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ONE-MAN ELECTROCHEMICAL AIR REVITALIZATION SYSTEM EVALUATION

FINAL REPORT

by

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for

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National Aeronautics and Space Administration



FOREWORD

This report was prepared by Life Systems, Inc., for the National Aeronautics and Space Administration Lyndon B. Johnson Space Center in accordance with the requirements of Contract NAS9-14658, "Air Revitalization and Hydrogen Sensor Development." The period of performance for the program was September 1, 1975 to August 31, 1976. The objective of the program was to test a One-Man, Electrochemical Air Revitalization System and to develop an in situ calibration concept for combustible gas detectors.

For simplicity, the work performed has been reported in two separate final reports. The development of the in situ calibration concept for combustible gas detectors is reported in LSI ER-284-13; while this report describes the results of the One-Man, Electrochemical Air Revitalization System test program.

All measurements and calculations contained in this report are expressed in SI (metric) units; conventional units are given in parentheses.

The overall Program Manager was F. H. Schubert, with the in situ calibration development activities directed by J. W. Shumar. Technical support for the One-Man, Electrochemical Air Revitalization System test program was provided by R. D. Marshall, T. M. Hallick, R. R. Woods and Dr. R. A. Wynveen.

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ACRONYMS

ARS	Air Revitalization System
BEARS	Breadboard Electrochemical Air Revitalization System
EARS	Electrochemical Air Revitalization System
EDC	Electrochemical Depolarized Carbon Dioxide Concentrator
EDCM	Electrochemical Depolarized Carbon Dioxide Concentrator Module
RH	Relative Humidity
TI	Transfer Index
TRHS	Triple Redundant Hydrogen Sensor
TSA	Test Support Accessories
WVE	Water Vapor Electrolysis
WVEM	Water Vapor Electrolysis Module

SUMMARY

A program to evaluate the performance of a one-man capacity, self-contained Electrochemical Air Revitalization System was successfully completed at Life Systems, Inc. The one-man system evaluated was designed, fabricated and assembled under a Life Systems-funded research and development program. The primary objective of the National Aeronautics and Space Administration-sponsored program was to demonstrate the technology readiness of the Electrochemical Air Revitalization System concept by characterizing the performance of this one-man system over wide ranges in cabin atmospheric conditions.

The Electrochemical Air Revitalization System consists of a Water Vapor Electrolysis Module to generate oxygen from water vapor in the cabin air, an Electrochemical Depolarized Carbon Dioxide Concentrator Module to remove carbon dioxide from the cabin air, a control/monitor instrumentation package that uses the Electrochemical Depolarized Concentrator Module power generated to partially offset the Water Vapor Electrolysis Module power requirements, and various structural and fluid routing components. The system was designed to meet the one-man metabolic oxygen generation and carbon dioxide removal requirements, thereby controlling cabin partial pressure of oxygen at 22 kN/m² (3.2 psia) and cabin pressure of carbon dioxide at 400 N/m² (3mm Hg) over a wide range in cabin air relative humidity conditions.

Prior to the start of program testing, the one-man system was refurbished to incorporate (1) the power-sharing current control concept, (2) a Life Systems-developed high-moisture tolerance carbonate electrolyte (LSI-D) and (3) customized, high-bubble pressure, low electrical resistance cell matrices for both the Electrochemical Depolarized Concentrator and Water Vapor Electrolysis Modules. High performance water vapor electrolysis anodes were available at time of system refurbishment but were not incorporated due to funding limitations.

System evaluation was accomplished through an extensive Parametric/Endurance Test program, exceeding the 75 days of operation goal by ten days. Nominal baseline operating conditions for the Parametric/Endurance Test were a carbon dioxide partial pressure of 400 N/m² (3 mm Hg) and a relative humidity range of 50 to 60%. A total of 85 days of system operation were accumulated. The average carbon dioxide removal efficiency at baseline conditions remained constant throughout the test at 82% (Transfer Index = 2.25 mass carbon dioxide/mass oxygen). The average electrochemical depolarized concentrator cell voltage was 0.49V. No long-term voltage decay was observed. The average water vapor electrolysis cell voltage increased at a rate of 49 μ V/hour from 1.87V to 1.97V. The relatively high water vapor electrolysis cell voltage results from the use of 1973 technology level anodes. A reduction in cell voltage and Water Vapor Electrolysis Module power requirements is possible based on Life Systems' 1975 developed water vapor electrolysis anodes. The data obtained showed that the Electrochemical Air Revitalization System met or exceeded the nominal one-man carbon dioxide removal and oxygen generation rates of 1.0 kg/d (2.2 lb/day) and 0.84 kg/d (1.84 lb/day), respectively, over a relative humidity range of 35 to 85% for cabin dry bulb temperatures between 291 and 297K (65 and 75F).

Parametric testing characterized the Electrochemical Air Revitalization System performance as a function of carbon dioxide partial pressure for a range of ambient to 933 N/m² (7 mm Hg), Electrochemical Depolarized Concentrator current densities from 16.1 to 32.3 mA/cm² (15 to 30 ASF), water vapor electrolysis current densities up to 75.3 mA/cm² (70 ASF) and relative humidities from 35 to 93%. At the nominal operating conditions, cabin carbon dioxide partial pressure could be maintained at 213 N/m² (1.6 mm Hg) at the nominal carbon dioxide generation rate and rise to 520 N/m² (3.9 mm Hg) at the maximum carbon dioxide generation rate of 1.22 kg/d (2.68 lb/day). The water vapor electrolysis met the oxygen generation requirements operating at the design current density of 53 mA/cm² (50 ASF) over the entire range of operating conditions.

The power-sharing feature developed by Life Systems and demonstrated at the 1/5 man level (Contract NAS9-14301) was incorporated into the one-man system prior to the start of the test program. The power-sharing concept successfully controlled water vapor electrolysis and electrochemical depolarized concentrator cell currents and fully utilized electrochemical depolarized concentrator power generated to reduce the net system power requirements by 40.5W or 11.2%. This power reduction corresponds to an equivalent weight savings of 19 kg (42 lb) assuming a power penalty of 0.27 kg/W (0.59 lb/W), a power conversion efficiency of 85% and a heat rejection penalty of 0.20 kg/W (0.44 lb/W). The electrochemical depolarized concentrator power would otherwise be rejected as heat to the cabin air.

Electrochemical Air Revitalization System technology readiness has been demonstrated at a size that provides a sound basis for multi-man, preprototype and prototype system designs. Continued development is recommended applying the operational experience gained on the Life Systems one-man capacity Electrochemical Air Revitalization System to the development of a multi-man system for incorporation into a Regenerative Life Support Evaluation experiment.

PROGRAM ACCOMPLISHMENTS

- 85-Days of system operation - Test goal was 75 days
- Extensive relative humidity testing completed over 35 to 90% range - A first at the one-man system level
- No electrochemical depolarized concentrator performance degradation after 85 days of extensive parametric testing - LSI-D electrolyte proven applicable
- Electrochemical depolarized concentrator voltage increased to 0.5V using LSI-D electrolyte - A technology breakthrough
- Power-sharing demonstrated as an effective way of reducing system equivalent weight - Approximately 19 kg/man (42 lb/man)
- Single blower concept proven compatible with Life Systems' high moisture tolerance cell designs - Reduces system complexity

- Electrochemical Air Revitalization System technology base demonstrated at system level - Ready for Regenerative Life Support Evaluations

INTRODUCTION

The Air Revitalization System (ARS) for future space vehicles may utilize a concept employing Water Vapor Electrolysis (WVE) for oxygen (O_2) production and partial humidity control and Electrochemical Depolarized Carbon Dioxide (CO_2) Concentration (EDC) for CO_2 control. One projected application of such an Electrochemical Air Revitalization System (EARS) is its use for a localized "topping" capability for O_2 production, and CO_2 and partial humidity control in areas of high-manned activities. As such, efficient operation over a wide relative humidity (RH) range and a design that is self-contained, except for external power, is required.

Such an end-item application imposes unique design requirements upon the system. Self-contained means a system which minimizes interfaces with on-board spacecraft facilities while localized control means providing cabin atmospheric control in the immediate working area independent of the central ARS and potentially under extremes in cabin air conditions.

Background

Water vapor electrolysis and electrochemical CO_2 concentration has shown great promise for use in future manned spacecraft. (1-11) The integration of the WVE/EDC for simultaneous O_2 generation, CO_2 control, and partial humidity control has been successfully demonstrated. (12-15) Under Contract NAS9-14301, a three-cell Breadboard EARS (BEARS) and a power-sharing controller were fabricated and tested. The power-sharing controller used the EDC-generated power to partially offset the power requirements of the WVE. The purpose of the present program was to expand this area of technology development by providing for the experimental characterization and parametric testing of a larger scale integrated WVE/EDC system which uses the power-sharing concept. Towards this end, the one-man capacity EARS developed under a Life Systems, Inc. (LSI)-funded program was modified, refurbished and used for the testing.

Program Objectives

The primary objective of the present program was to evaluate the one-man, EARS through an extensive test program designed to characterize WVE and EDC performance as a function of the major operating parameters that affect system performance: process air inlet pCO_2 and RH, and WVE and EDC current densities. The system performance parameters evaluated were EDC CO_2 removal efficiency and cell voltage, WVE cell voltage and the ability of the power-sharing controller to fully utilize EDC power generated.

(1) References cited in parentheses are found at the end of this report.

The specific program objectives were to

1. modify and refurbish the EARS system as required to insure successful completion of the proposed test program,
2. incorporate the power-sharing controller concept into the EARS instrumentation,
3. characterize EARS performance over a wide range in process air conditions and cell current density, and
4. demonstrate EARS performance for a minimum of 75 days without performance degradation or failure to meet system design specifications.

In addition to these specific objectives for the EARS, the development and testing of a laboratory breadboard Triple Redundant Hydrogen Sensor (TRHS) and its incorporation into the EARS Test Program was completed. The results of the TRHS portion of the present program are described in a separate final report. (16)

Program Organization

The program was organized into four tasks whose specific objectives were:

- 1.0 Define and perform the refurbishment activities and modifications required to insure that the existing LSI-developed one-man, EARS would successfully complete the proposed test program.
- 2.0 Reassemble and calibrate the Test Support Accessories (TSA) required for EARS testing.
- 3.0 Establish, implement and maintain a mini-Product Assurance program throughout the contractual period to search out quality weaknesses and define appropriate corrective measures.
- 4.0 Perform EARS testing, including Checkout/Shakedown testing and the Parametric/Endurance Test Program with emphasis placed on demonstrating steady-state EARS performance over the lower RH ranges.

The objectives of the program were met. The following sections review the EARS concept and hardware previously developed, the results of the work completed, the conclusions reached and recommendations made.

ONE-MAN ELECTROCHEMICAL AIR REVITALIZATION SYSTEM

The EARS consists of a WVE Module (WVEM), an EDC Module (EDCM), the Electrical Power-Sharing Controller, and the mechanical and electrical components required to control and monitor system operation.

Concept Description

The basic EARS concept is depicted schematically in Figure 1. The EARS concept combines two electrochemical processes (electrolysis of water vapor and electrochemical concentration of CO₂) with an electronic power-sharing technique to achieve O₂ generation, CO₂ removal and partial humidity control.

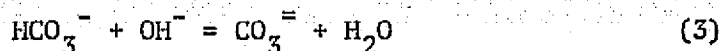
Electrochemical CO₂ Concentration Process

Carbon dioxide is removed from a flowing air stream as it passes over the cathode of an EDC cell. Each cell consists of two porous electrodes separated by a porous matrix containing an aqueous carbonate electrolyte. Plates adjacent to the electrodes provide passageways for distribution of the process gases and electrical current over the electrode surfaces. The process gas flow paths are summarized in the single-cell schematic shown in Figure 2 and the specific electrochemical and chemical reactions are detailed in Figure 3.

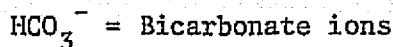
EDC Cell Reactions. Moist air containing CO₂ is fed into the cathode compartment where the electrochemical reaction of O₂ in the air, water and electrons form hydroxyl ions (OH⁻).



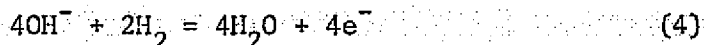
The CO₂ then reacts with the OH⁻ at the cathode to form carbonate ions (CO₃⁼) in two consecutive reactions.



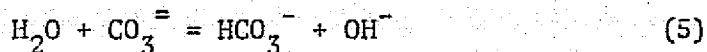
where



The output from the cathode compartment is moist air at a reduced partial pressure of CO₂ (pCO₂). The CO₂ as CO₃⁼ and unreacted OH⁻ diffuse through the bulk electrolyte to the anode, transporting current through the cell. At the anode, hydrogen (H₂) is fed into the cell where it is electrochemically reduced in the presence of OH⁻ to form water and electrons and decrease the concentration of OH⁻ in the anolyte.



The decrease in OH⁻ concentration shifts the carbonate/bicarbonate equilibrium toward the HCO₃⁻.



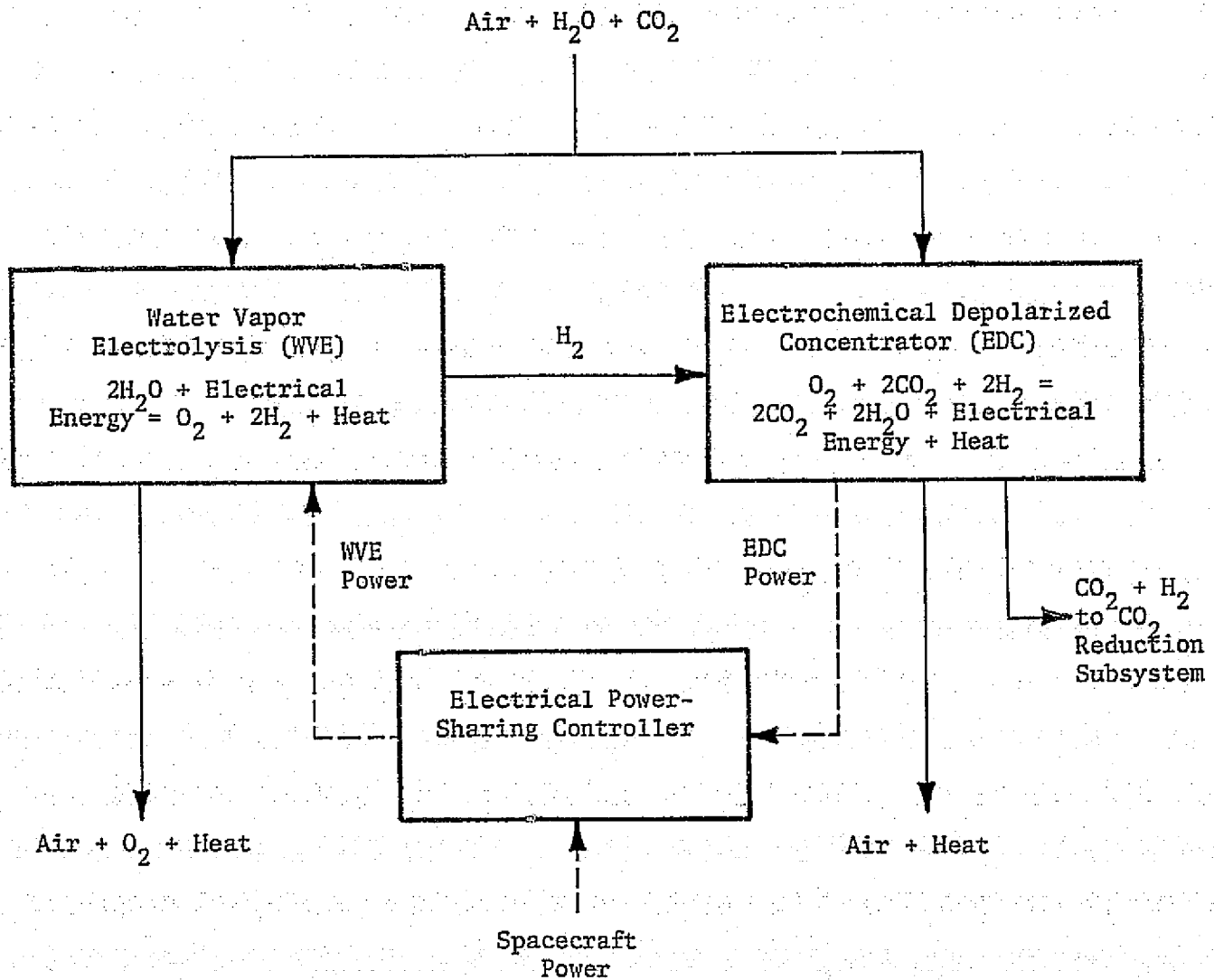


FIGURE 1 ELECTROCHEMICAL AIR REVITALIZATION CONCEPT

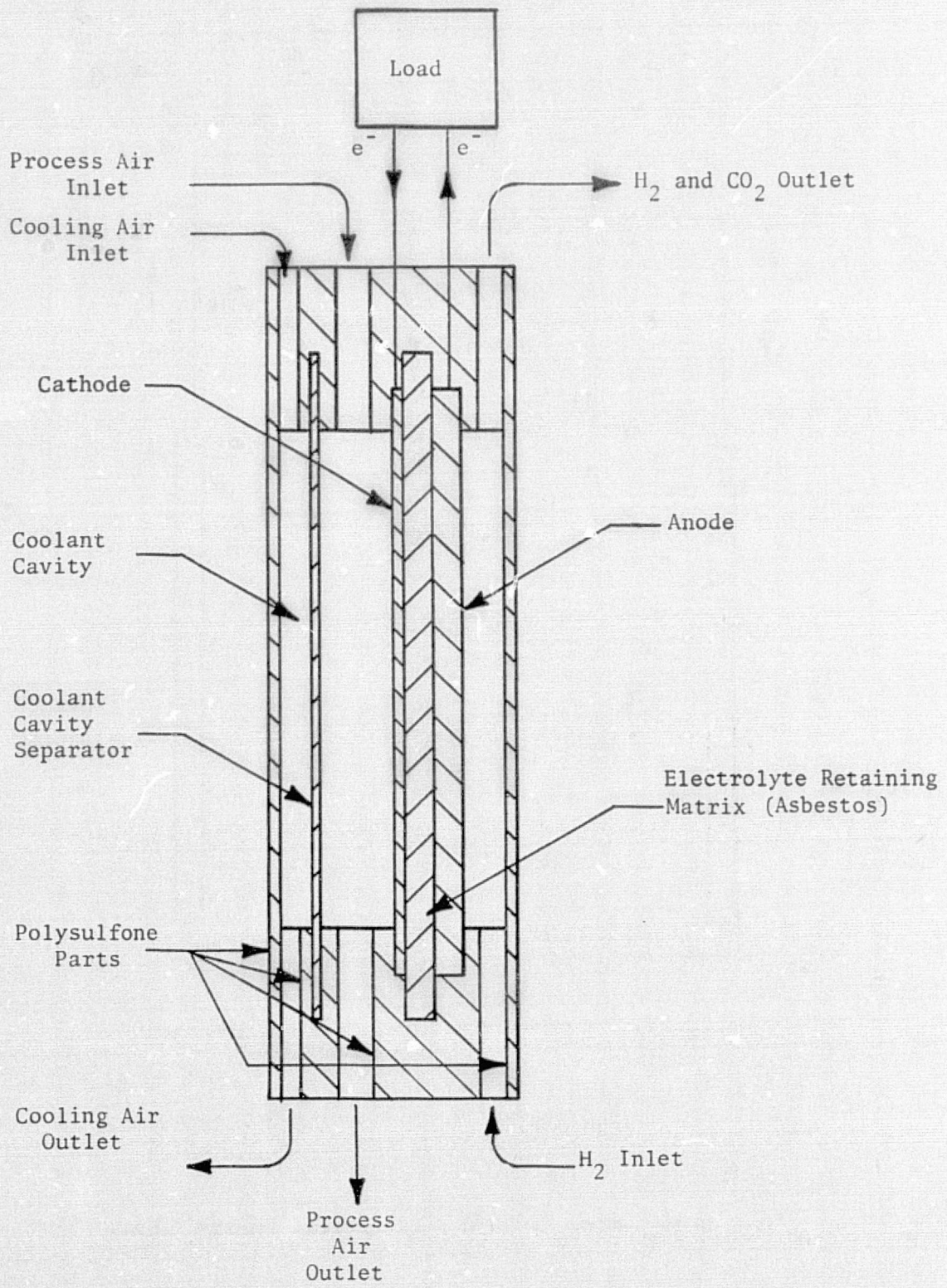
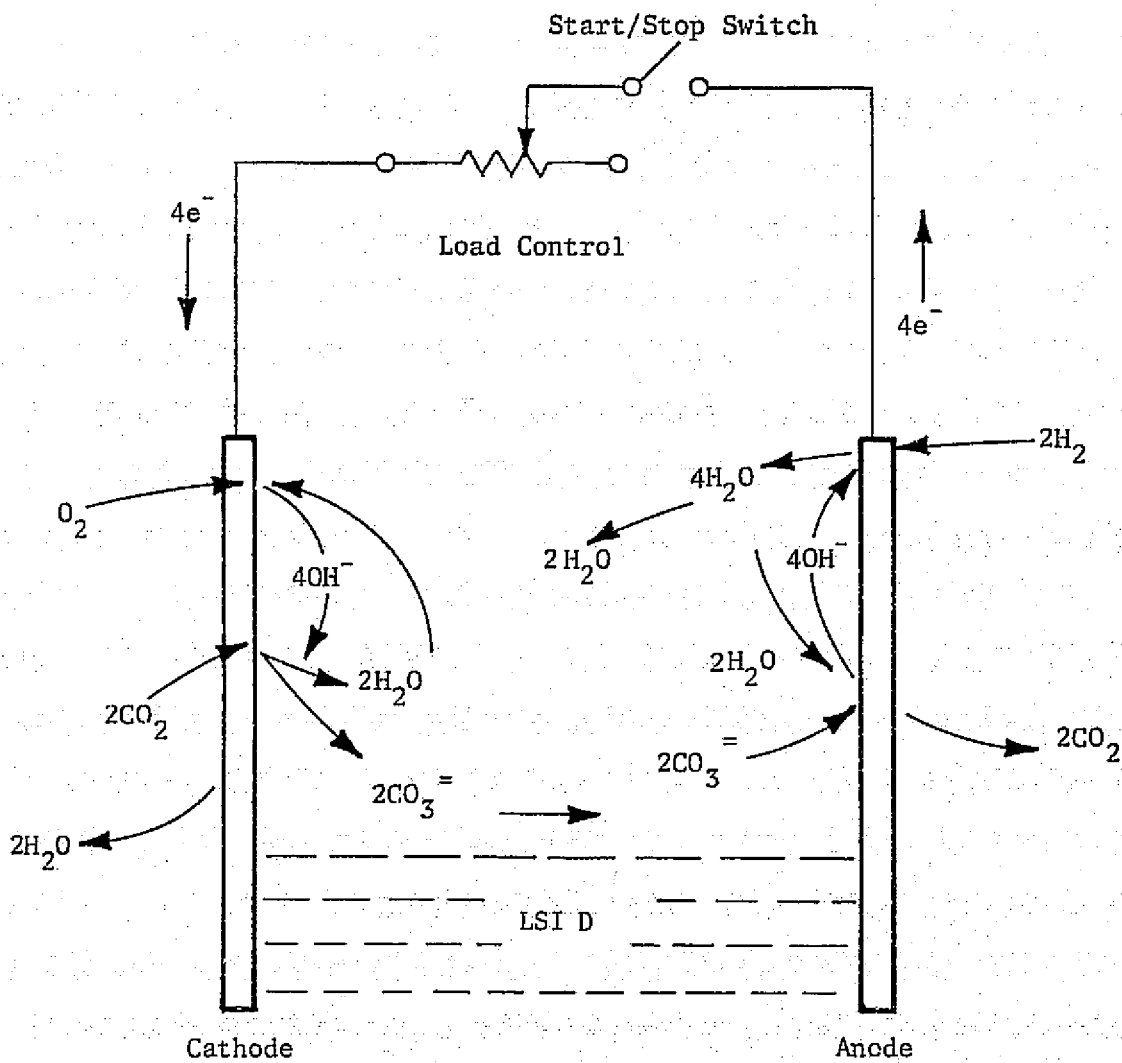
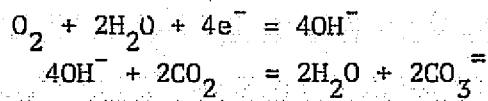


