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ELECTROCHEMICAL AIR REVITALIZATION SYSTEM OPTIMIZATION INVESTIGATION

FINAL REPORT

by

R. R. Woods, F. H. Schubert
and T. M. Hallick

October, 1975

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Prepared Under Contract No. NAS9-14301

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

LYNDON B. JOHNSON SPACE CENTER

National Aeronautics & Space Administration

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FOREWORD

The work described herein was conducted by Life Systems, Inc. during the period, September 1974 through October 1975, under Contract NAS9-14301. The Program Manager was F. H. Schubert. Life Systems, Inc. personnel contributing to the program included the following:

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F. Schubert	Mechanical Design and System Concept Derivation
R. Woods	Program Testing
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SUMMARY

Certain localized, high-manned activities aboard a spacecraft as well as short-term manned visits to experimental space labs require control of the atmosphere's oxygen (O_2), carbon dioxide (CO_2) and moisture. A program to develop an Electrochemical Air Revitalization System (EARS) has been sponsored by National Aeronautics and Space Administration (NASA) for the past few years. The work reported herein, EARS Optimization Investigation, is a portion of the overall development.

A program to characterize a Breadboard of an Electrochemical Air Revitalization System (BEARS) was successfully completed at Life Systems, Inc. (LSI). The BEARS is composed of three components: (1) a Water Vapor Electrolysis Module (WVEM) for O_2 production and partial humidity control, (2) an Electrochemical Depolarized Carbon Dioxide Concentrator Module (EDCM) for CO_2 control, and (3) a power-sharing controller, designed to utilize the power produced by the EDCM to partially offset the WVEM power requirements.

The program was completed in three phases: (1) selection and characterization of electrodes optimized for BEARS application (low voltage over wide ranges in humidity), (2) fabrication of a power-sharing controller based on a contractor developed concept, and (3) fabrication, assembly and testing of an integrated BEARS to characterize its performance and explore operational limits over wide ranges in cabin air relative humidity (RH).

During the first phase of the program, six different types of Water Vapor Electrolysis (WVE) anodes were evaluated. Based on previous in-house activities, a platinized screen cathode was selected as baseline for WVE application. This type of cathode was used throughout all WVE testing performed under this program. An E5B type WVE anode was selected and successfully characterized over a 35 to 90% RH range (for a 291 to 297K (64 to 75F) range in dry bulb temperature) and endurance tested for 45 days at optimum process air RH levels (>70%) followed by 19 days at lower RH levels (38 to 70%). An excess of 4700 hours of single-cell WVE operation was accumulated during this program.

The integrated power controller was fabricated, assembled and checked out at the component level during the second phase of the program. The controller demonstrated the ability to fully utilize the EDCM-generated power for operation of the WVEM. The direct utilization of the EDCM power results in additional savings since typical WVEM power conversion losses associated with the shared portion of power as well as the heat load penalty of rejecting the EDCM power do not occur.

During the third phase of the program a three-cell WVEM and a three-cell EDCM were fabricated utilizing electrochemical cell concepts developed for operation with process air having wide ranges in RH. Such concepts included internal air cooling for minimum thermal gradients, optimum electrode-to-matrix thickness ratios to tolerate large electrolyte volume fluctuations and selection of electrolytes compatible with projected RH limits without precipitation. After integration of the modules and power-sharing controller with the Ground Support

Accessories (GSA), the BEARS integrated shakedown, characterization and endurance testing was completed. The characterization consisted of successfully demonstrating the capability of the integrated system to operate over a RH range of 35 to 90% within the 291 to 297K (65 to 75F) dry bulb temperature range. The WVEM voltage increased as the process air RH decreased. The EDCM attained an optimum electrical performance between 60 and 80% RH while maintaining a constant rate of increase in CO_2 removal efficiency with decreases in inlet RHs. The EDCM was also characterized over a CO_2 partial pressure (pCO_2) range of ambient to 533 N/m^2 (4.0 mm Hg). Endurance testing, which followed the characterization tests, was conducted at both nominal and off-design operating conditions.

A total of 105 days (2520 hours) of integrated operation was accumulated during this phase of program activities.

Modifications to baseline operation were only necessary during or following extended operation at extremes in inlet RH conditions. A decrease in cooling air flow rate was required above a 78% process air inlet RH and complete stoppage of cooling air allowed operation at 90% RH, suggesting a simple cooling air flow control technique for future system development.

Similarly, a temporary reduction in WVEM current density was needed following extended operation at 92% RH (with 90% RH as an initial upper goal).

A Product Assurance Program was performed implementing the concepts of quality assurance, reliability, safety and materials control into the program effort. Activities included searching out quality weaknesses and ensuring that appropriate corrective action was taken, preparing a Failure Modes Effects and Criticality Analysis (FMECA), preparing a Metallic and Nonmetallic Materials Lists for the EDCM and WVEM, and establishing safety guidelines for the design and testing of the BEARS.

It is concluded from the results of this work that the concept of electrochemical air revitalization with power-sharing is a viable solution to the problem of providing a localized topping force for O_2 generation, CO_2 removal and partial humidity control aboard manned spacecraft. Continued development of the EARS concept is recommended, applying the operational experience and limits identified during the BEARS program to testing of a one-man capacity system and toward the development of advanced system controls to optimize EARS operation for given interfaces and requirements. Successful completion of this development will produce timely technology necessary to plan future advanced Environmental Control and Life Support System (ECLSS) programs and experiments.

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 portable and self-contained, except for external power, is required.

Such an end-item application imposes unique design requirements upon the system. Portability implies a system which is free-standing in the cabin and easily moved from place to place; self-contained means a system which minimizes interfaces with on-board spacecraft facilities; and 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.

Combining two electrochemical processes with a power-sharing controller concept, as illustrated in Figure 1, results in a concept that successfully satisfies the above design requirements.

Background

Water Vapor Electrolysis and EDC have shown great promise for use in future manned space missions. Development efforts under past National Aeronautics and Space Administration (NASA) contracts successfully demonstrated that the electrolysis of water into hydrogen (H_2) and O_2 can be performed in the vapor state over a wide range of humidity.[1-4] Electrolysis performed with water vapor eliminates the requirement for phase changes and the attendant phase separation problems. Other development efforts under NASA Ames Research Center (ARC) Contracts NAS2-4444, NAS2-6118 and NAS2-6478 and NASA Johnson Space Center (JSC) Contract NAS9-10273 resulted in an improved method for CO_2 control (the EDC) at pCO_2 levels of less than 400 N/m^2 (3 mm Hg).[5-11] Further activities in these areas were accomplished under NASA JSC Contract NAS9-11830 which demonstrated the feasibility of using an integrated WVE/EDC system for spacecraft O_2 generation, CO_2 control and partial humidity control.[12]

Program Objectives

The objective established for this program was to characterize the stability of high-performance WVE electrodes over a 35 to 90% RH range (291 to 297K (65 to 75F) dry bulb temperature) and to fabricate and endurance test a three-cell Breadboard of an Electrochemical Air Revitalization System (BEARS). The BEARS was to be tailored for operation over wide ranges in process air RH and would consist of an integrated WVE O_2 generator/dehumidifier, an EDC CO_2 removal system, and a power-sharing controller which uses the generated Electrochemical Depolarized CO_2 Concentration Module (EDCM) power to partially offset the Water Vapor Electrolysis Module (WVEM) power requirement.

(1) References cited in parentheses are found on page 84.

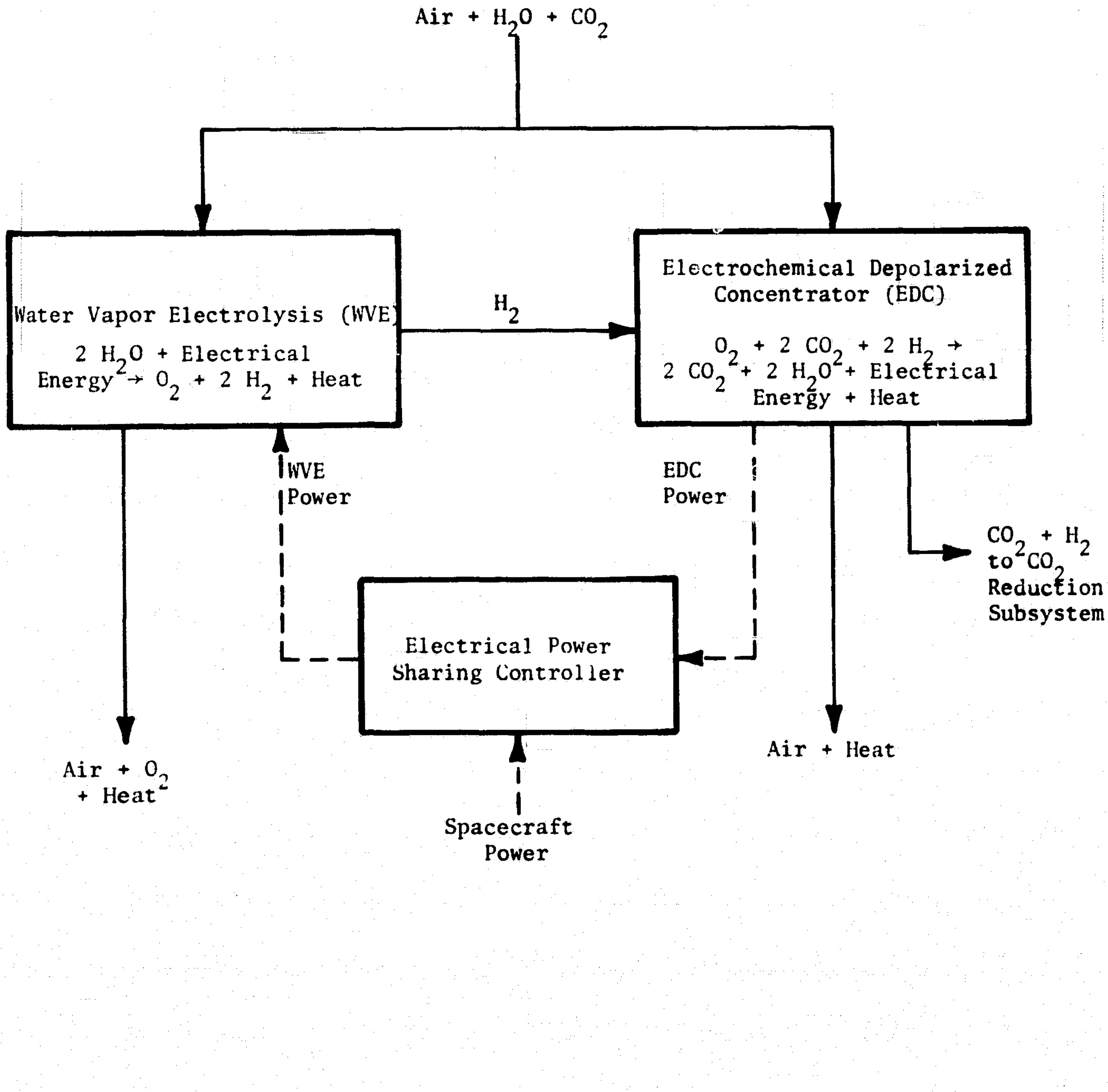


FIGURE 1 ELECTROCHEMICAL AIR REVITALIZATION CONCEPT

Program Organization

The program was divided into three phases:

1. Selection of WVE electrodes and characterization testing of the optimum electrode combination.

2. Design, assemble and functionally check out the power-sharing controller.

3. Design, fabricate, assemble and test an integrated breadboard consisting of a three-cell WVEM, a three-cell EDCM, a power-sharing controller and required Ground Support Accessories (GSA).

To accomplish the above, the program was divided into five tasks and program management and documentation functions. The specific objectives of the five tasks were:

1.0 Fabricate and assemble a WVEM and EDCM for O_2 generation, partial humidity control and CO_2 control.

2.0 Design, fabricate, assemble, calibrate and functionally check out the GSA for testing the WVE electrodes, the WVE/EDC power-sharing controller and the BEARS.

3.0 Establish, implement and maintain a mini-Product Assurance Program through all phases of contractual performance including design, fabrication, purchasing, assembly, testing, packaging and shipping consistent with a program focused on EARS optimization investigations.

4.0 Program testing, including development testing of the WVE electrodes, the WVE/EDC power-sharing controller and endurance testing of the BEARS.

5.0 Supporting technology studies associated with EARS technology advancement, including selection of WVE electrode(s) and fabrication of a WVE/EDC power-sharing controller.

The objectives of the program were met. The following seven sections summarize the work completed and are organized to define the BEARS concept, its hardware, GSA, Product Assurance activities and program test activities, followed by the conclusions and recommendations based on the work performed under the program.

ELECTROCHEMICAL AIR REVITALIZATION CONCEPT

The EARS concept combines two electrochemical/chemical processes (electrolysis of water vapor and electrochemical concentration of CO_2) with an electronic power-sharing technique to achieve O_2 generation, CO_2 removal and partial humidity control, as was shown in Figure 1. When integrating the three processes to perform these functions within a manned spacecraft atmosphere, certain design considerations must be included in the development of the system. Such considerations include electrolyte solubility limits, electrolyte/gas interface locations within the electrode-matrix-electrode composite, process air flow arrangement, and atmospheric conditions for eventual end-item application.

Oxygen Generation/Humidity Control Process

The O_2 generation/humidity control process is governed by the electrochemical reactions of water electrolysis in an acidic medium. The efficiency of the process is reflected by cell voltage and the fluid production and consumption rates can be calculated using Faraday's Law of Electrolysis.

Electrochemical Reactions

The generation of O_2 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 O_2 generation. Each cell consists of two porous electrodes separated by a porous matrix containing an aqueous acidic (sulfuric acid (H_2SO_4)) 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 2. The specific electrochemical reactions are detailed in Figure 3.

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, H_2 ions (H^+) and electrons.

$$2H_2O = 4H^+ + O_2 + 4e^- \qquad (1)$$

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^+.

$$4H^+ + 4e^- = 2H_2 \qquad (2)$$

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 electrolyte at the cathode. The overall reaction is exothermic and is accompanied by the consumption of electrical energy.

$$\text{Electrical Energy} + 2H_2O = 2H_2 + O_2 + \text{Heat} \qquad (3)$$

The performance of a WVE is reflected by the electrical efficiency (cell voltage).

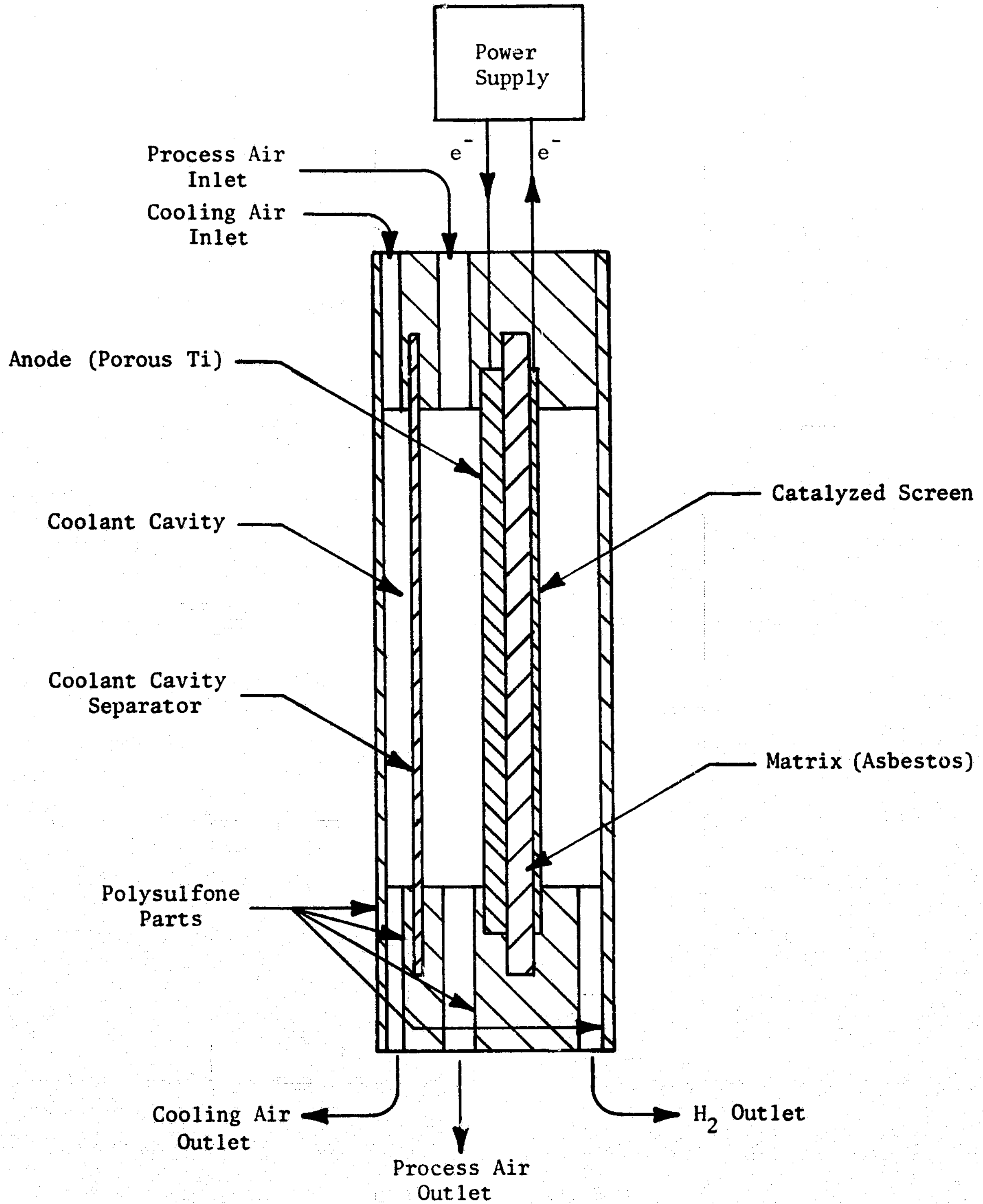
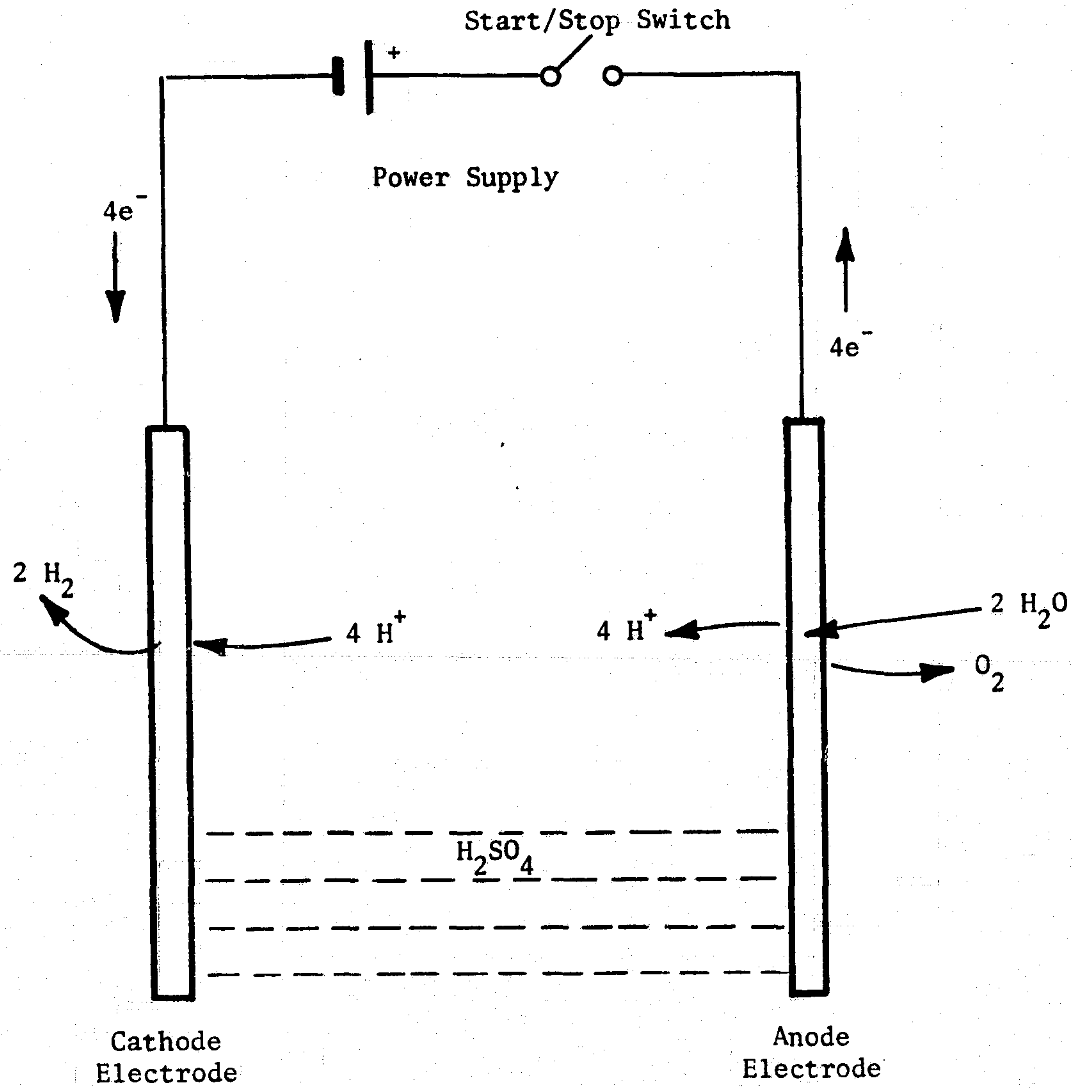


FIGURE 2 WVE SINGLE-CELL SCHEMATIC



Cathode Reactions:

$4\ H^+ + 4e^- = 2\ H_2$

Anode Reactions:

$2\ H_2O = O_2 + 4\ H^+ + 4e^-$

Overall Reaction:

Electrical Energy $+ 2\ H_2O = 2\ H_2 + O_2 +$ Heat

FIGURE 3 WVE FUNCTIONAL SCHEMATIC WITH REACTIONS

Electrical Efficiency

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 single-cell voltage representing high electrical efficiency or low power consumption to perform the electrochemical process of O_2 and H_2 generation.

Production and Consumption Rates

During operation of the WVEM, O_2 and H_2 gases are produced and water is consumed. According to Faraday's Law of Electrolysis, the gas production rates are given by the equations:

$$O_2 = 8.2 \times 10^{-5} (I)(N) \tag{4}$$

where

O_2 = O_2 production rate, g O_2/s

I = Cell current, A

N = Number of cells

$$H_2 = 1.04 \times 10^{-5} (I)(N) \tag{5}$$

where

H_2 = H_2 production rate, g H_2/s

The equation for the water consumption rate in the WVEM is:

$$H_2O = 9.24 \times 10^{-5} (I)(N) \tag{6}$$

where

H_2O = H_2O consumption rate, g H_2O/s

The power consumed and the waste heat produced by the WVEM during operation are described by equations generally used for electrochemical cells. The power is given by the equation:

$$P = (N)(I)(E) \tag{7}$$

where

P = The power, W

E = The average cell voltage, V

The amount of heat generated is determined by the difference between the operating cell voltage and the theoretical cell voltage and is given by the equation:

$$Q = (I)(N)\ (E-E_T) \tag{8}$$

where

Q = Heat produced, W

E_T = Theoretical cell voltage, V (1.23V for water vapor)

Carbon Dioxide Removal Process

The CO_2 removal process is governed by electrochemical as well as chemical reactions. Two parameters can be used to evaluate the process: CO_2 removal efficiency and electrical efficiency.

Electrochemical and Chemical Reactions

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 solution (LSI-B). 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 4, and the specific electrochemical and chemical reactions are detailed in Figure 5.

Moist air containing CO_2 is fed into the cathode compartment where the electrochemical reaction of O_2 in the air, water and electrons form hydroxyl ions (OH^-).

$$O_2 + 2H_2O + 4e^- = 4OH^- \tag{9}$$

The CO_2 then reacts with the OH^- at the cathode to form carbonate ions ($CO_3^=$) in two consecutive reactions.

$$CO_2 + OH^- = HCO_3^- \tag{10}$$

$$HCO_3^- + OH^- = CO_3^= + H_2O \tag{11}$$

where

HCO_3^- = Bicarbonate ions

The output from the cathode compartment is moist air at a reduced pCO_2. The CO_2 as $CO_3^=$ and unreacted OH^- diffuses through the bulk electrolyte to the anode, transporting the current through the cell. At the anode, H_2 is fed into the cell where it is electrochemically reduced in the presence of OH^- to form water and electrons, decreasing the concentration of OH^- in the anolyte.

