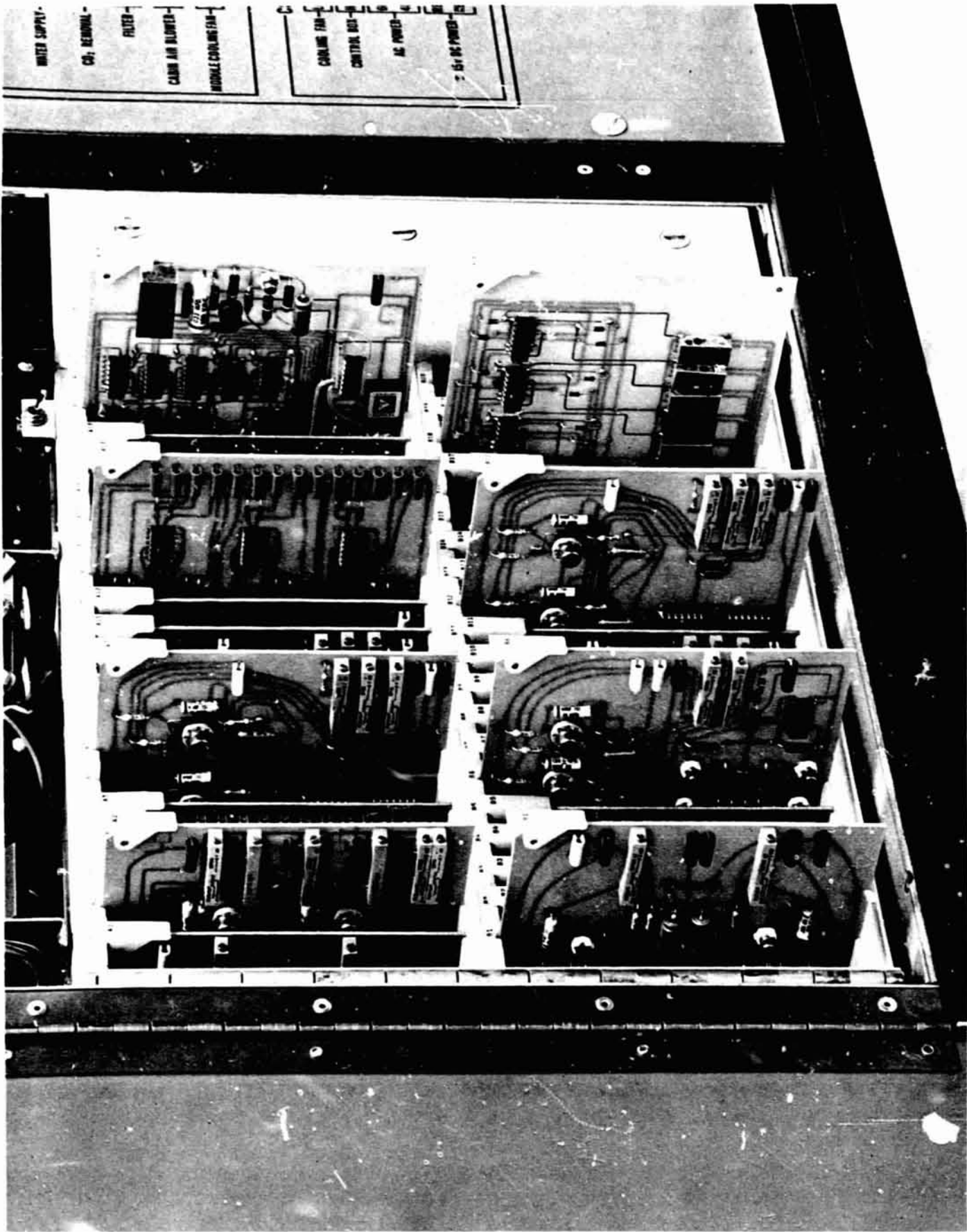


FIGURE 12 PRINTED CIRCUIT CARD ASSEMBLY

A group of circuits were designed for the CX-1 system to provide performance trend information, advance warning of impending problems and protection by automatic shutdown if certain critical parameters exceed preset limits.

Typical Printed Circuits. In general, each parameter monitored required a signal conditioning amplifier, level detectors, storage and lamp drivers. Figure 13, for example, shows the printed circuit cards used to monitor module temperature in the CX-1. One of the three identical circuits on the card in the center is used to convert a signal from the temperature sensor (thermistor) to a 0 to 5 volt DC signal. This signal is sent to level detectors contained on the upper right printed circuit card in Figure 13. The level detectors divide the analog temperature signal into four discrete ranges which are presented on the Trend Analysis and Fault Isolation portion of the Control and Status Panel. This card also contains memory circuits to retain the highest level reached during any time period until manually reset (acknowledged by the operator). The lower left card contains 14 lamp driver circuits, four of which are needed to drive the green, amber, red, and flashing red indicator lamps.

For increased safety and maintainability it is important to monitor the voltages of the individual cells in the concentrator module. This is accomplished by scanning the cells sequentially and connecting the scanner output to a signal conditioning circuit which, in turn, feeds the typical Level Detector, Storage Circuit and Lamp Drivers previously shown in Figure 13. The 15-cell scan relays for the CX-1 and their decoder-drivers are contained on two printed circuit cards shown in Figure 14.

Figure 15 is the printed circuit card which contains the scan oscillator, the scan counter which sequentially selects the relays, and the signal conditioning amplifier.

Blower Speed Control. The function of this control loop is to provide a manually adjustable air feed rate. This was necessary to enable changing the flow rate when the pCO_2 of the feed air was changed. The control employs an AC thyristor whose conduction angle is varied by means of an RC circuit, thus providing a variable output voltage.

Power Supply. The function of this device is to convert the 115 VAC, 400 Hz simulated spacecraft power into the ± 15 volts DC needed to operate the system's electronics. It employs a conventional transformer-rectifier supply feeding two series regulators.

Control and Status Panel. This panel, shown in Figure 16, has been divided into four sections. One section contains the performance trend analysis and fault detection and isolation indicators. The top part visually displays the operating status of the CO_2 Removal Unit; The bottom displays the status of the CO_2 Control Unit. A second section contains the displays for the failure prediction features.^(a) A third section indicates performance reliability by displaying system total operating time and number of shutdowns. A final section contains the system's minimal control. The performance status indicator lights are color coded to indicate normal, caution, warning and alarm levels whose meaning are summarized in Table 2.

^(a) The failure prediction concepts and circuits were designed and provisions made for incorporation into the hardware under NAS2-6118. Actual fabrication, installation, and testing will be carried out under NAS2-6478.(4)

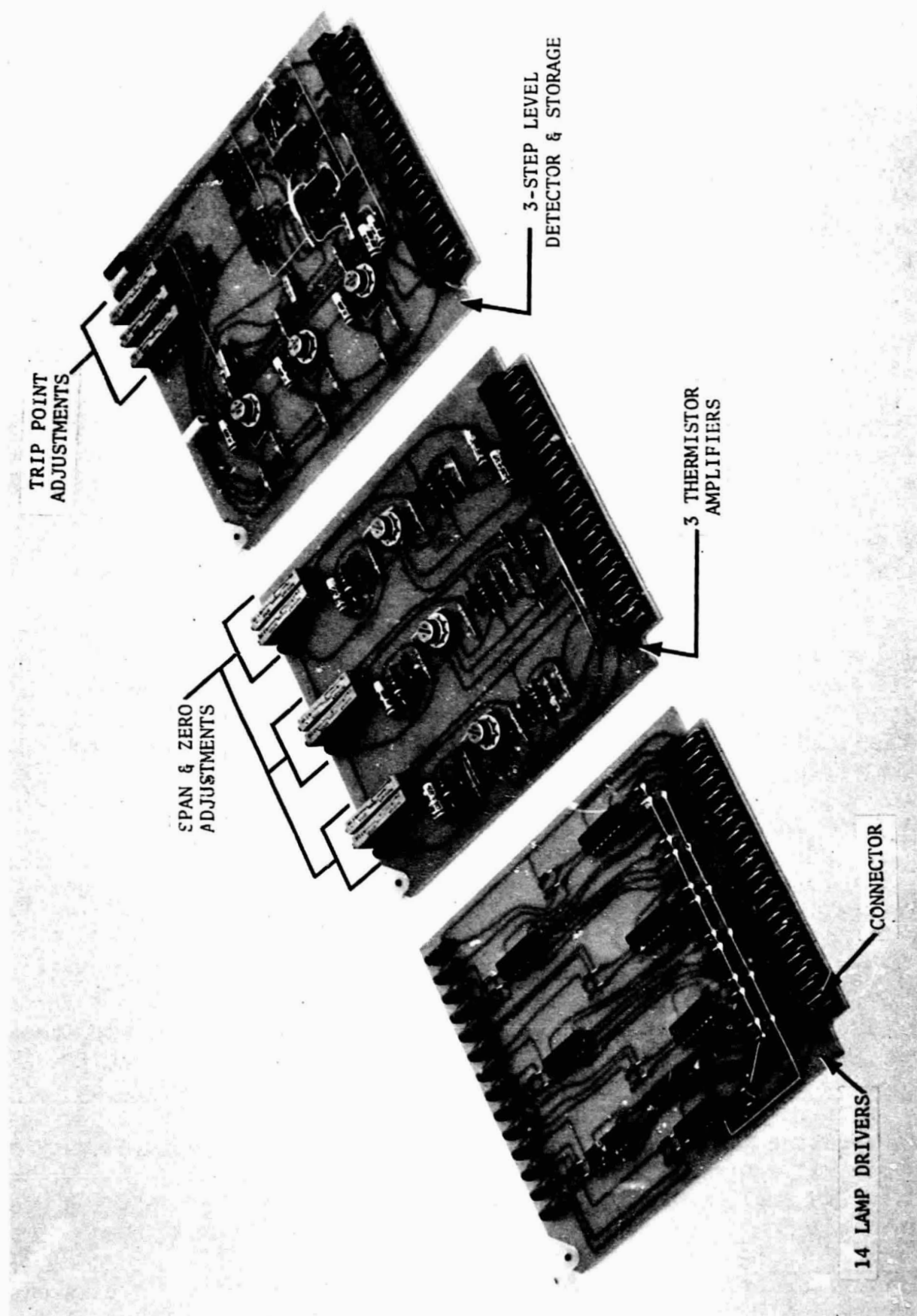


FIGURE 13 PC CARDS CONTAINING LAMP DRIVERS AND SIGNAL AMPLIFIERS,
LEVEL DETECTORS AND STORAGE

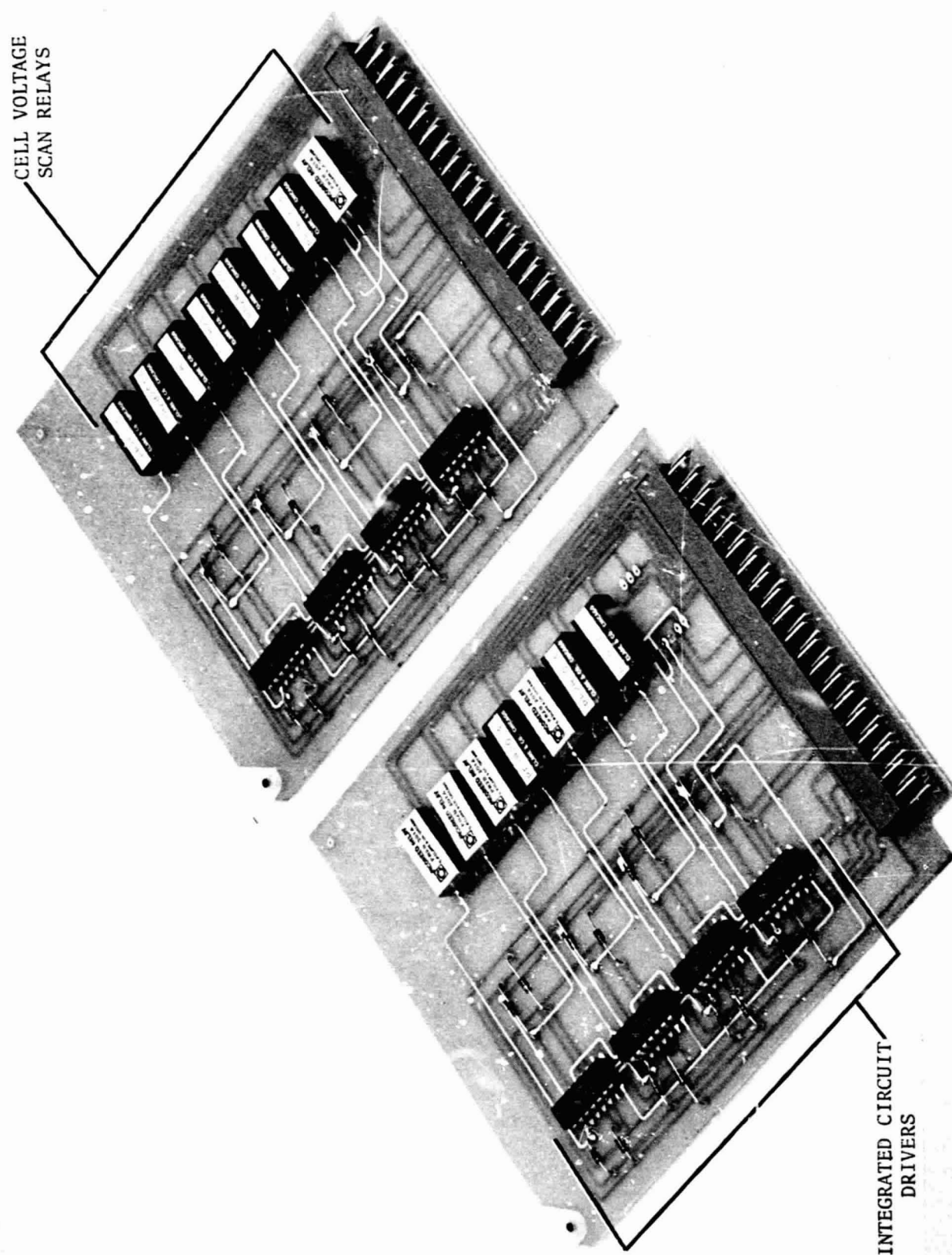


FIGURE 14 PC CARDS CONTAINING SCAN RELAYS AND DRIVERS

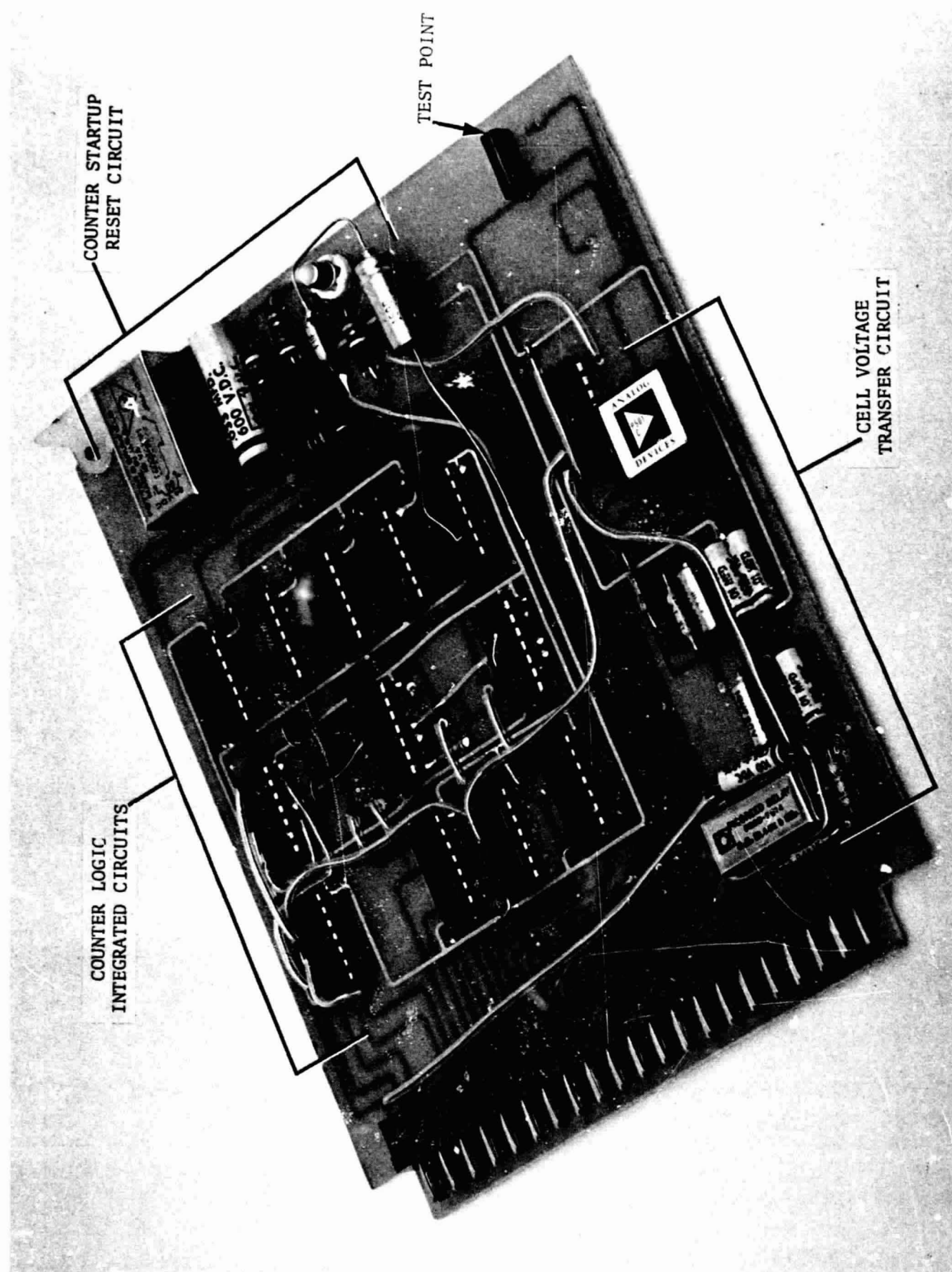


FIGURE 15 PC CARD CONTAINING SCAN COUNTER AND CELL VOLTAGE TRANSFER CIRCUIT.

