NASA CONTRACTOR REPORT 166538

Electrochemical Carbon Dioxide Concentrator Subsystem Development - Final Report

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. at Cleveland, Ohio under Contract NAS2-11129, during the period of December, 1981 through November, 1983. The Program Manager was Dr. Dennis B. Heppner. The personnel contributing to the program and their responsibilities are outlined below:

Personnel	Area of Responsibility
Mike J. Dahlhausen	Control and Monitor Instrumentation Software and Computer Hardware
Tim H. Hallick	Program Testing, Data Reduction, Module/Cell Configurations, Fabrication and Assembly
Dennis B. Heppner, Ph.D.	Program Manager, System Design and Analysis
Don W. Johnson	Control and Monitor Instrumentation Fabrication and Electronic Device Design, Assembly and Checkout
Ray Klimas	Control and Monitor Instrumentation Hardware Design
Eugene P. Koszenski	Product Assurance, Electrode/Matrix Development
Joel B. Lantz, Ph.D.	TRRHS Concept Review, Trade Studies and Design
Brian N. Livaich	Mechanical Component/System Assembly and Checkout, Data Recording
Franz Schubert	System Integration and Electrochemical Design

The contract's Technical Monitor is P. D. Quattrone, Chief, Advanced Life Support Office, NASA Ames Research Center, Moffett Field, CA.

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LIST OF ACRONYMS

A/D	Analog/Digital
BID	Built-in Diagnostic
CCA	Coolant Control Assembly
C/M I	Control/Monitor Instrumentation
CPU	Central Processing Unit
CS-1	One-Man Person EDC CO_2 Removal Subsystem
DVT	Design Verification Test
EDC	Electrochemical Depolarized CO_2 Concentrator
EDCM	EDC Module
EPROM	Erasable Programmable Read-Only Memory
FCA	Fluids Control Assembly
M/E A	Mechanical/Electrochemical Assembly
NASA	National Aeronautics and Space Administration
POR	Power on Reset
RAM	Random Access Memory
RH	Relative Humidty
RTD	Resistive Thermal Device
TRRHS	Triple Redundant RH Sensor
TSA	Test Support Accessories

SUMMARY

Regenerative carbon dioxide removal techniques are needed to sustain man in space for extended periods of time. The most promising concept for a regenerative carbon dioxide removal system is the Electrochemical Depolarized Carbon Dioxide Concentrator. This device allows for the continuous, efficient removal of carbon dioxide from the spacecraft cabin and delivery of the carbon dioxide premixed with hydrogen to a carbon dioxide reduction subsystem for subsequent oxygen recovery.

The objectives of this program for the Electrochemical Carbon Dioxide Concentrator subsystem were to (1) achieve high level of performance of a one-person electrochemical carbon dioxide concentrator subsystem with the ability to operate over wide ranges in relative humidity and H_2 back pressure, (2) demonstrate reliability by endurance testing the major components of an electrochemical concentrator subsystem, (3) demonstrate achievement of reproducible electrochemical cell and module performance and subsystem simplification concepts through extensive testing and (4) continue to improve and develop needed ancillary components. These objectives were successfully met. The program included (1) the fabrication, assembly and testing of an advanced one-person carbon dioxide removal subsystem based on a new electrochemical cell and module concept and unitized core composite cells, (2) endurance testing of the three major components of an electrochemical concentrator, i.e., a six-cell module with unitized composite cores, a Coolant Control Assembly and a Fluids Control Assembly, (3) test support accessories required for subsystem testing and (4) a preliminary design for a triple redundant relative humidity sensor with in situ calibration. A detailed mockup of an electrochemical concentrator subsystem as would be applicable for the Space Station was also developed.

A one-person electrochemical concentrator subsystem was fabricated, assembled and tested. The electrochemical module consists of six cells of a new construction. The new construction permitted the fabrication of any size modules without having to alter process air inlet and outlet duct work. All ancillary components fit onto an end plate which is easily adaptable to any size subsystem. A newly developed microcomputer based instrumentation, which is roughly 75% smaller in weight, volume and power than the previous series of instrumentation, was fabricated and used to control the one-person subsystem. The one-person system consistently demonstrated high level, repeated performance over 1,800 hours of operation and relative humidity variations between 30 and 85%. Average carbon dioxide removal efficiency was typically between 90 and 100% (versus the 85% design point) at a nominal carbon dioxide partial pressure of 400 Pa (3.0 mm of Hg). The cell voltages averaged 0.42 V. The module nominally sustained 35 kPa (5 psig) H_2-to-air differential pressures.

Endurance testing of three electrochemical carbon dioxide removal subsystem components was continued under the program. Over 11,000 h of additional operation was achieved on the six-cell module having the unitized composite core construction. Average carbon dioxide removal efficiency was typically greater than 70% at nominal carbon dioxide partial pressures of 400 Pa (3 mm of Hg). Cell voltages averaged 0.35 V.

A Fluids Control Assembly with its test stand performed for a total of 9,500 additional hours, which included over 10,000 test cycles. No failure of the Fluids Control Assembly was observed. The Coolant Control Assembly performed at or above its design point levels for over 9,400 additional hours (18,800 typical test cycles) Satisfactory mechanical performance was achieved on both of these devices.

A concept for a triple redundant relative humidity sensor based on directly sensing the moisture content of air was designed. The design incorporates in situ calibration with a repeatable gas pressure calibration source.

PROGRAM ACCOMPLISHMENTS

The key program accomplishments were as follows:

- Completed the fabrication of a one-person Electrochemical Depolarized carbon dioxide (CO_2) Concentrator (EDC) subsystem incorporating advanced electrochemical, mechanical and control and monitor instrumentation (C/M I) concepts. This subsystem, called the CS-1, included the design of an advanced, liquid-cooled unitized core/composite cell EDC module (EDCM) that features superior performance stability, inlet air relative humidity (RH) range tolerance, pressure capability and thermal characteristics and lower unit weight and volume relative to prior modules.

- Completed over 1,800 h of testing of the CS-1 with CO_2 removal efficiencies between 90 and 100%

- Designed and fabricated two new molds for injection molding polysulfone cell frame parts. The cell frames together with a new unitized core assembly permitted the assembly of six cell frames for the CS-1.

- Completed endurance testing of a prototype Fluids Control Assembly (FCA) which integrates 11 gas handling components required by the CS-1 into a single unit.

- Completed endurance testing of a prototype Coolant Control Assembly (CCA), which integrates a coolant pump, diverter valve and a liquid accumulator into a single unit.

- Modified a test stand which provided all the fluid, electrical and shutdown requirements for long-term, unattended testing of the CS-1.

- Developed a four-person EDC mockup. This mockup is useful to demonstrate the size of the CO_2 removal subsystem as would be developed for a Space Station.

- Completed a preliminary design of a triple redundant RH sensor (TRRHS), which will have in situ calibration and which will be miniature relative to the present RH or dew point sensor.

INTRODUCTION

Regenerative processes for revitalization of spacecraft atmospheres are essential for making long-term manned space missions a reality. An important air revitalization step is the collection and concentration of metabolically produced CO_2 for subsequent oxygen (O_2) recovery. This report discusses development of an electrochemically-based subsystem which performs that function.

Background

The EDC technique is the most promising technique for concentrating low level CO_2 from the air without incurring large weight and volume penalties. The EDC removes CO_2 continuously from low CO_2 partial pressure in a flowing air stream. The CO_2 exhaust, premixed with H_2, can be sent to a CO_2 reduction subsystem for recovery of the O_2 from the CO_2 or vented, as required. The EDC also generates electrical power which can be used in other life support processes (e.g., O_2 generation by water electrolysis) if that is desired.

