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Life Systems, Inc.

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LOW pCO_2 AIR-POLARIZED CO_2 CONCENTRATOR DEVELOPMENT

FINAL REPORT

by

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by

Life Systems, Inc.
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for

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NASA Headquarters

FOREWORD

The work reported herein was conducted by Life Systems, Inc. at Cleveland, Ohio under Contract No. NASW-5019 for a two Phase (Phase I and II) Ground-based Space Station Experiment Development Study Program entitled "Low pCO_2 Air-Polarized CO_2 Concentrator Development." The period of performance for the total contract (Phase I and Phase II) was eighteen (18) months, or from 11/03/95 through 06/01/97.

The overall objective of this program is to complete the effort required to characterize the performance and applicability of the electrochemical Air-Polarized Carbon Dioxide Concentrator process technology for space missions requiring low (i.e., less than 3 mm Hg) CO_2 partial pressure in the cabin atmosphere.

The National Aeronautics and Space Administration assigned Dr. Maurice Averner as the Contracting Officer's Technical Representative. The Principal Investigator of the program was Mr. Franz H. Schubert. Technical support was provided by the following individuals:

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LIST OF ACRONYMS

4BMS	Four-Bed Molecular Sieve
APC	Air-Polarized CO_2 Concentrator
ARS	Air Revitalization System
ECLSS	Environmental Control and Life Support Systems
ECS	Electrochemical CO_2 Separator
EDC	Electrochemical CO_2 Concentrator
EOS	Electrochemical O_2 Separator
ERCA	Electrochemically Regenerable CO_2 and Moisture Absorption
ISS	International Space Station
LiOH	Lithium Hydroxide
MCUs	Multi-Cell Units
NASA	National Aeronautics and Space Administration
pCO_2	CO_2 partial pressure
SAWD	Solid Amine Water Desorbed
WVE	Water Vapor Electrolysis

SUMMARY

This report documents the results of Life Systems' work for the "Low pCO_2 Air-Polarized Carbon Dioxide Concentrator Development" Program. The objectives of the program were to complete the effort required to verify the performance and applicability of the hydrogen-less electrochemical Air-Polarized Carbon Dioxide Concentration process for space missions requiring low carbon dioxide partial pressure, i.e., less than 3 mm Hg, in the cabin atmosphere. The performance and applicability was to be verified by performing actual testing using multi-cell modules. The multi-cell modules to be used were to be of an approximate one-person capacity (2.20 lb carbon dioxide removal per a 24-hr period) to demonstrate the technology at a readily scalable size.

Achieving low pCO_2 atmospheres in a space station or equivalent environment is important because:

1. High carbon dioxide levels of greater than 0.3% (2.3 mm Hg) will have impact on interpretability of microgravity experiment data which will limit the usefulness of a space station for scientific experiments.

2. Although the existing spacecraft standards relating to crew health/safety are not clear as to time limits of exposure, exposure of crew to high carbon dioxide levels in long duration space missions is regarded as highly undesirable.

As part of this development program the two key components of an air-polarized system, i.e., the Electrochemical Carbon Dioxide Separator Module and the Electrochemical Oxygen Separator Module, were fabricated and assembled into test stands equipped with various test support functions. Testing was conducted to characterize the performances of the Electrochemical Carbon Dioxide Separator Module and the Electrochemical Oxygen Separator Module, first separately and then integrated as an Air-Polarized Carbon Dioxide Concentrator.

The testing of the Integrated Air-Polarized Carbon Dioxide Concentrator demonstrated that: (1) carbon dioxide removal efficiencies were as high as 75% at 2.2 mm Hg (0.29%) and were still at 26% even at low, earth equivalent, ambient pCO_2 levels of 0.29 mm Hg (0.038%), and (2) carbon dioxide concentrations of higher than 95% can be achieved at the Electrochemical Oxygen Separator Module outlet without causing high Electrochemical Oxygen Separator Module cell voltages and while maintaining a 100% nominal oxygen transfer efficiency.

Using the test data obtained with the approximately one-person capacity Integrated Air-Polarized Concentrator, the characteristics for a four-person capacity system were projected. The results showed, a system sized to operate at a 2.2 mm Hg (0.29%) carbon dioxide level has a weight of 252 lb, a volume of 7.0 ft^3 and consumes 566 W of electrical power.

To compare the air-polarized concentrator technology with other candidate carbon dioxide removal systems, a study was completed comparing four-person capacity systems at 3 mm Hg and 2.2 mm Hg pCO_2. The candidate systems selected were an Electrochemical Depolarized Carbon Dioxide Concentrator, a Four-Bed Molecular Sieve, a Steam Adsorbed Solid Amine system and a Lithium Hydroxide based carbon dioxide removal system. As expected, the Electrochemical Depolarized Concentrator (using hydrogen) had the lowest equivalent weight considering launch weight and weight equivalents for power, heat load, propulsion, expendibles and oxygen consumption. The Air-Polarized Concentrator, however, compared well achieving the second lowest equivalent weight (after the electrochemical carbon dioxide concentration) compared to the other systems. The four person capacity APC characterized and defined herein is a candidate for a Space Station Flight Experiment that can generate desirable low pCO_2 levels of the station while proving the APC technology in a microgravity environment.

KEY ACCOMPLISHMENTS

The following key accomplishments resulted from completing the programs efforts.

- Verified the capability of the hydrogen-less electrochemical Air-Polarized Carbon Dioxide Concentrator to efficiently remove carbon dioxide from atmospheres having a partial carbon dioxide pressure as low as 0.29 mm Hg (0.038%), or equivalent to near earth ambient levels.

- Characterized the performance of five-cell electrochemical modules using flight-like 0.5 ft^2 cell hardware components for the electrochemical carbon dioxide separation and the electrochemical oxygen separation processes, providing results readily scalable to multi-person capacity systems.

- Defined a consistent set of nominal operating conditions for each individual electrochemical module to provide for their successful interaction when forming part of an integrated Air-Polarized Carbon Dioxide Concentration system.

- Successfully demonstrated integrated Air-Polarized Carbon Dioxide Concentrator system operation at a near one person capacity level over a wide range of key process parameters.

- Defined nominal operating conditions and physical characteristics for an Air-Polarized Carbon Dioxide Concentrator system to allow scaling to the four-person capacity level for eventual use as a Phase II Space Station Flight Experiment.

- Defined and established requirements and evaluation criteria to allow comparisons of candidate carbon dioxide removal technologies.

- Sized four other candidate carbon dioxide removal systems at the four-person capacity level and compared them with the Air-Polarized Carbon Dioxide Concentrator using total equivalent weight as a basis.

INTRODUCTION

During the past decade various technologies for removing carbon dioxide (CO_2) from air by a variety of methods have been developed for projected space applications. Under the sponsorship of the National Aeronautics and Space Administration (NASA), Life Systems has been involved in the development of various electrochemical CO_2 separation and processing concepts for use in space Environmental Control and Life Support Systems (ECLSS). These developments included the Electrochemical Carbon Dioxide Concentrator (EDC) using hydrogen (H_2), the Electrochemically Regenerable CO_2 and Moisture Absorption (ERCA) and the H_2-less Electrochemical CO_2 Separation (ECS) technology for use in Air-Polarized CO_2 Concentrators (APC).

While the EDC has always been known as the system characterized by low weight, power and volume, especially at pCO_2 levels equal to or less than 3 mm Hg [1,2] (see Figure 1)[1], the use of H_2 may not be desirable for some applications. As a result, Life Systems, under the sponsorship of NASA, developed the APC, i.e., an electrochemical H_2-less CO_2 separation process for those applications where H_2 use may not be desirable.

Projections of APC-based system studies had shown promise for the APC to be competitive, i.e., have equal to or better weight, power and volume characteristics, than other competing non-electrochemical techniques. Single and two cell development programs supported this promise[3,4,5] and resulted in the award of the current program to quantify, by testing, at a scaled up one person CO_2 removal level, APC operations to support these projections. Special emphasis was to be placed on operation at the lower pCO_2 levels projected and desirable for future space atmosphere requirements.

Background

Future long duration manned missions will require regenerative environmental control techniques to provide a habitable closed cabin atmosphere. An effective technique for removing CO_2 from the cabin atmosphere employs an electrochemical process for transferring CO_2 from a low pCO_2 environment in the cabin atmosphere to a higher pCO_2 stream isolated from the atmosphere. Achieving low pCO_2 atmospheres in space station environments is of paramount importance for the following reasons:

1. Carbon dioxide levels greater than 0.3% (2.3 mm Hg) will impact the interpretability of microgravity experiment data and limit the usefulness of platforms such as the Space Station for scientific experiments.

2. Although existing spacecraft standards related to crew health and safety are not well established with respect to CO_2 exposure limits, the exposure of crewmembers to high CO_2 levels in long duration space missions is regarded as highly undesirable.

(1) Numbers in parentheses refer to references listed in the Reference Section.

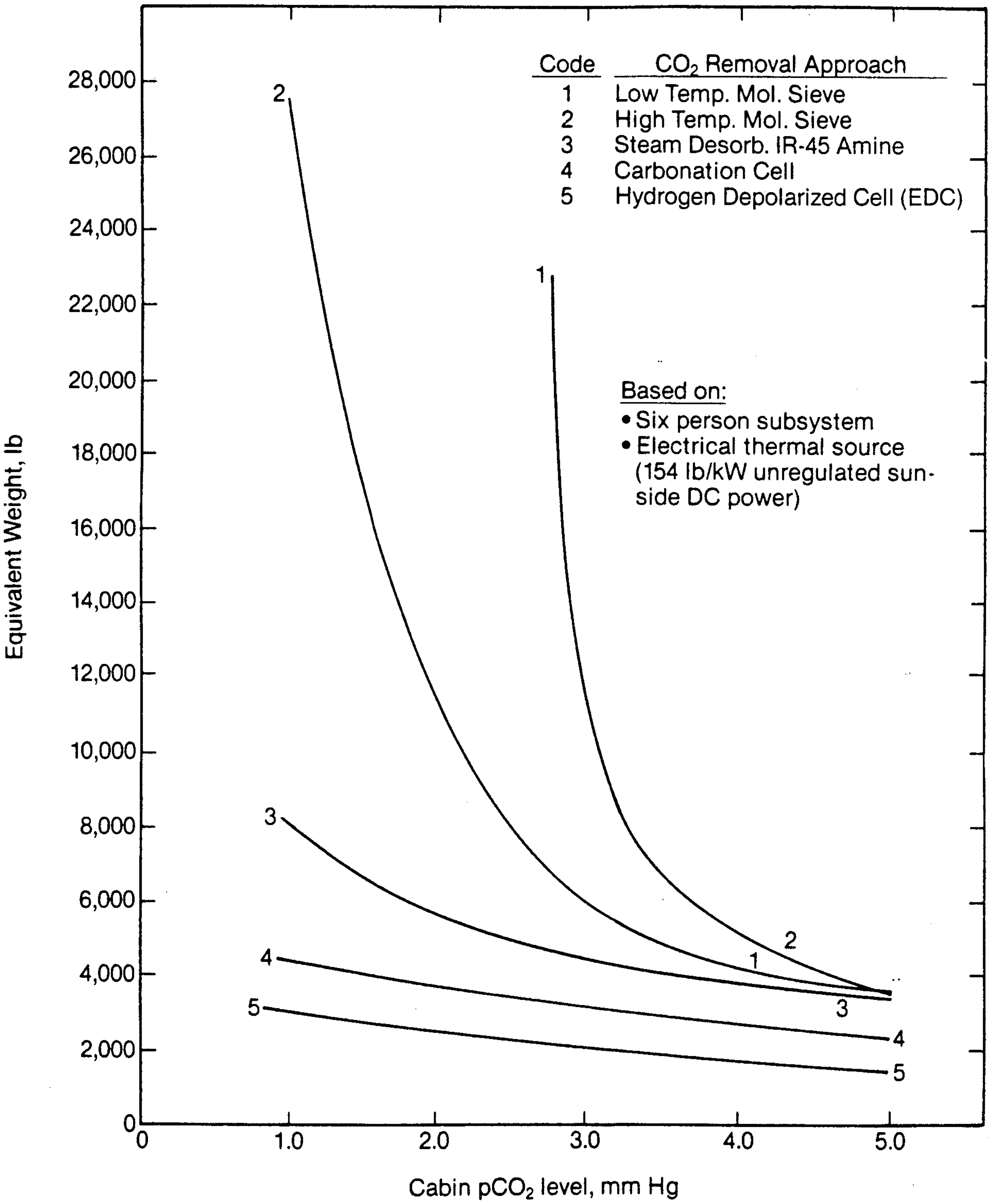

FIGURE 1 SSP CO_2 CONCENTRATOR STUDY TOTAL EQUIVALENT WEIGHT VS. pCO_2 SOLAR COLLECTOR THERMAL SOURCE

Life Systems, in collaboration with NASA, developed the APC process[3,4,5,6] which is an advanced electrochemical concept for continuous removal of metabolic CO_2 from cabin atmospheres at pCO_2 level as low as < 1 mm Hg. This technology requires electrical power but no expendables, such as H_2.

The APC process occurs in two stages. In the first stage, CO_2 is separated from the cabin atmosphere via an Electrochemical CO_2 Separator (ECS). This process involves the transfer of oxygen (O_2) as well as the transfer of CO_2. In the second stage, O_2 is removed from the CO_2/O_2 mixture via an Electrochemical O_2 Separator (EOS). This separation results in CO_2 concentrations in excess of 90%. A block diagram of the APC process technology, which is a combination of the ECS and the EOS processes, is shown in Figure 2. A detailed process description of the APC technology is presented in a later section of this report.

Program Objective

The objective of this Space Station Experiment Development Study Program is to verify the performance and applicability of the electrochemical CO_2 APC process technology for space missions requiring low CO_2 partial pressures (pCO_2), i.e., less than 3 mm Hg, in the cabin atmosphere. This effort was to be implemented by performing actual testing using Multi-Cell Units (MCUs) with flight-sized cells for verification of the performance characteristics projected in prior advanced electrochemical CO_2 removal technology study programs. The MCUs to be used were to be of an approximate one-person capacity (2.20 lb CO_2 removal per a 24-hr period) to demonstrate the technology at a readily scalable size.

Program Organization

To fulfill the objectives of this Ground-based Space Station Experiment Development Study Program, the program's technical efforts were divided into six (6) major tasks:

<u>Task</u>

1.0 Review and compare APC process technology with other CO_2 removal technologies intended for space applications.

2.0 Determine the scale-up modifications required to operate the ECS and EOS modules at an approximate one-person capacity.

3.0 Fabricate and assemble the ECS and EOS modules and test stands.

4.0 Verify the projections of the APC process technology for comparison to other CO_2 removal technologies through testing and analysis.

5.0 Prepare required documentation and implement data management activities.

6.0 Perform required program management.

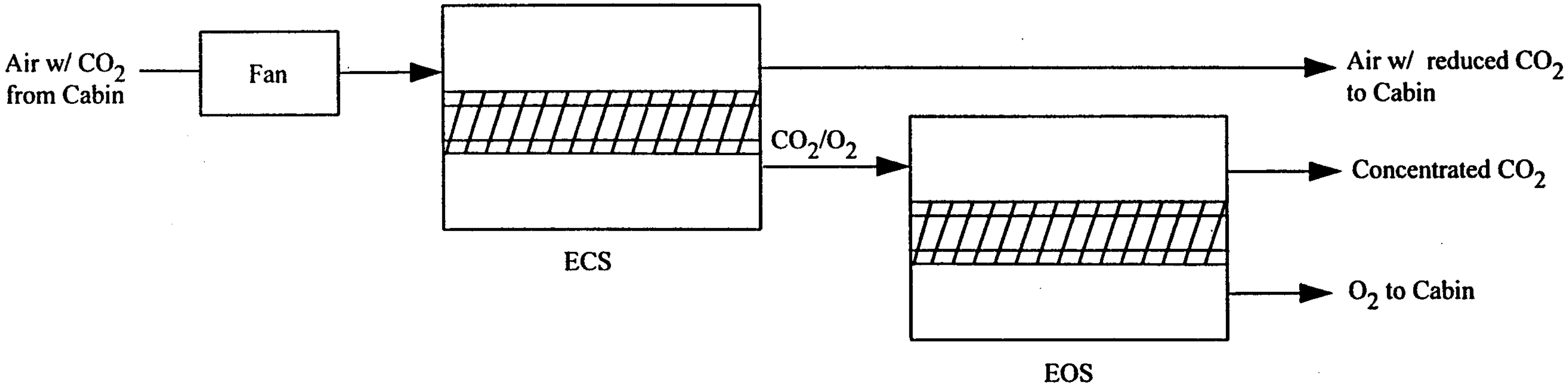

FIGURE 2 BLOCK DIAGRAM OF APC CO_2 REMOVAL SYSTEM

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End Products

The end products of this Ground-based Space Station Experiment Development Study Program are:

1. An expanded APC technology experimental database based on multi-cell electrochemical module tests.

2. A four person capacity APC-based CO_2 removal system definition based on the test results obtained.

3. A comparison of system level characteristics (weight, power, volume, etc.) of the four person capacity APC-based CO_2 removal system with other CO_2 removal systems.

4. A Preliminary definition of a full sized APC Space Station Flight Experiment Unit.

5. Six Quarterly Reports documenting the progress of the contractual efforts.

6. A Final Report summarizing the ground-based development program results.

Report Organization

This report is organized into four major sections in addition to this Introduction. These sections are followed by the conclusions and recommendations reached based on the work reported herein. The four major sections are:

- Air-Polarized Carbon Dioxide Concentrator Technology Description
- Test Hardware Development
- Test Program
- Air-Polarized Carbon Dioxide Concentrator Sizing and Comparisons

Two appendices are included, Appendices A and B, containing test criteria and data sheets, respectively, for the program testing completed. The appendices are followed by references and Standard NASA Form 298.

AIR-POLARIZED CARBON DIOXIDE CONCENTRATION TECHNOLOGY DESCRIPTION

The APC process occurs in two stages. In the first stage, CO_2 is separated from the cabin atmosphere via an ECS. This process involves the transfer of O_2 as well as the transfer of CO_2. In the second stage, O_2 is removed from the CO_2/O_2 mixture via an EOS. This separation results in CO_2 concentrations in excess of 90%. The functional schematics of the ECS and EOS processes are shown in Figure 3 and 4, respectively. A block diagram of the APC process technology, which is a combination of the ECS and the EOS processes, was shown in Figure 2.

Details of the electrochemical CO_2 separation and electrochemical O_2 separation processes are described below.

Electrochemical CO_2 Separation

The electrochemical CO_2 separation process removes CO_2 from the cabin atmosphere by reacting the CO_2 with hydroxyl ions (OH^-) electrochemically generated within a porous gas diffusion cathode according to the following half-cell reaction:

$$1/2O_2 + H_2O + 2e^- \rightarrow 2OH^- \quad (1)$$

The CO_2 reacts with the OH^- and is then transferred within the aqueous alkaline carbonate electrolyte from the cathode (atmosphere side) to the anode (CO_2 concentrating side). The CO_2 transfer occurs via carbonate (CO_3^{-2}) and bicarbonate (HCO_3^-) ions generated from the reaction of CO_2 with OH^- according to Reactions 2a and 2b, respectively:

$$CO_2 + OH^- \rightarrow HCO_3^- \quad (2a)$$

$$HCO_3^- + OH^- \rightarrow CO_3^{-2} + H_2O \quad (2b)$$

Reaction 2b occurs instantaneously, so Reaction 2a is the rate-determining step. Therefore, the conversion of CO_2 to CO_3^{-2} can be described by a single step as shown in Reaction 3:

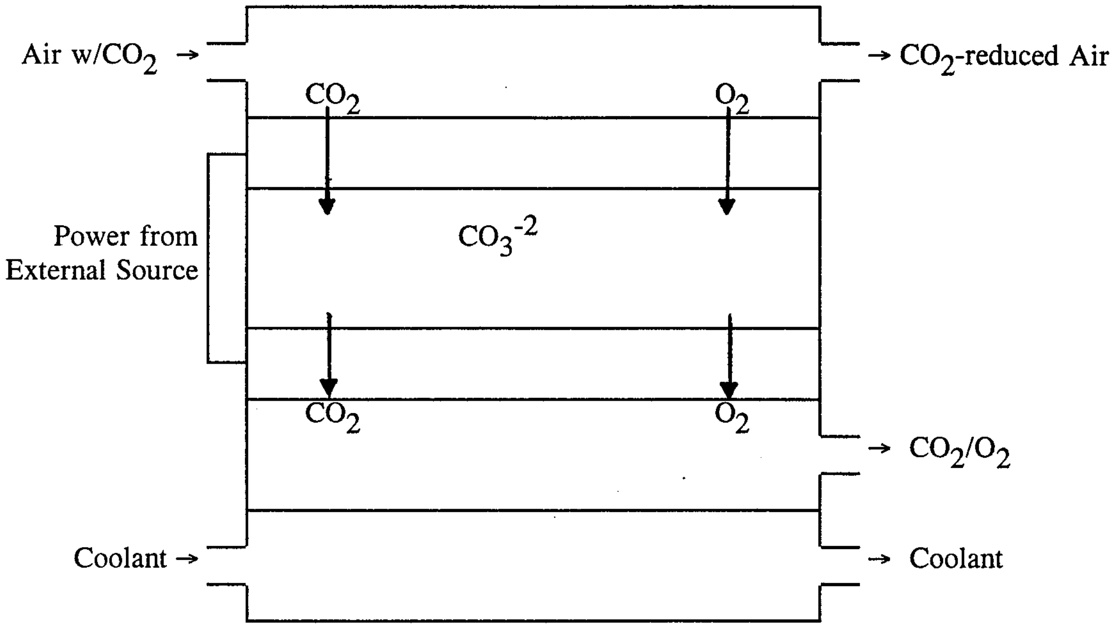
$$CO_2 + 2OH^- \rightarrow CO_3^{-2} + H_2O \quad (3)$$

When the concentration of OH^- is depleted, additional CO_2 can be absorbed by:

$$CO_2 + CO_3^{-2} + H_2O \rightarrow 2HCO_3^- \quad (4)$$

Combining Equations 3 and 4 results in an overall absorption reaction of:

$$2CO_2 + 2OH^- \rightarrow 2HCO_3^- \quad (5)$$



Electrode Reactions:

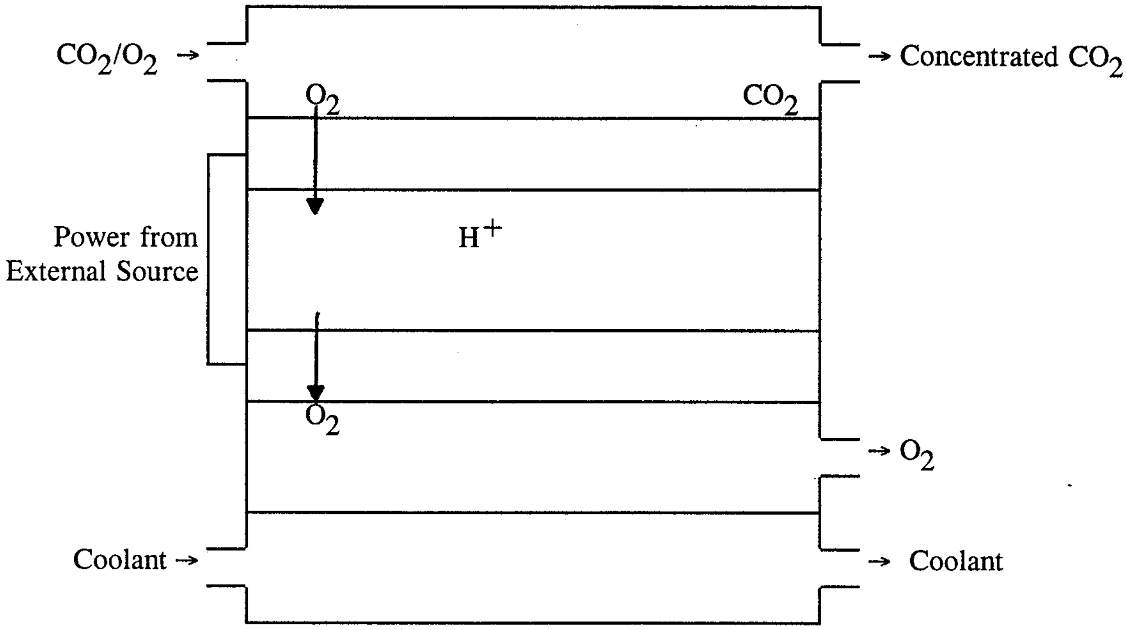
Cathode: $O_2 + H_2O + 4e^- \rightarrow 4OH^-$

$4OH^- + 2CO_2 \rightarrow 2CO_3^{-2} + 2H_2O$

Anode $2CO_3^{-2} \rightarrow 2CO_2 + O_2 + 4e-$

Overall: $(2CO_2 + O_2)_{cathode} \rightarrow (2CO_2 + O_2)_{anode}$

FIGURE 3 ELECTROCHEMICAL CO_2 SEPARATOR FUNCTIONAL SCHEMATIC



Electrode Reactions:

Cathode: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$

Anode $2H_2O \rightarrow O_2 + 4H^+ + 4e^-$

Overall: $(O_2)_{cathode} \rightarrow (O_2)_{anode}$

FIGURE 4 ELECTROCHEMICAL O_2 SEPARATOR FUNCTIONAL SCHEMATIC

The CO_3^{-2} and HCO_3^- ions formed at the cathode by Reactions 3 and 5, respectively, migrate toward the anode due to an electrical potential difference applied to the cell. The CO_2 is liberated within the electrolyte at the anode according to the following equations:

$$CO_3^{-2} \rightarrow CO_2 + 1/2O_2 + 2e^- \tag{6a}$$

and

$$2HCO_3^- \rightarrow 2CO_2 + H_2O + 1/2O_2 + 2e^- \tag{6b}$$

Combining Reactions 1, 3 and 6a results in a net overall reaction of:

$$[1/2O_2 + CO_2]_{cathode} \rightarrow [1/2O_2 + CO_2]_{anode} \tag{7a}$$

and combining Reactions 1, 5 and 6b results in a net overall reaction of:

$$[1/2O_2 + 2CO_2]_{cathode} \rightarrow [1/2O_2 + 2CO_2]_{anode} \tag{7b}$$

Reactions 7a and 7b represent the results of two different CO_2 transfer mechanisms which determine the electrochemical transfer efficiency of the CO_2 removal process. Reaction 7a shows that two moles of CO_2 are transferred per mole of O_2 compared to the four moles of CO_2 per mole of O_2 transferred per Reaction 7b. Whether the CO_2 transfer occurs mostly by Reaction 7a or Reaction 7b depends on several factors such as atmospheric CO_2 level, air flow rate, electrochemical cell current, operating temperature, etc. In this report Reaction 7a will be used for CO_2 removal efficiency calculations, i.e., transfer of one mole of CO_2 per 1/2 mole of O_2 co-transferred is equal to 100%.

Electrochemical O_2 Separation

As shown in Reactions 7a and 7b, the transfer of CO_2 from the cathode (atmosphere side) to the anode involves the transfer of O_2. The concentration of O_2 in the anode gas stream is dependent on the CO_2 transfer efficiency. The O_2 must be removed from the anode gas stream to yield a high CO_2 concentration for efficient downstream O_2 recovery processing (e.g., CO_2 reduction followed by water electrolysis).

As part of the APC technology, an electrochemical O_2 separation process is used to generate concentrated CO_2 by removing O_2 from the CO_2/O_2 mixture stream. An aqueous acidic electrolyte is used in the EOS cell core to prevent the transfer of CO_2 while allowing the transfer of O_2. This transfer of O_2 occurs via water molecules which diffuse from the cathode to the anode where they are dissociated into O_2 and hydrogen ions according to Reactions 8 and 9, respectively:

$$\text{Cathode:} \quad O_2 + 4H^+ + 4e^- \rightarrow 2H_2O \tag{8}$$

$$\text{Anode:} \quad 2H_2O \rightarrow O_2 + 4H^+ + 4e^- \tag{9}$$

The overall reaction is:

$$(O_2)_{cathode} \rightarrow (O_2)_{anode} \qquad (10)$$

which results in an increased CO_2 concentration in the cathode gas stream of the EOS. The concentrated CO_2 stream is sent to CO_2 reduction processes such as the Sabatier or the Bosch processor to eventually recover O_2. The O_2 produced at the anode is sent to the space cabin.

Expected Impact of APC Process Technology on CO_2 Removal for Space Applications

The APC process offers advanced electrochemical technology for the continuous removal of metabolic CO_2 from cabin atmosphere at low pCO_2 and will provide substantial gains to an overall Air Revitalization System (ARS):

- Continuous removal of CO_2 from the cabin atmosphere resulting in more uniform CO_2 concentration levels in the cabin atmosphere.
- An efficient H_2-less electrochemical CO_2 concentration technique.
- Variable CO_2 removal rates through control of cell current, air flow rate, etc.
- Minimal thermal heat loads and simple basic operating mode transitions due to operation at near ambient temperature and pressure.
- Variable capacity through addition or elimination of the number of electrochemical cells in the modules.
- Reduced power consumption, weight and volume requirements due to absence of expendables or regenerative processing.

TEST HARDWARE DEVELOPMENT

Two electrochemical modules, one for O_2 separation, one for CO_2 separation and associated mechanical and electrical test hardware were developed. The test hardware provided the flexibility to allow separate EOSM and ECSM testing, as well as provide for integrated APC testing. Special test equipment to allow for data acquisition and analysis was provided.

Test Hardware Development Approach

The hardware development approach chosen was consistent with the overall scope of the program, i.e., utilizing, to the maximum extent possible, existing Life Systems' electrochemical cell and test stand hardware. This approach included cost effective modifications of existing hardware where applicable.

A requirement adopted for the electrochemical cells at the beginning of the Program was that the active electrode area was to be similar to flight-like projections (i.e., 0.5 ft^2 per cell). Module size at a given set of operating conditions was to be equivalent to approximately a one-person CO_2 removal capacity (i.e., 2.2 CO_2 lb/day).

Ancillary mechanical and electrical components that would normally compliment the electrochemical modules to form a complete APC flight system were to be simulated using existing test stand or other hardware items. The hardware to be developed for the program testing had to allow for independent EOSM and ECSM testing as well as to be easily modifiable to complete an integrated APC test program.

O_2 Separation Hardware

The O_2 separation hardware consisted of a five-cell electrochemical module and its associated test stand and data acquisition hardware.

Electrochemical Module Hardware

Existing Water Vapor Electrolysis (WVE) cell and module hardware was used as a basis to develop a five-cell EOSM. Injection molded polysulfone cell frames with integral liquid coolant compartments and current distribution and collection components formed the primary building block of a five-cell EOSM. The heart of each cell, the unitized cell core, consisted of an anode, a cathode and an acid compatible separator, molded together with gas passage spacer screens into the unitized cell core assembly. End plates were constructed of glass filled polysulfone and all sealing was accomplished via commercial or specially molded Viton O-rings. Each unitized cell core was charged with phosphoric acid (H_3PO_4) electrolyte using Life Systems' electrochemical cell charging fixtures. Table 1 lists characteristics of key electrochemical cell components for the EOSM.

TABLE 1 EOS CELL COMPONENT CHARACTERISTICS

Component	Material	Thickness, in
Cathode Gas Cavity Spacer	Ti Exmet	0.050
Cathode Electrode	Noble Metal Catalyst on Pt Screen	0.011
Matrix	Mineral-based	0.015
Anode Electrode	Metal Oxides on Porous Ti Plaque	0.032
Anode Gas Cavity Spacer	Ti Exmet	0.100

The five electrochemical cells were arranged to provide for O_2/CO_2 mixture flow in series through the five cells and for parallel collection of the cathode product gas (O_2). Electrical current was routed to flow in series through the five cells. Liquid coolant passages were arranged to allow for parallel liquid coolant flow.

Test Stand and Data Acquisition Hardware for the EOSM

An existing test stand was modified to allow for EOSM testing, resulting in the schematic shown in Figure 5. The associated data acquisition system concept is shown in Figure 6. The EOSM test stand provided for measured and controlled flows of O_2 and CO_2 from bottled storage and for adjustable backpressure regulation of the cathode exit gas. A controllable and measurable liquid coolant flow supply was included, equipped with inlet and outlet temperature sensors. Multiple two-way and three-way valves completed the test hardware allowing for proper characterization of influent and effluent gas flows.

Electrically the test stand provided for adjustable module current and for associated module and cell voltage readouts and monitoring. Shutdown protection for high cell voltages was incorporated to safely and automatically shutdown the test should limits be exceeded.

Key data acquisition items included a Lira 3000 CO_2 Analyzer and a multi-channel Molytek data logger. Flow measurements were made using calibrated flow meters for the O_2 and CO_2 supplies and soap bubble flowmeters with a stopwatch for product gas flows.

CO_2 Separation Hardware

The CO_2 separation hardware consisted of a five-cell electrochemical module and its associated test stand and data acquisition hardware.

Electrochemical Module Hardware

Existing EDC module components formed the basis for the EOSM hardware. These components were modified consistent with the operational requirements of an ECSM. Primary emphasis was placed on supplying proper materials for current collection and for the unitized cell cores. Each of the latter consisted of two gas cavity spacers, an anode, a cathode and the cell separating material molded into a single unit. Table 2 lists characteristics of key cell components for the EOSM.