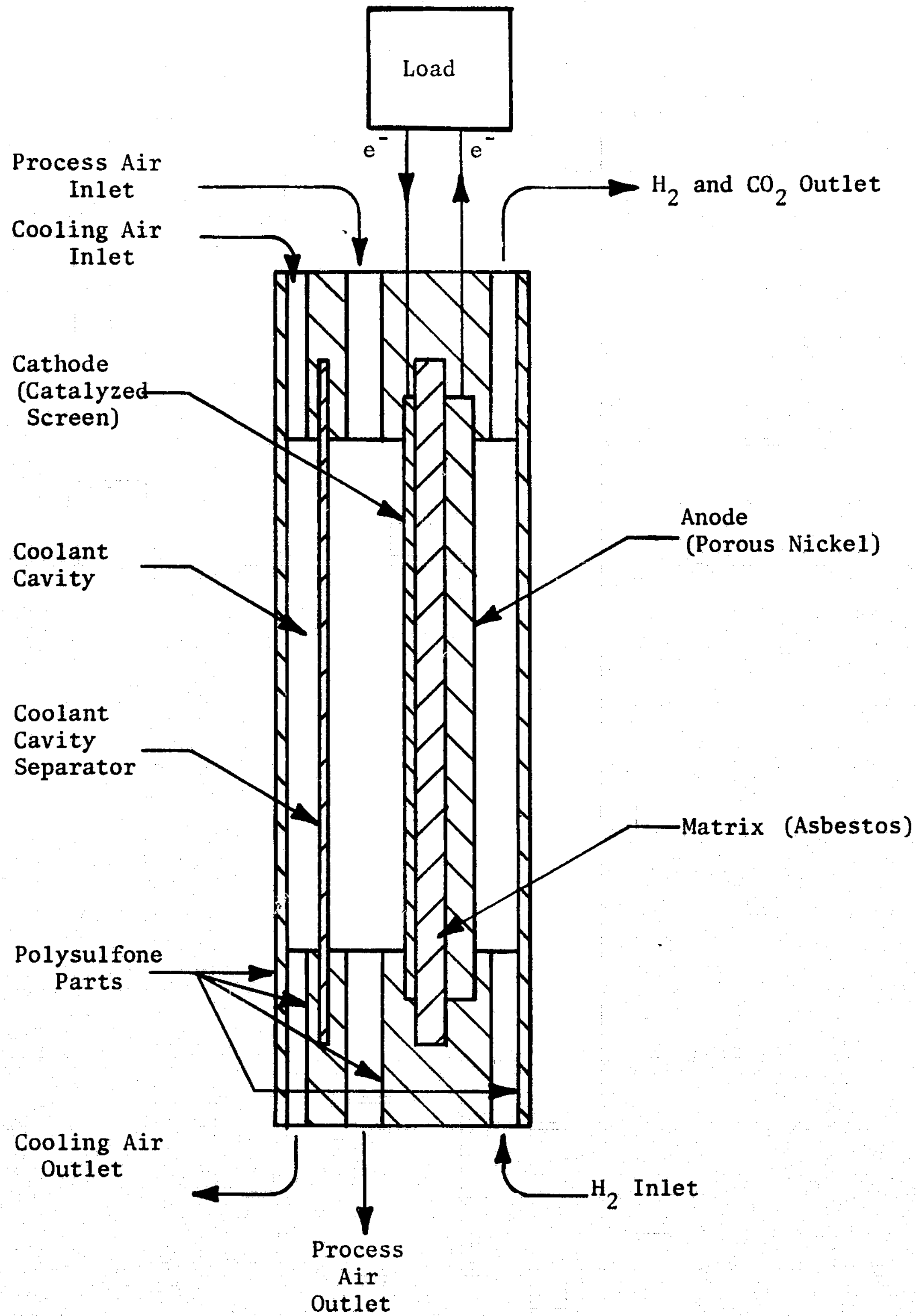
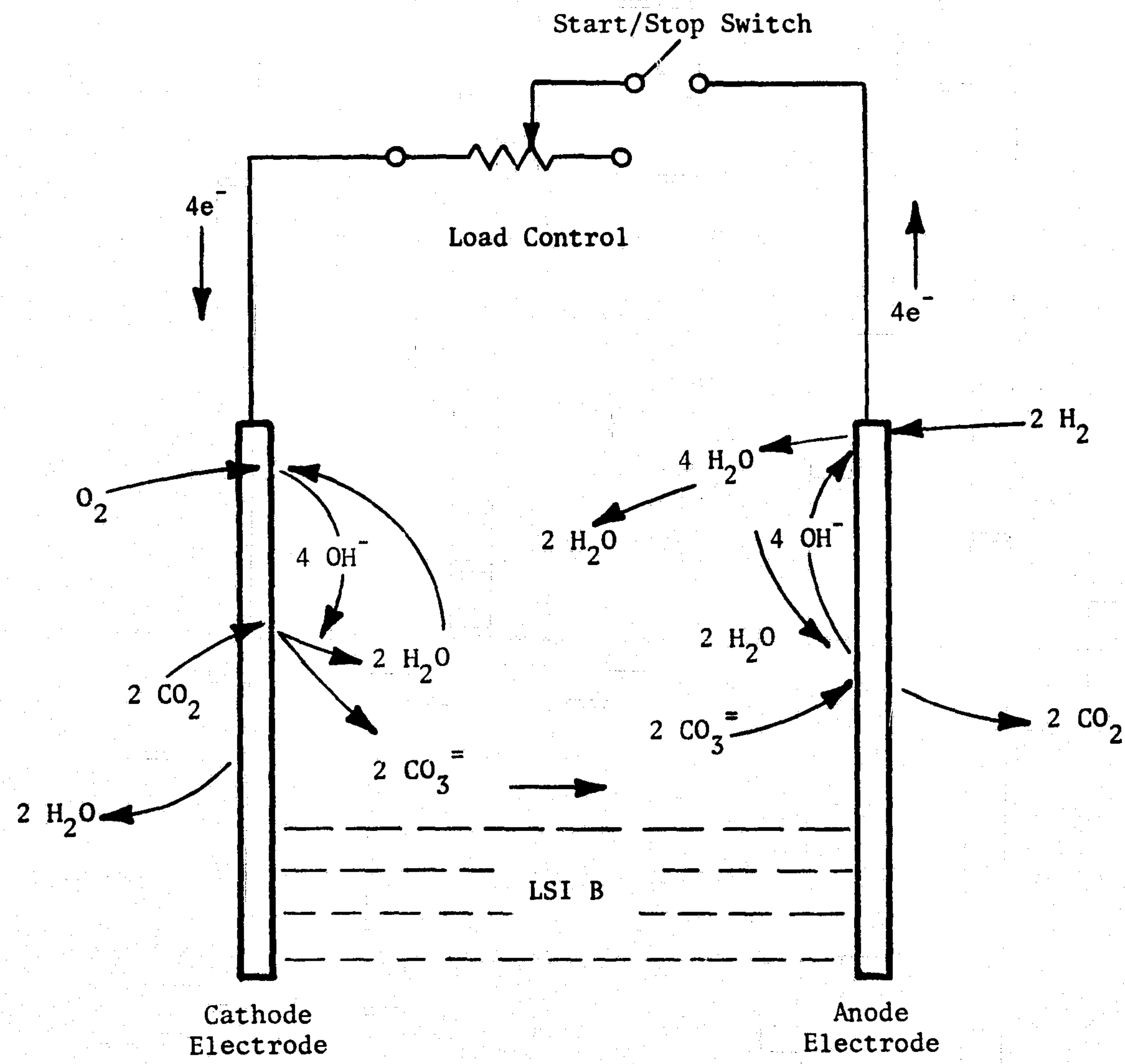


FIGURE 4 EDC SINGLE-CELL SCHEMATIC



<u>Cathode Reactions</u>:

$$O_2 + 2\ H_2O + 4e^- = 4\ OH^-$$
$$4\ OH^- + 2\ CO_2 = 2\ H_2O + 2\ CO_3^=$$

<u>Anode Reactions</u>:

$$2\ H_2 + 4\ OH^- = 4\ H_2O + 4e^-$$
$$2\ CO_3^= + 2\ H_2O = 4\ OH^- + 2\ CO_2$$

<u>Overall Reactions</u>:

$$O_2 + 2\ CO_2 + 2\ H_2 \rightarrow 2\ CO_2 + 2\ H_2O + \text{Electrical Energy} + \text{Heat}$$

FIGURE 5 EDC FUNCTIONAL SCHEMATIC WITH REACTIONS

$$4OH^- + 2H_2 = 4H_2O + 4e \quad (12)$$

The decreased concentrations of OH^- shifts the carbonate/bicarbonate equilibrium toward the HCO_3^-.

$$H_2O + CO_3^= = HCO_3^- + OH^- \quad (13)$$

At low OH^- concentrations, there are two mechanisms by which the evolution of the CO_2 bound in the form of HCO_3^- occurs. The first mechanism is:

$$HCO_3^- = CO_2 + OH^- \quad (14)$$

and the second is:

$$HCO_3^- + H_2O = H_2CO_3 + OH^- \quad (15)$$

$$H_2O + CO_2$$

where

H_2CO_3 = Carbonic acid

With the evolution of CO_2 and the production of the water at the anode, the transfer of both the CO_2 and current is complete. The water produced in the process transfers to the cathode and is absorbed into the process air flow. The output from the anode compartment is CO_2 mixed with unreacted H_2. The overall reaction is exothermic and is accompanied by the formation of electrical energy.

$$O_2 + 2CO_2 + 2H_2 = 2CO_2 + 2H_2O + \text{Electrical Energy} + \text{Heat} \quad (16)$$

The fluid consumption and production rates of the EDCM are equal in magnitude, but opposite in sign to those of the WVEM process as presented in Equations 4 through 8. The performance of an EDCM is reflected by CO_2 removal efficiency and electrical efficiency (cell voltage).

<u>Carbon Dioxide Removal Efficiency</u>

Inspection of the overall reaction, as based on the $CO_3^=$ transfer mechanism, shows that two moles of CO_2 can be transferred for one mole of O_2 consumed. This, by definition, represents a CO_2 removal efficiency of 100%. The equivalent mass ratio is 2.75 kg (lb) of CO_2 removed for each kg (lb) of O_2 consumed. This ratio has been referred to as the Transfer Index (TI).

<u>Electrical Efficiency</u>

The electrical energy produced by the electrochemical reaction in the EDCM is a function of the current density and average cell 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 cell voltage representing high electrical efficiency.

Power-Sharing Process

The power which the EDCM generates has historically been converted to heat and removed from the subsystem as a waste product. Efforts to use this power effectively have been unsuccessful until recently. Two methods which had been previously investigated are:

1. Utilizing the power to operate subsystem component(s).
2. Adding the power to the subsystem input power.[8]

Both of these methods require power conversion circuits for isolation and for conversion of the EDCM power to proper voltage levels. In addition, both methods would most likely require backup power sources. The net savings in system power will normally be more than offset by the increase in equivalent weight associated with the conversion and regulation circuits.

Life Systems, Inc. (LSI) 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 block diagram form 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 in this manner are:

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 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, 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.

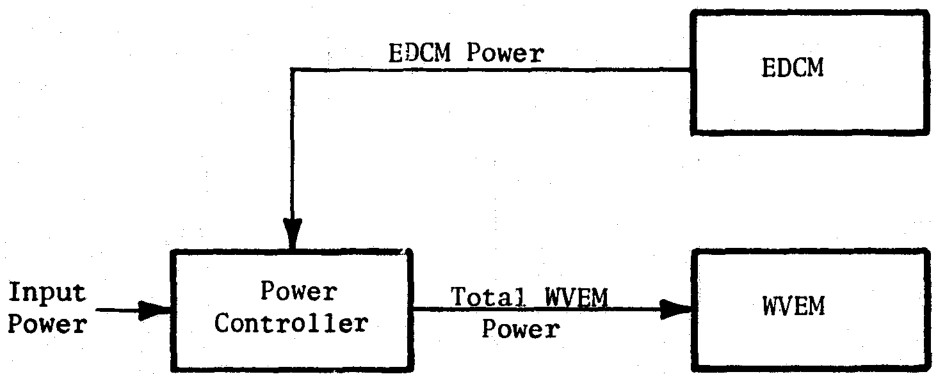


FIGURE 6 POWER CONTROLLER BLOCK DIAGRAM

Figure 7 is a detailed block diagram of the BEARS 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. They are connected together in series adding (voltages add) such that the total voltage of the Power Control A and the EDCM are 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 (5.00A in example shown). The remainder of the current for the WVEM comes from Power Control B. This 7.50A, when added to the 5.00A, results in 12.50A of WVEM current. The WVEM acts as a load and its terminal voltage is determined by the magnitude of the current passing through it and the performance characteristics of the WVEM electrochemical cells. Assuming this total WVEM voltage is to be 15.25V, a total of 190.63W are required by the WVEM. Since Power Control B feeds 7.50A at a terminal voltage of 15.25V, it will provide 114.38W of WVEM power. The remainder of the WVEM power (76.25W) comes from Power Control A and the EDCM. The EDCM operating at 12.21V and 5.00A will produce 61.05W and Power Control A whose terminal voltage will be 3.04V (15.25V minus 12.21V) will supply 15.20W. The total 190.63W comes, therefore, from the sum of Power Control A, Power Control B and the EDCM (114.38W + 15.20W + 61.05W = 190.63W).

Shunt B measures total WVEM current. This signal is used to control Power Control B output current such that the total is 12.50A when Power Control A current is added to it. Thus, for example, if Power Control A current were to be decreased from 5.00A to 4.00A, Power Control B current would increase from 7.50A to 8.50A to maintain the total at 12.50A. 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 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 no 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 for the EDCM.

Design Considerations

Based on the end-item application of an EARS, certain design considerations must be included early in its development. These considerations influence the general design specifications shown in Table 1. Particular emphasis must be placed on the temperature and humidity range of the cabin atmosphere in which the system has to operate. Both modules must interface directly with the cabin air to perform their electrochemical functions: the anode compartment of the WVEM, where water vapor contained in the air is electrolyzed to remove moisture and enrich the air with O_2, and the cathode compartment of the EDCM, where cathodic reduction of O_2 takes place, accompanied by the removal and transfer of CO_2.

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

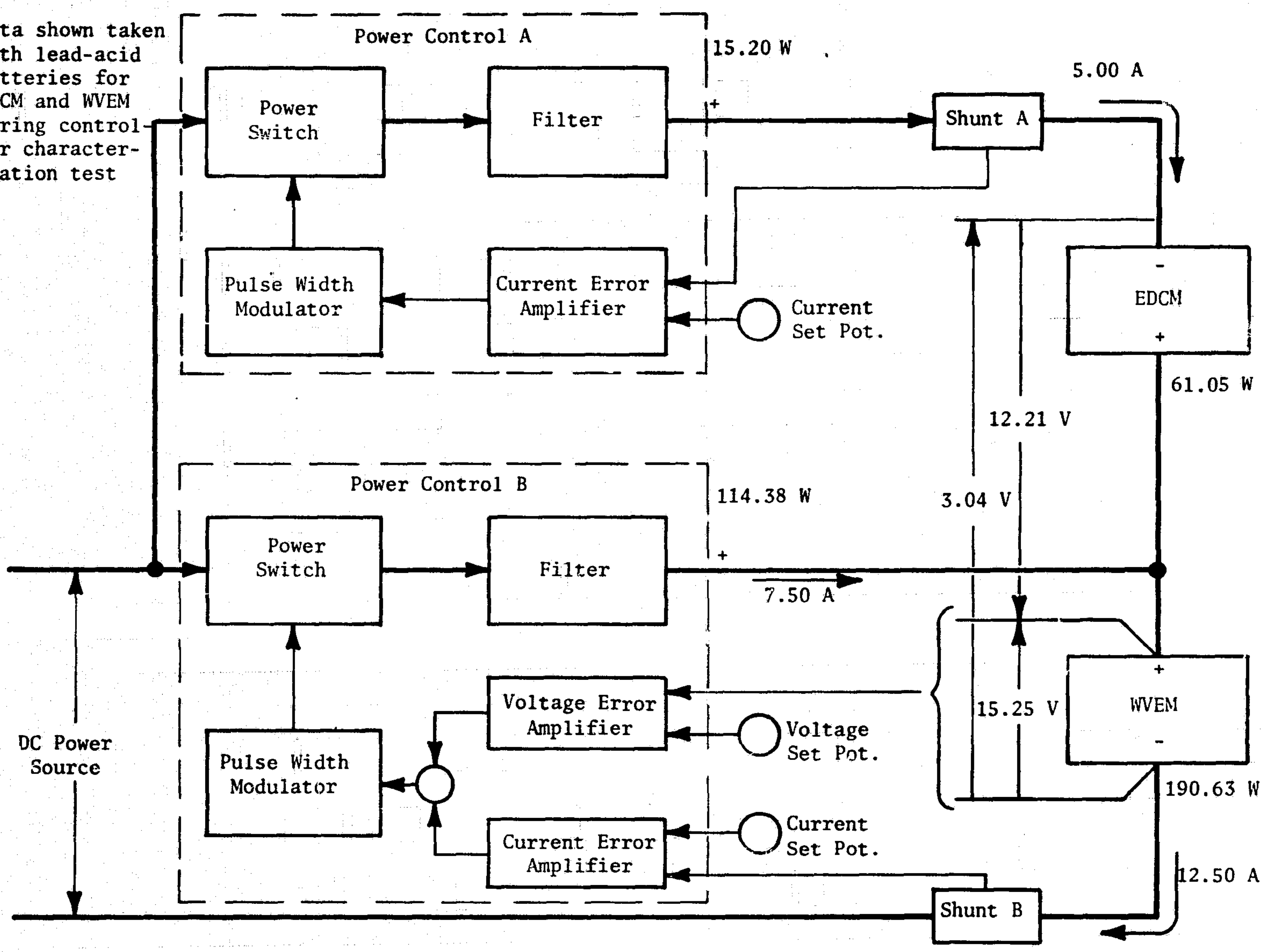


FIGURE 7 DETAILED BLOCK DIAGRAM OF POWER-SHARING CONTROLLER

TABLE 1 EARS DESIGN SPECIFICATIONS

Atmospheric Data	
Operational Gravity, g	0 to 1
Cabin Total Pressure, kN/m^2 (Psia)	
Design Point	101.34 (14.7)
Control Tolerance	±1.38 (±0.2)
Cabin O_2 Partial Pressure, kN/m^2 (Psia)	22.06 (3.2)
N_2 Partial Pressure, kN/m^2 (Psia)	78.9 (11.5)
Cabin Temperature Range, K (F)	291.3 to 296.9 (65 to 75)
Humidity Range, %	35 to 90
Cabin CO_2 Partial Pressure Range, N^2/m (Mm Hg)	333.3 to 400.0 (2.5 to 3.0)
Duty Cycle	Cyclic and Continuous

This direct interface between the module's electrolyte and the cabin air results in two electrolyte requirements:

1. The electrolyte must have an equivalent RH at its solubility limit, equal to or less than the lowest RH air present in the cell compartment.

2. The electrolyte/gas interface between the process gases (air and H_2) and the cell electrolyte must be maintained within the activated areas of the electrodes to prevent performance degradation or possible gas crossover. The changes in the electrolyte/gas interface locations are caused by the volume changes of an aqueous solution of electrolyte containing a fixed amount of solute as it equilibrates with the changing process air RH.

   In addition to the electrolyte related requirements, process fluid routing (series or parallel flow paths for process air, cooling air and H_2) must be evaluated and proper techniques selected. Also, characteristics relating capacity requirements (generation and removal rates) with extremes in atmospheric conditions (i.e., do low RH conditions coincide with high CO_2 removal and O_2 production rates) must be considered in developing system operational concepts and controls.

<u>Electrolyte Solubility Limits</u>

The requirement of electrolyte solubility limits placed on the WVEM and EDCM design by the required range in process air RH was solved through proper selection of the electrolytes. The electrolyte that was chosen for the WVEM was H_2SO_4. This selection was based upon the fact that H_2SO_4 can readily exist in equilibrium with RHs well below 20%, as shown in Figure 8.[13] Solubility limits, therefore, pose no problem for the temperature and humidity range requirements for the WVEM.

The EDCM requires a carbonate electrolyte to perform its CO_2 removal function. The carbonate electrolyte that was chosen for use in the EDCM was LSI-B. This selection was based upon LSI-B's solubility limit, at which the equivalent RH in equilibrium with the electrolyte is approximately 26% RH, as again illustrated in Figure 8.

<u>Electrolyte/Gas Interface Locations</u>

The requirement that the electrolyte/gas interfaces be maintained within the electrodes' active sites was resolved for the BEARS by selection of proper matrix/electrode configurations and size ratios and by the selection of proper initial electrolyte charge concentrations. In addition, an advanced cell design with internal air cooling was selected to minimize the loss in humidity tolerance due to thermal and water vapor pressure gradients.

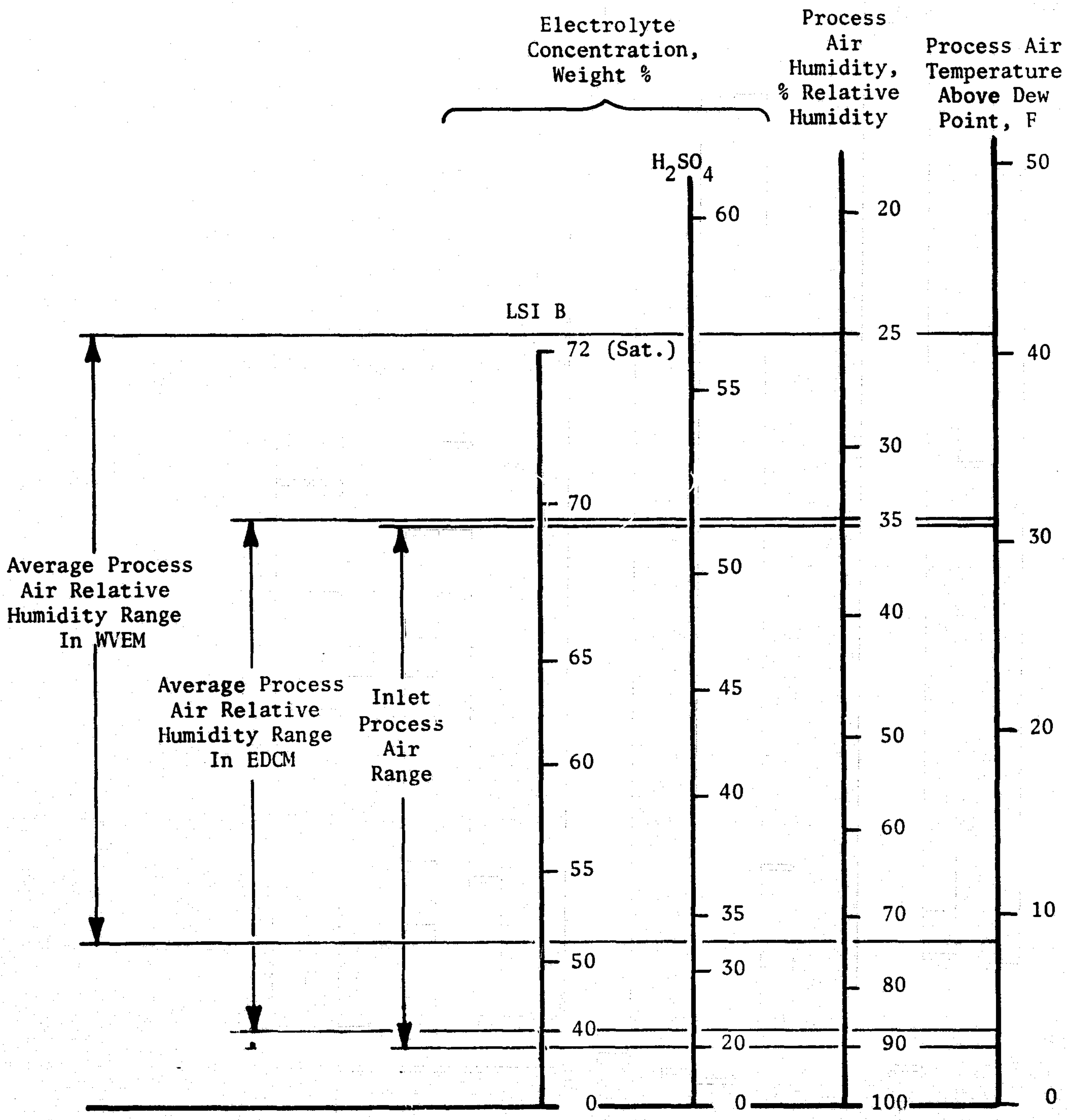


FIGURE 8 ELECTROLYTE CONCENTRATIONS

Efficient operation of the WVEM and the EDCM requires that the electrolyte/gas interfaces be maintained within the activated sites of the electrode structures since uncontrolled volume fluctuations cause either cell dryout with possible gas crossover or cell flooding with electrolyte loss. An aqueous electrolyte solution will reach equilibrium or a steady-state condition with the water vapor pressure of the surrounding air by either accepting or rejecting water. This water transport results in electrolyte volume fluctuations within the cell. Major factors affecting the magnitude of these fluctuations are the ranges and gradients in the partial pressure of water vapor in the process air and in the electrolyte (or cell) temperature, as well as the initial electrolyte charge concentration.

Thermal and Water Vapor Pressure Gradients. Thermal gradients exist within the EDC and WVE cells due to the removal of waste heat generated in the exothermic electrochemical reactions. These thermal gradients cause the electrolyte to equilibrate at a lower RH for a given water vapor pressure in the process air, resulting in a decrease in tolerance to low process air RH. Since the constraint for minimizing spacecraft facility interfaces requires the use of ambient cooling air rather than liquid-cooled cells or using prechilled cooling air, a special cell structure allowing for internally cooling the BEARS WVE and EDC cells was developed. This technique still allowed for separation of cooling and process air, but had lower thermal gradients than fin cooling used in the six-man CO_2 Collection Subsystem for the Space Station Prototype (SSP).[9] In the case of the baseline external fin heat removal, the differential temperature gradients on the surface of the electrode and perpendicular to the process air flow path are equal to 7.8K (14F) as compared to 0.6K (1F) for the internal air cooled method. Figure 8 illustrates the projected ranges in electrolyte RH levels that are expected for the BEARS WVEM and EDCM during operation over the inlet process air RH range indicated.

Gradients with water vapor partial pressure exist between the electrolytes and the process air of both types of cells due to the production (EDC) or consumption (WVE) of water. The direction of the water gradient is different for the EDCM than for the WVEM. The water-producing electrochemical reactions of the EDCM cause the higher water vapor pressure to be within the electrolyte while the water-consuming reaction of the WVEM creates the reversed gradient, with the process air having the higher water vapor pressure. The direction of the gradient in the EDCM aids in increasing the operational range in the low process air RH direction. The higher water vapor pressure of the electrolyte can result in a steady-state condition above the process air RH level if the thermal gradient perpendicular to both the process air flow and the electrode surface is small. In effect, this gradient tends to neutralize the effects of the thermal gradients, as illustrated by the effective EDCM RH range in Figure 8. Any effect on high process air RH tolerance limits can be overcome by decreased cooling air flows, allowing a higher electrolyte temperature for a given water vapor pressure.

The water vapor pressure gradients of the WVEM cause the electrolyte to equilibrate with a RH below that of the process air and when combined with any thermal gradients, cause the WVEM electrolyte to exist at even lower RH levels, as illustrated in Figure 8. This limitation will not be one of solubility because H_2SO_4 does not have a solubility limit per se, but results in decreased performance due to the increased H_2SO_4 concentration, electrolyte volume reduction and increased internal electrical resistence of the cell.

Selected Volume Ratio Technique. A direct method was selected for the BEARS cells to accommodate the anticipated ratio in electrolyte volume variations. This method utilized an internal electrolyte reservoir concept by sizing the ratio of the electrode-to-matrix volumes (thickness x area x porosity) available for electrolyte in such a fashion that the expected electrolyte volume changes, caused by variations in process air dew point and dry bulb temperatures, do not cause electrolyte gas interfaces to withdraw from the electrodes' active surfaces or to flood the cell.

In the WVEM, the maximum electrolyte volume ratio during operation with inlet process air RH from 90% to 35% is illustrated in Figure 9 and results in a 1.9:1 ratio. In the design of the WVEM, the porous titanium (Ti) anodes served as reservoirs and resulted in an electrode-to-matrix volume ratio sufficient to accommodate the expected volumetric changes. In the EDCM, the maximum required volume ratio is 2:1, as illustrated in Figure 10. In the design of the EDCM, a porous nickel (Ni) anode was used to accommodate the expected volumetric changes of the electrolyte when the process air RH changes from 90 to 35% RH.

In general, the higher the electrode-to-matrix available volume ratio, the greater the capacity of the cell to withstand ranges in electrolyte volume fluctuations without losing proper interface locations. Other considerations become important, however, when maximizing this ratio. Simply decreasing the thickness of the matrix to increase the volumetric ratio results in two process-hindering effects. The first is a decrease in the capability of the matrix to hold pressure differentials; while the second, is an increase in backdiffusion of process gases resulting in a decrease in CO_2 removal efficiency in the EDCM and a decrease in current efficiency in the WVEM. The CO_2 diffusion effect becomes pronounced as matrix thickness is decreased below 0.030 cm (0.012 in).[14]

The EDCM and WVEM electrodes and matrices for the BEARS were selected to allow for the required changes in the electrolyte volumes without decreasing the matrix thickness to a level where system performance would be adversely affected. Specific dimensions for the cell components are presented in the Breadboard Hardware Section of this report.