The CO_2 removal process takes place in a module consisting of a series of electrochemical cells. Each cell consists of two electrodes separated by a matrix containing an aqueous carbonate electrolyte solution. Plates adjacent to the electrodes provide passageways for distribution of gases and electrical current. Figure 1 shows the functional schematic of the EDC cell. Figure 2 details the specific electrochemical and chemical reactions which occur at the electrodes. As shown in Figure 2, the overall reaction is

$$O_2 + 2\ CO_2 + 2\ H_2 = 2\ CO_2 + 2\ H_2O + \text{electrical energy} + \text{heat} \qquad (1)$$

A theoretical maximum of two moles of CO_2 can be transferred for one mole of O_2 consumed. The observed ratio of CO_2 transferred to O_2 consumed represents the process removal efficiency. A defined efficiency of 100% occurs when 2.75 kg (6.05 lb) of CO_2 is removed for each kg (2.2 lb) of O_2 consumed.

The EDC concept utilizing alkaline metal carbonate electrolytes has evolved at Life Systems, Inc. (LSI) under the National Aeronautics and Space Administration (NASA) sponsorship through Contracts NAS2-6118, NAS2-6478, NAS2-8666 and NAS2-10204.[1-12] The concept has progressed from operation of single EDC cells to fabrication and testing of one-, three-, four- and six-person self-contained subsystems. These previous research and development activities resulted in demonstrated performance improvements in the electrodes, the electrolyte and the electrolyte retaining matrix. These programs also include development of unique peripheral components and advancement of technology relating to EDC subsystem integration with other spacecraft air revitalization subsystems.

(1-12) References cited at the end of this report.

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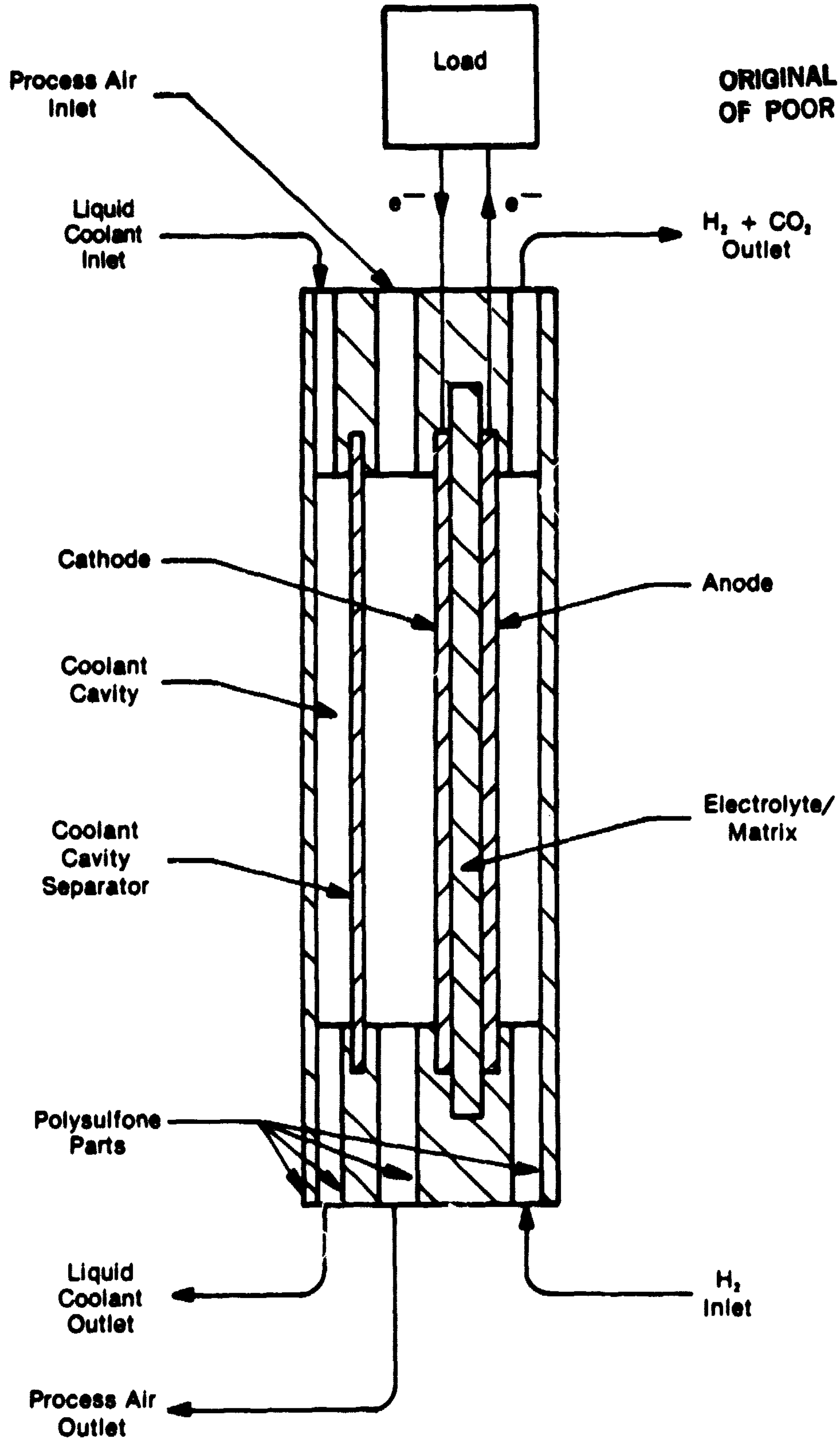
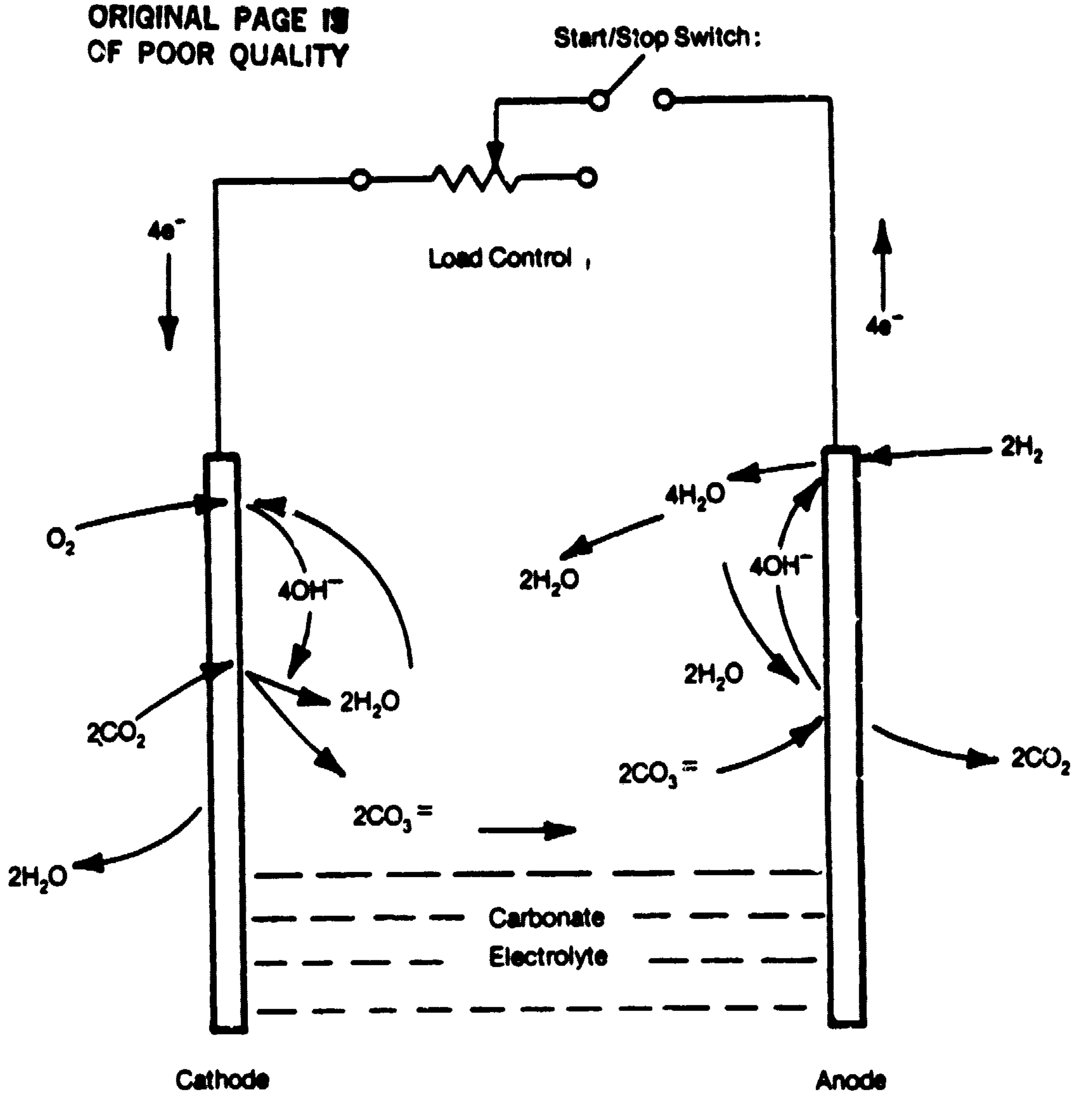