The full size 0.5 ft^2 cell hardware consisted of injection molded polysulfone frames with an integral liquid coolant compartment. A combination of silver and tantalum current collectors and current distribution tabs were used. Glass filled polysulfone end plates and cast aluminum inlet and exit air manifolds completed the ECSM construction. Each unitized cell core of the ECSM was charged with LSI-D, a Life Systems proprietary electrolyte used for electrochemical CO_2 removal cells. Vacuum charging was employed using a Life Systems electrolyte charging fixture. The five electrochemical cells were arranged to provide for parallel air flow through all five cells and a parallel collection of the cathode product gas.

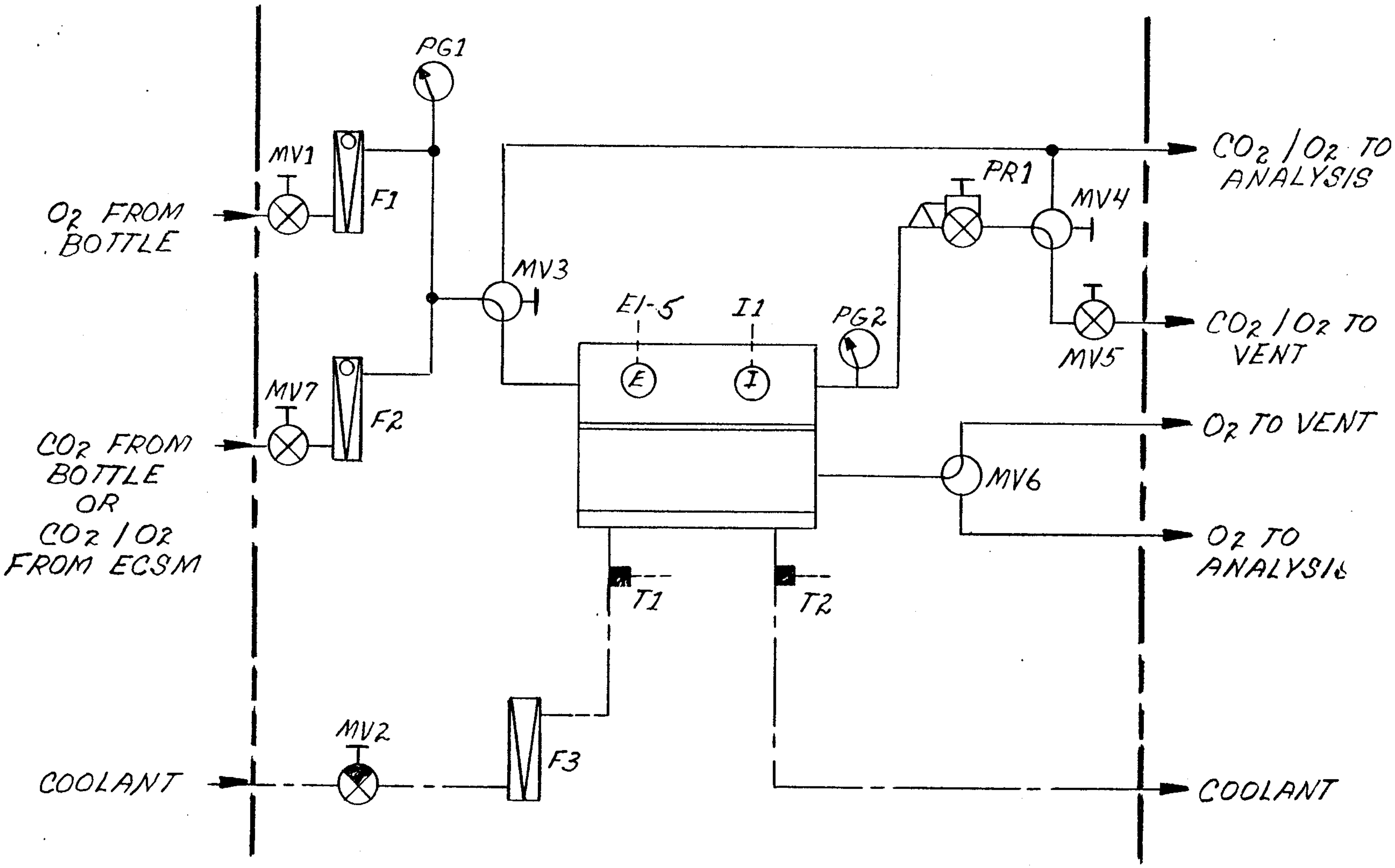
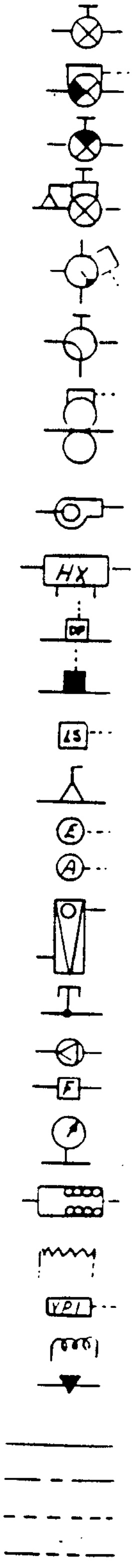


FIGURE 5 EOSM TEST SETUP MECHANICAL SCHEMATIC WITH SENSORS

LEGEND



VALVE, MANUAL SHUT OFF (OPEN)
VALVE, ELECTRICAL SHUTOFF (NORMALLY CLOSED)
ORIFICE, VARIABLE (MANUAL)
REGULATOR, BACK PRESSURE WITH MANUAL ADJ.
VALVE, ELECTRICAL DIVERTER
VALVE, MANUAL THREE-WAY
PUMP
BLOWER
HEAT EXCHANGER
SENSOR, DEW POINT
SENSOR, TEMPERATURE
SENSOR, LEVEL
SENSOR, PRESSURE
SENSOR, VOLTAGE
SENSOR, CURRENT
FLOW METER WITH FLOW CONTROL
ACCESS PORT, CAPPED
VALVE, CHECK
FILTER
GAUGE, PRESSURE
ACCUMULATOR (MECHANICAL)
HEATER, ELECTRICAL
VALVE POSITION INDICATOR, ELECTRICAL
COOLING COIL
ORFICE, FIXED
LINE, GAS
LINE, LIQUID
LINE, ELECTRICAL
MAINTAINABLE UNIT BOUNDARY

Figure 5 - continued

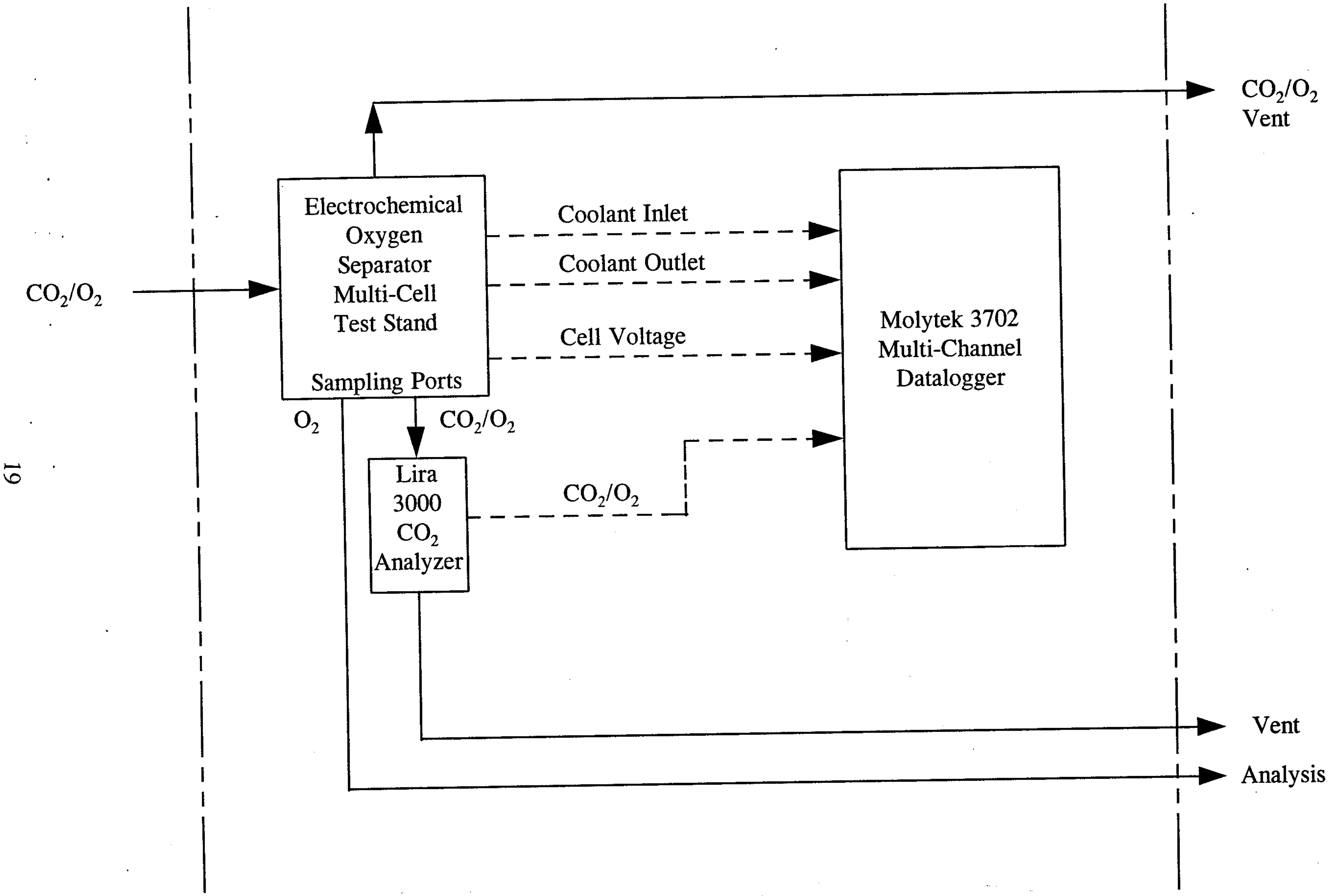


FIGURE 6 EOSM DATA ACQUISITION SYSTEM

TABLE 2 ECS CELL COMPONENT CHARACTERISTICS

Component	Material	Thickness, in
Cathode Gas Cavity Spacer	Ni Exmet	0.085
Cathode Electrode	Noble Metal Catalyst on Ni Screen	0.012
Matrix	Mineral-based	0.030
Anode Electrode	Metal Oxides on Porous Ti Plaque	0.040
Anode Gas Cavity Spacer	Ti Exmet	0.040

Electrical current was routed to flow in series through the five cells. Liquid coolant passages were arranged to allow for parallel liquid coolant flow, flowing countercurrent to the process air for more uniform temperature gradients.

Test Stand and Data Acquisition Hardware for the ECSM

An existing test stand was modified to allow testing of the five-cell ECSM. Figure 7 shows a schematic of the ECSM test stand while Figure 8 shows the associated ECSM data acquisition system.

The ECSM test stand provided for the capability to vary air flow rate, air relative humidity and air partial pressure of CO_2. In addition, a feedback controlled liquid coolant loop to control module temperature was included. Various valves, flow meters and pressure regulators were used to allow for maintaining desired fluidic conditions while sampling influent and effluent gas streams of the module.

The electrical hardware included the capability to select and maintain module current levels while monitoring individual cell and module voltages. Shutdown protection for high cathode exit air back pressure as well as for low cell voltages was incorporated. Exceeding setpoints automatically configured the system into a safe mode.

The analytical instruments and data acquisition hardware included two Lira 3000 CO_2 analyzers, one to measure the low range of pCO_2 in the inlet and exit of the process air stream, the second to measure the high levels of pCO_2 in the effluent cathode exhaust stream. Again, a Molytek multi-channel data logger was used to record key module and test stand parameters.

Integrated APC Hardware

Following the completion of the individual module testing, the modules were inspected to see if refurbishment was required. Test stand modifications were incorporated to allow integrated APC operation and data collection system.

Electrochemical Modules

Following the individual module tests both the EOSM and ECSM were removed from their respective test stands, partially disassembled, inspected and reassembled. No modifications or corrections were required.

Test Stands and Data Acquisition Hardware for the APC

The two module test stands were modified at their interfaces to allow sending the anode effluent O_2 and CO_2 mixture from the ECSM directly to the inlet of the EOSM. A variety of other interfaces were capped off since they were not used during integrated operation. The resulting schematics of the ECSM and EOSM sections of the integrated APC test stand are

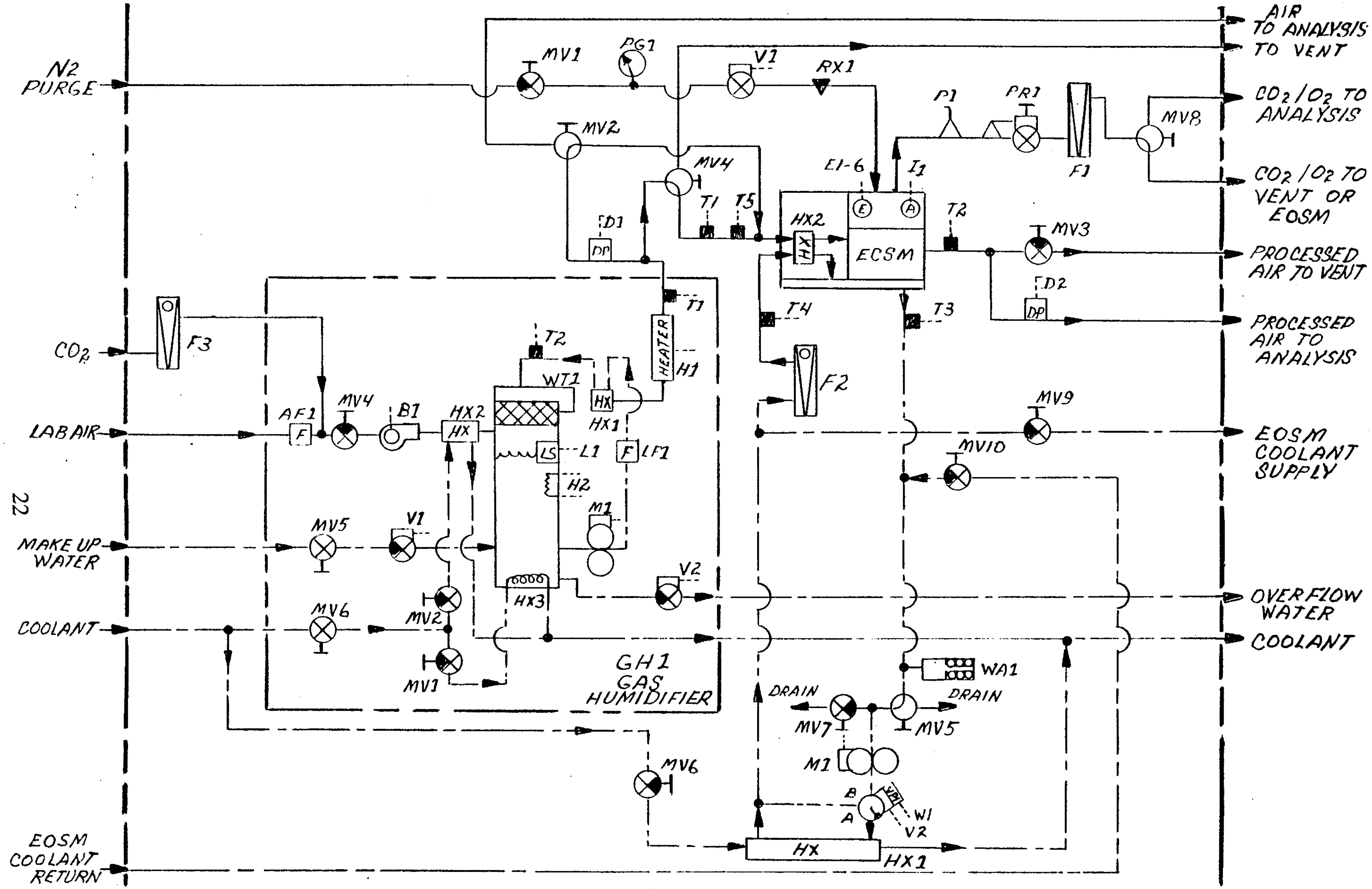


FIGURE 7 ECSM TEST SETUP MECHANICAL SCHEMATIC WITH SENSORS

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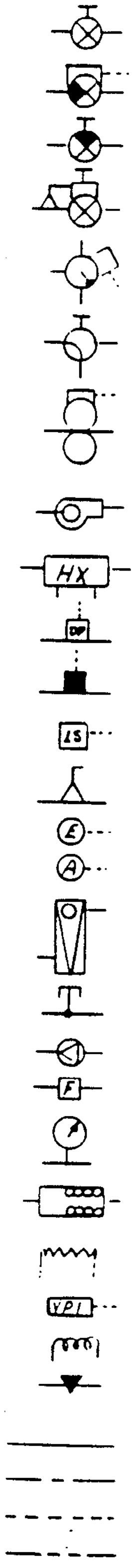
LEGEND



VALVE, MANUAL SHUT OFF (OPEN)
VALVE, ELECTRICAL SHUTOFF (NORMALLY CLOSED)
ORIFICE, VARIABLE (MANUAL)
REGULATOR, BACK PRESSURE WITH MANUAL ADJ.
VALVE, ELECTRICAL DIVERTER
VALVE, MANUAL THREE-WAY
PUMP
BLOWER
HEAT EXCHANGER
SENSOR, DEW POINT
SENSOR, TEMPERATURE
SENSOR, LEVEL
SENSOR, PRESSURE
SENSOR, VOLTAGE
SENSOR, CURRENT
FLOW METER WITH FLOW CONTROL
ACCESS PORT, CAPPED
VALVE, CHECK
FILTER
GAUGE, PRESSURE
ACCUMULATOR (MECHANICAL)
HEATER, ELECTRICAL
VALVE POSITION INDICATOR, ELECTRICAL
COOLING COIL
ORFICE, FIXED
LINE, GAS
LINE, LIQUID
LINE, ELECTRICAL
MAINTAINABLE UNIT BOUNDARY

Figure 7 - continued

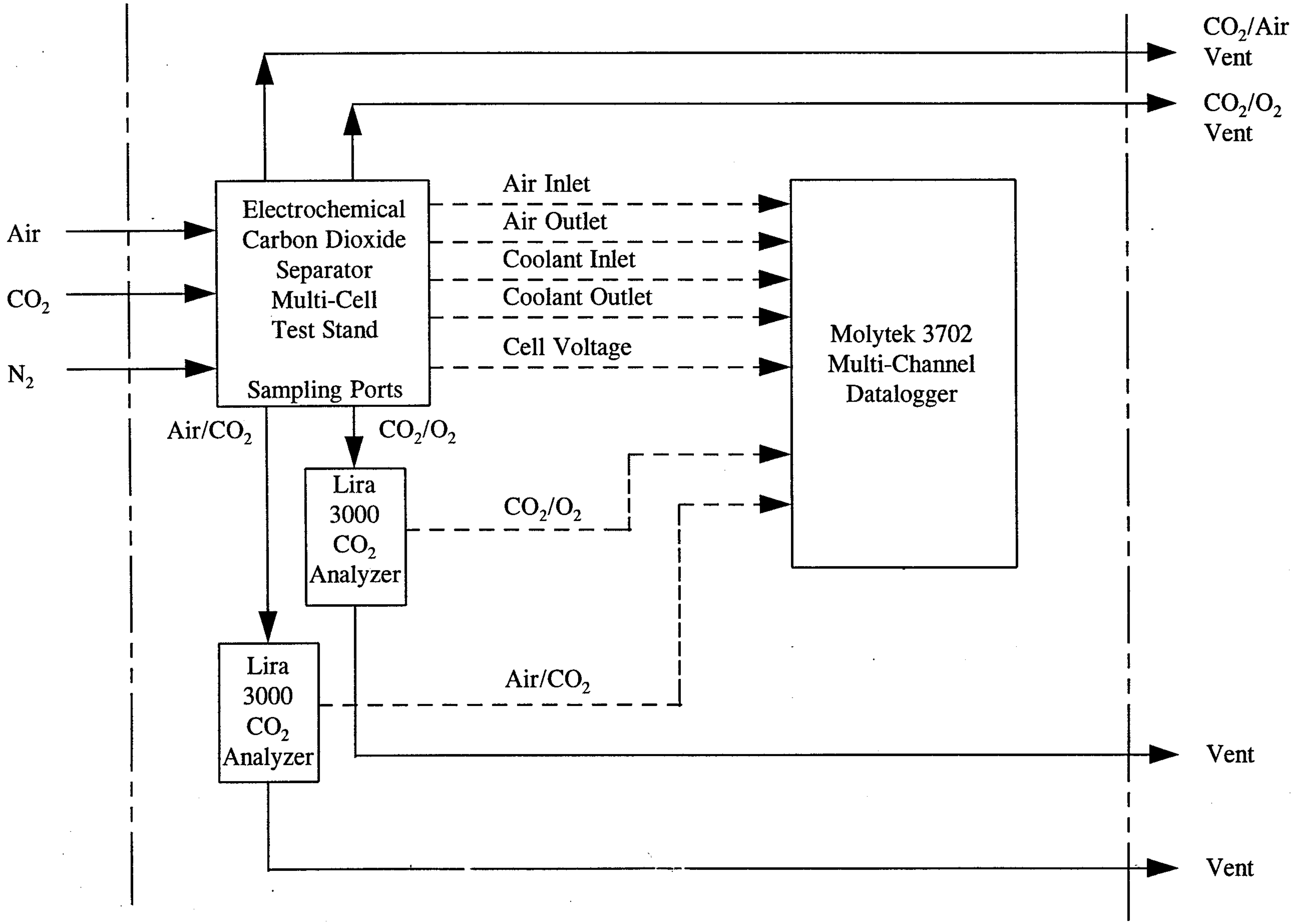


FIGURE 8 ECSM DATA ACQUISITION SYSTEM

shown in Figures 9 and 10, respectively. Figure 11 shows the APC data acquisition system using both high and low range pCO_2 Lira analyzers, soap bubble flowmeters for accurate gas measurements and the Molytek multichannel data logger. Figure 12 is a photograph of the integrated test setup used for APC testing.

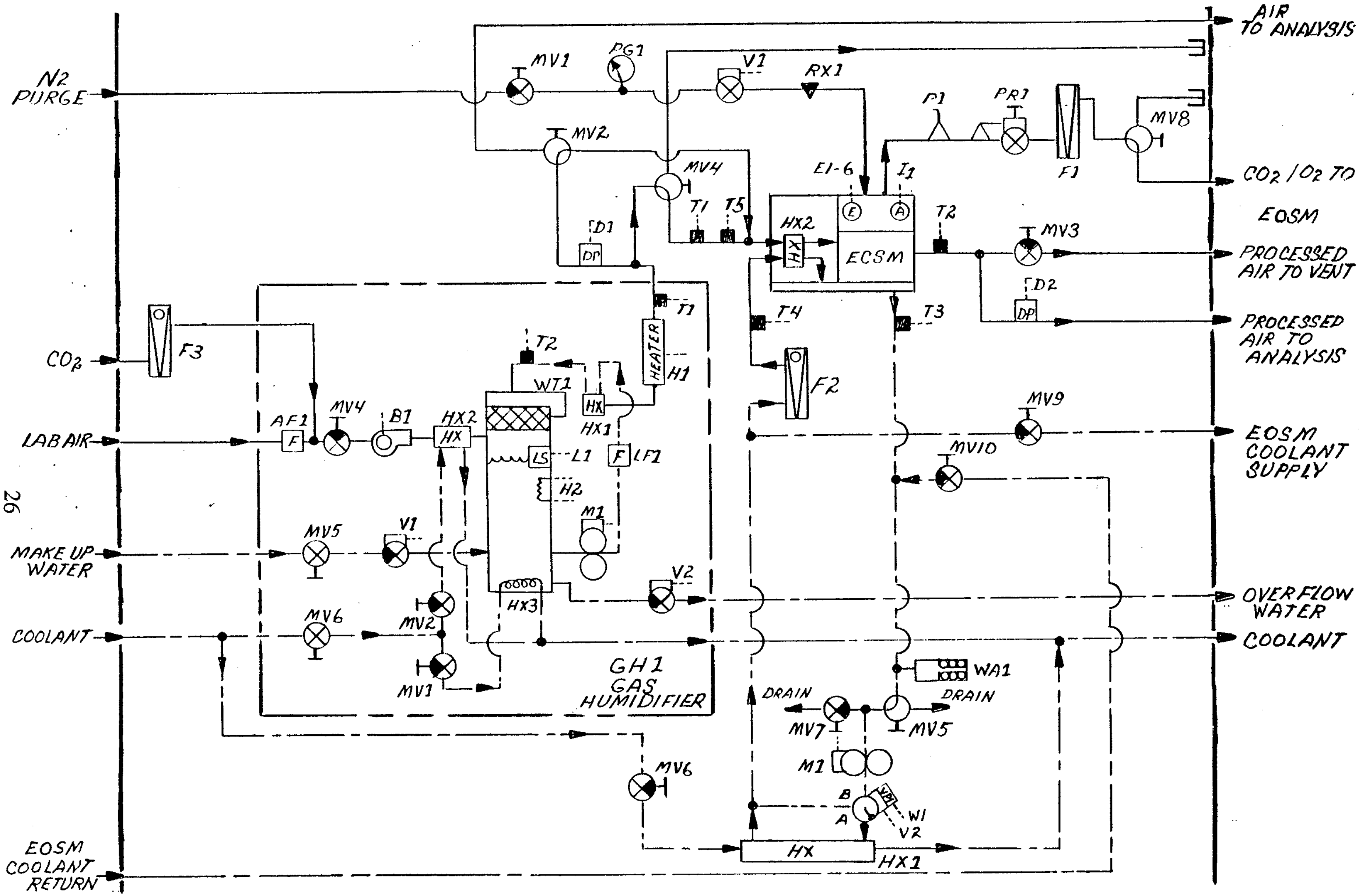


FIGURE 9 ECSM TEST SETUP MECHANICAL SCHEMATIC WITH SENSORS FOR INTEGRATED APC OPERATION

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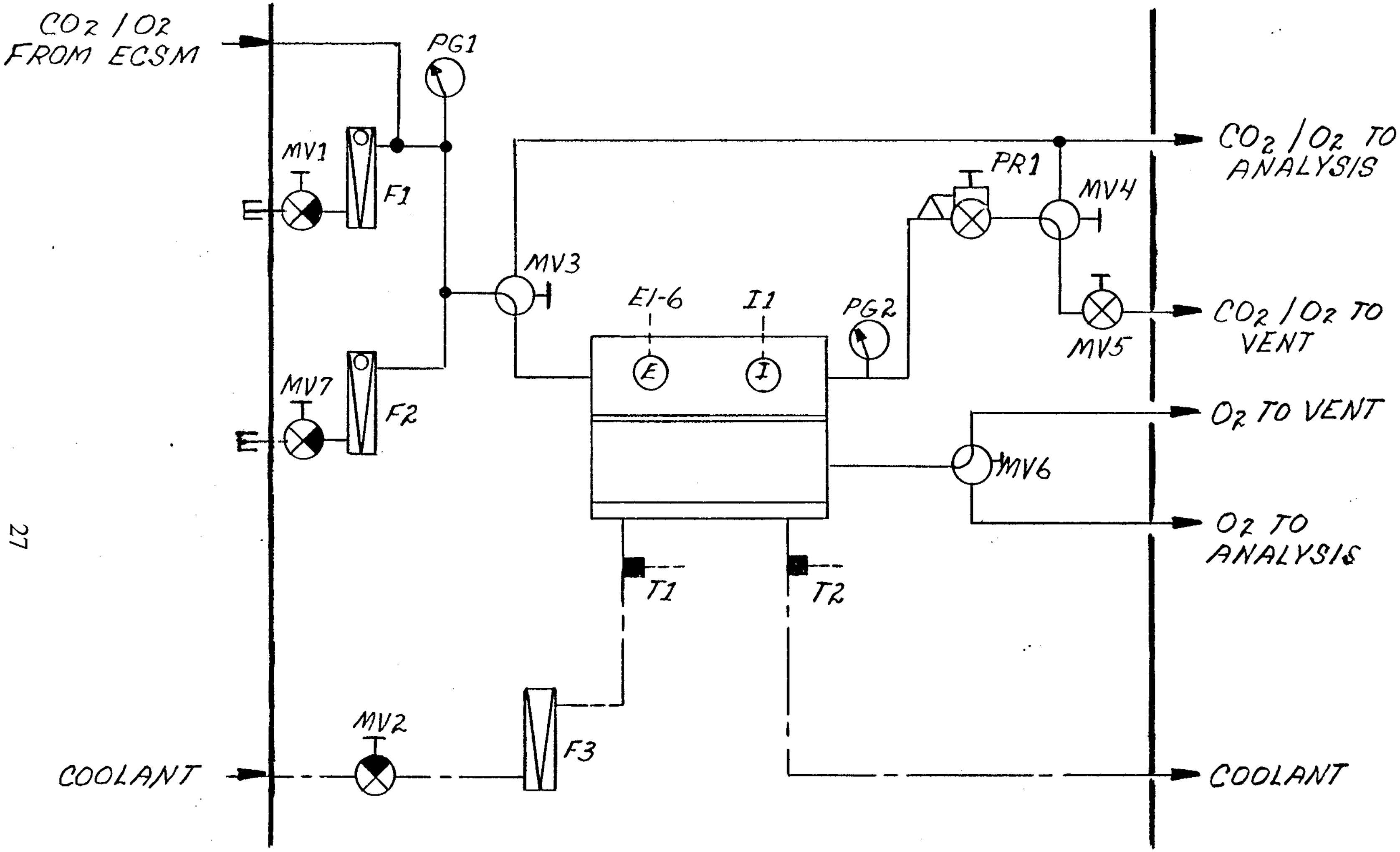

FIGURE 10 EOSM TEST SETUP MECHANICAL SCHEMATIC WITH SENSORS
FOR INTEGRATED APC OPERATION

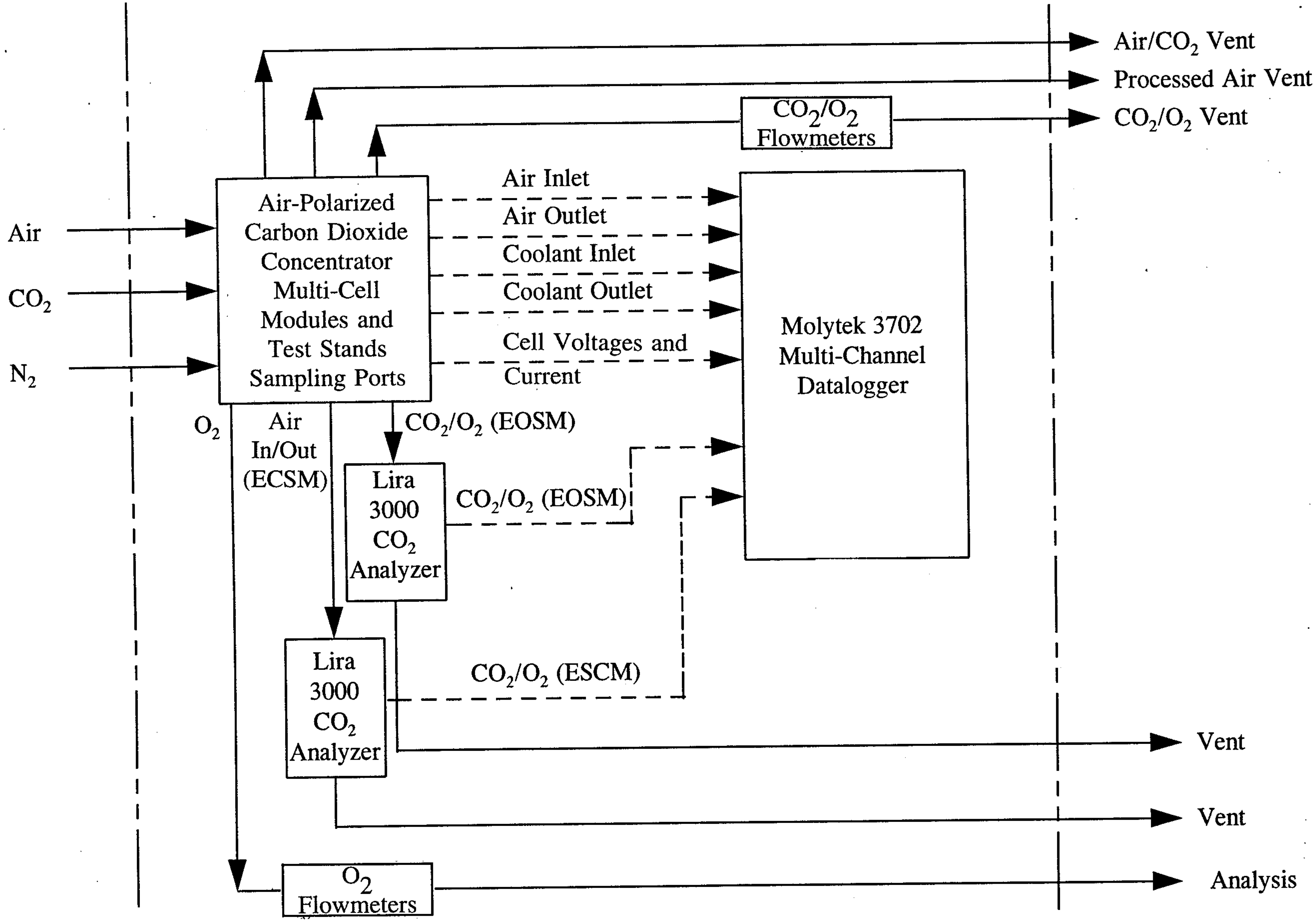

FIGURE 11 APC DATA ACQUISITION SYSTEM

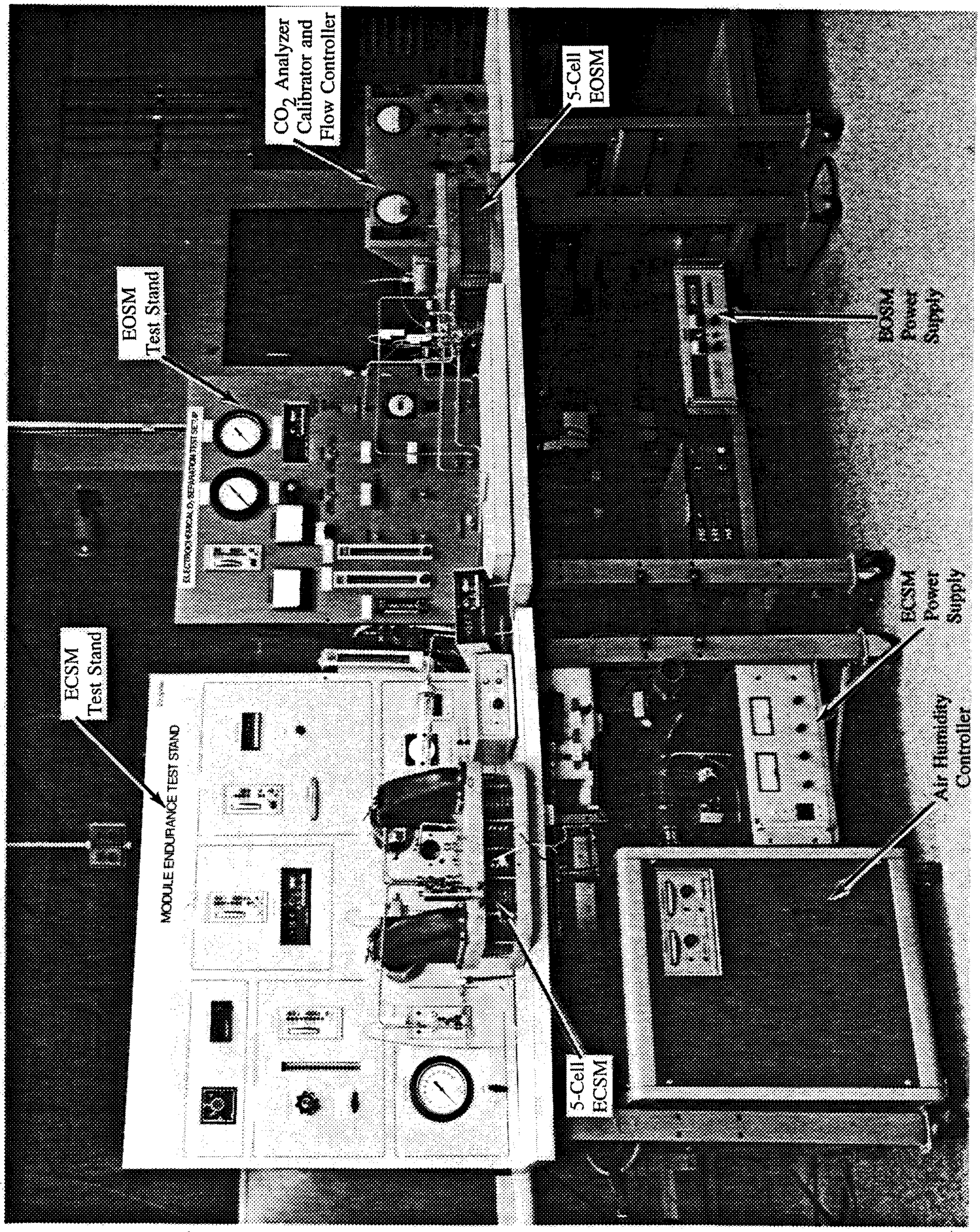

FIGURE 12 APC INTEGRATED TEST SETUP

TEST PROGRAM

An overall test program was defined based on the test objectives. A test sequence was established initially testing at the individual module level, followed by integrated APC testing.