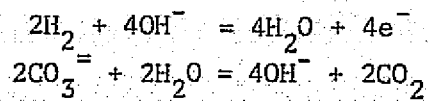
FIGURE 2 EDC SINGLE-CELL SCHEMATIC



Cathode Reactions:



Anode Reactions:



Overall Reactions:

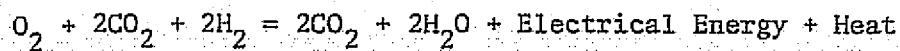
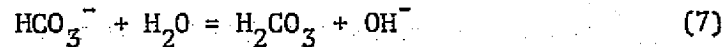


FIGURE 3 EDC FUNCTIONAL SCHEMATIC WITH REACTIONS

At low OH⁻ concentrations there are two mechanisms by which the evolution of the CO₂ bound in the form of HCO₃⁻ occurs. The first mechanism is:



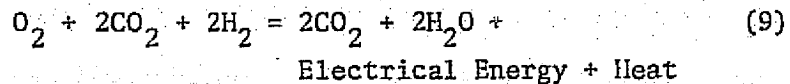
and the second is:



where

H₂CO₃ = Carbonic acid

With the evolution of CO₂ and the production of the water at the anode, the transfer of both the CO₂ and current is complete. The water produced in the process transfers to the cathode and evaporates into the process air flow. The output from the anode compartment is CO₂ mixed with unreacted H₂. The overall reaction is exothermic and is accompanied by the formation of electrical energy.



Carbon Dioxide Removal Efficiency. Inspection of the overall reaction, as based on the CO₃⁼ transfer mechanism, shows that two moles of CO₂ can be transferred for one mole of O₂ consumed. This, by definition, represents a CO₂ removal efficiency of 100%. The equivalent mass ratio is 2.75 kg (lb) of CO₂ removed for each kg (lb) of O₂ consumed. This ratio is referred to as the Transfer Index (TI).

Electrical Efficiency. The available electrical power produced by the electrochemical reaction in the EDCM is the product of the cell current and voltage. The theoretical open-circuit voltage is 1.23V. In practical applications and with current flowing, cell voltages of less than 1.23V result. Electrical efficiency is, therefore, reflected by cell voltage with high voltage representing high electrical efficiency.

Water Vapor Electrolysis Process

The generation of O₂ occurs at the anode of the WVE cell where water vapor is removed from a flowing air stream and is electrolyzed, resulting in partial humidity control in addition to O₂ generation. Each cell consists of two porous electrodes separated by a porous matrix containing an aqueous acidic electrolyte. Plates adjacent to the electrodes provide passageways for distribution of the process gases and the electrical current to the electrode surfaces. The process gas flow paths are summarized in the single-cell schematic shown in Figure 4. The specific electrochemical reactions are detailed in Figure 5.

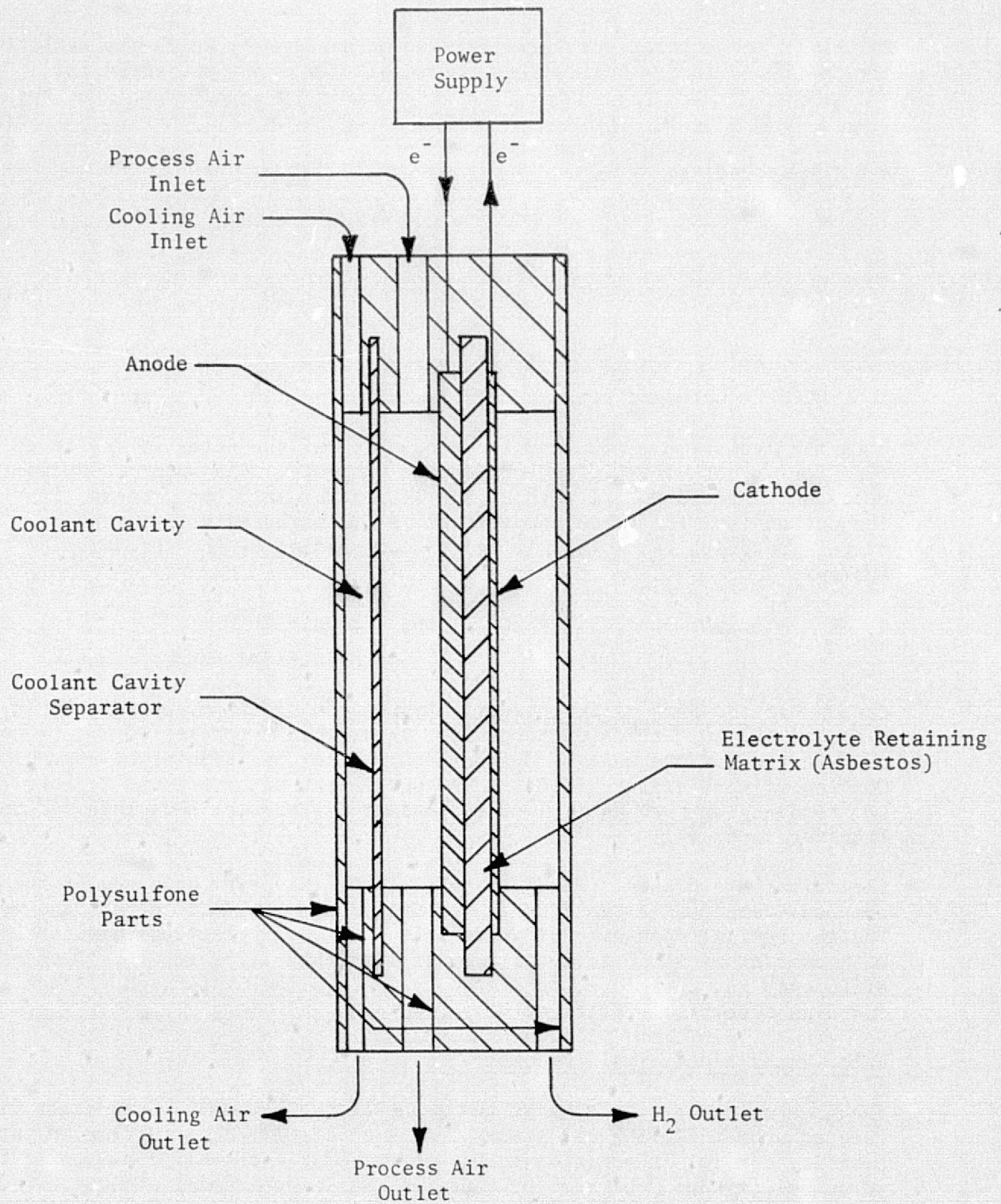
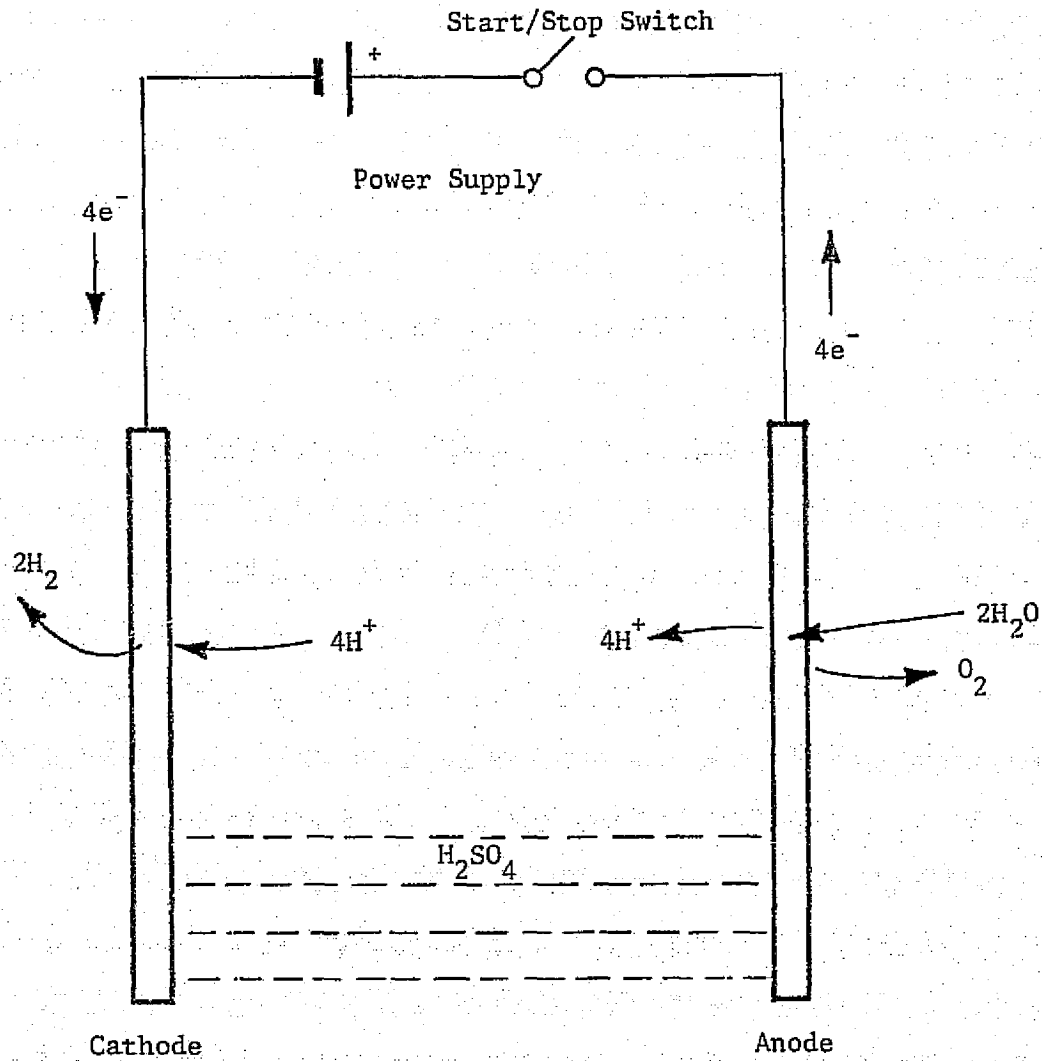
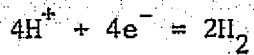


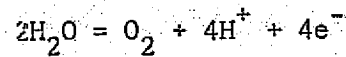
FIGURE 4 WVE SINGLE-CELL SCHEMATIC



Cathode Reactions:



Anode Reactions:



Overall Reaction:

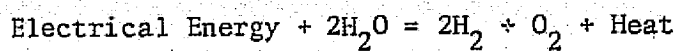
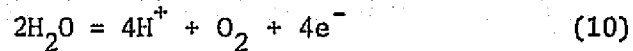


FIGURE 5 WVE FUNCTIONAL SCHEMATIC WITH REACTIONS

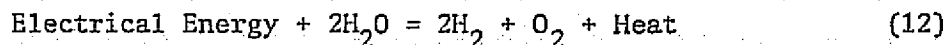
WVE Cell Reactions. Moist air is fed into the anode compartment where the water is absorbed into the electrolyte due to the water vapor pressure gradient that exists. The water is electrolyzed to form gaseous O_2 , hydrogen ions (H^+) and electrons.



The output of the anode compartment is dry air at an increased O_2 partial pressure (pO_2). The H^+ diffuse through the bulk electrolyte to the cathode, transporting the current through the cell. At the cathode, H_2 is produced by the electrochemical reduction of H^+ .



With the production of H_2 at the cathode, the transfer of the current is complete. The output from the cathode compartment is H_2 with a partial pressure of water (pH_2O) approximately in equilibrium with the catholyte. The overall reaction is endothermic and is accompanied by the consumption of electrical energy and the generation of waste heat.



Electrical Efficiency. The performance of a WVEM is reflected by voltage which is a direct measure of the power required by the WVEM. The electrical energy consumed by the electrochemical reaction occurring in a WVEM is a function of the current density and the average cell voltage. The theoretical electrochemical cell voltage is 1.23V. In practical applications, cell voltages above 1.23V result. The electrical efficiency is, therefore, reflected by the cell voltages, with low cell voltage representing high electrical efficiency or low power consumption to perform the electrochemical process of O_2 and H_2 generation.

Power-Sharing Process

The power which the EDCM generates has historically been converted to heat and removed from the subsystem as a waste product. Life Systems, Inc. has developed a concept for using EDCM power directly by supplying this power to a water electrolysis system (vapor or liquid) when the two are operated as part of an integrated system. Using this technique in an EARS, the EDCM power can be directly subtracted from the power required to operate the WVEM. The remaining power required to operate the WVEM is then obtained from the input power as shown in Figure 6. The power controller contains the circuits necessary to allow the utilization of EDCM power and to convert the input power to the voltage and current levels required by the WVEM.

The benefits of using EDCM power are:

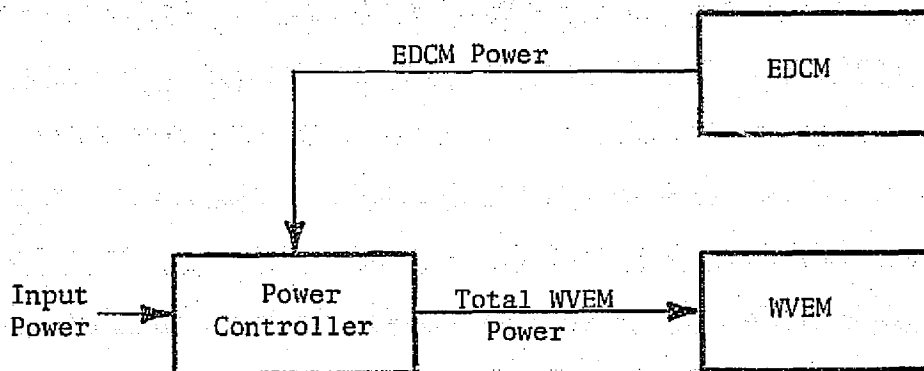


FIGURE 6 POWER CONTROLLER BLOCK DIAGRAM

1. One hundred percent of the EDCM power is utilized. It is not necessary to send it through a power conversion circuit before it is supplied to the WVEM.
2. There is no heat removal penalty associated with dissipating EDCM power as all of it is used.
3. The amount of power required from the input power source is reduced by an amount equal to EDCM power divided by the power conversion efficiency (typically 85 to 90%) which further reduces the heat load caused by power conversion losses.
4. The operation is completely automatic and requires no manual adjustment.
5. The concept is independent of cell area, current density, voltage and cell arrangement; i.e., series/parallel combinations.

A simple way to emphasize the benefits of power sharing is to compare the observed WVE cell voltage to the net or reduced WVE cell voltage (i.e., the resulting WVE cell voltage after subtracting the EDC power generated). The net WVE cell voltage then reflects the total EARS power required and heat generated. The net WVE cell voltage is given by the following equation:

$$E_{NET} = E_{OBS} - \frac{(E_{EDC})(N_{EDC})(I_{EDC})}{(N_{WVE})(I_{WVE})\eta} \quad (13)$$

where

E_{NET} = Net WVE cell voltage, V

E_{OBS} = Observed WVE cell voltage, V

E_{EDC} = EDC cell voltage, V

I_{EDC}, I_{WVE} = EDC and WVE current, respectively, A

N_{EDC}, N_{WVE} = Number of EDC and WVE cells, respectively

η = Spacecraft power conversion efficiency, fraction of unity

For the one-man, EARS containing 15 WVE cells at 12.2A, 15 EDC cells at 4.43A and a spacecraft power conversion efficiency of 0.85, equation (13) reduces to

$$E_{NET} = E_{OBS} - 0.47 (E_{EDC}) \quad (14)$$

Figure 7 shows the reduction in WVE cell voltage as a function of EDC voltage. For example, an EARS operating with an observed WVE cell voltage of 1.80V and an EDC cell voltage of 0.40V, has a net WVE voltage of 1.61V while an observed WVE cell voltage of 1.70V and an EDC cell voltage of 0.10V has a net WVE voltage of 1.65V. These two examples show that high EDC cell voltages can more than offset high WVE cell voltages and therefore reduce net system power required and heat generated.

Figure 8 is a detailed block diagram of the EARS power control circuits and their connection to the EDCM and WVEM. Input power is converted by means of two power controls, A and B, into constant currents. A part of the WVEM current is obtained from Power Control A and the EDCM in series. The remainder of the current comes from Power Control B. The EDCM and Power Control A are connected together in series such that the total voltage of Power Control A and the EDCM is equal to the WVEM voltage. Shunt A measures the EDCM current and the signal is used in Power Control A to maintain this current at the set value (5.0A in Figure 8). The remainder of the current for the WVEM (7.5A in Figure 8) comes from Power Control B to result in a total WVEM current of 12.5A.

Shunt B measures total WVEM current. This signal is used to control Power Control B output current such that the total is 12.5A when Power Control A current is added. For example, if Power Control A current were decreased from 5.0A to 4.0A, Power Control B current would increase from 7.5A to 8.5A to maintain the total of 12.5A. An additional feedback path is provided on Power Control B to limit maximum WVEM voltage. If WVEM voltage should reach this level, the current from Power Control B will be reduced in order to hold the WVEM voltage at the set maximum value.

With this concept, the total EDCM power is used with no power conversion efficiency penalties. Because the two modules are electrically in series, the WVEM current is always equal to or greater than the EDCM current. This, however, is not a limitation since, for an EARS application, the WVEM current must be greater than the EDCM current (for equal cell areas and series cell connections) to supply both the metabolic O_2 , and the O_2 and H_2 required for the EDCM.