Electrolyte Charge Concentration. The initial electrolyte charge concentration must fall within the limits of anticipated steady-state electrolyte RH ranges that the cells will encounter. These ranges can be determined by the data presented in Figures 8, 9 or 10. In general, a cell will be charged with an electrolyte concentration that will result in total utilization of all the available volume within the electrodes and matrix at the conditions that will result in the most dilute electrolyte concentration. Charging techniques and

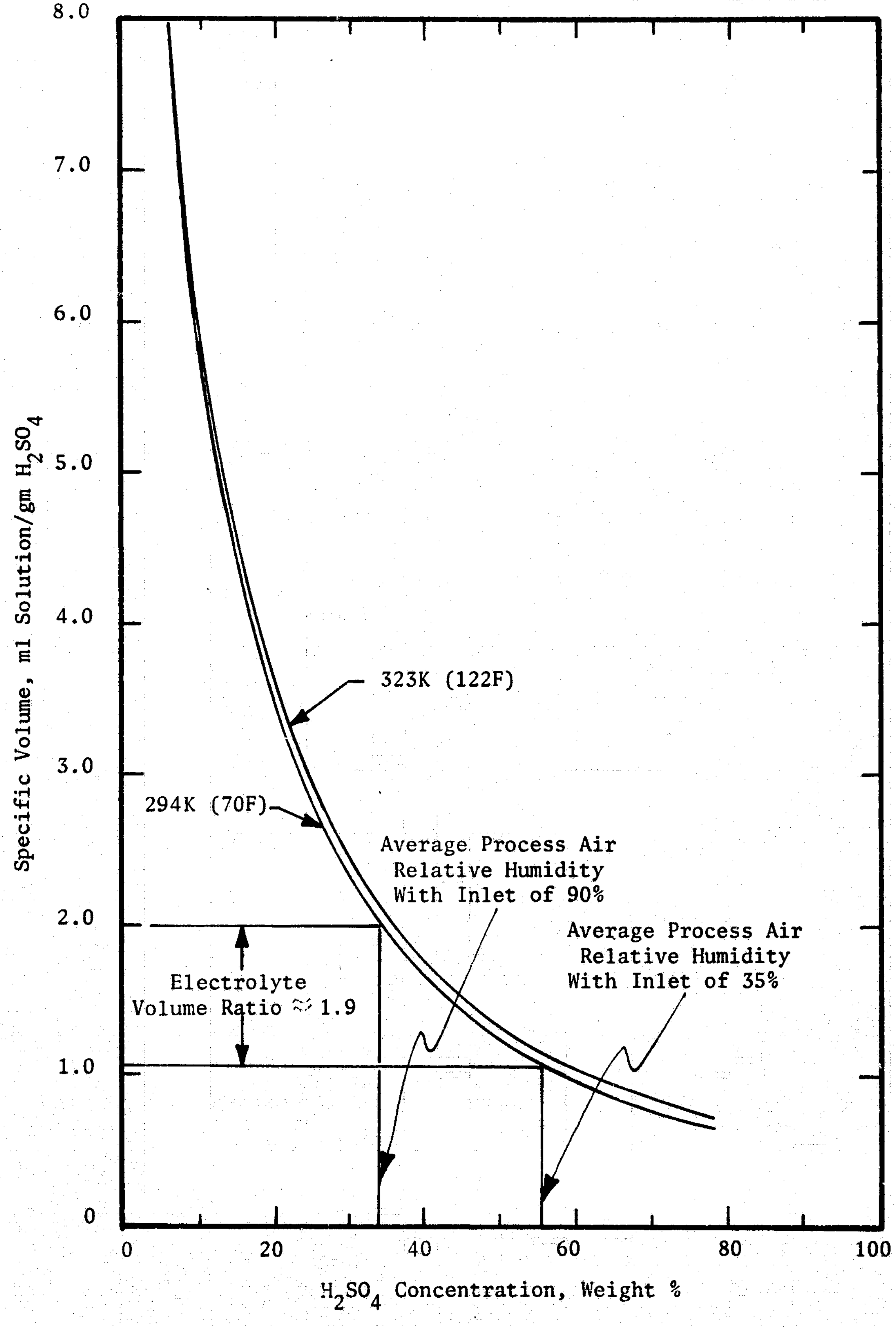


FIGURE 9 SPECIFIC VOLUME VERSUS CONCENTRATION OF AQUEOUS H_2SO_4

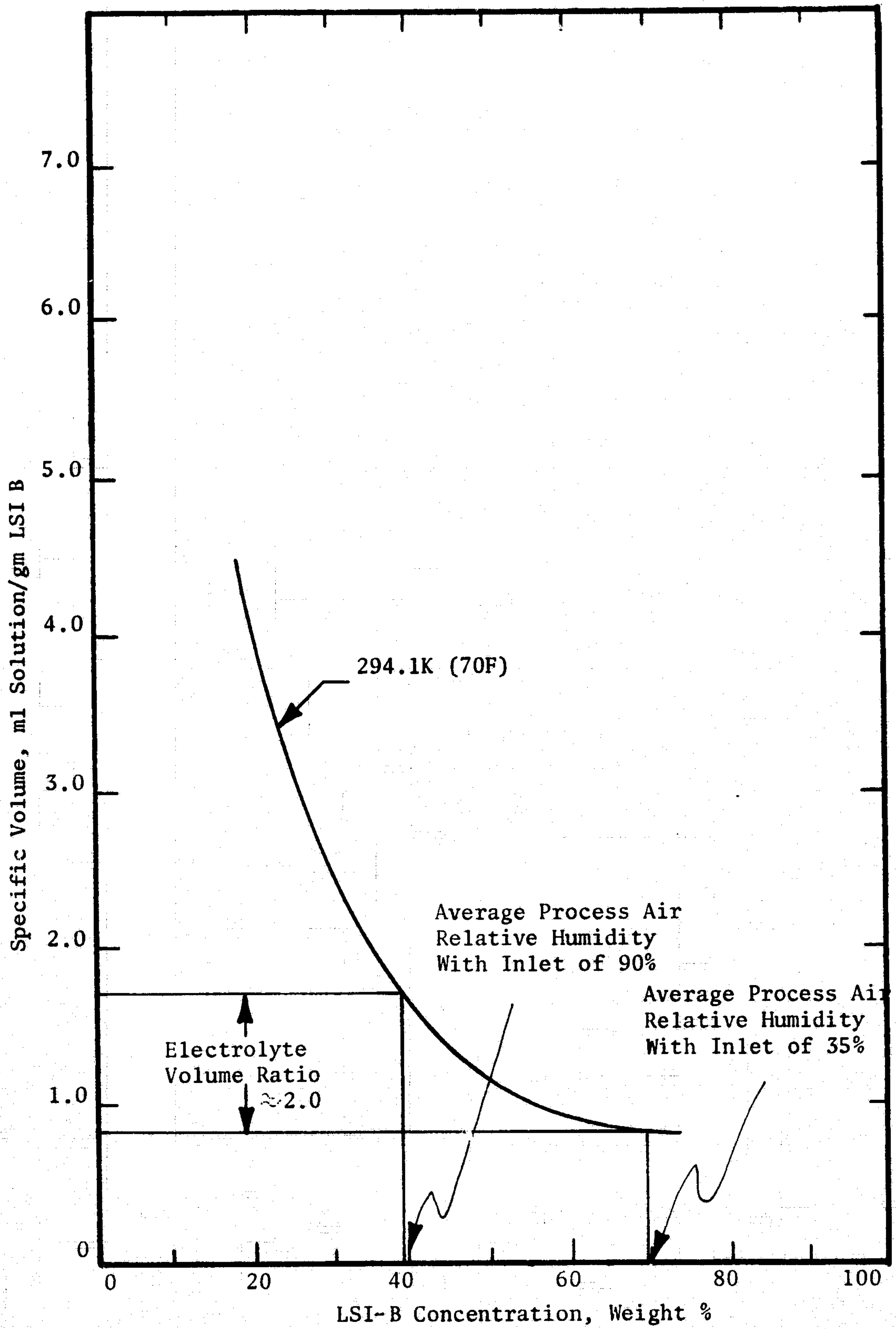


FIGURE 10 SPECIFIC VOLUME VERSUS CONCENTRATION OF AQUEOUS LSI-B

electrode and matrix configurations serve to select the actual concentration in the charging flask.

Process Fluid Flow Arrangements

Three process fluid streams interface with the electrochemical modules in the selected EARS concept: process air, cooling air and H_2/CO_2. Certain design considerations must be given to the selection of the flow arrangements of these fluids; i.e., series, parallel or combination of series parallel flow paths.

Process Air. The WVEM and EDCM can be arranged to have parallel or series process air flow. Based upon electrochemical demands, a series flow path is favored with the EDCM upstream of the WVEM. This arrangement allows the WVEM to take advantage of the water generated within the EDCM, resulting in a decrease in WVEM voltage for a given cell current density and cabin air humidity level.

The parallel process air flow arrangement has obvious advantages when considering the developmental nature of the BEARS program. This arrangement allows for independent evaluation of operating parameters during testing over the ranges of inlet conditions for both the EDCM and WVEM. Also, possible electrolyte carryover from the EDCM into the WVEM is prevented during the exploratory operation at high humidity extremes of the developmental test program.

Based on these considerations, a parallel process air flow path was selected for the BEARS. The fact that the WVEM generates the O_2 for use in the CO_2 removal process in the EDCM does not require the WVEM to be located upstream of the EDCM since the capacity effect of the cabin volume serves to dampen any pO_2 variations.

Cooling Air. Similar to the process air, either a parallel or series flow arrangement is possible for the cooling air stream. Since the lowest possible temperature in cooling air is desirable to meet, or lessen, the effects of low cabin RH limits for either module, a parallel flow path is optimum and was selected for the BEARS. High RH limits can be met by controlling cooling air flow rates.

Hydrogen/Carbon Dioxide. By definition of the EARS concept, the WVEM supplies the H_2 for use in the EDCM and, therefore, a series flow arrangement is required.

Cabin Atmosphere Considerations

An awareness of the potential impact of the cabin atmosphere composition and rates of change to reach limits for certain air constituents during potential end-item application is essential when probing for operational limits with a system such as the BEARS.

Under normal situations when an EARS is utilized for localized control of cabin air in high activity areas, the upper allowable RH level is reached well before the effects of decreased pO_2 and of increased pCO_2 are of concern. For example, with an inoperative ARS, the cabin RH reaches 100% in less than two hours, while the pCO_2 level reaches 2000 N/m^2 (15 mm Hg) in 14 hours and the pO_2 reaches emergency limits in 60 hours.[15] These relative rates of change imply that an EARS would generally operate with high inlet RHs and very seldom would there be an application requiring operation with high CO_2 removal and O_2 production requirements at low inlet RHs. This indicates that at low inlet RHs, the system could operate at decreased current levels. This type of operation suggests a control technique that could easily be integrated into the instrumentation of an EARS and would minimize taxing the system at extremely dry conditions when reduced capacity may be sufficient.

BREADBOARD HARDWARE

The breadboard hardware used in the program testing consisted of a three-cell WVEM, a three-cell EDCM, a power-sharing controller and required interconnecting plumbing and wiring.

Water Vapor Electrolysis Module

The WVEM used in the BEARS was of an advanced design for applications where tolerance to wide ranges in inlet air RH are required. A photograph of the three-cell WVEM is shown in Figure 11 with identification of call-outs presented in Table 2. The figure and corresponding table illustrate the process air sample ports, the outlet H_2 port, current and voltage tabs, and cooling air ports. The three cells of the WVEM were assembled with the process air and the H_2 flows in parallel. Module compression was provided by plexiglass end plates used for the developmental testing. Each single cell contained a platinized screen cathode, an asbestos matrix and an activated porous Ti anode. The cell housing and internal air cooling frames were made of injection-molded polysulfone plastic. The seals were Viton A flat gaskets and O-rings, while the current collectors and expanded metal (Exmet) cavity spacers were fabricated from Ti and gold-plated. A photograph of the single-cell parts is presented in Figure 12 and the cell characteristics are listed in Table 3. The active area of each cell was 0.023 m^2 (0.244 ft^2) and the cells were connected electrically in series.

Electrochemical Depolarized Carbon Dioxide Concentrator Module

The EDCM used in the BEARS was of an advanced design for application where tolerance to wide ranges in inlet air RH are required. A photograph of the three-cell EDCM is shown in Figure 11 with identification of call-outs presented in Table 2. The figure and corresponding table illustrate the process air sample ports, the inlet and outlet H_2 ports, current and voltage tabs, and cooling air ports. The three cells of the EDCM were assembled such that the process air flows were in parallel while the H_2 flow was in series through the three cells. The module compression was provided by plexiglass end plates

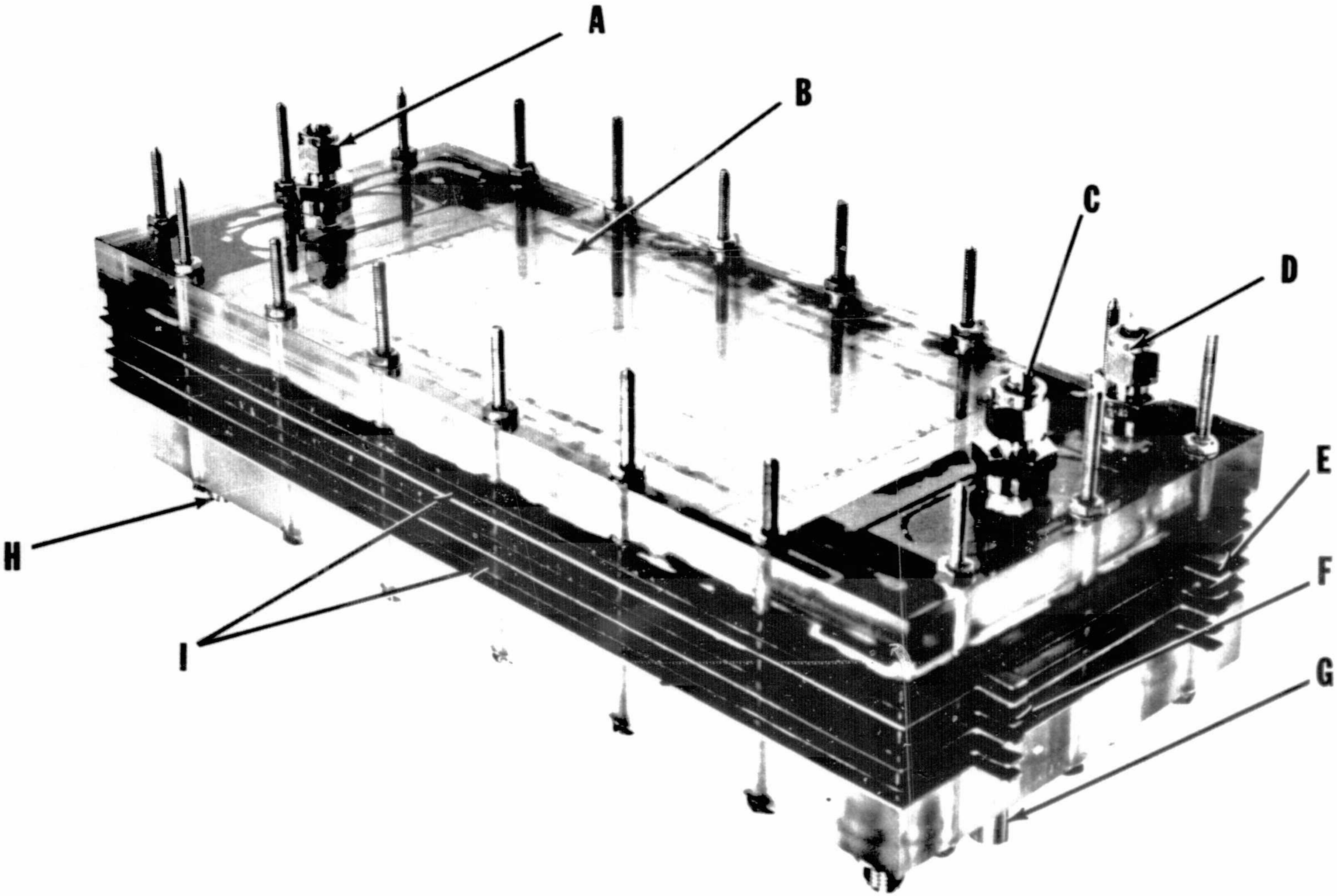


FIGURE 11 WVEM OR EDCM MODULE PHOTOGRAPH

TABLE 2 WVEM AND EDCM MODULE DESCRIPTION

Identifying Letter[(a)]	WVE Module Description	EDC Module Description
A	Inlet Process Air Sampling Port	Inlet Process Air Sampling Port
B	Cooling Air Cavity	Cooling Air Cavity
C	Outlet Process Air Sampling Port	Outlet Process Air Sampling Port
D	H_2 Cavity Port (Normally Closed)	Inlet H_2 Gas Port
E	Current Tabs	Current Tabs
F	Voltage Tabs	Voltage Tabs
G	Process Air Outlet	Process Air Outlet
H	Outlet H_2 + CO_2 Gas Port	Outlet H_2 Gas Port
I	Cooling Air Ports	Cooling Air Ports

(a) See Figure 11

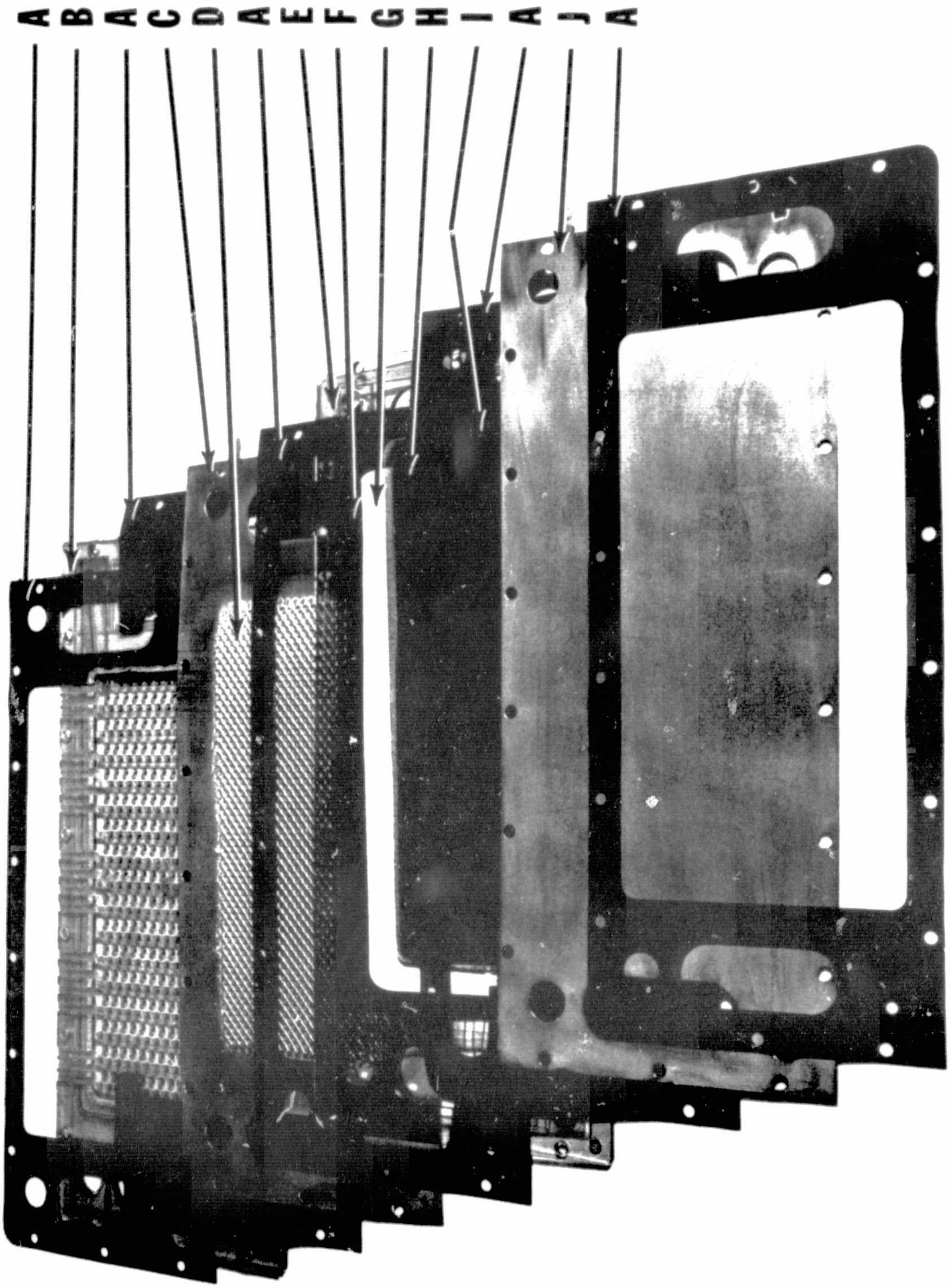


FIGURE 12 WVE OR EDC SINGLE-CELL ASSEMBLY PHOTOGRAPH

TABLE 3 WVE AND EDC SINGLE-CELL ASSEMBLY

WVE Identifying Letter (a)	WVE Hardware	Material of Construction
A	Gasket	Viton A
B	Internal Air Cooling Frame	Polysulfone
C	Anode Current Collector	Gold-Plated Ti
D	Exmet Air Cavity Spacer	Gold-Plated Ti
E	Cell Housing	Polysulfone
F	Anode	Activated Porous Ti
G	Matrix	Crocidolite Blue Asbestos
H	Cathode	Platinized Screen
I	Compression Ring	Polysulfone
J	Cathode Current Collector (Exmet H_2 Cavity Spacer Not Visible)	Gold-Plated Ti

EDC Identifying Letter (a)	EDC Hardware	Material of Construction
A	Gasket	Ethylene Propylene
B	Internal Air Cooling Frame	Polysulfone
C	Cathode Current Collector	Ni
D	Exmet Air Cavity Spacer	Ni
E	Cell Housing	Polysulfone
F	Cathode	Platinized Screen
G	Matrix	Chrysotile White Asbestos
H	Anode	Activated Porous Ni
I	Compression Ring	Polysulfone
J	Anode Current Collector (Exmet H_2 Cavity Spacer Not Visible)	Ni

(a) See Figure 12

used for the developmental testing. Each single cell contained a platinized screen cathode, an asbestos matrix and an activated porous Ni anode. The cell housing and internal air cooling frames were made of injection-molded polysulfone. Cell and module sealing was accomplished with ethylene propylene flat gaskets and O-rings. The EDCM had Ni current collectors and expanded Ni gas cavity spacers. A photograph of the single-cell parts is presented in Figure 12, while cell characteristics are listed in Table 3. The active area of each cell was 0.023 m^2 (0.244 ft^2) and the cells were connected electrically in series.

Power-Sharing Controller

The power-sharing controller as fabricated and tested for the BEARS program utilized switching regulators for high power conversion efficiency. The logic circuits and low level control circuits were constructed on printed circuit (PC) cards. The entire assembly was installed in a standard commercial enclosure. Figure 13 is a photograph of the controller, showing the front panel and the controls contained on it. These controls consisted of an AC power On/Off switch, EDCM and WVEM current set point potentiometers and an auto On/Off switch for each current control. This last type of switch allowed the controller to be used in unattended long-term testing of the system. When the switch was in the down position, the current was on. When the switch was in the middle position, the current was off, and when the switch was in the up position, the current was controlled by the automatic shutdown circuits contained in the BEARS GSA.

The controller was packaged so that removal of the four front panel screws would allow the entire front panel and chassis containing all internal components to be removed from the case. Figure 14 shows the controller removed from its case with the major components of the controller identified. There are two PC cards, one for each of the power control circuits. Adjustment capabilities for calibration and for setting the WVEM voltage limit were located on the PC cards. Connectors were located along the back panel to allow DC power to be fed to the controller, accept the shutdown signals from the GSA and provide current to the modules. A power cord was provided to supply 115V, 60 Hz logic power for the controller.

Integrated Breadboard

The three components used in the BEARS were integrated with the GSA (see discussion of GSA below) to perform the program testing. Only tubing and electrical connections were required for the hookup. The process and cooling air from the GSA was divided between the two modules to provide the parallel flow arrangements as discussed above. The EDCM and WVEM outlet process air flows were recombined to provide for data acquisition. The H_2 produced by the WVEM was routed directly from the outlet H_2 port to the EDCM inlet H_2 port to simulate integrated flight hardware. The modules were connected electrically to the breadboard power-sharing controller. The DC power for the power controller was provided by a GSA power supply.

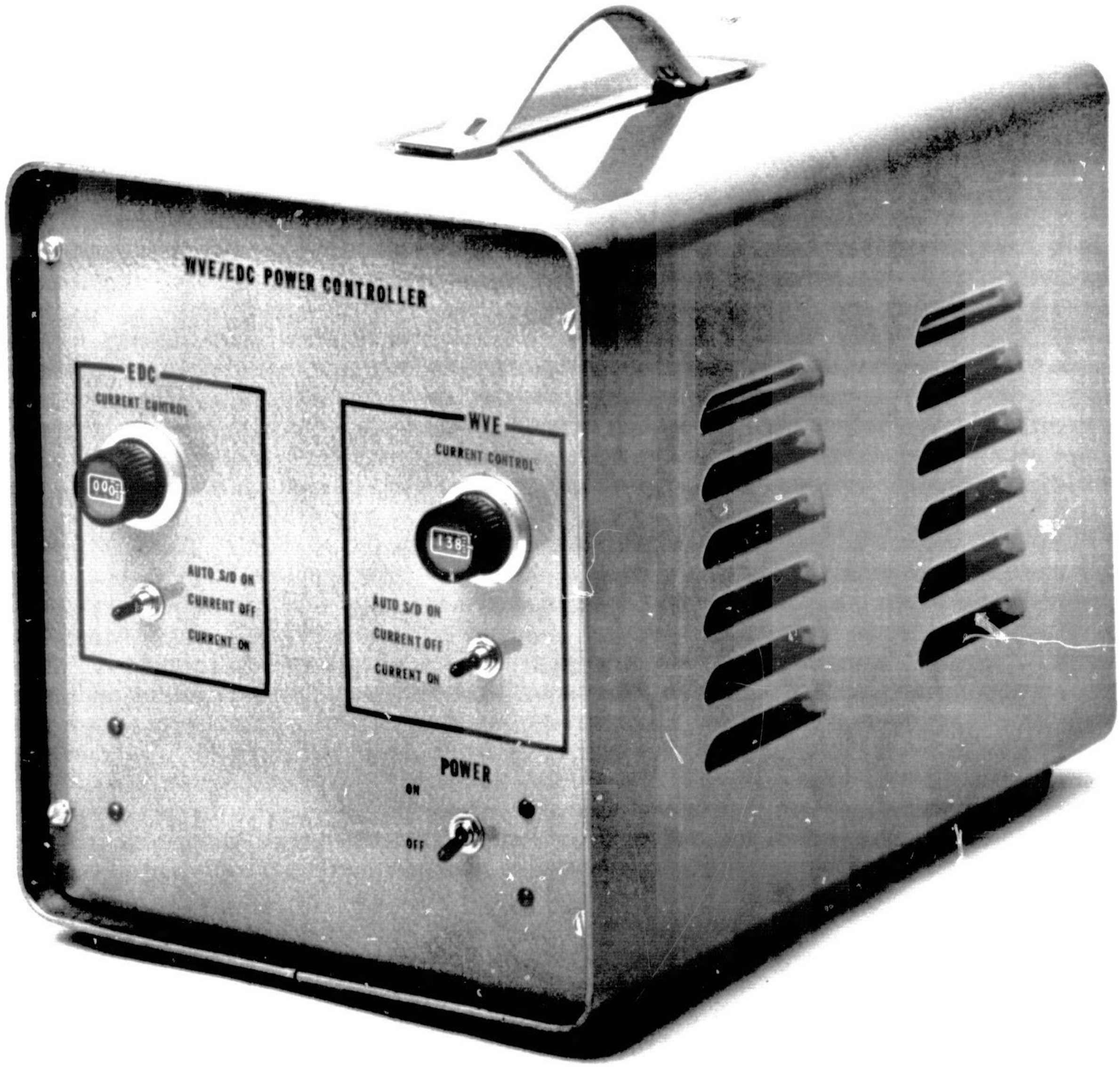


FIGURE 13 POWER-SHARING CONTROLLER

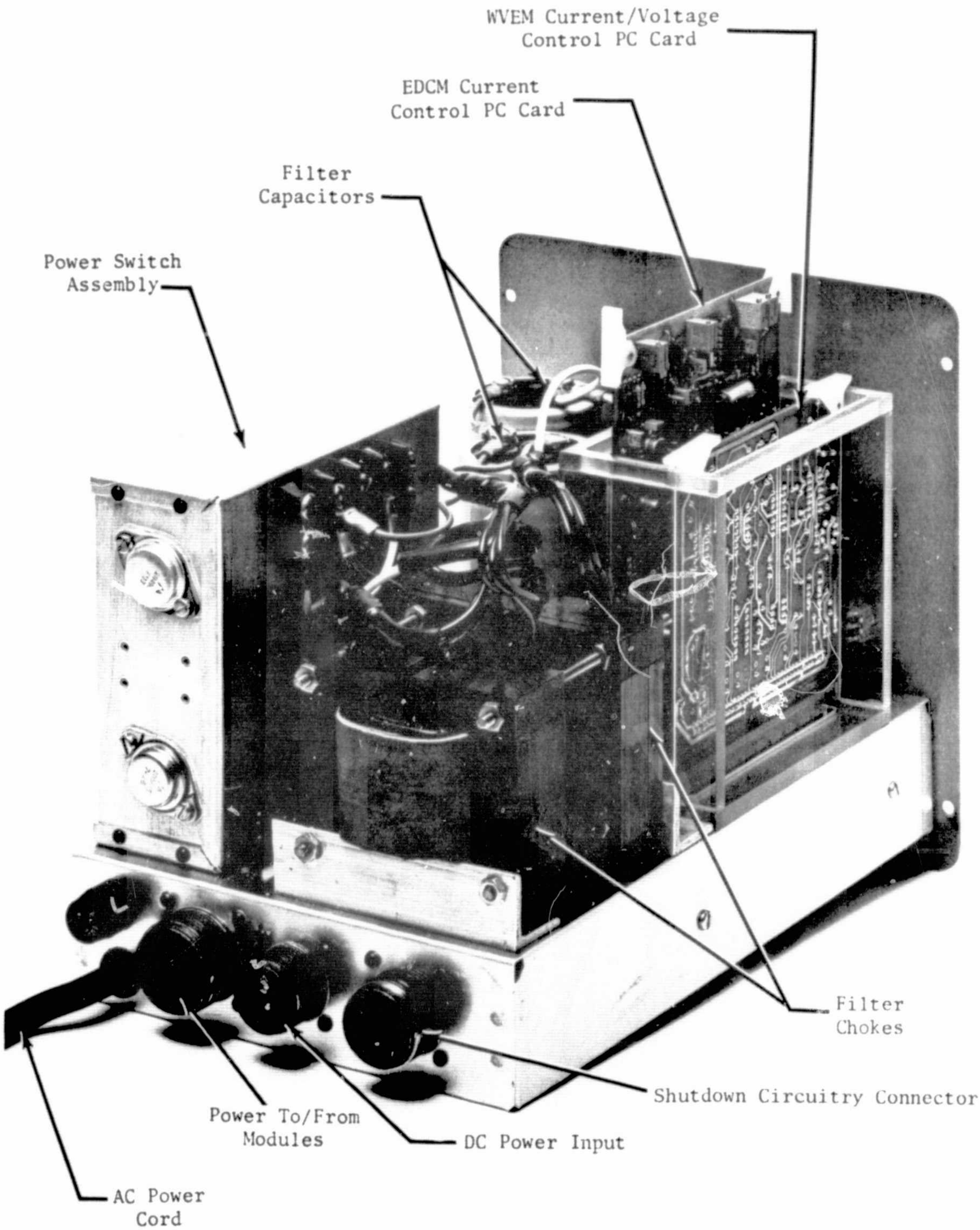


FIGURE 14 POWER-SHARING CONTROLLER, REAR VIEW

GROUND SUPPORT ACCESSORIES

Various items of support equipment were needed during the testing of the BEARS. Their function was to supply the fluids, electrical inputs, controls, instrumentation displays and protective shutdown instrumentation required for the operation of the BEARS.