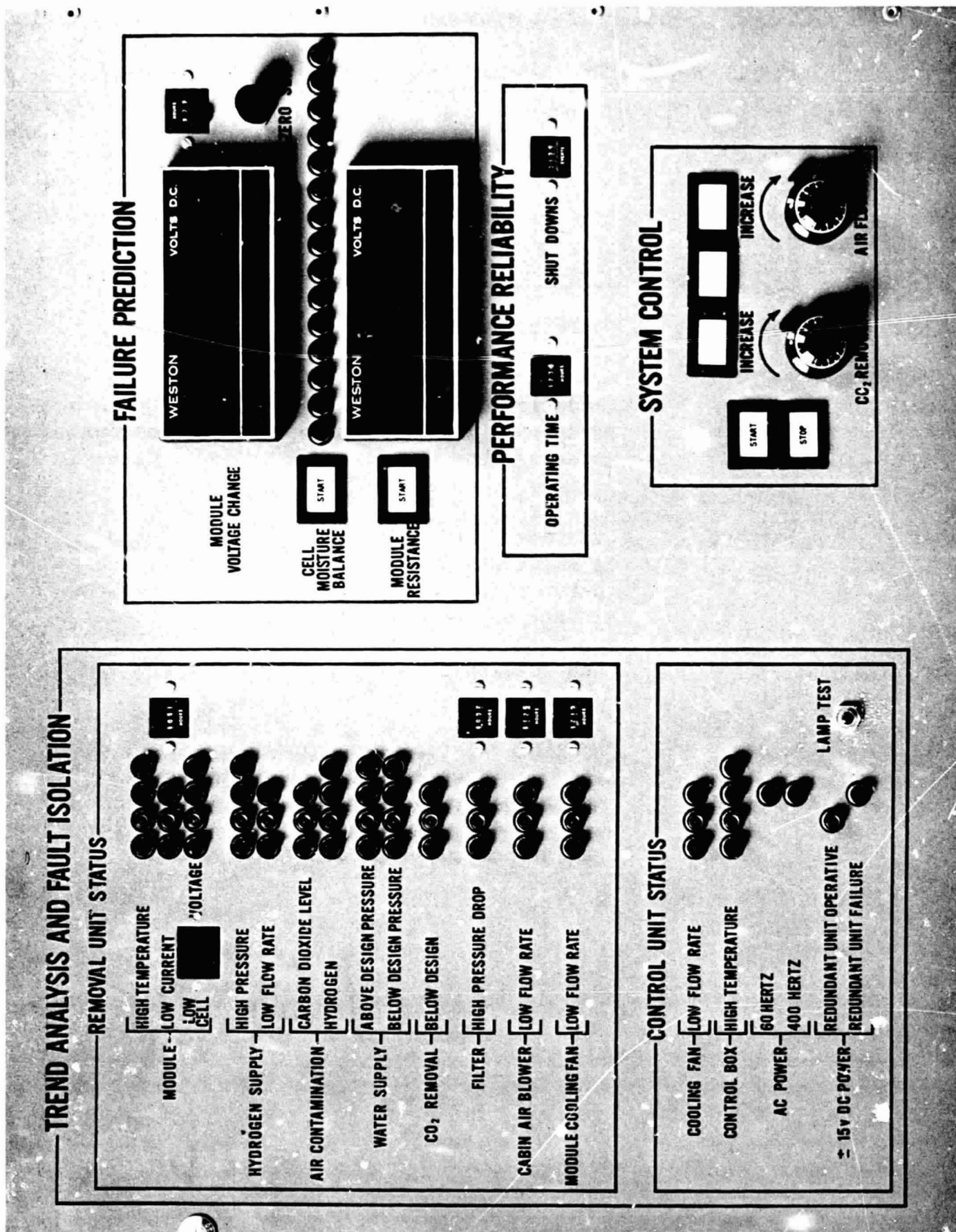


FIGURE 16 CONTROL AND STATUS PANEL

TABLE 2 CAUTION, WARNING, AND ALARM LEVELS

<u>Color</u>	<u>Condition</u>	<u>Response⁽⁵⁾</u>
Green	Normal	No response needed.
Amber	Caution	Condition developing that would result in a hazardous situation; predetermined response necessary but not necessarily time critical.
Red	Warning	Hazardous condition impending or developing in which urgent action is required by the operator to avoid an Alarm or other serious situation. Predetermined action by operator, but by direction of lead engineer rather than automatic reaction.
Flashing Red	Alarm	Existing hazardous condition in which automatic shutdown is necessary and occurs or emergency response of the operator required.

System Control. The control of the system has been designed to be simple. It consists of automatic startup or reset and shutdown at the pressing of a switch. It provides a manual adjustment for

- (1) varying current, and
- (2) varying process air flow rate.

Changes in current enables varying CO₂ removal rate or to maintain a constant CO₂ removal rate when the inlet pCO₂ level varies. The manual adjustment of process air flow rate (blower voltage control) enables changing flow conditions to compensate for variation in operating pressure and operating efficiency. The electronics' design allows many other operating conditions to be manually adjusted. To avoid errors, however, they are pre-set at Life Systems; e.g., operating temperature level. The reasons for including manual adjustment were (1) to allow for operation at off-design conditions during the Parametric Test Program and (2) as a step toward defining an automatic CO₂ removal control. (A version of the latter has been designed to automatically vary process air flow rate and concentrator current to yield highest CO₂ removal efficiency in response to changes in metabolic CO₂ generation rate. The latter is reflected by an increase in pCO₂ level when the greater metabolic generation rate occurs in a confined volume. The technique allows maintaining a given pCO₂ level wherever the pCO₂ level sensor, or sensor reflecting the highest pCO₂ level is located.)

System Summary Status Panel

The function of this panel is to present a summary of the real time status of the system. For convenience, it was located to the left on the Parametric Data Display Panel (see Figure 17) and considered a part of the Ground Support accessories. It contains:

- (1) A startup and reset switch, the latter to initiate a startup following automatic system shutdown;
- (2) A shutdown switch; and
- (3) A color-coded, four-light indicator to display normal, caution, warning or alarm summary status (see Table 2).

When operating at constant conditions, no other controls or indicators are required. In end-item application, however, the process air and other interface conditions will vary. Thus an automatic control is needed, has been designed, and will be incorporated into future hardware.

Which of the four status indicators on the System Summary Status Panel is lit is determined by summing the more than 20 sensors and system output parameters for operating status. One or more caution situations at the CX-1 will provide a caution indication on the System Summary Status Panel. One or more warning situations at the CX-1 will provide a warning indication on the System Summary Status Panel. The same for the alarm level.

To determine the cause of a caution, alarm or warning condition, one must view the Trend Analysis and Fault Isolation sections of the Control and Status Panel.

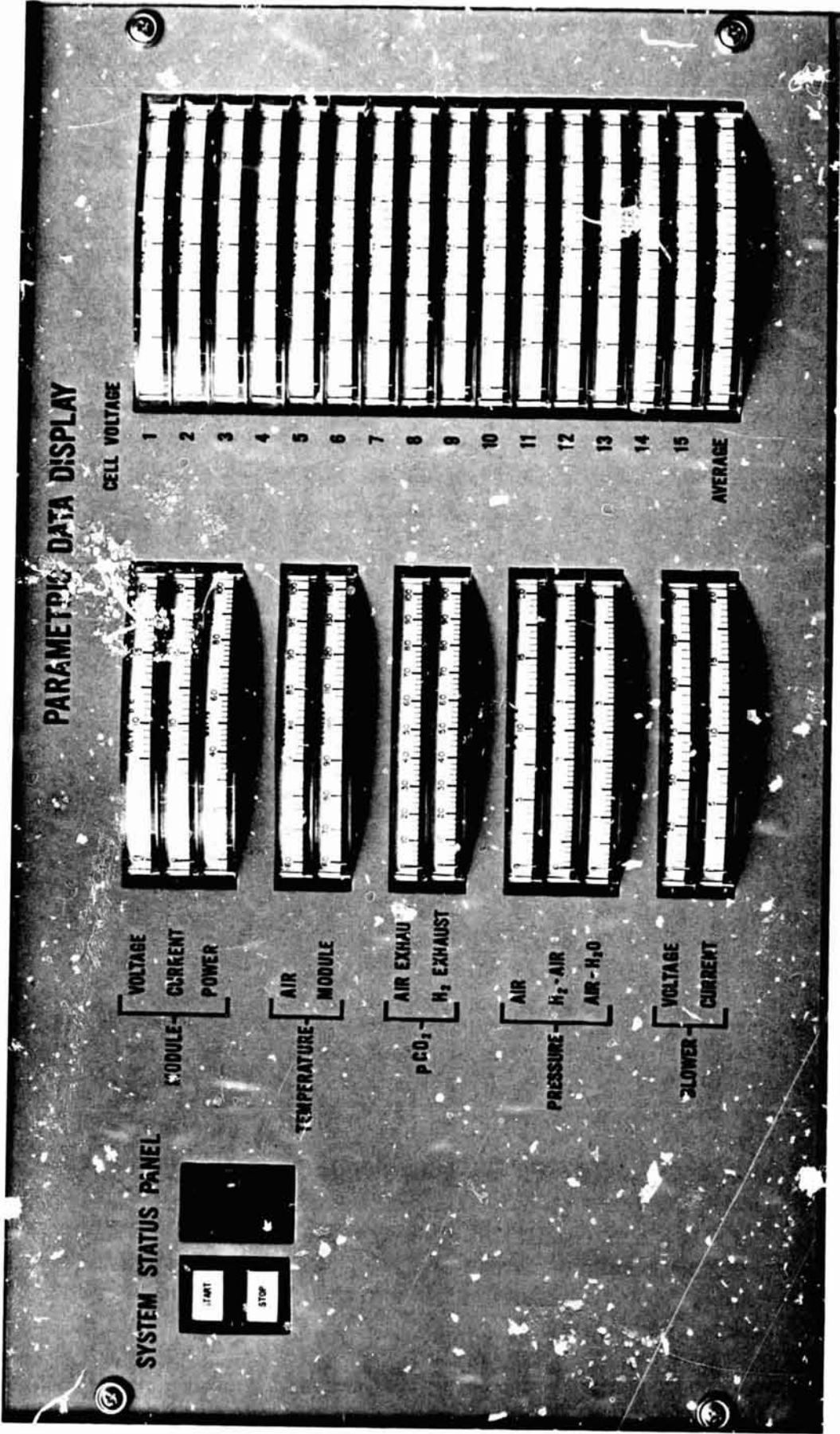


FIGURE 17 SYSTEM STATUS AND PARAMETRIC DATA DISPLAY PANELS

Here the status of the system is presented in detail with present status information for 19 areas where malfunctions can occur.

GROUND SUPPORT ACCESSORIES

Two factors contribute to the need for various items of support equipment. The first is the absence of the manned chamber or spacecraft atmosphere itself; O_2 , nitrogen (N_2), and trace constituents, e.g., CO_2 , H_2O , and contaminants, and the vehicle resources (i.e., power, H_2 , and H_2O). The second is the wide fluctuation in operating conditions which were imposed on the design by including parametric testing as part of the program. Four items of Ground Support Accessories were provided. They are:

- Space Station Power Simulator (SSPS)
- Integrated Logistics Support Unit (ILSU)
- Ground Checkout Unit
- Toxin Burner Unit

The relationship between these items and the CX-1 is shown in Figure 18. They are called Ground Support Accessories instead of Ground Support Equipment since they would not be required to start up or operate a flight system on the ground prior to a launch.

Space Station Power Simulator (SSPS)

The SSPS consists of a DC power supply and an AC power supply.

DC Power Supply. The 28 volt DC power supply used is a Hewlett Packard Model 6266B. It has overvoltage protection and continuously variable output voltage and current (0-40 volts at 0-5 amps).

AC Power Supply. The 400 Hz, 115 volt AC supply is a Vector Engineering, Inc., Model 200S. It is a precision solid-state AC-to-AC converter. It has continuously variable output voltage (0-130 volts) and 400 Hz frequency.

Integrated Logistics Support Unit (ILSU)

The unit consists of a Fluids Supply Section, a Cabin Air Simulator Section and the maintenance provisions.

Fluids Supply Section. By design, only minimum support fluids are required to operate the self-contained system at the nominal design conditions. Ambient air can be circulated through the module with CO_2 added to obtain the desired inlet pCO_2 for the particular experiment. This CO_2 , the H_2 for depolarization, and the H_2O for the internal humidifier cavities are the minimum fluids required. They can all be supplied from the Fluids Supply Section. Since this section contains two series connected ion exchange resin cartridges to remove anions and cations, ordinary tap water can be utilized.

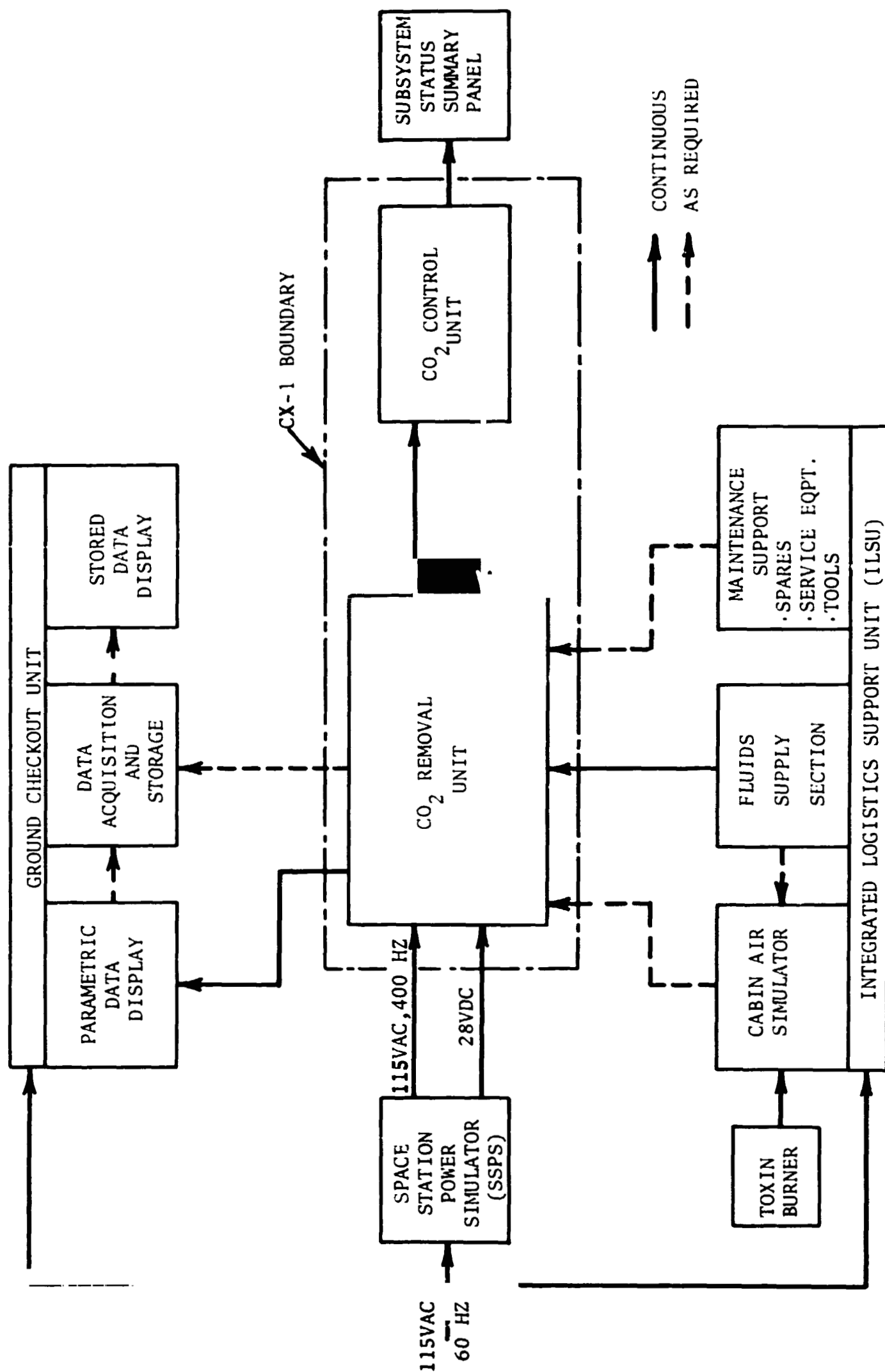


FIGURE 18 GROUND SUPPORT ACCESSORIES

Cabin Air Simulator Section. A separate setup was provided for tests requiring special O₂/N₂/CO₂ ratios. It consisted of an air blower, a source of O₂ to mix with the ambient air, a CO₂ blender, and provisions for analysis of the resulting cathode gas feed mixture. Gas analysis provisions include electrochemical pCO₂ and pO₂ sensors and a 0-2% or 0-0.5% CO₂ in air or O₂, Lira 300 analyzer.