FIGURE 1 EDC SINGLE-CELL SCHEMATIC



Cathode Reactions:

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

Anode Reactions:

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

Overall Reaction:

$O_2 + 2CO_2 + 2H_2 = 2CO_2 + 2H_2O$ + Electrical Energy + Heat

FIGURE 2 EDC FUNCTIONAL SCHEMATIC WITH REACTIONS

Program Objectives

The objectives of this program were to:

1. Using newly designed hardware, including cell frames and composite cores, fabricate and test a one-person liquid cooled EDC subsystem (the CS-1).

2. Demonstrate achievement of reproducible electrochemical module performance and subsystem simplification concepts through extensive testing.

3. Simplify and increase EDC subsystem reliability by design of a TRRHS.

4. Achieve reproducible and predictable high level EDC performance over ranges of relative humidity, H_2 backpressure and inlet CO_2 partial pressure for the CS-1 subsystem wider than previously demonstrated.

5. Continue to improve EDC subsystem performance.

The objectives of the program were met.

Report Organization

This Final Report covers the work performed during the period December, 1981 through November, 1983. The following major sections of this report present the technical results grouped according to:

- Advanced EDC cell and module
- One-person CO_2 removal subsystem
- Test support accessories
- Testing
- Supporting activities

These sections are followed by conclusions and recommendations based upon the work performed and by the references cited in the text.

ADVANCED EDC CELL AND MODULE

The heart of the EDC CO_2 Removal Subsystem is the EDCM and considerable attention was given to improving the individual cells and the overall module. The objectives of the composite cell with unitized core development were to achieve reproducible and predictable high level EDC performance over extended ranges of differential cell pressure and process air RH. The unitized core concept enables such improvements by providing permanently bonded, versus mechanically sealed, cell construction. This technology prevents gas leakage across the edges of a cell matrix and therefore permits operation at higher H_2-to-air differential pressures. It also provides uniformed matrix support and thickness both up to and including the edges, resulting in uniform electrolyte distribution and a superior RH tolerance range. The following subsections describe the core design and fabrication, the cell fabrication and the advanced EDC module.

Unitized Core Fabrication

Since a major driver for composite EDC cell construction was to enhance pressure differential and broaden RH capabilities, primary emphasis was directed toward selection of compatible materials and the fabrication technique for the unitized core, the heart of the cell. Following material selection, preliminary methodology and equipment were defined for fabricating the building

blocks of the unitized core (matrix, gas cavity spacers and electrodes) and assembly of the core. Initial fabrication procedures were then written, and fixtures were fabricated to allow building of a breadboard 7.3 x 7.3 cm (3 x 3 in) cell. This activity was performed on a prior program and showed that the fabrication procedures could be used to successfully develop a unitized core.(11) Under the present program these procedures and fixtures were upgraded to permit the fabrication of a unitized core for the new CS-1 cell design, which has an active area of 465 cm^2 (0.5 ft^2). Six of these unitized core assemblies were fabricated for the CS-1 and none failed throughout the testing of this subsystem.

The unitized core combines the following five major elements of the electrochemical cell: (1) Process air gas cavity spacer, (2) the airside electrode (cathode), (3) the cell matrix, (4) the hydrogen side electrode (anode) and (5) the H_2 gas cavity spacer. Fabrication of the unitized core involves, first, the application of epoxy rims around the perimeters of the process gas cavity spacers and the cell matrix. This creates three subassemblies. These subassemblies are then combined with the electrodes, using more epoxy, to form the unitized core. This approach provides a uniform support of the cell matrix over its entire area, thereby avoiding edge distortion, maximizing gas pressure sealing characteristics of the electrochemical cell and promoting uniform response of the electrolyte to humidity changes.

The key structural material selected for the unitized core fabrication is an epoxy resin. It forms the frames around the matrix and the expanded metal gas cavity spacers and provides final sealing of the various building blocks to form the unitized core. This material is compatible with the environment, exhibits sufficient strength and has the needed flexibility. Critical requirements of the fabrication process include maintaining proper epoxy thickness and uniformity and excluding air bubbles and pockets in the cured epoxy rim. These parameters are controlled using combinations of heat, pressure and vacuum applications. Care must be taken to ensure that all components of the core are properly aligned with respect to the gas inlet and outlet areas, that the cell matrix and electrode active areas are free from epoxy, and that an effective epoxy seal is achieved around the edge of the unitized core.

Composite Cell Fabrication

The overall concept for the composite EDC cell design and fabrication consists of the unitized core as discussed above, injection-molded polysulfone plastic frames for manifolding and distributing the process gases and internal coolant, and current collectors for delivering current to the cell. The composite cell polysulfone cell frame is fabricated as two sections - an air frame and an H_2 frame. These are so named because of the process fluids, air and H_2, that they come in contact with. A coolant cavity cover is epoxied to the air frame and then the cathode current collector is laser-welded to the current tabs. The H_2 frame, with the anode current collector laser-welded to its current tab, is then epoxied together with the air frame. This fabrication process provides an isolated internal liquid coolant cavity for the EDC cells.

Process fluid isolation is accomplished by an arrangement of O-rings that provide seals between each composite cell in the module stack. A molded O-ring was designed and fabricated to provide intercell sealing around the entire periphery of the cell frame. This provided sealing of process air from internal to external of the module.

Figure 3 shows the unitized core and composite cell elements. Under this program, five molds were designed, fabricated and used to make cell parts. Two large molds were used to make the two polysulfone cell frame parts. The H_2 frame, in particular, was the most difficult to injection mold because of its large size and thickness. Several trial and error molding injection attempts were made until the parts came out satisfactorily. Nonetheless, the molds were very precise: the parts (air and H_2 frames) from the two separate molds fit together almost perfectly. Three smaller molds were developed for a large sealing O-ring and two types of silver tabs (one for each type of frame) used to transfer the current to the silver foil current collectors. All other cell parts were machined or purchased as commercially available parts.