An overall schematic of the GSA is shown in Figure 15 illustrating process fluid flow paths, sensor locations, module integration and control instrumentation. Figure 16 shows a photograph of the front panel of the GSA, while Table 4 identifies the various controls, meters and instrumentation called out on Figure 16.

Fluid Interfaces

The GSA provided the necessary control of the process fluids to allow for operation over the specified ranges in inlet conditions. The process fluids required by the BEARS are process air, cooling air, H_2 and nitrogen (N_2).

The GSA conditioned air from a compressed air supply to provide the process air to the modules. A saturator tank controlled the inlet dew point from 274.7K to 295.8K (35 to 73F), while an in-line heater controlled the dry bulb temperature at the desired level between 291.3 and 296.9K (65 and 75F). The inlet pCO_2 was controlled from ambient (approximately 0.033 kN/m^2 (0.25 mm Hg) to 0.533 kN/m^2 (4 mm Hg)) by adding CO_2 to the process air stream.

The cooling air was provided by an external blower. Ambient air was drawn through a heat exchanger into an inlet cooling air manifold where it was divided equally between the two modules. The cooling air was recombined in an outlet manifold prior to passing through the cooling air blower. A liquid coolant, controlled by a differential temperature controller, flowed through the heat exchanger to maintain the cooling air temperature equal to the process air temperature.

Also included as part of the GSA were H_2 and N_2 gas supplies. The H_2 gas was provided to allow for EDCM operation without operation of the WVEM. The N_2 gas was included for manual purging prior to scheduled shutdowns and startup of the BEARS.

Electrical Power

All electrical and electronic monitoring and control instrumentation of the GSA utilized 120V, 60 Hz AC power. The power to the power-sharing controller was supplied by a 25 amp, 0 to 36V DC-regulated power supply.

Engineering Parameters

The GSA provided for the acquisition of the data necessary to evaluate WVEM and EDCM performance using the instrumentation listed in Table 5. The expected

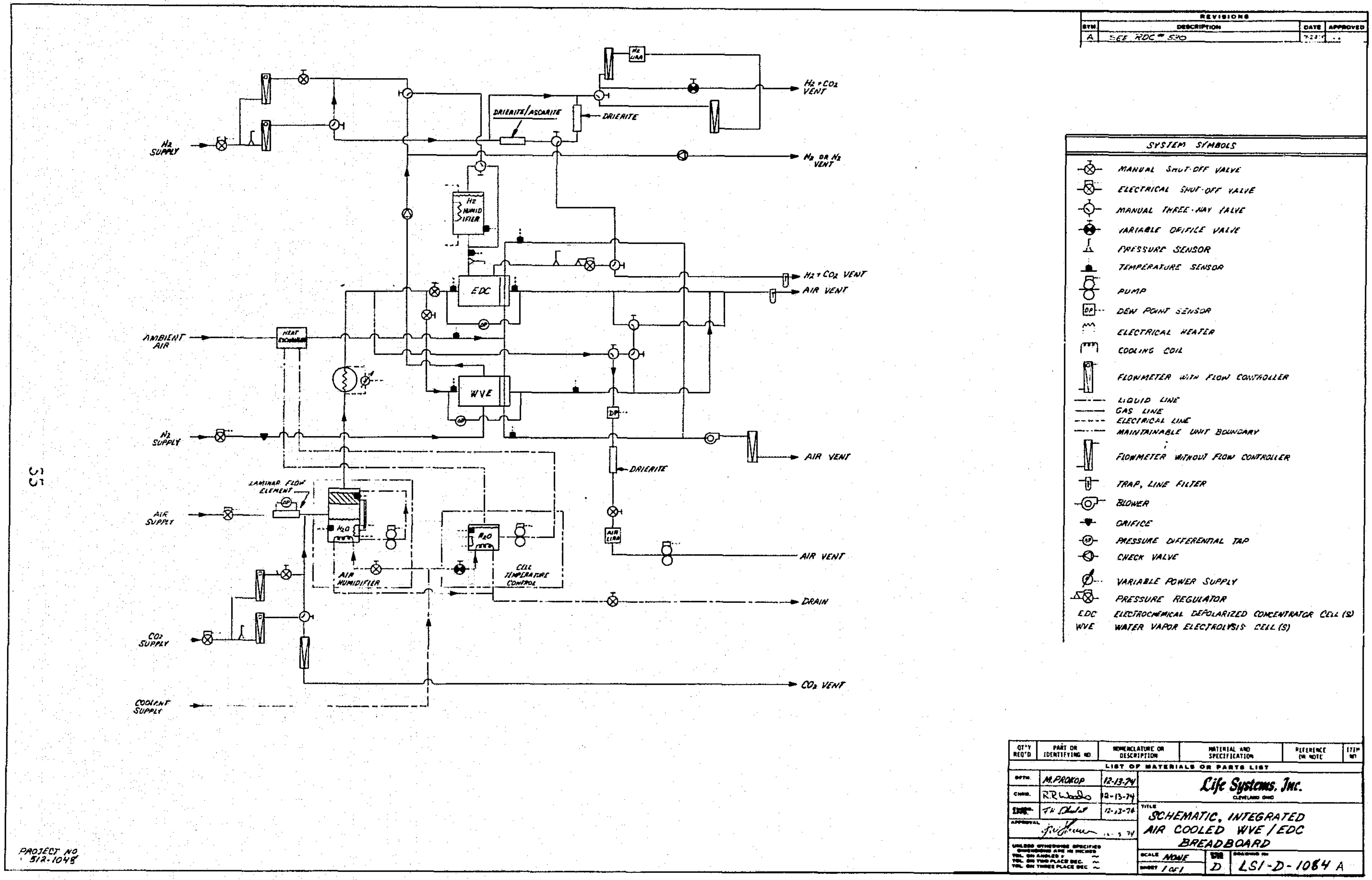


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FIGURE 15 BEARS GSA SCHEMATIC

Life Systems, Inc.

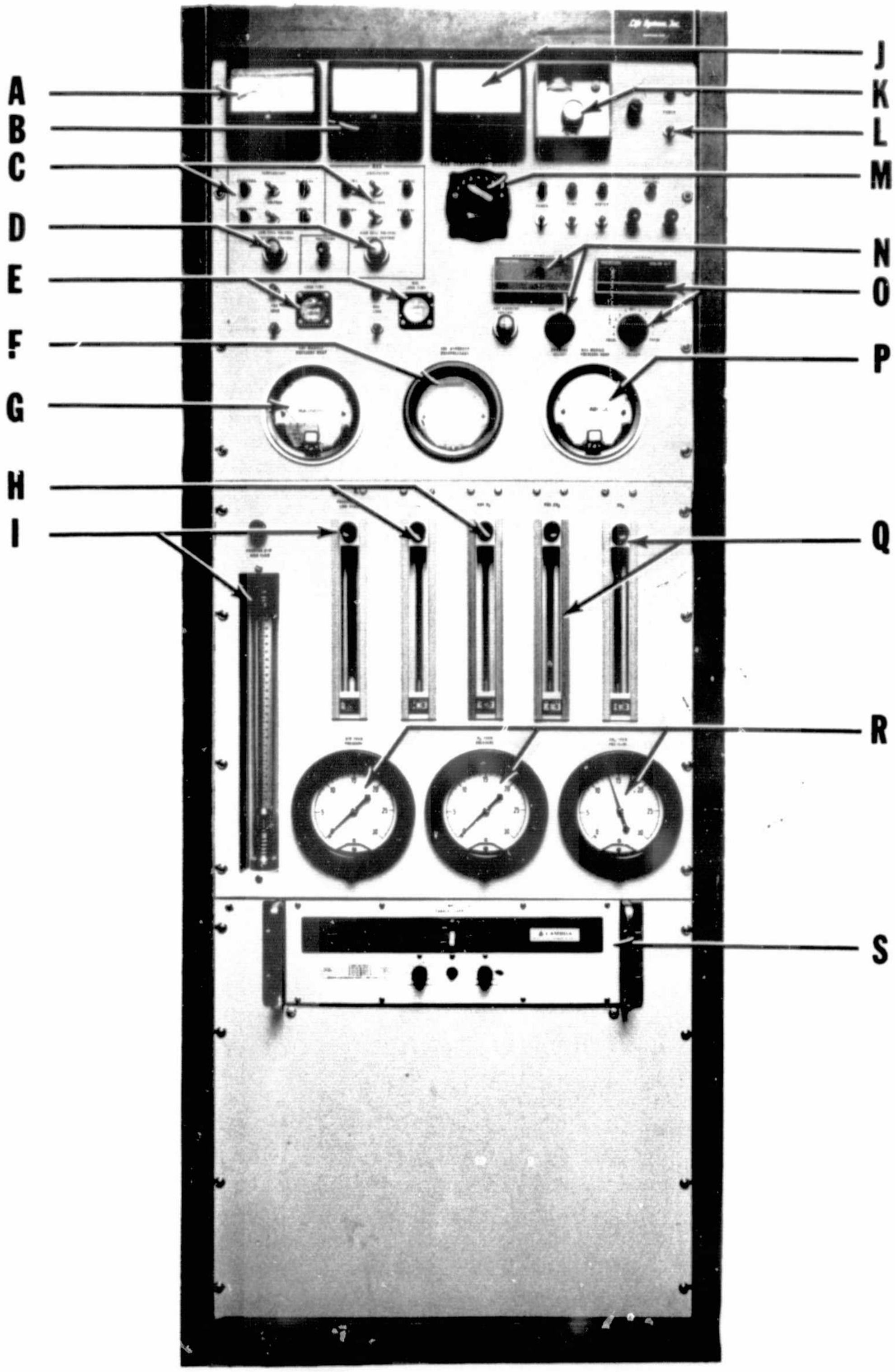

FIGURE 16 GSA FRONT PANEL PHOTOGRAPH

TABLE 4 GSA INSTRUMENTATION

GSA Identifying Letter	Instrumentation on GSA Front Panel
A	EDCM temperature indicator with high temperature shutdown set point
B	WVEM temperature indicator with high temperature shutdown set point
C	WVEM and EDCM shutdown override switches and indication lights
D	EDCM low voltage and WVEM high voltage shutdown potentiometers
E	Operational timers
F	H_2/CO_2 exhaust pressure gauge
G	EDCM process air differential pressure gauge
H	GSA H_2 flow meters
I	GSA process air flow meters
J	Thermocouple readout display
K	Differential temperature control for cooling air
L	GSA power on switch
M	Thermocouple selection switch
N	EDCM and WVEM current display and selection switch
O	EDCM and WVEM voltage display and selection switch
P	WVEM process air differential pressure gauge
Q	GSA process CO_2 flow meters
R	GSA process gas inlet feed pressure gauges
S	GSA power supply

See Figure 16

Other GSA Instrumentation

1. Percent CO_2 in air LIRA
2. Percent CO_2 in H_2 LIRA
3. Dew point hygrometer
4. Ambient thermometer
5. Ambient barometer
6. Power controller inlet voltmeter
7. Power controller inlet ammeter
8. Flow turbine for cooling air
9. Bubble flow meters and wet test meter

TABLE 5 PARAMETRIC TEST INSTRUMENTATION

Type of Measurement	Type of Instrument	Measurement Location	Expected Accuracy
Temperature	Marlox Thermocouples	Process air EDC and WVE in and out; cooling air in and out	±2K (4F)[(a)]
Dew Point Temperature	EG&S Dew Point Hygrometer Model 880	Process air EDC and WVE inlet and outlet	±0.5K (1F)
CO_2 in H_2, %	Lira Infrared Analyzer Model 300	EDC H_2 & CO_2 outlet	±1%
CO_2 in Air, %	Lira Infrared Analyzer Model 300	EDC process air in and out, and WVE out	±1%
Process Air Flow Rate	Wet test meter; calculations from pCO_2 and amount of CO_2 added; module ΔP calibration	WVE and EDC in and out	±3%
Cooling Air Flow Rate	Flow transducer	Combined EDC and WVE out	±3%
CO_2 & H_2 Flow Rates	Wet test meter Bubble flow meter	EDC CO_2 & H_2 out	±1%
Current	Weston Digital Meter	EDC module WVE module	±0.1 Amp
Current	Lambda DW90	Power Supply Output	±0.3 Amp
Voltage	Weston Digital	EDC cells WVE cells EDC and WVE modules	±0.002 Volt
Voltage	Simpson	Power supply output	±0.2 Volt
Continuous Votlage Record	Rustrak	WVE module	±5%
Pressure	Magnehelic gauge	EDC H_2 & CO_2 exhaust ΔP of WVE process air ΔP of EDC process air	±2%

(a) Locally calibrated by mercury thermometer to within ±0.5K (1F) accuracies of each device, along with location of the sampling ports are indicated in the table. Specifically, the GSA provided for the data acquisition of the following parameters for both the EDCM and WVEM: dry bulb temperatures, dew points and pCO_2 for the inlet and outlet process air streams; dry bulb temperature for inlet and outlet cooling air; flow rates for the process air, cooling air, $CO_2 + H_2$ and CO_2 streams; cell voltages and module currents. The GSA also provided for the measurement of the pressure and pCO_2 levels of the EDCM anode exhaust gas.

During testing, the test stand facilities continuously recorded the three WVEM and three EDCM individual cell voltages and monitored the input current and voltage to the power-sharing controller. A sample test log used for BEARS testing is shown in Figure 17. The parameters are cross referenced to Table 4, identifying the instrumentation used for each parameter.

Protective Shutdown Circuits

The GSA used for the BEARS testing provided for four automatic shutdowns: EDCM high temperature, WVEM high temperature, low single-cell EDCM voltage and high single-cell WVEM voltage. As a result of an automatic shutdown, the current to both modules was reduced to zero and all process gas solenoid valves were closed. The EDCM and WVEM temperature shutdown levels were controlled by adjustable trip points on the module temperature readouts as shown in Figure 16. The voltage shutdown levels were manually adjustable with potentiometers located on the front panel of the GSA. The individual cell voltages were automatically scanned by GSA circuitry to allow for shutdown due to out-of-tolerance operation of any of the six individual single cells. Each of the four shutdown circuits was connected to an indicator light on the GSA front panel to identify which type of shutdown had occurred. Override switches were provided to isolate each shutdown circuit separately.

PRODUCT ASSURANCE PROGRAM

A mini-Product Assurance Program was implemented during the BEARS optimization investigation. The Product Assurance Program included Quality Assurance, Reliability, Safety and Materials Control functions. Quality Assurance was necessary to insure reproducibility of the BEARS design and configuration during subsequent development. Reliability was included to identify and eliminate any failure modes that might prevent application of this system to a manned spacecraft flight. Safety was included to insure that no system or system component characteristic would be dangerous to personnel or equipment during testing. The Materials Control was included in preparation for the material specifications that would be imposed on a system designed for manned space flight and to insure the application of materials that would be compatible with the various fluids used within the BEARS.

Quality Assurance

The Quality Assurance activities performed during the fabrication and assembly of the BEARS were included to insure that no defective components or parts

Life Systems, Inc. CLEVELAND, OHIO 44122	LOG OF TEST	SHEET OF	DATE
	MODEL/PART NO. EDCM	TEST PLAN NO.	ER-247-8
		PROJ. NO.	512-1048
TYPE OF TEST	NAME OF RIG BEARS	TEST ENGR.	

Time						Instrumentation (a)
Load Time, Hr						E
% CO_2, In						1
% CO_2, Out						1
CO_2 Reading, cc/sec						9
CO_2 Flow, cc/min						-
Background, % CO_2						1
Combined % CO_2, Out						1
Temp. Process Air In, TC No., F						J,M#3 (b)
Temp. Module, TC No., F						A
Dew Point Air In, F						3
Dew Point Air Out, F						3
Inlet, % RH						-
Outlet, % RH						-
I, A						N
Voltage, V Cell No. 1						0
Cell No. 2						0
Cell No. 3						0
Total						0
Temp. Cooling Air In, F						J,M#6
Temp. Cooling Air EDC Out, F						J,M#5
ΔP EDC Module in Water						G
EDC Process Air Flow, Cfm						-
% CO_2 in H_2						2
H_2 and CO_2 Reading, cc/sec						9
H_2 and CO_2 Flow, cc/min						-
Temp. Ambient, F						4
Ambient Pressure, mm Hg						5
pCO_2, mm Hg						-
Air Flow, Process, Scfm						-
CO_2 Transferred, scc/min						-
Transfer Index, Air Side						-
Transfer Index, H_2 Side						-
Combined Dew Point Out, F						3

(a) See Table 4
(b) Thermocouple Selection Switch Position Number

continued-

FIGURE 17 TEST LOG

Figure 17 - continued

Life Systems, Inc. CLEVELAND, OHIO 44122	LOG OF TEST	SHEET OF	DATE
	MODEL/PART NO. EDCM	TEST PLAN NO.	ER-247-8
		PROJ. NO.	512-1048
TYPE OF TEST	NAME OF RIG BEARS	TEST ENGR.	

Time						Instrumentation[a]
Load Time, Hr						E
Temp. Air In, TC No., F						J,M#2
Temp. Module, TC No., F						B
Dew Point Air In, F						3
Dew Point Air Out, F						3
Inlet % RH						-
Outlet % RH						-
I, A						N
Voltage, V Cell No. 1						O
Cell No. 2						O
Cell No. 3						O
Total						O
Cooling Flow Rate, Cfm						8
Temp. Cooling Air In, F						J,M#6
Temp. Cooling Air WVE Out, F						J,M#4
ΔP WVE Module in Water						P
WVE Process Air Flow, Cfm						-
Temp. Ambient, F						4
Ambient Pressure, mm Hg						5
H_2 Backpressure, Psig						F
Power Supply, A						7
Power Supply, V						6

(a) See Table 4

were incorporated into the test hardware. These activities consisted of performing receiving inspections of all vendor supplied parts, including preparation of required documentation; insuring that assembly techniques specified in the design drawings were complied with and were consistent with the developmental nature and scope of the program; insuring that configuration control was provided by monitoring the drawing and change control procedures; and monitoring the testing of the BEARS.

Reliability

A Failure Mode Effects and Criticality Analysis (FMECA) was performed for the cells of the electrochemical modules and the interconnecting plumbing. This level of effort was consistent with the developmental nature and scope of the present program.

In the FMECA, all hypothesized equipment failure modes are analyzed and classified according to criticality levels as listed below:

Criticality

I	A single failure which could cause loss of personnel.
IIa	A single failure whereby the next associated failure could cause loss of personnel.
IIb	A single failure whereby the next associated failure could cause return of one or more personnel to earth or loss of subsystem function(s) essential to continuation of space operations and scientific investigation.
III	A single failure which could not result in loss of primary or secondary mission objectives or adversely affect crew safety.

Two Criticality IIA failure modes were identified as a result of the FMECA performed. The failure modes are associated with H_2 leakage from the H_2 or H_2 + CO_2 components to ambient or into the process air stream. These hazards are inherent in H_2 bearing systems and, therefore, cannot be eliminated. In this case, the hazards can be minimized by incorporation of triple redundant instrumentation which provide for system N_2 purge and shutdown when module temperature is out-of-tolerance or when H_2 is sensed by combustible gas sensors within the system.

Safety

As part of the Product Assurance Program, a safety review of the BEARS preliminary design and its GSA was performed to insure that safety considerations were included. The safety features listed below were incorporated into the design of the BEARS and its GSA to provide for personnel and equipment safety during testing.

1. Emergency shutdown capabilities were incorporated in the GSA for all critical parameters. These included: EDC and WVE module high temperature shutdowns, EDC low voltage shutdown and WVE high voltage shutdown.

2. Ambient combustible gas sensors were incorporated to provide BEARS shutdown when H_2-in-air concentration exceeded 2%.

3. High pressure fluids were limited to less than 310 kN/m^2 (45 psia).

4. Pipes, hoses and tubes were coded to indicate the fluid, hazard and function.

5. Only one piece of rotating equipment was needed in the BEARS GSA: a cooling air blower. The blower had all rotating parts enclosed.

6. Manual override techniques were provided on the critical automatic functions to permit safe operation during an emergency.

7. Any electrical equipment which presented a shock hazard was covered with a protective guard.

8. The BEARS GSA was electrically grounded to protect against shock.

9. Surface temperatures in the system were limited to a range of 277 to 316K (40 to 110F).

10. Circuit breakers were incorporated to protect equipment from damage due to high current drain.

11. Sharp edges and corners were eliminated or adequately covered to prevent injuries.

12. An N_2 purge was included in the BEARS and all H_2 and H_2 + CO_2 lines were purged prior to startup, and prior to and after maintenance.

Materials Control

A Materials Control Program was implemented for the BEARS. Considering the developmental nature of the program, only the materials associated with the WVEM and the EDCM cells were evaluated from a flight-acceptability standpoint. The evaluation was performed in two categories: metallic and nonmetallic. The acceptability of metallic materials was based on the SSP Design Criteria Handbook.[16]

Table 6 lists the metallic materials present in the EDCM and WVEM of the BEARS. The table describes the usage of the material and the disposition of the material relative to the guidelines of the referenced Design Criteria Handbook.

TABLE 6 METALLIC MATERIALS SUMMARY

Material Generic Name	Usage	Disposition
WVEM		
Titanium	Current Collectors, Exmet	Acceptable[(a)]
Gold	Electroplated, Conductive Coating on Current Collectors and Exmet	Acceptable[(a)]
Platinum	Cathode	Acceptable
Titanium	Anode	Acceptable[(a)]
Stainless Steel (316)	Fittings, Plumbing	Acceptable
Copper	Electrical Leads	Acceptable
EDCM		
Nickel	Current Collectors, Exmet	Acceptable
Gold	Electroplated Conductive Coating on Current Collectors and Exmet	Acceptable
Nickel	Cathode/Anode	Acceptable
Platinum	Cathode/Anode	Acceptable
Stainless Steel (316)	Fittings, Plumbing	Acceptable
Copper	Electrical Leads	Acceptable

(a) O_2 pressure is less than 145 kN/m^2 (21 psi).

The nonmetallic materials were screened for acceptability to CSD-SS-012, "Nonmetallic Materials Requirements for Manned Testing of the Space Station Prototype Environmental/Thermal Control and Life Support System."[17] Table 7 lists the nonmetallic materials present in the EDCM and WVEM cells. Material usage, disposition and qualifying comments are also listed in the table. All nonmetallic materials are acceptable or conditionally acceptable. Polysulfone and ethylene propylene had been submitted to NASA for flammability tests in the as-used configuration as part of the SSP program. Both materials were acceptable as configured.[9]

TEST PROGRAM

The test program was divided into three major areas of investigation: (1) WVE electrode evaluation, (2) power-sharing controller evaluation and (3) integrated breadboard testing. The objective of the first phase of testing, WVE electrode evaluation, was to select an optimum WVE anode followed by characterization and endurance testing of that electrode. The objective of the second phase of testing, power-sharing controller evaluation, was to demonstrate the feasibility and characterize the performance of the power-sharing controller concept. The objective of the final phase of testing, integrated breadboard testing, was to characterize the performance of the BEARS over wide ranges in operating parameters. The integrated breadboard testing was performed according to a Master Test Plan which was approved both by Contractor and NASA personnel.

Water Vapor Electrolysis Electrode Evaluation

This phase of testing was designed to select an optimum WVE anode for EARS application from a number of Contractor-developed electrodes. Once an optimum WVE anode was identified, its performance was characterized as a function of process air RH and operating time. A total of over 4700 hours of single-cell WVE operation was accumulated during this phase of testing.

Water Vapor Electrolysis Electrode Selection

A selection philosophy was established followed by single-cell testing to characterize the selected electrode.

Selection Philosophy. The WVE anode selection philosophy established for the BEARS program was to base the initial selection of candidate anodes on Contractor-developed performance data consisting of cell voltages as a function of current density. The best performing electrode was then to be endurance tested at constant, optimum operating conditions for a period of 500 to 1000 hours followed by characterization of its voltage at constant current density while the RH of the process air would be varied over the range of 35 to 90%. Should the candidate electrode not be able to complete successfully the initial endurance test, the next lower performing electrode was to be used to perform the RH characterization experiment. Following the endurance and RH characterization test, the selected anode was again to be placed on endurance testing until 45 days of operation had been accumulated.