Test Objectives

The test objectives were two-fold. First, to test individually the modules, to establish test conditions and module operating characteristics that would allow for eventual integrated APC testing; and secondly, to obtain test data to allow sizing of a full sized (four person capacity) APC for CO_2 removal from low pCO_2 atmospheres.

These objectives were met by first testing the five-cell EOSM for various simulated ECSM anode effluent flow rates and O_2 to CO_2 mixture ratios, followed by testing a five cell ECSM for various ranges in processor air inlet conditions. Sizing data for an APC system was derived from data obtained during both the integrated APC as well as the individual testing of the two five-cell electrochemical modules.

Selection and Definition of Initial Test Conditions

Selection of nominal operating conditions for the two modules was performed as an iterative process requiring consideration of key parameters such as dewpoints, temperatures, module electrical performance, CO_2 removal efficiency, electrolyte characterics and module current levels. The output of this effort resulted in the nominal operating conditions for the EOSM and ECSM as shown in Tables 3 and 4, respectively. Vapor pressures of the two electrolytes i.e., H_3PO_4 as well as LSI-D, for the EOSM and ECSM, respectively, were investigated to determine proper moisture interaction of the gas flows from one module to the other. Vapor pressure versus temperature for these two electrolytes are shown in Figures 13 and 14, respectively.

The CO_2 removal efficiency of the ECSM determines the cathode feed gas composition for the EOSM. In order to characterize this interface, the curves shown in Figure 15 were prepared which show the percent of O_2 and CO_2 in the anode vent gas from the ECSM as a function of the ECSM's CO_2 removal efficiency. A nominal design point of a 60% CO_2 removal efficiency at a pCO_2 of 2.3 mm Hg, was initially selected and used to prepare Tables 3 and 4. This efficiency resulted in a nominal 45% O_2 and 55% CO_2 cathode feed gas mixture to the EOSM. As shown in Figure 15, subsequent ECSM testing showed higher then 60% efficiencies were achievable. As a result, the operating conditions were subsequently adjusted to a 75% efficiency, as discussed in the ECSM and APC test sections.

Since the EOSM has its cathode compartments connected fluidically in series to enhance removal of the O_2 from the mixture of O_2 and CO_2 feed gas, the outlet of an upstream cell constitutes the inlet conditions for a downstream cell, and so on. For reference, the conditions at each of the five EOSM cell inlets and outlets were calculated. The results are shown in Table 5 which shows the flow rates of O_2 and CO_2 for a variety of ECSM CO_2

TABLE 3 INITIAL FIVE-CELL ELECTROCHEMICAL OXYGEN SEPARATION MODULE (EOSM) OPERATING PARAMETERS

	Nominal
Current	
Level, A	6.0
% of ECSM, %	75
Module Temp, F	83
Cathode Feed	
Flow Rate, sccm	311
Composition, % O_2/% CO_2	45/55[(a)]
Stoichiometric Ratio	1.33
Temperature, F	72
Dewpoint, F	67
Pressure (outlet), psig	1.0
Coolant	
Flow Rate, lb/hr	50
Temperature, F	82
Anode Vent Pressure, psig	0

(a) Equivalent to 60% Electrochemical Carbon Dioxide Separation Module (ECSM) carbon dioxide (CO_2) removal efficiency at 2.3 mm Hg pCO_2 in air feed stream (140 sccm of oxygen (O_2) and 171 sccm CO_2).

TABLE 4 INITIAL FIVE-CELL ELECTROCHEMICAL CARBON DIOXIDE SEPARATION MODULE (ECSM) OPERATING PARAMETERS

	Nominal
Current, A	8.0
Module Temp, F	83
Cathode Air	
Flow Rate, ACFM	9.0
pCO_2, mm Hg	2.3
Pressure, psia	15
Temperature, F	75
Dewpoint, F	63
RH, %	64
Coolant	
Flow Rate, lb/hr	50
Temperature, F	82
Anode Vent	
Pressure, psig	1.0
O_2 Flow, sccm	140
CO_2 Flow, sccm	171[(a)]

(a) A total of 171 sccm carbon dioxide (CO_2) at the projected CO_2 removal efficiency of 60% for a 2.3 mm Hg pCO_2 in the ECSM Cathode Air Feed Stream.

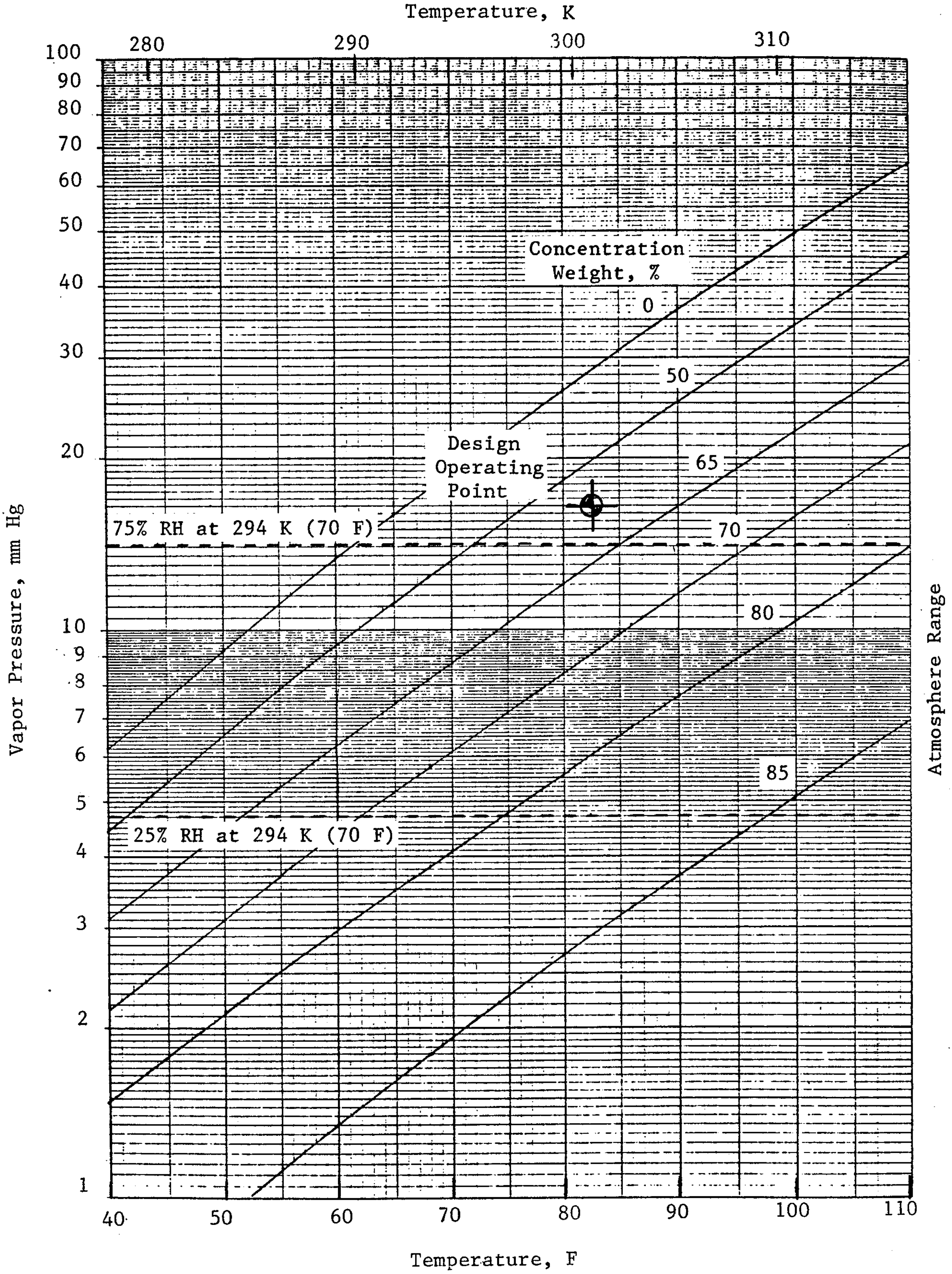

FIGURE 13 WATER VAPOR PRESSURE FOR AQUEOUS H_3PO_4

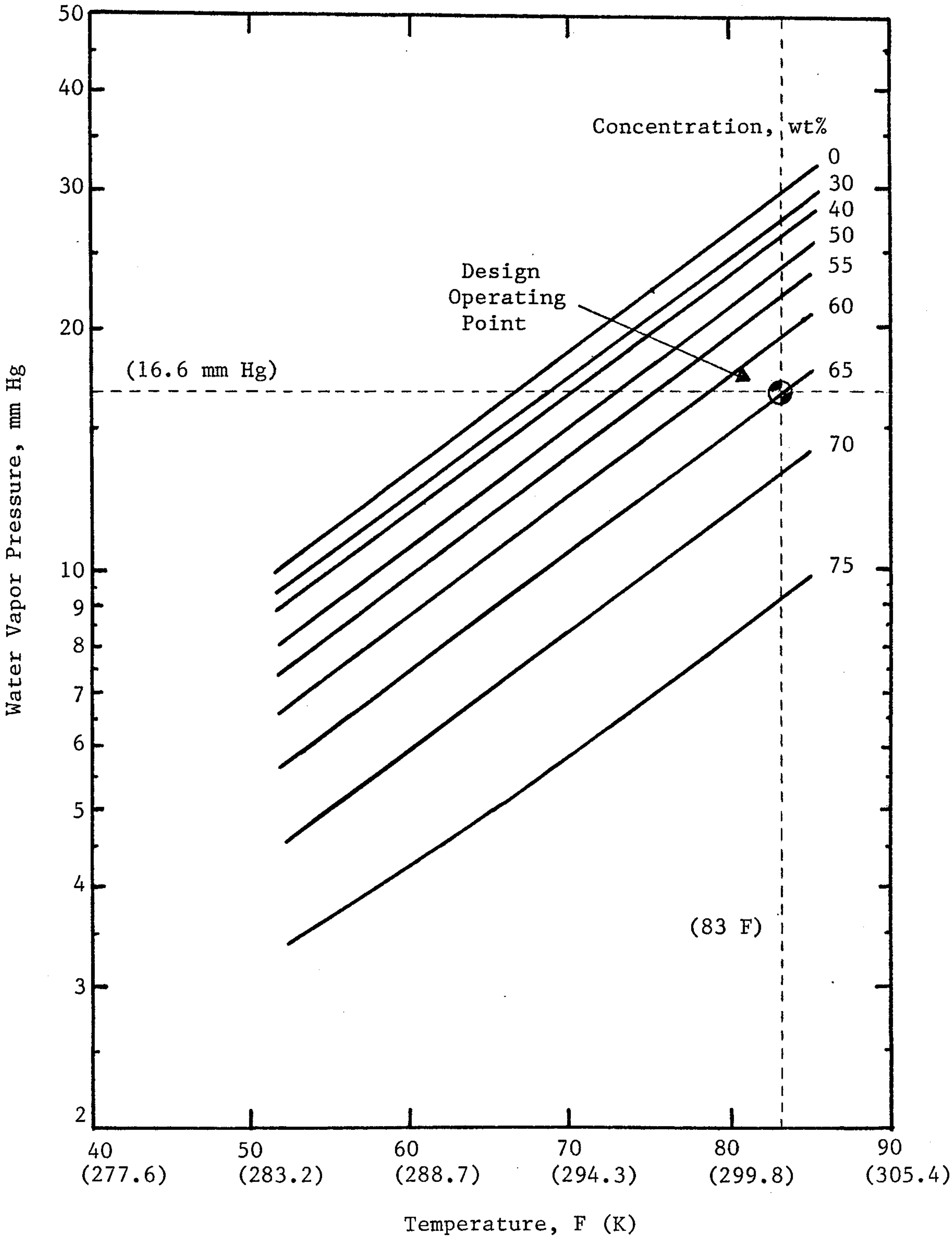

FIGURE 14 WATER VAPOR PRESSURE OF LSI-D ELECTROLYTE

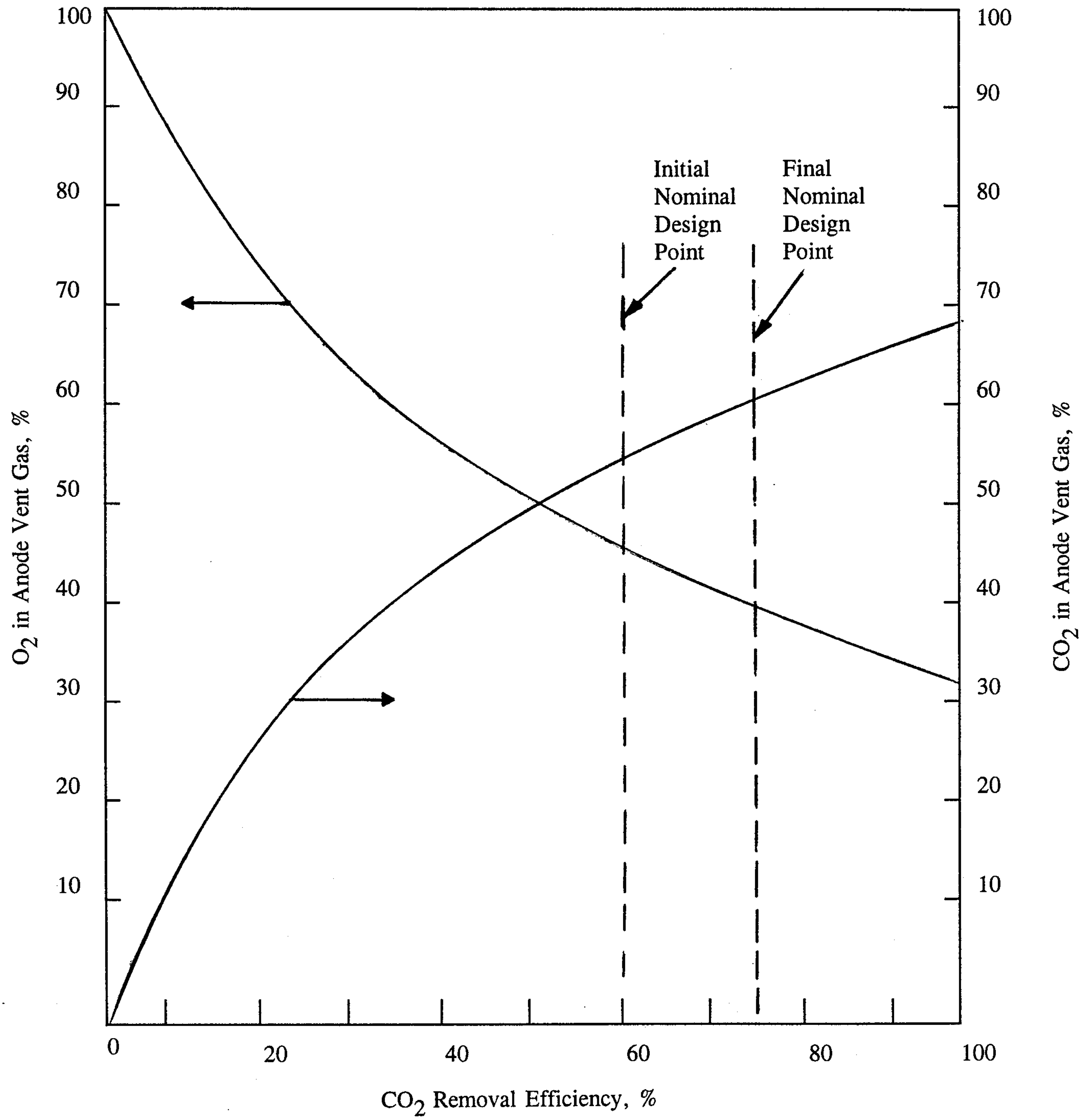

FIGURE 15 ECSM ANODE VENT GAS COMPOSITION AS A FUNCTION OF CO_2 REMOVAL EFFICIENCY

TABLE 5 FIVE-CELL CARBON DIOXIDE (CO_2) CONCENTRATING PROCESS

ECSM CO_2 Removal Efficiency, %	EOSM Cell Compartment[b]	Flow Rate, sccm O_2/CO_2[a]									
		Cell No. 1		Cell No. 2		Cell No. 3		Cell No. 4		Cell No. 5	
		In	Out	In	Out	In	Out	In	Out	In	Out
0	C	140/0	119/0	119/0	98/0	98/0	77/0	77/0	56/0	56/0	35/0
	A	0/0	21/0	21/0	42/0	42/0	63/0	63/0	84/0	84/0	105/0
20	C	110/57	119/57	119/57	98/57	98/57	77/57	77/57	56/57	56/57	35/57
	A	0/0	21/0	21/0	42/0	42/0	63/0	63/0	84/0	84/0	105/0
40	C	140/110	119/110	119/110	98/110	98/110	77/110	77/110	56/110	56/110	35/110
	A	0/0	21/0	21/0	42/0	42/0	63/0	63/0	84/0	84/0	105/0
60	C	140/170	119/170	119/170	98/170	98/170	77/170	77/170	56/170	56/170	35/170
	A	0/0	21/0	21/0	42/0	42/0	63/0	63/0	84/0	84/0	105/0
80	C	140/228	119/228	119/228	98/228	98/228	77/228	77/228	56/228	56/228	35/228
	A	0/0	21/0	21/0	42/0	42/0	63/0	63/0	84/0	84/0	105/0
100	C	140/284	119/284	119/284	98/284	98/284	77/284	77/284	56/284	56/284	35/284
	A	0/0	21/0	21/0	42/0	42/0	63/0	63/0	84/0	84/0	105/0

(a) For a current of 8A through the ECSM and 6A through the EOSM.
(b) C = Cathode Compartment, A = Anode Compartment.

removal efficiencies. This table was prepared for the initial nominal current levels of 6.0 Amps and 8.0 Amps for the EOSM and ECSM, respectively. These current levels were selected from previous data[3,4].

The nominal inlet air relative humidity for the ECSM was selected to be 64%, representative of a dry bulb temperature of 75 F and a dewpoint temperature of 63 F, as indicated on Figure 16. To control the module temperatures, a requirement of 50 lb/hr of 82 F liquid (water) coolant was calculated and was supplied by the test stands to each of the two modules.

Electrochemical O_2 Separation Testing

Using the previously established test operating conditions (see Table 3) a test sequence was defined and testing of the EOSM completed.

EOSM Test Sequence

The test sequence established and completed for the EOSM was as follows:

1. Checkout testing
2. Shakedown testing
3. Design verification testing
4. Parametric testing

The various parameter ranges of cathode feed, currents and coolant flows and remarks for these four test phases are shown in Appendix A, Tables A-1 through A-4, respectively. A data sheet for the EOSM testing was prepared for the four test phases and is shown in Appendix B, Figure B-1.

EOSM Test Results

Test results for the individual EOSM testing are shown in Figures 17 through 20. These results were also compared to past test data obtained with a two cell module.[3,5] These comparisons are plotted in Figures 21 and 22. The nominal operating condition for the EOSM are indicated on each of the figures. The results compare well with the previous data, indicating that scaling to the five-cell module level did not cause loss in performance.

The EOSM data was analyzed and reduced. The analysis concentrated on identifying any changes in nominal operating conditions for integrated APC operation. Slight changes in module temperature levels, dewpoints and ECSM electrolyte concentration resulted to allow for a closer match for integrated operation. The changes are discussed in the next section under ECS Testing.

Two other aspects of EOSM operation were analyzed due to their importance with respect to future integrated system operation and efficient performance. These parameters are

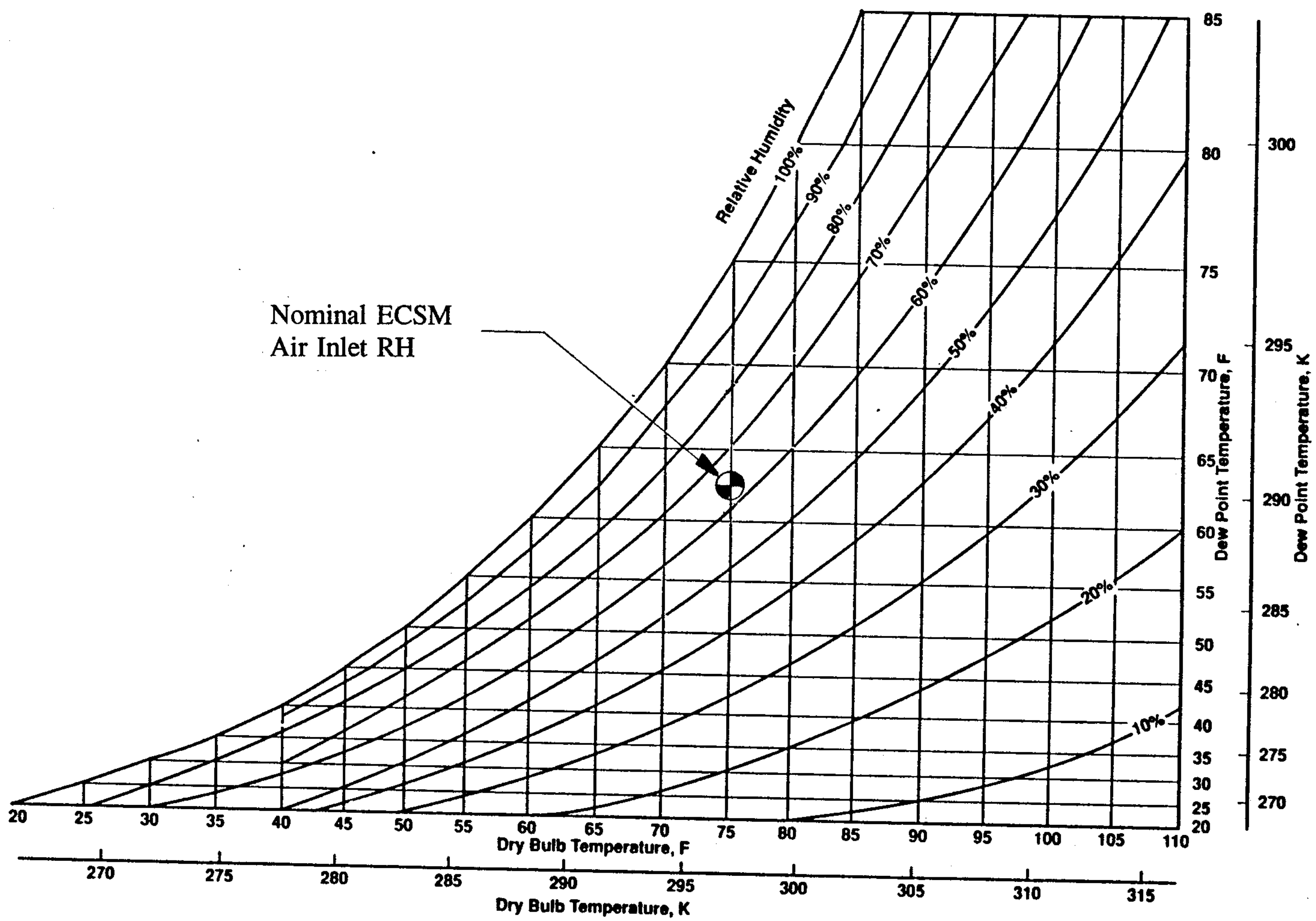

FIGURE 16 NOMINAL INLET AIR HUMIDITY CONDITIONS USED FOR APC TESTS

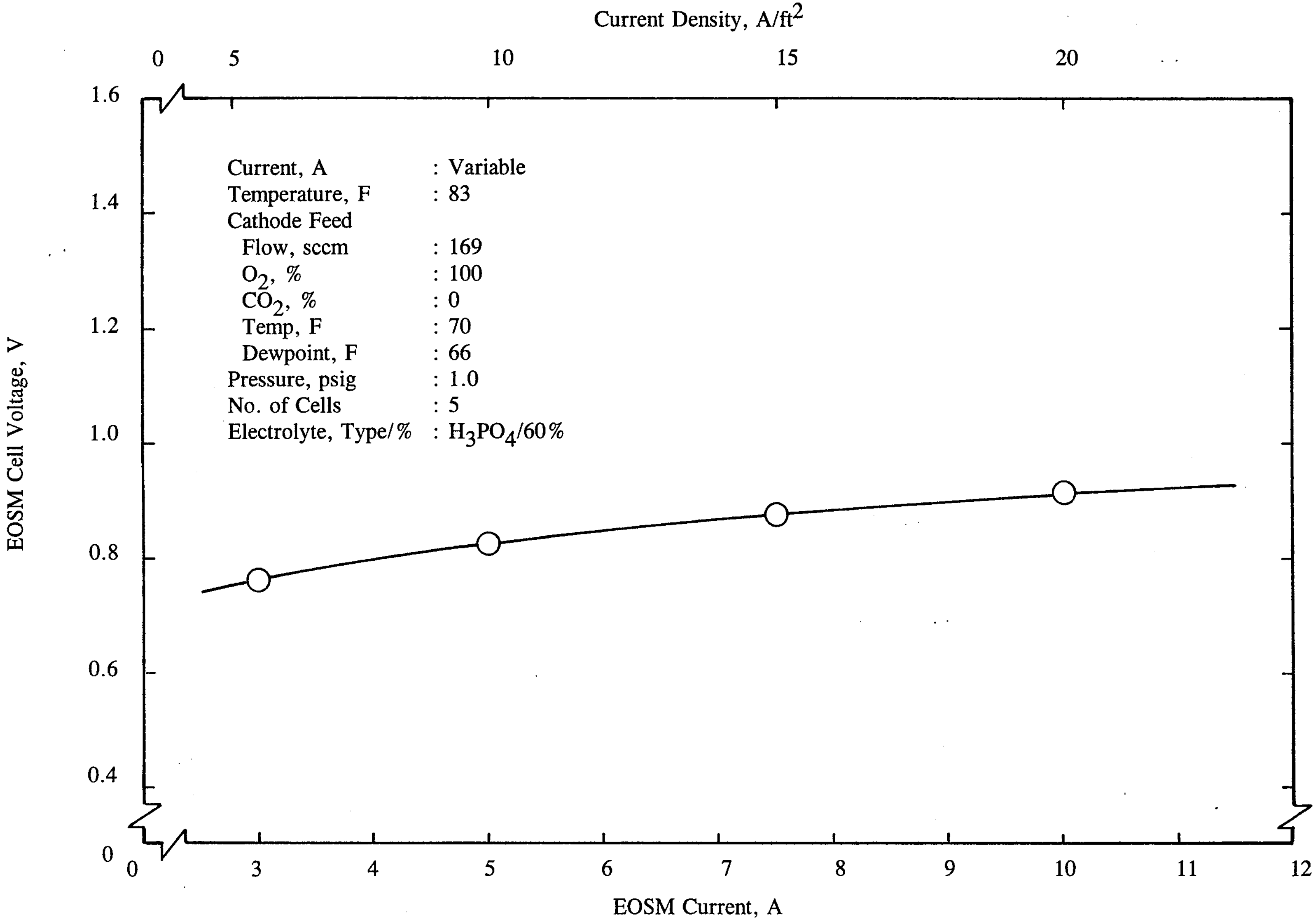

FIGURE 17 EFFECT OF CURRENT ON EOSM CELL VOLTAGE WITH PURE O_2 FEED

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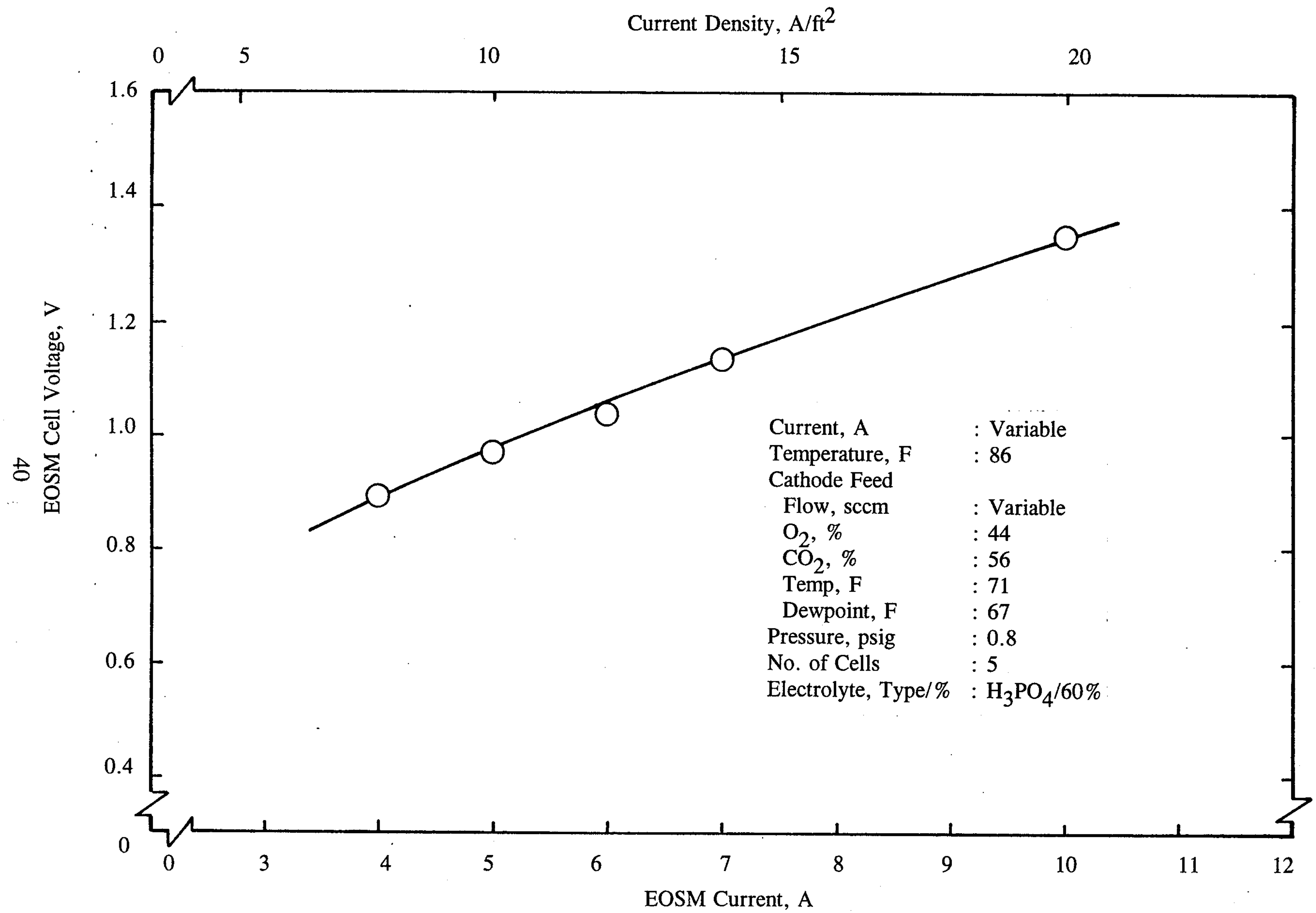