Advanced EDC Module

The advanced EDCM is designed as a liquid-cooled module, composed of six unitized core composite cells for superior performance and differential pressure capability. Each composite cell consists of the electrochemical elements described above. The selected number of cells, six, was based on the one-person CO_2 removal rate of 1.0 kg/d (2.2 lb/d) and a current density of 21.3 mA/cm^2 (19.8 ASF). The module has additional CO_2 removal capacity if operated at higher current density.

The advanced composite cell frames incorporated into the CS-1 feature integral process air manifolds. These are apparent in the module drawing, Figure 4. This design simplifies interfacing with the process air; only one set of inlet and outlet ducts are required to interface the process air no matter how many cells are in the module. It also enhances module storage life by permitting capping of the manifolds to avoid dryout (versus sealing the module in plastic bag). Most importantly, it allows vacuum charging of the total module (versus one cell at a time) with electrolyte. This ensures uniform charging of all cells, allows isolation of the cells from the atmosphere after they are charged (since they are already assembled into a module) and saves considerable time.

The advanced, composite cell frame design provided vastly improved (from prior cell designs), permanently sealed coolant cavities. The several advantages of this design were proven during testing:

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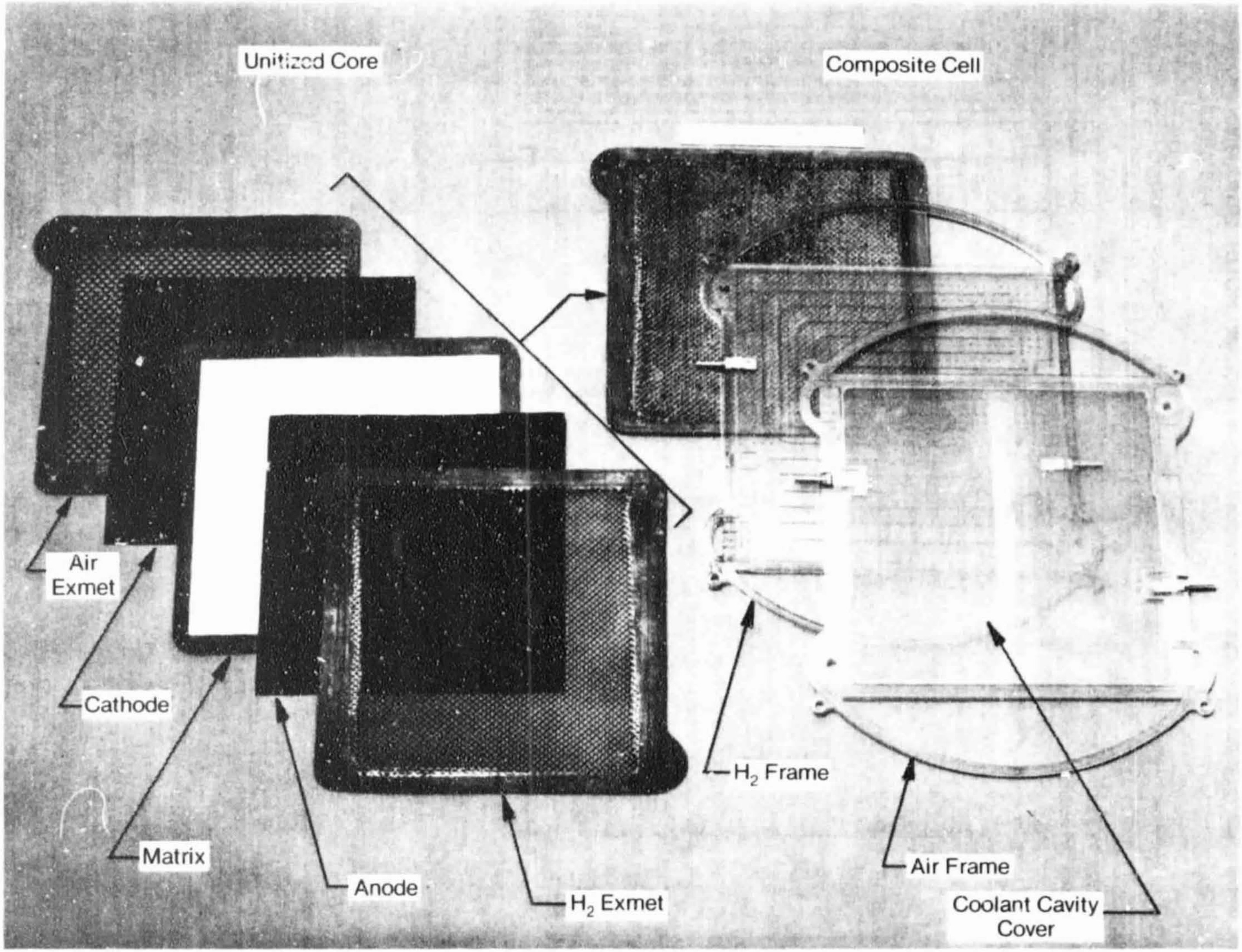

FIGURE 3 CS-1 UNITIZED CORE AND COMPOSITE CELL

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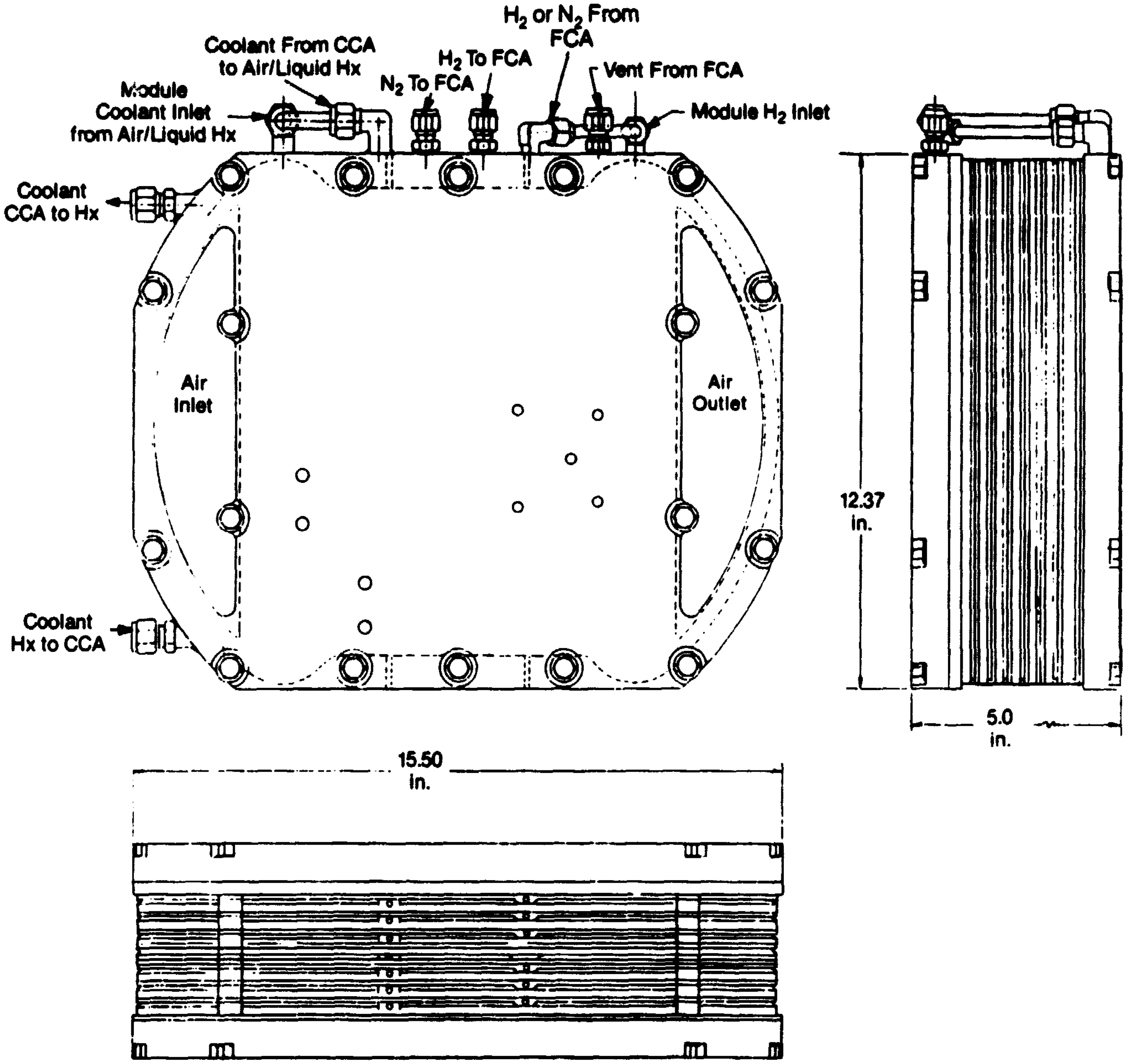