TABLE 7 NONMETALLIC MATERIALS SUMMARY

Material Generic Name	Usage	Disposition
WVEM		
Asbestos	Electrolyte Matrix	Acceptable
Polysulfone	Cell Housing	Conditionally Accepted
Viton A	O-Rings and Gaskets	Acceptable
Teflon (TFE)	Bolt Insulation	Acceptable
Polysulfone	Cooling Air Housing	Conditionally Accepted
EDCM		
Asbestos	Electrolyte Matrix	Acceptable
Polysulfone	Cell Housing	Conditionally Accepted
Ethylene Propylene	O-Rings and Gaskets	Conditionally Accepted
Teflon (TFE)	Bolt Insulation	Acceptable
Polysulfone	Cooling Air Housing	Conditionally Accepted

Current Density Data. Figure 18 shows the performance of five Contractor-developed WVE electrodes for a range in current density of 10 to 60 mA/cm^2 (9.3 to 55.8 ASF). Of the five electrodes shown, the E5 electrode was the Contractor-selected baseline anode prior to the time of the BEARS test program initiation. An E5 electrode had been previously and successfully operated for a period of 2400 hours at 54 mA/cm^2 (50 ASF).

Initial Endurance Test. All testing with candidate anodes was performed using BEARS baseline sized and configured cells. The test cathodes were platinized screen electrodes previously selected by the Contractor as optimum for WVE application.

A parallel test approach using two test stands was selected for the initial endurance test phase. In this parallel test approach, an E5 electrode, proven at the time to be the most reliable electrode of the five candidates, was put on test. The specific electrode selected for testing had already accumulated the 2400 hours of operation referred to above. While electrode E5 was evaluated, a simultaneous test activity on the second test stand was performed to evaluate the remaining candidate electrodes for potential replacement of the E5 should one with better and more stable performance characteristics be identified.

Figure 19 shows a timetable of activities during the WVE electrode evaluation program depicting the sequence of events and their chronological relationships. Table 8 contains a brief summary of the results of the initial endurance test phase with reasons for selection or discontinuation of a particular electrode test indicated.

The candidate E5 electrode was operated for 790 hours at constant conditions and demonstrated a maximum single-cell voltage of 1.92V at a current density of 54 mA/cm^2 (50 ASF). The detailed results of this test are illustrated in Figure 20, with the average operating conditions and the cause of the single shutdown indicated in Table 9. Following completion of 790 hours of testing at a stable average cell voltage of 1.90V, at 54 mA/cm^2 (50 ASF), the RH characterization test was started. At that time, the specific E5 electrode had accumulated a total of 3190 hours, including the 2400 hours of pre-contract testing.

During the RH characterization of the E5 electrode, pre-characterization endurance testing of the E5B electrode was started based on the results of current density evaluation (see Figure 18) of the E5B electrode. Also, during this general time frame as shown in Figure 19, electrodes E5A, E5C and E8 were evaluated and rejected for the various reasons indicated in Table 8. Electrode E6 had been rejected earlier as noted in Figure 18 and Table 8.

Since the difference between electrodes E5 and E5B was only a change in the activation procedure, the long-term voltage stability of the E5B electrode was considered similar to that of the E5 electrode. To verify this assumption, the E5B electrode was put on endurance testing while the E5 RH characterization test was continued. The results of the E5B endurance testing are presented in

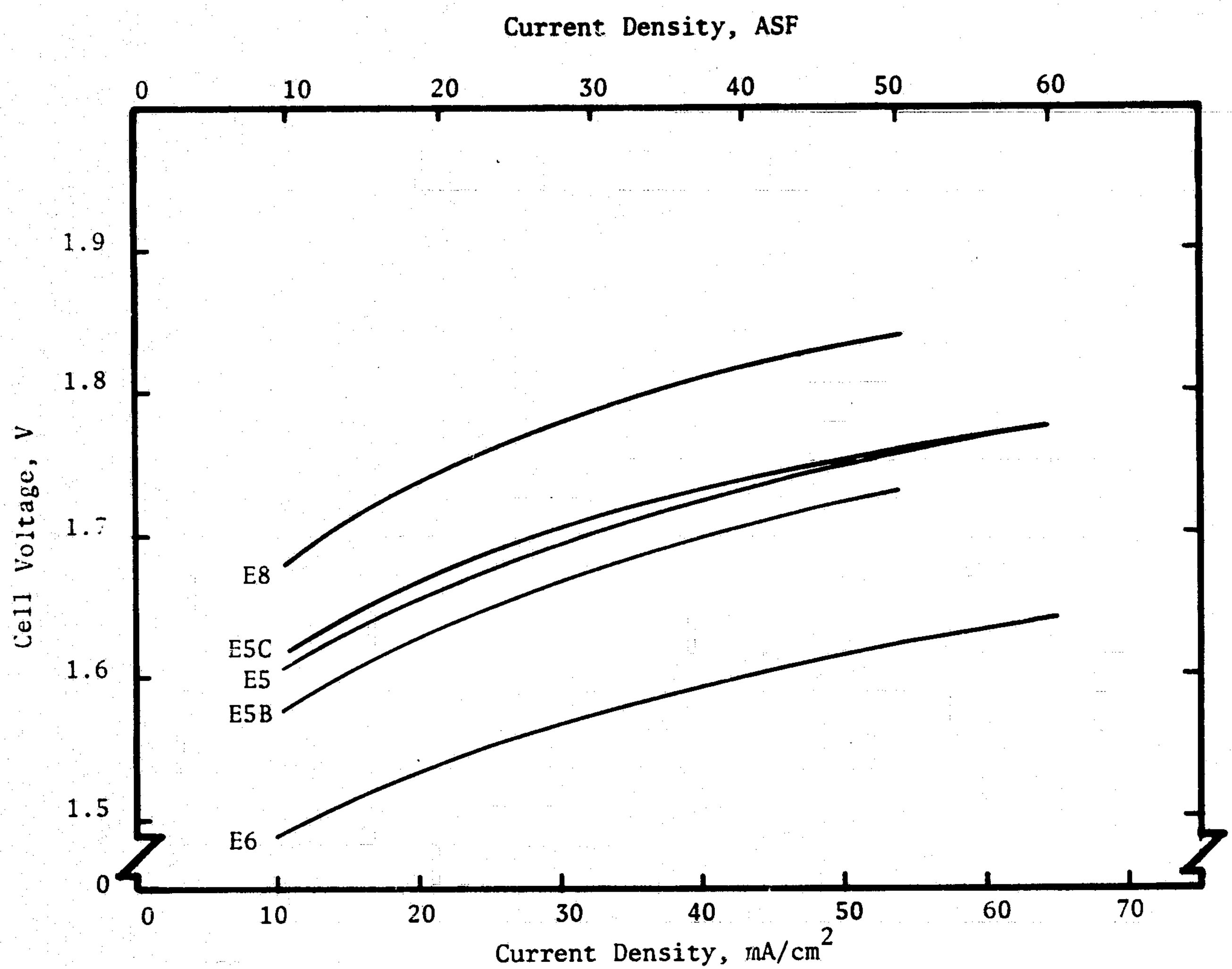

FIGURE 18 WVE ELECTRODE CURRENT DENSITY EVALUATION

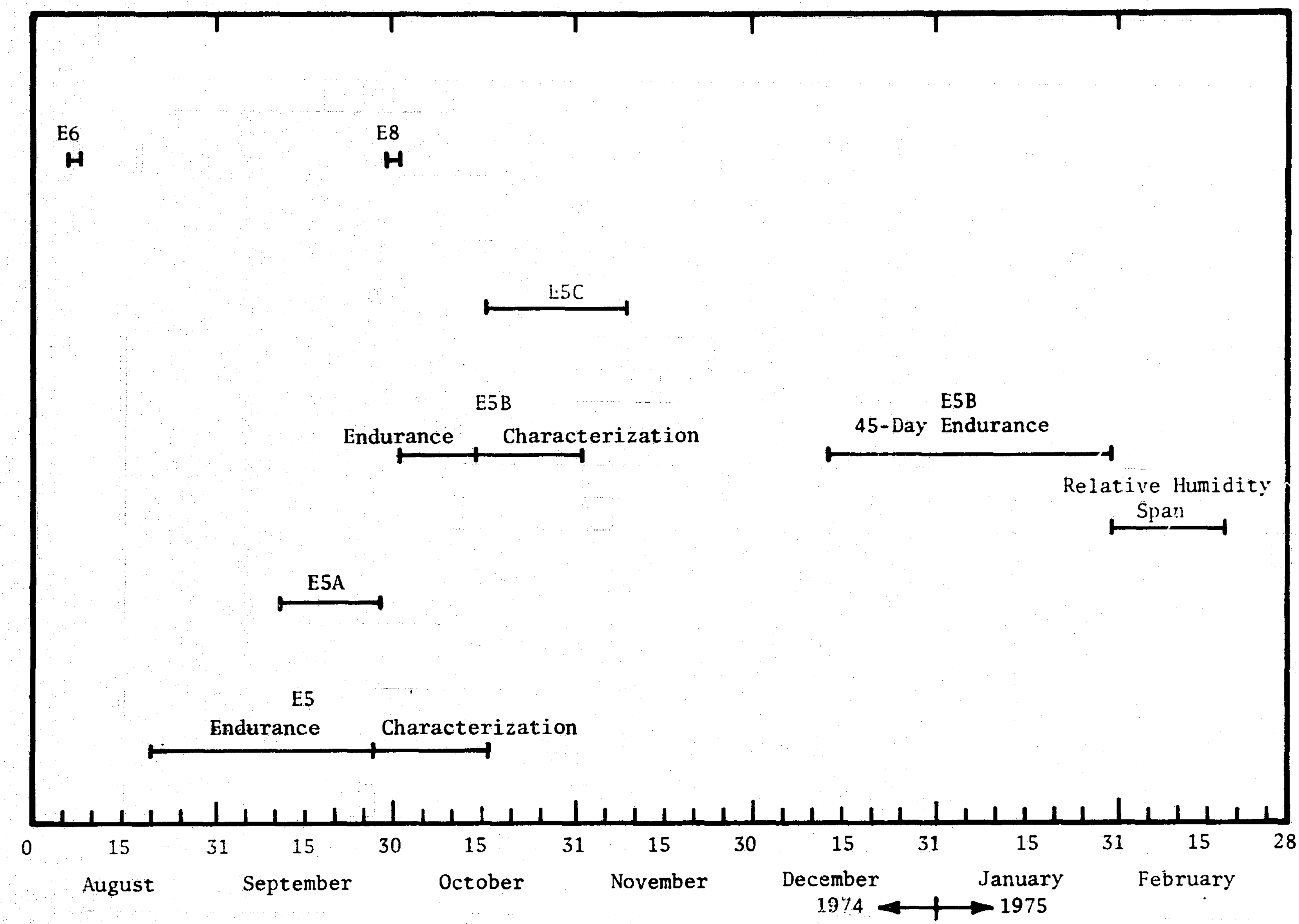

FIGURE 19 WVE ELECTRODE EVALUATION TIMETABLE

TABLE 8 EVALUATION OF WVE ELECTRODES (ANODES)

Electrode	Comment
E6	This electrode exhibited excellent voltage versus current density characteristics but within 24 hours the voltage was 1.88V at 53.8 mA/cm^2 (50 ASF) and a black substance coated the air exhaust resulting in increased voltages above acceptable levels.
E6A[a]	Similarly to E6, this electrode formed a black substance and a voltage of 2.0V at 53.8 mA/cm^2 (50 ASF) within 22 hours of operation.
E8	Testing was terminated after 50 hours of operation due to poor voltage (1.96V at 53.8 mA/cm^2).
E5A[a]	This electrode showed good voltage characteristics, but there was no gain or advantage over E5.
E5B[a]	This E5 type electrode exhibited very good voltage characteristics, maximum voltage of 1.82 v at 53.8 mA/cm^2 (50 ASF) with an inlet relative humidity of 50 to 60%, an improvement over the baseline E5 electrode.
E5C[a]	This E5 type electrode also illustrated good voltage characteristics; voltages between 1.85 and 1.88V at 53.8 mA/cm^2 (50 ASF) for an inlet relative humidity between 70 and 50%, but there was no gain or advantage over E5B.

(a) Same catalyst as base electrode (E6, E5, etc.) but variation in activation procedure.

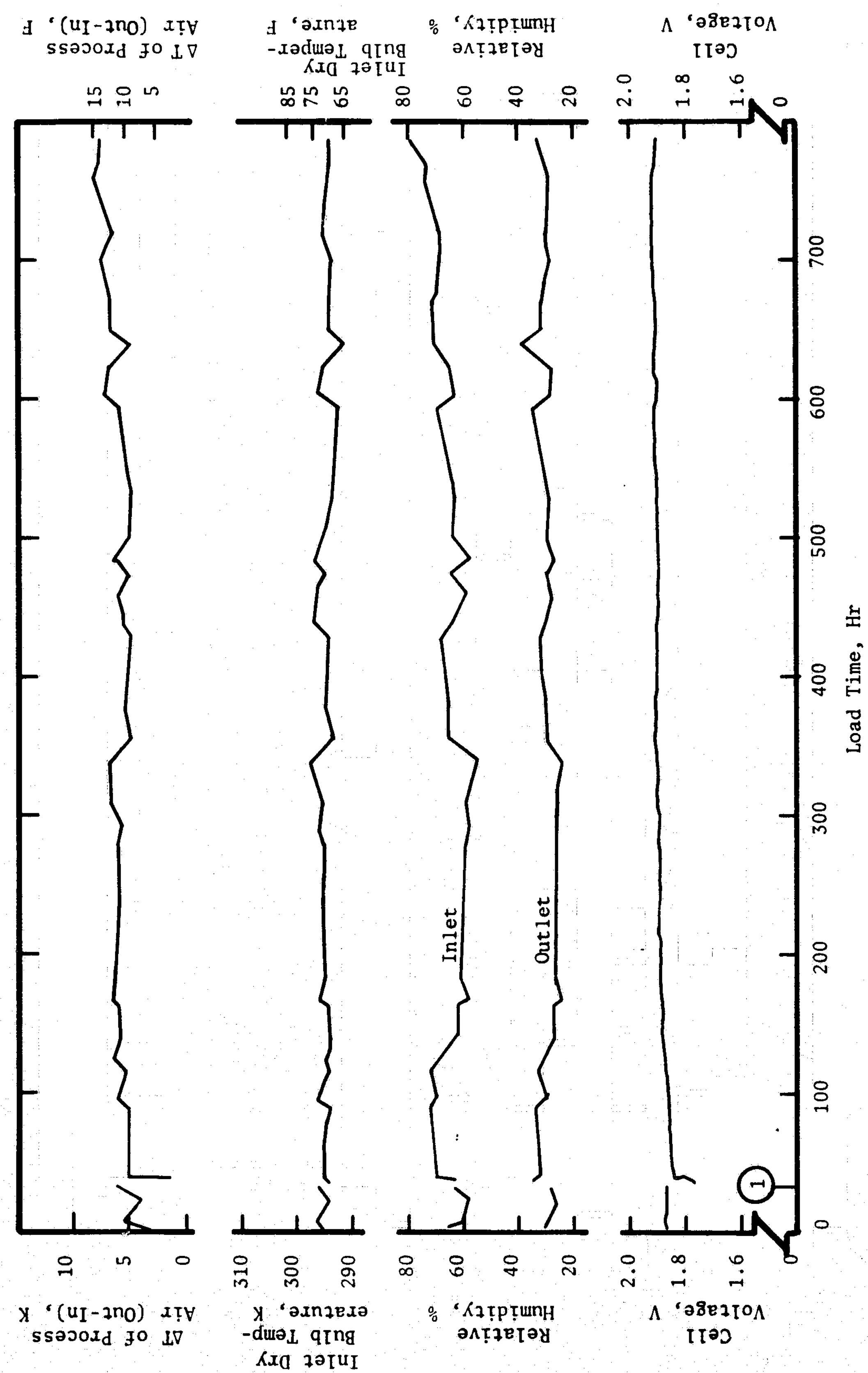

FIGURE 20 WVE PERFORMANCE FOR E5 ELECTRODE

TABLE 9 WVE ENDURANCE TEST LEGEND
FOR E5 ELECTRODE AND E5B ELECTRODE

Legend		
Anode	E5	E5B
Cathode	Platinized Screen	Platinized Screen
Matrix	Crocidolite Blue Asbestos	Crocidolite Blue Asbestos
Test Operating Time, Hr	790	315
Total Anode Operating Time, Hr	3190	315
Charge Concentration, % H_2SO_4	51	51
Current Density, mA/cm^2 (ASF)	53.8 (50)	53.8 (50)
Process Air Flow Rate, m^3/s (Scfm)	2.8×10^{-4} (0.60)	2.8×10^{-4} (0.60)
Pressure	Ambient	Ambient

Shutdowns E5	Comment	Load Time, Hr
1. Power failure to building	Restart	37.5

Shutdowns E5B	Comment	Load Time, Hr
No shutdowns	Not Applicable	Not Applicable

Figure 21 with operating conditions listed in Table 9. The E5B electrode exhibited an average cell voltage of 1.82V at 54 mA/cm^2 (50 ASF). Based on the results of this test, the E5 electrode characterization test was stopped, and the E5B electrode was selected as baseline for the BEARS. Characterization testing as a function of process air RH was continued using the E5B electrode.

RH Characterization Test. The characterization test results of the E5 and E5B electrodes, as a function of process air RH over a range of 35 to 90% for a dry bulb temperature range of 291 to 297K (65 to 75F), are presented in Figure 22. The improvement in cell voltage of the E5B electrode over the E5 electrode is clearly shown in the figure. The remaining test conditions for the characterization test were similar to those used in the initial endurance test as shown in Table 9 (as applicable).

The results presented in Figure 22 show a strong dependency of cell voltage on process air inlet RH at RH levels below 60%. Between 35 and 40% RH and at temperatures of less than 292.7K (67.5F) the data shows scatter, indicating difficulty in maintaining stable cell voltages.

Endurance Testing

With the completion of the RH characterization of the baseline E5B electrode, endurance testing was begun. Initially, a 45-day endurance test at optimum RH conditions was performed, followed by 360 hours of operation (in addition to contract experiments) at lower inlet RHs.

Optimum Relative Humidity. The objective of the 45-day endurance test at optimum conditions was to demonstrate the performance of the electrode selected as the LSI optimum WVE following initial endurance and characterization testing. The results of this testing are presented in Figure 23 with the shutdown summary contained in Table 10. Operation was maintained during the major portion of the testing with an inlet RH of 80 to 90% and a dry bulb temperature of 293 to 295K (70 to 73F). During this operation, the cell demonstrated voltage between 1.75 and 1.8V at the baseline current density of 54 mA/cm^2 (50 ASF).

Low Relative Humidity. With the successful completion of the 45-day endurance testing at optimum conditions, the inlet RH was lowered to investigate this effect on cell operating performance over extended periods of time. This testing was in addition to that scheduled under the program. The test philosophy established was that when a limiting RH level was reached, operation would be continued at a decreased current density level. The results of this testing are presented in Figure 24.

Power-Sharing Controller Evaluation

The power-sharing controller was evaluated at the component level prior to integration with the two modules and the GSA. The evaluation consisted of checkout and characterization testing. The controller was also evaluated as

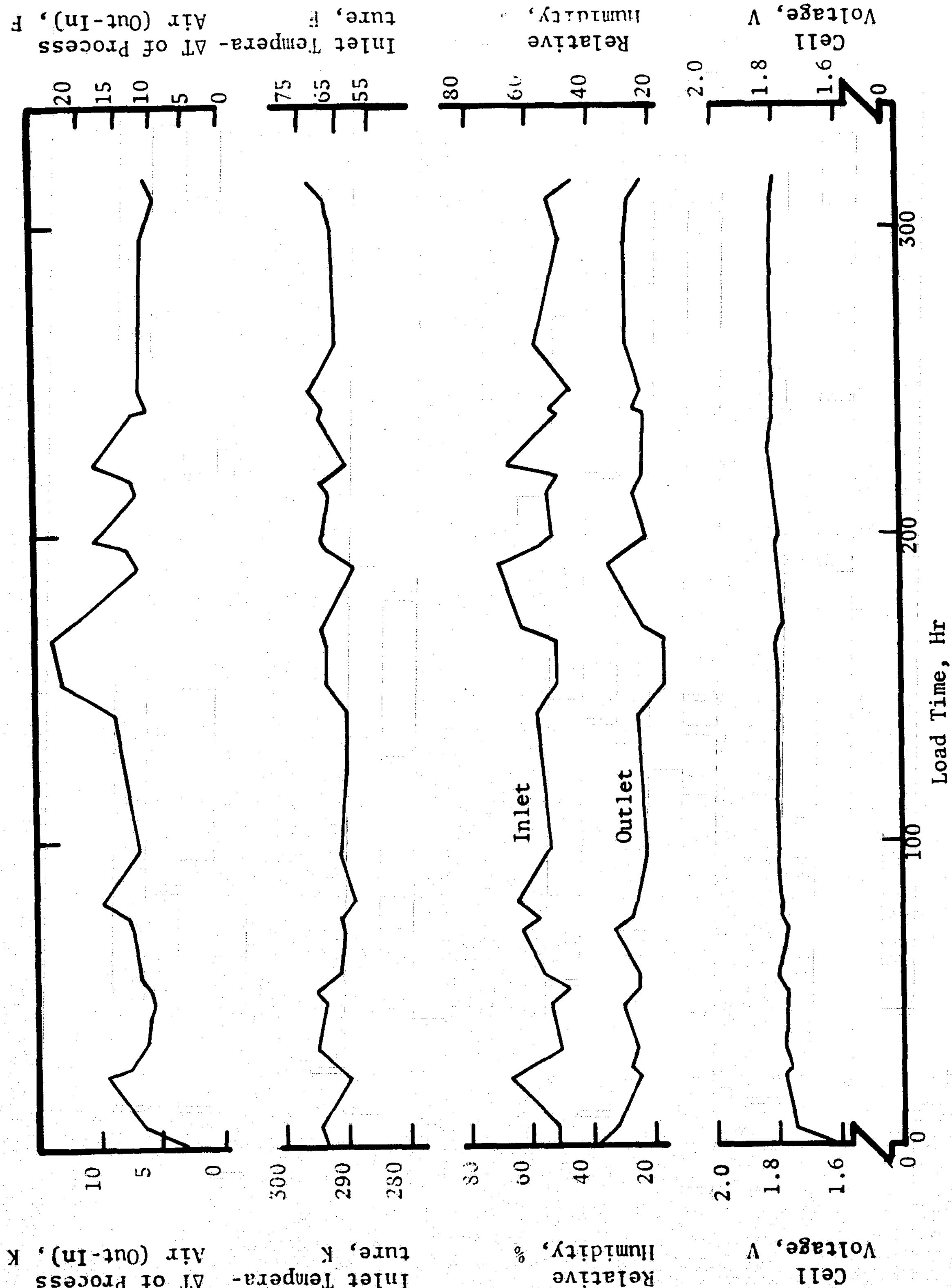

FIGURE 21 WVE PERFORMANCE FOR E5B ELECTRODE

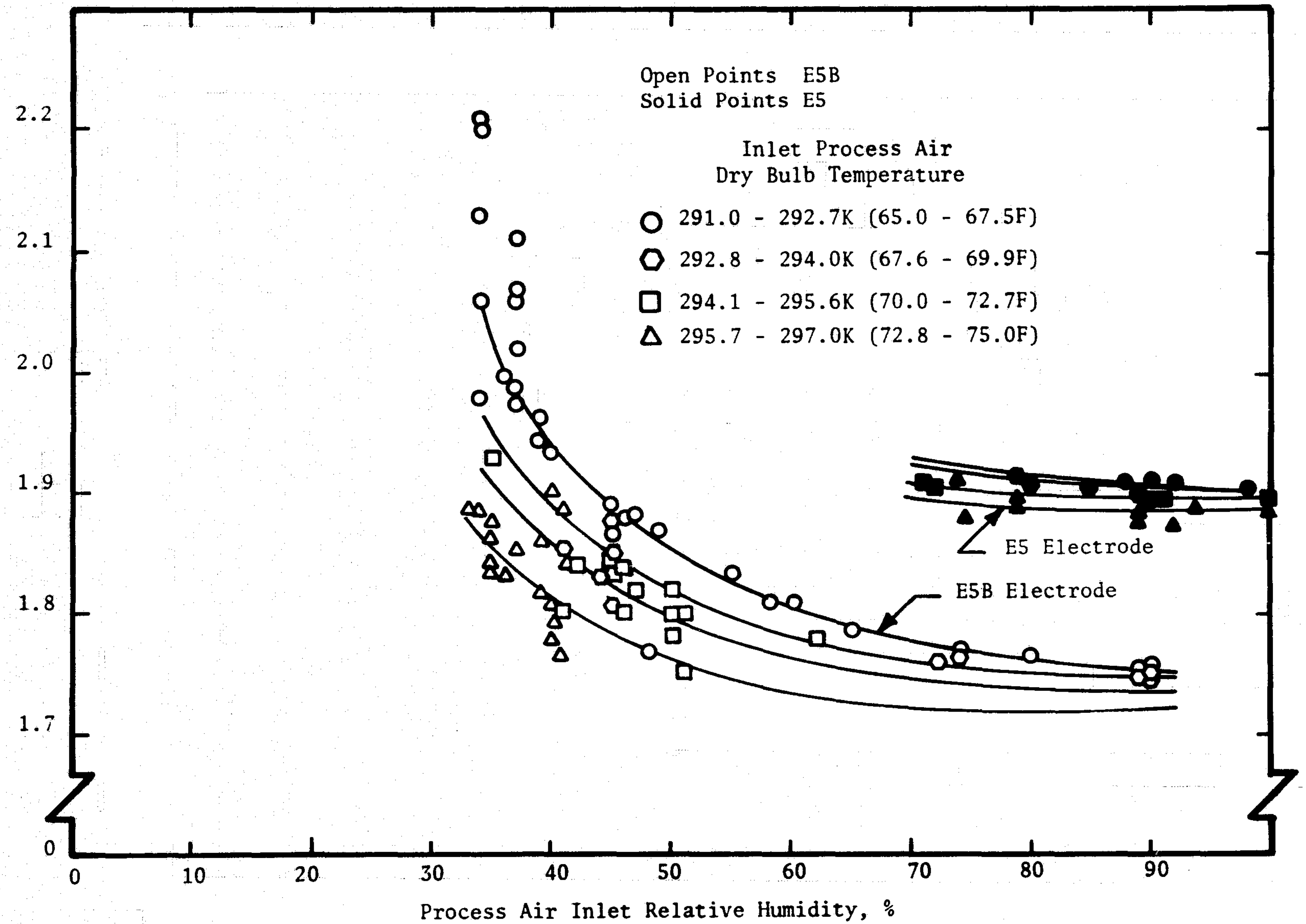

FIGURE 22 EFFECTS OF PROCESS AIR RELATIVE HUMIDITY AND TEMPERATURE ON WVE VOLTAGE

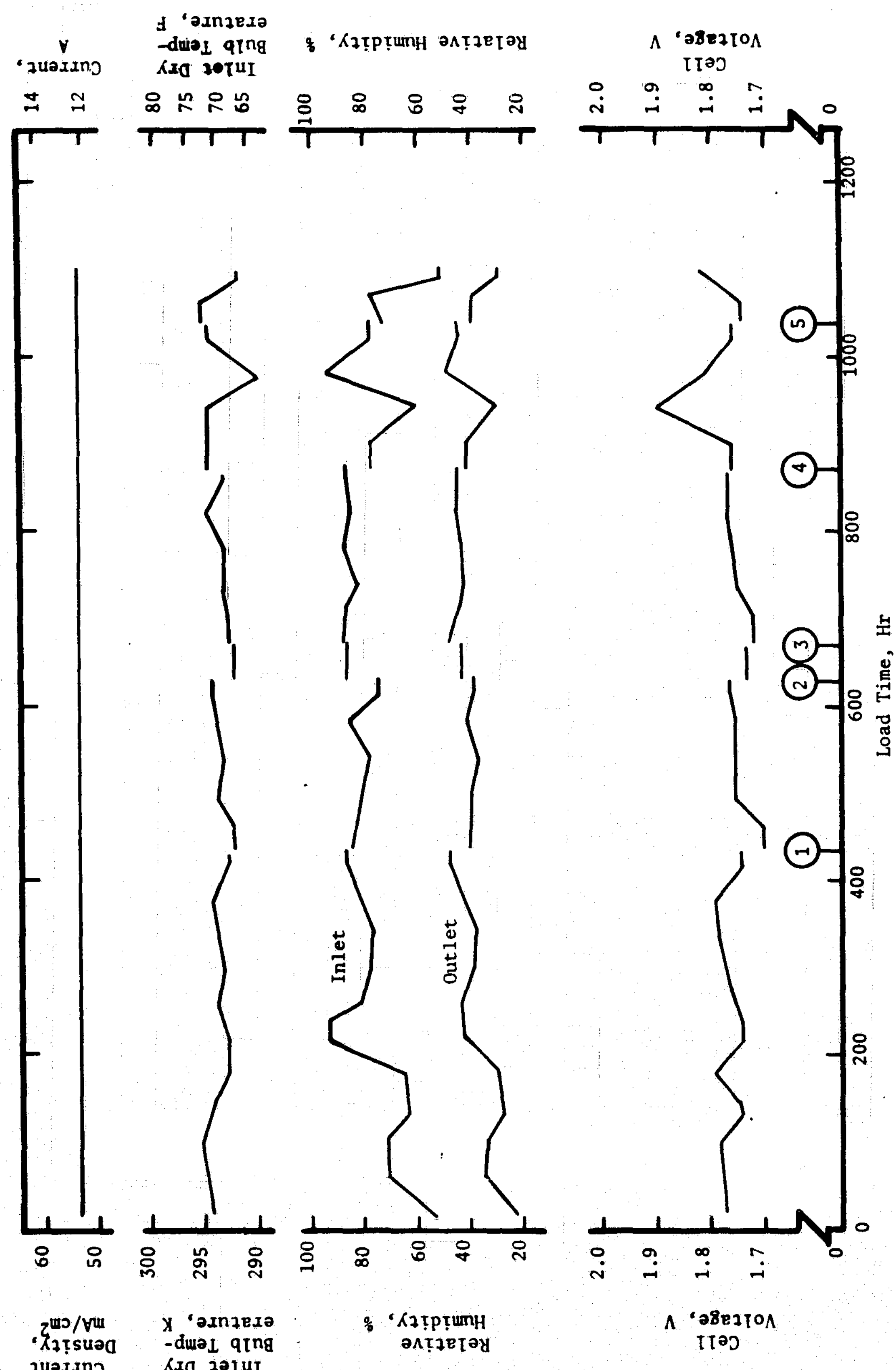

FIGURE 23 45-DAY ENDURANCE TEST

TABLE 10 LEGEND AND SHUTDOWN SUMMARY
45-DAY WVE ENDURANCE TEST

Legend	
Anode	E5B
Cathode	Platinized Screen
Matrix	Crocidolite Blue Asbestos
Test Operating Time, Hr	1080
Total Anode Operating Time, Hr	1830
Charge Concentration, % H_2SO_4	51.5
Current Density, mA/cm^2 (ASF)	53.8 (50)
Process Air Flow Rate, m^3/s (Scfm)	2.8×10^{-4} (0.60)
Pressure	Ambient