Maintenance Support. This part of the development was devoted to defining and collecting together the spare parts and tools needed to maintain the system. The special emphasis given to minimizing system downtime during testing as a result of component and parts failures paid off during the test program. Of the 2,764 parts that make up the system only 15 failed - a reset timer, 6 light bulbs, a digital voltmeter, a lamp driver integrated circuit, and, as a result of a single component malfunction after 3,689 hours, 4 relays and 2 other integrated circuits. Because of the exploratory development nature of the program, however, spares provisioning was limited to the less costly parts using a remove, repair, and reinstall maintenance philosophy.

The spare parts included for the CO₂ Removal Unit were an air filter, cooling fan, H₂O and H₂ solenoid valves, fittings, clamps, and spares for all the module parts (e.g., matrices, polysulfone parts, bipolar plates, etc.). For the Control Unit, the spares were restricted to the component part level, i.e., transistors, semi-conductors, resistors, capacitors, relays, connectors, printed circuit cards, digital and linear integrated circuits, coils, and circuit breakers.

The system was designed to avoid the need for any special tools for assembly or disassembly. Only eight tools are needed to assemble (and disassemble) the CX-1 form (into) its eight major items or assemblies.^(a) The tools needed are cited in Table 3 and include 1 pliers, 2 screwdrivers, and 5 wrenches. The goal is to avoid the need for any tools during removal of line replaceable units for maintenance or, as a minimum, any special tool not part of the vehicle's regular maintenance tools.

Ground Checkout Unit

The purpose of this unit was to provide a real time display of the parametric data obtained on the system during the testing activities. The Parametric Test Panel contained meters for continuously monitoring 15 different system parameters in addition to the individual voltages of the module's 15 cells. Connection to the CX-1 was through a multiwire cable and a connector that allowed the system to run with or without attachment to the data acquisition system. Figure 17 is a photograph of the Parametric Data Display.

An Ampex recorder was used as needed to record all system parameters. A timer was designed and used to activate data taking once every hour. A stored data display panel was used to provide visual readout of data during playback of the recorded data if any unaccountable performance was observed following unattended overnight or weekend operation.

(a) The major parts are module, process air filter, process air blower, cooling fan, solenoid valves, water accumulator, control and status panel, and PC card assembly with the removable cards.

TABLE 3 MAINTENANCE TOOLS^(a)

<u>Tool No.</u>	<u>Description</u>	<u>Qty.</u>	<u>Utilized On</u>
1	Wrench, Open End, 3/8"x7/16"	2	<u>Module</u> - Remove 1/8" damper line and module locks <u>Blower</u> - Remove 4-1/4-20x5/8" bolts <u>Solenoid Valve</u> - Loosen bracket <u>Water Accumulator</u> - Remove 1/8" line to module <u>Control and Status Panel</u> - Remove cable clamps, remove hinge bolts from unistrut frame
2	Wrench, Open End, 19/32"x11/16"	1	<u>Module</u> - Remove H ₂ inlet and outlet lines <u>Solenoid Valve</u> - Remove inlet and outlet nuts
3	Wrench, Open End, 1/2"x9/16"	1	<u>Solenoid Valve</u> - Remove inlet and outlet nuts <u>Water Accumulator</u> - Remove nuts
4	Wrench, Adjustable, 8"	1	<u>Module</u> - Assistance wrench for nut removal <u>Solenoid Valve</u> - Wrench for nut removal <u>Water Accumulator</u> - Wrench for nut removal
5	Wrench, Ignition, Open-Boxed, 5/16"x11/32"	1	<u>PC Card Assembly</u> - Hold hexagonal nuts
6	Screwdriver, 3/16" Face Width	1	<u>Module</u> - Remove hose clamp <u>Blower</u> - Remove hose clamp <u>Fan</u> - Remove power leads and loosen clamps
7	Screwdriver, 1/4" Face Width	1	<u>PC Card Assembly</u> - Loosen 1/4 turn fasteners, remove dress plates, and remove flathead screws
8	Pliers, Channel Lock, 9"	1	<u>Module</u> - Install hose clamp <u>Blower</u> - Install hose clamp

(a) All are projected to be contained in a standard maintenance tool kit, e.g., all were found in the kit provided for the 90-day test of a regenerative life support system.⁽²⁾

Toxin Burner Unit

Open-loop ambient air was generally used to supply air to the CX-1. A Toxin Burner Unit was incorporated to circumvent introduction of non-oxidized trace contaminants into the CX-1 with the air. The unit consisted of:

1. A catalytic reactor to oxidize impurities at a temperature of 700F (371C);
2. A thermostatically controlled electric heater to maintain the burner's operating temperature;
3. Regenerative heat exchanger to raise the feed air temperature to near the burner's temperature with the burner's exhaust gas heat; and
4. A final, gas-liquid heat exchanger to return the burner's exhaust gas to room temperature using H₂O as the coolant.

It was added to the ground accessories after 552 hours into the Endurance Test Program.

PRODUCT ASSURANCE PROGRAM

This program included the activities associated with Quality Assurance of the hardware and with incorporating Reliability, Maintainability, and Safety, into the design and monitoring the results.

Quality Assurance Activities

These included establishing and implementing a Parts Inspection Program, maintaining a record of nonconforming articles and materials and their disposition, implementing control over the special processing required in the fabrication of certain module parts, quality workmanship, and controlling configuration through the Life Systems' standard drawing and change control procedure.

Reliability

A design review meeting was successfully completed prior to initiation of system fabrication.

All the CX-1 electronic parts and materials were evaluated according to a preferred parts and materials list.⁽⁶⁾ The CX-1 was designed and fabricated as a category IIIb, Research Type Equipment. Criticality of failures was of a minor classification since neither loss of life, serious injury or loss of mission (critical) or degradation of mission objectives or injury (major) was involved. The parts and materials were selected from Sections 3 and 4 of Reference 6 or their commercial type equivalents.

Provisions were made on the Control and Status Panel to monitor operating time and shutdown events. A total of 6,400 operating hours were accumulated on the

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CX-1. During the 180-day (4,320 hour) endurance test, 24 shutdown events occurred, only one due to a malfunctioning system part. (In that case, a piece of recently installed, ground support accessory fed electronic noise into the cell voltage scanning circuit, causing part malfunctioning.)

Other ways in which reliability was incorporated into the design included:

1. A simple startup/shutdown operating procedure (see Page 5);
2. Extensive use of previously proven electrical, mechanical, and electrochemical components and parts;
3. Parts were screened for performance critical characteristics and adjustments made where weaknesses existed;
4. Discussions were held with vendors regarding component capabilities and an evaluation was made of their past performance in delivering reliable components;
5. Performance levels were derated (e.g., design for 2-man level but nominally operated at the 1-man level);
6. A program for continuous monitoring of performance malfunctions was carried out to serve as a reference base for future development;
7. The circuits previously designed, tested and found reliable⁽³⁾ were utilized wherever possible; and
8. By design, the number of system components needed to perform the CO₂ removal function was minimized

Maintainability

A maintainability function was carried out during the program. During the design phase emphasis was on eliminating system components, avoiding the need for servicing or maintenance, and configuring the hardware for accessibility as required during unscheduled maintenance times.

Servicing. The only identified servicing is monitoring of the System Status Summary Panel for advanced warning of any impending out-of-tolerance operating condition. Because the CX-1 was an engineering pre-prototype, it did not include automatic controls to adjust performance to maximize CO₂ removal and electrical process efficiencies. By design, the system avoids servicing, with system performance monitoring projected to be done by a computerized, on-board checkout system.

Scheduled Maintenance. By design, all scheduled maintenance was avoided or eliminated. An operating life of more than 5 years is projected for the electrochemical CO₂ concentrating system because of the static nature of the process and such design philosophies as derating the system operating components.

Unscheduled Maintenance. Prior to completing the design, a Failure Mode and Effects Analysis was carried out. Most likely causes of failure to perform its CO₂ removal function were identified according to the rate at which failure would occur (see Table 4).

Maintainability Monitoring. During the program, conscious effort was taken to monitor component malfunctions. The objective was to establish component replacement times for making projections as to system maintainability. During the 6,400 hours of testing only 10 component parts failed (see Table 5). Seven parts failures were associated with lights; 5 normally-on bulbs and 1 segment of the digital light bulb in the cell counter burned out and a lamp driver integrated circuit (IC) failed. Of the remaining three failures, 1 was the resettable timer, another the digital voltmeter, and the final a scan relay.

Failure of the scan relay after 3,689 hours resulted from an improper sequencing of the scan circuits caused by electrical noise originating in a recently installed ground support accessory. The improper sequencing caused several cells to be shorted through the relay contacts. Once one relay failed, 3 more went along with an IC.

Of the ten component failures, none caused any alteration in CO₂ removal performance, none compromised safety and only the scan relay resulted in a system shutdown.

Performance Trend Analysis. The trends in 19 system performance parameters are visually displayed. For most parameters the trends are divided into three levels: caution, warning and alarm (Table 2). Totally, the CX-1 can indicate 113 different levels of performance status: 29 normal, 30 caution, 32 warning, and 22 alarm. This compares with the two parameters monitored and two parameter levels indicated for the CO₂ concentrator subsystem of the Aircrew O₂ Flight Breadboard System (FBS).⁽¹⁾ The more knowledge available on system status, the more likely unscheduled shutdowns can be avoided. Performance trend analysis as demonstrated on the CX-1 has not been used in the past but, undoubtedly will be used with future generations of regenerative life support subsystems because of the crew time it can save, the increased system safety, and the simpler subsystem integration when unscheduled shutdowns are avoided.

Fault Detection and Isolation. The 113 parameter levels also serve as fault detectors. Once a parameter has passed outside the normal operating band, the caution, warning or alarm indication will remain lit even though the parameter returns to normal or a less critical status level. If the CX-1 passes into an alarm status, shutdown automatically occurs. It will not restart unless the reset switch is pressed and will then continue to run unless the fault has not been corrected. For the CX-1, fault detection and fault isolation are one and the same. In the future, isolation of the cause of a detected fault should be provided; for example, a built-in fault indicator light would identify which printed circuit card contains the part that failed. To completely isolate faults to the line replaceable unit level will require more development activity. In the interim, a knowledge of subsystem operation and an instruction manual on troubleshooting will be adequate.

Access for Maintainability. The CX-1 was packaged for ease in accessibility to any malfunctioned component. The maintenance concept assumed a swing-out unit

TABLE 4 PROJECTED MAJOR CAUSES FOR SUBSYSTEM FAILURE^(a)

<u>Major Causes For Failure</u>	<u>Speed of Failure</u>	
	<u>Gradual</u>	<u>Fast</u>
1. Out-of-tolerance in operating conditions(b)	X	Possible
2. Loss of fluid (H ₂ , air) supplies		X
3. Loss of part calibration	X	
4. Human error	Possible	Possible
5. Leakage of fluid (H ₂ , air, H ₂ O)	X	Possible
6. Failure of electronic or electrical part		X
7. Failure of sensor	X	X
8. Loss in electrical contact	Possible	X
9. Loss of electrode activity	X	
10. Breakdown of defective material (not part)	X	
11. Mechanical failure of process air blower	Possible	X
12. Mechanical failure of cooling fan	Possible	X

(a) Defined as inability to perform its CO₂ removal function.

(b) At the interface between the CX-1 and the Ground Support Accessories.

TABLE 5 SUMMARY LIST OF COMPONENTS THAT MALFUNCTIONED^(a)

<u>Time, Hours</u>	<u>Component Malfunction</u>	<u>Secondary Malfunction</u>
504	Reset Timer, Part No. 2200-ET-1	None
1,306	Bulb, Part No. 2200-I59	None
1,334	Bulb, Part No. 2200-I5	None
1,834	Digital Voltmeter, Part No. 2200-DVM-1	None
2,301	Bulb, Part No. 2200-I59	None
2,301	Bulb, Part No. 2200-I62	None
3,335	Bulb, Part No. 2300-I4	None
5,335	Lamp Driver, Part No. 2108-IC1	None
3,689	Scan Relay, Part No. 2116-K0, -K1, or -K3	(b)
3,912	One segment of 9, Digital Bulb, Part No. 2200-DR-1	None

(a) Meaning failures that resulted from a breakdown in a mechanical, electrical, or electrochemical part, component, material, seal or contact.

(b) Adding new ground accessory caused failure in a scan relay the group of parts numbered 2116-K0, 2116-K1, and 2116-K3 which, in turn, caused failure of the other two group parts, transfer relay number 2113-K2 and integrated circuit number 2113-IC9.

(Figure 11), pivoting about an axis located in the front left corner. This approach provided access to the hardware on the front, back, top, bottom, right side and left side. No component access, however, is required from the top, bottom or left side. The module is removed from the right side; the blower, and air inlet and exhaust line components out the back. All electronics were maintainable from the front. Laboratory personnel can install the module in 4 minutes and remove it from the system in 3 minutes. All other components could be installed or removed in less time.

Safety

Safety was designed into the system to protect the equipment and personnel after completing a Safety Hazard Analysis on the concept. The presence of H_2 within the electrochemical concentrator is a residual hazard and must be and was given constant consideration. Catastrophic, critical, and marginal safety hazard categories were avoided or eliminated.^(a)

Safety Features for Equipment Protection. Design features and hardware included to protect the equipment in event of a malfunction are:

1. A built-in caution and warning system to provide advanced warning of a situation developing which, if not attended to, could lead to degradation in performance or damage to equipment.
2. An automatic, fail-safe shutdown system (alarm condition) to prevent operation under conditions that could damage equipment.
3. Circuit breakers to protect source of power and to prevent internal equipment from additional damage due to fault causing high current drain.
4. Power supplies were designed to accept peaks and transients by planned selection of component ratings.
5. Operating the only liquid line at a negative pressure relative to ambient and locating the line so as not to damage equipment in event of failure in line seals (e.g., away from electrical lines and components).
6. A three-level, H_2 -in-air contamination sensor in the air exhaust and operation of the H_2 at 8 inches H_2O (2×10^3 Newtons/ m^2) above the air pressure.^(b)

(a) These categories are defined as those condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, or subsystem or component malfunction will (a) cause death or incapacitating injuries to personnel by severe degradation of performance, (b) result in a hazard requiring immediate corrective action for personnel or subsystem survival, or (c) degrade performance but which can be counteracted or controlled without major damage or any injury to personnel.

(b) Successful operation of a H_2 -in-air sensor requires that it be exposed to air from all the cells that might contain the H_2 . A confined cathode manifold system was designed, therefore, to ensure that a representative mixture of air from all the cells was sampled.

Safety Features for Personnel Protection. Design features and hardware included to protect personnel in event of a malfunction are:

1. Completion of a Failure Modes and Effects Analysis to identify faults and design to avoid them before freezing the design.
2. Incorporation of two levels in off-design operation indication to alert personnel of impending operating problems without causing stress or anxiety and automatic provisions to shut down the subsystem at set points established at levels to prevent hazards or equipment damage.
3. A human engineered design to make misconnection of the H₂, air, or H₂O lines impossible.
4. Electrical grounding to protect personnel from shock although low voltage levels were generally used with the few higher voltages (110 VAC) located in out-of-the-way locations and marked.
5. No sharp edges are exposed on either the inside or outside of the system.
6. Rotating equipment limited to the process air blower and cooling air fan with rotating components contained within component housings.
7. Noise pollution, and the operator stress resulting from it, avoided by a design which uses low speed air movers.
8. All system control and monitor instrumentation adjustments made in the front (e.g., manual operation during parametric testing and electronic and mechanical equipment checkout and calibration).

TESTING

Five types of test activities were carried out during the program:

1. Component Design Verification Tests
2. Component Calibration Tests
3. System Shakedown Test
4. Parametric Test Program (System Design Verification Test)

Effects of H₂ Flow Rate Variation
Effects of O₂ Partial Pressure Variation
Effects of CO₂ Partial Pressure Variation
Effects of Temperature Variations
Effects of CO₂ Removal Rate Variations
Effects of Pressure Variations
Effects of Pressure Differential Variations

5. Endurance Test Program

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In addition to the above, Parallel Testing activities were completed to further advance technology and to support the development. These activities included:

- Operation at less than 85F (29C)
- Operation at less than 14.7 psia (1.0×10^5 Newtons/m²)
- Operation with new electrode structures
- Operation of an integrated Oxygen Reclamation System

Component Verification Tests

Engineering specified that Component Verification Tests (CVT's) were necessary for the following parameters and components: module's CO₂ removal rate, module's cathode pressure drop, process air blower flow versus pressure, H₂O accumulator, H₂ pressure drop across module, cooling air temperature rise and pressure drop across module fins, and all PC cards. All component designs were verified during this phase of the program.

Component Calibration Tests

Product Assurance specified that calibration tests be carried out on the blower flow versus voltage and the following parameter monitoring equipment located in the Ground Support Accessories: all flow meters, pressure gages, ammeter, and pCO₂ and pO₂ analyzers. These calibrations were completed.

All set points on the PC cards were set based upon simulating levels at the sensor input points to the cards.

System Shakedown Tests

When all components had been assembled and integrated into a self-contained system which, in turn, was integrated with the Ground Support Accessories, a shakedown test was initiated. The following actions were required prior to successfully completing the Shakedown Test:

Ground Support Accessories:

1. A H₂ regulator was added to the Fluid Supply Section to prevent the module from receiving a pressure surge when the system start button was pushed and the H₂ solenoid valve opened.
2. A water-cooled, heat exchanger was incorporated into the Cabin Air Simulator to return the process air to room temperature prior to entering the module. The air was heated while passing through the auxiliary blower used to force it through the flow meter.

CO₂ Removal Unit:

1. Several of the titanium clad current collector plates exhibited gas leaks which required module disassembly and plate repair. (The collectors used were those fabricated under NAS2-4444, where the leaks developed when platinum current collectors were spot-welded to the titanium.)