FIGURE 4 COMPOSITE CELL EDC MODULE FOR CS-1

- First, the coolant cavity design significantly improved thermal conduction from the cathode, where most of the heat is produced, because the thickness of plastic between it and the coolant was minimized. Heat removal and cell temperature regulation was therefore improved. Conversely, the new design reduced thermal conduction from the anode, where water is produced, since there now exists an increased thickness of insulating plastic and a foil current collector. This provides desirably higher anode temperatures. The effect was to provide improved cooling and temperature regulation at the primary point of heat production and promote water removal at the point of water generation.

- Second, when cell operation ceases, the anode temperature drops to the coolant temperature at the same time water production stops, and cell dryout is avoided. Conversely, the coolant temperature is not so low as to permit condensation. This was again borne out in the testing; approximately 15 applications of current (startup) occurred with no problems. This approach also should avoid damage to cells that electrically are isolated by any in situ cell maintenance techniques that jumper out inactive cells.

- The bonded cavity seal proved to be more reliable than the prior mechanical (O-ring) seals. Throughout the testing there were no leaks from the internal H_2 cavity to the external atmosphere or across the matrix from the H_2 to the air side. The module held pressure at 34.5 kPa (5 psig) from the beginning of the testing to the end.

- The coolant is intrinsically electrically isolated from the cell, eliminating the need to electrically isolate coolant components. Indeed, in the CS-1 design the coolant is distilled water. There was no need to use specialized nonconducting fluids as in the past. There were no electrical grounding problems associated with the CS-1.

The CS-1 EDCM component weight summary is shown in Table 1. It should be noted that the top and bottom end plates used in the CS-1 were made from stainless steel and naturally were heavy. Stainless steel was selected for several reasons. First, the material was inexpensive and machining costs were fairly minimal. Secondly, the top end plate and, to a certain extent the bottom, contain fluid pathways and structural strength was required to ensure no breakthrough of these pathways. For instance, the top end plate has nine separate channels drilled into it. With stainless steel, these channels could be drilled and then plugged and welded on the outside. With other materials the sealing would be more difficult. Another reason was the unavailability of the desired alternate material (glass-filled polysulfone) in the size required to make the end plates. Even though the stainless steel was a convenient and at this point, necessary material it is recognized that the top and the bottom end plates presently comprise almost 80% of the total CS-1 EDCM weight. Probably a 60 to 70% reduction in this area can be achieved with alternate materials. However, these have to be evaluated in terms of structural strength and their ability to support the various internal passages without other impacts (such as significantly increased thickness).

TABLE 1 CS-1 EDCM WEIGHT SUMMARY

Part	Qty	Unit Weight, kg (lb)	Total Weight kg (lb)
Top End Plate Assembly	1	16.40 (36.00)	16.40 (36.00)
Bottom End Plate Assembly	1	20.10 (44.20)	21.10 (44.20)
Top Insulation Plate	1	0.91 (2.00)	0.91 (2.00)
Bottom Insulation Plate	1	1.00 (2.20)	1.00 (2.20)
H_2 Frame	7	0.30 (0.67)	2.13 (4.69)
Air Frame	7	0.08 (0.17)	0.54 (1.19)
Unitized Core	6	0.33 (0.73)	1.99 (4.38)
Coolant Cavity Cover	7	0.09 (0.20)	0.64 (1.40)
Molded O-ring	9	0.01 (0.03)	0.12 (0.27)
H_2 Frame Current Collector	6	0.05 (0.12)	0.33 (0.72)
Air Frame Current Collector	6	0.06 (0.13)	0.35 (0.78)
FCA Adapter Plate	1	0.60 (1.32)	0.60 (1.32)
CCA Adapter Plate	1	0.71 (1.57)	0.71 (1.57)
Bolts, Washers, Nuts, Epoxy	Misc.	0.55 (1.20)	0.55 (1.20)
		Total	46.33 (101.92)[a]

a. A flight unit, with lightweight end plates, would weigh 20.8 kg (45.8 lb)

ONE-PERSON CO_2 REMOVAL SUBSYSTEM

The major achievement under this program was the fabrication, assembly and successful testing of a one-person CO_2 removal subsystem, the CS-1. This section describes the design and fabrication of the CS-1. Testing is covered in a subsequent section. This section includes a general description including specifications and a schematic, a description of the Mechanical/Electrochemical Assembly (M/E A) and a description of the C/M I.

General Description

The overall CO_2 removal process and control scheme is shown in Figure 5. The M/E A includes a six-cell EDCM and all components required to sense and control gaseous and liquid fluid flows to and from this module. The C/M I controls overall subsystem operation through the sensors and actuators located on the M/E A. The C/M I also monitors and interprets subsystem operational parameters and through the use of a communication link can display values on a separate video monitor. It can also, through the communication link, provide for appropriate changes in operational modes in response to operator inputs or subsystem malfunctions.

Application

Two applications were considered for the CS-1. They include use in the Shuttle Orbiter as a replacement of the existing lithium hydroxide (LiOH) CO_2 removal function. The second application is part of a central air revitalization system as would be found in the Space Station. Because of increased interest in the Space Station recently, the CS-1 was tested extensively in the central application range.

Specifications

General design specifications are listed in Table 2. The RH/temperature range projected for the Space Station application is shown in Figure 6. Overall fluid, electrical and thermal inputs and outputs for the CS-1 are further illustrated in Figure 7.