Shutdowns	Comment	Load Time, Hr
1. Shutdown, Operator Error	Reconditioned	412.0
2. Shutdown, Manual to Replumb BEARS GSA	Restart	626.5
3. Building Power Failure	Restart	670.0
4. Building Power Failure	Restart	870.4
5. Building Power Failure	Restart	1020.3

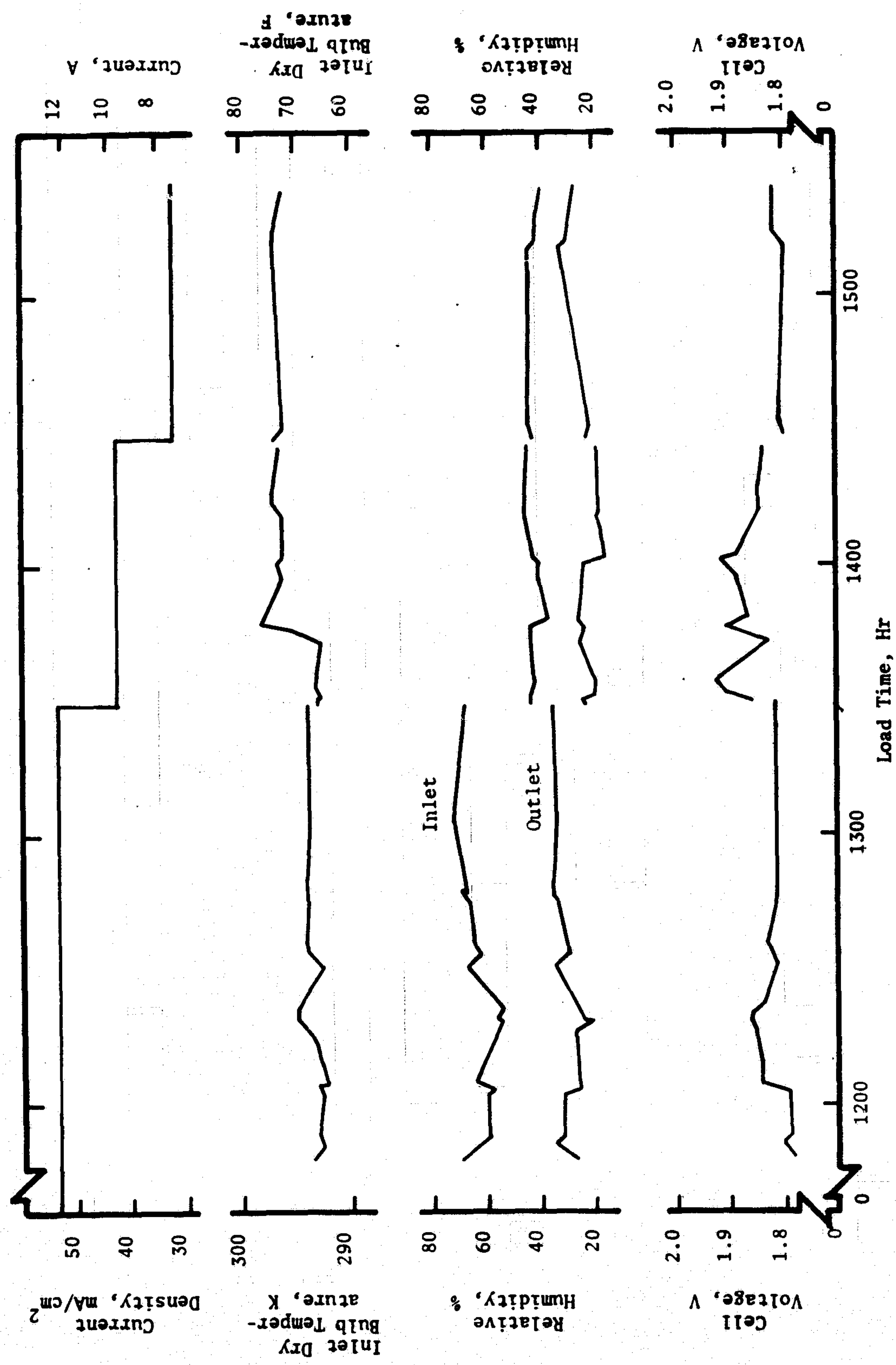

FIGURE 24 EXTENDED SINGLE-CELL WVE TEST

part of the integrated breadboard endurance test. The results of this testing have been included in this section.

Checkout Test

The control logic circuits for the power-sharing controller were assembled on two boards. After these boards were assembled, they were completely tested in the Contractor's PC board tester. All circuit functions were successfully demonstrated with simulated inputs and loads. Following controller assembly, all wiring was checked for continuity. The PC boards were then installed in the controller and its operation tested using resistive dummy loads.

Characterization Test

The performance of the controller was characterized using 12V lead-acid batteries in place of the WVEM and EDCM. This was done so that inadvertent damage to the electrochemical modules would be prevented while the controller was exercised over its operating range. As shown in Figure 7, the EDCM is connected in series adding with Power Control A (their voltages add). This series combination is connected in parallel with Power Control B and the combination used to feed current to the WVEM. With this connection, every watt of EDCM power is fed to the WVEM.

Figure 25 is a plot of the data taken during the characterization tests of the controller. The data shows that the WVEM power drawn from the WVEM power controller is reduced by the exact amount of EDCM power generated. Figure 26 shows the overall performance of the controller, including its power conversion efficiency. From this curve it can be seen that as EDCM power is increased the controller input power decreases at any WVEM power requirement.

Figure 27 shows the variation in overall controller efficiency as the EDCM and WVEM powers are varied. The power conversion efficiency of the controller is determined by subtracting EDCM power from WVEM power and dividing the result by the controller input power. When EDCM power equals WVEM power, the conversion efficiency drops to zero. This is an indication that the power conversion circuits use a certain amount of power to make currents flow through the modules even when the net output power (i.e., WVEM power minus EDCM power) is zero. Thus, for example, if the WVEM requires 60W and the EDCM is delivering 60W, the controller will require about 21W to keep the current flowing through the modules. This results in zero conversion efficiency. However, it should be noted that this 21W would be required whether the EDCM power-sharing circuits were incorporated or not. Figure 28 is a plot showing the input power reduction as a function of EDCM and WVEM powers.

The circuits used for Power Controls A and B (see Figure 7) were designed for a one-man level system at about 25A and 20V for the water electrolysis power supply. They are, therefore, not optimized for use in the one-fifth man capacity BEARS. For any final application, the power controls should be

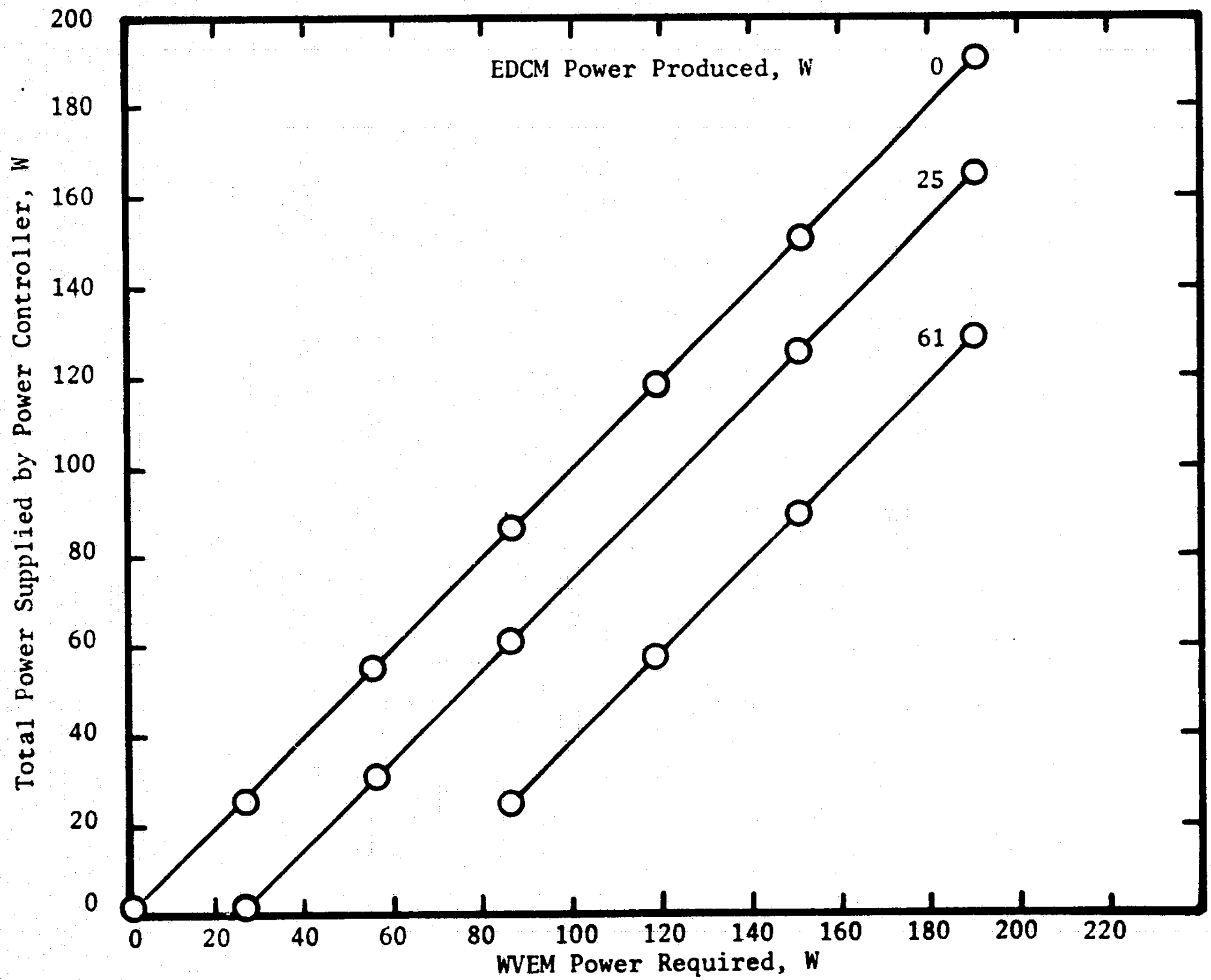

FIGURE 25 EDCM POWER UTILIZATION

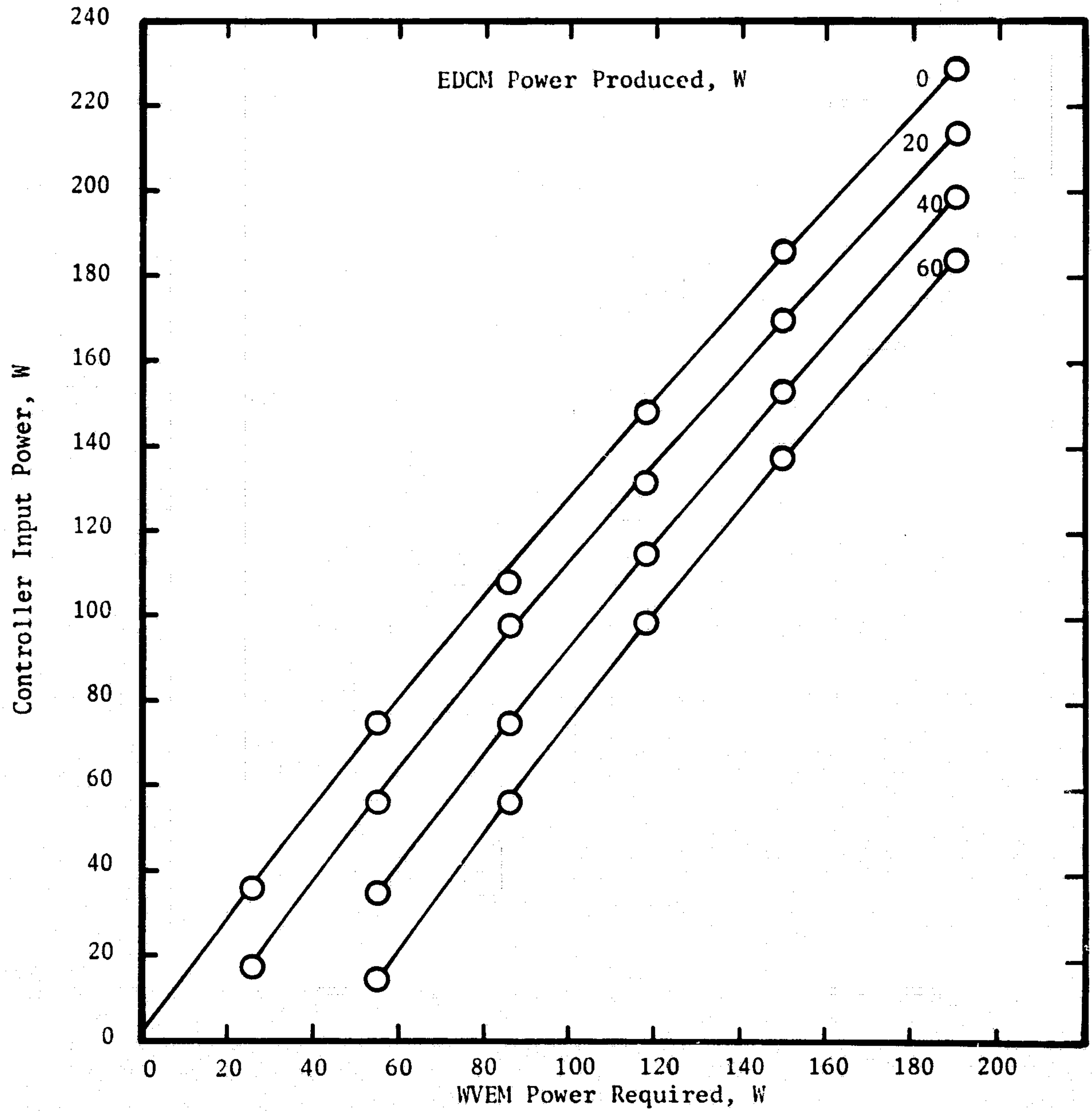

FIGURE 26 POWER-SHARING CONTROLLER PERFORMANCE

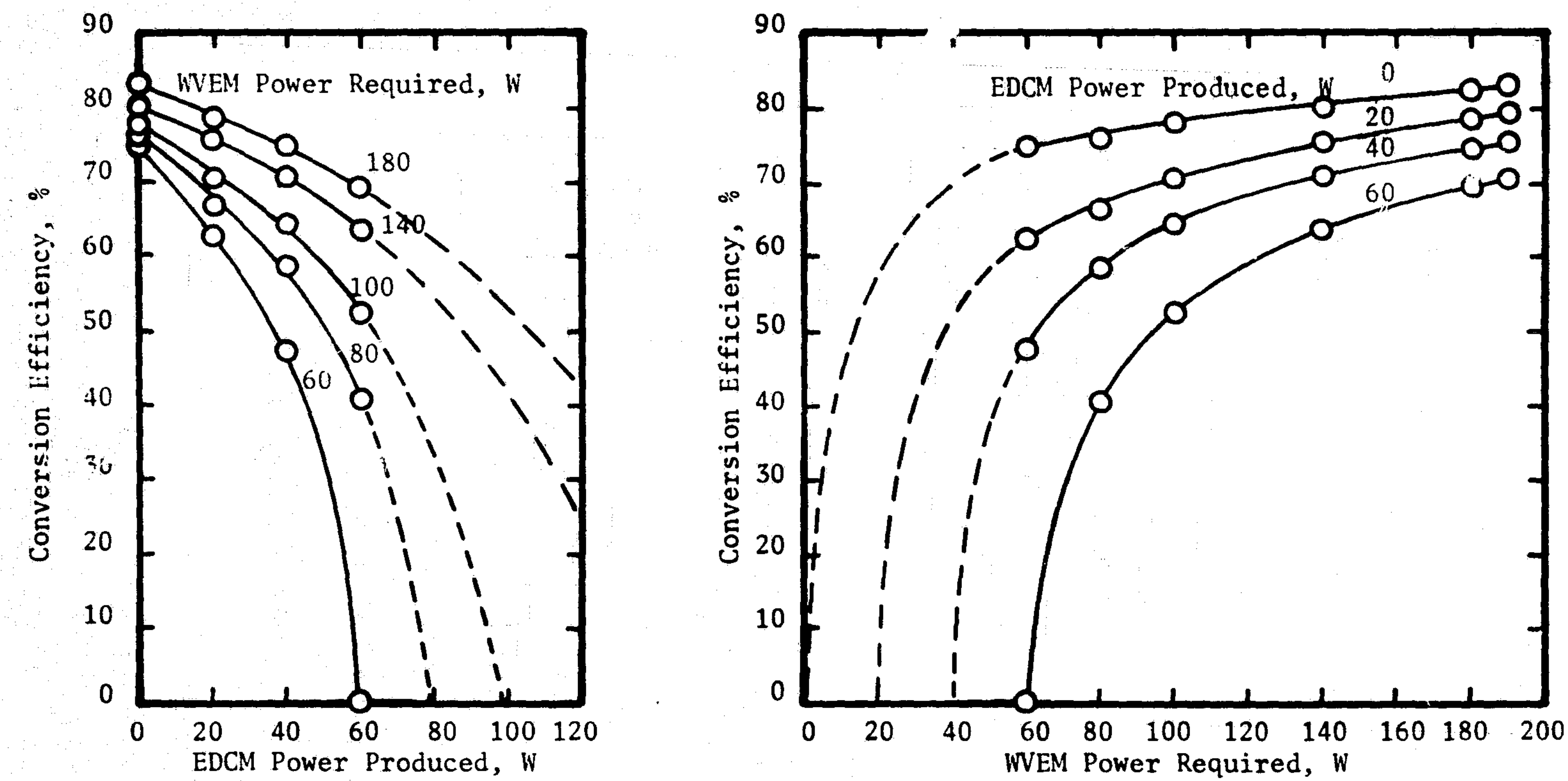

FIGURE 27 POWER CONTROLLER CONVERSION EFFICIENCY

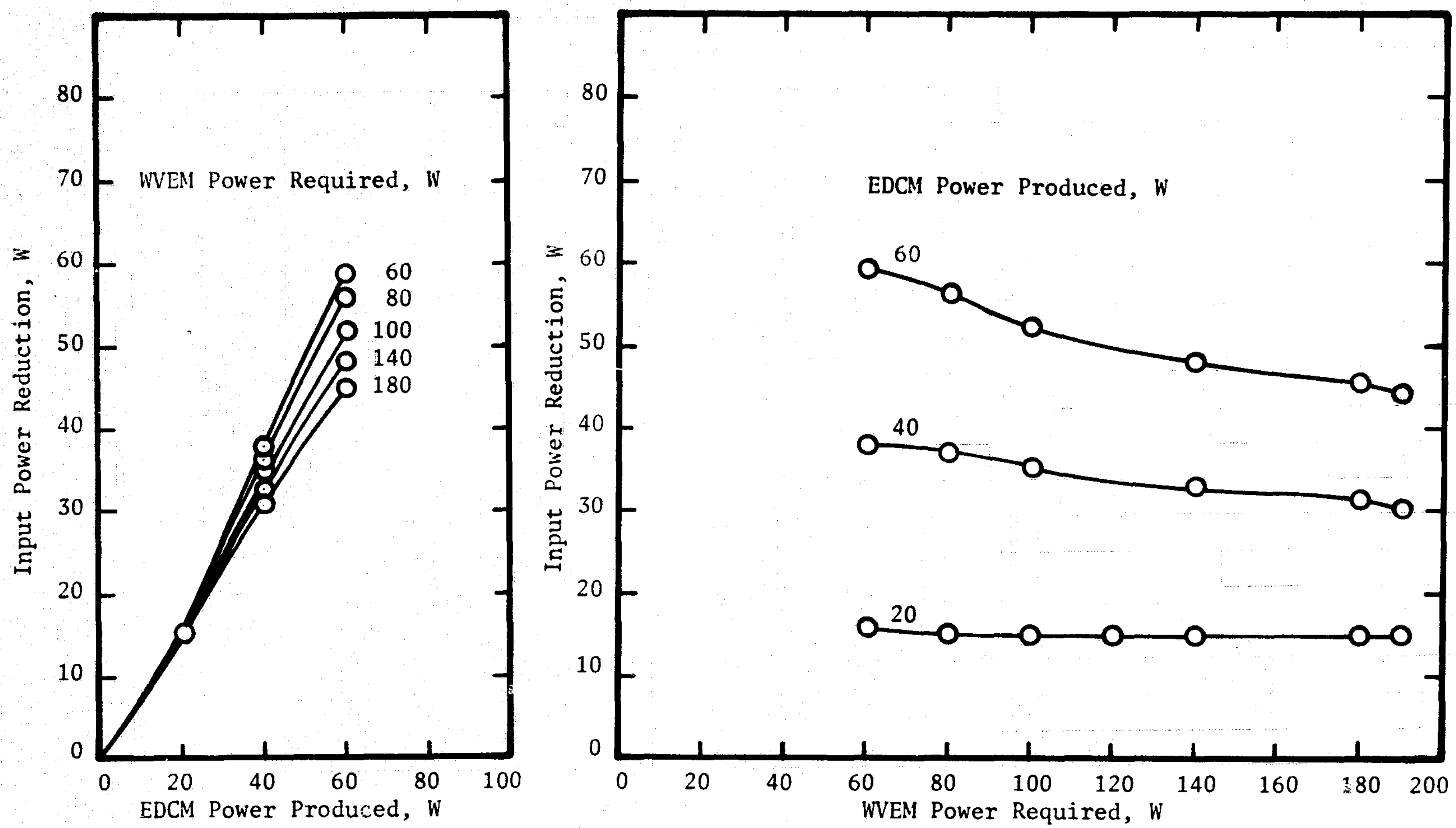

FIGURE 28 POWER CONTROLLER INPUT POWER REDUCTION

optimized such that they will operate within the peak efficiency range during normal operation of the system.

The maximum efficiency realized during these tests was approximately 83%. The power conversion efficiencies are always variable with the operating point, and optimum efficiency can only be obtained at one single operating point. However, a controller can be designed such that variation in efficiency is relatively small over the normal or expected range in power requirements by sizing the controller to operate near its maximum power output, including considerations for EDCM-supplied power.

Endurance Test

During the integrated BEARS endurance testing, the power-sharing controller successfully illustrated the use of EDCM-produced power over a total operating time of 2510 hours. Only two controller-related malfunctions occurred. The first was caused by an integrated circuit failure. The symptom of this failure was an erratic and uncontrollable current in the WVEM. When the controller was disassembled and the circuits tested, a failed linear integrated circuit operational amplifier was found. This failure occurred after 300 hours of operation. Because the components had not been aged and were not high-reliability devices, this was considered to be a normal infant mortality failure. There was no evidence that the component was overstressed in any way by circuit design. It was replaced and testing was continued.

Later in the endurance testing, the two filter chokes in the power controller emitted a high-pitched audible noise. The power switches in the power control circuits operate at an audible frequency which is applied to the filter chokes. The laminations and windings of the chokes were not securely held in place and started to vibrate, generating an objectionable noise. The controller was shut down, the two filter chokes were removed, encapsulated in epoxy and reinstalled in the controller, successfully eliminating the noise.

Integrated Breadboard Testing

The integrated breadboard testing was designed to evaluate the performance of the BEARS over a wide range of inlet process air conditions, and identify operational limits of the EARS concept. The integrated breadboard testing was divided into three phases: shakedown, checkout and endurance testing. The shakedown testing was to establish baseline operation of the BEARS while the checkout test was to verify performance at both extremes in process air RH (35 and 90%). The endurance test was designed not only to determine the effects of operating time on system performance, but also to include the effects of process air pCO_2 and RH variations. A timetable of events depicting the integrated BEARS testing showing chronological relationship is presented in Figure 29. Table 11 identifies the system shutdowns and the corrective actions taken, while Table 12 summarizes the system shutdowns according to type.