CO₂ Control Unit:

1. The H₂ flow and process air flow reference thermistors had to be more isolated from the flowing gas streams than initially planned to obtain proper functioning.
2. Resistors were needed on the cabin pCO₂ indicators to prevent the drive circuit from being subjected to excessive surge currents when the lamps came on.
3. The cell voltage amplifier circuits had to be modified. Both contacts of the scanning relays did not open simultaneously which caused the cell voltage amplifier output to vary over wide ranges during the cell sampling cycle. In addition, the capacitor storing this voltage between samples did not hold the charge long enough. A different sampling scheme was used to correct the problems.
4. Electrical noise caused certain level detectors to improperly trip other level detectors. To reduce the noise level, ground wires connecting the PC connectors were rerouted and approximately 1% of hysteresis was added to the level detector circuits.
5. The one hertz oscillator had its ground return brought out separately from the printed circuit card because it interfered with the module's current at cooling fan temperature control circuits.

Test Objective. The objective of the shake-down test was 8 hours of continuous operation at the nominal operating design point. Two weeks were required before all the bugs were worked out of the test hardware and the test successfully completed. The design Transfer Index (TI) of 1.9 lb CO₂ (0.86 kg) removed per lb O₂ consumed was exceeded by 10%. The electrical process efficiency reflected by the operating voltage was lower than projected by 10% because of the lower (77F versus 85F) (25C versus 29C) operating temperature and some loss of electrode activity due to handling.^(a) This did not compromise the hardware since electrical efficiency was of secondary interest.

Parametric Test Program

This program was successfully completed.

Measurements of Performance. Various parameters can be used to describe the performance of the ECO₂CS.

CO₂ Removal Efficiency,
Electrical Efficiency,
Time without Maintenance, and
Percent CO₂ Removed per Pass

(a) The electrodes used were removed from a 15-cell module with out internal humidification after endurance testing it for 1,850 hours under NAS2-4444.

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The figure of merit indicating CO₂ removal process efficiency is the Transfer Index, TI. This is the pounds of CO₂ removed per pound of O₂ consumed. One pound (0.45 kg) of O₂ generates sufficient OH⁻'s to remove 2.75 lb (1.24 kg) CO₂ according to the cathode reactions cited in Figure 1.

The electrical efficiency is the observed cell voltage divided by the theoretical voltage of 1.23; for simplicity, it can be reflected by the cell voltage. (Power efficiency would include the product of operating voltage times current flowing. The operating voltage level again directly reflects power output under constant current conditions.)

Mean-time-between maintenance can be expressed as the length of time the system removes the required CO₂ (1) without unscheduled shutdown or (2) without any part malfunctioning. This measurement of performance has considerable significance. It reflects the amount of development effort required before the numbers projected for failure rates of a flight system (e.g., 52×10^{-6} failures/hour) can be quoted with high confidence.

The percentage CO₂ removed from the process air directly affects the quantity of air that must be circulated through the system. Several examples are presented in Table 6. Advantages that result from a lower air flow rate are:

1. Process air blower power is decreased, and
2. Electrochemical module reliability will tend to increase since less (contaminated) air must be processed.

As shown in Figure 19, a system designed with an air flow rate of 200 cfm (5,660 lpm) will have processed 15 days into a simulated mission what a 40 cfm (1,130 lpm) design will process in 180 days, following 30 days of Design Verification Testing prior to beginning the test.

At present, electrical (or power) efficiency has less impact on concept applicability than the Transfer Index (TI), the mean time between unscheduled shutdowns, or percent CO₂ removed. The TI and voltage (E) were used to evaluate performance during the Parametric Test activity. The mean-time-between shutdowns was measured and evaluated as part of the Endurance Test Program. The high percentage CO₂ removed (low air flow) is inherent in the CX-1 design.

Parameter Ranges. Table 7 summarizes the range over which the parameters were varied during the system Design Verification Tests.

H₂ Flow Rate. Variation of H₂ flow over the range 1 to 4 times the stoichiometric flow had no effect on the TI. It remained constant at 2.35. The effect of H₂ flow rate on average cell voltage is shown in Figure 20.

O₂ Partial Pressure. The variations in the partial pressure of O₂ entering the cathode had no effect on the TI over the range 21 to 100% O₂. The diluents were the gases contained in air (mainly N₂). The average cell voltage increased from 0.37 to 0.41 volts for the O₂ percentage increase. The observed effects are shown in Figure 21.

CO₂ Partial Pressure. Increasing the pCO₂ at the cathode inlet increased the TI and average cell voltage as shown in Figure 22. The pCO₂ was varied from 2.0 to 14 mm Hg.

TABLE 6 EFFECT OF PERCENT CO₂
REMOVED FROM THE PROCESS AIR²

INLET pCO ₂ LEVEL, MM HG	AIR FLOW RATE REQUIRED TO REMOVE 0.55 LB (0.25 KG) CO ₂ /HR ^(a) , SCFM (SLPM) ^(b)	
	59% CO ₂ REMOVED	12% CO ₂ REMOVED
3.0	35 (990) ^(c)	175 (4,950)
2.0	52 (1,470)	263 (7,440)
1.0	104 (2,940)	525 (14,860)
0.23	454 (12,800)	2,283 (64,600)

(a) Nominal 6-man rate, 13.2 lb CO₂/day (6.0 kg/day) ÷ 24 hr.

(b) Standard (70F, 14.7 psia) (21C, 1.0x10⁵ Newtons/m²) Cubic Feet Per Minute (slpm).

(c) Nominal design and endurance operating point for the CX-1, flow rate of 5.8 scfm (164 slpm).

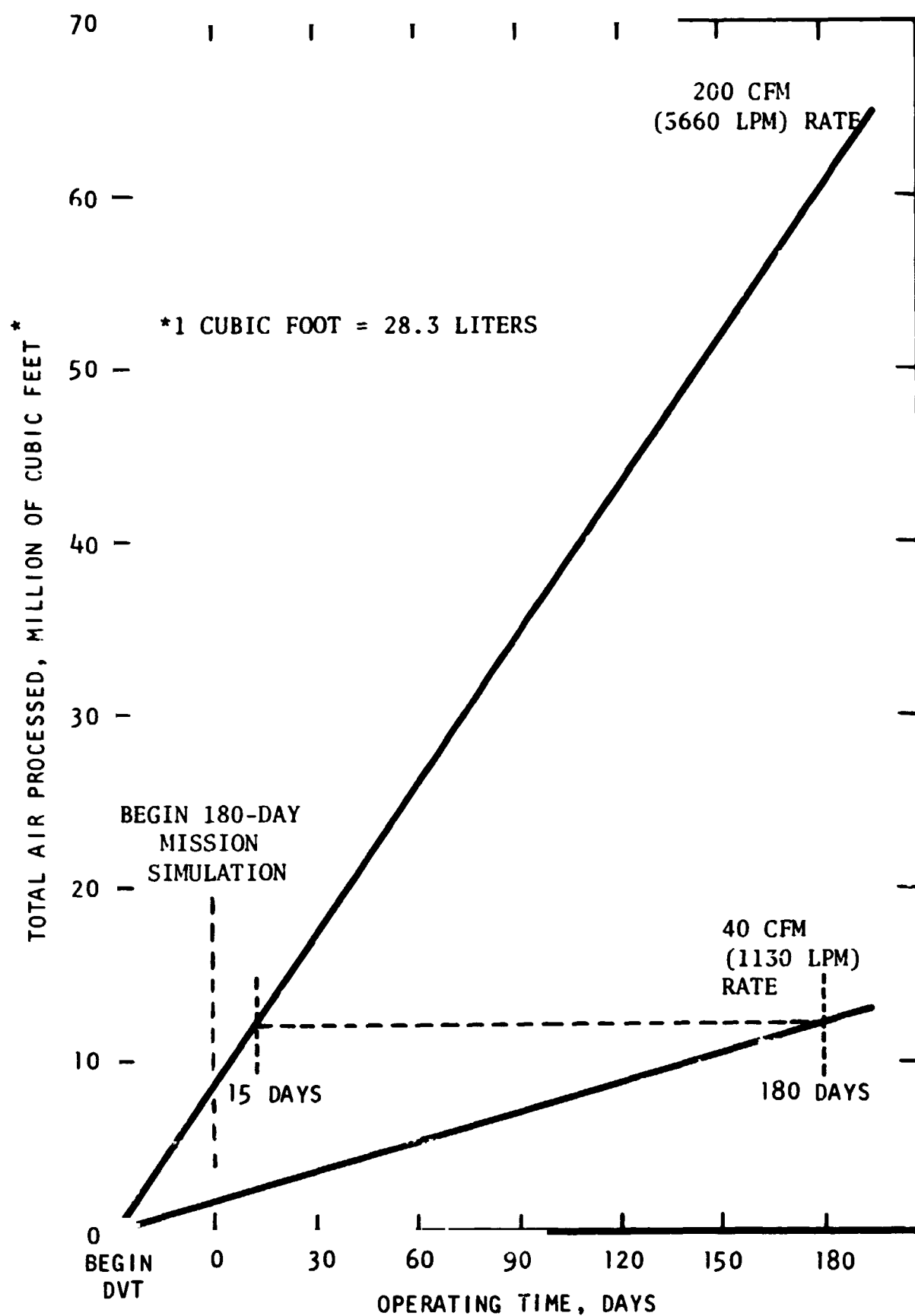


FIGURE 19 PROCESS AIR VOLUME VERSUS OPERATING TIME

TABLE 7 SUMMARY OF PARAMETRIC PERFORMANCE CHARACTERIZATION CURVES

Parameter Varied	Range	Transfer Index	Cell Voltage	T _c F (C)	P _c psia	pCO ₂ L mm Hg	pO ₂ L psia, 2 (Newtons/m ²)	H ₂ Flow, slpm	Air Flow, slpm	Current, amp
H ₂ Flow Rate	1.1S to 4S ^(a)	Independent	Figure 20	77 (25)	AMB ^(b)	3.0	3.1 (2.1x10 ⁴)	VAR ^(c)	187	4.8
Process Air pO ₂	21 to 100% ^(d)	Figure 21	Figure 21	77 (25)	AMB	3.0	VAR	1.1	187	4.8
Process Air pCO ₂	0.23 to 14 mm Hg	Figure 22	Figure 22	77 (25)	AMB	VAR	3.1 (2.1x10 ⁴)	1.1	187	4.8
Temperature	70 to 85F (21 to 29C)	Independent	Figure 23	.VAR	AMB	3.0	3.1 (2.1x10 ⁴)	1.1	187	VAR
Capacity Expressed as Current Density	10 to 35 ASF ^(e) (10.8 to 37.7 ma/cm ²)	Figure 24	- -	77 (25)	AMB	3.0	3.1 (2.1x10 ⁴)	1.1	187	VAR
Absolute Process Air Pressure	5 psia (3.4x10 ⁴ Newtons/m ²) to AMB	Figure 25	Figure 25	77 (25)	VAR	3.0	3.1 (2.1x10 ⁴)	1.1	187	4.8
H ₂ to Process Air Pressure Differential	-2 to +2 psid (±1.4x 10 ⁴ Newtons/m ²)	Figure 26	Figure 26	77 (25)	AMB	3.0	3.1 (2.1x10 ⁴)	1.1	187	4.8

(a) S = Number of times stoichiometric quantity required by current flowing.

(b) AMB = Ambient Pressure, 730 to 750 mm Hg.

(c) VAR = Variable.

(d) Although N₂ is indicated as the diluent, it was the constituents found in air (i.e., small percentages of inert gas, etc.).

(e) ASF = Amps² Per Ft².