Mechanical/Electrochemical Assembly

The M/E A is illustrated schematically in Figure 8. The four primary components are:

- The EDCM, which is the CO_2 concentration element
- An FCA, which regulates EDCM back pressure and N_2 and H_2 flows
- The CCA, which in conjunction with the liquid/liquid heat exchanger permits temperature regulation of the EDCM
- A current controller (liquid-cooled), which regulates the current to the EDCM

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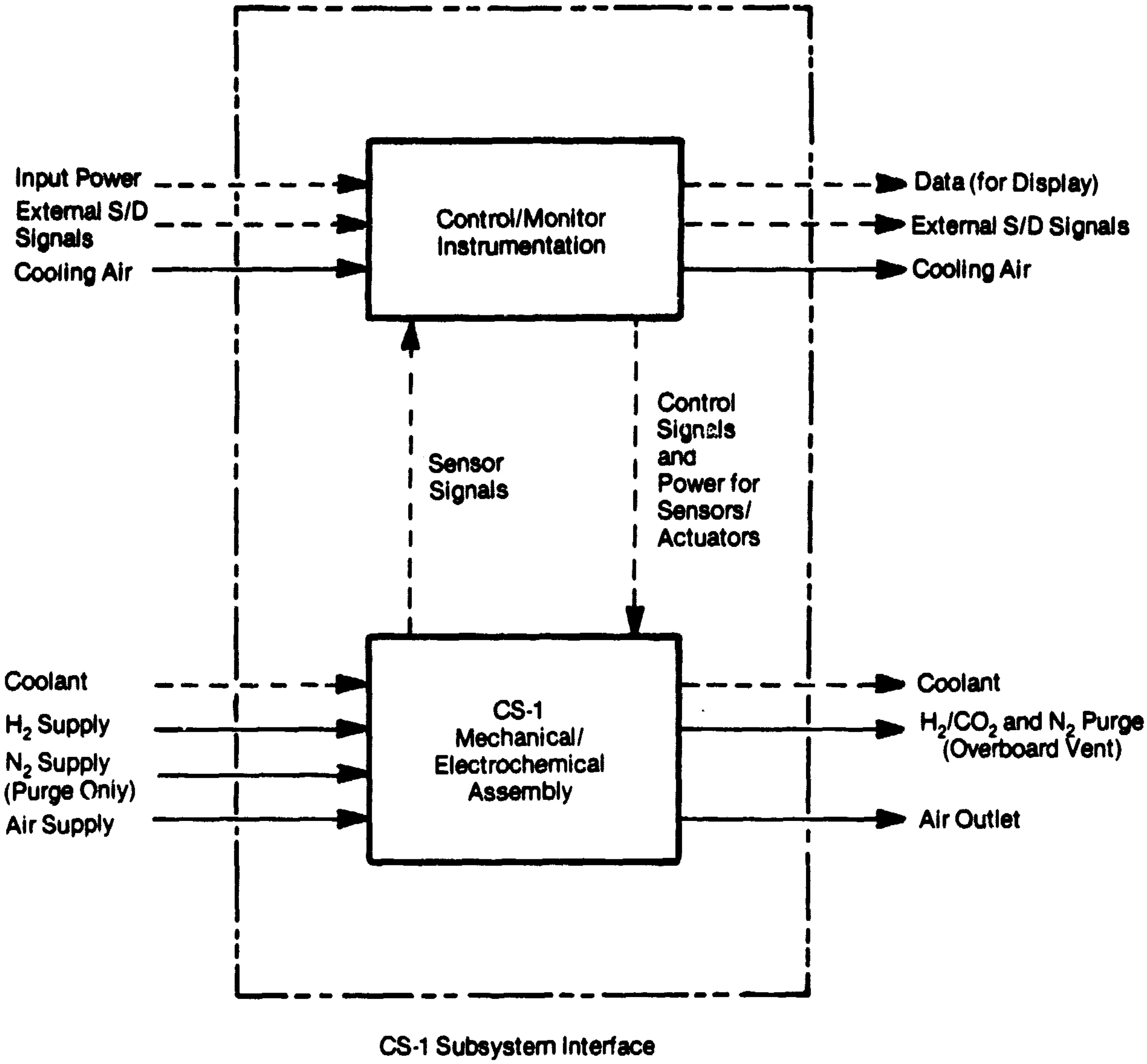

FIGURE 5 CS-1 PROCESS BLOCK DIAGRAM

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TABLE 2 CS-1 DESIGN SPECIFICATIONS

	Application	
	Central	Shuttle
Crew Size	1	1
CO_2 Removal Rate, kg/d (lb/d)	1.0 (2.2)	1.0 (2.2)
Cabin pCO_2, Pa (mm Hg)		
Daily Average	400 (3.0)	667 (5.0)
Maximum	667 (5.0)	1.013 (7.6)
Cabin pO_2, kPa (psia)	22.1 (3.2)	22.1 (3.2)
Cabin Temperature, K (F)	286 to 297 (60 to 75)	291 to 302 (65 to 84)
Cabin Dew Point, K (F)	277 to 286 (40 to 60)	277 to 289 (39 to 61)
Cabin Pressure, kPa (psia)	101 (14.7)	101 (14.7)
Process Air Humidity Range, %	See Figure 6	20-80
Liquid Coolant		
Temperature (max), K (F)	280 (45)	275 to 295 (35 to 71)
Flow Rate, kg/h (lb/h)	432 (950)	432 (950)
H_2 Supply		
Flow Rate, kg/h (lb/h)	0.007 (0.014) 2.9 Stoichiometric (at 9.9A)	0.0024 (0.0053) 1.2 Stoichiometric (at 9.0A)
Pressure, Pa (psia)	173 (25)	173 (25)
Relative Humidity, %	0 to 75	0 to 5
Purge Gas		
Type	N_2	N_2
Pressure, kPa (psia)	173 (25)	173 (25)
Electrical Power		
VAC	115, 400 Hz, 1Ø	115, 400 Hz, 1Ø
VDC	28	28
Gravity	0 to 1	0 to 1
Noise Criteria, db	55	55