FIGURE 18 EFFECT OF CURRENT ON EOSM CELL VOLTAGE WITH 54±2% CO_2 IN FEED

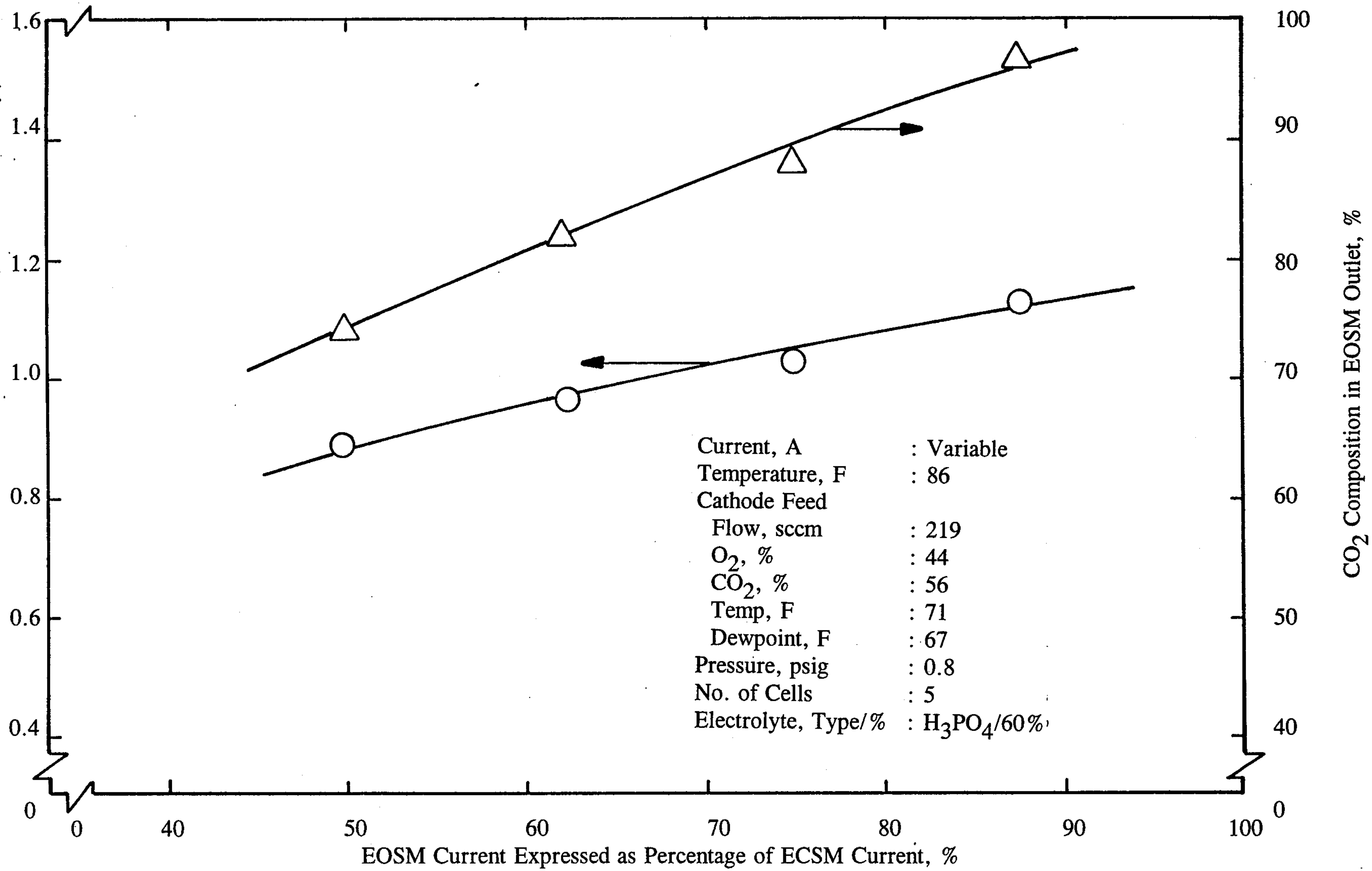

FIGURE 19 EOSM CELL VOLTAGE AND CO_2 COMPOSITION IN THE EOSM OUTLET VERSUS EOSM TO ECSM CURRENT PERCENTAGE

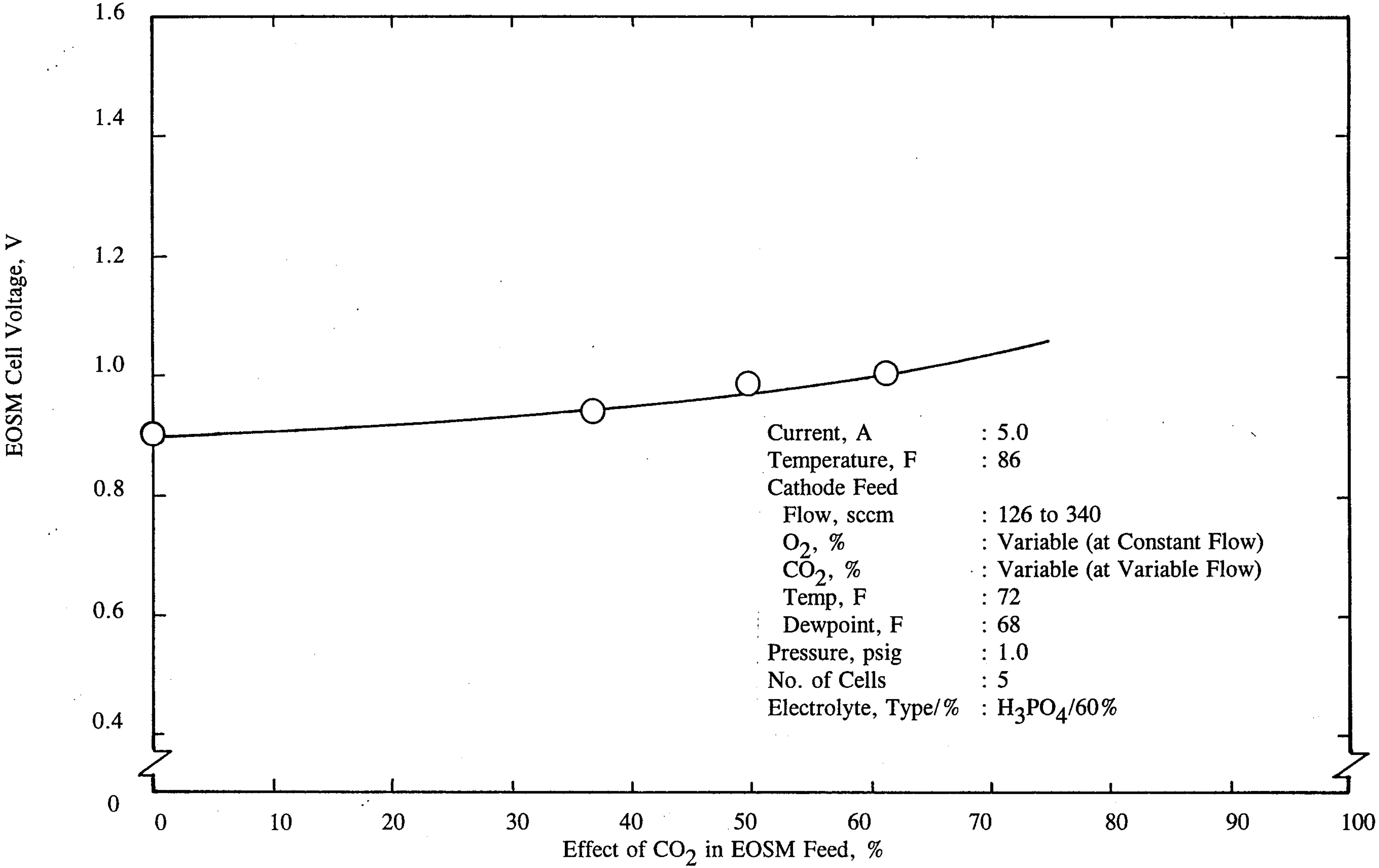

FIGURE 20 EFFECT OF VARIABLE CO_2 IN EOSM FEED STREAM ON EOSM CELL VOLTAGE

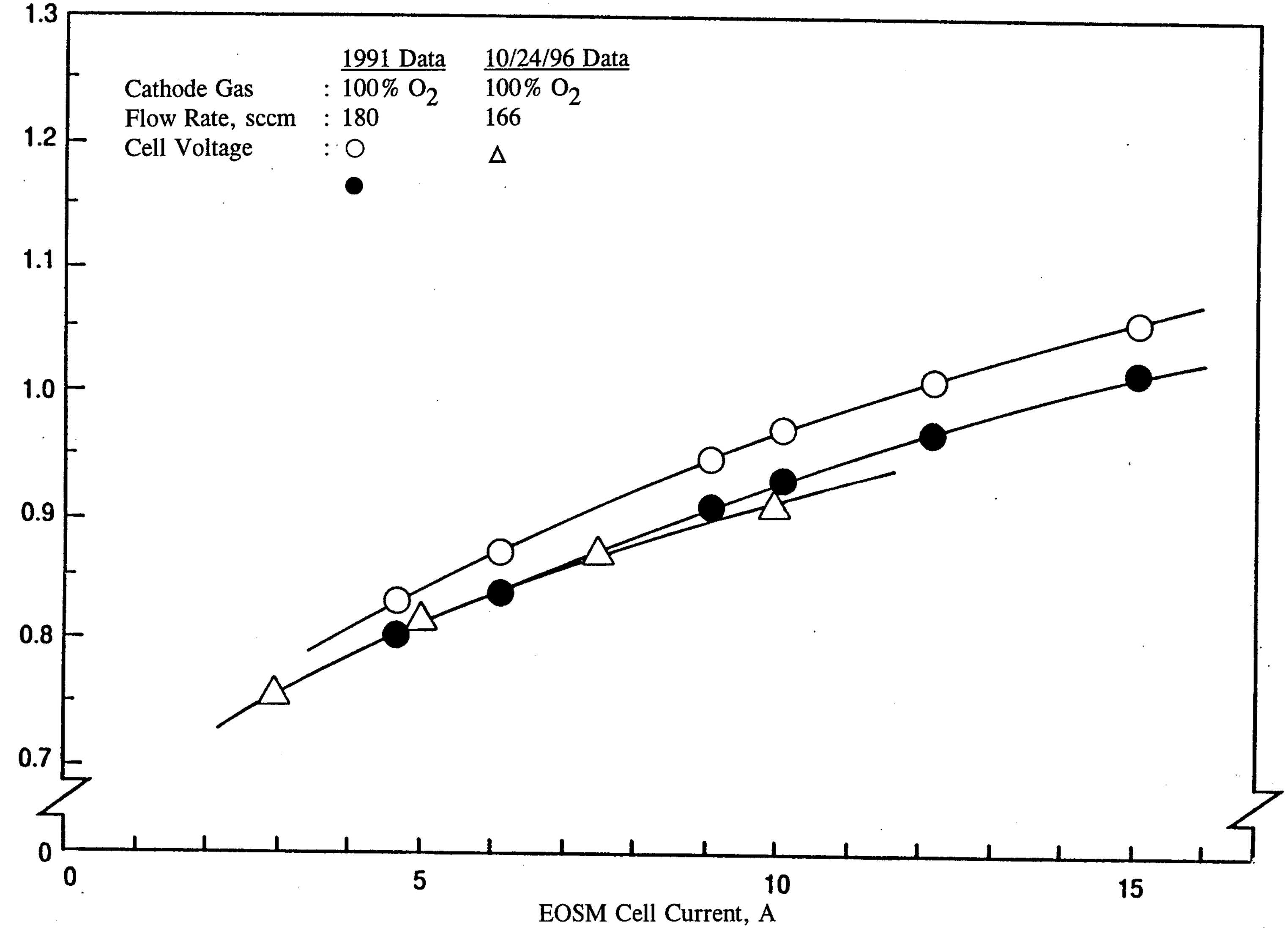

FIGURE 21 COMPARISON OF EFFECT OF CELL CURRENT ON EOSM CELL VOLTAGE WITH PURE O_2 WITH PREVIOUS DATA

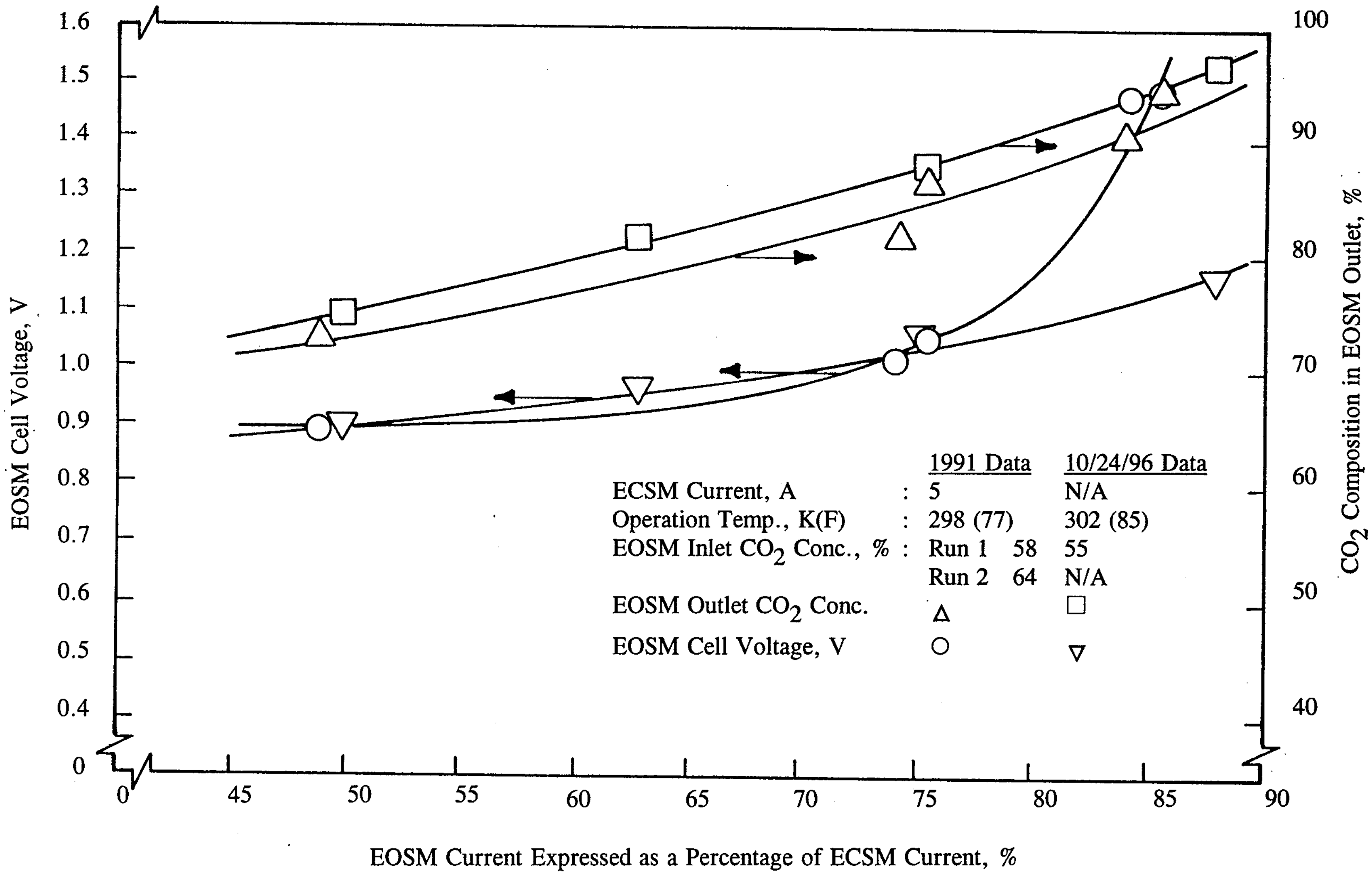

FIGURE 22 COMPARISON OF EOSM CELL VOLTAGE AND CO_2 COMPOSITION IN THE EOSM OUTLET VERSUS EOSM CURRENT WITH PREVIOUS DATA

electrochemical current efficiency of the EOSM, i.e., the amount of O_2 transferred on a per coulomb basis as well as the lowest stoichiometric level of cathode feed gas that can be sustained. The latter defines how much of the O_2 contained in the O_2 and CO_2 mixture can be removed by the EOSM resulting in the lowest remaining O_2 to be fed to a CO_2 reduction process, i.e., a Sabatier or Bosch, where the O_2 would combine with H_2 to form water for re-electrolization.

A 100% O_2 theoretical transfer efficiency is equal to 3.48 standard (at 32 F, 760 mm Hg) cm^3/min of O_2 for each cell-ampere flowing. For example, for a five-cell module operating at 8 A the theoretical anode output in O_2 is equivalent to 139.2 standard cm^3 of O_2/min. Based on this calculation, all data points accumulated during the EOSM operation were reduced resulting in a range of O_2 transfer efficiencies from 93.4 to 102.3%. The average transfer efficiency for all data points was 99.8%. Based on these actual test results, within the accuracy of the measuring instrumentation, a 99.5% transfer efficiency will be assumed in future EOSM sizing of an integrated APC.

During the current density spans, while operating with 54±2% of CO_2 in the cathode feed, the stoichiometry of the feed gas was varied from 2.54 to 1.02. A stoichiometric feed value of 1.00 would result theoretically in all of the O_2 supplied to the cathode compartments being transferred to the anode compartments of an EOSM. For a stoichiometric feed value of 1.00 no O_2 would be left in the cathode exhaust gas. A goal in APC operation is to have as little as possible O_2 left, meaning operation close to a 1.00 stoichiometric feed rate is desirable. Actual operation at a 1.02 stoichiometric feed rate was achieved with steady conditions indicating that efficient gas mixing and flow distribution occurred within the five serially connected EOSM cells. A conservative value of 1.05 (95% of all O_2 fed to the EOSM will be transferred back to the atmosphere) was selected for integrated APC sizing.

The five-cell EOSM module was disassembled for visual inspection to see if any anomalies had resulted from the test phase completed. No unusual observations were made and the module was reassembled for integrated APC testing.

Electrochemical CO_2 Separation Testing

Test conditions for the ECSM testing were evaluated and adjusted as required, based on EOSM testing. A test sequence was defined and testing of the five-cell ECSM was completed.

ECSM Test Condition Verification

Based on the EOSM test results, slight adjustments to the nominal operating conditions previously shown in Tables 3 and 4 were made. These new conditions are represented in Tables 6 and 7, for the ECSM and EOSM, respectively. The differences are minor reflected in a decrease in module nominal operating temperatures for both modules from 83 to 80 F and a lowering of the cathode gas nominal inlet dewpoint to the EOSM from 67 to 63 F. These adjustments were made to match the characteristics of the anode vent gas of the ECSM

TABLE 6 FIVE-CELL ELECTROCHEMICAL CARBON DIOXIDE SEPARATION MODULE (ECSM) OPERATING PARAMETERS

	Nominal
Current, A	8.0
Module Temp, F	80
Cathode Air	
Flow Rate, ACFM	15[(a)]
pCO_2, mm Hg	2.3
Pressure, psia	15
Temperature, F	75
Dewpoint, F	63
RH, %	64
Coolant	
Flow Rate, lb/hr	50
Temperature, F	80
Anode Vent	
Pressure, psig	1.0
O_2 Flow, sccm	140
CO_2 Flow, sccm	171[(b)]

(a) Nominal range of 12 to 18 ACFM.
(b) A total of 171 sccm carbon dioxide (CO_2) at the projected CO_2 removal efficiency of 60% for a 2.3 mm Hg pCO_2 in the ECSM Cathode Air Feed Stream.

TABLE 7 FIVE-CELL ELECTROCHEMICAL OXYGEN SEPARATION MODULE (EOSM) OPERATING PARAMETERS

	Nominal
Current	
Level, A	6.0
% of ECSM, %	75
Module Temp, F	80
Cathode Feed	
Flow Rate, sccm	311
Composition, % O_2/% CO_2	45/55[a]
Stoichiometric Ratio	1.33
Temperature, F	72
Dewpoint, F	63
Pressure (outlet), psig	1.0
Coolant	
Flow Rate, lb/hr	50
Temperature, F	80
Anode Vent Pressure, psig	0

(a) Equivalent to 60% Electrochemical Carbon Dioxide Separation Module (ECSM) carbon dioxide (CO_2) removal efficiency at 2.3 mm Hg pCO_2 in air feed stream (140 sccm of oxygen (O_2) and 171 sccm CO_2).

with its 65% w/w electrolyte cell core concentration. Initially a 56% w/w LSI-D electrolyte concentration was contemplated, but based on the EOSM performance a higher ECSM electrolyte concentration was selected as a better match. The nominal inlet air humidity conditions to be used for the ECSM and integrated APC testing remain the same as was shown in Figure 16. The air flowrate through the ECSM was adjusted from a nominal 9 ACFM to 15±3 ACFM to allow for better (more constant) test stand air flow control.

ECSM Test Sequence

The test sequence established and completed for the ECSM and used was as follows:

1. Checkout testing
2. Shakedown testing
3. Design verification testing
4. Parametric testing

The various parameter ranges of cathode feed air, current levels and coolant flows and remarks for these four test phases are shown in Appendix A, Tables A-5 through A-8, respectively. A two page set of data sheets used for the ECSM testing was prepared for the four test phases. The data sheets are shown in Appendix B, Figure B-2.

ECSM Test Results

Test results for the ECSM testing are shown in Figures 23 through 31. These results were also compared to past test data obtained with a two cell module.[3,5] This comparison is plotted in Figure 32. The operating condition for the ECSM are indicated on each plot. As can be seen from Figure 32, the present results compare well with past performance, indicating that scaling to the approximately one person, five-cell module did not adversely affect performance.

Effects of Module Current Density. The effects of current density over the range of 6 to 20 ASF (3 to 10 A) were investigated for the ECSM for nominal inlet air pCO_2 values of 0.3 mm Hg, 1.25 mm Hg, 2.2 mm Hg and 3.6 mm Hg. Figures 23 through 26 show the effects of current density on average ECSM cell voltage for the four pCO_2 levels listed above. As expected, cell voltage increases with increasing current density resulting in higher power consumption at higher currents. Also, a slight decreasing effect in average ECSM cell voltage is observed with increasing pCO_2. These results are similar to those typically observed with electrochemical CO_2 removal cells.

Figures 27 through 30 show the effect of current density over the same current ranges and the other key parameter of ECSM operation i.e., CO_2 removal efficiency. Historically[1,3,7] CO_2 removal efficiency reaches a peak value from 15 to 25 ASF. The same results were observed at each of the four pCO_2 levels tested. A sharper drop off at lower current densities in CO_2 removal efficiencies compared to those observed with an EDC were experienced with

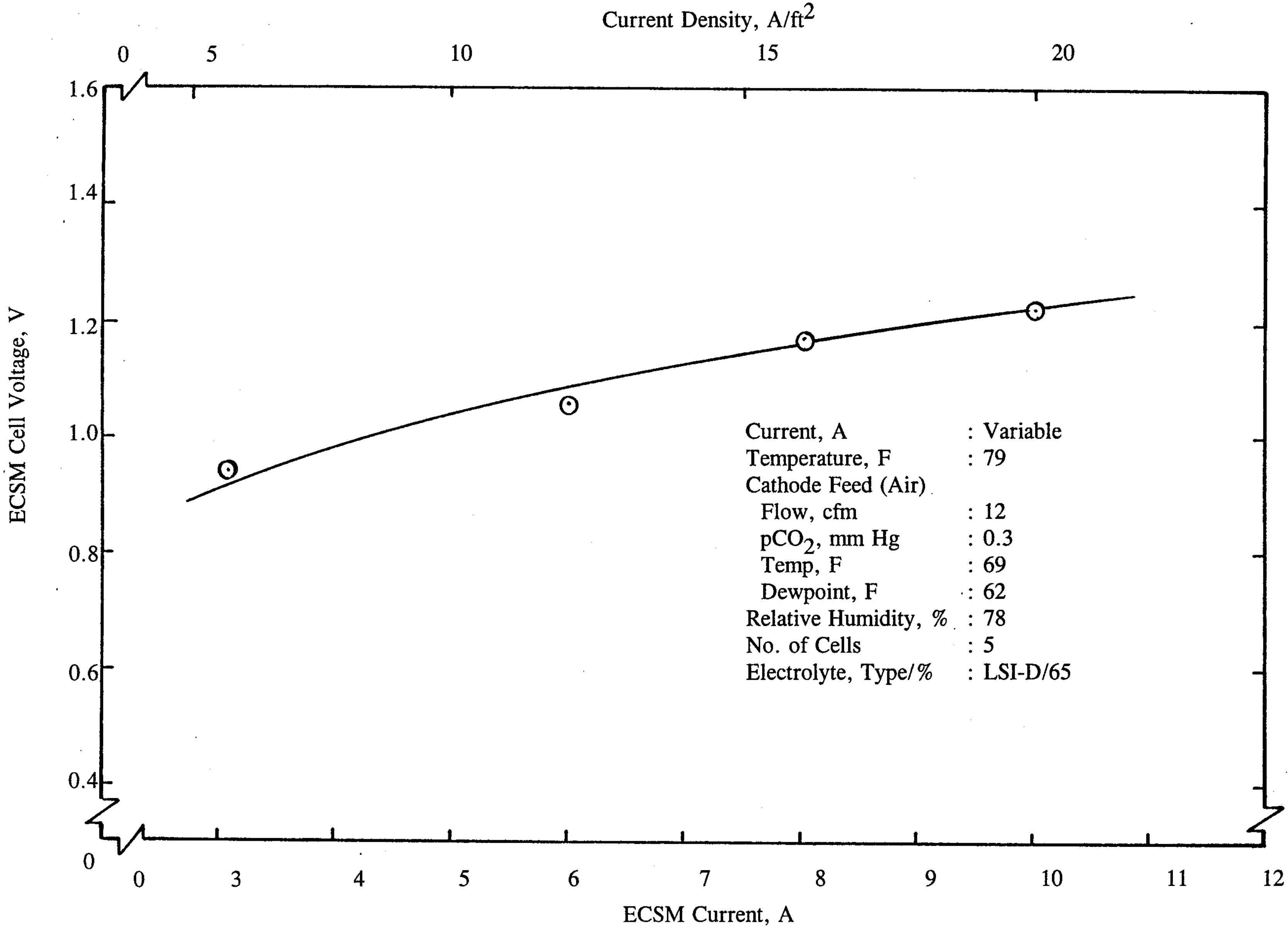

FIGURE 23 EFFECT OF CURRENT ON ECSM CELL VOLTAGE (AIR INLET pCO_2 - 0.3 mm Hg)

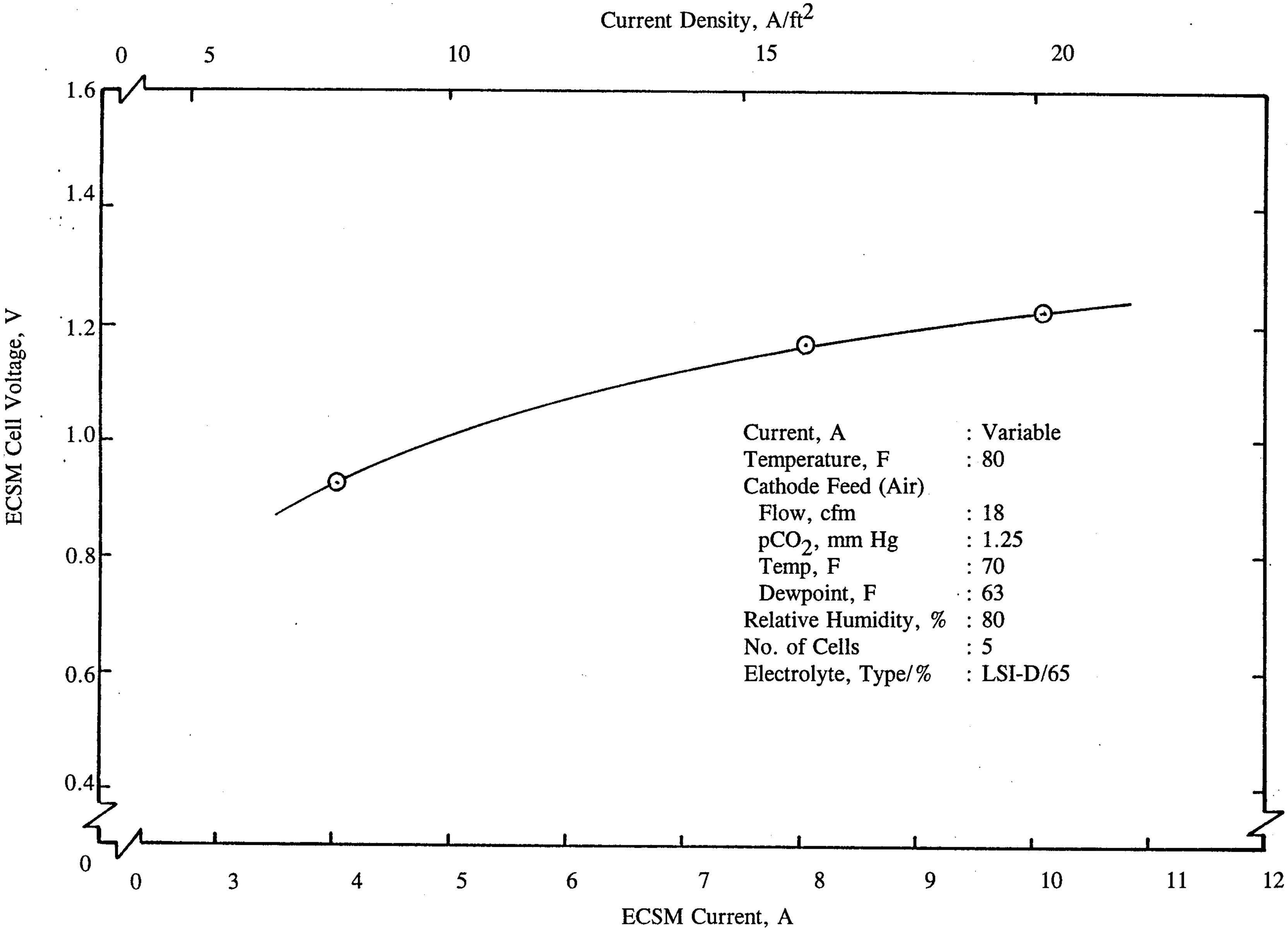

FIGURE 24 EFFECT OF CURRENT ON ECSM CELL VOLTAGE (AIR INLET pCO_2 - 1.25 mm Hg)