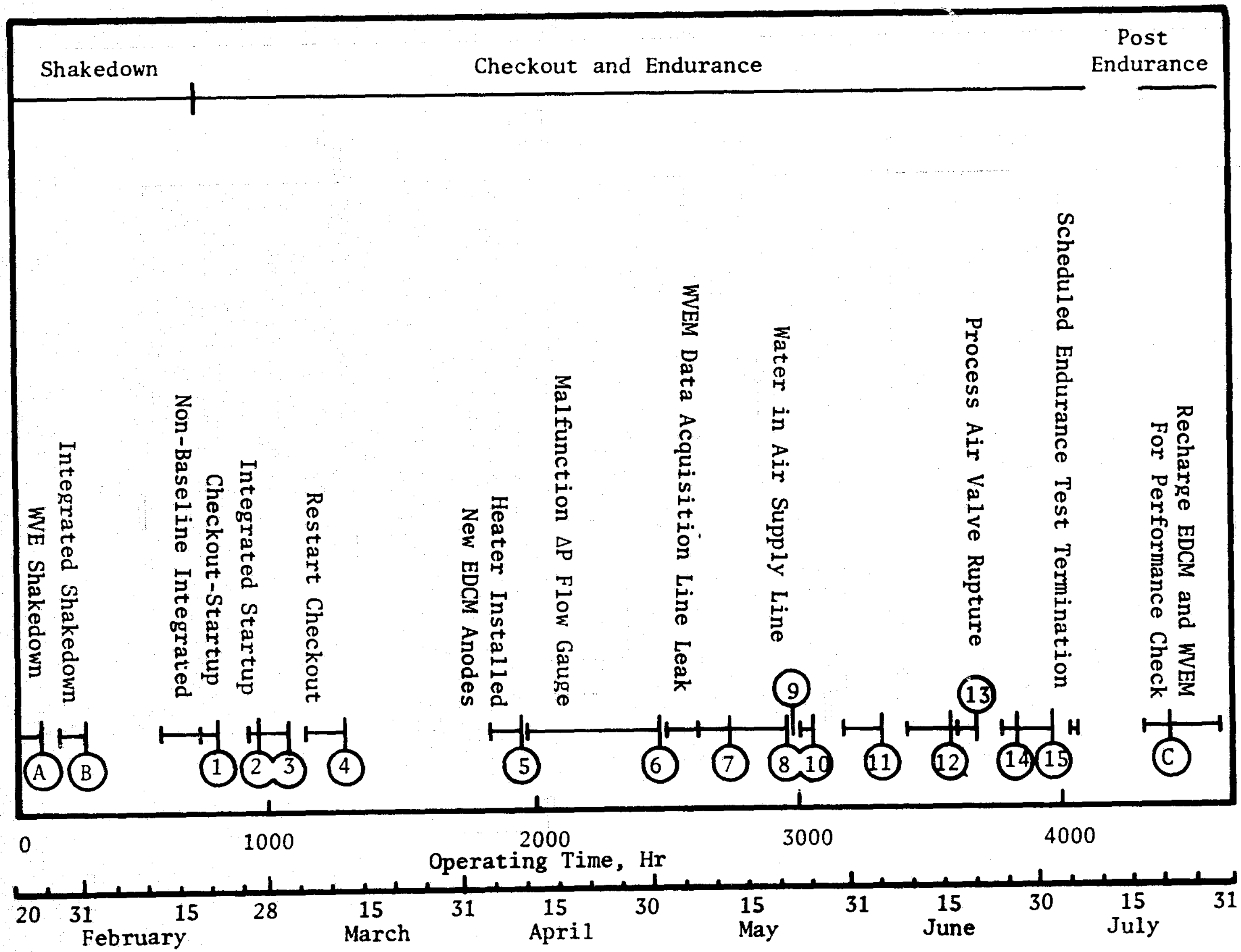

FIGURE 29 BEARS TESTING TIMETABLE

TABLE 11 BEARS SHUTDOWN LIST

Shutdown No.	Cause of Shutdown	Corrective Action
1	Accidental shutoff of coolant supply to cooling air heat exchanger resulted in high module temperature shutdown	Coolant valve reopened and system restarted
2	Power controller component failure (integrated circuit) caused high current drift with overvoltage shutdown	Integrated circuit replaced and system restarted
3	Operator initiated shutdown when EDCM failed to hold 2 psid H_2-to-air back-pressure	Asbestos shim added to all EDCM cell matrices and cells recharged with electrolyte
4	Operated initiated shutdown when saturator (process air) heater failed	EDCM cell dry out; module disassemble with anodes replaced; replacement heater ordered.
5	Operator initiated shutdown when a process air leak developed in the saturator tank	Reinforcement of transition duct between tank and test stand
6	Operator shutdown to eliminate excessive noise of power controller filter	Filter base support epoxied to frame of controller
7	Automatic shutdown due to low voltage EDCM. Caused by extended operation (>60 hr) above 90% RH	Increased H_2 and CO_2 back-pressure
8	Building power failure	Restart
9	Operator shutdown when water was noted in air supply line. Dryer low pressure drain malfunction	New drain ordered, maintenance and repair performed
10	Dryer low pressure drain malfunction	Replaced old automatic drain with continuous constant volume drain
11	Building power failures (3)	Restart
12	Building power failure	Restart
13	Process air valve rupture	Repaired
14	Building power failure and heater failure	Replaced heater in saturator tank. Restart

Table 11 - continued

Shutdown No.	Cause of Shutdown	Corrective Action
15	Building power failure	Restart
A	Scheduled operator shutdown	Restart
B	Scheduled operator shutdown	Restart
C	Building power failure (Post endurance test)	Restart

TABLE 12 BEARS SHUTDOWN SUMMARY

Total Shutdowns	Attributed To	Shutdown Number
1	Operator Error	1
6	Loss of Building Power	8, 11, 12, 14, 15, C[a]
5	Failure of GSA	4, 5, 9, 10, 13
2	Module Related Shutdown	3, 7
2	Power Controller Related Shutdown	2, 6
16	TOTAL	

(a) During post endurance test.

Test Methodology

The goal for the selection of the test methods and procedures was the generation of accurate test data for the evaluation of the BEARS performance. Provisions were included to record unscheduled maintenance operations as well as deviations from the Master Test Plan. When such activities occurred, the reason for the unplanned action, the action taken and the length of time the system operated abnormally were recorded. Also, for failures during the testing, the methodology provided for notification of the NASA Technical Monitor. Corrective actions resulting from such a failure were not performed without his approval unless timely corrective action was deemed necessary in order to prevent any detrimental effect on the system.

Shakedown Testing

The first integrated BEARS testing performed was the shakedown test.

Objective. The objective of the shakedown testing was to establish integrated operation of the EDCM, WVEM and power-sharing controller at baseline operating conditions, as listed in Table 13.

Results. The integrated baseline operation was successfully demonstrated and the results of the shakedown testing are illustrated in the first 170 hours of system load time as shown in Figures 30 and 31.

Checkout Testing

The second integrated BEARS testing performed was the checkout test.

Objectives. The objectives of the checkout testing of the BEARS was to verify system performance throughout the process air RH range of 35 to 90% for a 291 to 297K (65 to 75F) dry bulb temperature range with a minimum objective of verifying system performance at the high and low RH extremes.

Results. The results of the checkout tests are illustrated in Figure 32. This figure indicates the inlet process air conditions at which successful operation was achieved within the specified RH and temperature range. No modifications to baseline conditions were necessary to maintain short-term (less than 12 hours) operation at the extremes in inlet conditions.

During the checkout testing, an operator shutdown (Number 3, Table 11) was initiated when the EDCM could not hold a 13.8 kN/m^2 (2 psi) H_2-to-air pressure differential. A leak between the H_2 and process air cavities at the matrix edge and near the process air outlet end of Cell 2 was noted. The leak was corrected by adding 1.3 cm (0.5 in) wide asbestos shims to the edges of all EDCM cell matrices. The asbestos shim provided additional compression capability to the cell and provided the required differential pressure capabilities necessary for continued testing.

TABLE 13 BASELINE CONDITIONS

EDCM

Air Flow/Cell, m^3/s (Scfm)	3.78×10^{-4} (0.80)
pCO_2, N/m^2 (mm Hg)	400 (3)
Inlet RH, %	60 to 70
Inlet Process Air Temperature, K (F)	294 ± 3 (70 ± 5)
Cooling Air Flow Rate/Cell, m^3/s (Scfm)	3.3×10^{-3} (7)[a]
Current, A	4.88
Current Density, mA/cm^2 (ASF)	21.5 (20)

WVEM

Air Flow/Cell, m^3/s (Scfm)	3.78×10^{-4} (0.80)
Inlet RH, %	60 to 70
Inlet Process Air Temperature, K (F)	294 ± 3 (70 ± 5)
Cooling Air Flow Rate/Cell, m^3/s (Scfm)	3.3×10^{-3} (7)[a]
Current, A	12.2
Current Density, mA/cm^2 (ASF)	53.8 (50)

(a) The cooling air flow rate was based upon the maximum cooling capacity required at "worst" dry bulb and dew point conditions of the process air. Adjustments to this value were made based upon actual operation at the extremes in process air conditions.

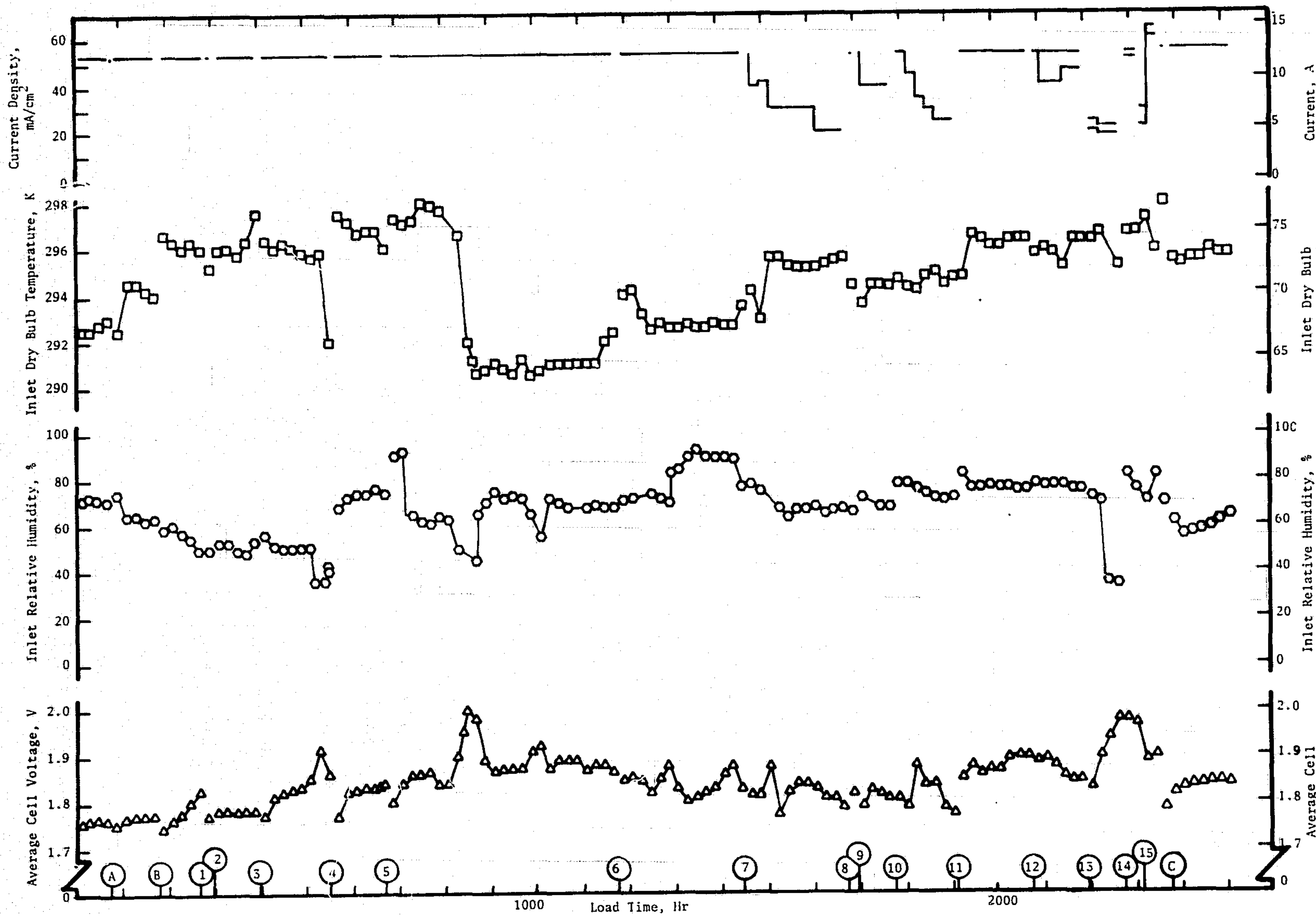

FIGURE 30 WVEM PERFORMANCE

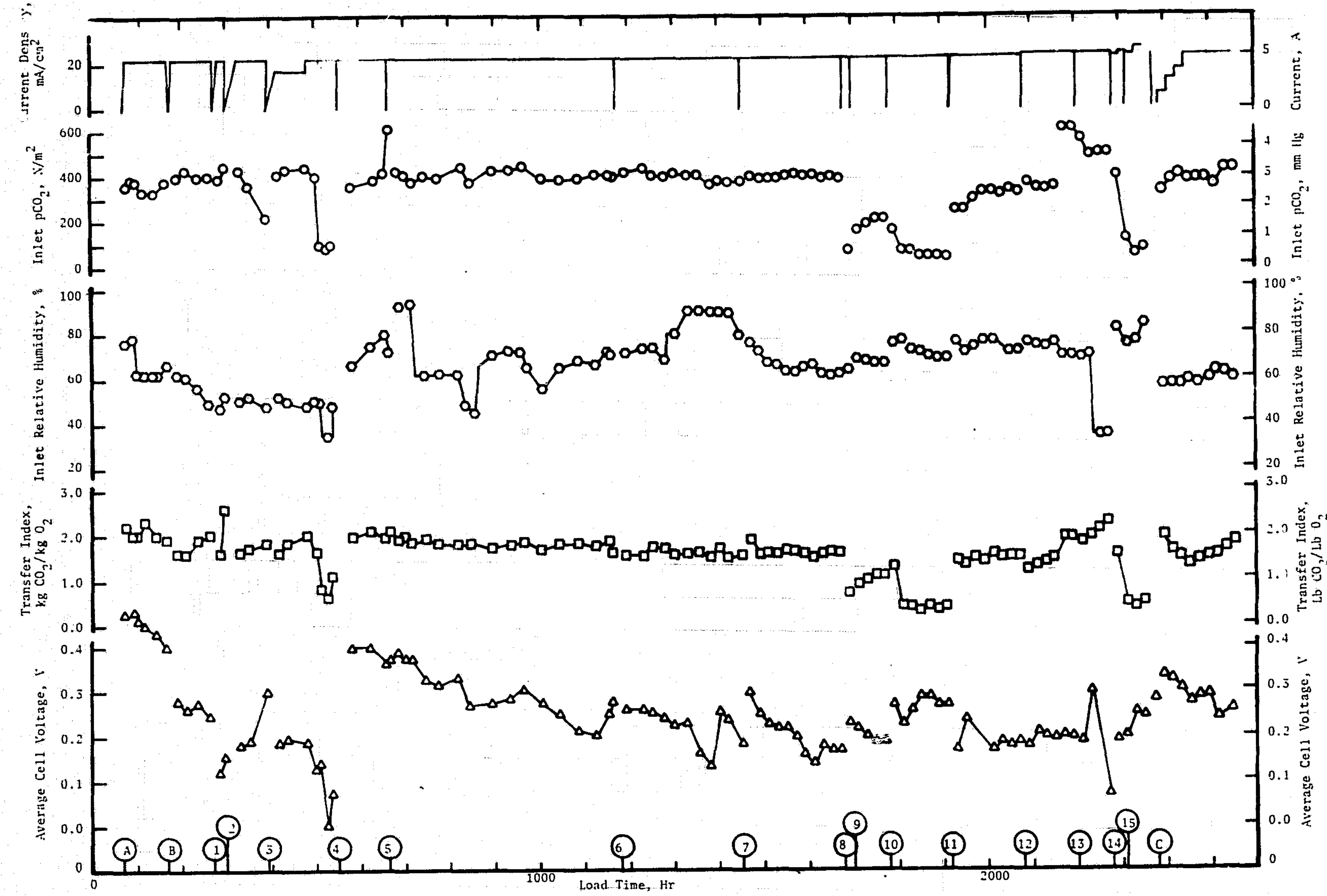

FIGURE 31 EDCM PERFORMANCE

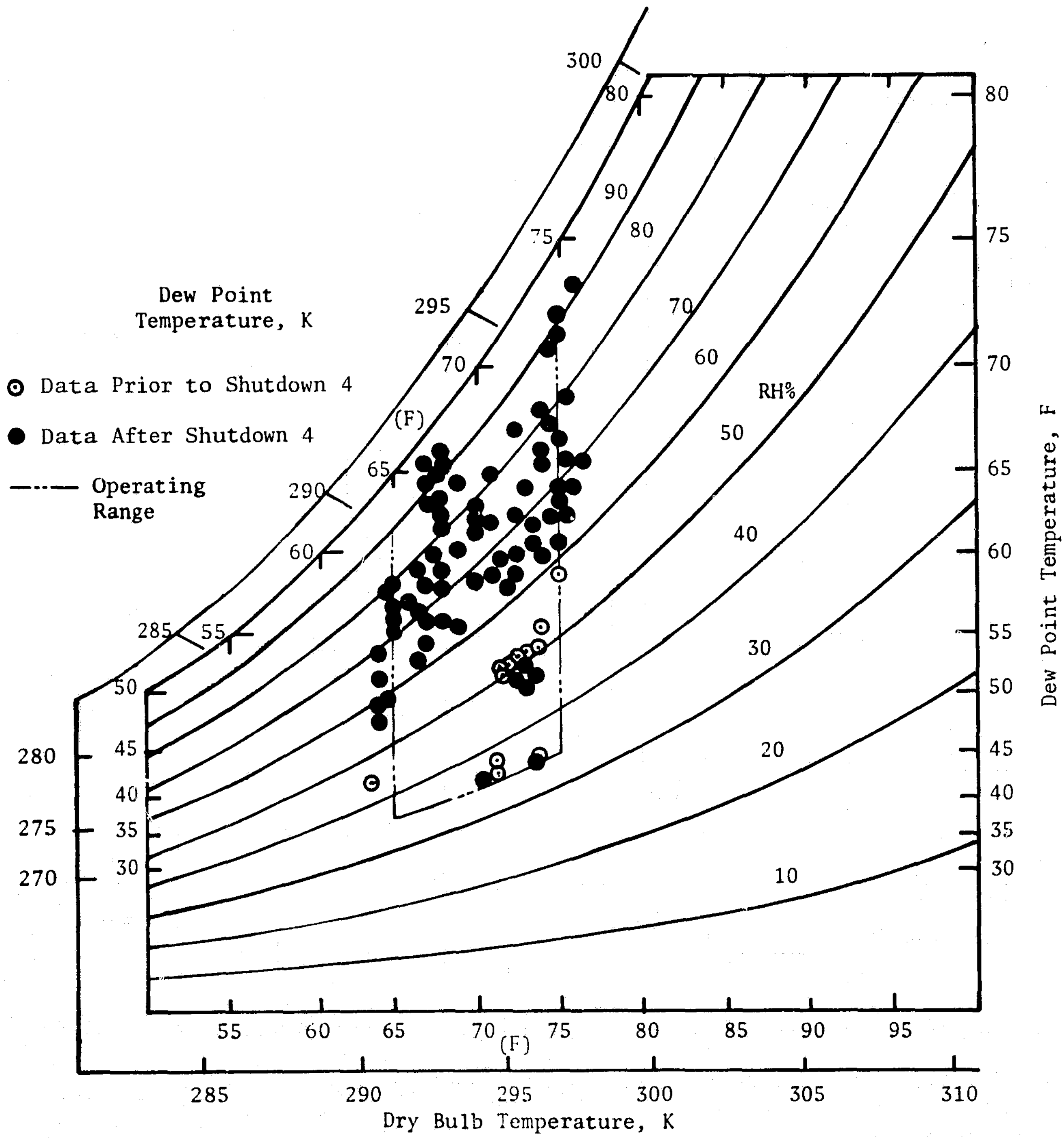

FIGURE 32 CHECKOUT TEST OPERATING RANGE

After approximately 400 hours of total integrated operation, decreases in EDCM cell voltages in excess of those normally experienced[8,10] in early EDC endurance testing were observed (see Figure 31). The decrease in cell voltage, as well as in Ti continued to increase more rapidly until a saturation heater (GSA) selected shutdown (Shutdown 4, Table 11) stopped testing. A review of test history prior to Shutdown 4 showed that during Shutdowns 1 and 2 of the checkout testing a trickle current of 0.05A was allowed to flow through the EDCM although an automatic system shutdown accompanied by process gas flow stoppage had occurred. This current resulted in a negative (1.0 to 2.0V) voltage for the EDCM cells. This condition existed for approximately 16 hours for the first shutdown and 5 hours for the second shutdown. Negative voltage levels of this magnitude fall within the region where Ni corrodes in a carbonate electrolyte with potential anode (porous Ni) performance degradation.[18] A decision to continue testing, after the observation of the negative voltages, after Shutdowns 1 and 2, had been made since the EDCM voltages, although relatively low, were not decreasing immediately after each shutdown. Shutdown 4 was caused by a saturator heater failure. As a result of this failure, the process air RH dropped to less than 25%. Since 25% RH is below the precipitation limit of the EDCM electrolyte, the decision was then made to disassemble the EDCM. Disassembly was considered necessary since EDCM performance after precipitation of the electrolyte is not representative of the true capabilities of the EDCM. Also, visual observation for electrolyte precipitation and low voltage anode damage is the only practical technique. The WVEM was not disassembled since H_2SO_4 can readily exist without precipitation at less than 25% RH.

Upon disassembly, the anticipated electrolyte precipitation was noted on both the anodes and cathodes of the EDCM cells, but less extensive than projected. It was also noted that the porous Ni anodes showed the degradation caused by exposure to corrosive electrical potentials. The loss of anode effectiveness had not been previously observed, nor had EDCM cells with porous Ni anodes been subjected to negative voltages of that magnitude and time as was experienced during the BEARS checkout testing. Based upon the results and findings of the disassembly of the EDCM, the porous anodes were replaced and testing was restarted. It was concluded that anode degradation is not a problem when long-term negative potentials are prevented. This was verified during disassembly following the scheduled endurance test termination. After the reintegration of the EDCM with the GSA, checkout testing was continued and successfully completed by demonstrating operation of the system at an inlet RH of 90% in addition to the operation at 35% RH prior to Shutdown 4, as shown in Figure 32.

Endurance Testing

The third and final test performed with the integrated BEARS was the endurance test.

Objective. The objective in the endurance testing was the characterization of integrated performance for 90 days of operation, including determination of the effects of inlet pCO_2 levels between ambient (33.3 N/m^2 (0.25 mm Hg)) and 533 N/m^2 (4.0 mm Hg) and operation with an inlet process air RH from 35 to

90%. Identifying the effects of accelerated transient periods between RH levels was also an objective of the testing.

Results. The performance characterization testing is a function of time which was obtained for the BEARS over 98 days (2360 hours) of integrated operation. Following this testing, an additional 150 hour of post-endurance testing was performed, bringing the total of integrated BEARS operation to 104 days. The performance of the WVEM and EDCM during the 104 days of testing are illustrated in Figures 30 and 31, respectively. Results of the power-sharing controller performance during the 104 days of testing (initially scheduled for operation during the final 60 test days) was presented in an earlier section of this report.

General WVEM Performance. Figure 30 shows the current density, inlet air dry bulb temperature, inlet air RH and average cell voltage for the integrated testing of the WVEM as a function of time. Table 13 lists the remaining baseline operating conditions for the endurance testing. The module was operated as part of the integrated BEARS, over a process air inlet RH range of 34 to 92%, and a dry bulb temperature range of 291 to 298K (65 to 80F). The average cell voltage for baseline conditions during the endurance test was approximately 1.85V at 54 mA/cm^2 (50 ASF).

Figure 30 illustrates that the WVEM performance was successfully maintained at 53.8 mA/cm^2 (50 ASF) for the first 1450 hours and for the last 500 hours of operation. At 1400 hours, following extended operation, (100 hours) at an inlet RH of 90 to 92%, WVEM current was lowered to maintain cell voltages at less than the selected upper limit (2V). Following approximately 400 hours of operation at less than baseline current density, (41 mA/cm^2 (38 ASF)), operation at 53.8 mA/cm^2 (50 ASF) was again successfully established. At the lower current density, cell voltages averaged 1.82V. After shutdown, Number 12, Cell 3 of the WVEM failed to hold 54 mA/cm^2 (50 ASF) at less than 2V. A current shunt was incorporated in series with Cell 3 to allow baseline current density to the other two cells while the third could be operated at a reduced level of (48 mA/cm^2 (44.5 ASF)) to maintain acceptable voltage performance (approximately 1.88V).

The major reason for the difficulty of the WVEM cells to sustain 53.8 mA/cm^2 (50 ASF) within an acceptable voltage limit, at extended operating conditions near the end of the testing, is a result of probing for the operational limits of the modules. For example, in trying to establish upper limits at high humidity operation, incipient electrolyte carryout into the air cavities was used as the only practiced method to identify that such limits had been reached. Each time this occurs, small changes in the electrolyte content of the cells result which cause differences in cell operation characteristics when returning to other RH levels. This assumption was verified during a post-endurance run following an electrolyte recharge. All three WVEM cell voltages averaged 1.82V for an inlet RH between 50 and 60% at baseline current density. Also, during disassembly of the WVEM, following the post-endurance test, no visible degradation of any cell components was detected.

General EDCM Performance. Figure 31 shows the current density, inlet air pCO_2, inlet air RH, TI and average cell voltage for the integrated testing of the EDCM as a function of time. Table 13 lists the remaining baseline operating conditions for the endurance testing. The module was operated, as part of the integrated BEARS, over a process air inlet RH range of 34 to 92% and a dry bulb temperature range of 291 to 298K (65 to 80F).

Initial cell voltages of the EDCM were between 0.40 to 0.45V, at 21.5 mA/cm^2 (20 ASF) typical of high moisture tolerance cells (porous Ni anodes) at initial optimum condition. This level was demonstrated with both ends of EDCM electrodes. After approximately 500 hours of operation with the replacement anodes (after Shutdown 4), the average cell voltage leveled at approximately 0.20V at baseline current for the remainder of the endurance test. This end-of-endurance-test value is lower than the average cell voltage normally obtained with baseline screen electrodes (0.30V) for a central CO_2 removal system and small changes in process air RHs.[8] Similar reasoning, as was used for the WVEM performance variations due to probing for operational limits, applies to the EDCM results. This reasoning was again supported during the post-endurance testing when an EDCM current density span demonstrated the average EDCM electrical performance of 0.33V, 0.32V, 0.30V and 0.28V at 5.4, 10.8, 16.1 and 21.5 mA/cm^2 (5, 10, 15 and 20 ASF), respectively (see Figure 31 near the 2400 hour mark).