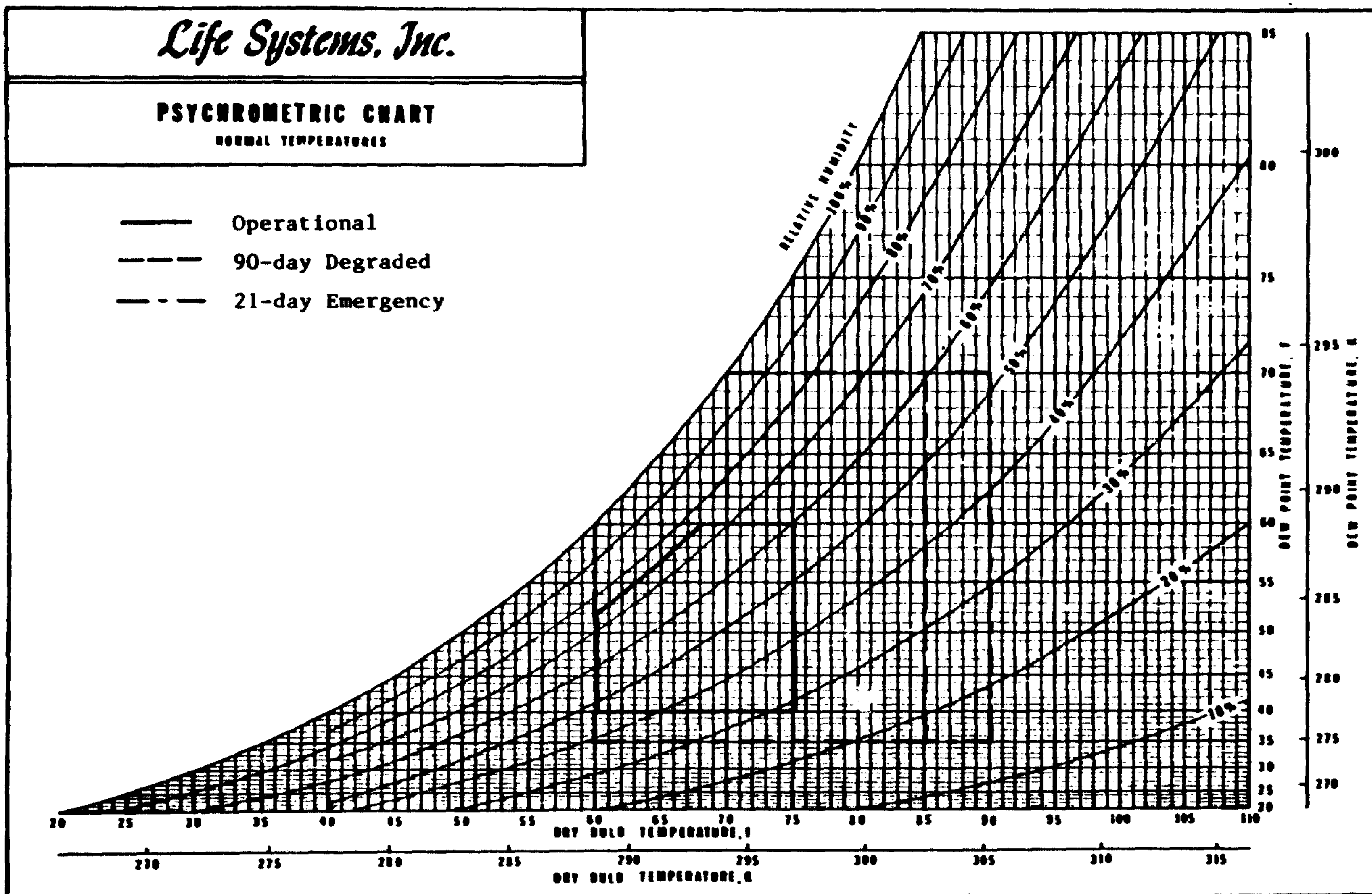

FIGURE 6 CENTRAL AIR HUMIDITY SPECIFICATION RANGES

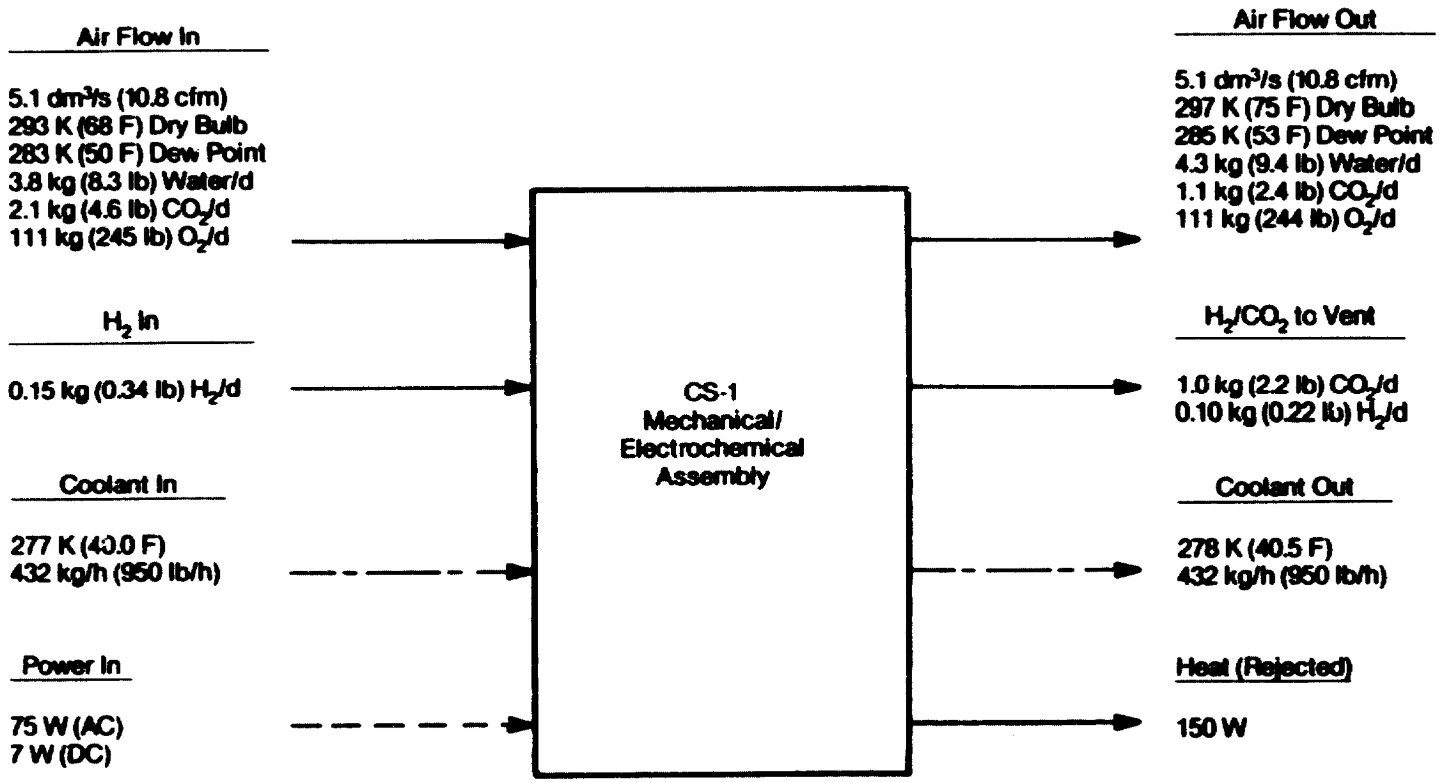

FIGURE 7 CS-1 MASS AND ENERGY BALANCE

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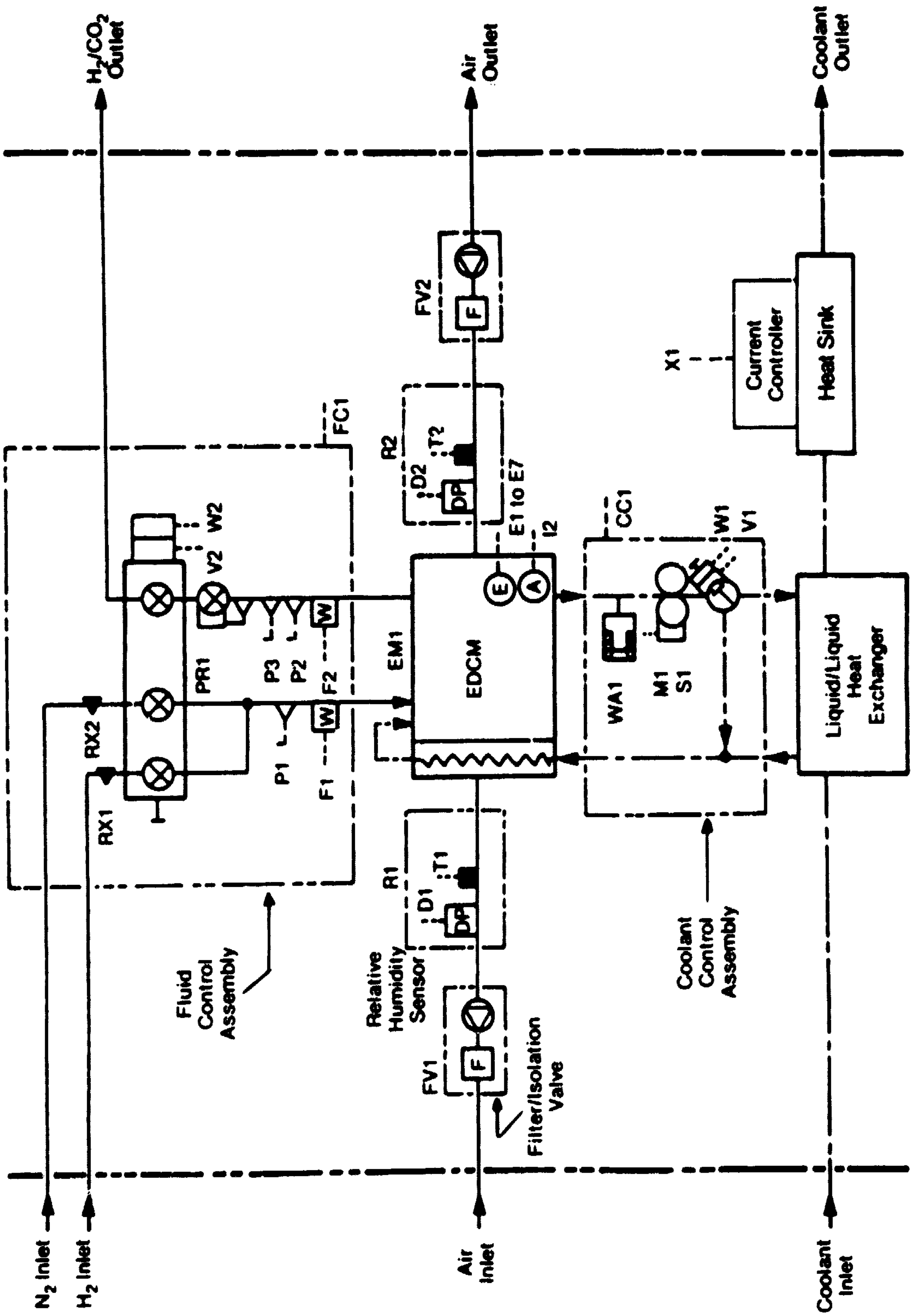