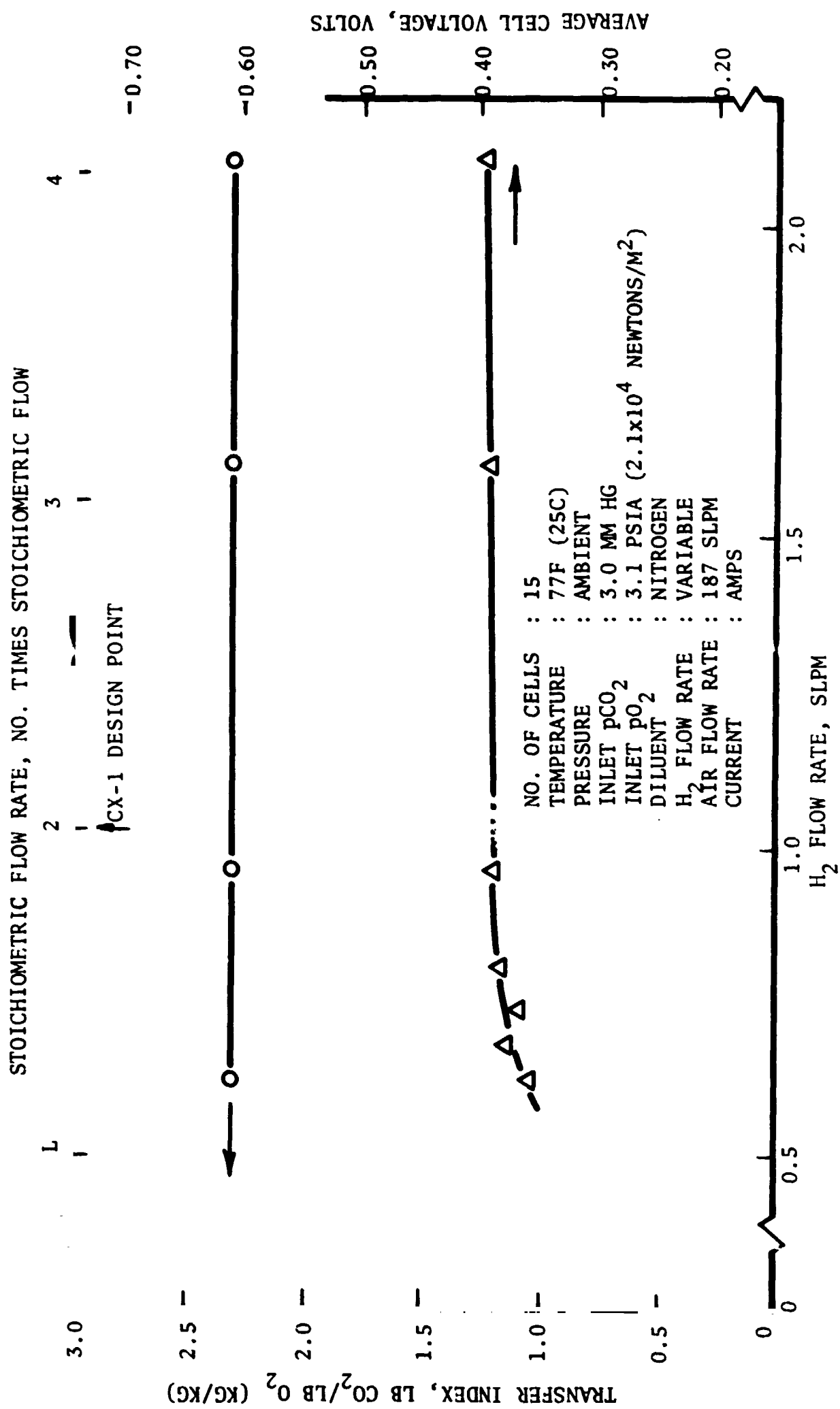


FIGURE 20 EFFECT OF H₂ FLOW RATE ON TI AND VOLTAGE

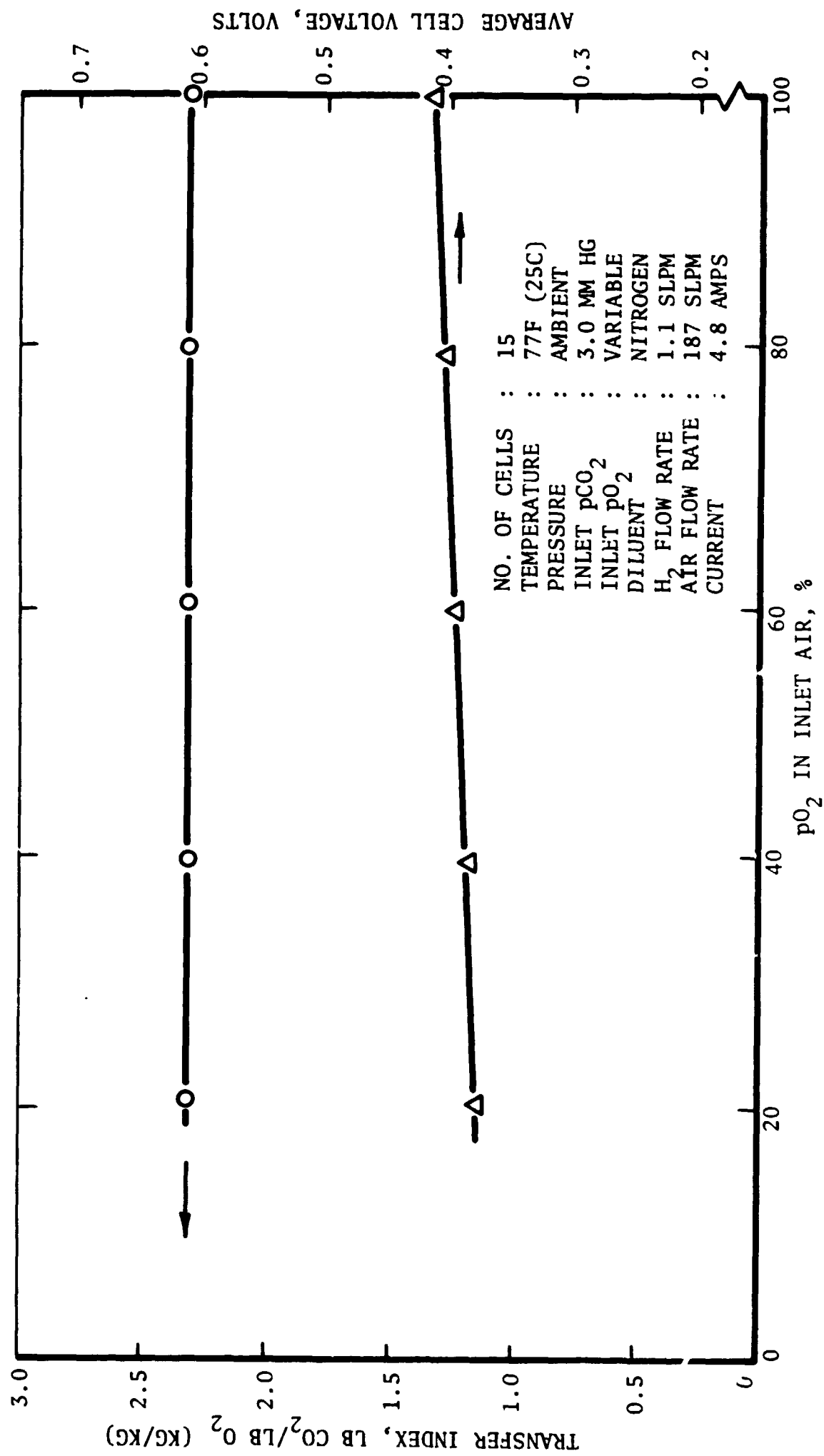


FIGURE 21 EFFECT OF PARTIAL PRESSURE OF O₂ ON TI AND VOLTAGE

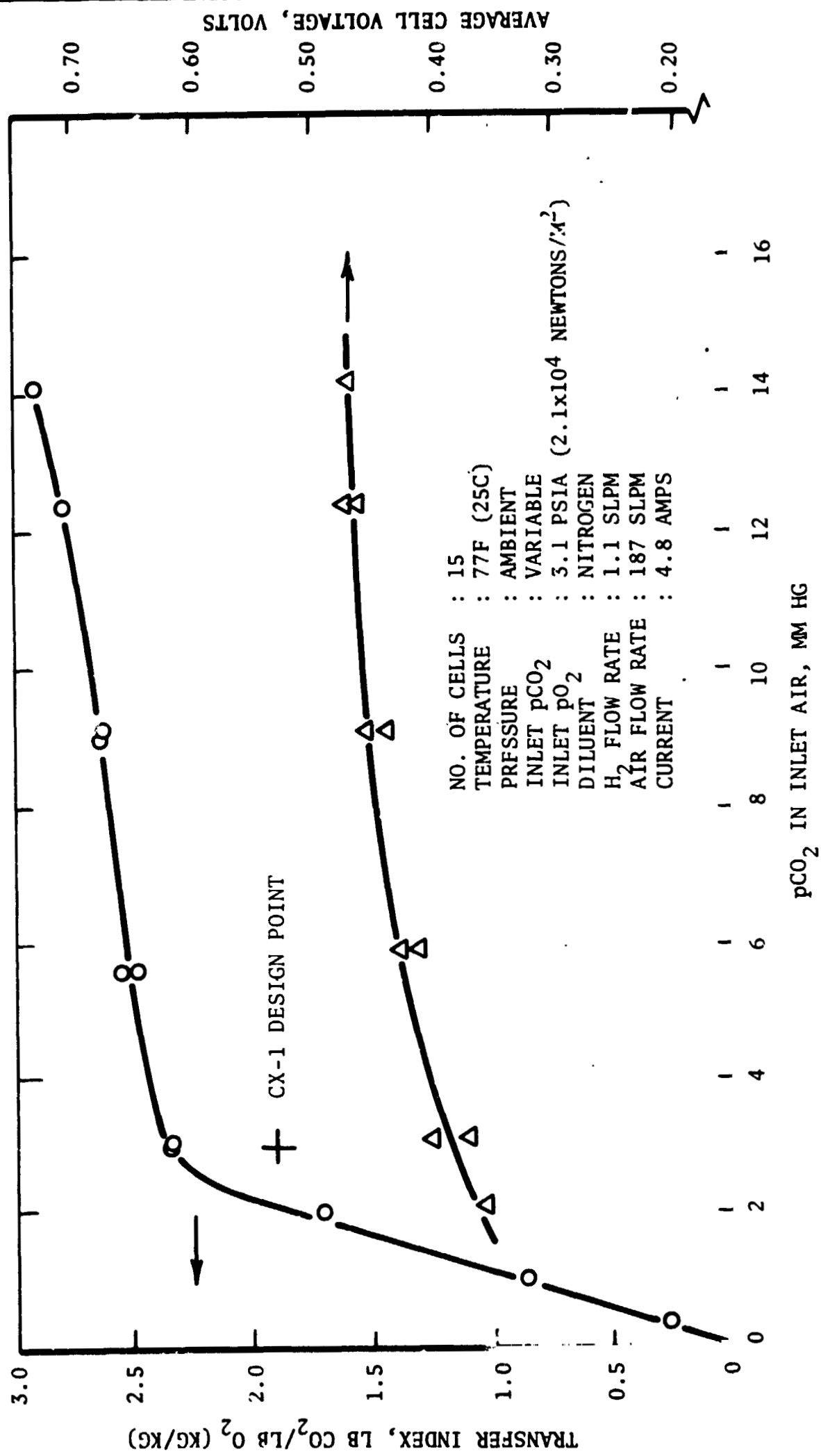


FIGURE 22 EFFECT OF CATHODE INLET PARTIAL PRESSURE OF CO₂ ON TI AND VOLTAGE

Temperature. Changes in operating temperature had negligible effect on the TI over the range 70 to 85F (21 to 29C). It remained constant at 2.30. Decreasing the operating temperature lowered the module's average cell voltage as shown in Figure 23.

Capacity. The system was operated over the CO₂ removal range 1.2 to 3.4 lb/day (0.54 to 1.5 kg/day). Figure 24 shows the current density variation needed to effect this variation in CO₂ removal and the effect on the TI and quantity of CO₂ removed in lb/day.

Pressure. When the ambient pressure was decreased from 15 to 5 psia (1.0×10^5 to 2.1×10^4 Newtons/m²) the TI decreased from 2.3 to 2.0 and the average cell voltage decreased from 0.39 to 0.31 volts as shown in Figure 25.

Pressure Differentials. Variations in this parameter over the range ± 2 psid ($\pm 1.4 \times 10^4$ Newtons/m²) had no effect on the TI or the average cell voltage as indicated in Figure 26. Under normal operation the pressure differential between the cathode and anode compartments varies from 4 to 1 inch of H₂O (1.0×10^3 to 2.4×10^2 Newtons/m²). (The air has a parallel flow through the module; the H₂ has a series flow.)

Endurance Test Program

Prior to initiation of this program several changes were made, including:

1. Modifications to reduce system noise level;
2. Replacement of the H₂O vacuum regulator with a simpler procedure to increase concept reliability by removing a component;
3. Checking the performance trend analysis sensor trip levels; and
4. Increasing the time constant on level detectors to 15 milliseconds to avoid shutdowns due to transient signals.

Three sources of noise existed. The two, high speed cooling fans and the cabin air blower. The latter is common to all CO₂ removal methods and is needed to pass air through a CO₂ removal device. By design, however, the flow rate required to remove a given mass of CO₂ is kept small by removing a larger percentage per pass through the concentrator. This decreases blower noise and power compared to designs considered that removed less CO₂ per pass and required higher air flows. The electronics air cooling fan was replaced with H₂O as a coolant. The module's cooling fan was replaced with a low speed device. The latter was also provided with a capability to cool ambient air in anticipation of the increased temperature during the summer months.

Endurance Test Results. Figure 27 presents the observed variations in TI and cell voltage as a function of time. Reproducibility of TI measurements taken one hour apart is typically within ± 0.1 TI unit. The data generally was taken with the system operating at the conditions cited in Table 8.