System Design

The function of the EARS is to simultaneously meet the nominal metabolic O_2 generation and CO_2 removal requirements of one man as specified in Table 1. Table 1 indicates that the metabolic O_2 requirements and the removal of respiratory and perspiratory-generated water cannot be controlled simultaneously since both insufficient as well as excess water conditions can exist. The portion of water consumed in the WVEM for the generation of the O_2 and H_2 required by the EDCM has no net effect on cabin humidity since an equal amount of water is regenerated in the EDCM during the CO_2 removal process.

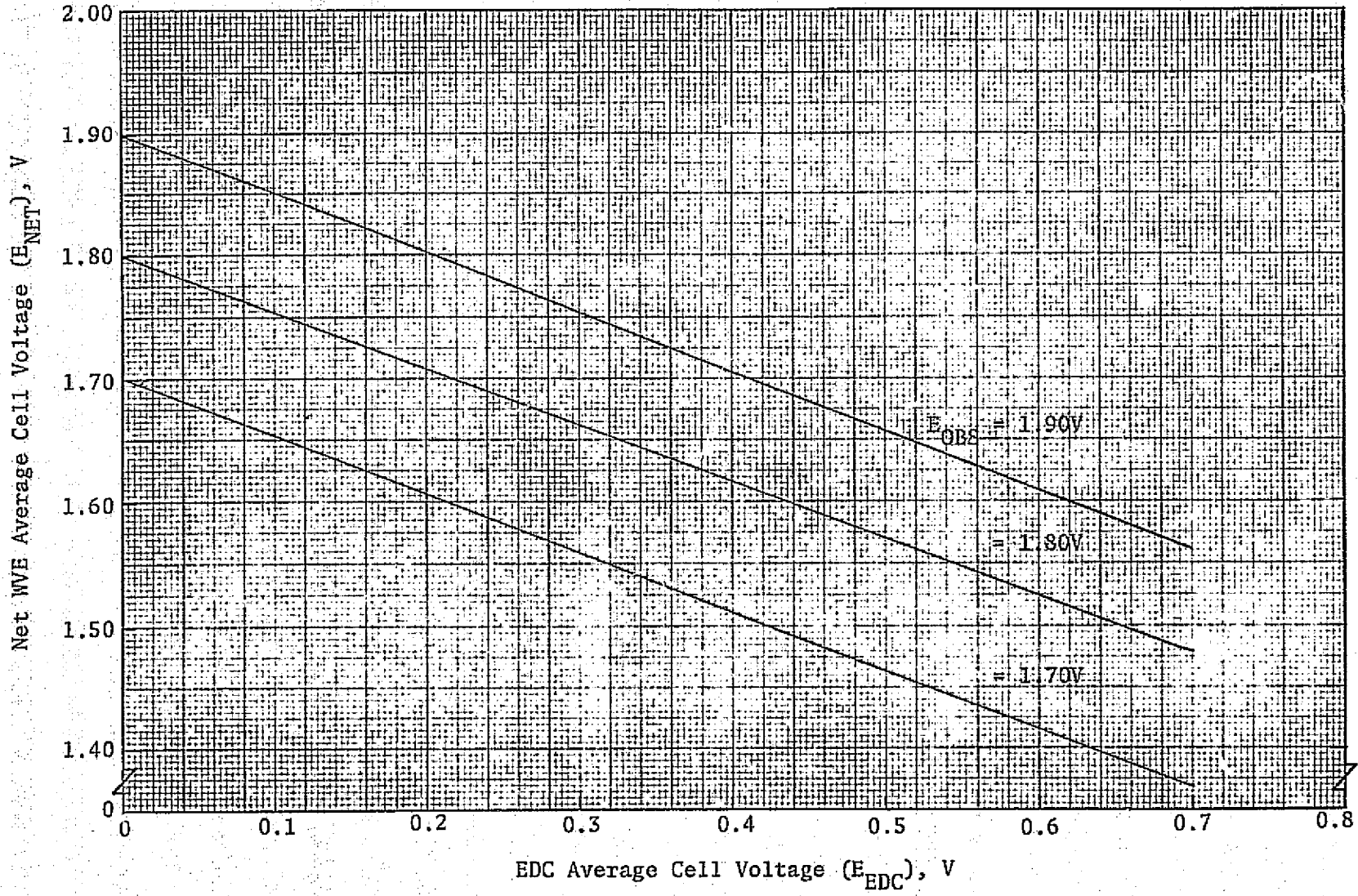


FIGURE 7 NET WE CELL VOLTAGE VERSUS EDC CELL VOLTAGE

NOTE: Data shown taken with lead-acid batteries for EDCM and WVEM during controller characterization test

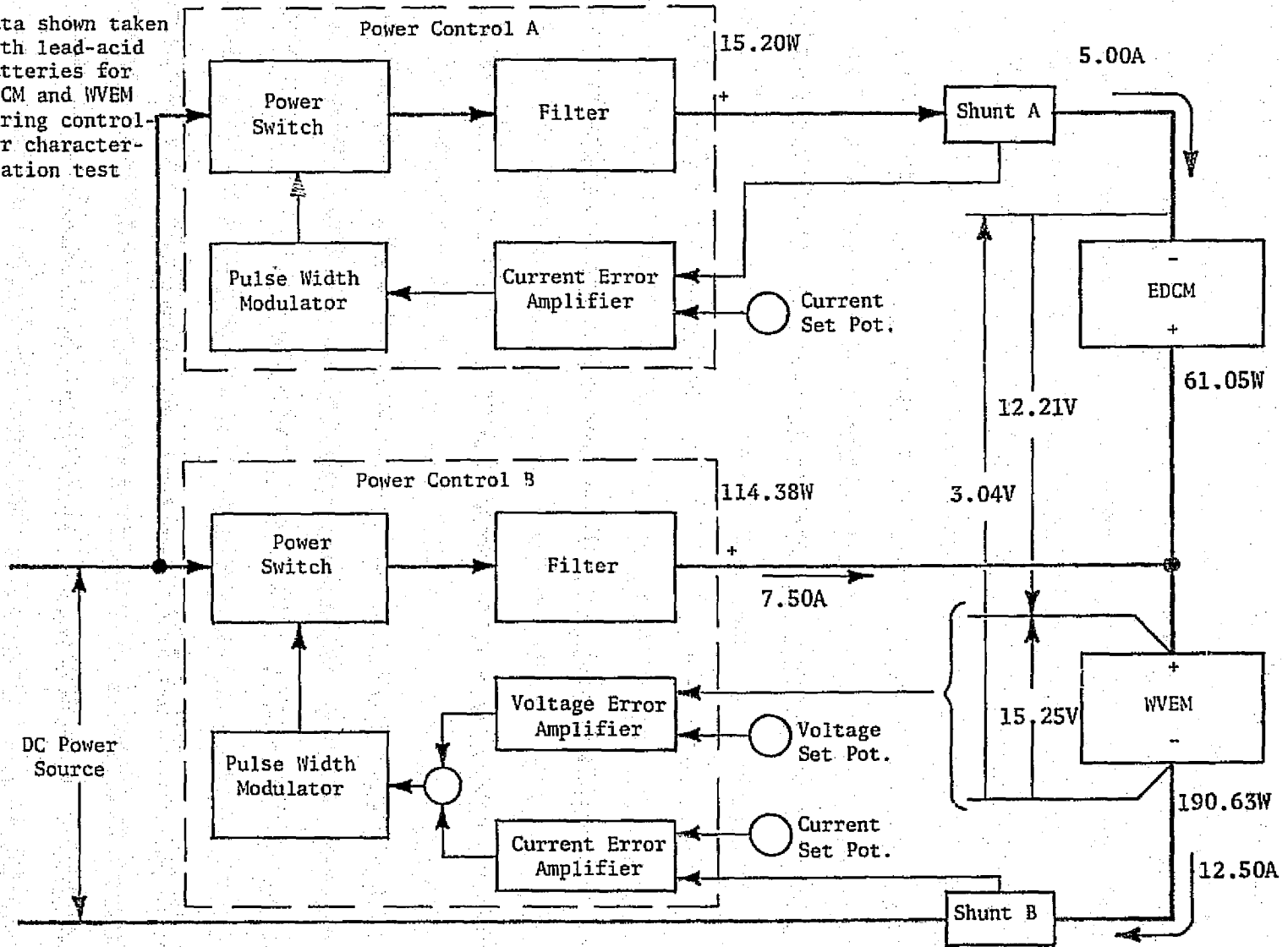


FIGURE 8 DETAILED BLOCK DIAGRAM OF POWER-SHARING CONTROLLER

TABLE 1 METABOLIC CREW DATA

Perspiration and Respiration,
kg H₂O/Man-d (Lb H₂O/Man-Day)

a. Nominal	1.50 (3.31)
b. Minimum (291K (65F) - Cabin Temp.)	0.59 (1.31)
c. Maximum (297K (75F) - Cabin Temp.)	3.67 (8.09)

Metabolic Oxygen Consumption,
kg O₂/Man-d (Lb O₂/Man-Day)

a. Nominal	0.84 (1.84)
b. Minimum	0.77 (1.69)
c. Maximum	1.00 (2.20)

Carbon Dioxide Production,
kg CO₂/Man-d (Lb CO₂/Man-Day)

a. Nominal	1.00 (2.20)
b. Minimum	0.87 (1.92)
c. Maximum	1.22 (2.68)

The detailed specifications to which the EARS was designed are listed in Table 2. The system was designed to be self-contained, portable and to provide localized atmospheric control. Emphasis was placed on minimizing system interfaces with potential on-board spacecraft facilities. The portability concept employed was one which allowed the system to be free-standing in the cabin and to be easily moved from place to place.

Electrochemical Depolarized CO₂ Concentrator Module Design

The function of the EDCM is to remove metabolically produced CO₂ and control the cabin pCO₂ at less than or equal to 400 N/m² (3 mm Hg). Because of the large RH operating range, 35 to 90%, the high moisture tolerance EDC cell design was used.⁽¹⁵⁾ This cell design allows the electrolyte/electrode interface to move in and out of the porous anode without losing contact with the electrode to accommodate electrolyte volume fluctuations accompanying changes in RH.

Selection of the electrolyte is critical to the cell design. Previous high moisture tolerance EDC cells utilized LSI-B electrolyte. Previous test results however, showed that irreversible changes in cell performance can occur following operation at low, <40%, RH levels. Subsequently a new electrolyte, LSI-D, was developed at LSI. Testing at the single-cell level verified that there were no irreversible changes in cell performance over the entire 35 to 90% RH range using LSI-D electrolyte and the high moisture tolerance cell design. In addition, higher cell voltages were observed, 0.50V versus 0.25 to 0.40V. The LSI-D electrolyte was therefore selected for use in the EARS.

The EDC module requires fifteen cells at a current density of 19.4 mA/cm² (18 ASF). The nominal CO₂ removal efficiency expected was 76% (TI = 2.1) at a pCO₂ of 400 N/m² (3 mm Hg) and 50 to 60% RH. The EDCM characteristics are summarized in Table 3.

Water Vapor Electrolysis Module Design

The function of the WVE module is to generate metabolic O₂, O₂ and H₂ for use in the EDC, and to remove water vapor from the cabin air for partial local humidity control. Because of the large RH operating range, the high moisture tolerance WVE cell design was used.⁽¹⁵⁾ As in the EDC cell design, electrolyte volume fluctuations are accommodated in a porous electrode. The electrolyte used is sulfuric acid (H₂SO₄). The basic WVE cell design is the same as that used previously with the exception of the anode. The EARS was built prior to the BEARS program and used an earlier anode design (designated as E5 as opposed to the E5B used during the BEARS testing). The E5 electrode has an inherently higher cell voltage of 0.10 to 0.15V than the E5B electrode. Replacement of the anodes with the better-performing E5B or even more recently-developed higher performance anodes was not accomplished due to funding limitations.

The WVE module consists of fifteen cells which operate at the current density of 53.8 mA/cm² (50 ASF). The nominal expected average cell voltage for the E5 electrodes is 1.90V. The WVEM characteristics are summarized in Table 3.

TABLE 2 DETAILED ONE-MAN WVE/EDC DESIGN SPECIFICATIONS

Crew Data

Number of Crew	1
CO ₂ Removal Rate (Nominal), kg/d (Lb/Day)	1.0 (2.2)
O ₂ Generation Rate (Nominal), kg/d (Lb/Day)	
Metabolic	0.84 (1.84)
CO ₂ Removal System (76% Eff)	0.48 (1.05)
H ₂ O Generation Rate (Nominal), ^(a) kg/d (Lb/Day)	1.50 (3.31)

Spacecraft Data

Cabin Total Pressure, kN/m ² (Psia)	
Design Point	101.4 (14.7)
Control Tolerance	±1.4 (±0.2)
Cabin O ₂ Partial Pressure, kN/m ² (Psia)	22.1 (3.2)
N ₂ Partial Pressure, kN/m ² (Psia)	78.9 (11.5)
Cabin Temperature Range, K (F)	291 to 297 (65 to 75)
Relative Humidity Range, %	35 to 90% ^(b)
CO ₂ Partial Pressure, N/m ² (mm Hg)	400 (3.0)
Duty Cycle	Continuous
Operational Gravity	0 to 1 g

(a) It should be recognized that not all the metabolic water is handled by the EARS

(b) As a goal

TABLE 3 ONE-MAN MODULE DESIGN CHARACTERISTICS

	WVEM	EDCM
Module Weight, kg (Lb)	2.04 (45)	25.4 (56)
Module Dimensions, cm (In)	14.7 x 34.0 x 18.5 (5.8 x 13.4 x 7.3)	14.7 x 34.0 x 18.5 (5.8 x 13.4 x 7.3)
Number of Active Cells Per Module	15	15
Number of Modules Required	1	1
Active Area Per Cell, cm ² (Ft ²)	227 (0.244)	227 (0.244)
Current Density (Nominal) mA/cm ² (ASF)	53.8 (50)	19.4 (18.1)
Current, A	12.2	4.43
Cell Voltage (Nominal), V	1.90	0.40
CO ₂ Transfer Efficiency (Nominal), (a) %	N/A	76
Power Consumed Per Module, W	348	-26.6
Waste Heat Produced Per Module, W	123	55.2
O ₂ Generated Per Module, kg/d (Lb/Day)	1.31 (2.89)	-0.48 (-1.05)
H ₂ Generated Per Module, kg/d (Lb/Day)	0.16 (0.36)	-0.06 (-0.13)
H ₂ O Removed Per Module, kg/d (Lb/Day)	1.48 (3.25)	-0.54 (-1.18)
Air Flow Per Module, dm ³ /s (Scfm)	5.7 (12)	5.7 (12)
Air Flow Per Module (Cooling), dm ³ /s (Scfm)	49.6 (105)	49.6 (105)

(a) At an inlet pCO₂ of 400 N/m² (3.00 mm Hg) and 50 to 60% RH

Control/Monitor Instrumentation Design

The function of the EARS instrumentation is to control and monitor EARS performance. The following features were incorporated:

1. Power sharing to utilize EDC power generated and reduce total system power requirements.
2. Automatic one button start, one button stop.
3. Performance trend analysis for fault isolation.
4. Automatic fail-safe shutdown when a critical parameter exceeds a preset level.
5. Manual overrides on all system controls.
6. An optional cell temperature-to-inlet process air dew point differential temperature (ΔT) control.

The EARS instrumentation circuits are contained in an instrumentation package separate from the mechanical hardware.

Control Functions. The function of the control instrumentation circuits is to maintain system operating parameters at desired levels or within preset limits. The EARS contains three such controls:

1. The Power Controller using the power sharing concept.
2. Sequencing controls for automatic startup and fail-safe shutdown.
3. The ΔT control.

The power-sharing control discussed previously maintains the WVE-to-EDC current ratio at a preset level and reduces the total system power required by using 100% of the EDC power generated. The sequencing controls operate valves, blowers, module currents and other system components in response to mode change commands such as startup and shutdown. The three primary system operating modes are power off, shutdown (system ready to be operated) and normal. The sequencing controls enable automatic mode transitions between these three operating modes when commanded manually or automatically initiated by the monitoring instrumentation or upon loss of system power. The ΔT control allows the cell temperature-to-inlet process air dew point temperature differential to be controlled at a preset level.

The ΔT control concept is primarily used to increase EARS performance, specifically EDC CO_2 removal efficiency, at high ($\geq 70\%$) RH levels by reducing cooling air flow rate and allowing the EDC cells to increase in temperature. The higher internal cell temperature allows the cell to operate at a lower average RH than indicated by the inlet process air conditions. This control concept

has been verified for other EDC applications^(6,7) and during previous EARS and BEARS testing.⁽¹⁵⁾ The AT control was not used during the EARS testing to demonstrate that separate process air and cooling air blowers and the AT control itself are not required. Also, projected operating specifications for an EARS, and for cabin environments in general, will not have the 70 to 90% RH design requirement. During system testing the cooling air flow rate was preset and maintained at a constant rate.

Monitoring Functions. The function of the monitoring instrumentation is to provide performance trend analysis and fault isolation information which can be used to alert operators to potential problems before the problem becomes critical. The monitoring instrumentation also provides automatic shutdown signals for crew and equipment safety. Seven critical parameters requiring automatic system shutdown were identified and incorporated into the EARS. They are (1) high WVE individual cell voltage, (2) low EDC individual cell voltage, (3) high EDC module temperature, (4) high WVE module temperature, (5) high AT, (6) low AT and (7) high H₂ backpressure. Since the AT control was not used, the high and low AT shutdowns were not used and were manually overridden during testing.

System Operation

A schematic of the EARS is presented in Figure 9. The system is simple and has few components. Process air is drawn in series, first through the EDCM and then through the WVEM. This concept allows the WVEM to take advantage of the water vapor generated within the EDCM resulting in an increase in WVE current density capability at a given cell voltage and cabin air humidity level.

Filters are provided upstream and downstream of each of the modules. The two electrochemical modules are internally air-cooled with cooling air passages separate from process air compartments. The concept of internal air cooling minimizes thermal gradients while still allowing process air flow rate to be sized strictly based on CO₂ removal requirements. A separate blower is used to pull cooling air through the internal cooling passages. The generated H₂ flows from the WVEM to the EDCM where it becomes enriched with CO₂ and passes through the pressure transducer and backpressure regulator before venting the system. A nitrogen (N₂) purge capability is also incorporated. Purging is only performed for H₂-carrying passages. A variety of sensors are used to control and monitor system performance.

Hardware Description

A photograph of the EARS showing the separate mechanical and instrumentation packages is presented in Figure 10. The EARS components are listed in Table 4. The overall dimensions for the mechanical components assembly are 35.6 x 40.4 x 63.2 cm (14.0 x 15.9 x 24.9 in) or 0.09 m³ (3.2 ft³). The instrumentation enclosure is 37.3 x 27.9 x 30.5 cm (14.7 x 11.0 x 12.0 in) or 0.03 m³ (1.1 ft³).