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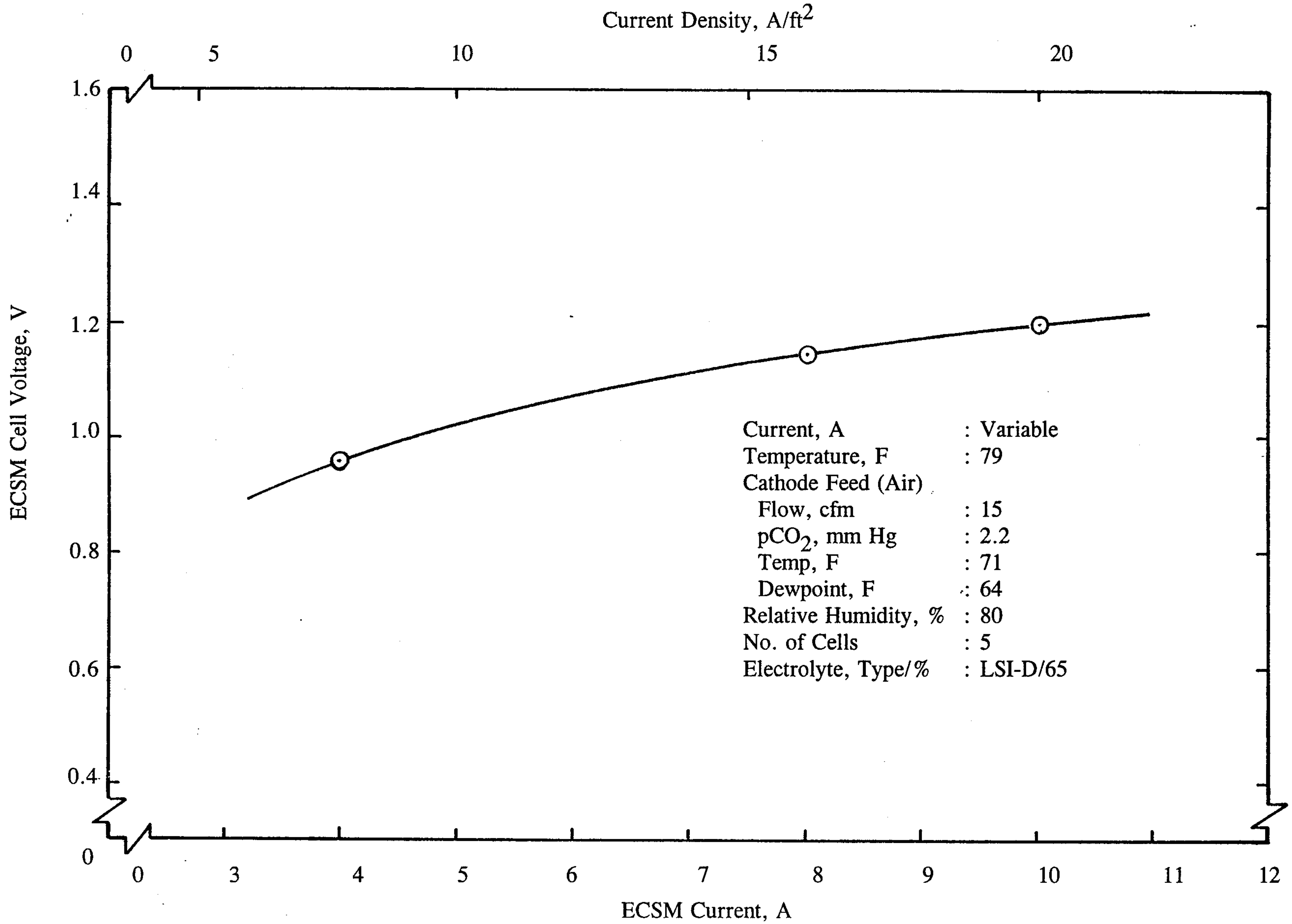

FIGURE 25 EFFECT OF CURRENT ON ECSM CELL VOLTAGE (AIR INLET pCO_2 - 2.2 mm Hg)

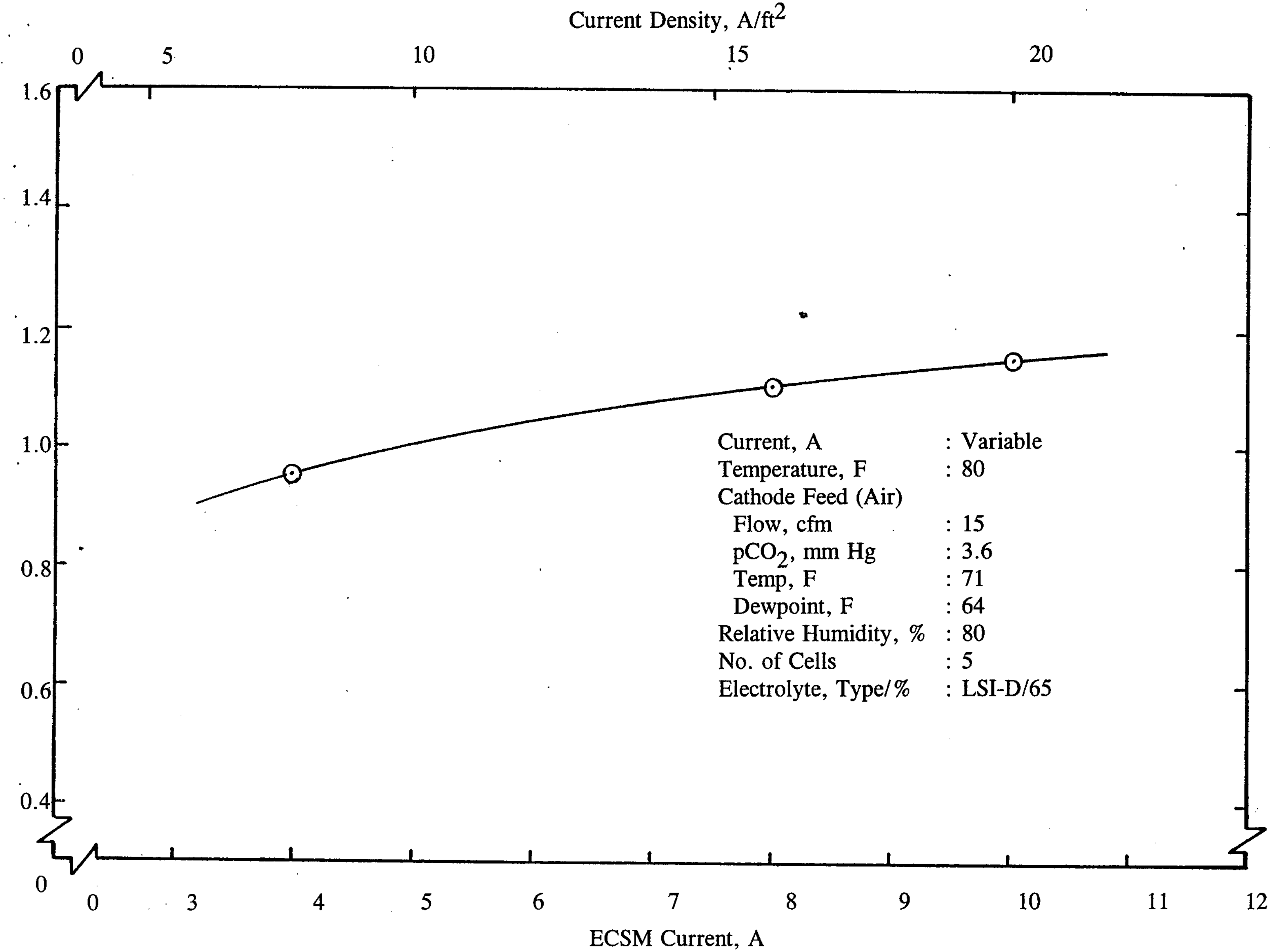

FIGURE 26 EFFECT OF CURRENT ON ECSM CELL VOLTAGE (AIR INLET pCO_2 - 3.6 mm Hg)

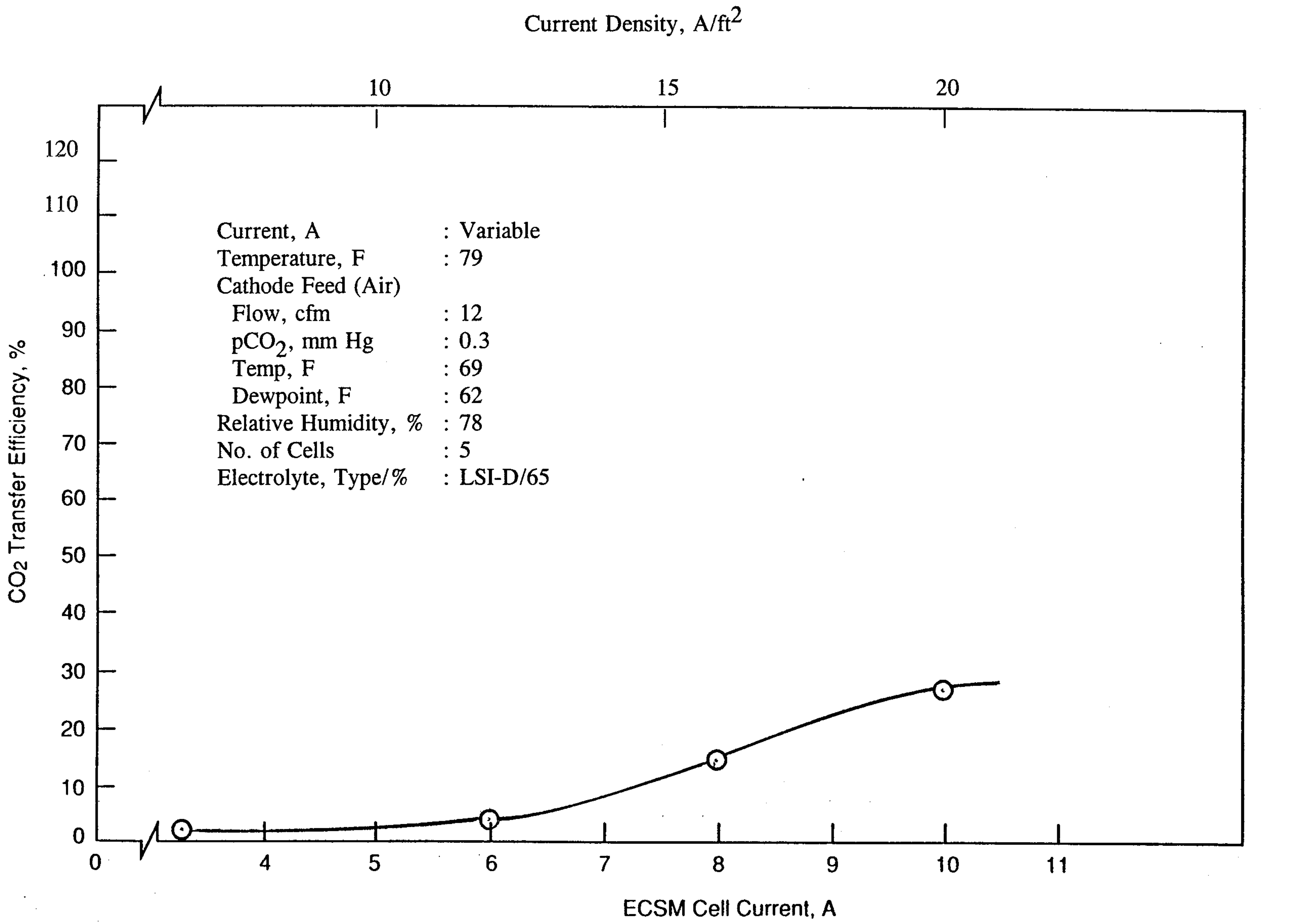

FIGURE 27 EFFECT OF CURRENT ON ECSM CO_2 TRANSFER EFFICIENCY (AIR INLET pCO_2 - 0.3 mm Hg)

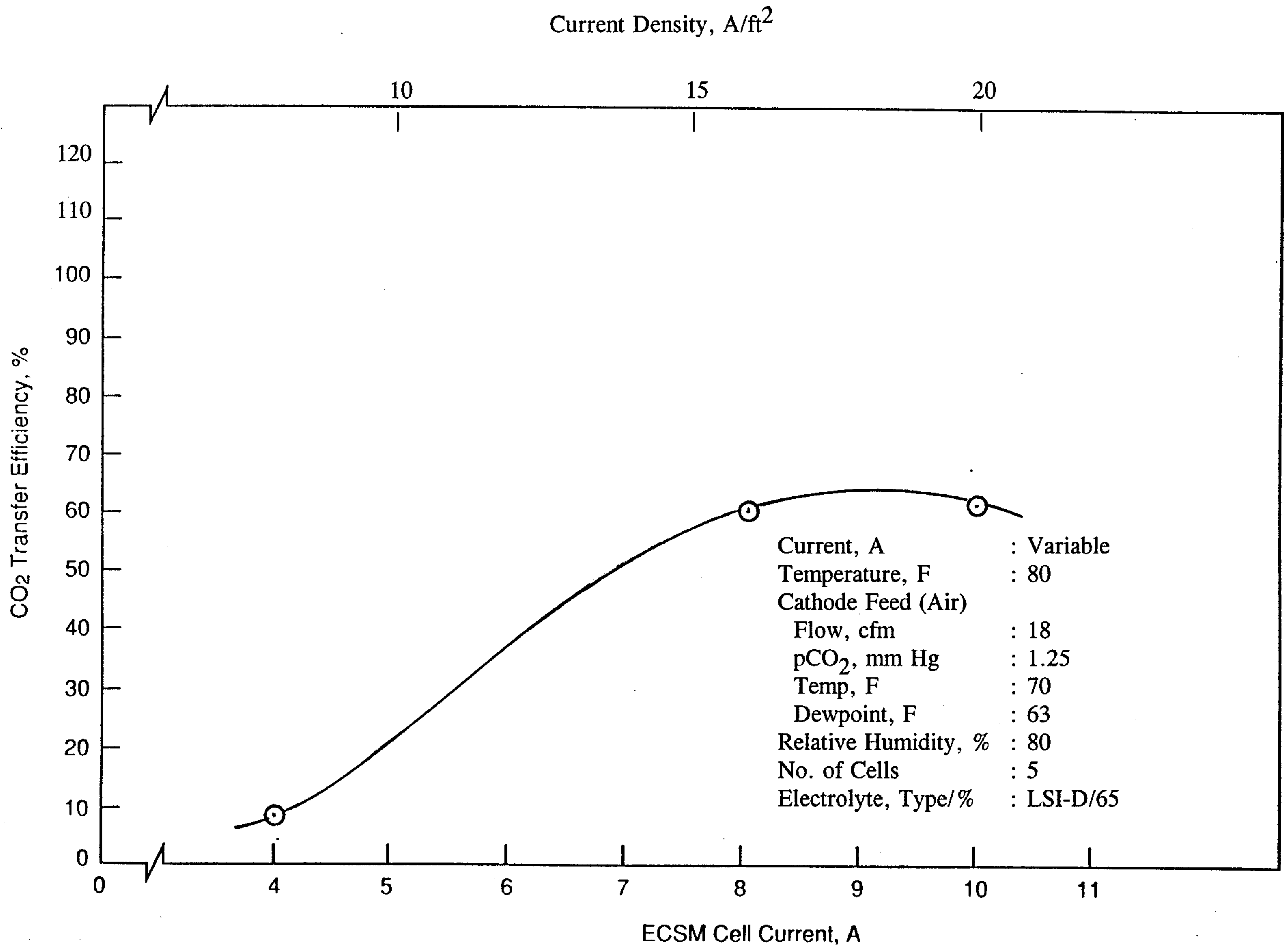

FIGURE 28 EFFECT OF CURRENT ON ECSM CO_2 TRANSFER EFFICIENCY (AIR INLET pCO_2 - 1.25 mm Hg)

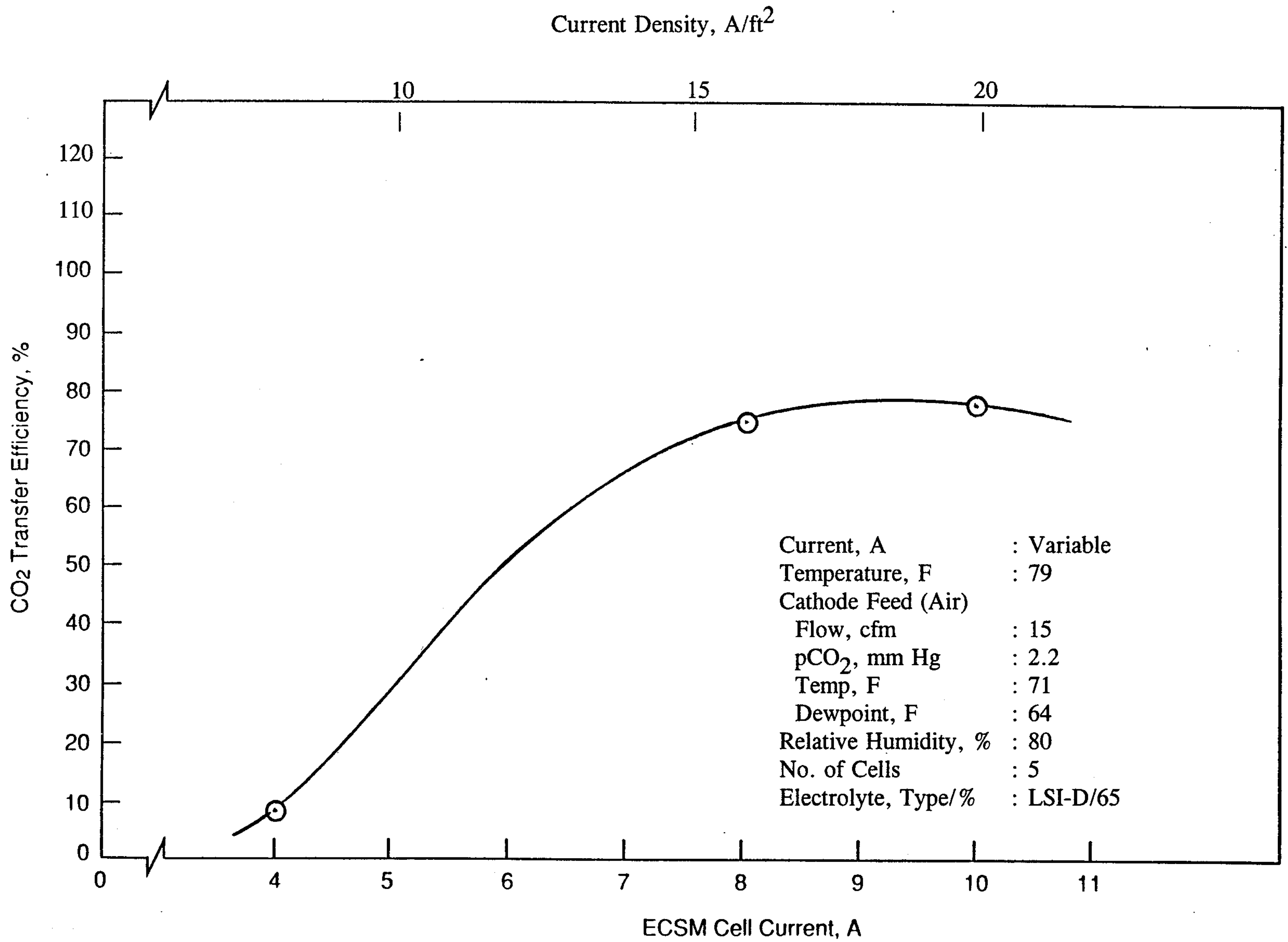

FIGURE 29 EFFECT OF CURRENT ON ECSM CO_2 TRANSFER EFFICIENCY (AIR INLET pCO_2 - 2.2 mm Hg)

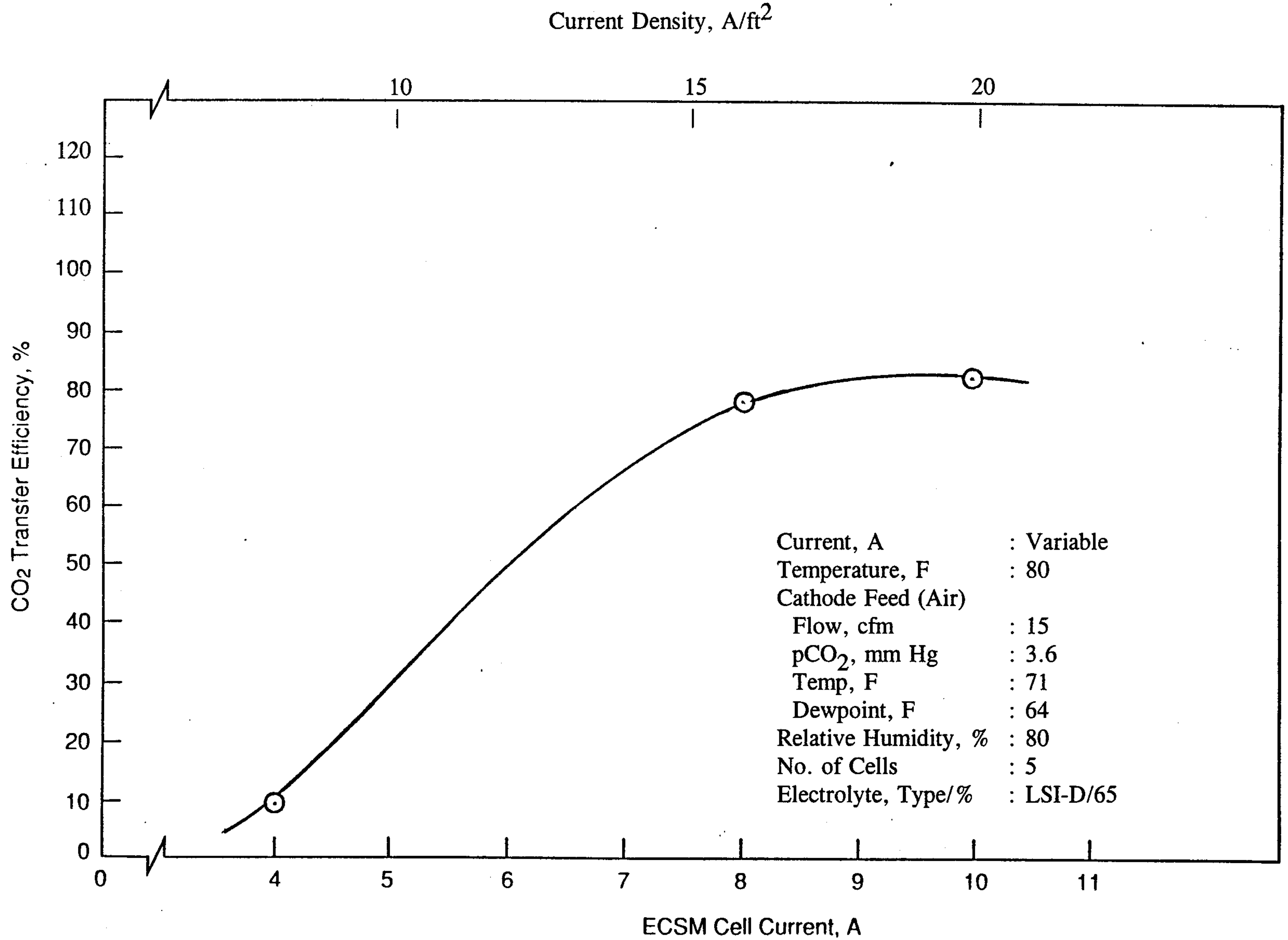

FIGURE 30 EFFECT OF CURRENT ON ECSM CO_2 TRANSFER EFFICIENCY (AIR INLET pCO_2 - 3.6 mm Hg)

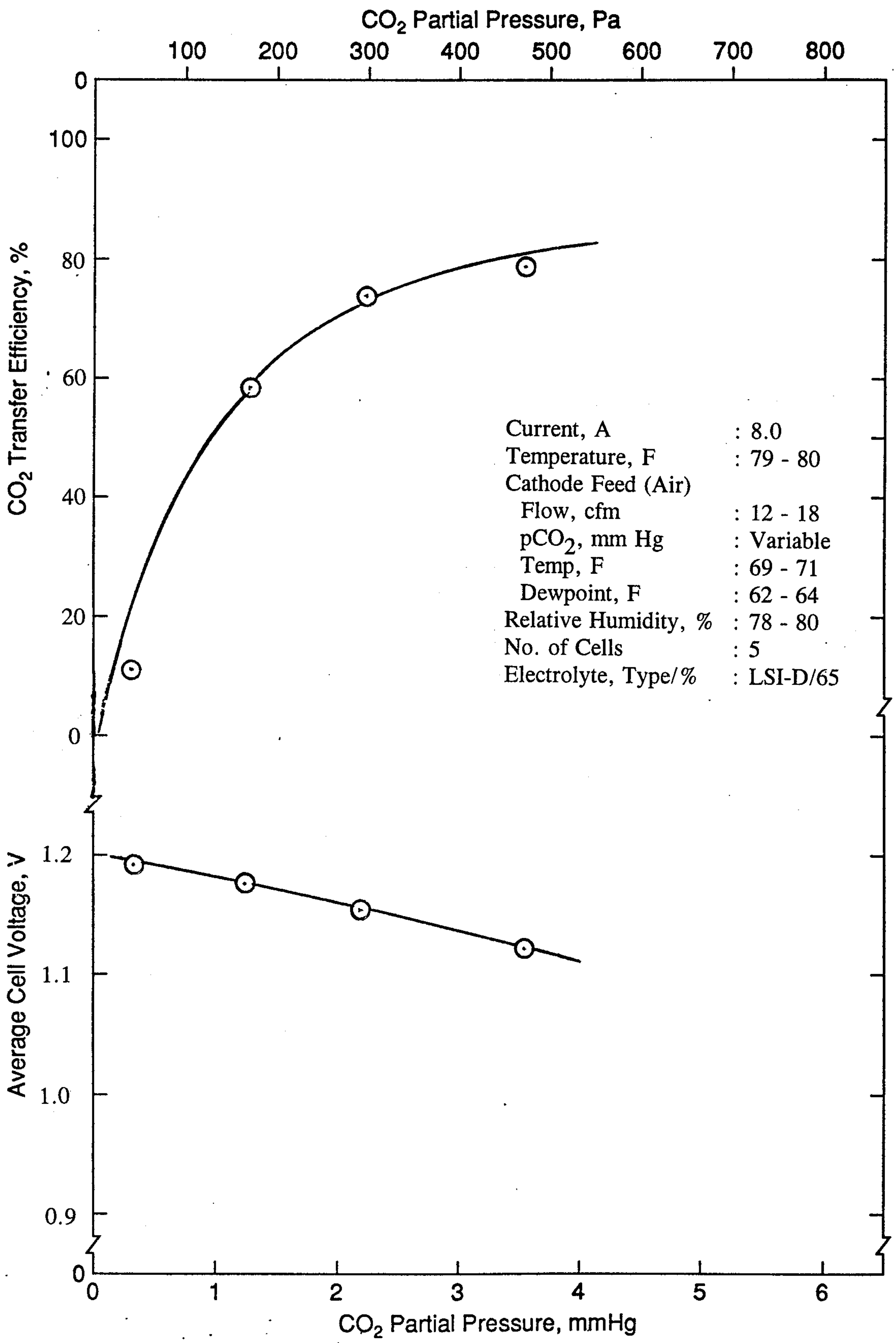

FIGURE 31 ECSM CELL VOLTAGE AND CO_2 TRANSFER EFFICIENCY VERSUS INLET AIR pCO_2 AT NOMINAL CELL CURRENT OF 8.0 A

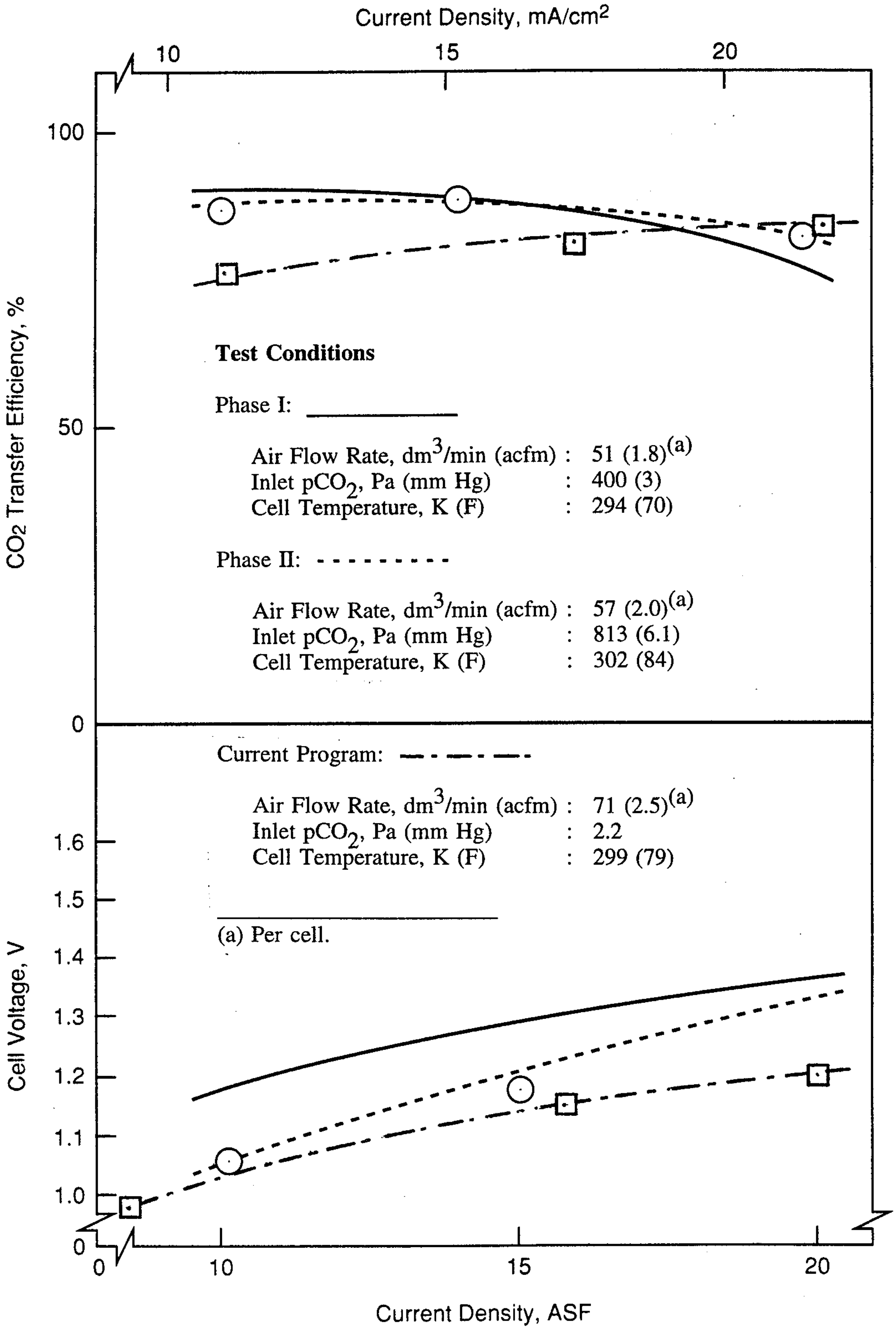

FIGURE 32 COMPARISON OF ECSM CELL VOLTAGE AND CO_2 TRANSFER EFFICIENCY VERSUS CURRENT DENSITY WITH PAST DATA

an ECSM. Overall system sizing and final operating condition selection will be influenced by this observation.

Effects of ECSM Inlet Air pCO_2. The data obtained during the current density span testing was cross plotted at 8 A to determine the effects of pCO_2 on the key parameters of an ECSM: CO_2 transfer efficiency and average cell voltage. Figure 31 shows these key ECSM parameters versus pCO_2 in the cathode feed air. As expected, CO_2 transfer efficiency is a strong function of air inlet pCO_2, but achieves a near constant value at and beyond the 2 mm Hg pCO_2 level. The shape and levels observed compare well with historical data for electrochemical CO_2 removal systems.[3]

Cell voltage is a weak function of inlet air pCO_2 as shown in the lower part of Figure 31. Historically, a slight decrease in cell voltage with increasing pCO_2 has been observed. The current data shows this trend. Voltage levels are consistent with past data obtained for the test conditions shown for H_2-less electrochemical CO_2 removal cells.[3,5]

Integrated APC Testing

Based on an analysis of the ECSM and EOSM test results, the operating conditions for both modules were re-evaluated to identify if any final adjustments were required for integrated APC Testing. The APC test sequence was then established, all APC testing completed and the results analyzed. A summary of characteristics for APC sizing was prepared.

Adjustment of Test Conditions

Based on the ECSM test results, only slight adjustments to the nominal operating conditions were necessary. These final conditions are shown in Tables 8 and 9 for the ECSM and EOSM, respectively. The differences are reflected in an increase in CO_2 in the effluent from the ECSM cathode compartments due to the higher CO_2 removal efficiencies achieved (nominal 75% versus 60%) for the properly tuned ECSM. A decrease in nominal air flow rate to 10±1 scfm (equivalent to 2 scfm per cell) was selected based on minor test stand modifications that allowed for better air flow control. Nominal air inlet relative humidity remained the same at 64%.