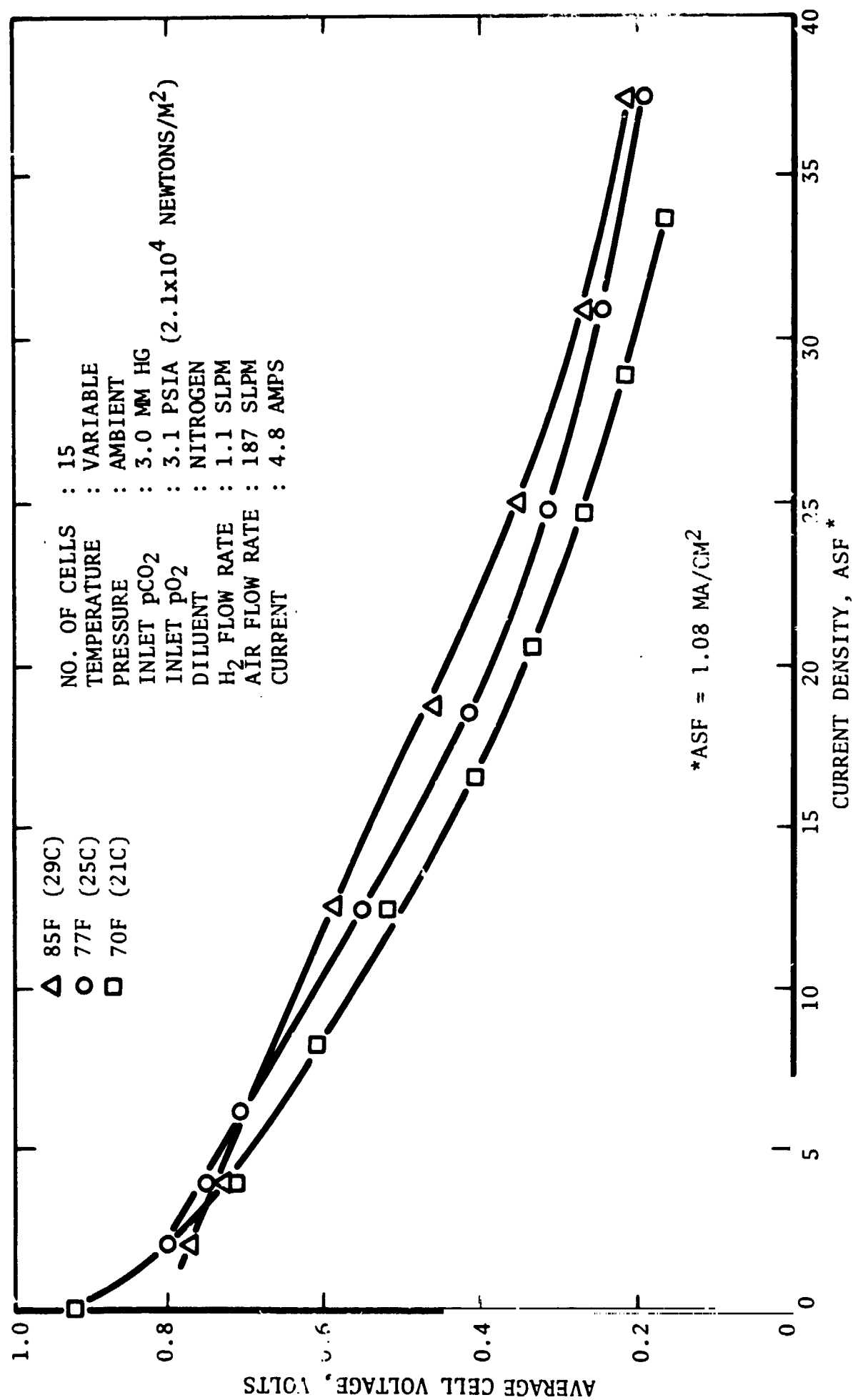


FIGURE 23 EFFECT OF TEMPERATURE ON VOLTAGE

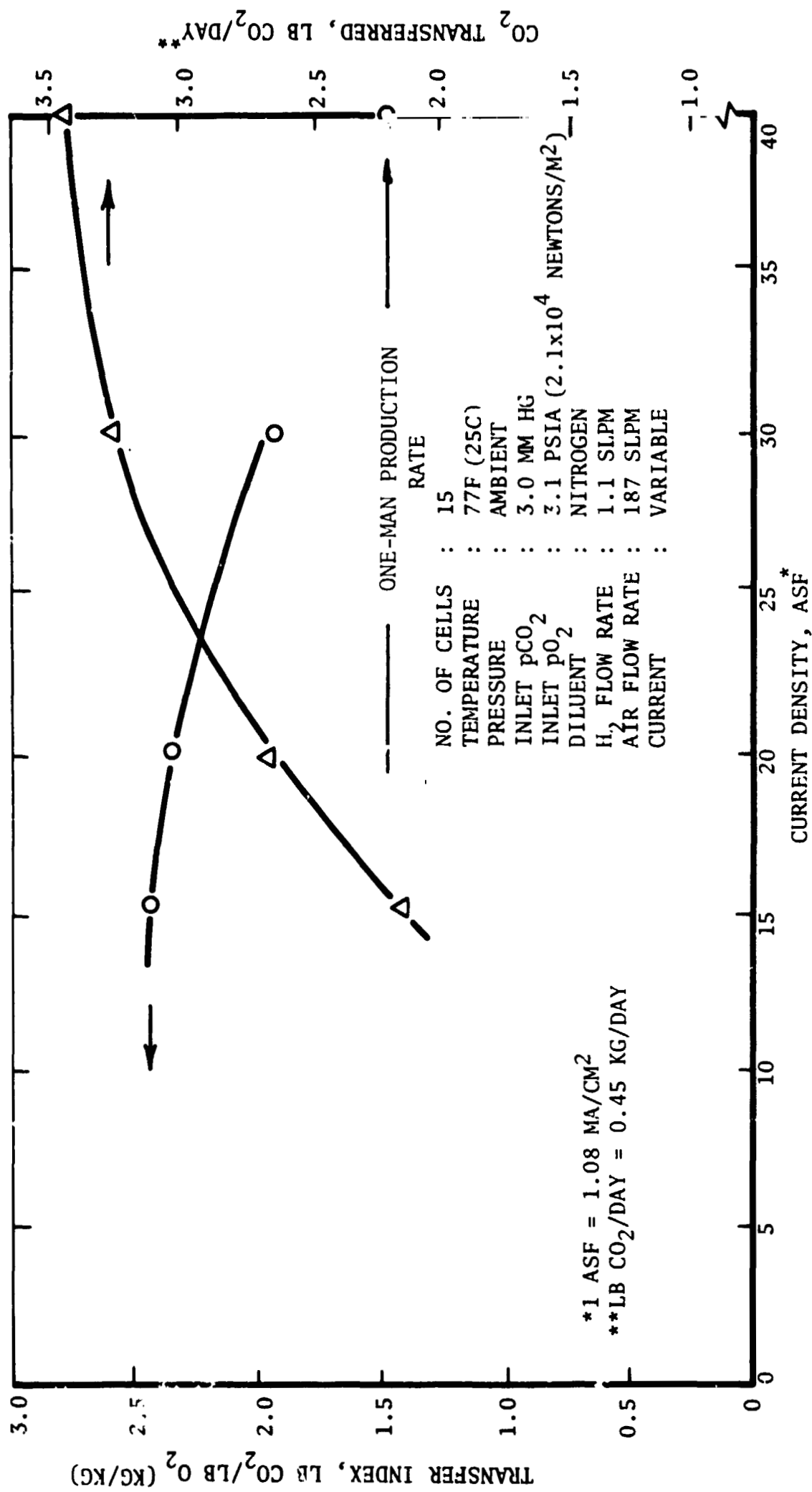


FIGURE 24 EFFECT OF CURRENT DENSITY ON CO₂ REMOVAL CAPACITY

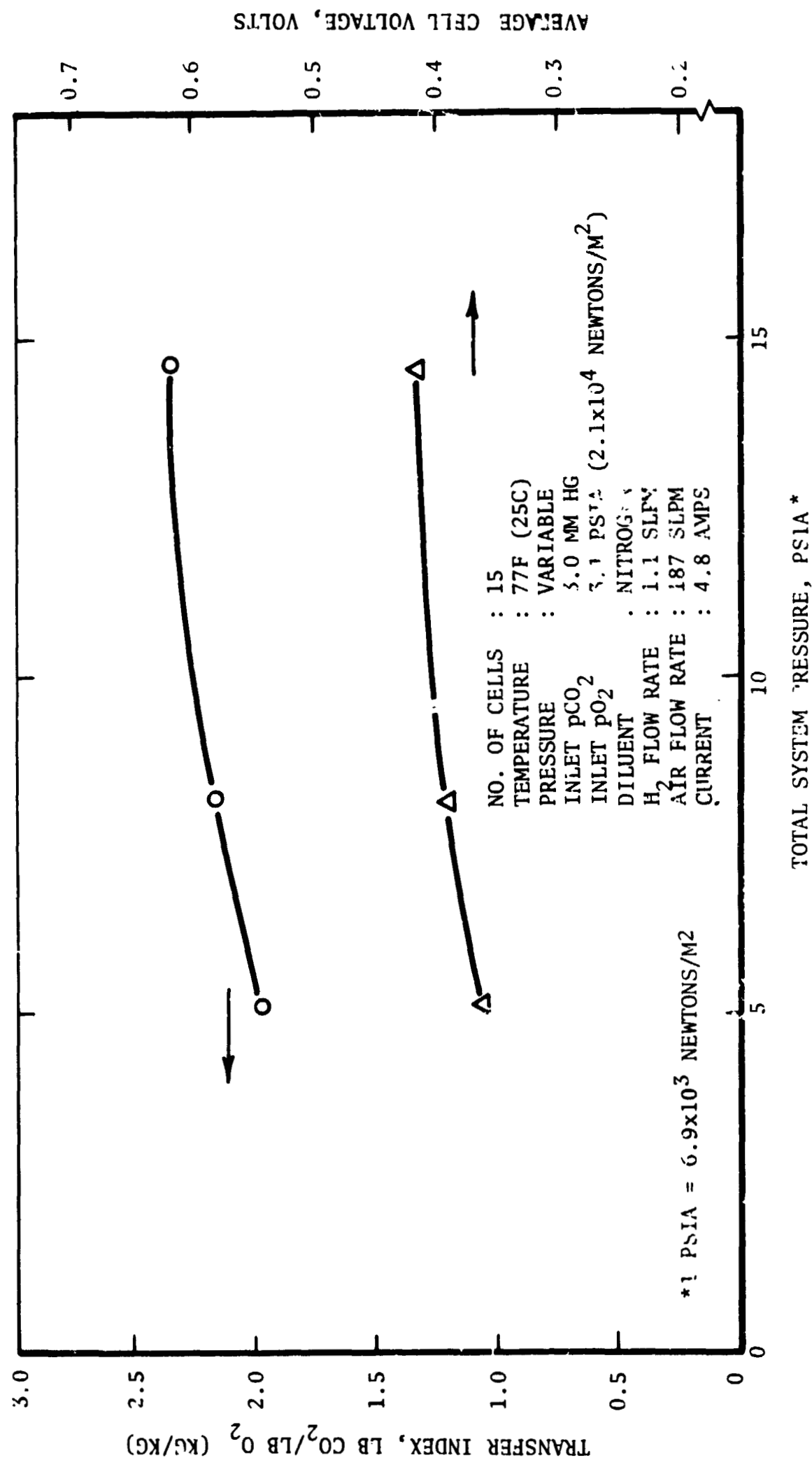


FIGURE 25 EFFECT OF PROCESS AIR PRESSURE ON TI AND VOLTAGE

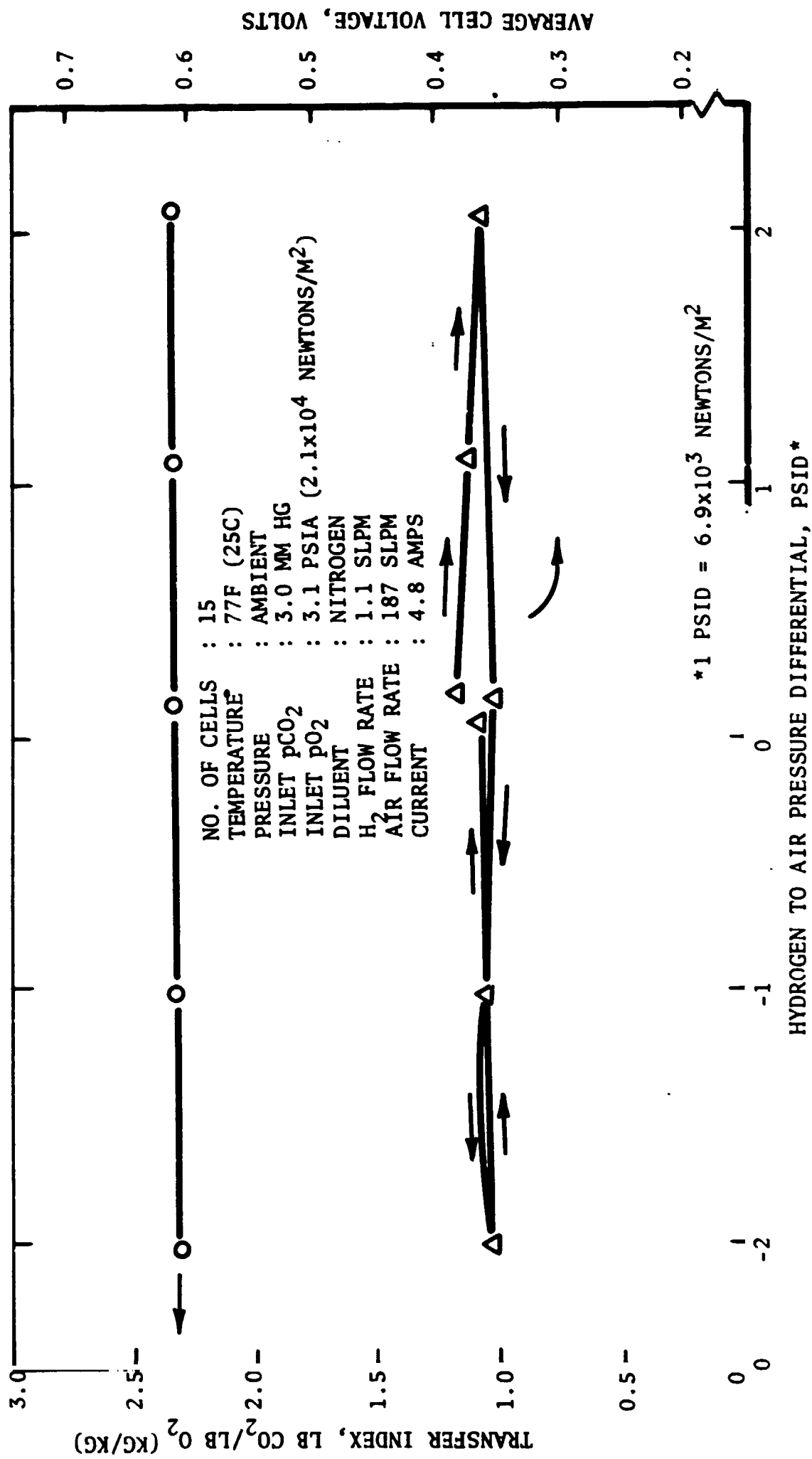
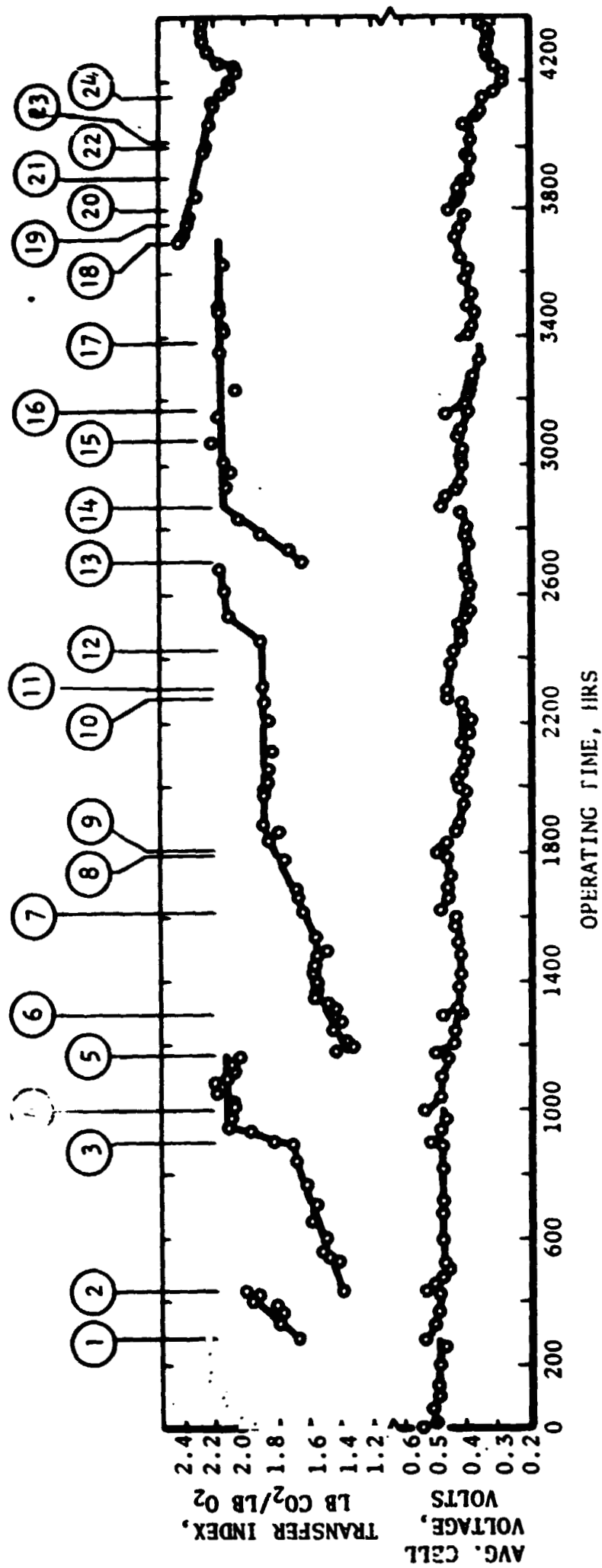


FIGURE 26 EFFECT OF PRESSURE DIFFERENTIALS ON TI AND VOLTAGE



ONE-MAN ENDURANCE TEST RESULTS

FIGURE 27 ONE-MAN SYSTEM ENDURANCE TEST RESULTS - EFFECT OF TIME ON T1 AND VOLTAGE

TABLE 8 NORMAL ENDURANCE TEST OPERATING CONDITIONS

Module	
Temperature	79F (26C)
Current	4.8 amps
Process Air	
pCO ₂	3.0 mm Hg
pO ₂	3.1 psia (2.1x10 ⁴ Newtons/m ²)
Temperature	71F (22C)
Dew Point	69F (21C)
Flow Rate	3.3 scfm (150 slpm)
Pressure	Ambient
H ₂ Supply	
Temperature	70F (21C)
Dew Point	-40F (-40C)
Flow Rate	1.2 slpm
Pressure	Ambient

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The following conclusions can be drawn:

1. The device can perform its CO₂ removal function for over 180 days but failure to maintain proper operating conditions curtails reliability.
2. Variations in CO₂ removal rate occur while operating at constant current as a result of changes in the services at the system's interfaces (e.g., air flow, dew point and temperature).
3. Variations that occur in cell voltage are generally attributable to variations in operating conditions, although a continuous decrease in operating voltage of 10 to 20 microvolts per cell-hour might be superimposed on the performance.
4. The cause for the decrease in TI following successive module recharges with electrolyte (1,2,5, and 13) is not known.

Causes of System Shutdowns

During the 180-day endurance test, 24 shutdowns occurred due to:

- (a) loss of laboratory electrical power (10);
- (b) failure in the Ground Support Accessories (6);
- (c) operator error (4); and
- (d) low cell voltage (4).

Table 9 summarizes the shutdowns according to cause and frequency. Table 10 presents the shutdown chronology.

Loss of Electrical Power. Nine of the ten shutdowns caused by loss of the laboratory's commercial electrical power were a result of storms in the area. The other failure resulted from an interruption in community power because of a cut in the power lines at a construction project. Most interruptions were short but occurred during the night or weekend when the laboratory was unattended.

It is recommended that shutdown circuits used in the future be modified to allow for an automatic restart following return of power.

Failure of Ground Support Supplies. Of the six shutdowns associated with the ground support equipment, two were caused by a failure in the 400 Hz power supply, one resulted from a malfunction in the H₂ supply regulator, and three were due to intermittent electrical interaction between a liquid coolant supply and the CX-1 control circuits. After 3,600 hours into the test a closed loop, liquid cooling unit was added to replace building H₂O as the coolant. It caused shutdowns because of its electrically noisy ON/OFF type controls used to maintain coolant temperature. The first was caused by an interaction that caused a component in the electronic cell voltage scan circuit to fail, contributing to the only shutdown due to a CX-1 part failure. The other two resulted in shutdowns falsely attributed to a low cell voltage. The last of the two occurred while

TABLE 9 SHUTDOWN CAUSE SUMMARY

	<u>Frequency</u>	<u>Shutdown Number</u>
1. Loss of laboratory/ building power	10	6,7,8,9,10,12,15, 16,20,23
2. Failure of ground support equipment	6	2,3,14,18,19,21
3. Operator error	4	1,17,22,24
4. Low cell voltage	4 (a)	4,5,11,13
TOTAL	24	

(a) Two (4 and 5) were directly a result of the prior shutdown.

TABLE 10 SHUTDOWN CHRONOLOGY

<u>Number</u>	<u>Time, Hrs</u>	<u>Cause</u>
1	288*	Error in operating ground support air supply (flooded module)
2	439*	Failure of ground support 400 Hz power supply (dried module)
3	904	Failure in ground support 400 Hz power supply (dried module)
4	1,001	Low cell voltage(a)
5	1,173*	Low cell voltage(a)
6	1,306	Laboratory power failure caused by storm
7	1,618	Laboratory power failure caused by storm
8	1,794	Laboratory power failure caused by storm
9	1,810	Laboratory power failure caused by storm
10	2,278	Laboratory power failure caused by storm
11	2,307	Low cell voltage
12	2,424	Laboratory power failure caused by storm
13	2,708*	Manual shutdown due to observed low cell voltage
14	2,873	Failure of ground support H ₂ regulator
15	3,080	Laboratory power failure caused by storm
16	3,168	Laboratory power failure caused by cut in municipal power line
17	3,380	Operator error in failing to provide ground support with H ₂ supply
18	3,689	Electronic interaction between newly installed ground support liquid coolant supply and CX-1 controls leading to failure of electronic scan circuit component
19	3,748	Coolant supply interaction(b)
20	3,796	Laboratory power failure caused by storm
21	3,889	Coolant supply interaction(b)
22	3,991	Operator shorted sensor terminals while measuring air exhaust dew point
23	4,005	Laboratory power failure caused by storm
24	4,150	Operator error in failure to supply ground support equipment with required H ₂ supply

*Indicates the module was subsequently recharged with electrolyte.

(a) Shutdown number 3 left the module in a dehydrated condition because of the continuous flowing of makeup CO₂. Complete electrical performance was not re-established in spite of efforts made to rehumidify the module. One or two cells always remained very sensitive to tolerance of the process air humidity.

(b) Continuing, but always erratic, electrical noise originating in the ground support cooler installed after 3,600 hours of testing caused erratic interaction with the electronic voltage scan circuit. Periodically a shutdown would occur with the fault isolation panel indicating low voltage as the cause, although all cell voltages were normal. Coolant supply was removed after the second such shutdown occurrence

the Parametric Data Display was observed to be indicating that all cell voltages were normal. The coolant unit was subsequently removed and the problem was eliminated.

It is recommended that in the future, ground support power and H₂ supplies be provided in a redundant fashion and that no changes be made to the Ground Support Accessories during the endurance test unless absolutely necessary.

Operator Error. Of the four shutdowns due to operator error, three were associated with improper operation of the Ground Support Accessories (one in operating the process air supply and two by failing to maintain the H₂ supply over a weekend). The fourth operator error was caused by shunting the H₂ contamination sensor terminals during the time a manual check was being made of air exhaust dew points.

To eliminate these causes of failure it is recommended that redundant H₂ supplies be used, that more attention be paid to the use of Ground Support Accessories that are, in turn, designed for simpler operation and that points where shorting is possible be covered.

Low Cell Voltage. Four shutdowns were caused by a low cell voltage. Each could be attributed to a flooded or dry operating condition. Three of these (numbers 4, 5 and 11) were a result of conditions generated by previous shutdowns. One (number 13) was manually initiated when a moisture imbalance, created while varying the interface specifications, led to low voltages on two cells.

Module Recharge. During the 180-day test the electrochemical module was recharged with electrolyte four times: after 288 hours, 439 hours, 1,173 hours, and 2,708 hours.

The first recharge was necessary after an error in operating the air process controls within the Ground Support Accessories. The decision was made to recharge because it occurred within the first 6% of the endurance test and to endurance test a module known to have an improper electrolyte level did not seem appropriate.

The second recharge occurred following a failure in the ground support 400 Hz cycle power supply. At that particular time (439 hours into the test) the system shut down with the failure in the 400 Hz cycle power supply. The CO₂ being used to raise the air's pCO₂ level to 3 mm Hg, however, did not shut off with the rest of the system. During the course of the next 18 hours, therefore, dry CO₂ continued to flow through the electrochemical module. This desiccated the module electrolyte dictating it be recharged to establish a known level of moisture.

The third recharge was made after an identical situation to that leading to the second recharge. The CO₂ solenoid was subsequently electrically wired into the CX-1 shutdown circuit to prevent further occurrences of this type.

The fourth and final recharge was made after approximately 2,700 hours on test. During this period two of the module's cells had voltage levels that decreased excessively. The cause was attributed to a moisture imbalance brought about by inadequate control of operating conditions. The module was recharged to re-establish the electrolyte concentration.

PARALLEL TEST ACTIVITIES

Various test activities were carried out in parallel with the CX-1 design and testing. The objective was to advance the technology. The testing accomplished were:

1. Evaluate changes in baseline operating conditions.
2. Design and demonstrate insitu maintenance.
3. Evaluate alternate electrode forms.
4. Evaluate alternate electrolytes.
5. Complete a 30-day test on an Oxygen Reclamation System formed by integrating an electrochemical CO₂ concentrating subsystem, a Sabatier reactor, and a static feed water electrolysis subsystem.
6. Design ECO₂CS failure prediction techniques.

Changes in Baseline Operating Conditions

Prior to initiation of the program, CO₂ concentrator operation was carried out at temperatures of 100 to 130F (38 to 54C) and pCO₂ levels of 5 to 15 mm Hg. Operation, therefore, was extended to include (a) temperatures less than 85F (29C), (b) pCO₂ levels less than 3 mm Hg, and (c) air supply pressures of less than ambient.