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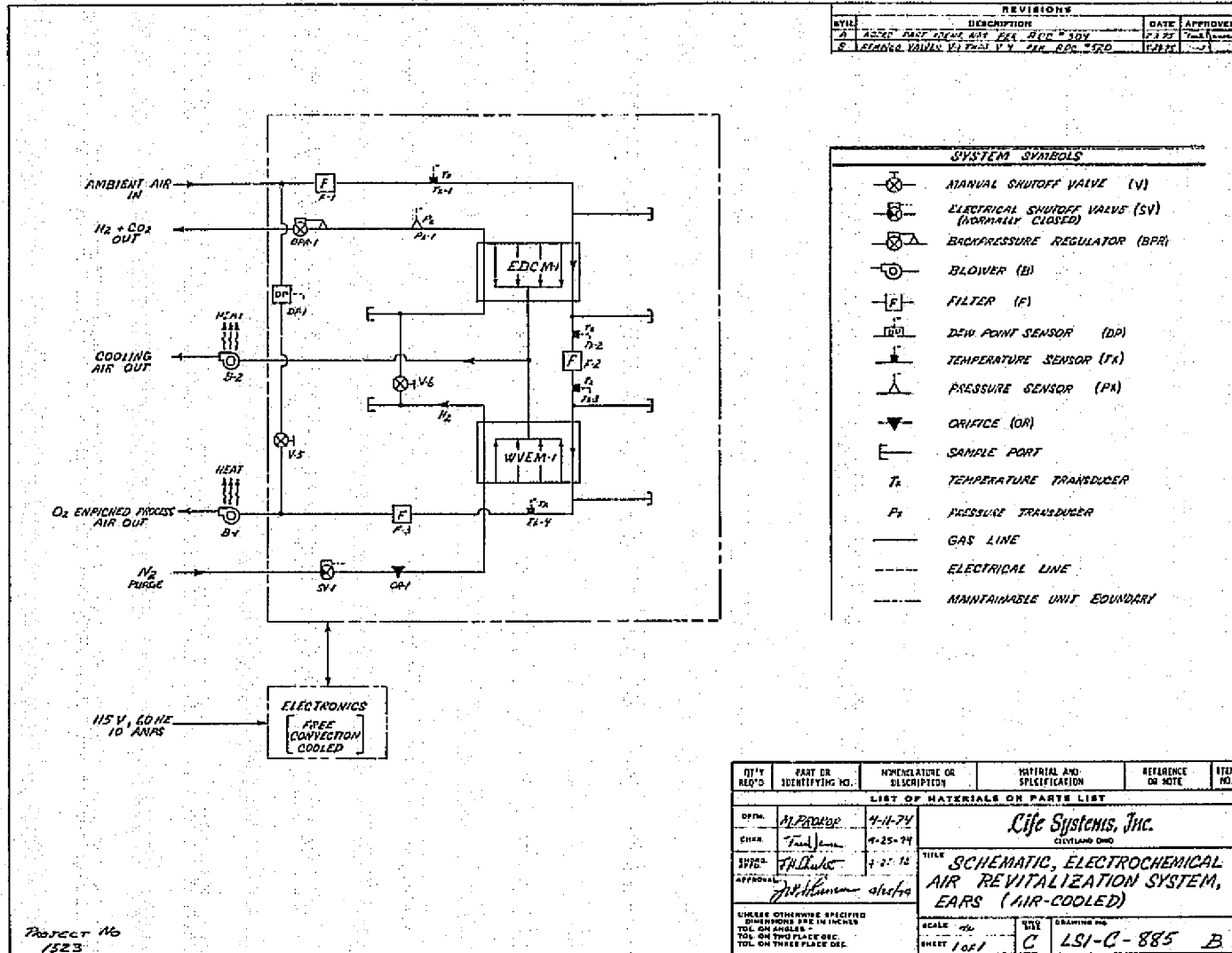


FIGURE 9 EARS SCHEMATIC

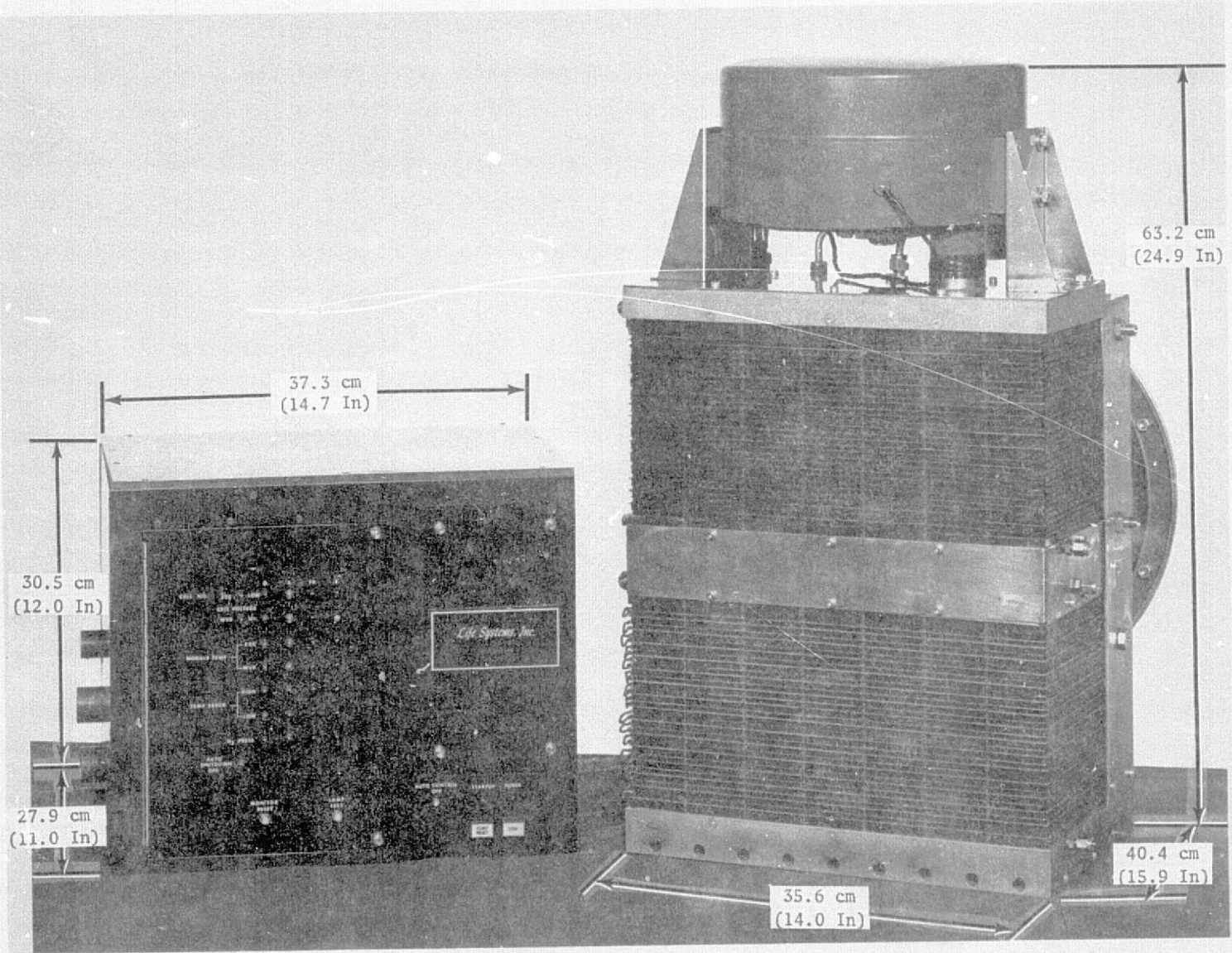


FIGURE 1C ELECTROCHEMICAL AIR REVITALIZATION SYSTEM HARDWARE

TABLE 4 ONE-MAN, EARS COMPONENT LIST

<u>Component</u>	<u>Req.</u>	<u>Manufacturer</u>
Module, EDC	1	LSI
Module, WVE	1	LSI
Regulator, Back Pressure	1	Conoflow
Valve, Solenoid, Normally Open	1	Skinner
Blower, Cooling Air	1	Amphenol
Blower, Process Air	1	Rotron
Orifice, N ₂ Purge	1	Lee Jet
Instrumentation, Control and Monitor	1	LSI
Filter, Process Air	3	LSI
Sensor, Dew Point	1	EG & G
Sensor, Pressure, H ₂	1	Columbia
Sensor, Temperature	4	LSI
Valve, Shutoff, Manual	2	Whitey

EDC Module

The function of the EDCM is to remove metabolically-produced CO_2 . The EDCM consists of fifteen cells electrically-connected in series. Cooling air and process air are manifolded through each of the cells in parallel. Hydrogen flow is in series through the fifteen cells. Figures 11 and 12 are photographs of the EARS mechanical components assembly showing the EDCM located below the WVEM. Figure 13 is a photograph of the individual cell components.

WVE Module

The function of the WVEM is to generate metabolic O_2 , O_2 and H_2 for the EDCM, and remove water vapor from the process air. The WVEM consists of fifteen cells electrically connected in series. All gas flow paths are in parallel through each of the fifteen cells. The WVEM is shown in Figure 11 above the EDCM in the EARS mechanical components assembly. The basic cell construction is the same for the WVE and the EDC with the exception of the specific materials used. The WVE cell hardware is shown in Figure 13.

Control/Monitor Instrumentation

The function of the EARS instrumentation is to control and monitor system performance. The control and monitor circuits are packaged together and are contained in a separate enclosure. The instrumentation enclosure is shown in Figures 14 and 15. Trend and fault analysis information is displayed on the front panel along with the start and stop buttons. Performance trends are indicated by a series of four lights for each of the seven critical parameters: green (normal), amber (caution), flashing red (warning) and red (alarm/shutdown). Individual cell voltages for both modules are sequentially scanned. The cell number and module to which the voltage trend information applies are displayed to the left of the performance trend indicator lights.

The 16 maintainable printed circuit cards are located directly behind the Trend and Fault Analysis Panel. Manual controls and overrides are located behind a removable panel since access to manual controls is not necessary during normal system operation. Overrides for the seven system shutdowns, blowers, N_2 purge valve and module currents are provided along with the manual EDCM and WVEM current adjustments.

Process Air Blower

The function of the process air blower is to provide an air flow rate of $5.7 \text{ dm}^3/\text{s}$ (12 scfm) through the WVE and EDC modules in series ($0.38 \text{ dm}^3/\text{s}$ -cell ($0.8 \text{ scfm}/\text{cell}$)) at a pressure drop of $4 \text{ kN}/\text{m}^2$ (16 in water). The process air blower is shown in Figure 11.

Cooling Air Blower

The function of the cooling air blower is to draw cooling air in parallel through the WVE and EDC modules to remove waste heat generated in the electro-

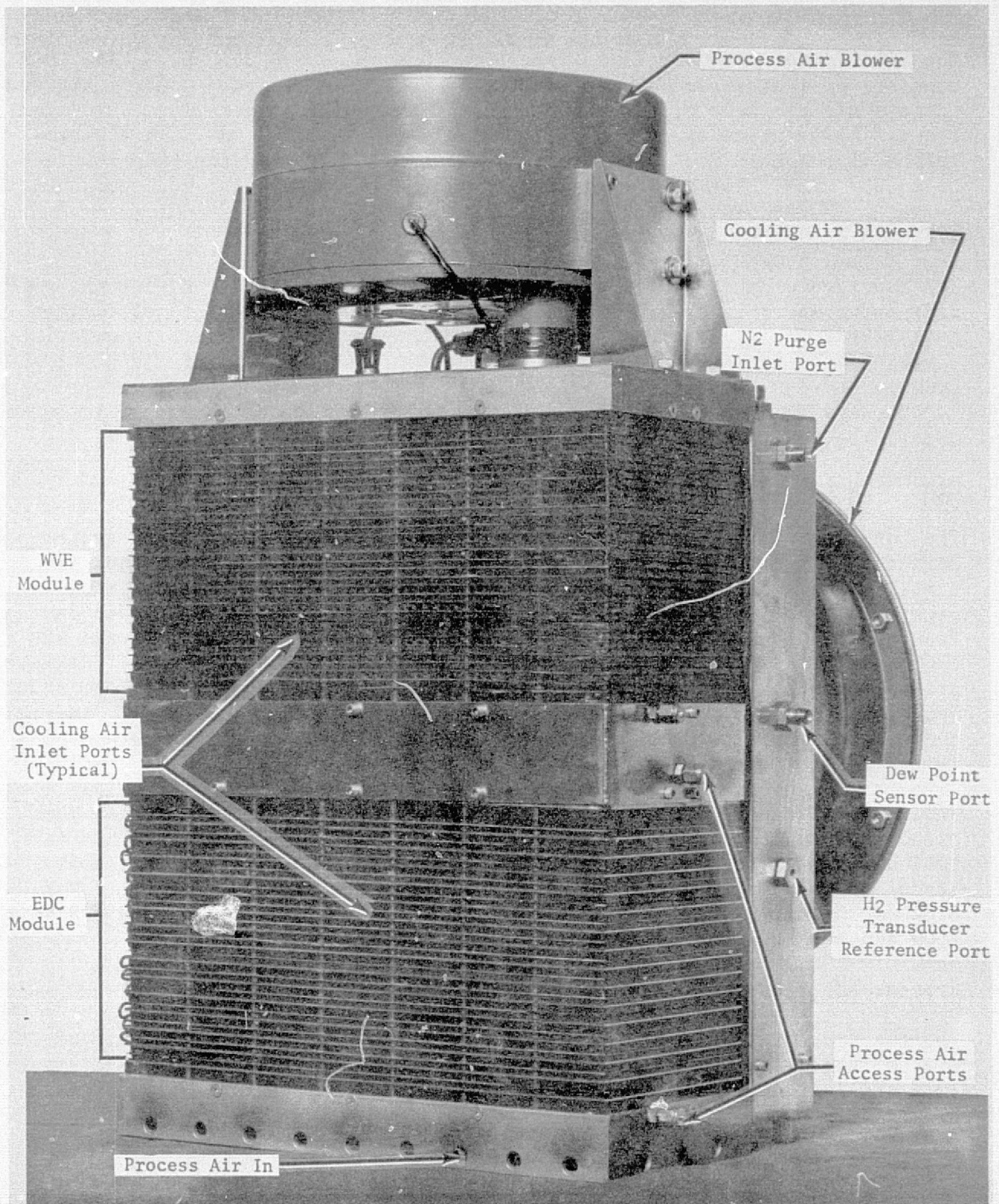


FIGURE 11 EARS MECHANICAL COMPONENTS ASSEMBLY - FRONT VIEW

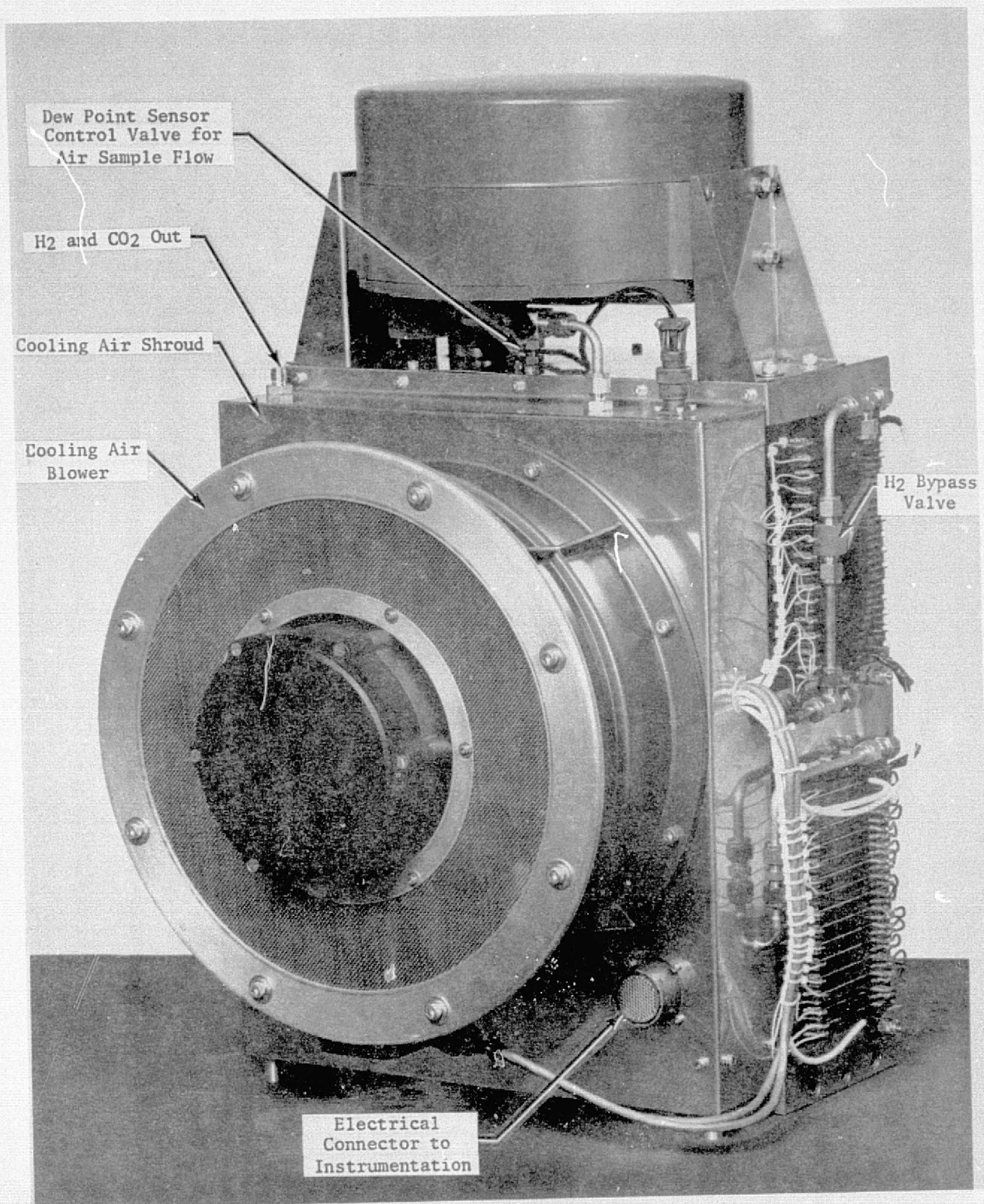
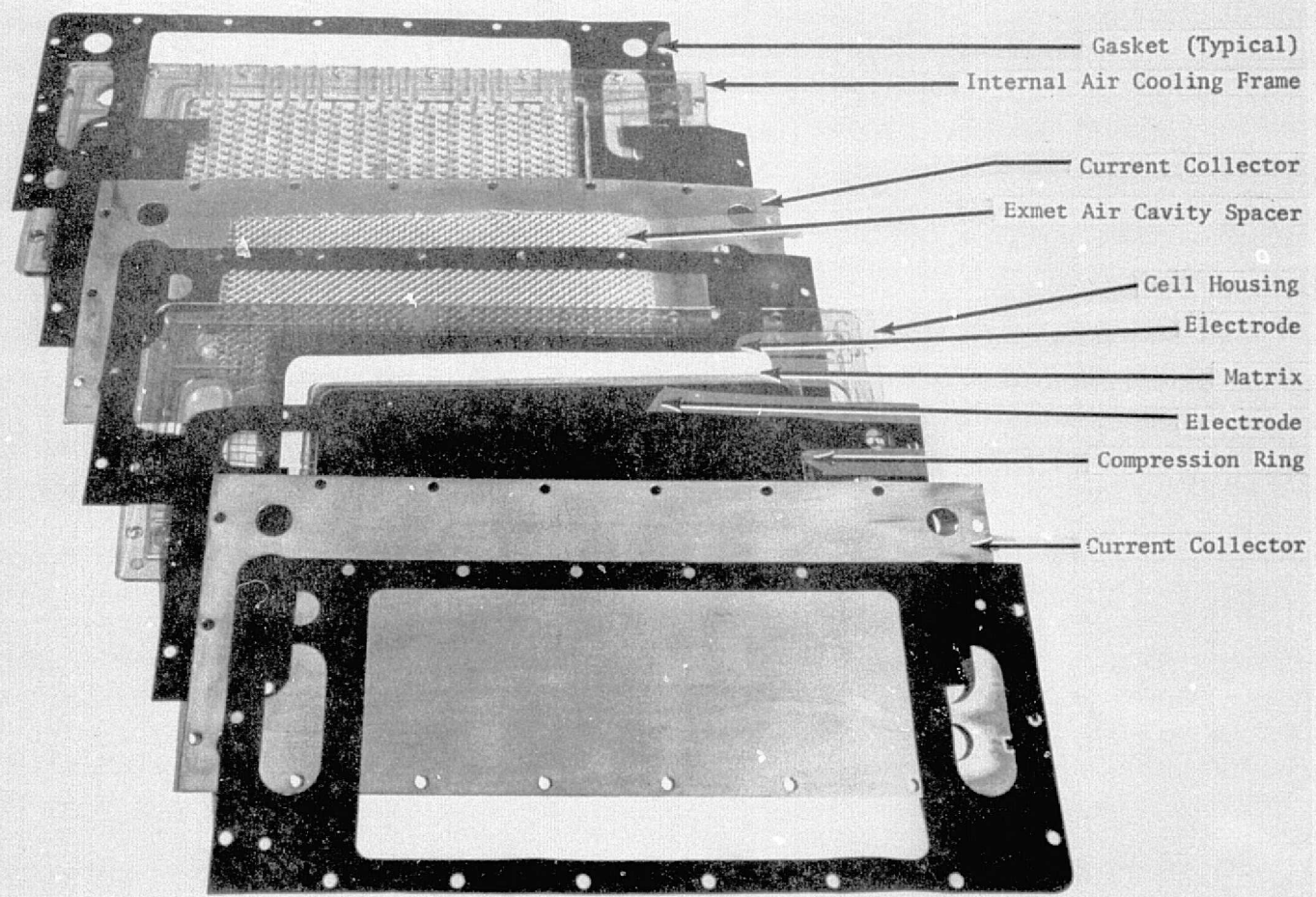


FIGURE 12 EARS MECHANICAL COMPONENTS ASSEMBLY - REAR VIEW



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FIGURE 13 EDC OR WVE SINGLE-CELL ASSEMBLY