The plot of CO_2 removal efficiency (TI), as a function of time (Figure 31), indicates that an average value of approximately 1.8 was obtained at a process air pCO_2 level of 400 N/m^2 (3 mm Hg), and general baseline condition as shown in Table 13. Initial startup performance, both with the first set of porous Ni anodes, as well as with the second set of porous Ni anodes, showed initial performance levels of 2.0 TI.

The lower TI values shown near the conclusion of the endurance test is a result of the required operation at low process air pCO_2, and pCO_2 scans. During the latter, a TI of 2.25 was obtained at 2 pCO_2 of 533 N/m^2 (4 mm Hg). This scan was performed near 2250 hours (see Figure 31), with an inlet process air RH of 35%. Increases in TI with dryer conditions is consistent with previously observed EDC performance.[19] The drop in TI at the 2300 hour mark is the result of a second pCO_2 span.

During the post-endurance test, a TI of 1.8 was obtained at 373 N/m^2 (2.8 mm Hg). Following the post-endurance test, the EDCM was disassembled. No visible degradation of the electrodes, or other cell components, was noticed.

Effects of Process Air Inlet pCO_2. The effect of inlet pCO_2 on EDCM CO_2 removal and electrical performance is shown in Figure 33. The data was collected over the time period of approximately 1800 to 2200 hours as shown in Figure 31. The operating conditions were those shown in Figure 31, with the remaining operating parameters near baseline (see Table 13). For comparison, least squares curves for TI and cell voltage of previous baseline configured EDC data as a function of pCO_2 and also presented in Figure 33.[7] The shapes of the TI performance curves are similar, with near identical performance achieved

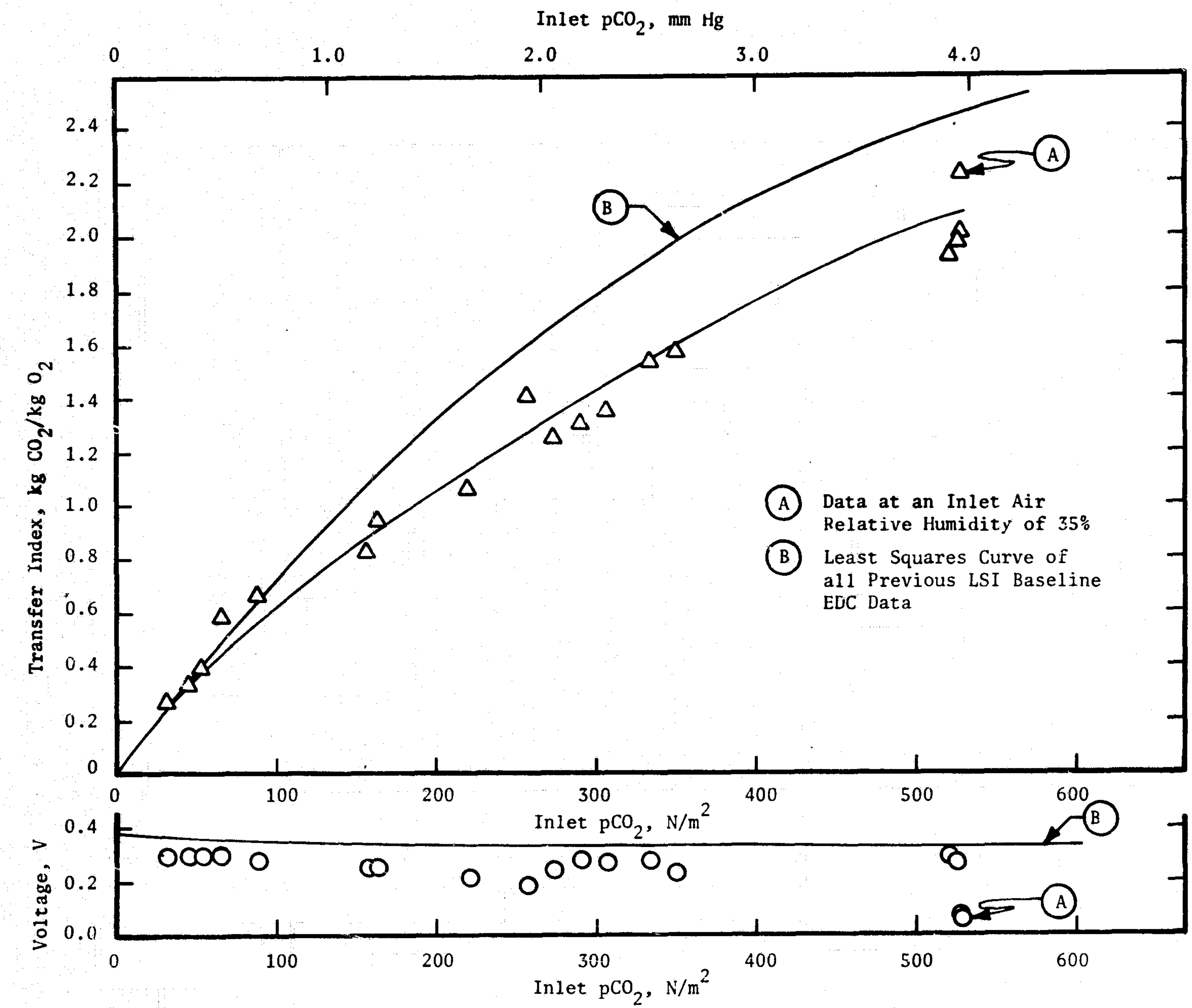

FIGURE 33 EDCM CO_2 REMOVAL PERFORMANCE VERSUS INLET pCO_2

in the less than 100 N/m^2 (0.75 mm Hg) pCO_2 region. At higher pCO_2 values, the BEARS curve is less (approximately 17% at 400 N/m^2 (3 mm Hg)) than the least squares curve of previous EDCM data. The average cell voltages vary little with pCO_2, with the BEARS voltages less than 0.10V lower than previous data. The major reason for these differences in performance is that central CO_2 collection system baseline cells (all screen electrodes) are optimized for operation over a small range in operating conditions while the BEARS EDCM is optimized for operation over wide RH ranges with wide ranges of electrolyte-gas interface location variations. This is partially demonstrated by the data on Figure 33 where, at a pCO_2 of 533 N/m^2 (4 mm Hg), the TI varied from 1.9 to 2.25 for a change in process air RH from 70 to 35%.

Effects of Process Air Inlet Relative Humidity. The effects of process air inlet RH on the primary performance parameters of the EDCM (TI and average cell voltage) and WVEM (average cell voltage) are summarized in Figures 34, 35 and 36. The data is based on representative data points collected throughout the BEARS checkout and endurance testing. No attempt was made to curve fit the results, but the data was presented to indicate general trends in performances.

Figure 34 shows that the electrical efficiency, as represented by average EDCM cell voltage, is optimum between the RH levels of 60 and 80%. Figure 35 shows a constant increase in CO_2 removal performance (TI) with decreasing inlet process air RH.

This decrease in cell voltage above the 80% RH level, as shown in Figure 34, is caused by resulting increases in the electrolyte volume, resulting in partial electrode flooding and decreased electrolyte/electrode/gas interfaces. Also contributing to the lower average EDCM cell voltage is the lower electrical conductivity at the decreased electrolyte concentration.

Decreases in cell voltage at less than 60% process air RH are due to a combination of increased electrical resistance at increased electrolyte concentrations, and withdrawal of the liquid/gas interface from optimum activation (catalyzed) sites in the electrodes.

The increases in TI with decreasing RH, i.e. decreasing electrolyte volume, can be primarily attributed to the decreased distance that the $CO_3^=$ has to travel through the electrolyte. Loss of optimum catalyzed electrode sites and the small (partial electrode thickness) increase in gas diffusion distance at low RH electrolyte volumes has negligible effects on CO_2 removal.

The WVEM demonstrated a decrease in terminal cell voltage with increases in process air RH as shown in Figure 36. This decrease was caused by increases in electrolyte water content and electrode/electrolyte contact.

To maintain operation for extended periods of time at inlet RH levels above 78% it was necessary to decrease the cooling air flow through both BEARS modules. This caused an increase in the temperature pickup of the process air

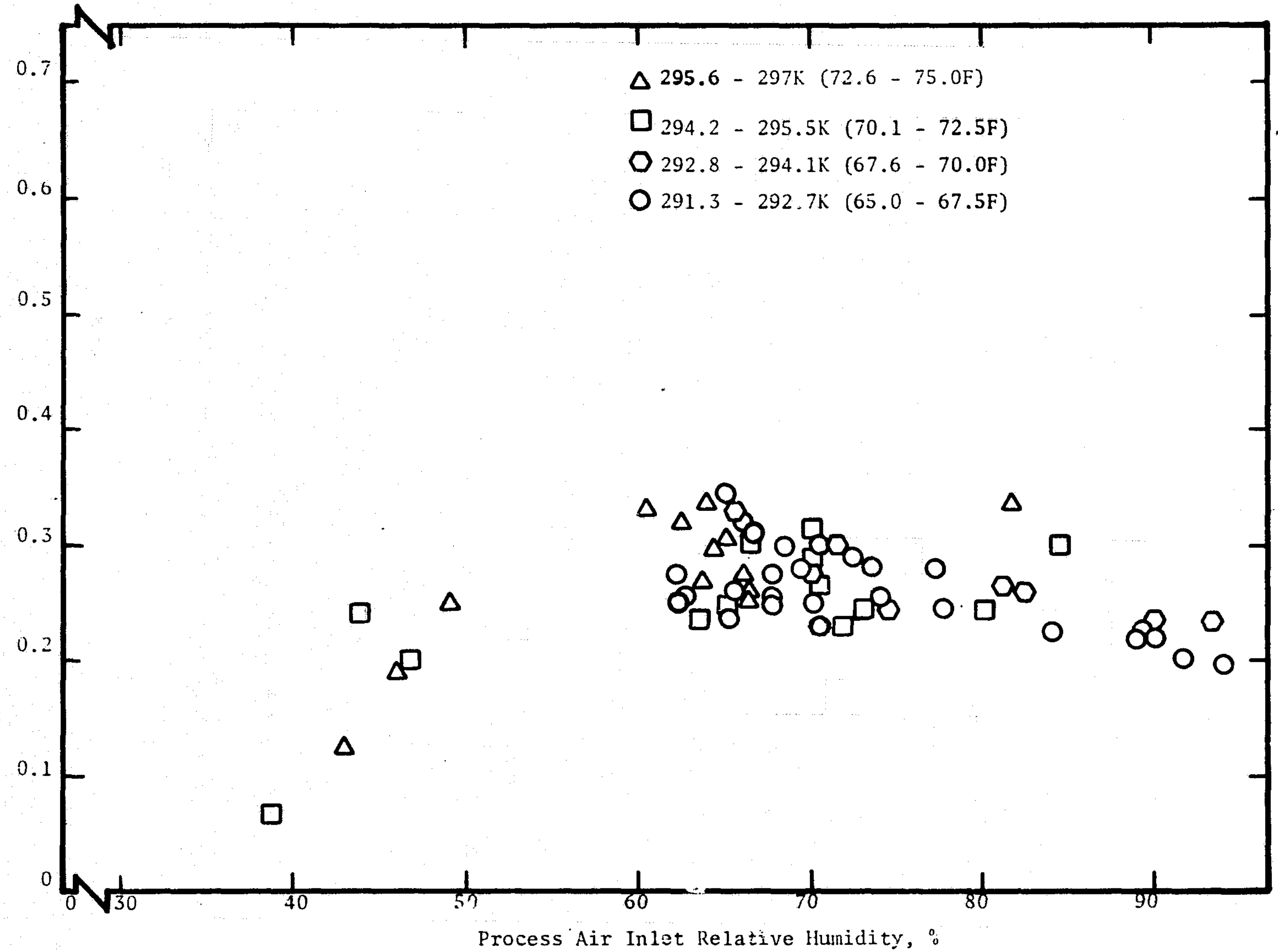

FIGURE 34 EDCM ELECTRICAL PERFORMANCE VERSUS RELATIVE HUMIDITY

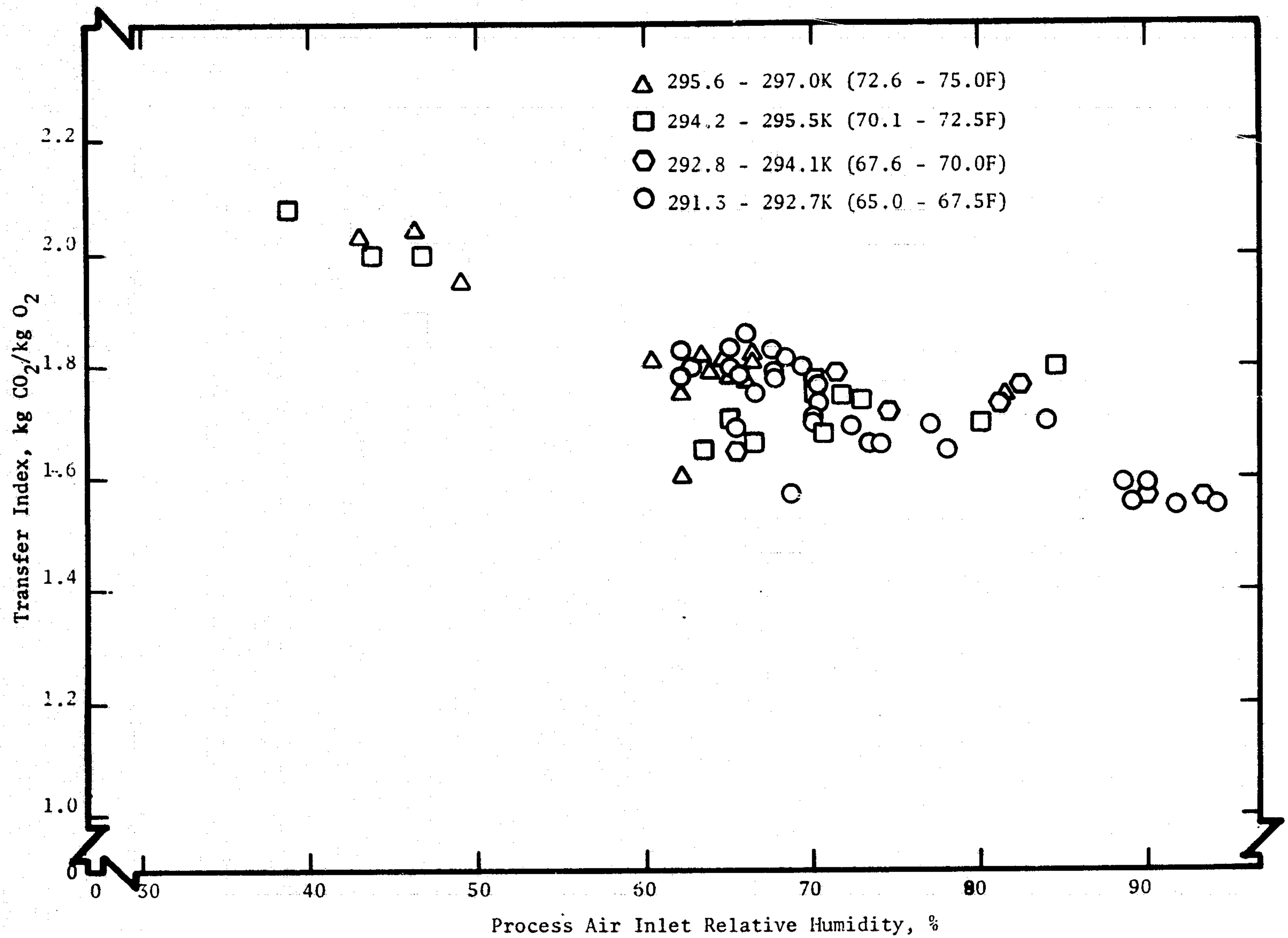

FIGURE 35 EDCM CO_2 REMOVAL PERFORMANCE VERSUS RELATIVE HUMIDITY

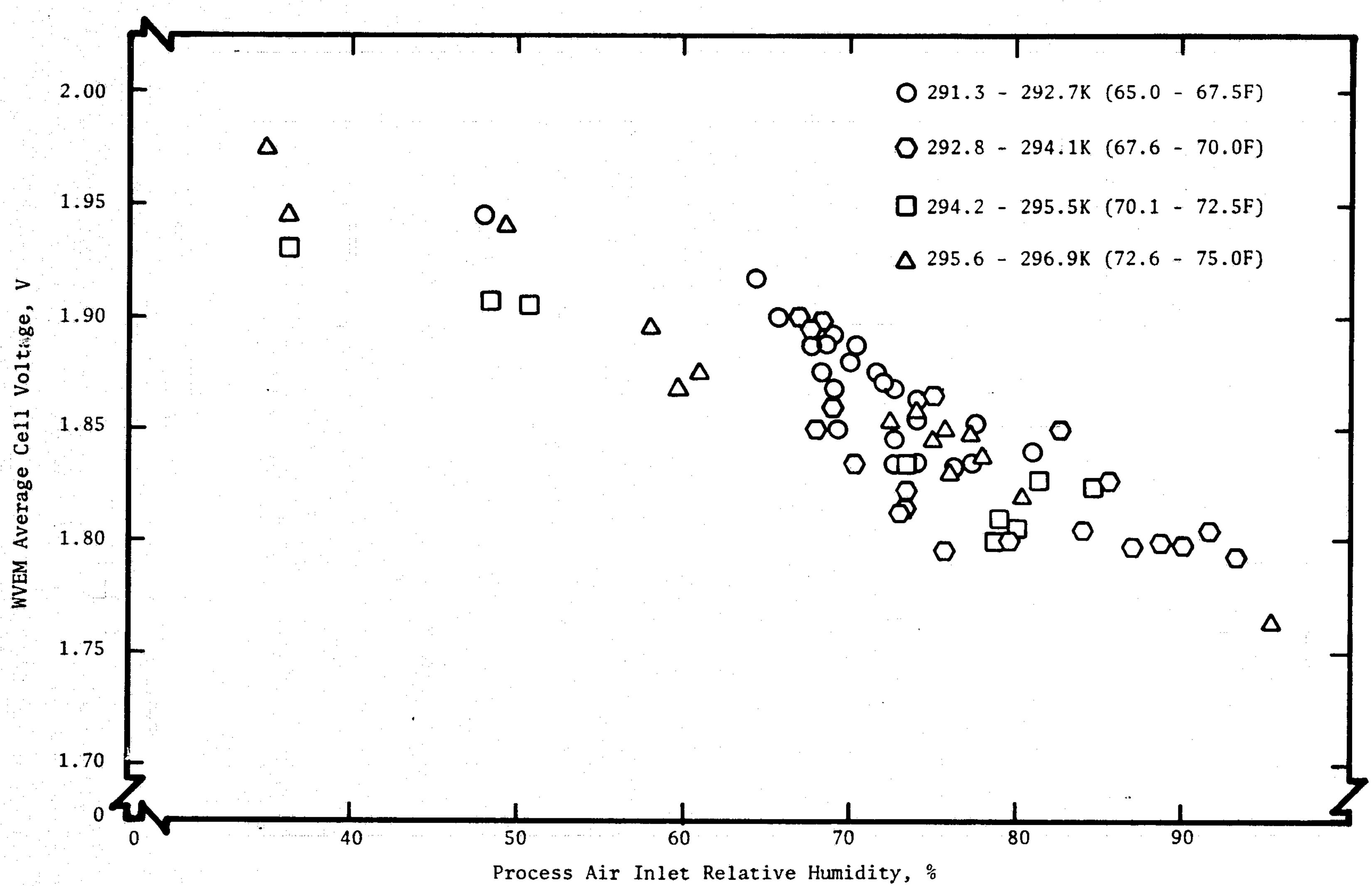

FIGURE 36 WVEM PERFORMANCE VERSUS RELATIVE HUMIDITY

within the module, resulting in a lowering of the average process air RH within the air cavity. For operation at 90% inlet process air RH, the cooling air flow rate was completely stopped. Both modules appeared to require cooling air flow reduction at similar RH levels and no special provisions, other than simply reducing blower voltage, were required. A simple control technique for future system application can readily be projected from this data.

The final objective of the testing was to characterize the effect of accelerated transient periods between process air RH levels. During the testing, four accelerated transient periods were performed: decreases from 92 to 62% and 70 to 35% RH and increases from 44 to 66% and 68 to 90% RH. These transients in operation were induced at load times of 710 and 2230 hours, and 853 and 1278 hours, respectively, as illustrated in Figures 30 and 31. The accelerated decreases in inlet process air RH caused the WVEM voltage to increase as the electrolyte established the new steady-state concentration. This performance was similar to slower transient operation of the WVEM and no special effect was noted. The EDCM showed only minor effects on cell voltage and TI with the drop to 62% RH, but a substantial decrease in electrical performance and an increase in TI resulted from the accelerated decrease to 35% RH. The average EDCM cell voltage fell to 0.07V, while the TI improved to 2.25 at 533 N/m^2 (4 mm Hg).

The accelerated increase in RH resulted in rapid improvements in WVEM voltage as the increased water flux into the electrolyte increased the volume and water content of the electrolyte. The larger increase in inlet RH from 44 to 66% caused the EDCM voltage to decrease from 0.33V to 0.27V, but performance improved returning to 0.31V after 115 hours of operation at the increased inlet RH level. The smaller increase to 80% RH illustrated no major changes in EDCM performance.

CONCLUSIONS

The following conclusions are a result of the development program:

1. An integrated EARS can successfully perform O_2 removal and partial cabin air humidity control over a range in RH of 35 to 90% for a 291 to 297K (65 to 75F) dry bulb temperature range using the high humidity tolerance electrochemical cell configuration employed in the BEARS.

2. Of the five Contractor-developed WVE anodes, the E5B is most suited for an EARS application. Using this electrode, only a 4% rise in cell voltage (from 1.77V to 1.84V) at 54 mA/m^2 (50 ASF) over a 2500 hour operation was observed.

3. The power-sharing controller concept used in the BEARS testing effectively reduces system power requirements and heat loads by directly using all of the EDCM-produced power to partially offset the power used by the WVEM. In this manner, additional power and heat load savings result since power conditioning losses are reduced

by the fraction of EDCM supplied power. For example, the heat load and power penalty of a one-man capacity WVEM and associated power conditioning can be reduced by 18 to 24W (out of 321 to 350W).

4. Basing process air flow requirements on CO_2 removal and O_2 requirements rather than cooling requirements and using a separate flow path for cooling air provides for a simple cooling air control technique to allow operation at high RH values without requiring reduction in system capacities.

5. Metabolically-induced changes in cabin air RH, pO_2 and pCO_2 are such that low RHs accompanied by high O_2 generation and CO_2 removal requirements are unlikely. This characteristic suggests a system control technique of lowering module currents at low RH extremes resulting in a smaller-sized system for a given application since EDCM and WVEM voltages present limits to low RH operation at given current densities.

RECOMMENDATIONS

The following recommendations are a result of the development program:

1. Characterize the performance of a one-man capacity, self-contained EARS over the operational limits investigated with the BEARS.

2. Design, fabricate and test a power-sharing controller designed to operate within its maximum efficiency range at a one-man EARS level.

3. Evaluate control techniques to maintain optimum EDCM and WVEM performance over the widest range in ambient conditions without decreasing the operational range of the system. Provisions for trends identified during the BEARS testing for EDCM electrical and CO_2 removal performance and WVEM electrical performance with variations in RH should be incorporated. These techniques should incorporate provisions for cooling air flow control as well as current controls based on RH and capacity requirements.

REFERENCES

1. Conner, W. J., Greenough, B. M. and Cook, G. M., "Design & Development of a Water Vapor Electrolysis Unit," NASA CR-607, Lockheed Missiles and Space Company, Sunnyvale, CA, September, 1966.

2. Celino, V. A. and Wydeven, "Development Status of the Water Vapor Electrolysis System," Paper No. 71-AV-24, ASME Conference, San Francisco, CA, July, 1971.

3. Clifford, J. E., et al, "A Water Vapor Electrolysis Cell With Phosphoric Acid Electrolyte," NASA CR-73170, Battelle Memorial Institute, September, 1966.

4. Wydeven, T. and Smith, E., "Water Vapor Electrolysis," Aerospace Medicine, Volume 38, p 1045, 1967.

5. Wynveen, R. A. and Quattrone, P. D., "Electrochemical Carbon Dioxide Concentrating System," Paper No. 71-AV-21, SAE/ASME/AIAA Conference, San Francisco, CA, July 12-14, 1971.

6. Wynveen, R. A., Schubert, F. H. and Powell, J. D., "One-Man, Self-Contained CO_2 Concentrator System," Final Report, Contract NAS2-6118, NASA CR-114426, Life Systems, Inc., Cleveland, OH, March, 1972.

7. Marshall, R. D., Schubert, F. H. and Carlson, J. N., "Electrochemical Carbon Dioxide Concentrator: Math Model," Final Report, Contract NAS2-6478, NASA CR-114639, Life Systems, Inc., Cleveland, OH, August, 1973.

8. Powell, J. D., Schubert, F. H., Marshall, R. D. and Shumar, J. W., "Six-Man, Self-Contained Carbon Dioxide Concentrator Subsystem," Final Report, Contract NAS2-6478, NASA CR-114743, Life Systems, Inc., Cleveland, OH, June, 1974.

9. Kostell, G. D., Schubert, F. H., Shumar, J. W., Hallick, T. M. and Jensen, F. C., "Six-Man, Self-Contained Carbon Dioxide Concentrator Subsystem for Space Station Prototype (SSP) Application," Final Report, Contract NAS2-6478, NASA CR-114742, Life Systems, Inc., Cleveland, OH, May, 1974.

10. Schubert, F. H. and Quattrone, P. D., "Development of a Six-Man, Self-Contained Carbon Dioxide Collection Subsystem for Spacecraft Application," Paper No. 74-ENAs-16, Intersociety Conference on Environmental Systems, Seattle, WA, July 29-August 1, 1974.

11. Samonski, F. G. and Neel, J. M., "Atmosphere Revitalization for Manned Spacecraft - An Assessment of Technology Readiness," 24th IAF Congress, Baku USSR, October, 1973.

12. Huddleston, J. C. and Aylward, Dr. J. R., "Development of an Integrated Water Vapor Electrolysis Oxygen Generator and Hydrogen Depolarized Carbon Dioxide Concentrator," Contract NAS9-11830, NASA CR-115575, Hamilton Standard, Windsor Locks, CT, May, 1972.

13. Fasullo, D. T., "Sulfuric Acid, Use and Handling," McGraw-Hill, New York, pp 286-287, 1965.

14. Lin, C. H. and Winnick, J., "An Electrochemical Device for Carbon Dioxide Concentration, II Steady-State Analysis CO_2 Transfer," I&EC Process Design and Development, Volume 13, p 63, January, 1974.

15. Schubert, F. H. and Marshall, R. D., "Integrated Water Vapor Electrolysis and Electrochemical Depolarized Concentrator," Annual Status Report, ER-192, Life Systems, Inc., Cleveland, OH, April, 1973.

16. "Design Criteria Handbook," SSP Document No. 9, Revision A, Hamilton Standard, Windsor Locks, CT, November 14, 1970.

17. "Nonmetallic Material Requirements for Manned Testing of the Space Station Prototype (SSP), Environmental/Thermal Control and Life Support Systems," Document No. CSD-SS-012, Crew Systems Division, Johnson Space Center, Houston, TX, April 26, 1972.

18. Huebscher, R. G., "Water Electrolysis Cell and Static Feed Background Information Report," Contract NAS2-4444, ER-7256-7, TRW, Cleveland, OH, November, 1968.

19. Marshall, R. D., Carlson, J. N. and Schubert, F. H., "Electrochemical Carbon Dioxide Concentrator Subsystem Math Model," Final Report, Contract NAS2-6478, NASA CR-137565, Life Systems, Inc., Cleveland, OH, September, 1974.