The results with a single cell and a 14-cell module were positive (similar to those already cited for the CX-1, Figures 14, 15, and 17). They enabled the CX-1 normal baseline design to be changed to a lower operating temperature and a lower level of inlet pCO₂, with a demonstrated lower ambient pressure capability.

Design and Demonstrate Insitu Maintenance

Prior CO₂ concentrator programs employed a module maintenance concept. If one cell failed the module was replaced (or recharged with electrolyte). Cell failure is defined as the inability to sustain module operating current as indicated by a negative cell voltage. A method was defined and demonstrated to allow module maintenance at the cell level. It consisted of electrically isolating the cell while it remained physically within the module. This was possible by designing the module with each cell electrically insulated except for the series electrical connections made externally. To remove a cell only required removing one electrical lead and wiring it to the appropriate terminal of the next cell in the series. No fluid line connections were changed. The method was successfully demonstrated on cells 1, 3, 8, 9, 14 and 15 of the CX-1 module. The result of an insitu cell maintenance, for example, could be the conversion of a 15-cell module into a 14-cell module operating at higher current density or one operating at reduced capacity if the current is maintained constant.

Alternate Electrode Forms

Three variations in electrode structures were tested.

Use of Palladium. The CX-1 baseline design employed electrodes using platinum black as the catalyst. For comparison purposes parallel tests were made with baseline electrodes replaced by ones employing palladium black; first at the anode, then at the cathode and each time with the opposite electrode being the baseline cathode or anode, respectively. Figure 28 summarizes the results of the comparisons made at a constant set of operating conditions. The results indicate that the baseline configuration had better electrical efficiencies than cells employing a palladium electrode with substitution of the palladium at the anode being more efficient than its substitution at the cathode. Duplicate palladium anodes were run to indicate reproducibility. No change in TI was observed with these changes in electrode structure.

Gold Plated, Nickel Screen Anode. The baseline design employs a platinum screen support for the anode. Substituting a gold-plated, nickel screen had no effect on TI or cell voltage and allows for a lower fabrication cost.

Electrode Thickness. An evaluation was made of electrodes that would be 1/2 as thick as the 10 mil baseline electrode. Figure 29 summarizes the results indicating that the baseline design performs slightly better with a thicker electrode.

Alternate Electrolytes. Rubidium carbonate (Rb_2CO_3) and cerium carbonate (Ce_2CO_3) were considered as alternatives to the Cs_2CO_3 electrolyte. Cerium carbonate had too low a solubility ($<1\%$) to be useful.

A cell was successfully operated with 40% Rb_2CO_3 as the electrolyte. Figure 30 shows the electrical performance observed in comparison with CX-1 baseline performance at comparable operating conditions. The increased ohmic portions of the observed terminal voltage with Rb_2CO_3 as the electrolyte only partially accounts for the observed lower electrical efficiency of the Rb_2CO_3 configuration. The remainder is most likely attributable to activation polarization influenced by the rubidium ion.

Oxygen Reclamation System

A 1-man, Oxygen Reclamation System (ORS) was designed. It consisted of an electrochemical CO_2 concentrator subsystem, a static feed H_2O electrolysis subsystem and a Sabatier reaction subsystem. Figure 31 is a block diagram and material balance for the ORS. It was used to carry out four experiments:

1. Evaluate operation of a Sabatier Reactor with the normal CO_2 concentrator anode exhaust, including the nominal H_2O vapor present.
2. Evaluate operation of the concentrator under design conditions optimized for the Sabatier Reactor (higher H_2 levels).
3. Evaluate the effect of H_2O recovered from the Sabatier Reactor on static feed electrolysis performance.

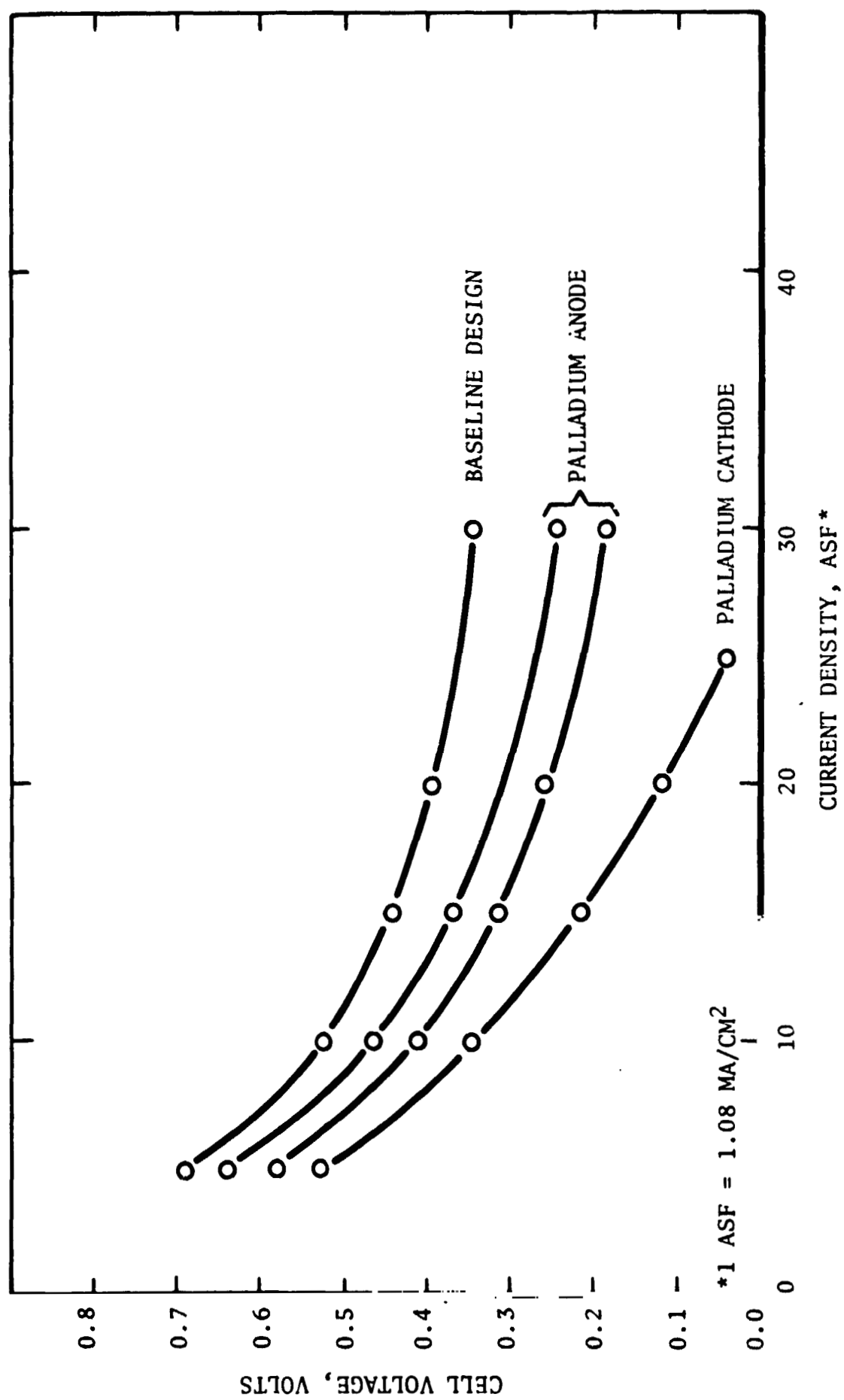


FIGURE 28 EFFECT OF VARIATION IN ELECTROCATALYST

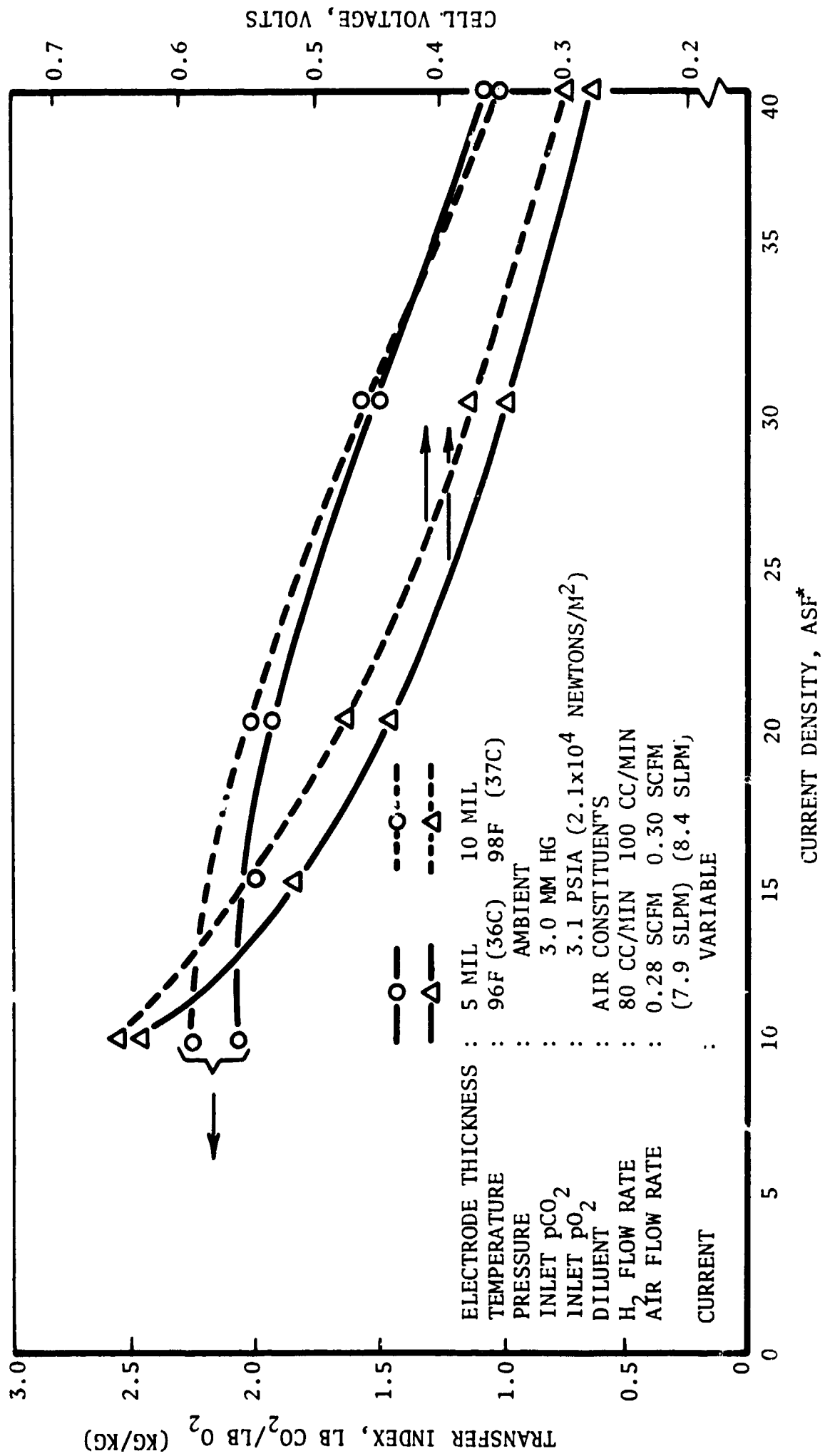


FIGURE 29 EFFECT OF ELECTRODE THICKNESS

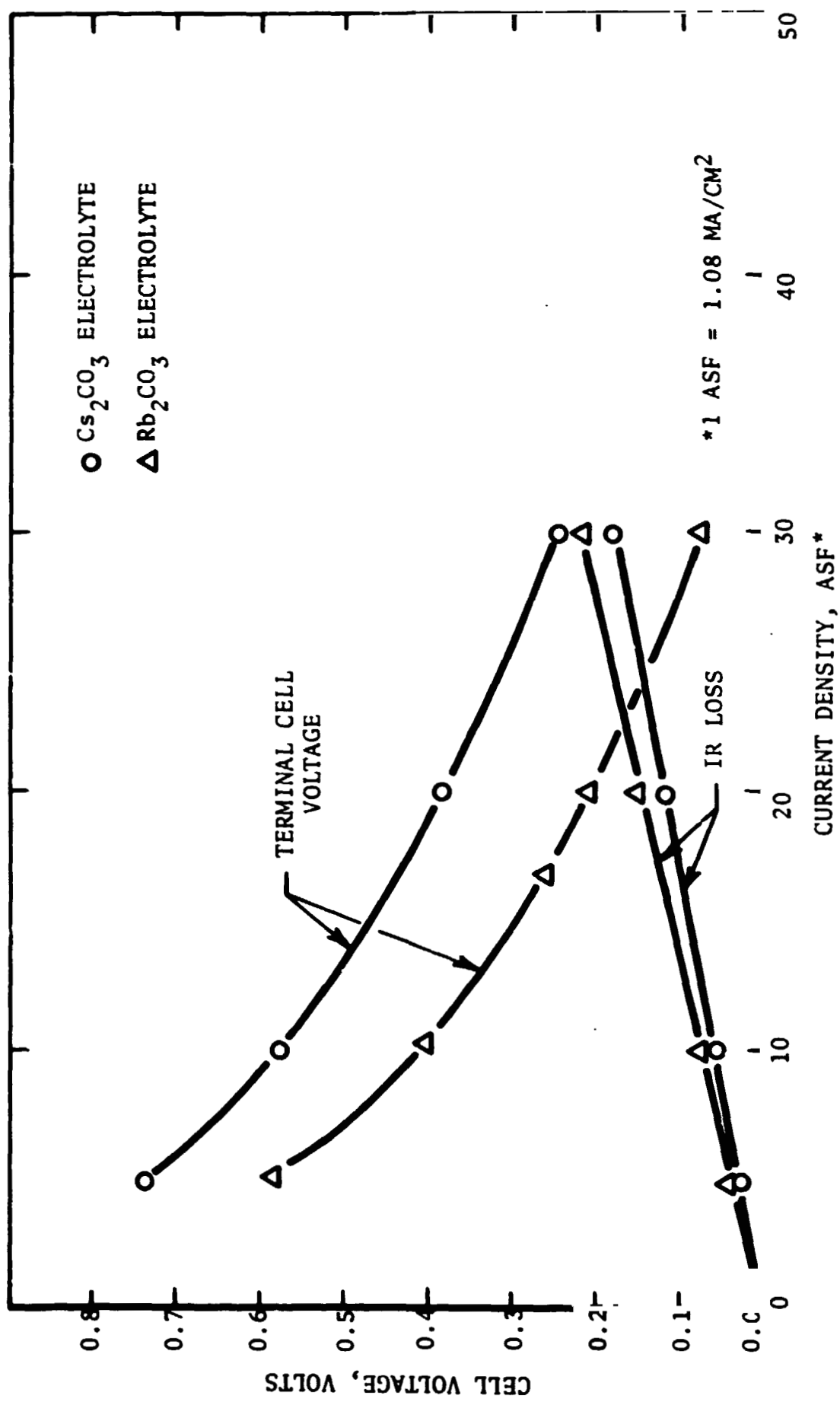


FIGURE 30 EFFECT OF ELECTROLYTE: Cs_2CO_3 AND Rb_2CO_3

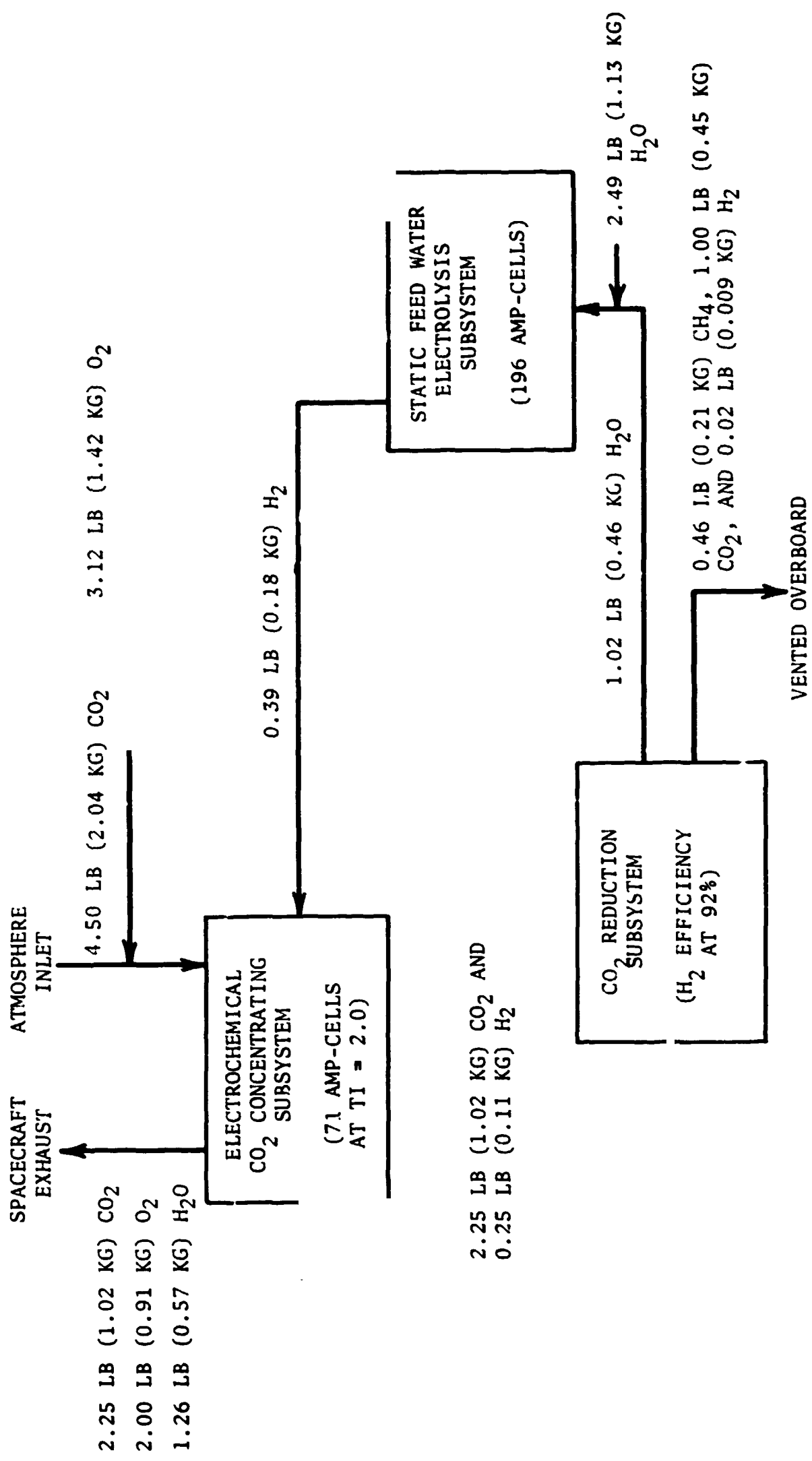


FIGURE 31 OXYGEN RECOVERY SYSTEM BLOCK DIAGRAM AND MATERIALS BALANCE

4. Evaluate integrated ORS operation over a 30-day period.

The Static Feed Water Electrolysis Subsystem used was that contained as part of the Laboratory Breadboard developed under NAS2-4444.⁽³⁾ Figure 32 is a photograph of the test setup. The Sabatier Reactor used was provided by the Langley Research Center, described by Ames⁽⁷⁾, and delivered to NASA under Contract NAS1-8254.