APC Test Sequence

The test sequence established and completed for the APC was as follows:

1. Checkout testing
2. Shakedown testing
3. Design verification testing
4. Parametric testing

The various parameter ranges of APC cathode feed air, CO_2 levels, current levels and coolant flows and remarks for these four test phases are shown in Appendix A, Tables A-9 through

TABLE 8 FIVE-CELL ELECTROCHEMICAL CARBON DIOXIDE SEPARATION MODULE (ECSM) OPERATING PARAMETERS

	Nominal
Current, A	8.0
Module Temp, F	80
Cathode Air	
Flow Rate, ACFM	10[(a)]
pCO_2, mm Hg	2.3
Pressure, psia	15
Temperature, F	75
Dewpoint, F	63
RH, %	64
Coolant	
Flow Rate, lb/hr	50
Temperature, F	80
Anode Vent	
Pressure, psig	1.0
O_2 Flow, sccm	140
CO_2 Flow, sccm	210[(b)]

(a) Nominal range of 9 to 11 ACFM.
(b) A total of 210 sccm carbon dioxide (CO_2) at the projected CO_2 removal efficiency of 75% for a 2.3 mm Hg pCO_2 in the ECSM Cathode Air Feed Stream.

TABLE 9 FIVE-CELL ELECTROCHEMICAL OXYGEN SEPARATION MODULE (EOSM) OPERATING PARAMETERS

	Nominal
Current	
Level, A	6.0
% of ECSM, %	75
Module Temp, F	80
Cathode Feed	
Flow Rate, sccm	350[a]
Composition, % O_2/% CO_2	40/60[b]
Stoichiometric Ratio	1.33
Temperature, F	72
Dewpoint, F	63
Pressure (outlet), psig	1.0
Coolant	
Flow Rate, lb/hr	50
Temperature, F	80
Anode Vent Pressure, psig	0

(a) Equivalent to 75% Electrochemical Carbon Dioxide Separation Module (ECSM) carbon dioxide (CO_2) removal efficiency at 2.3 mm Hg pCO_2 in air feed stream (140 sccm of oxygen (O_2) and 210 sccm CO_2).

A-12, respectively. A three page set of data sheets for the APC testing was prepared for the four test phases. The data sheets are shown in Appendix B, Figure B-3.

APC Test Results

Test results and/or conditions for the integrated APC testing are shown in Figures 33 through 40. The operating condition for the ECSM or EOSM of the integrated APC are indicated on each plot. Analysis and discussion of the APC test data obtained for variations in APC inlet air pCO_2, inlet air relative humidity and current densities (for both modules) are presented below.

Effects of APC Inlet Air pCO_2. The effects of the pCO_2 level of the inlet air supplied to the APC was investigated for four nominal values: 0.3 mm Hg (ambient air level), 1.0 mm Hg, 2.2 mm Hg and 3.0 mm Hg. All other parameters were held nominally at the values as reflected in Tables 8 and 9.

Figure 33 shows the key APC parameters, i.e., CO_2 transfer efficiency and average cell voltage of the ECSM versus the CO_2 partial pressure in the cathode feed air. As expected, CO_2 transfer efficiency is a strong function of inlet air pCO_2, but achieves a near constant value at and beyond the 1.0 mm Hg pCO_2 level. The shape and levels observed compare well with historical data for electrochemical CO_2 removal systems.[3]

Cell voltage is a very weak function of inlet air pCO_2, as shown in the lower part of Figure 33. Historically, a slight decrease in cell voltage with increasing pCO_2 has been observed. The current data shows this trend beyond the 2.0 mm pCO_2 level. Voltage levels are consistent with past data obtained for the test conditions shown and for H_2-less electrochemical CO_2 removal cells.[3,5]

Effects of APC Inlet Air Relative Humidity. Three regions of inlet relative humidity of the process air were explored: (1) Above i.e., slightly wetter, than the nominal ECSM air inlet humidity range; (2) hot and dry; and (3) cold and dry. The latter two are the more difficult inlet relative humidities to accommodate and therefore were chosen to challenge the integrated APC. Figure 34 shows these three regions, indicated by shaded areas, together with the nominal ECSM air inlet relative humidity point.

Figure 35 plots CO_2 transfer efficiency as a function of air inlet relative humidity over a 40 to 80% range. The figure indicates, by vertical bars, the general range in CO_2 removal efficiencies achieved. A trend of a slight increase in CO_2 transfer efficiency with increasing relative humidity is noted. This slight increase is due to the generally higher operating temperatures characteristic of the higher RH values chosen.

Similarly, ECSM average cell voltage as a function of inlet air relative humidity is plotted in Figure 36. As expected, a slight decrease in cell voltage is observed at the higher relative humidity values, again, due to the typically higher module operating temperatures

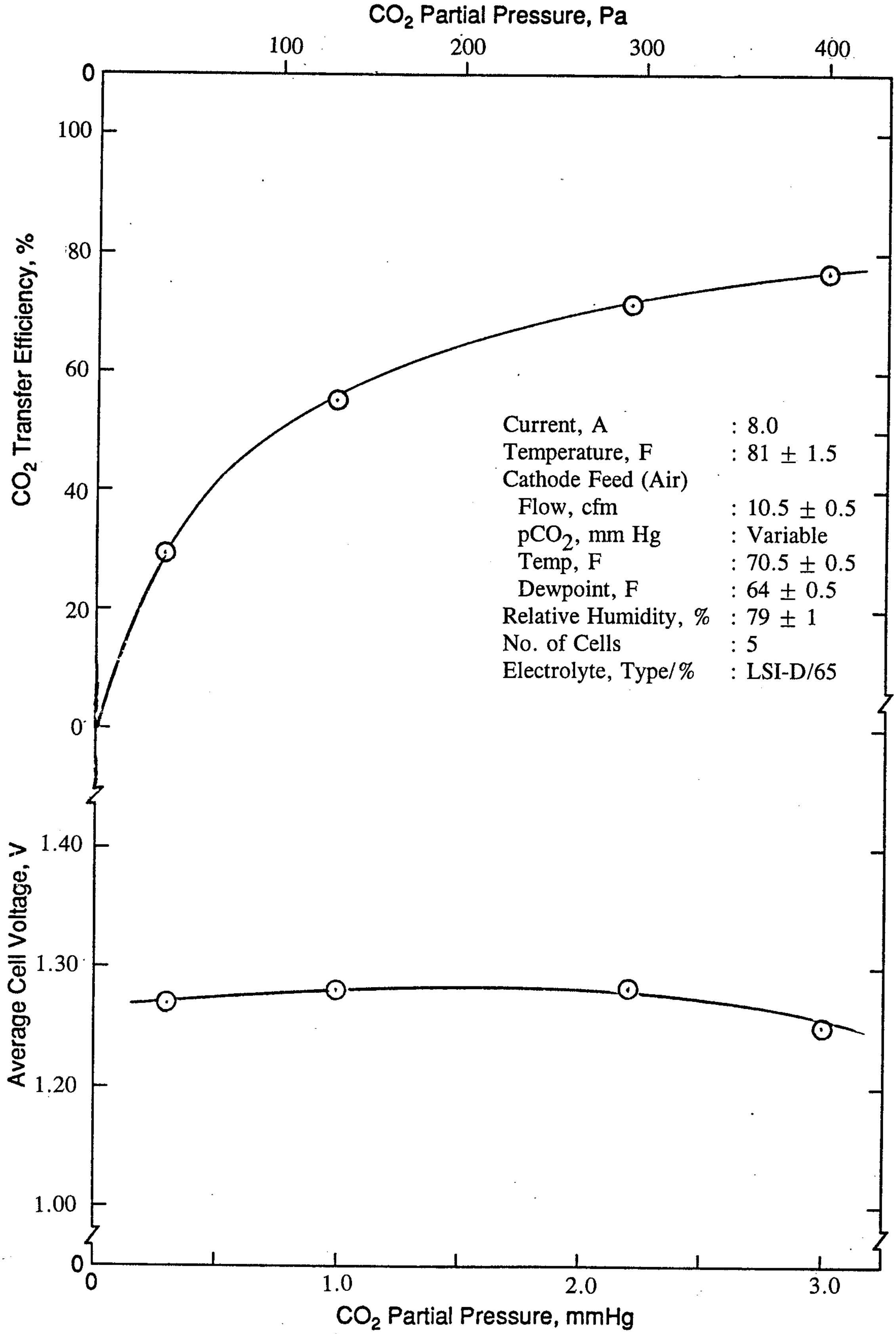

FIGURE 33 APC ECSM CELL VOLTAGE AND CO_2 TRANSFER EFFICIENCY VERSUS INLET AIR pCO_2 AT NOMINAL CELL CURRENT OF 8.0 A

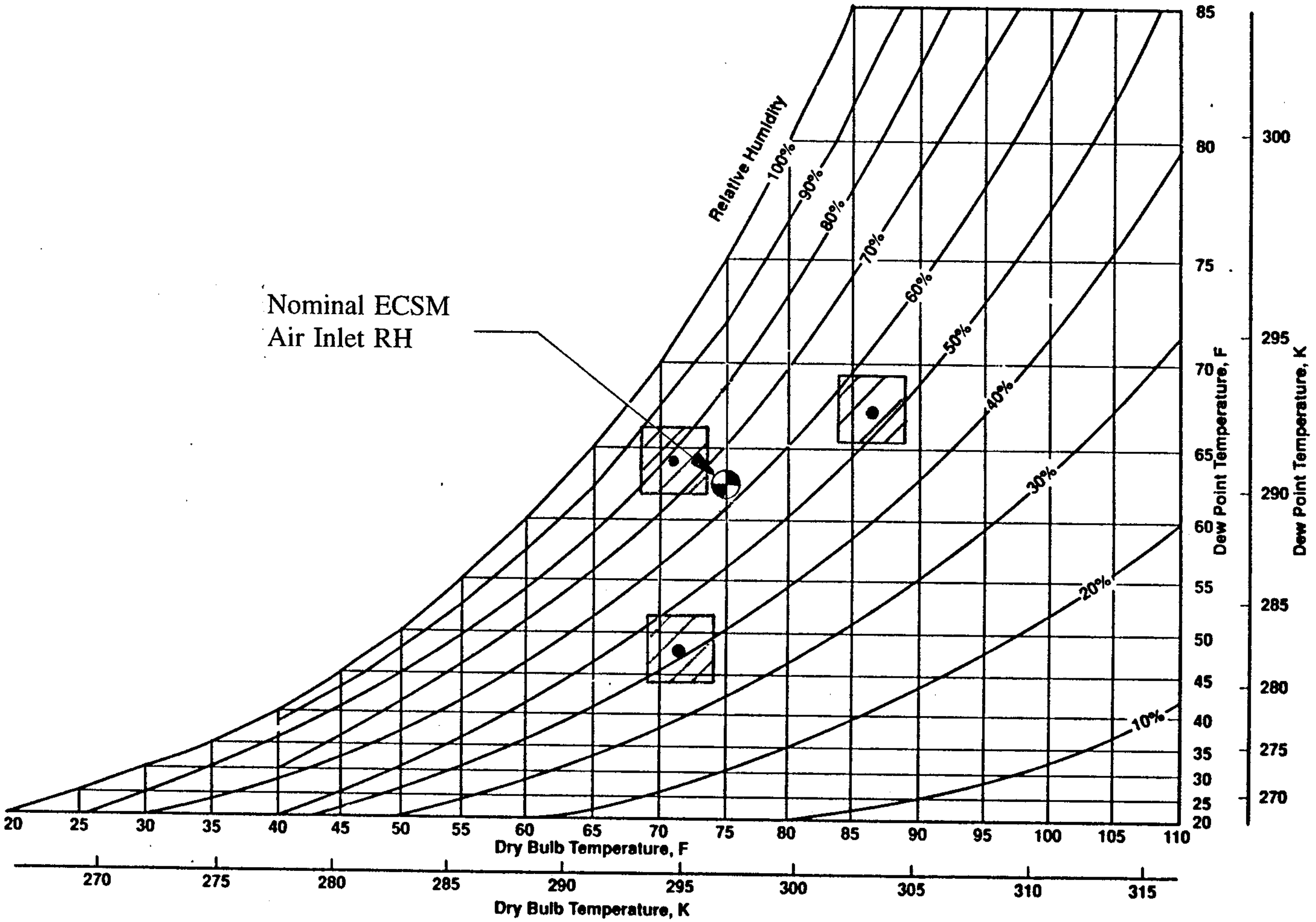

FIGURE 34 INLET AIR HUMIDITY CONDITIONS USED FOR APC TESTS

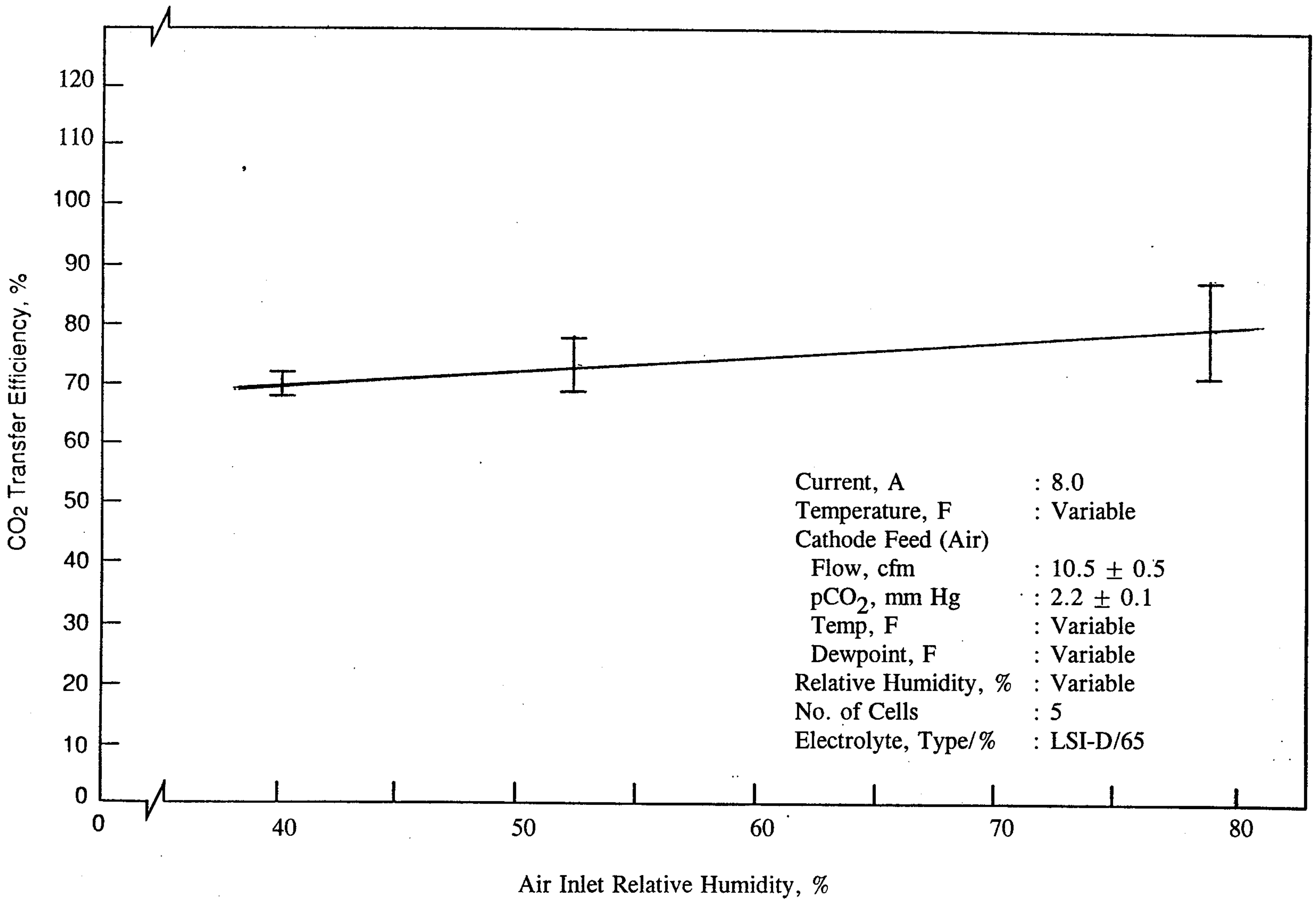

FIGURE 35 EFFECT OF AIR INLET RELATIVE HUMIDITY ON APC CO_2 TRANSFER EFFICIENCY (AIR INLET pCO_2 = 2.2 mm Hg)

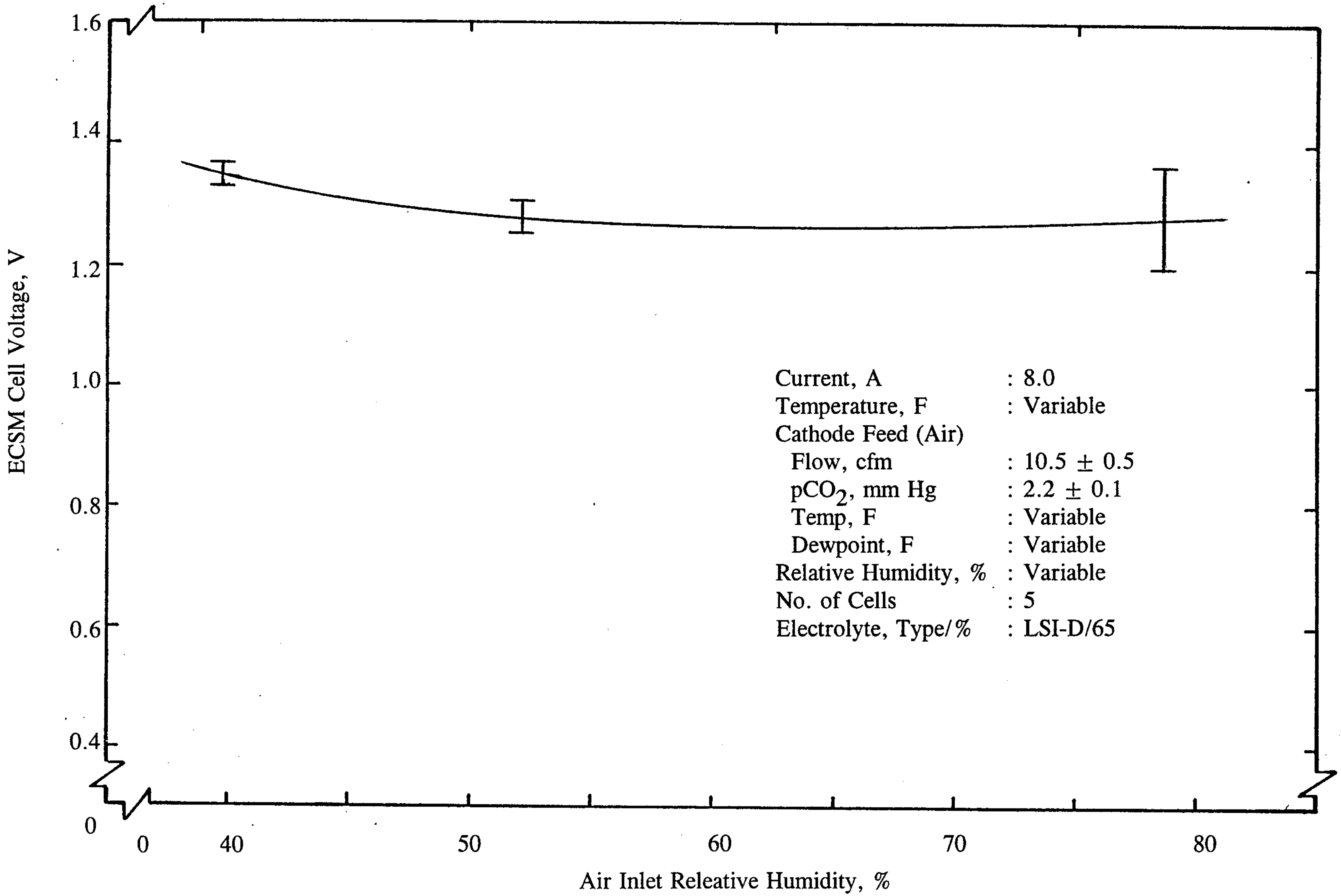

FIGURE 36 EFFECT OF AIR INLET RELATIVE HUMIDITY ON APC ECSM CELL VOLTAGE
(AIR INLET pCO_2 = 2.2 mm Hg)

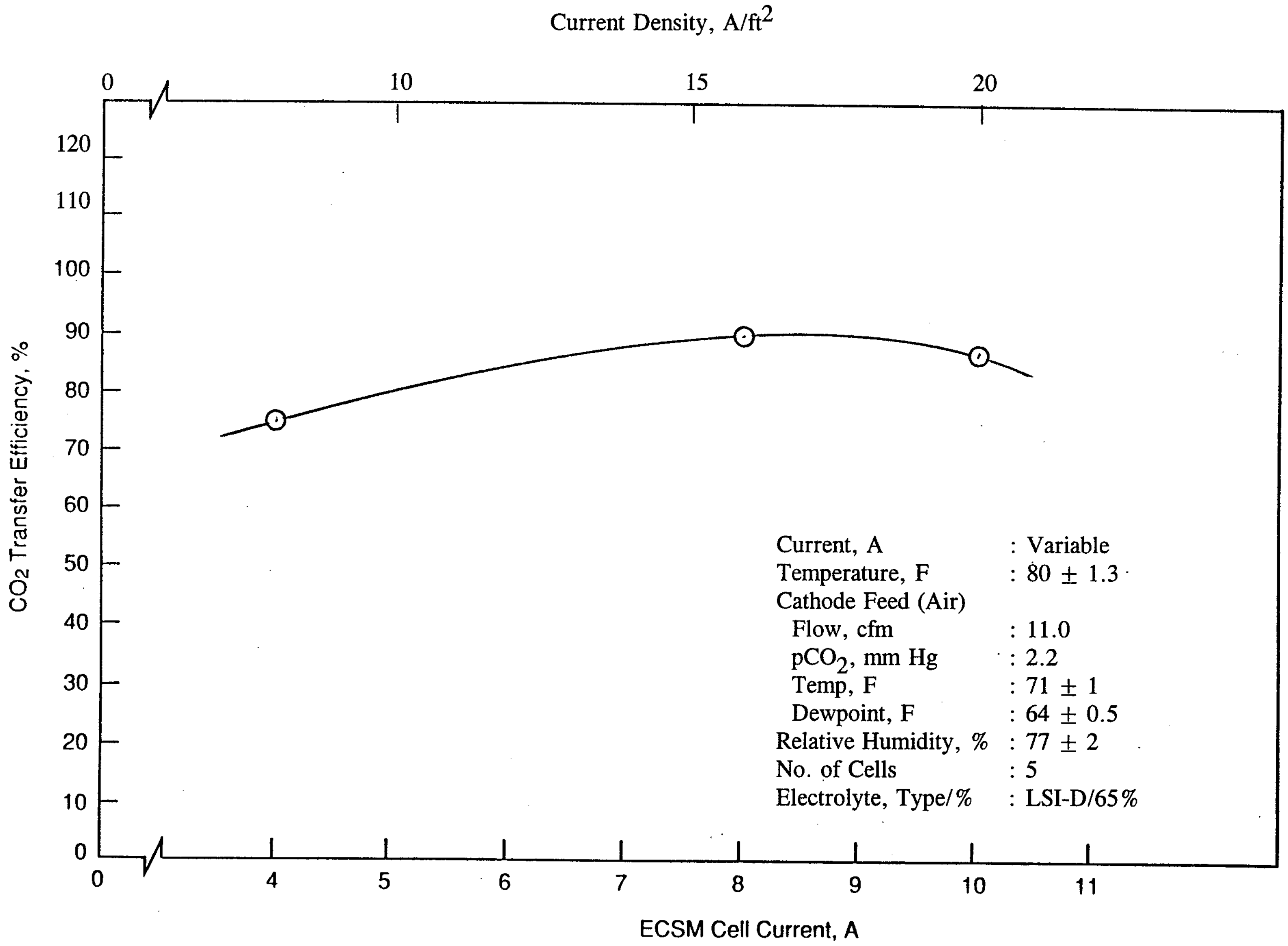

FIGURE 37 APC ECSM CO_2 TRANSFER EFFICIENCY VERSUS CELL CURRENT FOR SELECTED CO_2 INLET COMPOSITIONS

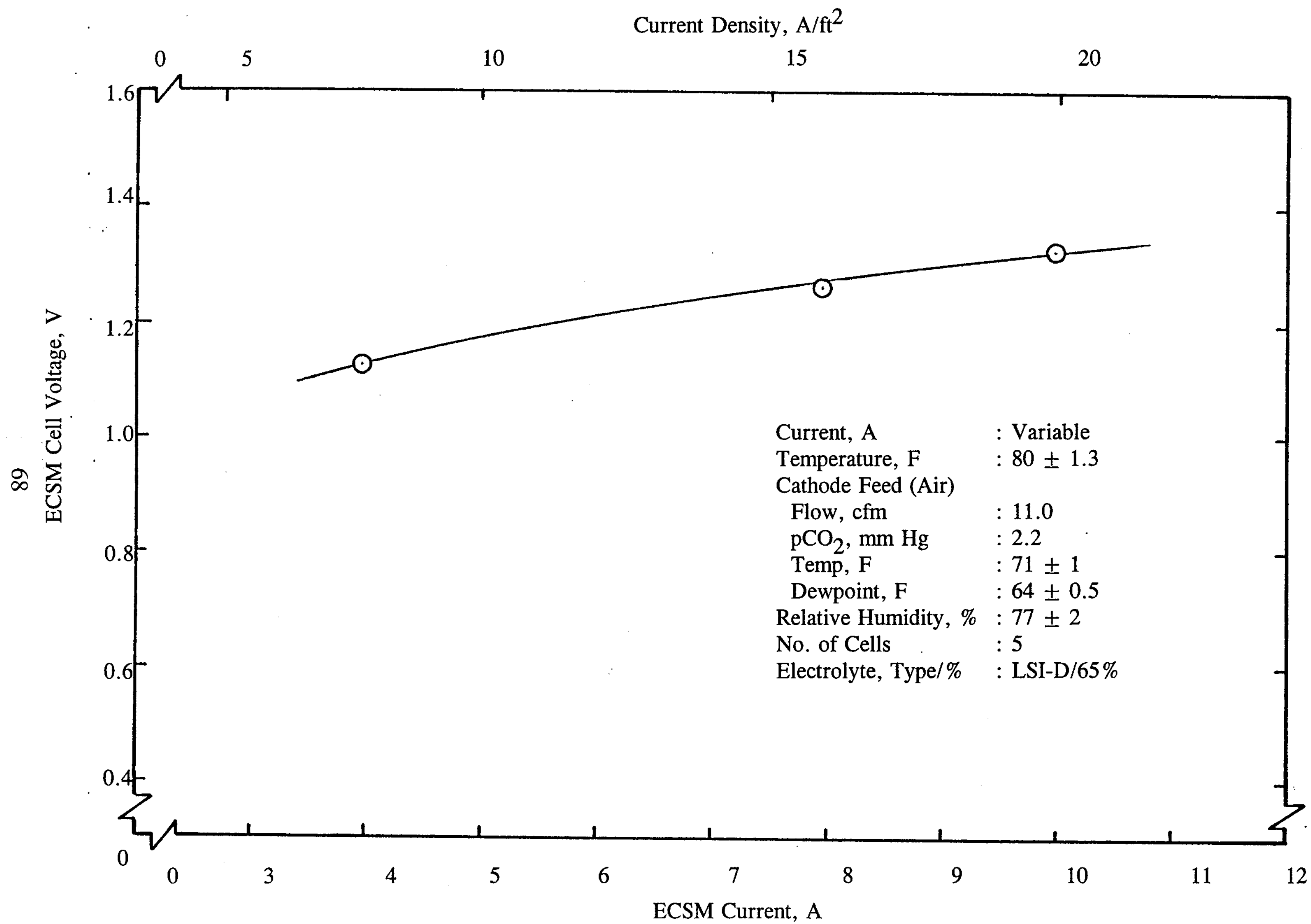

FIGURE 38 EFFECT OF CURRENT ON APC ECSM CELL VOLTAGE

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Life Systems, Inc.

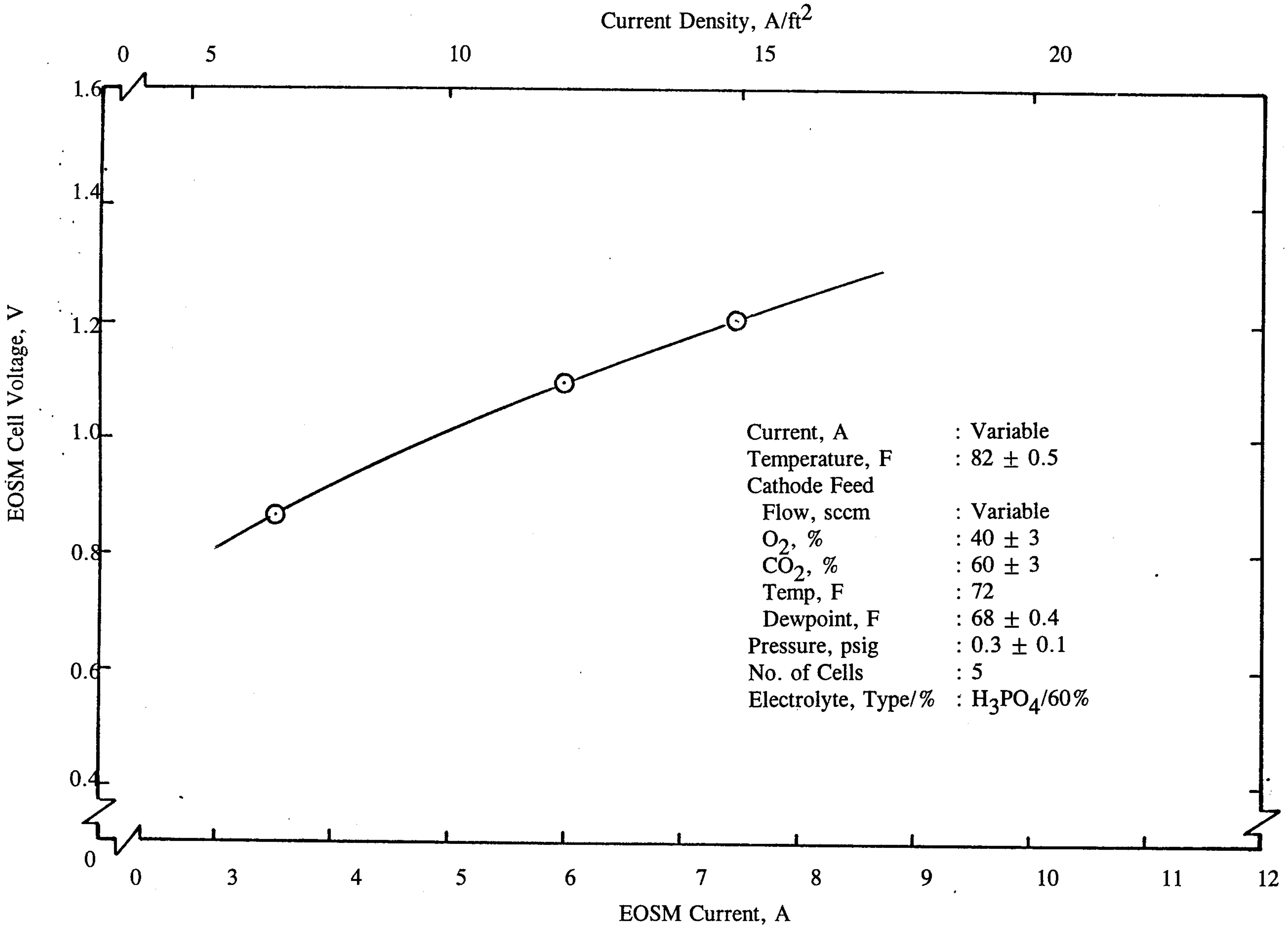

FIGURE 39 EFFECT OF CURRENT ON APC EOSM CELL VOLTAGE

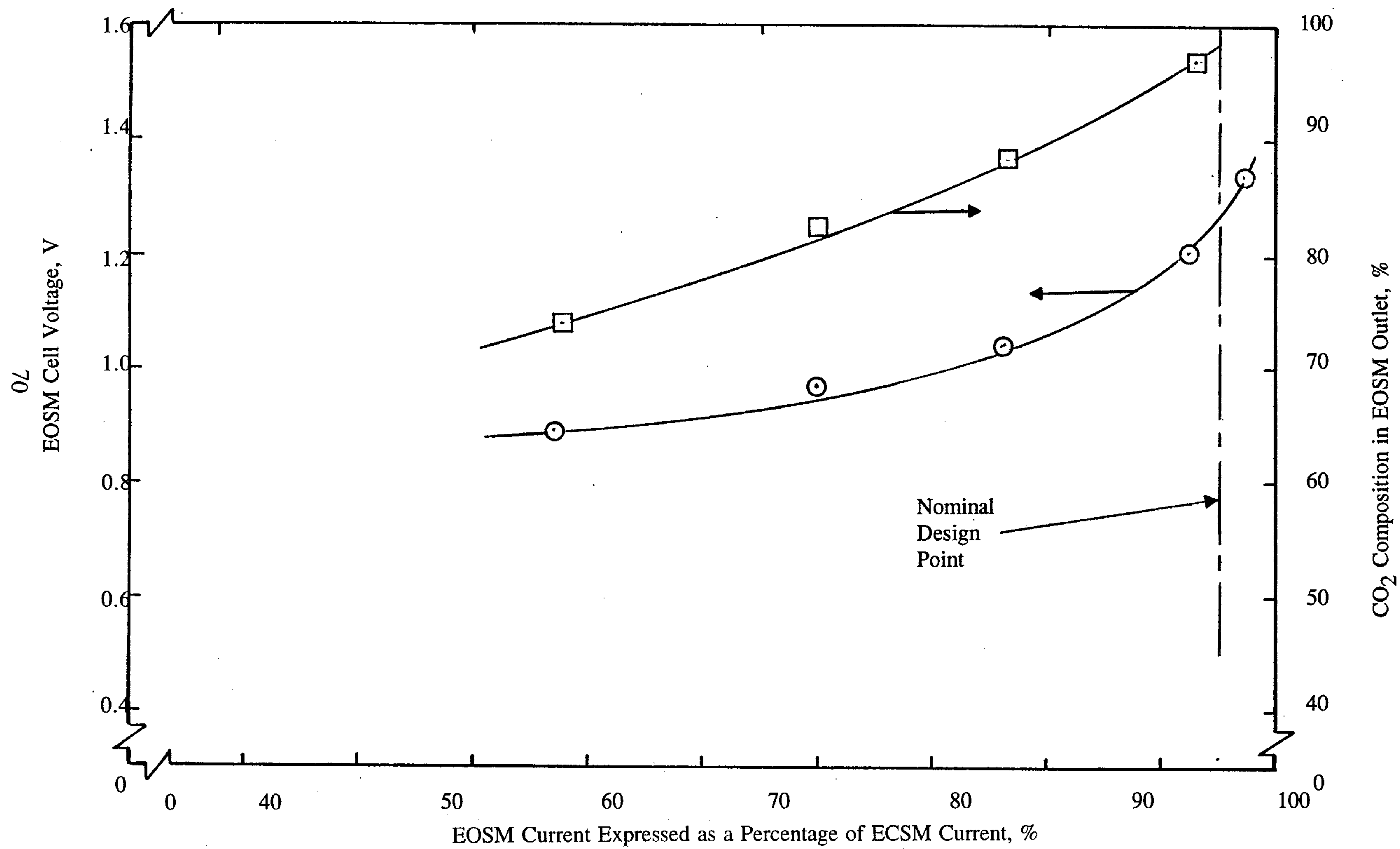

FIGURE 40 EOSM CURRENT EXPRESSED AS PERCENTAGE OF ECSM CURRENT

characteristic of higher relative humidities. Lower voltages are desirable, since they are representative of lower power requirements.