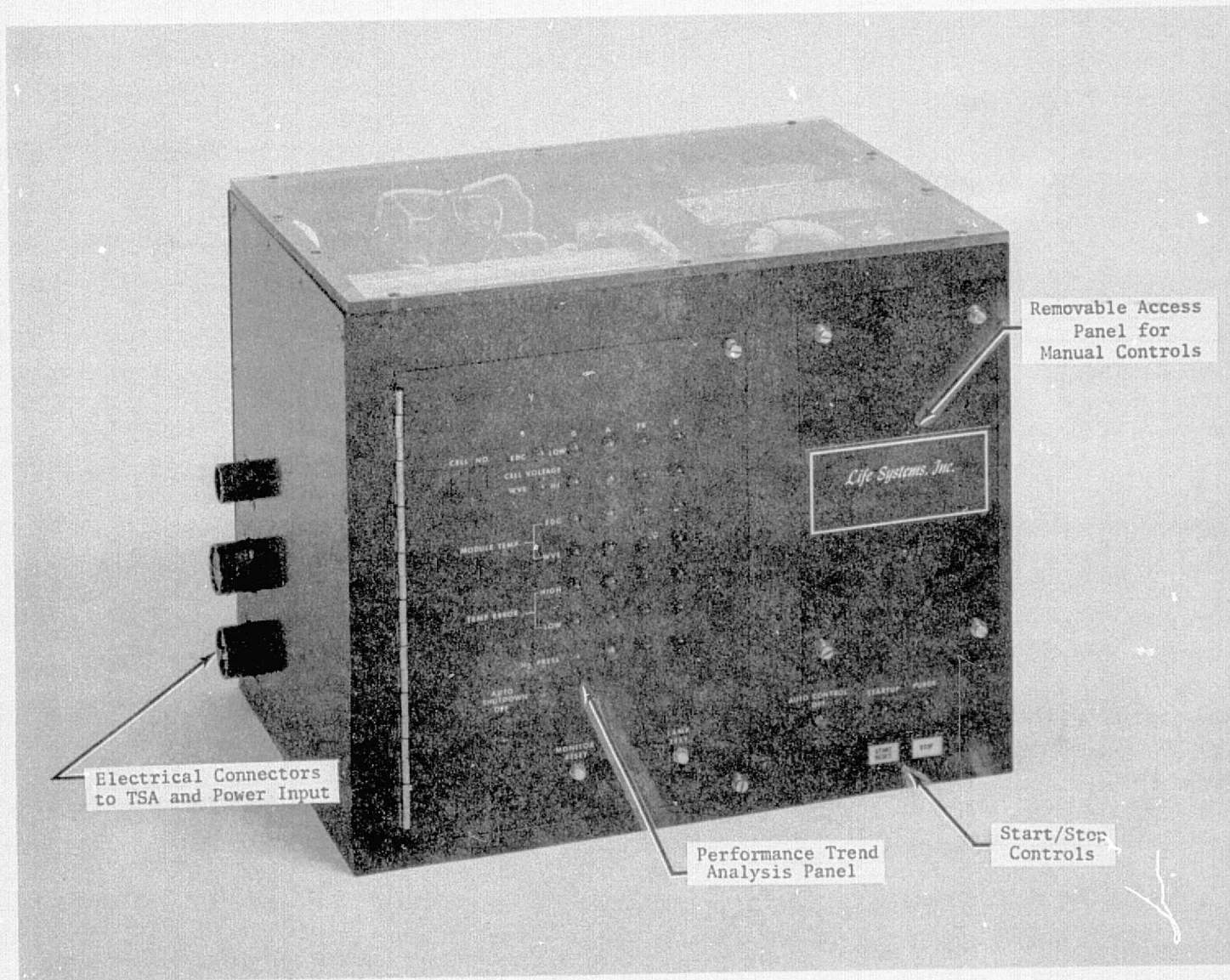


FIGURE 14 EARS INSTRUMENTATION ENCLOSURE

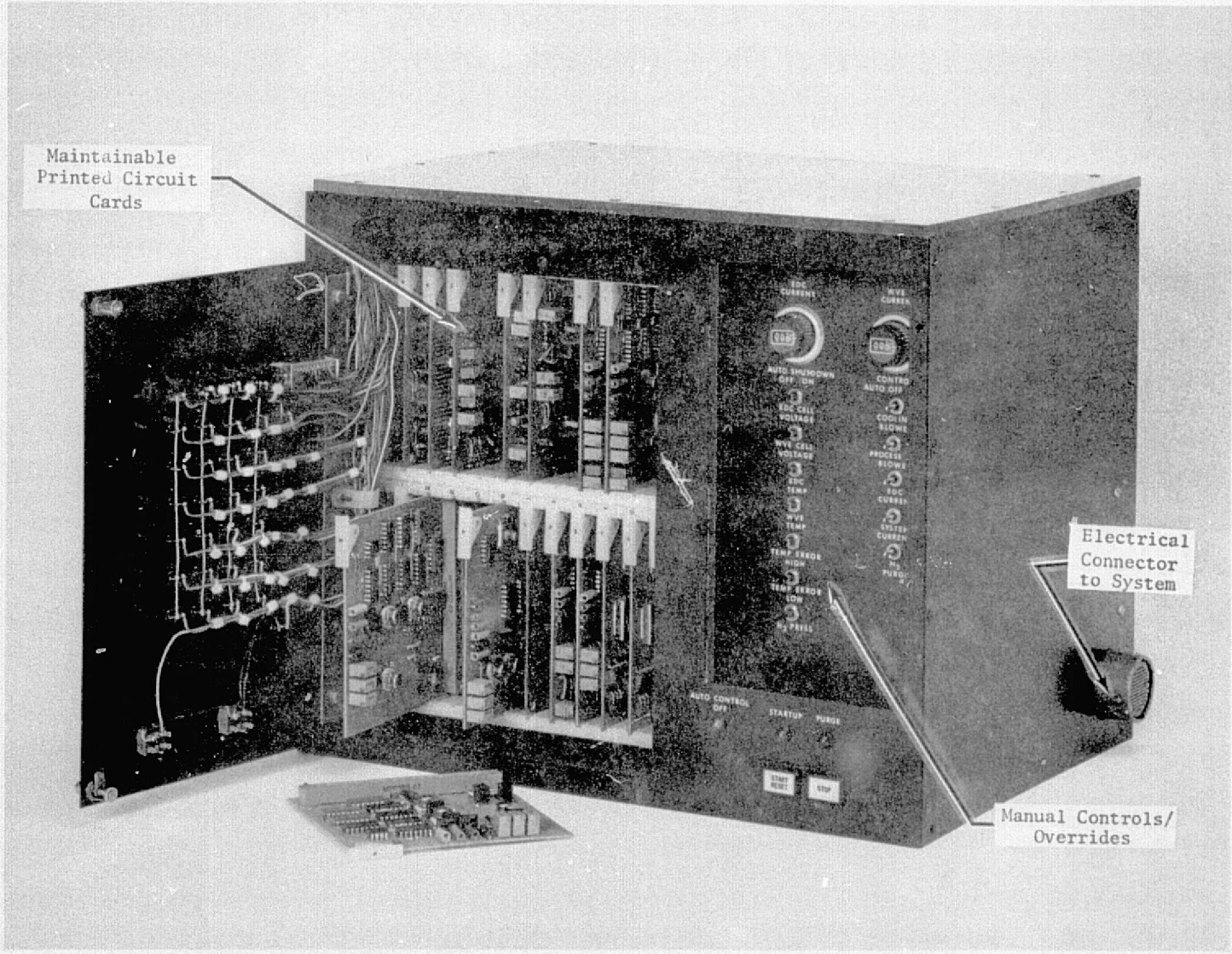


FIGURE 15 EARS INSTRUMENTATION WITH ACCESS PANELS REMOVED/OPEN

chemical cell reactions. The cooling air flow rate is approximately 99.1 dm³/s (210 scfm) at a pressure drop of 0.9 kN/m² (3.5 in water). The cooling blower is shown in Figure 12.

Hydrogen Backpressure Regulator

The function of the H₂ backpressure regulator is to maintain the pressure within the system's H₂-containing lines and components at a level greater than or equal to 6.9 kN/m² (1 psi) above ambient pressure. The H₂ pressure is maintained above ambient to insure that any possible H₂ leakage would be internal-to-external and would therefore be sensed by a H₂-in-air sensor such as the TRHS. The backpressure regulator is located at the rear of the mechanical components assembly below and to one side of the cooling air blower (not visible in Figure 12).

Additional Components

Pressure transducers, thermistors, the dew point sensor, solenoid valves, filters and manual valves are located on or inside the cooling air blower shroud. The function of these additional components is to monitor system performance and route gas streams appropriately during normal operation and mode transition sequences.

Refurbishment Activities

Since the EARS was built and tested prior to the present contract, various refurbishment activities were required prior to beginning the test program. These activities included:

1. incorporation of the power-sharing concept into the control/monitoring instrumentation package of the EARS,
2. incorporation of a cooling air blower speed control to reduce blower noise and allow a constant fixed cooling air flow rate,
3. replacement of the WVE cell matrices with LSI-developed customized matrices to increase the tolerance to differential pressure (H₂ to air) without increasing electrical resistance,
4. replacement of the EDC cell matrices with LSI-customized asbestos matrices for high moisture tolerance, high differential pressure applications,
5. disassembly, cleaning and reassembly of electrochemical cell parts,
6. reassembly of the EARS, including recharge of the individual modules,
7. incorporation of monitoring capability to continuously print out individual WVEM and EDCM cell voltages to chart recorders, and

8. replacement of minor electrical printed circuit card components which proved faulty.

TEST SUPPORT ACCESSORIES

The function of the TSA is to supply the fluid and electrical interfaces required to operate the EARS and to display operating parameter levels in engineering units. The TSA schematic is shown in Figure 16. A photograph of the EARS test facility, including the TSA, is presented in Figure 17.

Fluid Interfaces

The EARS TSA provides all necessary fluid interfaces to vary process operating conditions as needed. Ambient air at a controlled flow rate is mixed with CO_2 to attain the desired pCO_2 level and then cooled prior to entering the air saturator tank. This precooling removes heat generated by the blower. The air is then saturated with water vapor to slightly above the desired dew point temperature. An automatic saturator tank fill sequence is provided so that the saturator tank remains full during unattended operation. After leaving the saturator tank the air passes through a condensing heat exchanger which controls the desired dew point temperature. Any excess water or condensate is removed in a trap and returned to the saturator tank. The process air dry bulb temperature is controlled by heating the saturated air stream to the desired temperature prior to entering the EARS system.

Cooling air is drawn from the ambient by the EARS cooling air blower through a heat exchanger which maintains the cooling air at the same temperature as that of the process air. Process air vents through the TSA so that the flow rate can be measured. Cooling air is vented to ambient. Nitrogen purge gas is supplied upon shutdown at a controlled flow rate and dew point using a flow controller and saturator tank. The TSA also supplies H_2 required during shakedown and EDC verification testing prior to integrated EARS system operation.

Electrical Interfaces

The TSA supplies 115 VAC, 60 Hz, single-phase power to the EARS system. The power interface is the only electrical interface required by the system. The TSA, however, does provide a system shutdown signal to protect the EARS against out-of-tolerance RH conditions caused by a TSA failure. The RH shutdown signal works by setting the desired dew point temperature and tolerance band, and the desired dry bulb temperature and tolerance band on the RH shutdown controller (See Figure 17). In this manner the TSA RH shutdown signal insures that the EARS will not receive process air outside the desired humidity window during unattended operation.

Data Display of Engineering Parameters

The TSA provides for the data acquisition and display of the following system parameters for both the EDC and WVE modules: dry bulb temperature, dew points and pCO_2 of the inlet and outlet process air, dry bulb temperature of the inlet and outlet cooling air, module and individual cell voltages, and current.

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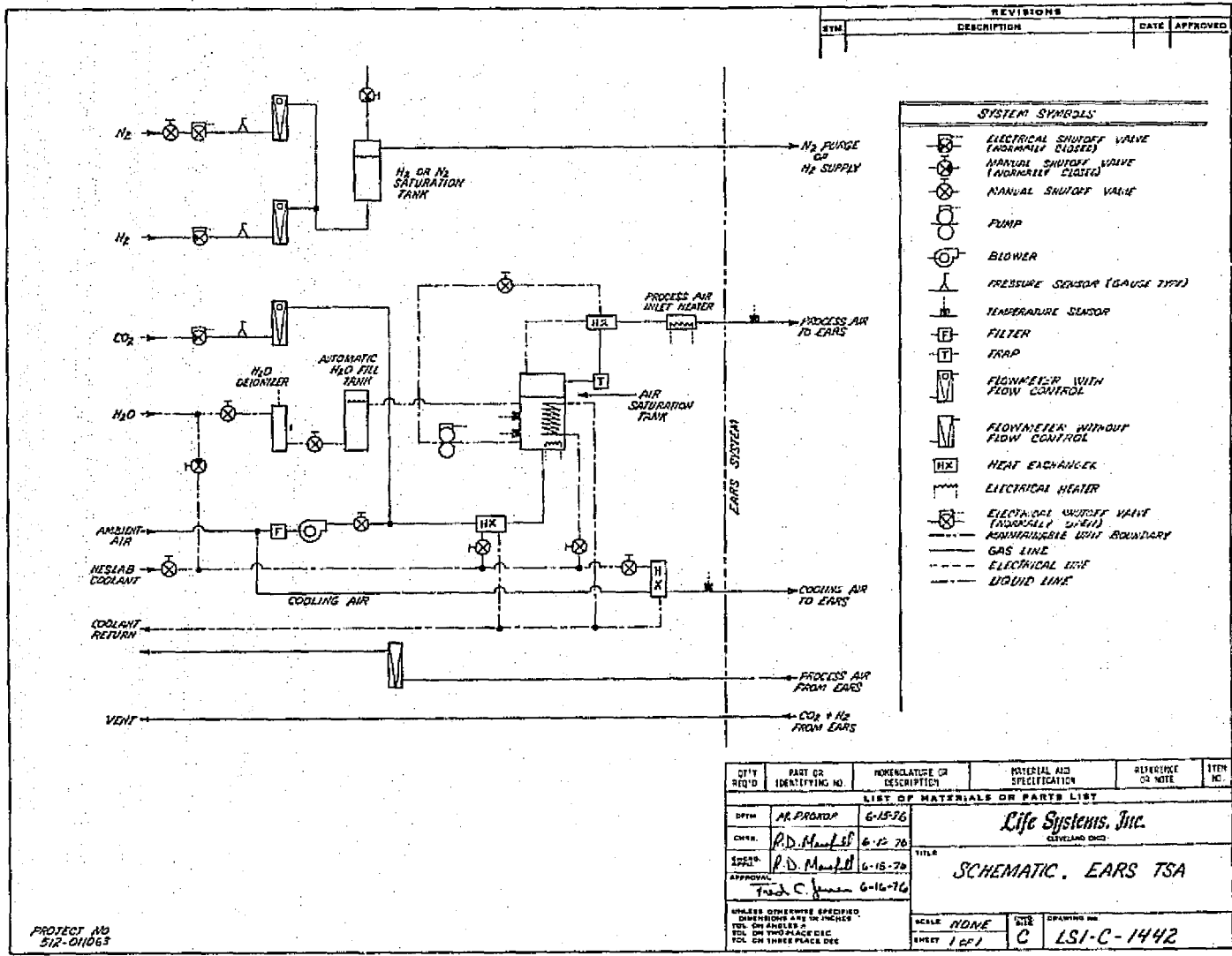


FIGURE 16 EARS TSA SCHEMATIC

Life Systems, Inc.

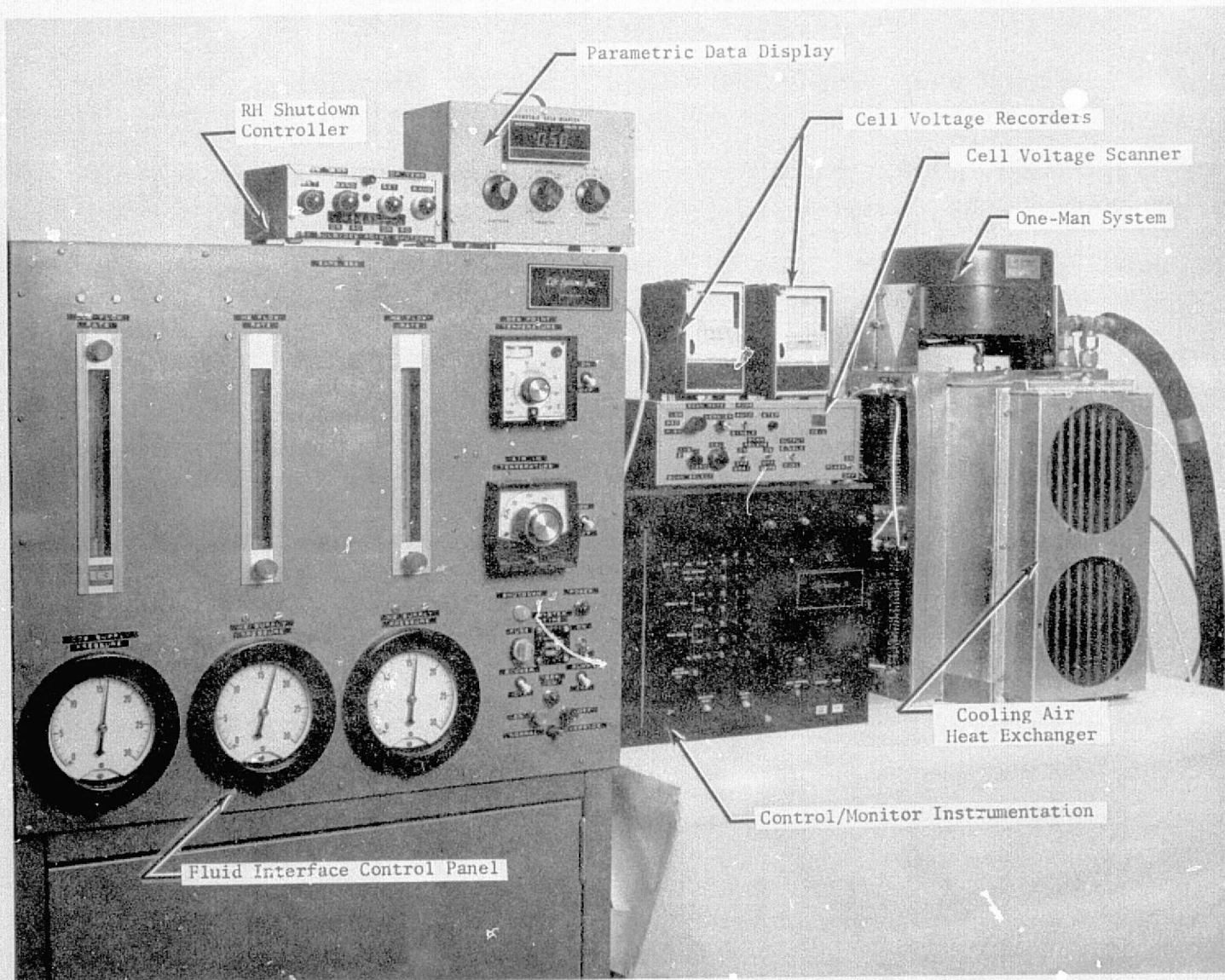


FIGURE 17 EARS TEST FACILITY

The EDC and WVE individual cell voltages are continuously monitored and recorded on two chart recorders. The test stand also provides for measuring the pCO_2 of the anode exhaust gas and the H_2 and CO_2 exhaust pressure. The parametric values related to the TSA and EARS operation are measured using the devices listed in Table 5. The expected accuracy of each device is also listed, along with the location of the sampling ports. Each parameter can be read directly in engineering units from a single digital panel meter using multi-position selector switches (See Figure 17).

MINI-PRODUCT ASSURANCE PROGRAM

A mini-Product Assurance Program was established, implemented and maintained throughout all phases of contractual performance including design, fabrication, purchasing and testing.

Quality Assurance

Quality Assurance activities were included during the design studies, interface requirement definitions and during inspection of fabricated and purchased parts. The objective was to search out quality weaknesses and provide appropriate corrective action. Also, a quality assurance effort was involved in the preparation of the final report with the objective of identifying and resolving deficiencies that could affect the quality of future equipment.

Reliability

Reliability personnel participated in the program to insure (1) proper calibration of test equipment and TSA instrumentation, (2) adherence to test procedures and (3) proper recording and reporting of test data and observations. A survey of the system and TSA design was performed to determine the calibration requirements for testing. Appropriate components were calibrated during assembly and after installation.

A test procedure was followed to insure that all critical parameters were properly monitored and that the testing conformed to the program's quality assurance and safety procedures. All major testing required that a test plan be completed and reviewed.

Safety

A safety program was initiated to assure adherence to safety standards and procedures essential to protect personnel and equipment. The program consisted of identifying possible adverse subsystem characteristics, reviewing designs and design changes for potential safety hazards, reviewing NASA Alerts for safety information and incorporating the equipment's protective features.