Sabatier Operation with Normal CX-1 Anode Exhaust. The Sabatier reactor was operated with a normal CX-1 anode exhaust; a CO_2/H_2 ratio of 15:1 by weight and 1:1.45 by volume or moles (and less than 20 mm Hg of H_2O vapor pressure). This is a CO_2 -rich mixture. The H_2 conversion efficiency measured was 100%. The test data indicated that the small H_2O vapor content in the exhaust had negligible effect on reactor efficiency in keeping with other results.⁽⁸⁾ The reactor performance was equivalent to that reported by others at similar operating conditions.⁽⁷⁾

CO_2 Concentrator Operated for Normal Sabatier Reactor Operation. The CO_2 concentrator was also operated with a H_2 flow rate 1.0 times the stoichiometrically required rate for the Sabatier Reactor. This corresponds to a CO_2/H_2 exhaust ratio of 5.45:1 by weight and 1:4.0 by volume. The H_2 and CO_2 conversion efficiencies were 89%.

Projections for regenerative life support systems indicate that only a portion (e.g., 60% by weight) of the CO_2 concentrated from the spacecraft atmosphere would be converted to methane and H_2O and the remainder vented overboard as part of the Propulsion Subsystem. Normal electrochemical concentrator operation, however, premixes all the CO_2 with H_2 . This situation is comparable to passing all the excess CO_2 through the reactor prior to venting. Such a procedure shifts the Sabatier reaction equilibrium toward the desired complete utilization of H_2 . In addition, the excess CO_2 would aid in keeping reaction temperature down and would decrease the reactor's product gas H_2O vapor pressure. The latter slightly raises the amount of product gas cooling required for H_2O recovery.

Sabatier Reactor Operated for Various CO_2/H_2 Mixture Ratios. Figure 33 shows CO_2 and H_2 conversion efficiencies experimentally obtained with the Sabatier reactor of the ORS as a function of gas mixture ratios. To the right of the one-times stoichiometric line (Sx1) the mixture is CO_2 -rich; to the left of this line the mixture is H_2 -rich. Complete H_2 conversion results in the most efficient life support system operation employing partial O_2 recovery. The data indicates that operation with the CO_2 -rich mixture obtained from the concentrator is desirable. Values of 9:1 for CO_2/H_2 mixture ratios are presently projected for typical regenerative life support systems operation. Experimental data obtained with the ORS operated at this ratio showed a 98.5% H_2 conversion efficiency.

Water Electrolysis Operation with Sabatier Reactor Generated Water. Sabatier reactor generated H_2O was collected and used in the H_2O electrolysis subsystem. No change in WES performance was observed. The recovered H_2O required passage through an ion exchange column to remove its residual ionic contaminants.

Thirty-Day Test. Following characterization of the Sabatier reaction using the baseline CO_2 concentrator H_2/CO_2 exhaust mixture and vice versa, a 30-day test was successfully carried out. All three subsystems demonstrated the same performance at the end of 30 days of integrated testing as they did at the beginning. Performance characteristics included Sabatier reactor temperature and conversion efficiency; CO_2 concentrator Transfer Index and voltage; and H_2O electrolysis

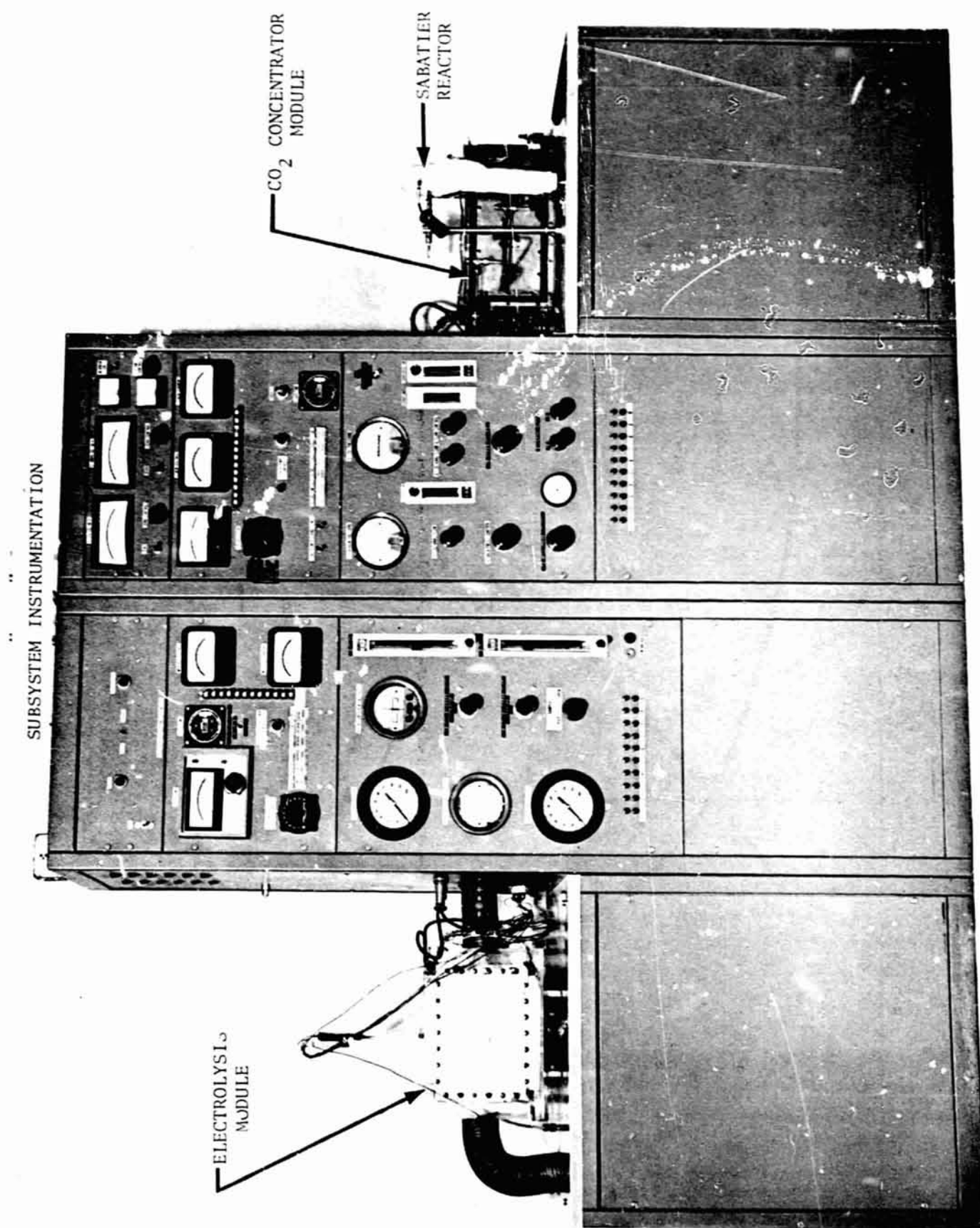


FIGURE 32 OXYGEN RECOVERY SYSTEM BREADBOARD

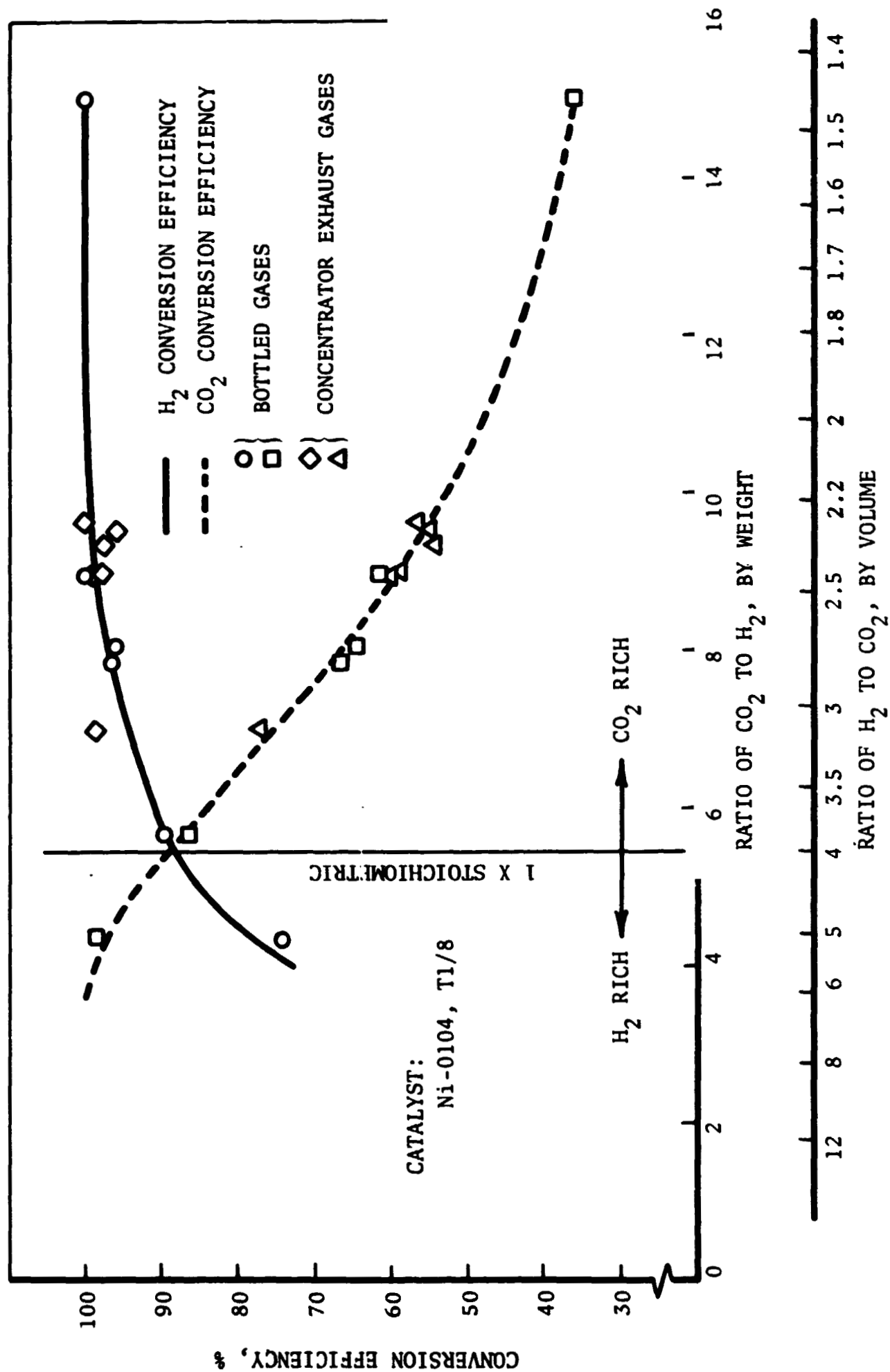


FIGURE 33 CONVERSION EFFICIENCIES OF CO₂ AND H₂

operating voltage. It can be concluded that the H_2 and CO_2 that fed the Sabatier reactor did not contain trace ingredients that affect Sabatier catalyst (Harshaw Ni-0104, T1/8); the CO_2 concentrator performance is not changed using electrolytically generated H_2 and O_2 ; and the H_2O electrolysis system can operate successfully with H_2O recovered from a Sabatier reactor.

Failure Prediction

If the ECO_2CS shuts down no CO_2 is available to react with the H_2 generated by the H_2O electrolysis subsystem. The electrochemical CO_2 removal process is continuous and does not require CO_2 accumulation. In addition, shutting down the ECO_2CS means no reactants are available to maintain the CO_2 reduction reactor at temperature. Thus, although the buildup in cabin pCO_2 with a shutdown in the ECO_2CS is slow, such a shutdown imparts other subsystems with which it interfaces.

The performance trend analysis feature was incorporated, therefore, to minimize the chance of shutdown by alerting the operator to an out-of-tolerance in operating status. This feature, however, was not module oriented and, therefore, did not focus on the heart of the CO_2 removal process, the electrochemical module.

Effort was focused on designing a method to predict when a failure in the module might be occurring. Three failure prediction tests and circuits to automatically carry them out were designed:

1. A test to monitor the module's voltage change since startup and to be carried out continuously. It indicates a resultant change in a module's three types of polarization - actuation or catalyst oriented, concentration or mass transfer oriented, and ohmic or electrolyte moisture level oriented.
2. A test to monitor the electrical capacity of each individual cell once every 24 hours for a 15 minute test period. It indicates both ohmic and concentration portions of cell polarization.
3. A test to monitor the module's internal resistance once every 30 minutes with a sampling time of less than 1 second. It evaluates only the ohmic portion of the module's polarization.

When used together, these three methods of predicting failure (a) cover long-term effects (Test No. 1); (b) cover medium range (24 hour) changes responding to out-of-tolerance in operating conditions (Test No. 2); and (c) cover short range (30 minute) changes in response to out-of-tolerance operating conditions (Test No. 3). The tests are all module oriented and, with development, could become the major method for monitoring whether the ECO_2CS will be able to maintain its CO_2 removal function in the future based on present time module characteristics.

CONCLUSIONS

The following conclusions were reached as a result of this development activity:

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1. The Electrochemical CO₂ Concentrating System is able to continuously perform its CO₂ removal function for periods well beyond 260 days but successful, continuous operation requires that interface supplies (e.g., electrical power, H₂, process air) be supplied within specifications for the design.
2. A major contribution to successful operation was the identification of out-of-tolerance operating conditions before shutdown to enable identification of the fault before performance degradation occurred, i.e., performance trend analysis.
3. The materials of construction used in the electrochemical module showed no signs of deterioration after operating for over 260 days.
4. Standby power to eliminate shutdowns during momentary power interruptions would increase system availability.
5. As the size of the electrochemical module increases, the ability to tolerate out-of-specification conditions at the interface becomes more limited due to nonuniformity between cell locations and materials of construction.
6. Electrical insitu cell maintenance can be an effective means of reducing system spares and maintaining system performance.
7. Utilization of internal humidification allowed process air dew point variations of +3 to -5F (+2 to -3C) compared to ±2F (±1C) without it.
8. The CO₂ concentrator is inherently quiet in operation but absolute quiet will not be possible because of the need for a process air supply blower and intermittent operation of a cooling air supply fan. The latter, however, could be avoided by switching to a liquid cooling design. Blower and fan noise is decreased by avoiding use of high speed fans and keeping the process air flow rate to a minimum.
9. Over the range tested the efficiency of the CO₂ removal process was affected by current density and pCO₂ of the process air but was unaffected by the H₂ flow rate or H₂-to-air pressure differential, operating temperature, process air pO₂ or total pressure, and operating time.
10. Over the ranges tested the electrical efficiency of the process was affected by current density, pCO₂, pO₂ and total pressure of the process air, H₂ flow rate, operating temperature and time but was unaffected by the H₂-to-air pressure differential.
11. Replacing the CO₂ concentrator's cesium carbonate electrolyte with rubidium carbonate had negligible effect on the CO₂ removal efficiency but lowered the electrical efficiency considerably.
12. The low solubility of cerium carbonate makes its use as an electrolyte in a CO₂ concentrator impractical.

13. Employing screen electrodes having platinum as the electrocatalyst results in better electrical efficiencies than employing electrodes having palladium. The CO₂ removal efficiency was electrocatalyst independent.
14. Employing a 10 mil matrix instead of a 30 mil matrix to hold the electrolyte increased the electrical performance of the cell slightly but did not affect the CO₂ removal efficiency.
15. Operating a Sabatier reactor with the anode gas of an electrochemical concentrator (H₂, CO₂ and H₂O vapor) did not affect operating efficiency of the Sabatier reaction. Hydrogen conversion efficiencies were in excess of 98% above CO₂-to-H₂ weight ratios of 9.0.
16. Operating an electrochemical CO₂ concentrator with the gaseous products from a H₂O electrolysis system had no effect on the operation of the concentrator.

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