Effects of Module Current Densities. The effects of current density over the range of 8 to 20 ASF for the ECSM and 7 to 15 ASF for the EOSM were investigated. Figure 37 shows CO_2 transfer efficiency as a function of ECSM current and current density. As expected[3] a slight maximum was reached near the 8 Amp or 16 ASF conditions. The data was taken at a nominal pCO_2 level of 2.2 mm Hg.

Figure 38 shows ECSM average cell voltage as a function of ECSM current and current density. The data compares favorably with past data[3,5] and shows an increase in cell voltage as a function of increasing current/current density.

The nominal CO_2 transfer efficiency design point was increased from 60 to 75%, based on the integrated testing. As a result, the O_2 to CO_2 mixtures sent to the EOSM will generally range from 40±3% to 60±3%, as was also shown on Figure 15.

Figure 39 shows the effect of EOSM current and current density on EOSM cell voltage. The figure shows typical cell voltage trends as a function of current and current density for the nominal conditions indicated. The results for integrated APC testing were similar to those obtained for the EOSM tests.

The effect of variations in O_2 stoichiometry on EOSM performance was also investigated. The closer the stoichiometric value to 1.0, the less O_2 is sent to a CO_2 reduction subsystem to form water for re-electrolysis. The latter presents a penalty to the system. Stoichiometry can also be expressed as a percentage based on the ratio of the product of EOSM current times its number of cells to the product of ECSM current times its number of cells. For example, 100% is equal to a stoichiometric value of 1.0 a 95% ratio value is equal to 1.053, 90% is equal to 1.111, etc. Figure 40 shows EOSM performance for up to a 98% current level of the ECSM (at an equal number of cells). A nominal value of 95% was selected.

Summary of Electrochemical Characteristics for APC Sizing

Table 10 lists the physical and performance characteristics for sizing of the electrochemical modules for an APC system. The characteristics were based on both the individual module and the integrated APC test results achieved as part of this program. Since both ECSM and EOSM use physically similar cell hardware to that developed by Life Systems for EDC operation, characteristics of EDC cells established for flight hardware have been used in Table 10.

TABLE 10 PHYSICAL AND PERFORMANCE CHARACTERISTICS FOR ELECTROCHEMICAL MODULE SIZING FOR APC APPLICATION

	ECSM	EOSM
Nominal Module Current[a], A	8.0	7.5
Cell Voltage, V	1.25	1.20
Stoichiometric O_2 Flow	N/A	1.053[a]
Cell Characteristics		
Active Area, ft^2	0.5	0.5
Thickness, in	0.4	0.4
Weight, lb	2.2	2.2
CO_2 Removal Efficiency, %	75	N/A
Air Flow/Cell, SCFM	2.0	N/A
Air Inlet pCO_2		
mm Hg	2.2	N/A
%	0.29	N/A
Liquid Coolant Flow, lb/hr/cell	10	10

(a) Final minor adjustments to currents will result during APC sizing since fractional cells are not possible.
(b) Based on the inverse of (EOSM Current x EOSM No. of Cells) ÷ (ECSM Current x ECSM No. of Cells) = 0.95.

APC SIZING AND COMPARISONS

Requirements were defined and comparison criteria established to allow for sizing and comparison of an APC with four competitive CO_2 removal technologies. The four competing technologies selected were an Electrochemical Depolarized Concentrator (EDC), a Four-Bed Molecular Sieve (4BMS), a Solid Amine Water Desorbed (SAWD) system and a system based on a non-regenerable technique i.e., Lithium Hydroxide (LiOH). Except for the LiOH based system, all systems must incorporate the required hardware and controls to allow CO_2 to be delivered to a CO_2 reduction system such as a Sabatier or Bosch. The latter requirement eliminated configurations or concepts where CO_2 is vented to space vacuum or where space vacuum is used to desorb CO_2.

Requirements Definition and Comparison Criteria

The atmospheric characteristics with which a CO_2 removal systems must interface were selected based on those typically projected for the Space Station use.(10) These values are presented in Table 11. The CO_2 partial pressures selected for this study were equal to and less than 3 mm Hg. A competing system's size was first determined at the 3 mm Hg level using data from literature, as available, followed by its projection at 2.2 mm Hg. The APC and EDC, of course, were sized based on actual 3.0 mm Hg and 2.2 mm Hg test data.

System sizing and comparison requires also definition of a crew size, i.e., the amount of CO_2 to be removed for a given time period. Literature cites generally CO_2 technologies sized for four-person applications, or equivalent to 8.8 lb of CO_2 for 24 hour period. A four-person CO_2 generation rate was selected. A ten year mission duration was chosen, which is similar to that projected for the International Space Station (ISS).

A common denominator is required for one-to-one comparisons. The common denominator chosen for the CO_2 technologies comparisons was total equivalent weight, consisting of fixed hardware launch weight, weight of expendibles required for a ten year mission, weight penalty for power consumption, weight penalty for heat load rejection, weight penalty for orbit-keeping propulsion and weight penalty for O_2 consumption. The resulting CO_2 removal sizing and comparison criteria are quantified in Table 12. The quantification of weight penalties for various parameters were based on those presented in literature as referenced in Table 12.

While launch volumes for each system were determined and are presented in this report, no easy conversion to equivalent weight could be defined or was available in literature. Hence, the system volume numbers are presented for relative informational purposes only.

The complexity of calculating the weight of spares required based on various reliabilities to meet a ten year life was not incorporated in this system comparison, but is recommended as a follow on activity. As a result, comparisons are made based on the assumption that the system hardware will work properly for the ten year mission duration selected.

TABLE 11 SPACE STATION ATMOSPHERE REQUIREMENTS

Total Pressure, lb/in^2	14.5 - 14.9
Oxygen Partial Pressure, lb/in^2	2.83 - 3.35
Temperature, F	65 - 80
Dew Point Temperature, F	40 - 60
Ventilation Flow Rate, ft/min	15 - 40
CO_2 Partial Pressure, mm Hg	$\leq$3.0

TABLE 12 CO_2 REMOVAL SYSTEM SIZING AND COMPARISON CRITERIA

Atmosphere Requirements	See Table 11
Crew Size	4
CO_2 Removal Rate, lb/day	8.8
Mission Duration, Years	10
Power Penalty, lb/W	0.79[a]
Heat Load Penalty, lb/W	0.24[a]
Propulsion Penalty, lb/W	0.06[a]
O_2 Consumption Penalty, lb/lb O_2/day	82.2[b]

(a) See Ref. No. 11.
(b) Based on data presented in Ref. Nos. 8 and 12.

APC System and Definition Sizing

Based on the requirements and criteria established above, a four-person capacity CO_2 removal system based on APC technology was defined and sized. The results are presented in Table 13 summarizing detailed characteristics of the ECS module, the EOS module, ancillary components and a summation of characteristics for the total system at the two pCO_2 levels indicated.

A summary of the benefits of a APC based CO_2 removal system are:

- The APC operates continuously (versus cyclically), i.e., removes CO_2 continuously to help maintain the level of CO_2 in the cabin atmosphere more uniformly than any cyclically operating system.

- The rate of CO_2 removal can be controlled by varying operating parameters such as cell current, air flow rate, etc.

- It operates at near ambient temperature and pressure, resulting in minimum thermal losses and simple transition operations.

- The capacity of the system can be easily varied for different missions by adding or reducing the number of electrochemical cells in the cell modules.

- The APC does not require any expendables or regeneration process, resulting in low power consumption, weight and volume requirements.

Alternate CO_2 Removal Systems Definition and Sizing

The same requirements and sizing criteria established for the APC were used to define and size the four alternate systems, an EDC, a 4BMS, a SAWD and a LiOH based system.

Electrochemical Depolarized CO_2 Concentrator Technology

The EDC technology, which also has been developed at Life Systems,[7,8,9,13] is based on the same technology as the ECS portion of the APC with the exception that H_2 is used at the anode. The electrochemical process that occurs at the cathode of the EDC is identical to the electrochemical process occurring at the cathode of the ECS, namely CO_2 from the cabin atmosphere reacts with OH^- ions electrochemically generated within a porous gas diffusion cathode according to the following half-cell reaction:

$$1/2O_2 + H_2O + 2e^- \rightarrow 2OH^- \qquad (11)$$

The CO_2 reacts with the OH^- and is then transferred within the aqueous alkaline carbonate electrolyte from the cathode (atmosphere side) to the anode (CO_2 concentrating side). The

TABLE 13 PROJECTED PHYSICAL AND OPERATIONAL CHARACTERISTICS OF THE AIR-POLARIZED CO_2 CONCENTRATOR

Operating Cycle	:	Continuous
Capacity	:	Four-Person
Inlet pCO_2, mm Hg	:	3.0 and 2.2
Cabin Temperature	:	65 to 80
Cabin Pressure, psia	:	14.7
Dewpoint, F	:	40 to 60

ECS Module:		pCO_2 = 3.0 mm Hg	pCO_2 = 2.2 mm Hg
Air Flow Rate, acfm	:	62	68
O_2 Transferred, lb/day	:	4.10	4.27
No. of Cells	:	31	34
Active Cell Area, ft^2	:	0.50	0.50
Current Density, ASF	:	16.8	15.9
Cell Voltage, V	:	1.25	1.25
Power, W	:	312	324
Weight, lb	:	95	102
Volume, ft^3	:	2.58	2.77
Heat Rejection, W	:	221	230
EOS Module:			
O_2 Delivered to Cabin, lb/day	:	3.90	4.06
No. of Cells	:	31	34
Active Cell Area, ft^2	:	0.5	0.50
Current Density, ASF	:	15.9	15.1
Cell Voltage, V	:	1.20	1.20
Power, W	:	296	308
Weight, lb	:	95	102
Volume, ft^3	:	2.58	2.77
O_2 Delivered for CO_2 reduction, lb/day	:	0.20	0.21
Heat Rejection, W	:	197	205

continued-

Table 13 - continued

		pCO_2 = 3.0 mm Hg	pCO_2 = 2.2 mm Hg
Ancillary Components:[(a)]			
Power, W	:	55	55
Weight, lb	:	47	47
Volume, ft^3	:	1.42	1.42
Heat Rejection, W	:	55	55
Total System:			
Power, W	:	735[(b)]	763[(c)]
Weight, lb	:	238	252
Volume, ft^3	:	6.56	6.96
Heat Rejection, W	:	545[(b)]	566[(c)]
O_2 Penalty[(d)], lb/day	:	0.20	0.21
Expendable, lb/10 years	:	None	None

(a) Includes fluids and coolant control assemblies, current controllers, heat exchangers, valves, air ducts, etc., for the overall APC System.
(b) Includes 72 W for power conditioning losses.
(c) Includes 76 W for power conditioning losses.
(d) That which is converted to water in a CO_2 reduction subsystem and must be re-electrolyzed.

CO_2 transfer occurs via CO_3^{-2} and HCO_3^- ions generated from the reaction of CO_2 with OH^- according to Reactions 12a and 12b, respectively:

$$CO_2 + OH^- \rightarrow HCO_3^- \tag{12a}$$

$$HCO_3^- + OH^- \rightarrow CO_3^{-2} + H_2O \tag{12b}$$

Reaction 12b occurs instantaneously, so Reaction 12a is the rate-determining step. Therefore, the conversion of CO_2 to CO_3^{-2} can be described by a single step as shown in Reaction 13:

$$CO_2 + 2OH^- \rightarrow CO_3^{-2} + H_2O \tag{13}$$

When the concentration of OH^- is depleted, additional CO_2 can be absorbed by:

$$CO_2 + CO_3^{-2} + H_2O \rightarrow 2HCO_3^- \tag{14}$$

combining Equation 13 and 14 results in an overall absorption reaction of:

$$2CO_2 + 2OH^- \rightarrow 2HCO_3^- \tag{15}$$

The CO_3^{-2} and HCO_3^- ions formed at the cathode by Reactions 13 and 15, respectively, migrate toward the anode due to an electrical potential difference applied to the cell.

$$CO_3^{-2} + H_2 \rightarrow H_2O + CO_2 + 2e^- \tag{16a}$$

and

$$2HCO_3^- + H_2 \rightarrow 2H_2O + 2CO_2 + 2e^- \tag{16b}$$

Combining Equations 1, 13 and 16a results in:

$$1/2O_2 + H_2 + CO_{2(cathode)} \rightarrow H_2O + CO_{2(canode)} \tag{16c}$$

While combining Equations 1, 15 and 16b results in:

$$1/2O_2 + H_2 + 2CO_2 \rightarrow H_2O + 2CO_{2(canode)} \tag{16d}$$

The anode gas stream is a mixture of CO_2, excess H_2 and water vapor, which can be sent to CO_2 reduction processes such as the Sabatier or Bosch processors.

A block diagram of the electrochemical depolarized CO_2 concentration process is shown in Figure 41. The projected physical and operational characteristics of an EDC CO_2 removal system are shown in Table 14 at the two pCO_2 levels indicated.

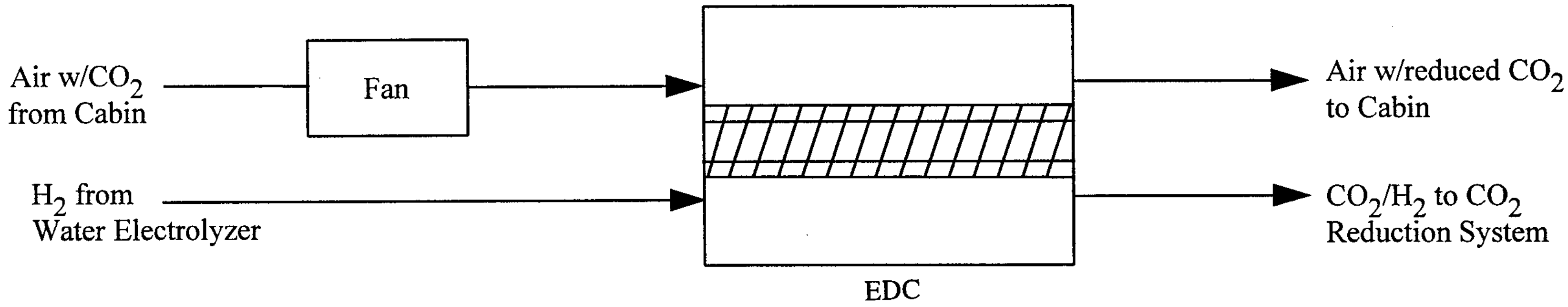

FIGURE 41 BLOCK DIAGRAM OF EDC CO_2 REMOVAL SYSTEM

TABLE 14 PROJECTED PHYSICAL AND OPERATIONAL CHARACTERISTICS OF THE ELECTROCHEMICAL DEPOLARIZED CO_2 CONCENTRATOR (EDC)

Operating Cycle	:	Continuous	
Capacity	:	Four-Person	
Inlet pCO_2, mm Hg	:	3.0 and 2.2	
Cabin Temperature, F	:	65 to 80	
Cabin Pressure, psia	:	14.7	
Dewpoint, F	:	40 to 60	
		pCO_2 = 3.0 mm Hg	pCO_2 = 2.2 mm Hg
EDC Module:			
Air Flow Rate, acfm	:	54	58
No. of Cells	:	30	32
Active Area, ft^2	:	0.50	0.50
Current Density, ASF	:	16	16
Cell Voltage, V	:	0.45	0.45
Power, W	:	(108)[(a)]	(115)[(a)]
Weight, lb	:	89	93
Volume, ft^3	:	2.36	2.49
Heat Rejection, W	:	180	192
Ancillary Components:			
Power, W	:	155	155
Weight, lb	:	41	41
Volume, ft^3	:	1.64	1.64
Heat Rejection, W	:	198[(b)]	201[(c)]
Total System:			
Power, W	:	90[(d)]	86[(e)]
Weight, lb	:	130	135
Volume, ft^3	:	4.00	4.13
Heat Rejection, W	:	378	393
O_2 Penalty, lb/day	:	3.80	4.04
Expendable, lb/10 years	:	None	None

(a) Generated power.
(b) Includes 43 W heat load for power conversion of module generated power (108 (1.0 - 0.6)) = 43 W based on 60% power conversion efficiency for EDC generated power.
(c) Assumes 46 W heat load for power conversion of module generated power (115 (1.0 - 0.06)) = 46 W.
(d) Assumes 108 W of module generated power available at a 60% power conversion efficiency (155 W - 0.6 (108) W) = 90 W.
(e) Assumes 115 W of module generated power available at a 60% power conversion efficiency (155 W - 0.6 (115)W) = 86 W.

Four-Bed Molecular Sieve Technology

The 4BMS CO_2 removal system[14,15,16] is based on the process of chemical adsorption. Figure 42 shows the block diagram of the 4BMS CO_2 removal process for space applications. Cabin air is drawn by the fan through a desiccant bed of Molecular Sieve type 13X to dehumidify the air stream. The dehumidified air then flows through the precooler where the heat of compression, the heat generated by the blower motor and the heat of adsorption generated in the desiccant bed are removed. Next, the cooled, dry air flows through a CO_2 adsorption bed of Molecular Sieve type 5A where the CO_2 is removed and the air is heated. The warmed CO_2-free air is then passed through a desorbing desiccant bed where it is rehumidified before returning to the cabin.

As the CO_2 is adsorbed by one bed, the second bed undergoes CO_2 desorption via pressure and thermal cycling. In the desorption process, the air pump is used to save the residual air by removing it from the bed and exhausting it to the process air outlet. To facilitate CO_2 desorption, the air pump is turned off and the adsorbent bed is heated to help drive off the CO_2. As sufficiently high temperatures are reached, the CO_2 is desorbed from the zeolite surface and returns to the gas phase, causing the pressure in the bed to rise. At a given time in the half-cycle the pump is restarted, thereby removing the desorbed CO_2 and routing it to the pressurized, fixed-volume accumulator. At the end of the half-cycle, the selector valves change position, allowing the newly regenerated beds to become the adsorbing beds and vice versa, and the next half-cycle begins.[14]

One complete cycle of the 4BMS consists of each CO_2 sorbent bed undergoing an adsorption half-cycle and a desorption half-cycle. Likewise, the desiccant beds are alternatively absorbing and desorbing water. The standard half-cycle time is 90 minutes, however, the half-cycle time is adjustable.

The projected physical and operational characteristics of a 4BMS CO_2 removal system are shown in Table 15 at the two pCO_2 levels indicated.

Solid Amine CO_2 Absorption Technology

The solid amine CO_2 adsorption process uses a regenerable solid sorbent that is a weakly based ion exchange resin for CO_2 removal.[8,17,18] The active ingredient of the resin is a polythyleneimine ($(C_2H_5N)_2$)-coated microspherical acrylic substrate material (HS-C) or its derivative (HS-C+).[17] The microspherical substrates expose large surface areas of the amine to the cabin atmosphere for CO_2 and H_2O removal. The resin chemically absorbs CO_2 by first combining with water to form a hydrated amine and then CO_2 reacts with the hydrated amine to form a bicarbonate according to the following equations, respectively:

$$\text{amine} + H_2O \rightarrow \text{amine}\cdot H_2O \tag{17a}$$

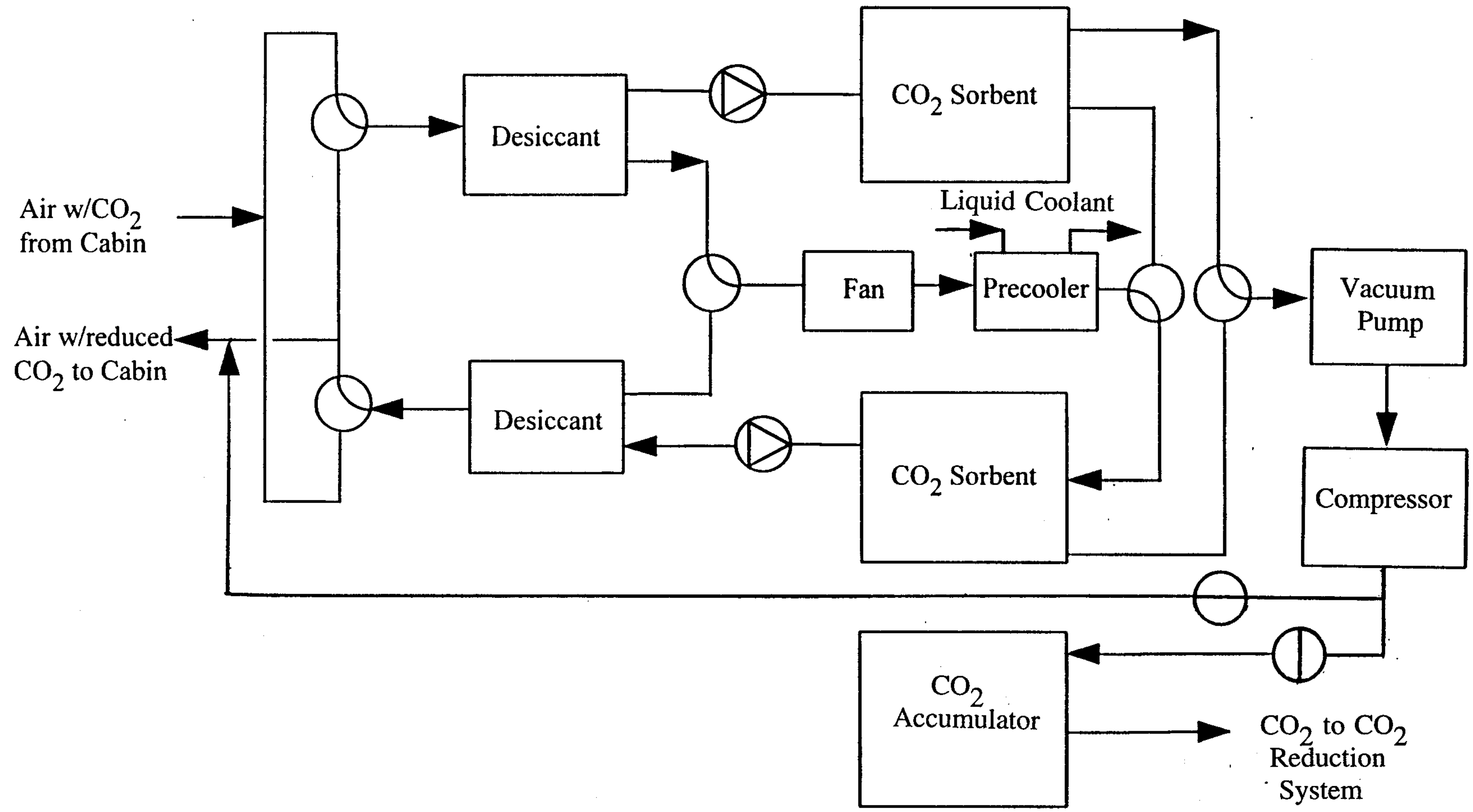

FIGURE 42 BLOCK DIAGRAM OF 4-BED MOLECULAR SIEVE CO_2 REMOVAL SYSTEM

TABLE 15 PROJECTED PHYSICAL AND OPERATIONAL CHARACTERISTICS OF THE FOUR-BED MOLECULAR SIEVE CO_2 REMOVAL SYSTEM

Operating Cycle	:	Cyclic (Variable
Capacity	:	Four-Person
Inlet pCO_2, mm Hg	:	3.0 and 2.2
Cabin Temperature, F	:	65 to 80
Cabin Pressure, psia	:	14.7
Dewpoint, F	:	40 to 60

		pCO_2 = 3.0 mm Hg	pCO_2 = 2.2 mm Hg
Space Station Baseline System[(a)]:			
Air Flow Rate, acfm	:	12	20
Power, W	:	587	945
Weight, lb	:	408	535
Volume, ft^3	:	13.5	17.0
Heat Load, W	:	587	945
Expendables, lb/10 years			
Air	:	625	790
Water	:	89	112
Ancillary Components for CO_2 Collection[(b)]:			
Power, W	:	250	250
Weight, lb	:	42	42
Volume, ft^3	:	3.5	3.5
Heat Load, W	:	250	250
Total System:			
Power, W	:	837	1,195
Weight, lb	:	450	577
Volume, ft^3	:	17.0	20.5
Heat Load, W	:	837	1,195
Expendable, lb/10 years	:	714	902

(a) 3.0 mm Hg data Based on Ref. No. 14.
(b) Based on Ref. No. 8.

and

$$amine{\cdot}H_2O + CO_2 \rightarrow amine{\cdot}H_2CO_3 \quad (17b)$$

The amine is regenerated by applying heat to break the amine-bicarbonate bond and thus releasing the CO_2 by the following reaction:

$$amine{\cdot}H_2CO_3 + \text{steam heat} \rightarrow H_2O + CO_2 + amine \quad (18)$$

The major components of the solid amine CO_2 removal system are the canisters containing the packed amine beds. A subsystem typically has multiple canisters depending on mission design requirements such as operational constraints, vehicle volume, crew size, power availability and maintenance/repair philosophy. A block diagram of a two-canister system is shown in Figure 43. A blower pushes cabin air through an amine canister (upper one) during the absorption cycle. Carbon dioxide and water are co-absorbed onto the sorbent media. The CO_2 and H_2O molecules are desorbed by low pressure steam. A compressor pumps the CO_2 into an accumulator for processing by a CO_2 reduction subsystem. The two-canister system operates by alternating the absorb/desorb cycles of each canister.

The projected physical and operational characteristics of a SAWD CO_2 removal system are shown in Table 16 at the two pCO_2 levels indicated.

<u>Lithium Hydroxide CO_2 Absorption Technology</u>

Lithium hydroxide cartridges(18,19) have been used for CO_2 removal from air for submarines and a variety of space applications (e.g., Space Shuttle cabin air CO_2 removal, Extravehicular Mobility Unit (EMU) CO_2 removal). A block diagram of a LiOH CO_2 removal process is shown in Figure 44.

Lithium hydroxide absorbs CO_2 according to the following equation:

$$2LiOH + CO_2 \rightarrow Li_2CO_3 + H_2O \quad (19)$$

Because LiOH is a strong alkaline material, the efficiency of CO_2 removal is excellent; however, the reaction product, lithium carbonate (Li_2CO_3), is not readily regenerable. Therefore, continuous resupply of LiOH cartridges to, return of spent cartridges from, and storage of fresh and spent cartridges in space vehicles are required to support the long-duration space applications.

The projected physical and operational characteristics of a LiOH CO_2 removal system are shown in Table 17. No size differences were assumed for operation at 2.2 mm Hg versus 3.0 mm Hg.

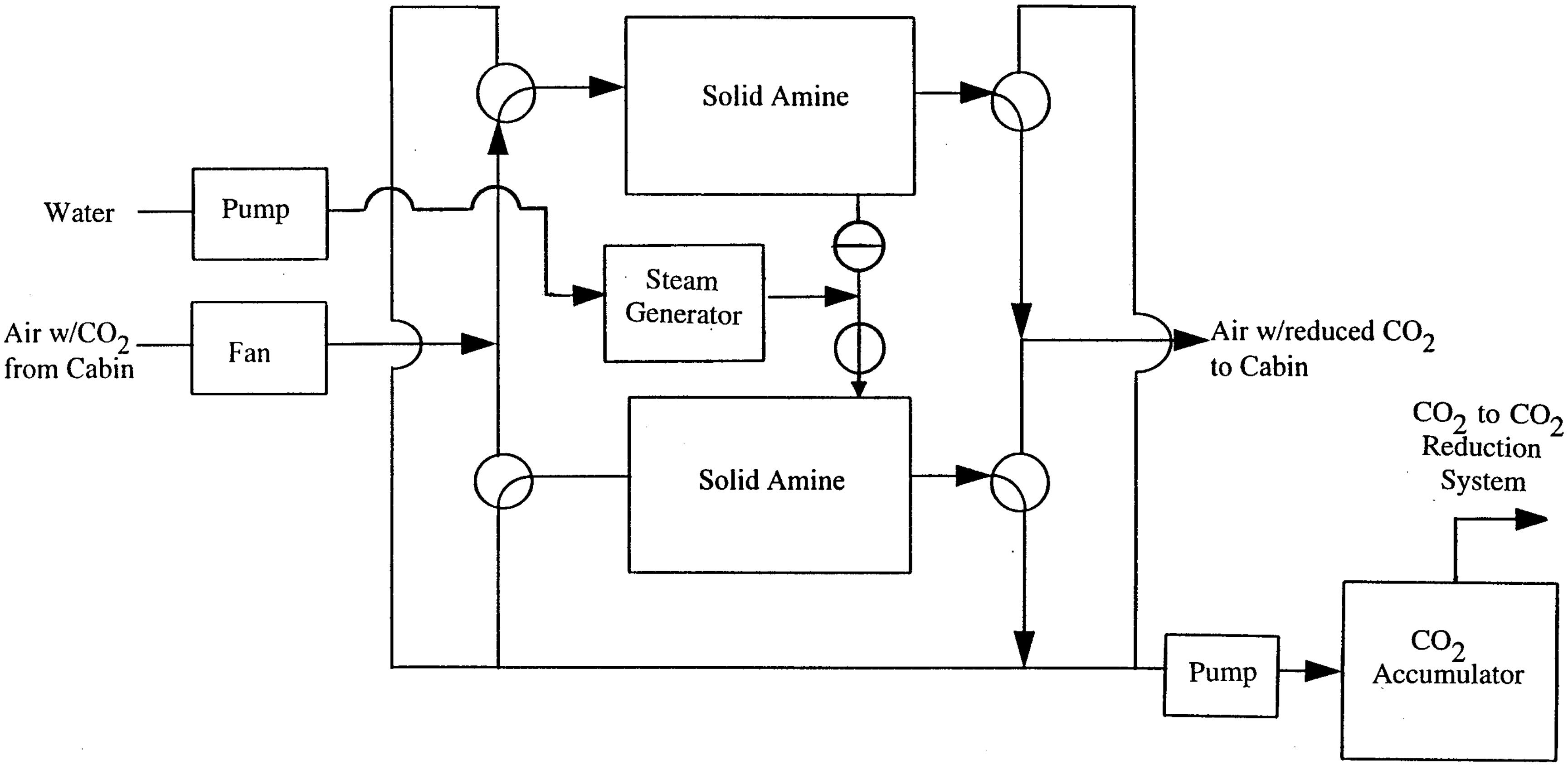

FIGURE 43 BLOCK DIAGRAM OF SOLID AMINE CO_2 REMOVAL SYSTEM

TABLE 16 PROJECTED PHYSICAL AND OPERATIONAL CHARACTERISTICS OF A STEAM DESORBED SOLID AMINE CO_2 REMOVAL SYSTEM

Operating Cycle	:	Cyclic (Variable)
Capacity	:	Four-Person
Inlet pCO_2, mm Hg	:	3.0 and 2.2
Cabin Temperature, F	:	65 to 80
Cabin Pressure, psia	:	14.7
Dewpoint, F	:	40 to 60

		pCO_2 = 3.0 mm Hg	pCO_2 = 2.2 mm Hg
System (Without CO_2 Collection)[a]:			
Air Flow Rate, scfm	:	27	35
Power, W	:	470	612
Weight, lb	:	189	220
Volume, ft^3	:	6.4	7.2
Heat Load, W	:	470	612
Expandables	:	None	None
Ancillary Components for CO_2 Collection[b]:			
Power, W	:	250	250
Weight, lb	:	42	42
Volume, ft^3	:	3.5	3.5
Heat Load, W	:	250	250
Total System:			
Power, W	:	720	862
Weight, lb	:	231	262
Volume, ft^3	:	9.9	10.7
Heat Load, W	:	720	862
Expendables, lb/10 years	:	None	None

(a) 3.0 mm Hg data based on Ref. No. 2.
(b) Based on Ref. No. 8.