TEST PROGRAM

The EARS Test Program was designed to evaluate the integrated WVE and EDC performance characteristics as a function of the primary operating parameters

TABLE 5 PARAMETRIC TEST INSTRUMENTATION

<u>Type of Measurement</u>	<u>Type of Instrument</u>	<u>Measurement Location</u>	<u>Expected Accuracy</u>
Temperature	Thermistors	Process air EDCM and WVEM in and out; cooling air in and out	±1.5K (3F) ^(a)
Dew Point Temperature	EG&G Dew Point Hygrometer Model 880	Process air EDCM and WVEM in and out	±1K (2F)
CO ₂ in H ₂ , %	Lira Infrared Analyzer Model 300	EDCM H ₂ and CO ₂ outlet	±1%
CO ₂ in Air, %	Lira Infrared Analyzer Model 300	EDCM process air in and out, and WVEM out	±1%
Process Air Flow Rate	Flow transducer	Process air outlet from WVEM	±1%
CO ₂ and H ₂ Flow Rates	Wet Test Meter	EDCM CO ₂ and H ₂ out	±1%
Current	Weston Digital Meter	EDCM and WVEM	±0.1A
Voltage	Western Digital Meter	EDC and WVE cells, EDCM and WVEM	±0.002V
Continuous Voltage	Rustrak Chart Recorder	WVE and EDC individual cell voltages	±5%
Continuous Temperature	Honeywell Chart Recorder	Process air EDCM in and out, WVEM out and cooling air in	±5%
Pressure	Pressure Transducer	EDCM H ₂ and CO ₂ exhaust	±2%

(a) Locally calibrated by mercury thermometer to within ±0.5K (1F)

that affect system performance, process air inlet $p\text{CO}_2$ and RH, and cell current density. System evaluation was completed during a Parametric/Endurance Test Program which included characterization of WVE and EDC performance (1) at baseline conditions, (2) over a $p\text{CO}_2$ range of ambient to 933 N/m^2 (7 mm Hg), (3) over a current density range of $\pm 50\%$ of baseline and (4) over an RH range of 35 to 90% for a dry bulb temperature range of 291 to 297K (65 to 75F). Prior to the Parametric/Endurance Test, a system Checkout/Shakedown Test was conducted to insure integrated TSA/EARS operability and to identify and correct potential problems.

Checkout/Shakedown Test

The objective of the EARS Checkout/Shakedown Test was to verify the operability of the reassembled EARS when integrated with the TSA. The purpose of the testing was to correct misalignments, to establish and reevaluate operating procedures and to familiarize personnel with integrated EARS and reconditioned TSA operation. All sensors and monitoring circuits were checked and calibrated, and all parameter shutdown set points were established.

During the checkout testing, a power transistor in the module control circuit shorted causing the bridge rectifier which supplies module power to fail. The cause of the failure was diagnosed as an infancy type of failure of an electronic component. The damaged parts were identified, reordered and replaced. No other problems were encountered during the shakedown testing.

Parametric/Endurance Test

The objective of the EARS Parametric/Endurance Test was to characterize system performance during 75 days of operation. Three parametric tests were run during this time to determine the effect of $p\text{CO}_2$, current density and process air inlet RH on system performance. The baseline operating conditions for the test are presented in Table 6. An EDC current density of 21.6 mA/cm^2 (20 ASF) was selected as baseline for direct comparison to previous data as opposed to the design value of 19.4 mA/cm^2 (18 ASF) (See Table 3).

Partial Pressure of CO_2 Test

The effect of $p\text{CO}_2$ levels on EARS performance was determined.

Objective. The objective of the $p\text{CO}_2$ testing was to determine the effect of process air inlet $p\text{CO}_2$ levels of ambient to 933 N/m^2 (7 mm Hg) on EDC performance. The WVE is not affected by changes in the $p\text{CO}_2$.

Results. The results of the $p\text{CO}_2$ testing are presented in Figure 18. The data was collected over the system operating time period of approximately 470 to 600 hours. The $p\text{CO}_2$ was varied during the testing with each $p\text{CO}_2$ level maintained for 4 to 20 hours, depending on the severity of the change, to insure steady-state performance data. The CO_2 removal efficiency at 400 N/m^2 (3 mm Hg) was 82% (TI = 2.25). The CO_2 removal efficiencies at the extremes of the $p\text{CO}_2$ range were 44% at 67 N/m^2 (0.5 mm Hg) and 89% at 933 N/m^2 (7 mm Hg).

TABLE 6 BASELINE OPERATING CONDITIONS

EDC

Air Flow/Cell, dm^3/s (Scfm)	0.37 (0.80)
pCO_2 , N/m^2 (mm Hg)	400 (3)
Inlet Relative Humidity, %	50 to 60
Inlet Process Air Temperature, K (F)	294 ± 3 (70 ± 5)
Cooling Air Flow Rate/Cell, dm^3/s (Scfm)	3.3 (7) ^(a)
Current, A	4.88
Current Density, mA/cm^2 (ASF)	21.5 (20)

WVE

Air Flow/Cell, dm^3/s (Scfm)	0.37 (0.80)
Inlet Relative Humidity, %	50 to 60
Inlet Process Air Temperature, K (F)	294 ± 3 (70 ± 5)
Cooling Air Flow Rate/Cell, dm^3/s (Scfm)	3.3 (7) ^(a)
Current, A	12.2
Current Density, mA/cm^2 (ASF)	53.8 (50)

(a) The cooling air flow rate is based on the maximum cooling capacity required at "worst" dry bulb and dew point conditions of the process air.

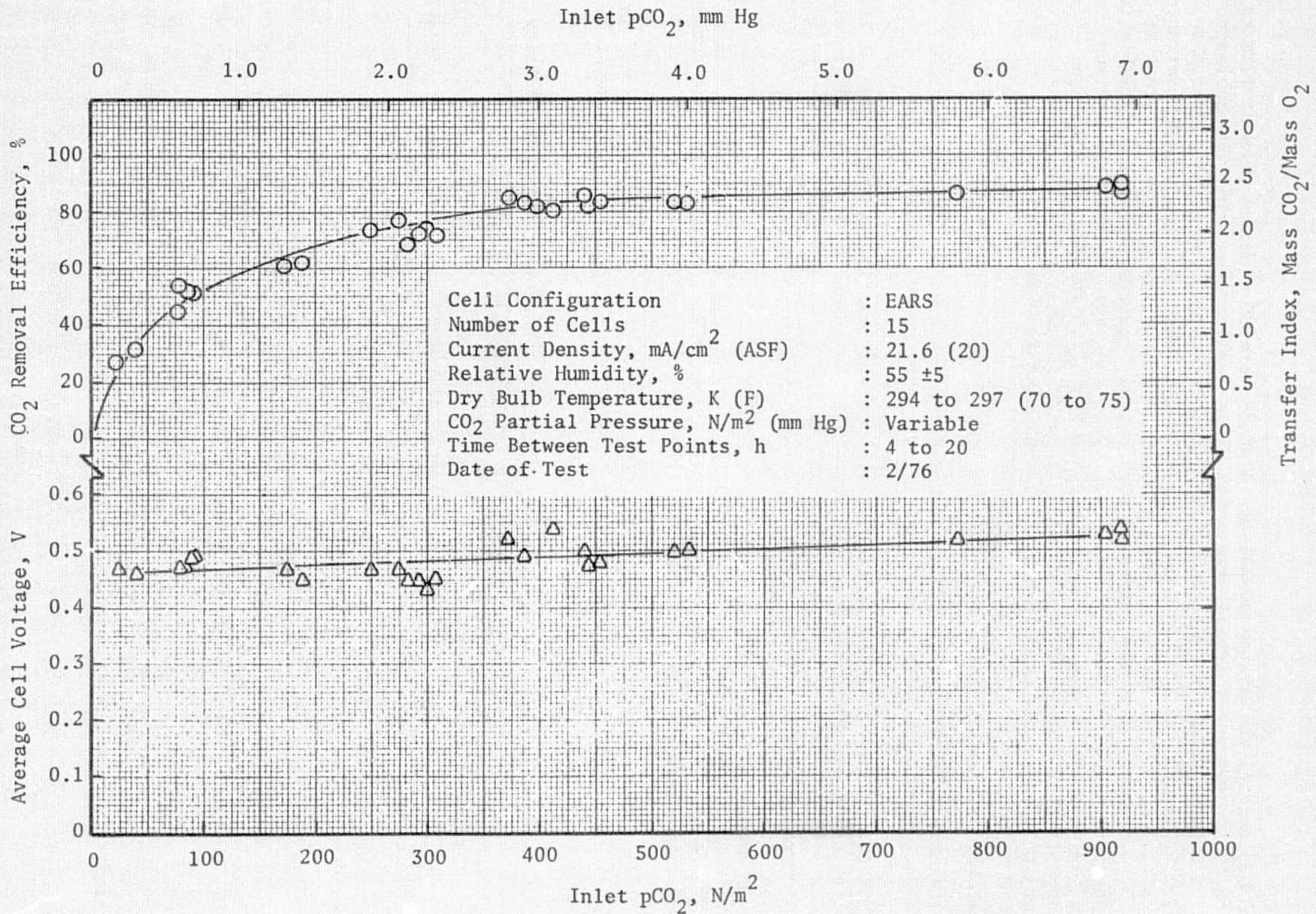


FIGURE 18 EFFECT OF INLET $p\text{CO}_2$ ON EDC PERFORMANCE AT 21.6 mA/cm² (20 ASF)

A CO₂ removal efficiency of 82% corresponds to a CO₂ removal rate of 1.18 kg/d (2.60 lb/day). For actual spacecraft cabin applications, this EDC overcapacity for a continuous 1.0 kg/d (2.2 lb/day) CO₂ generation rate would lower the cabin pCO₂ to 213 N/m² (1.6 mm Hg). At a continuous maximum CO₂ generation rate of 1.22 kg/d (2.68 lb/day), the cabin pCO₂ would only rise to 520 N/m² (3.9 mm Hg) to meet the increased CO₂ removal requirement. For a variable CO₂ generation profile based on crew duty cycle and cabin volume, the maximum cabin pCO₂ would always be less than 520 N/m² (3.9 mm Hg). In practical applications, the maximum pCO₂ would be only slightly above the nominal level, or for the one-man EARS approximately 267 N/m² (2.0 mm Hg). (8,17)

Current Density Test

The effect of current density on EDC and WVE performance and the combined effect of pCO₂ and EDC current density was determined.

Objective. The objective of the current density testing was to determine the effects of current density on EDC and WVE performance for various pCO₂ levels. Current density limits were established at the point where (1) the EDC voltage dropped to below 0.0V, (2) WVE cell voltage rose to above 2.0V or (3) ±50% of the design current density was attained.

Test Results. The effect of pCO₂ on EDC performance for 16.1 and 26.9 mA/cm² (15 and 25 ASF) are presented in Figures 19 and 20, respectively. The current density test data was collected over the period of approximately 680 to 1180 hours. During this test the system was operated for seven days at an EDC current density of 16.1 mA/cm² (15 ASF), four days at 26.9 mA/cm² (25 ASF) and four days at 32.3 mA/cm² (30 ASF), although no pCO₂ span was performed at 32.3 mA/cm² (30 ASF).

A cross plot of the CO₂ removal efficiency as a function of current density for various pCO₂ levels is presented in Figure 21. The optimum current density increases with increasing pCO₂ levels. For a pCO₂ level of 400 N/m² (3 mm Hg), the optimum CO₂ removal efficiency occurred between 20 and 22 mA/cm² (18.6 and 20.4 ASF). The EDC average cell voltage was higher than obtained for previous EARS/EDC cell configurations. At the 21.6 mA/cm² (20 ASF), the average EDC cell voltage was 0.50V which corresponds to 36.6W of available power. The average EDC cell voltage as a function of current density is presented in Figure 22.

Figure 23 shows the average WVE cell voltage obtained as a function of current density. The current density for the WVE during the testing was 2.5 times that of the EDC. The WVE, however, having the lower performance E5 anodes, was unable to maintain an average cell voltage lower than the 2.0V limit for long-term operation at current densities higher than 59.2 mA/cm² (55 ASF). For comparison, a short term, eight-hour WVE current density span at 72% RH was performed immediately following system restart after shutdown number 4 at approximately 780 hours. The results of this short term test are shown in Figure 23.

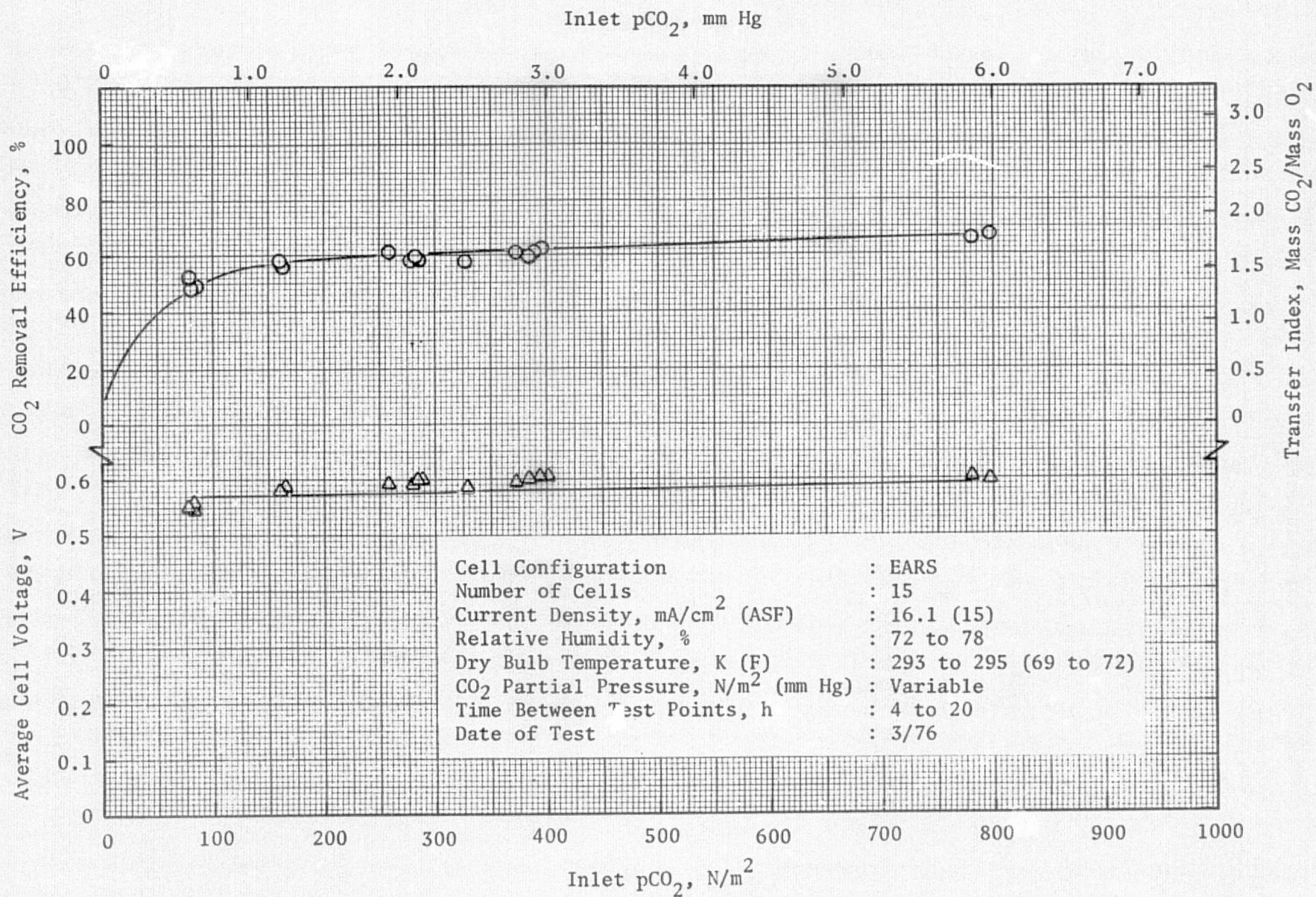


FIGURE 19 EFFECT OF INLET $p\text{CO}_2$ ON EDC PERFORMANCE AT 16.1 mA/cm² (15 ASF)

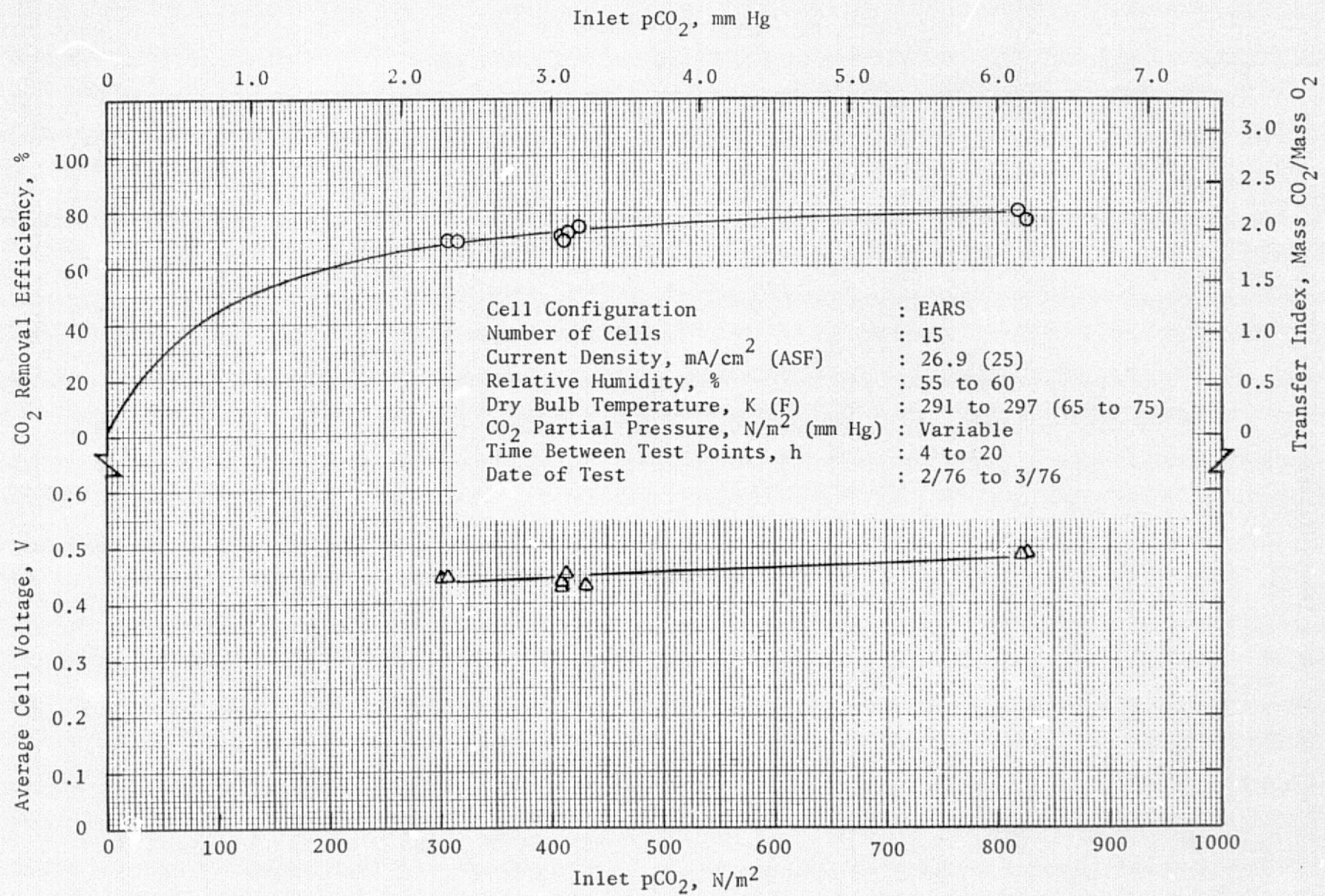


FIGURE 20 EFFECT OF INLET pCO₂ ON EDC PERFORMANCE AT 26.9 mA/cm² (25 ASF)

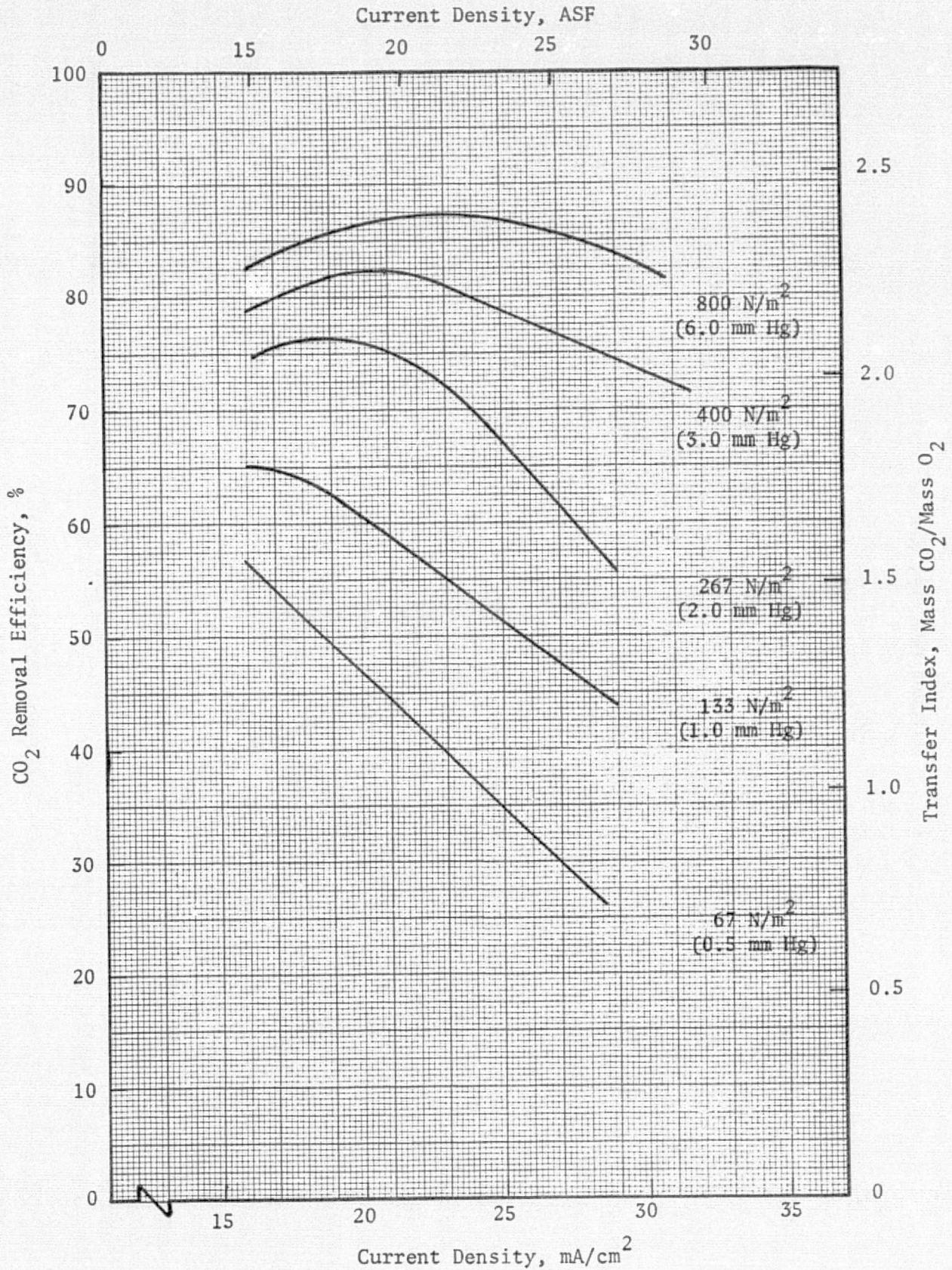


FIGURE 21 EFFECT OF CURRENT DENSITY ON CO₂ REMOVAL AT VARIOUS pCO₂ LEVELS

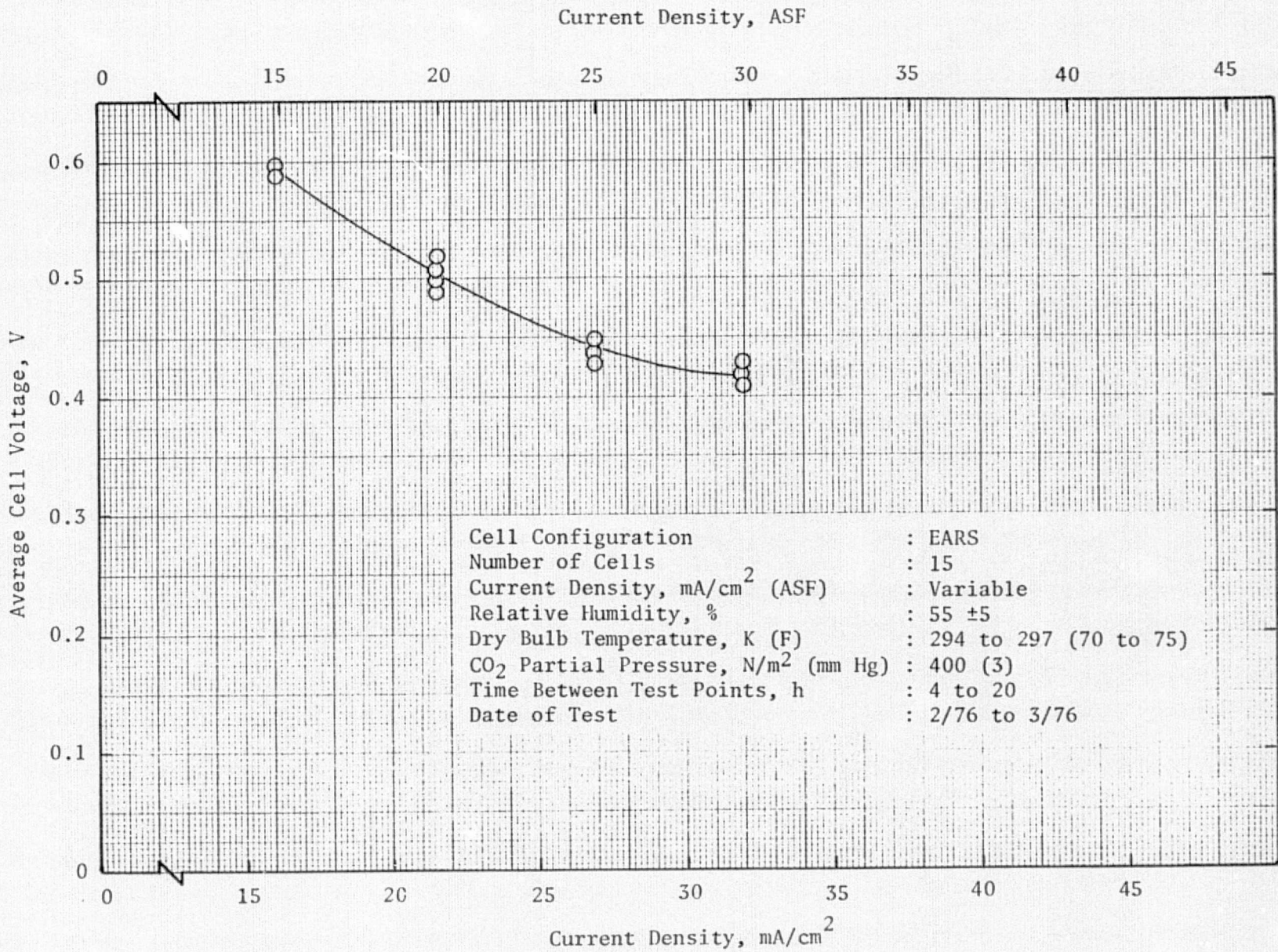


FIGURE 22 EFFECT OF CURRENT DENSITY ON EDC VOLTAGE

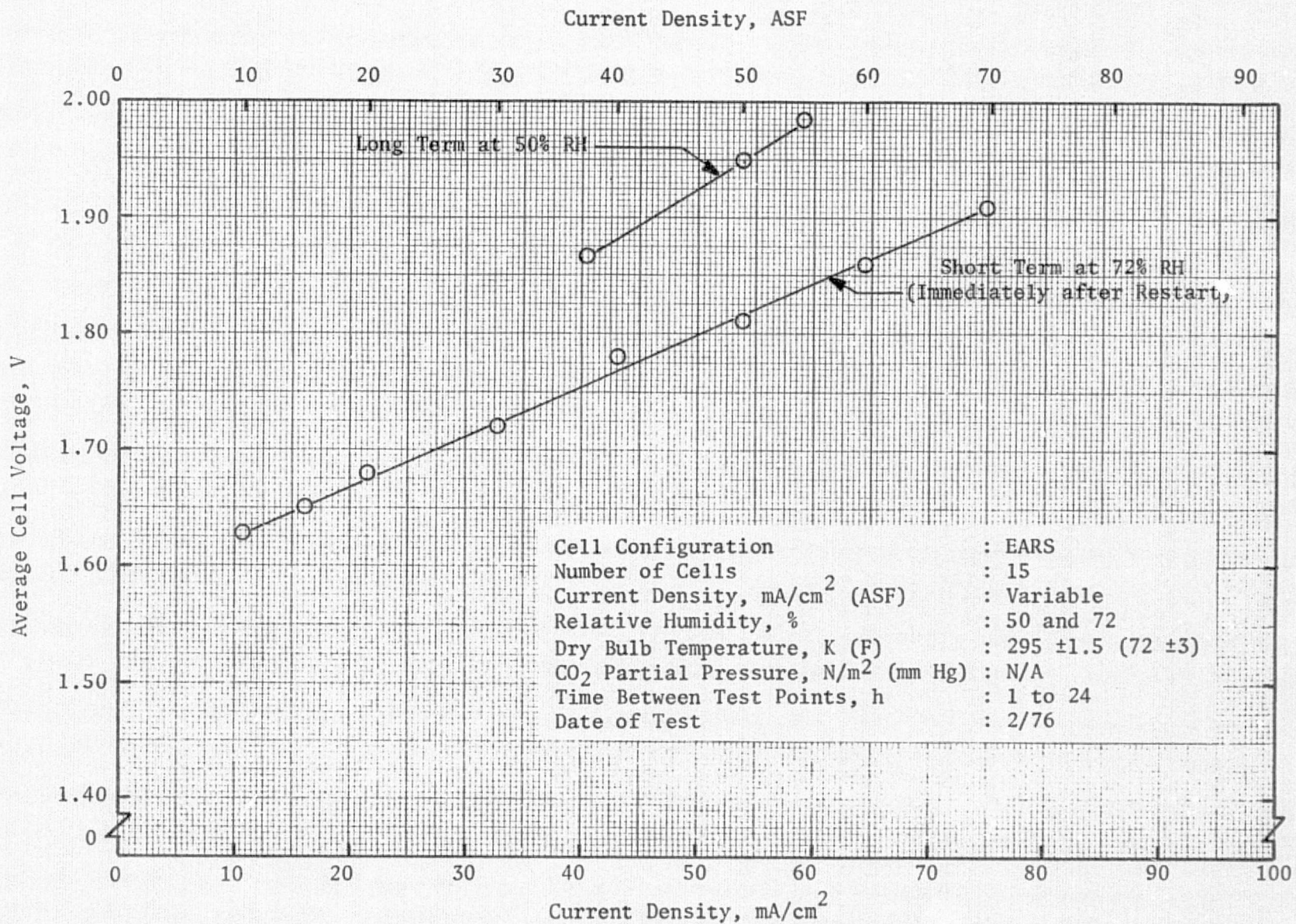


FIGURE 23 EFFECT OF CURRENT DENSITY ON WVE VOLTAGE

Relative Humidity Test

The effect of process air RH on EARS performance was determined.

Objective. The objective of the RH testing was to evaluate the ability of the EARS to perform its design function (i.e., O₂ generation and CO₂ removal) over an RH range of 35 to 90% for dry bulb temperatures between 291 and 297K (65 and 75F).

Results. The effect of RH on EDC performance and WVE performance is presented in Figures 24 and 25, respectively. The data was collected over the system operating time period of approximately 1220 to 1930 hours. Process air RH was varied during the test with each RH level maintained for 4 to 20 hours, depending on the severity of the change, to insure steady-state performance data. The EARS test conditions demonstrated during the RH testing are presented in Figure 26. Emphasis was placed on operation over the more difficult low RH range (<50%).

The EDC performance, as measured by cell voltage, reached a maximum between 50 and 60% RH. Cell voltage decreased at RH levels above 60% and below 50%. The cell voltages presented in Figure 24 were normalized to 297K (75F) to eliminate temperature effects. Figure 27 shows the effect of temperature on EDC cell voltage at 50% RH. The slope of a least-squares fit straight line to the data is 8 mV/K (4 mV/F).

The CO₂ removal efficiency remained steady at an average value of 82% (TI = 2.25) between 35 and 70% RH but decreased sharply to 64% (TI = 1.75) at 90% RH. Since the system requires a CO₂ removal efficiency of 69% for a nominal one-man CO₂ removal rate, the EDC performed its design function over the RH range of 35 to 85%. Of prime importance is the constant CO₂ removal efficiency over the 35 to 70% RH range which is the projected RH range for future EARS/EDC applications in the Regenerative Life Support Evaluation experiment. (18)

As expected, WVE cell voltage increased as RH decreased. During the testing all cell voltages remained below 2.0V over the entire RH range. The WVE₂ successfully performed its design function, i.e., operated at 53.8 mA/cm² (50 ASF) over the entire RH range of 35 to 90%. The data presented in Figure 25 was normalized to 297K (75F) using the data presented in Figure 28. The slope of the least-squares fit straight line to the test data is -10 mV/K (-5 mV/F).

Parametric/Endurance Test Summary

The EARS performance data obtained during the Parametric/Endurance Test are plotted as a function of time in Figure 29. Only those data points obtained at baseline operating conditions are included. Testing covered a total of 85 days (2038 hrs) of operation. The last 33 days during the RH testing were continuous without any type of shutdown. A total of six shutdowns occurred during the testing. Three were system related and three were TSA related. The shutdowns, reasons and corrective actions are summarized in Table 7.