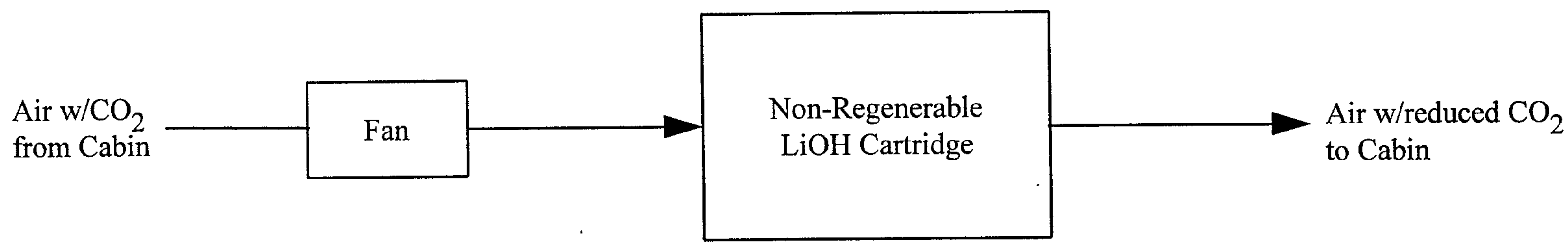

FIGURE 44 BLOCK DIAGRAM OF LITHIUM HYDROXIDE CO_2 REMOVAL SYSTEM

TABLE 17 PROJECTED PHYSICAL AND OPERATIONAL CHARACTERISTICS OF THE LITHIUM HYDROXIDE CO_2 REMOVAL SYSTEM

Operating Cycle	: Cyclic
Capacity	: Four-Person
Inlet pCO_2, mm Hg	: 3.0
Cabin Temperature, F	: 65 to 80
Cabin Pressure, psia	: 14.7
Dewpoint, F	: 40 to 60
<u>Total System</u>:	
Air Flow, SCFM	: 14
Power, W	: 30
Weight, lb	: 1,613[a]
Volume, ft^3	: 51.5
Heat Load, W	: 90
Expendables, lb/10 years	: 63,803

(a) For initial 90 days using data from Ref. No. 19 (1.36 lb of LiOH/lb CO_2 and 0.677 lb packaging/lb CO_2).

CO_2 Removal System Comparison Summary

Table 18 presents a side-by-side comparison of key parameters of the five CO_2 removal technologies discussed in this final report. The final basis for comparison is total equivalent weight as defined in the requirements section above. All competing systems, except for the EDC, were first sized based on inlet air pCO_2 of 3.0 mm Hg and were then adjusted for operation at an inlet air pCO_2 of 2.2 mm Hg. Test data from EDC operation at 2.2 mm Hg was also used to size an EDC at 2.2 mm Hg.

As expected the EDC results in the lowest equivalent weight by approximately a factor of two, when compared to the next best regenerative CO_2 removal technology. Also, as expected, the LiOH nonregenerative concept results in a total equivalent weight of over two orders of magnitudes larger than for example that for the EDC. The subsystem with the second lowest equivalent weight after the EDC is the APC both when compared at 3.0 mm Hg and at 2.2 mm Hg pCO_2 air inlet conditions. The APC advantage becoming greater, as expected, at the lower pCO_2 levels.

Projected APC Space Station Flight Experiment (Phase II) Configuration

Figure 45 represents the configuration of the APC subsystem that is projected to be flown as a Space Station Flight Experiment for a potential Phase II APC development effort. The subsystem consists of nine mechanical components as shown in Table 19. Readiness of each components for the flight experiment is also indicated. The APC subsystem hardware that can be flown as a Space Station experiment would look very similar to the hardware shown in Figure 46 which is a four-person capacity EDC. The EDC is similar to the ECS of an APC except that the EDC requires hydrogen at the anode side. Life Systems has over 20 years' experience in the development of EDC hardware.

The physical characteristics of such a Phase II APC are those that were presented in Table 13. Such an APC Flight Experiment could perform the actual CO_2 removal function and generate desirable low cabin pCO_2 levels aboard the Space Station, with the Baseline Space Station CO_2 Removal System, a 4BMS, functioning as the backup.

TABLE 18 EQUIVALENT WEIGHT COMPARISON OF FOUR-PERSON CAPACITY CO_2 REMOVAL SYSTEMS FOR SPACE APPLICATION AT pCO_2 LEVELS OF 2.2 AND 3.0 mm Hg

	CO_2 Removal Technology								
	APC		EDC		4BMS		SAWD		
	2.2 mm Hg pCO_2	3.0 mm Hg pCO_2	2.2 mm Hg pCO_2	3.0 mm Hg pCO_2	2.2 mm Hg pCO_2	3.0 mm Hg pCO_2	2.2 mm Hg pCO_2	3.0 mm Hg pCO_2	LiOH
Power, W	763	735	86	90	1,195	837	862	720	30
Weight, lb[(a)]	252	238	135	130	577	450	262	231	1,613
Volume, ft^3[(a)]	7.0	6.6	4.1	4.0	20.5	17.0	10.7	9.9	51.5
Heat Load, W	566	545	393	378	1,195	837	862	720	30
Expendables, lb/10 yrs	0	0	0	0	902	714	0	0	63,803
O_2 Consumed, lb/day	0.21	0.20	4.04	3.80	0	0	0	0	0
Penalty, lb									
Power	603	581	68	71	944	661	681	569	24
Heat Load	136	131	94	91	287	201	207	173	7
Propulsion	46	44	5	5	72	50	52	43	2
O_2 Consumed	17	16	332	312	0	0	0	0	0
Total Equivalent Wt, lb	1,054	1,010	634	609	2,782	2,076	1,202	1,016	65,449

(a) Initial launch, with 90 day resupply, as required.

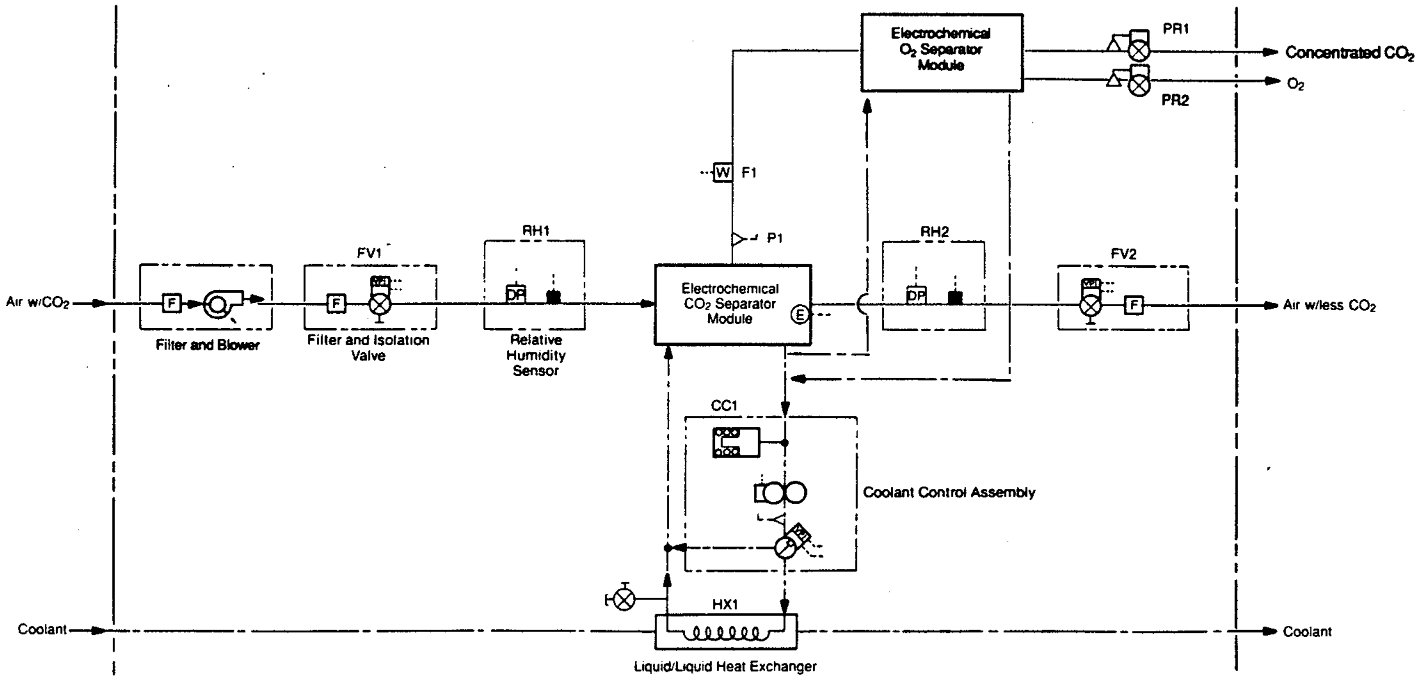

FIGURE 45 APC SUBSYSTEM MECHANICAL SCHEMATIC WITH SENSORS

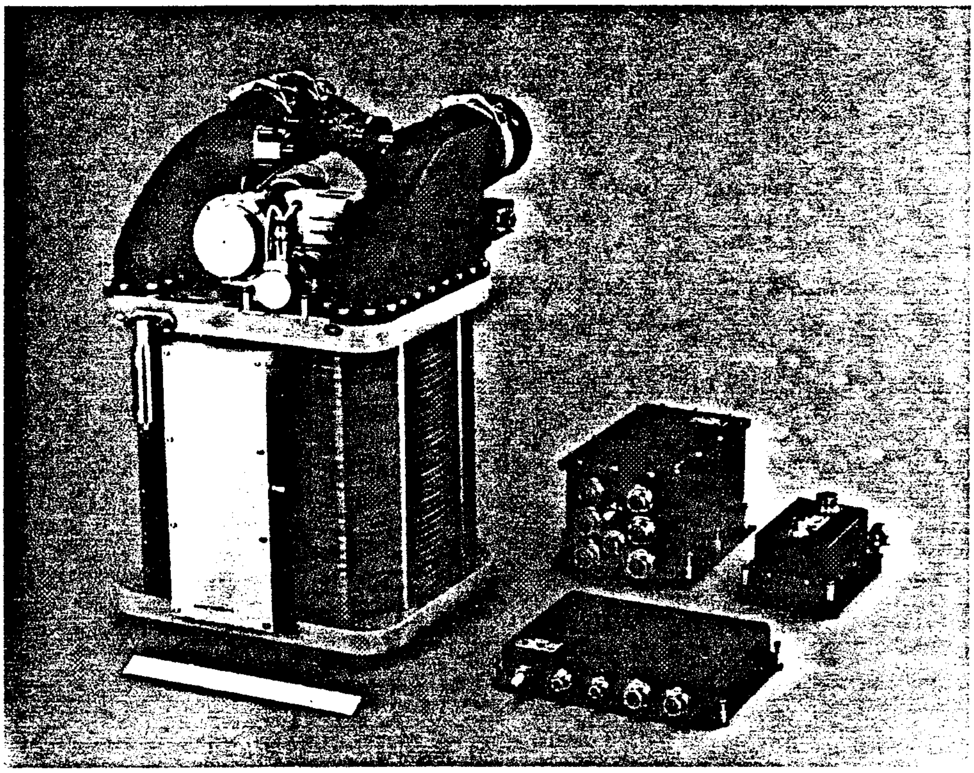

FIGURE 46 FOUR-PERSON CAPACITY EDC HARDWARE SIMILAR TO APC FLIGHT HARDWARE CONFIGURATION

TABLE 19 CURRENT STATUS OF APC COMPONENTS FLIGHT READINESS

	Components	Readiness[a]
1.	ECS Module	4.1
2.	EOS Module	4.1
3.	Coolant Control Assembly	5.4
4.	Filter and Isolation Valve Assemblies	5.4
5.	Relative Humidity Sensors Assemblies	5.4
6.	Heat Exchanger Assembly	5.4
7.	Filter and Blower Assembly	5.4
8.	Control/Monitor Instrumentation	8

(a) The level of components' flight readiness is based on NASA's Technology Maturity Scale as shown below:

Description	Level
Operational	8
Engineering Model Tested in Space	7.2
Engineering Model Qualified	7.1
Prototype Developed to Qualify	6.3
Prototype Tested in Test Bed - Unmanned	6.2
Prototype Tested at Contractors	6.1
Preprototype Tested at NASA	5.4
Preprototype Tested at Contractors	5.3
Major Function Tested at NASA	5.2
Major Components Tested at Contractors	5.1
Critical Hardware Tested	4.3
Critical Function Tested Over Time	4.2
Critical Function Demonstrated (Scale to Full Size)	4.1
Conceptual Design Tested Experimentally	3.2
Conceptual Design Tested Analytically	3.1
Conceptual Design Formulated	2
Basic Principles Observed and Reported	1

(a) Definitions:

Preprototype - Constructed of commercially available components to demonstrate fit, form and function.

Prototype - Constructed with optimized components and packaging and subjected to design qualification environmental tests to qualify a design prior to fabrication of flight model equivalents. Prototype hardware is not intended for flight use.

Engineering Model - Full size structural model, dimensionally correct including interfaces, and functionally identical to the flight unit but not necessarily fully qualified.

CONCLUSIONS AND RECOMMENDATIONS

The following conclusions are derived based on the work completed:

1. An electrochemical CO_2 concentration system based on Air-Polarized Technology is the most competitive CO_2 removal system for applications where H_2 may not be desirable.

2. An APC based CO_2 removal system can effectively and efficiently remove carbon dioxide from atmosphere with CO_2 partial pressures as low as 0.3 mm Hg (equivalent to earth-like ambient conditions).

3. Operating conditions and ranges can be established that allow for integrated operation of an electrochemical CO_2 separation module and an electrochemical O_2 separation module.

4. An Electrochemical Depolarized CO_2 Concentrator (EDC) is still the most effective and efficient CO_2 removal system especially for low pCO_2 requirements and where the use of H_2 is not objectionable.

5. Scale up from previously tested single and two-cell subscale modules to five-cell electrochemical modules using flight-like sized hardware is feasible without impact on performance.

6. Based on the scaling results obtained low risk projections can be made scaling to the four-person capacity level using the operating conditions and characteristics derived as part of this effort.

The following recommendations are made based on the work performed:

1. Initiate a test program that evaluates APC technology at the approximate one person capacity level for extended period of times i.e., six month or greater.

2. Initiate a flight experiment definition study that would lead to a Preliminary Design of a one to four person capacity APC-based CO_2 removal system to flown as a Space Station Flight Experiment aboard the ISS.

3. Update the CO_2 removal system comparison study to include reliability, i.e., spares, into the total equivalent weight calculation.

4. Investigate the availability and applicability of membrane CO_2 separation (from O_2) to determine if the EOSM function can be more efficiently performed by such a membrane process.

APPENDIX A

TEST GRIDS

TABLE A-1 EOSM CHECKOUT/CALIBRATION TEST GRID

	Cathode Feed					Current, A	Coolant		Monitored Parameters, Remarks, etc.
	Rate, sccm	CO_2, %	P, psig	T, F	DP, F		Flow, lb/hr	Temp, F	
Assembly of Components	No	--	--	--	--	No	No	No	Verify correct installation of components
Pressure Test	No	--	--	--	--	No	No	No	Apply fluids but no flow (5 psid)
Calibration									
All sensors, gauges, flowmeters	AR[(a)]	AR	AR	AR	AR	AR	AR	AR	Some may require calibration before assembly
All actuators	No	No	No	No	No	AR	AR	AR	
Lira IR analyzer	AR	AR	AR	No	No	No	No	No	
Cathode Feed Flow	Up to 600	0	1.0	72	67	No	No	No	
Coolant Flow	No	--	--	--	--	No	50	82	
Module Operation	140 to 280	0	1.0	72	67	6.0	50	82	O_2 Flow
Module Operation	311	55	1.0	72	67	6.0	50	82	CO_2/O_2 flow

(a) AR = As Required.

10/15/96

TABLE A-2 EOSM SHAKEDOWN TEST GRID

	Cathode Feed						Coolant		
	Rate, sccm	CO_2, %	P, psig	T, F	DP, F	Current, A	Flow, lb/hr	Temp, F	Monitored Parameters, Remarks, etc.
Module Operation	311	55	1.0	70	57	6.0	50	70	Minimum of 24 hours continuous operation

TABLE A-3 EOSM DESIGN VERIFICATION TEST GRID

	Cathode Feed					Current,	Coolant		Monitored Parameters,
	Rate, sccm	CO_2, %	P, psig	T, F	DP, F	A	Flow, lb/hr	Temp, F	Remarks, etc.
Module Operation	311	55	1.0	72	67	6.0	50	82	· Monitor all parameters · Adjust module coolant flow to operate cell at the specified temperature · Minimum of 3 days, with starts and stops

TABLE A-4 EOSM PARAMETRIC TEST GRID

Cathode Feed						Coolant		
Rate, sccm	CO_2, %	P, psig	T, F	DP, F	Current, A	Flow, lb/hr	Temp, F	Monitored Parameters, Remarks, etc.
140	0	1.0	72	67	6.0	50	82	· Monitor all parameters
233	40	1.0	72	67	6.0	50	82	
280	50	1.0	72	67	6.0	50	82	· Adjust module coolant flow to operate cell at the specified temperature and dewpoint
350	60	1.0	72	67	6.0	50	82	
175	0	1.0	72	67	7.5	50	82	
292	40	1.0	72	67	7.5	50	82	
350	50	1.0	72	67	7.5	50	82	
438	60	1.0	72	67	7.5	50	82	
117	0	1.0	72	67	5.0	50	82	
195	40	1.0	72	67	5.0	50	82	
234	50	1.0	72	67	5.0	50	82	
293	60	1.0	72	67	5.0	50	82	

TABLE A-5 ECSM CHECKOUT/CALIBRATION TEST GRID

	Cathode Feed (Air) Rate, scfm	Cathode Feed (Air) pCO_2, mm Hg	Cathode Feed (Air) T, F	Cathode Feed (Air) DP, F	Current, A	Coolant Flow, lb/hr	Coolant Temp, F	Monitored Parameters, Remarks, etc.
Assembly of Components	No	--	--	--	No	No	No	Verify correct installation of components
Pressure/Leak Test	No	--	--	--	No	No	No	Apply fluids but no flow (5 psid)
Calibration								
All sensors, gauges, flowmeters	AR[(a)]	AR	AR	AR	AR	AR	AR	Some may require calibration before assembly
All actuators	No	No	No	No	AR	AR	AR	
Lira IR analyzer	AR	AR	No	No	No	No	No	
Cathode Feed Flow	Up to 12.0	(b)	75	63	No	No	No	
Coolant Flow	No	--	--	--	No	50	80	
Module Operation	9.0	2.3	75	63	8.0	50	80	Anode Gas Exit Flow Rate and pCO_2

(a) AR = As Required.
(b) Ambient.

12/20/96

TABLE A-6 ECSM SHAKEDOWN TEST GRID

	Cathode Feed (Air)				Current, A	Coolant		Monitored Parameters, Remarks, etc.
	Rate, scfm	pCO_2, mm Hg	T, F	DP, F		Flow, lb/hr	Temp, F	
Module Operation	9.0	2.3	75	63	8.0	50	80	Minimum of 4 hours continuous operation

TABLE A-7 ECSM DESIGN VERIFICATION TEST GRID

	Cathode Feed (Air)				Current,	Coolant		Monitored Parameters,
	Rate, scfm	pCO_2, mm Hg	T, F	DP, F	A	Flow, lb/hr	Temp, F	Remarks, etc.
Module Operation	9.0	2.3	75	63	8.0	50	80	· Monitor all parameters · Adjust module coolant and humidifier conditions to operate cell at the specified temperature and RH · Minimum of 2 days, with starts and stops

TABLE A-8 ECSM PARAMETRIC TEST GRID

	Cathode Feed (Air)					Coolant		
	Rate, scfm	pCO_2, mm Hg	T, F	DP, F	Current, A	Flow, lb/hr	Temp, F	Monitored Parameters, Remarks, etc.
Nominal Air Condition	9.0	2.3	75	63	8.0	50	80	· Monitor all parameters
	9.0	2.3	75	63	4.0	50	80	
	9.0	2.3	75	63	10.0	50	80	
	9.0	3.5	75	63	8.0	50	80	
	9.0	3.5	75	63	4.0	50	80	
	9.0	3.5	75	63	10.0	50	80	
	9.0	1.0	75	63	8.0	50	80	
	9.0	1.0	75	63	4.0	50	80	
	9.0	1.0	75	63	10.0	50	80	

TABLE A-9 APC CHECKOUT/CALIBRATION TEST GRID

	Air Flow (ECSM) Rate, scfm	Air Flow (ECSM) pCO_2, mm Hg	Air Flow (ECSM) T, F	Air Flow (ECSM) DP, F	Current, A ECSM	Current, A EOSM	Module Temp., F ECSM	Module Temp., F EOSM	Coolant ECSM & EOSM Flow, lb/hr	Coolant ECSM & EOSM Temp, F	Monitored Parameters, Remarks, etc.
Assembly of Components	No	--	--	--	No	No	--	--	No	No	• Verify correct installation of components
Pressure	No	--	--	--	No	No	--	--	No	No	• Apply fluids but no flow • Bypass and Normal positions
Calibration • All sensors, gauges, flowmeters • All actuators • Lira IR analyzer	--	--	--	--	--	--	--	--	--	--	• Some may require calibration since last use
Air Flow	Up to 18.0	Amb	75	63	No	No	--	--	No	No	
Coolant Flow	--	--	--	--	No	No	--	--	50	80	
Module Delta Ps	--	--	--	--	No	No	--	--	No	No	• After charging before assembly
Module Operation											
ECSM	15.0	Amb	75	63	Up to	Up to	80	--	50	80	
EOSM	--	--	--	--	10	0.8 (ECSM)	--	82	50	80	• CO_2/O_2 and O_2 flow

TABLE A-10 APC SHAKEDOWN TEST GRID

	Air Flow (ECSM)				Current, A		Module Temp., F		Coolant ECSM & EOSM		Monitored Parameters, Remarks, etc.
	Rate, scfm	pCO_2 mm Hg	T, F	DP, F	ECSM	EOSM	ECSM	EOSM	Flow, lb/hr	Temp, F	
At EOSM Bypass Position: • Minimum one hour continuous operation	12.0	2.3	75	63	8.0	0.0	80	82	50	80	• ECSM anode exit flow vented
At Normal Position: • 4 hours	12.0	2.3	75	63	8.0	6.0	80	82	50	80	

TABLE A-11 APC DESIGN VERIFICATION TEST GRID

	Air Flow (ECSM)				Current, A		Module Temp., F		Coolant ECSM & EOSM		Monitored Parameters, Remarks, etc.
	Rate, scfm	pCO_2 mm Hg	T, F	DP, F	ECSM	EOSM	ECSM	EOSM	Flow, lb/hr	Temp, F	
At Normal Position:	12.0	2.3	75	63	8.0	6.0	80	82	50	80	• Monitor all parameters • Adjust modules' coolant flow rate and/or temperature to operate cells at the specified temperature

TABLE A-12 APC PARAMETRIC TEST GRID

	Air Flow (ECSM) Rate, scfm	pCO$_2$ mm Hg	T, F	DP, F	Current, A ECSM	Current, A EOSM	Module Temp., F ECSM	Module Temp., F EOSM	Coolant ECSM & EOSM Flow, lb/hr	Coolant ECSM & EOSM Temp, F	Monitored Parameters, Remarks, etc.
pCO$_2$	12.0	3.0 2.3 1.0	75	63	8.0	6.0	80	82	50	80	• Monitor all parameters
Dewpoint	12.0	2.3	75 80 65	63 67 40	8.0	6.0	80 83 55	82 85 60	50	80	• Adjust module's coolant flows rate and/or temperature to operate cells at the specified temperature and dewpoint
Current Density	12.0	2.3	75	63	8.0 4.0 10.0	6.0 3.0 7.5	80	82	50	80	

APPENDIX B

DATA SHEET FORMS

Life Systems, Inc. CLEVELAND, OHIO 44122	LOG OF TEST	SHEET 1 OF 1	DATE
	MODEL / PART NO. EOSM	TEST PLAN NO. TR-1739-3-2	
		PROJ. NO. 1705	

TYPE OF TEST	NAME OF RIG	TEST ENGR.
EOSM	EOSM Test Setup	F. H. Schubert

Data Point Number										
Date										
Time										
Amb. Temp., F										
Amb. Pres., mm Hg										
Current, A										
Cell Voltage, VDC										
Cell No. 1										
Cell No. 2										
Cell No. 3										
Cell No. 4										
Cell No. 5										
Module Voltage, VDC										
Cathode Feed										
O_2 Flow Meter										
O_2 Flow, accm										
CO_2 Flow Meter										
CO_2 Flow, accm										
O_2 %/CO_2 %										
Pressure, psig										
Temperature, F										
Dewpoint, F										
Coolant										
Coolant Flow Meter										
Coolant Flow, lb/hr										
Coolant Temp. Out, F										
Coolant Temp, In, F										
Product O_2										
Volume, acc										
Time, sec										
Flowrate, accm										
Theoretical Flow, sccm										
Efficiency, %										
Cathode Exit Flow										
Volume, acc										
Time, sec										
Flowrate, accm										
Lira Reading (R_Scale)										
CO_2, %										

F-606 (8/74)

OPERATOR SIGNATURE/DATE

Life Systems, Inc. CLEVELAND, OHIO 44122	LOG OF TEST MODEL / PART NO. ECSM	SHEET 1OF 2	DATE
		TEST PLAN NO. TR-1739-3-2	
		PROJ. NO. 1705	
TYPE OF TEST ECSM	NAME OF RIG ECSM Test Setup	TEST ENGR. F. H. Schubert	

Data Point Number										
Date										
Time										
Amb. Temp., F										
Amb. Pres., mm Hg										
Current, A (I1)										
Cell Voltage, VDC										
Cell No. 1 (E1)										
Cell No. 2 (E2)										
Cell No. 3 (E3)										
Cell No. 4 (E4)										
Cell No. 5 (E5)										
Cathode Feed (Air)										
CO_2 Flow Meter (F3)										
CO_2 Flow, accm										
Lira Reading (R_Scale)										
pCO_2, mm Hg										
pCO_2(Backgrd) mm Hg										
Temperature, F (T1)										
Dewpoint, F (D1)										
Coolant										
Coolant Flow Meter (F2)										
Coolant Flow, lb/hr										
Coolant Temp. Out, F (T3)										
Coolant Temp. In, F (T4)										
Product CO_2/O_2										
Volume, acc										
Time, sec										
Flowrate, accm										
Flowmeter (F1)										
Dewpoint, F (D3)										
Lira Reading (R_Scale)										
CO_2, %										
Pressure, psig (P1)										
Cathode Exit (Air)										
Temperature, F (T2)										
Dew Point, F (D2)										
Lira Reading (R_Scale)										
CO_2, %										

F-606 (8/74)

OPERATOR SIGNATURE/DATE

Life Systems, Inc. CLEVELAND, OHIO 44122	LOG OF TEST	SHEET 2 OF 2	DATE
	MODEL / PART NO. ECSM	TEST PLAN NO. TR-1739-3-2	
		PROJ. NO. 1705	
TYPE OF TEST ECSM	NAME OF RIG ECSM Test Setup	TEST ENGR. F. H. Schubert	

Data Point Number										
Date										
Calculated Values										
Air Flow, SCFM										
Air Inlet RH, %										
O_2 Theoretical, SCCM										
Air Outlet RH, %										
LSI-D Eqiv, Conc, %										
CO_2 Rem. EFF, %										
Transfer Index										
Avg. Cell Volts, VDC										

F-606 (8/74)

OPERATOR SIGNATURE/DATE

Life Systems, Inc. CLEVELAND, OHIO 44122	LOG OF TEST	SHEET 1OF 3	DATE
	MODEL / PART NO. ECSM of APC	TEST PLAN NO. TR-1739-3-2	
		PROJ. NO. 1705	
TYPE OF TEST INTEGRATED APC	NAME OF RIG APC Test Setup	TEST ENGR. F. H. Schubert	

Data Point Number										
Date										
Time										
Amb. Temp., F										
Amb. Pres., mm Hg										
Current, A (I1)										
Cell Voltage, VDC										
Cell No. 1 (E1)										
Cell No. 2 (E2)										
Cell No. 3 (E3)										
Cell No. 4 (E4)										
Cell No. 5 (E5)										
Cathode Feed (Air)										
CO_2 Flow Meter (F3)										
CO_2 Flow, accm										
Lira Reading (R_Scale)										
pCO_2, mm Hg										
pCO_2(Backgrd) mm Hg										
Temperature, F (T1)										
Dewpoint, F (D1)										
Coolant										
Coolant Flow Meter (F2)										
Coolant Flow, lb/hr										
Coolant Temp. Out, F (T3)										
Coolant Temp. In, F (T4)										
Product CO_2/O_2										
Flowmeter (F1)										
Dewpoint, F (D3)										
Pressure, psig (P1)										
Cathode Exit (Air)										
Temperature, F (T2)										
Dew Point, F (D2)										
Lira Reading (R_Scale)										
CO_2, %										

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OPERATOR SIGNATURE/DATE

Life Systems, Inc. CLEVELAND, OHIO 44122	LOG OF TEST	SHEET 2 OF 3	DATE
	MODEL / PART NO. EOSM OF APC	TEST PLAN NO. TR-1739-3-2	
		PROJ. NO. 1705	
TYPE OF TEST INTEGRATED APC	NAME OF RIG APC Test Setup	TEST ENGR. F. H. Schubert	

Data Point Number										
Date										
Time										
Current, A										
Cell Voltage, VDC										
Cell No. 1										
Cell No. 2										
Cell No. 3										
Cell No. 4										
Cell No. 5										
Coolant										
Coolant Flow Meter										
Coolant Flow, lb/hr										
Coolant Temp. Out, F										
Coolant Temp, In, F										
Product O_2										
Volume, acc										
Time, sec										
Flowrate, accm										
Cathode Exit Flow										
Volume, acc										
Time, sec										
Flowrate, accm										
Lira Reading (R_Scale)										
CO_2, %										

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OPERATOR SIGNATURE/DATE

Life Systems, Inc.
CLEVELAND, OHIO 44122

LOG OF TEST

MODEL / PART NO. ECSM OF APC

SHEET 3 OF 3 | DATE

TEST PLAN NO. TR-1739-3-2

PROJ. NO. 1705

TYPE OF TEST: INTEGRATED APC | NAME OF RIG: APC Test Setup | TEST ENGR.: F. H. Schubert

Data Point Number										
Date										
Calculated Values (ECSM)										
Air Flow, SCFM										
Air Inlet RH, %										
O_2 Theoretical, SCCM										
Air Outlet RH, %										
LSI-D Eqiv, Conc, %										
CO_2 Rem. EFF, %										
Transfer Index										
Avg. Cell Volts, VDC										
Calculated Values (EOSM)										
Theory O_2 Flow, SCCM										
O_2 Trnsfr. EFF, %										
Stoichiom. Flow In										
O_2 Removed, %										

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13. ABSTRACT (Maximum 200 words)

Life Systems completed a Ground-based Space Station Experiment Development Study Program which verifies through testing the performance and applicability of the electrochemical Air-Polarized Carbon Dioxide Concentrator (APC) process technology for space missions requiring low (i.e., less than 3 mm Hg) CO_2 partial pressure (pCO_2) in the cabin atmosphere.

Required test hardware was developed and testing was accomplished at an approximate one-person capacity CO_2 removal level. Initially, two five-cell electrochemical modules using flight-like 0.5 ft^2 cell hardware were tested individually, following by their testing at the integrated APC system level. Testing verified previously projected performance and established a database for sizing of APC systems.

A four person capacity APC system was sized and compared with four candidate CO_2 removal systems. At its weight of 252 lb, a volume of 7 ft^3 and a power consumption of 566 W while operating at 2.2 mm Hg pCO_2, the APC was surpassed only by an Electrochemical Depolarized CO_2 Concentrator (EDC) (operating with H_2), when compared on a total equivalent basis.

14. SUBJECT TERMS
Air-Polarized CO_2 Concentrator Development, CO_2 Removal System, Low pCO_2, Electrochemical, Air Revitalization

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