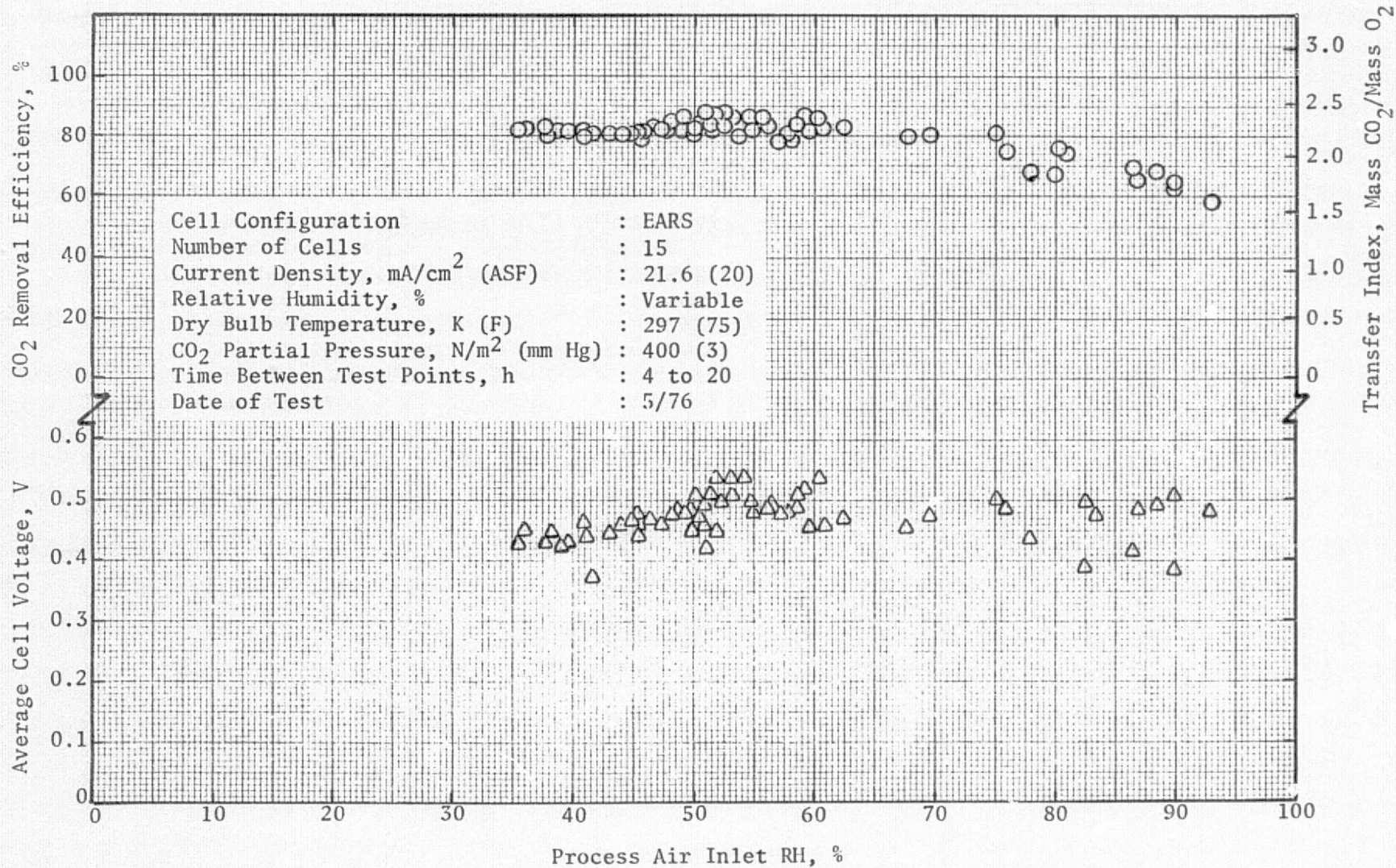


FIGURE 24 EFFECT OF RELATIVE HUMIDITY ON EDC PERFORMANCE

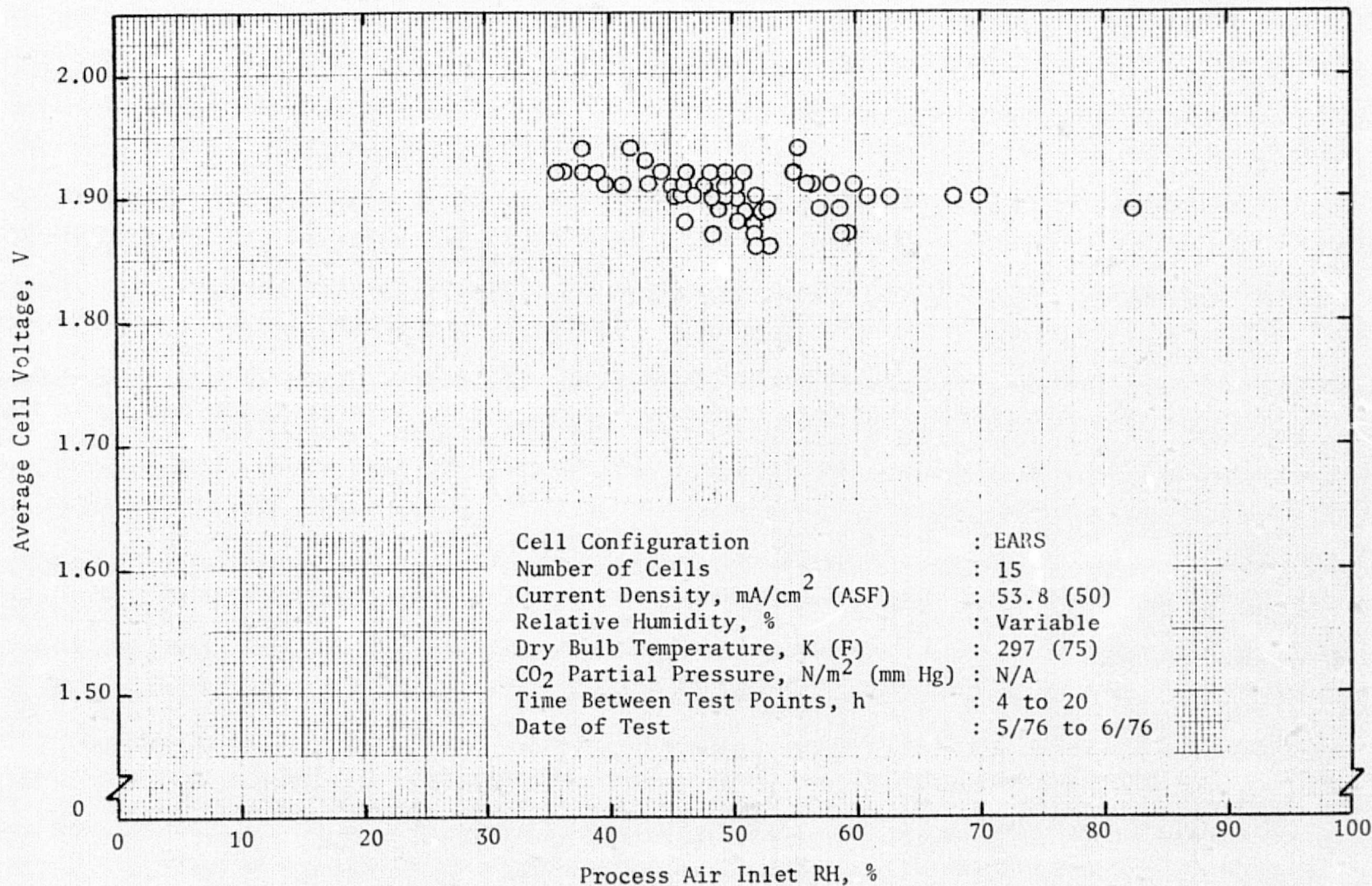


FIGURE 25 EFFECT OF RH ON WVE VOLTAGE

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PSYCHROMETRIC CHART
NORMAL TEMPERATURES

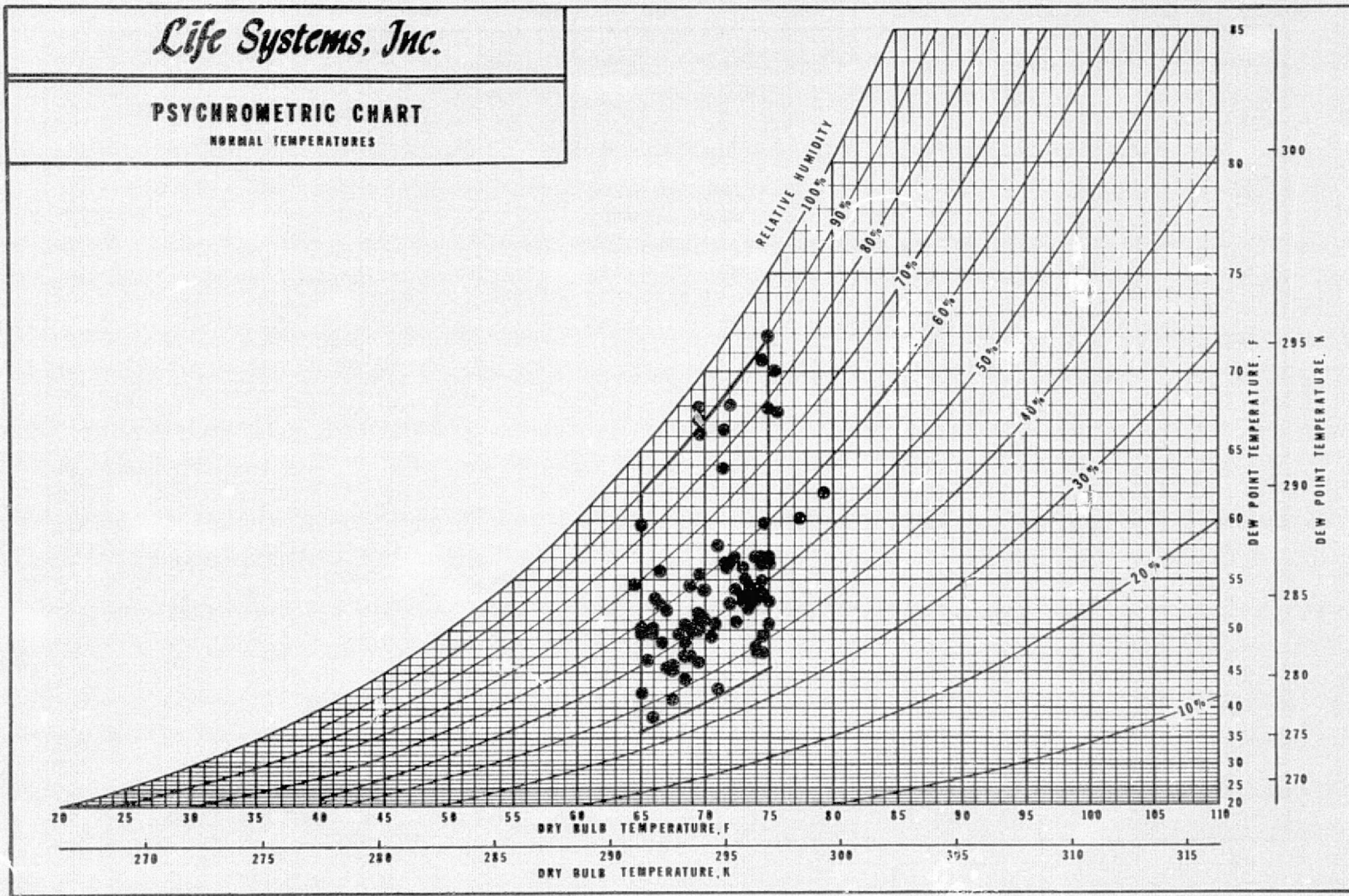


FIGURE 26 DEMONSTRATED EARS OPERATION OVER RH RANGE

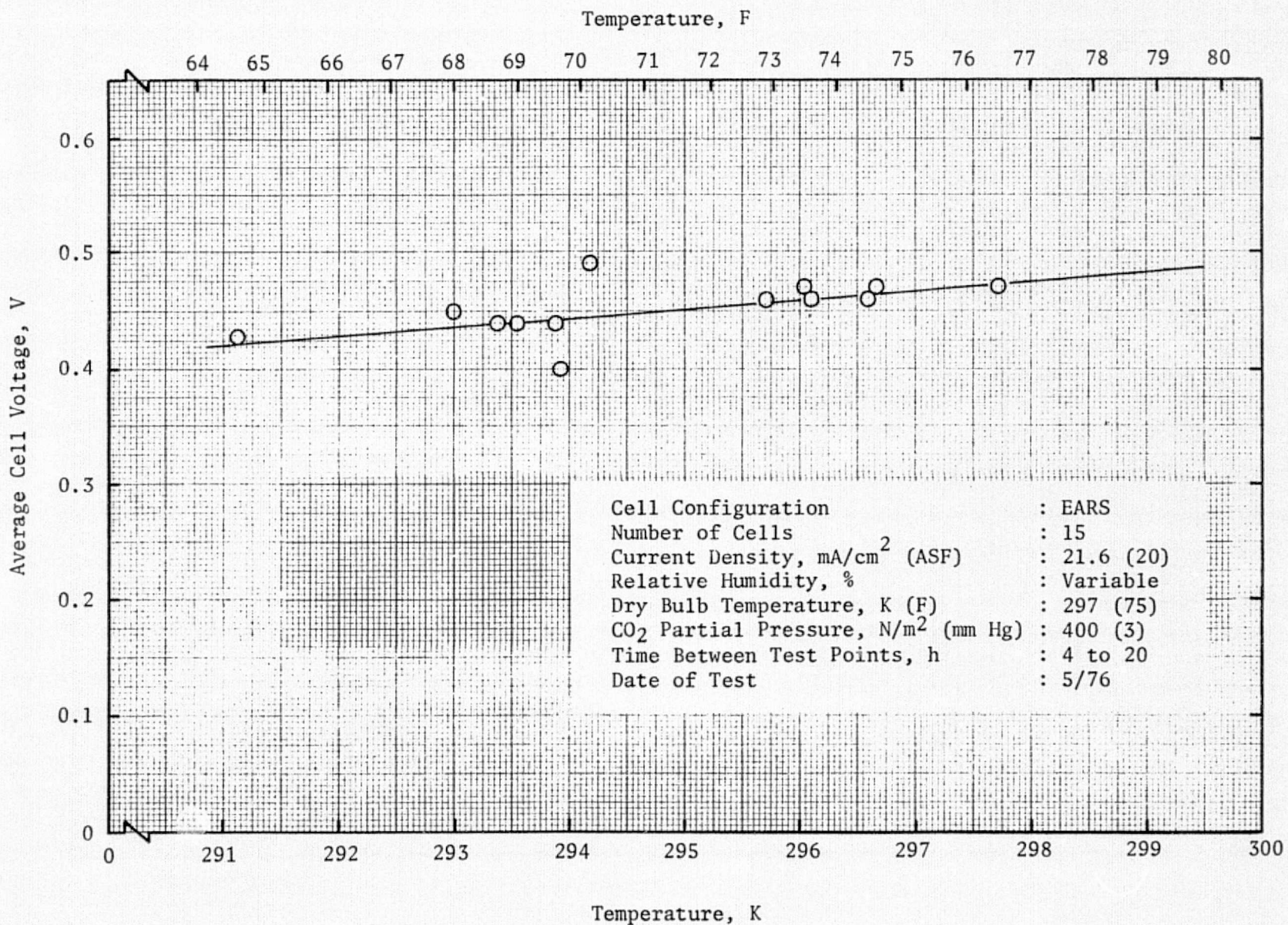


FIGURE 27 EFFECT OF TEMPERATURE ON EDC VOLTAGE

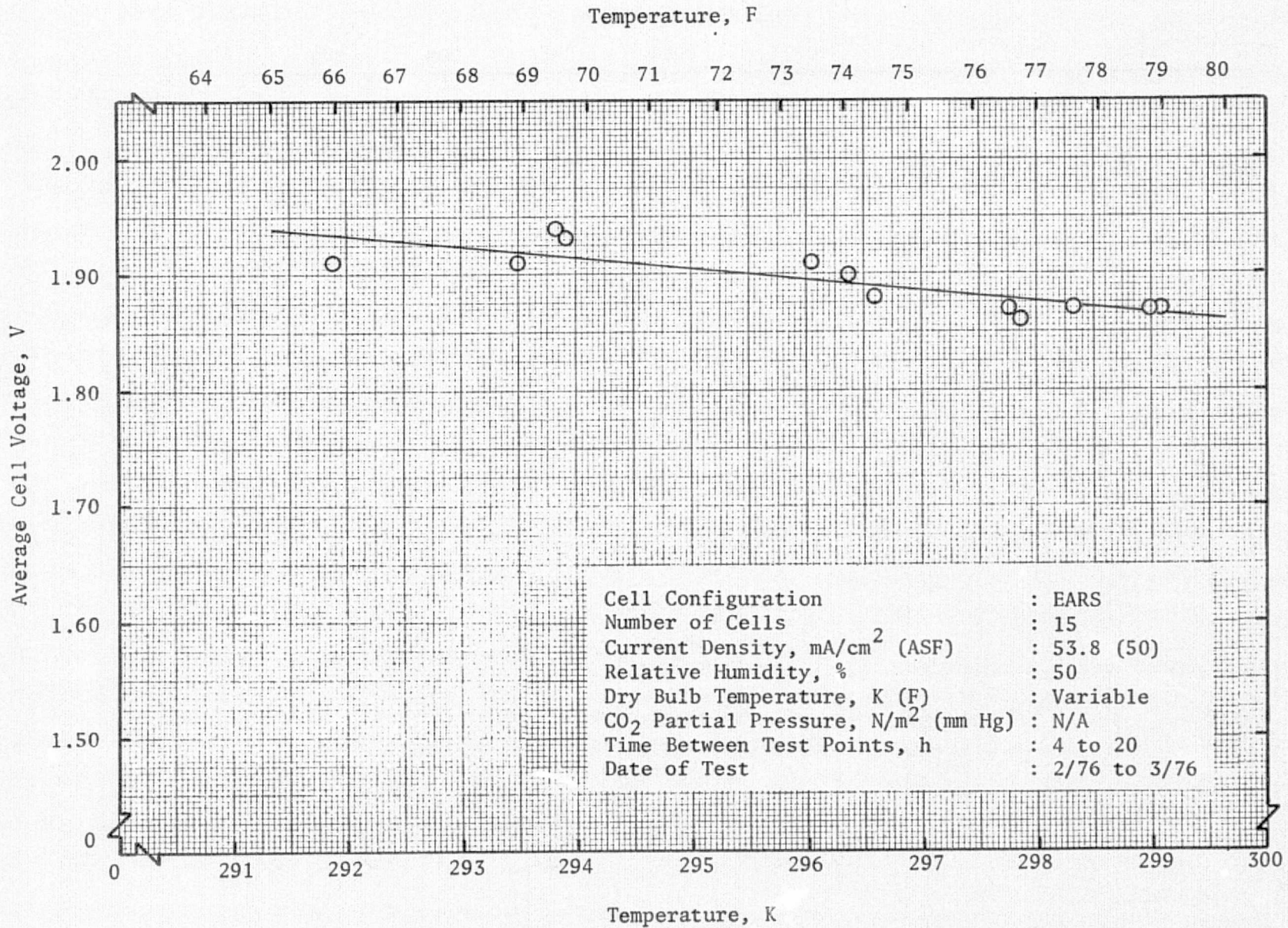


FIGURE 28 EFFECT OF TEMPERATURE ON WVE VOLTAGE

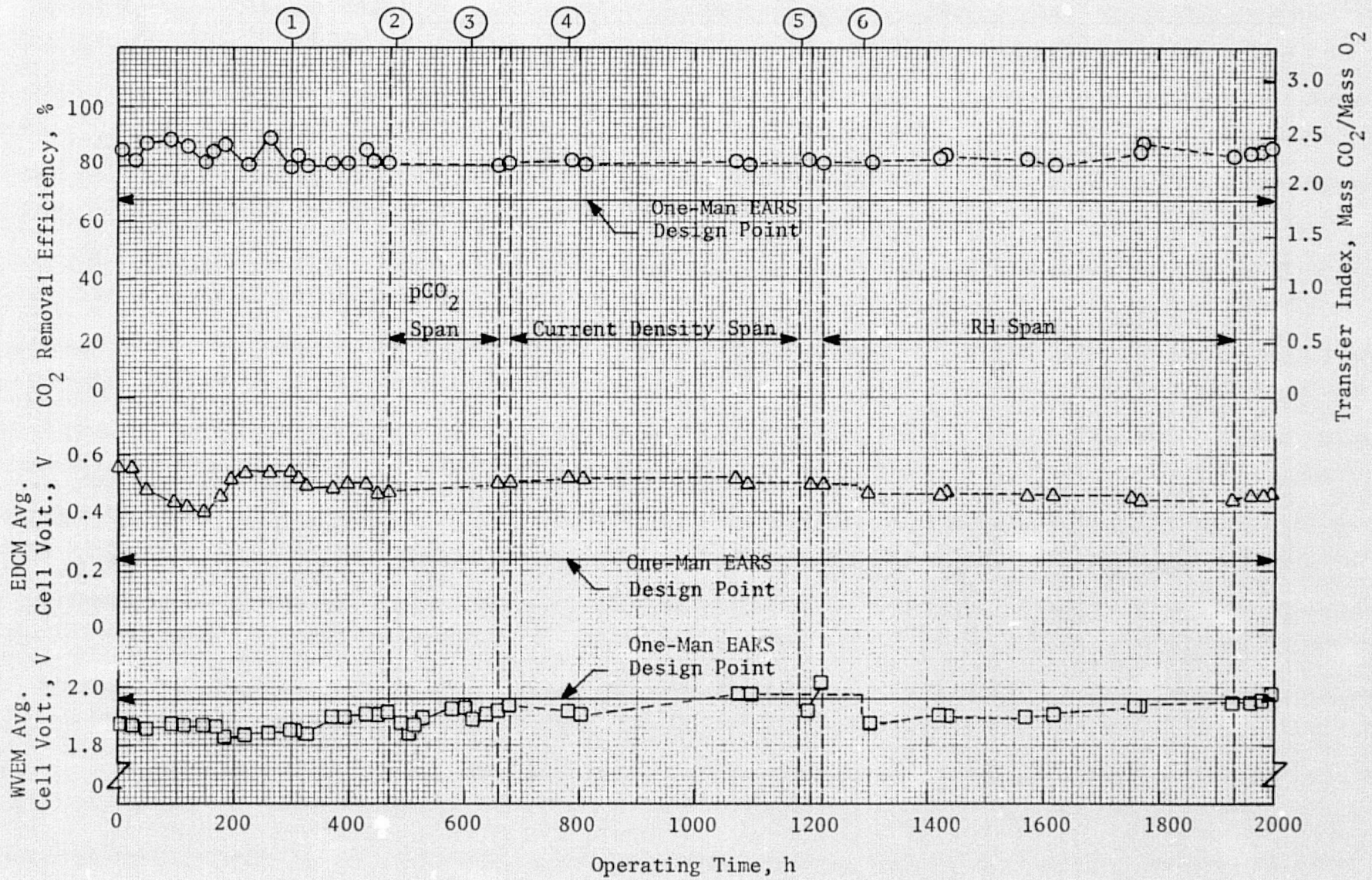


FIGURE 29 ONE-MAN, EARS PARAMETRIC/ENDURANCE TEST

TABLE 7 ONE-MAN, EARS SHUTDOWN SUMMARY

Shutdown No.	Cause of Shutdown	Corrective Action
1	Operator shutdown to investigate erratic current readings (TSA)	Minor electrical components replaced
2	TSA RH shutdown due to "noise" from cooling blower	RH shutdown time delay incorporated
3	Low individual cell voltage shutdown	Restarted at baseline conditions
4	Operator shutdown to investigate inconsistent TSA and system temperature readings	System thermistor and TSA thermocouple recalibrated
5	Low individual cell voltage shutdown following operation for 4 days at 32.3 mA/cm ² (30 ASF)	Restarted at baseline conditions
6	Operator shutdown when module operational limits were exceeded at 90% RH and 292K (67F)	Recharged WVE module and EDC module

The purpose of selectively plotting the test results for baseline operating conditions was to show system performance as a function of time only. The average WVE voltage rose during the testing from an initial value of 1.87V at startup to a final cell voltage of 1.97V at test termination. This change results in an average voltage degradation of approximately 49 $\mu\text{V/hr}$. This voltage degradation is comparable to that obtained for the E5B electrode previously tested, (15) except at a higher absolute level of 0.14V.

The average EDC showed a step change of 0.03V or from 0.50 to 0.47V during the testing. All of the 0.03V decrease occurred following module recharge (shutdown No. 6) and was therefore not time related. Minor fluctuations in EDC performance during startup (<200 hours) are attributable to establishing and verifying preselected baseline operating conditions and normal EDC startup voltage losses. No CO_2 removal efficiency degradation was observed during the testing. A summary of the performance data and its impact on power and heat generation is presented in Table 8. The calculations include only the power and heat generation associated with the WVE and EDC modules.

CONCLUSIONS

The following conclusions were reached based on the development program:

1. The EARS concept with power-sharing is a viable solution to provide O_2 generation, CO_2 removal and partial humidity control aboard manned spacecraft in an equivalent weight-effective manner.
2. The EARS tested is capable of controlling cabin pO_2 and pCO_2 over an RH range of 35 to 85%. The nominal system performance at the end of 85 days of testing was (1) CO_2 removal efficiency of 82%, (2) an EDC cell voltage of 0.47V and (3) a WVE cell voltage of 1.97V.
3. The LSI-D electrolyte is superior to the previously used electrolytes and should be used for future EARS applications. No performance degradation, either CO_2 removal efficiency or EDC voltage was noted after more than 2,000 hours of operation and long-term exposure to process air RH ranges from 35 to 60%.
4. The power-sharing concept is applicable to system level operation. Direct scale-up, incorporation into the one-man, EARS and 85 days of testing were completed.
5. The use of LSI-D electrolyte has further enhanced the attractiveness of power sharing by providing for increased EDC cell voltages (over 0.5V per cell at 19 mA/cm^2 (18 ASF)).
6. Continuous, long-term operation of an EARS at low RH values (35 to 60%) is possible as demonstrated by 33 days of uninterrupted operation during the RH span at the end of the EARS test program.

TABLE 8 ONE-MAN, EARS PERFORMANCE SUMMARY^(a)

CO ₂ Removal Efficiency, %	82
Average Cell Voltage, V	
WVEM	1.97
EDCM	0.47
Spacecraft Power Required, W	
WVEM	361.0
EDCM	<u>-40.5</u> ^(b)
Total	320.5
Heat Generated, W	
WVEM	135.0
EDCM	<u>55.6</u>
Total	190.6
Equivalent Weight Savings	
Due to Power Sharing, kg (Lb)	
Power at 0.268 kg/W (0.59 Lb/W)	10.90 (23.9)
Heat Rejection at 0.198 kg/W (0.437 Lb/W) ^(c)	<u>8.02 (17.7)</u>
Total	18.92 (41.6)

(a) After 2000 hours of operation

(b) Assuming 85% Spacecraft power conversion efficiency, i.e.,
34.4W/0.85 = 40.5W

(c) Without power sharing, EDC power would be rejected as heat

7. A combined, single process air and cooling air blower concept is compatible with LSI's internally air-cooled cell design concept as demonstrated through operation without temperature control and with equal process and cooling air inlet dry bulb temperatures.
8. Electrochemical Air Revitalization System technology readiness has been demonstrated, including LSI's high moisture tolerance electrochemical cell design and high performance LSI-D electrolyte at a scaled-up level to provide a sound basis for multi-man preprototype and prototype system designs.

RECOMMENDATIONS

The following recommendations are a direct result of this program.

1. A multi-man, engineering preprototype of an EARS system should be designed, fabricated and tested as the next logical development step towards an EARS flight experiment demonstration.
2. The next generation EARS should include LSI-D electrolyte, LSI customized matrices and the advanced EDC module design. Modification of the advanced design to tolerate wide RH ranges has been verified at the single cell level. The advanced EDCM uses a single blower for both cooling and process air flow and decreases blower power because of its low cell pressure drop.
3. Future EARS should incorporate higher performance, i.e. lower cell voltage, WVE electrodes. Water vapor electrolysis cell voltages of less than 1.70V and 1.75V have been demonstrated at the single cell level for 30 days and 100 days of operation, respectively.
4. Testing of the EARS at the projected RLSE mission profile (i.e., cycle variation in $p\text{CO}_2$, humidity, $p\text{O}_2$) is recommended to obtain transient performance data for an EARS prototype design and subsequent flight experiment evaluation.

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