FIGURE 8 CS-1 MECHANICAL SCHEMATIC

In addition to the primary components, two of which integrate several discrete device functions, the subsystem includes: (a) two filter/isolation valves (inlet and outlet), (b) two dry bulb temperature sensors (c) two dew point temperature sensors, which when combined with the dry bulb temperature sensors, are used to measure inlet and outlet RH and (d) a liquid/liquid heat exchanger.

The principal M/E A components besides the EDCM, which was discussed previously, are described further below.

Fluids Control Assembly

The CS-1 EDCM, like its precursors, will require monitoring and control of H_2 flow, H_2 back pressure and N_2 purge gas flow. These functions previously performed by 11 discrete components, have now been integrated into a single, lightweight, low volume FCA. This assembly, pictured in Figure 9, was developed under a prior program and has been endurance tested for almost 20,000 hours. The CS-1 is the first application for the FCA in a subsystem.

Coolant Control Assembly

Three elements are essential for temperature control of the liquid-cooled EDCM: a circulation pump, a diverter valve to regulate the proportions of module coolant flowing through and around a liquid/liquid heat exchanger (connected to a central coolant source) and a liquid/gas accumulator to accommodate module coolant expansion/contraction. These discrete components, which require individual mounting and interconnecting plumbing, have been replaced by an integrated CCA. This item, pictured in Figure 10, also was developed under a prior program and has been extensively endurance tested and this program represents the first time it has been used in a CO_2 removal subsystem.

Current Controller

The current controller, Figure 11, provides a regulated current sink for the power generated by the EDCM. For the CS-1 it is packaged as a separate device. It is designed to be liquid cooled and located with the CS-1 M/E A. The central coolant source that interfaces with the CCA also removes the waste heat from the current controller. Placement of the current controller near the EDCM reduces the length of the electrical leads between the module and the current controller and thereby minimizes voltage drops.

The CS-1 current controller was fabricated, checked out and installed in the subsystem. This unit is an improvement over prior EDC current controllers, not only in size reduction but also in the method and efficiency of controlling current and dissipating the EDCM-produced power. It uses power field effect transistors mounted on a thermal surface (see Figure 12) and instrumentation amplifiers for control and sensing. The thermal surface or base of the current controller is in direct contact (physical and thermal) with a liquid-cooled heat sink in normal operation as shown in Figure 13. The current controller was packaged separately from the heat sink to allow removal and maintenance of the controller without breaking into the spacecraft coolant line. Characteristics and operating conditions of the current controller and heat sink are

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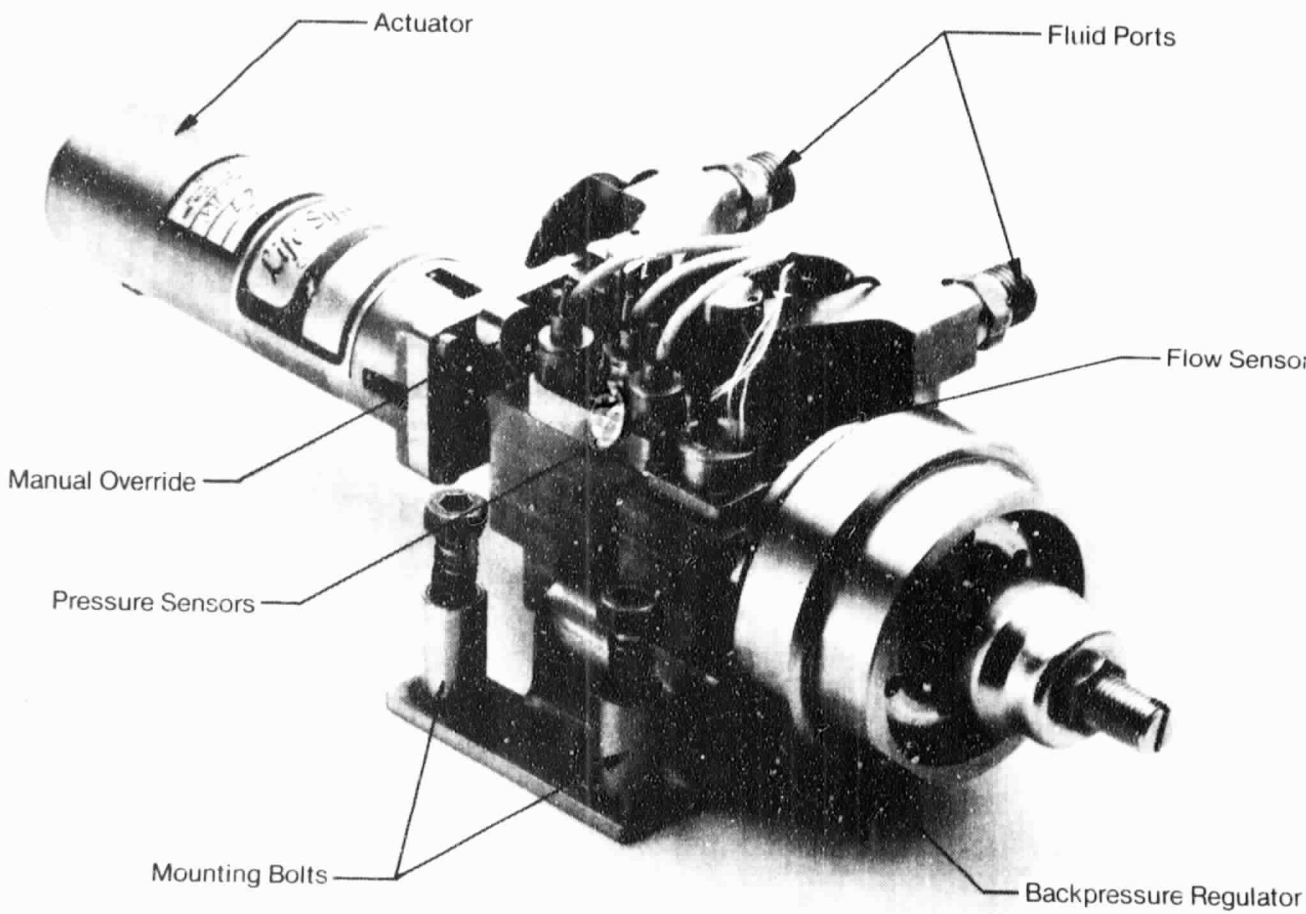

FIGURE 9 FLUIDS CONTROL ASSEMBLY

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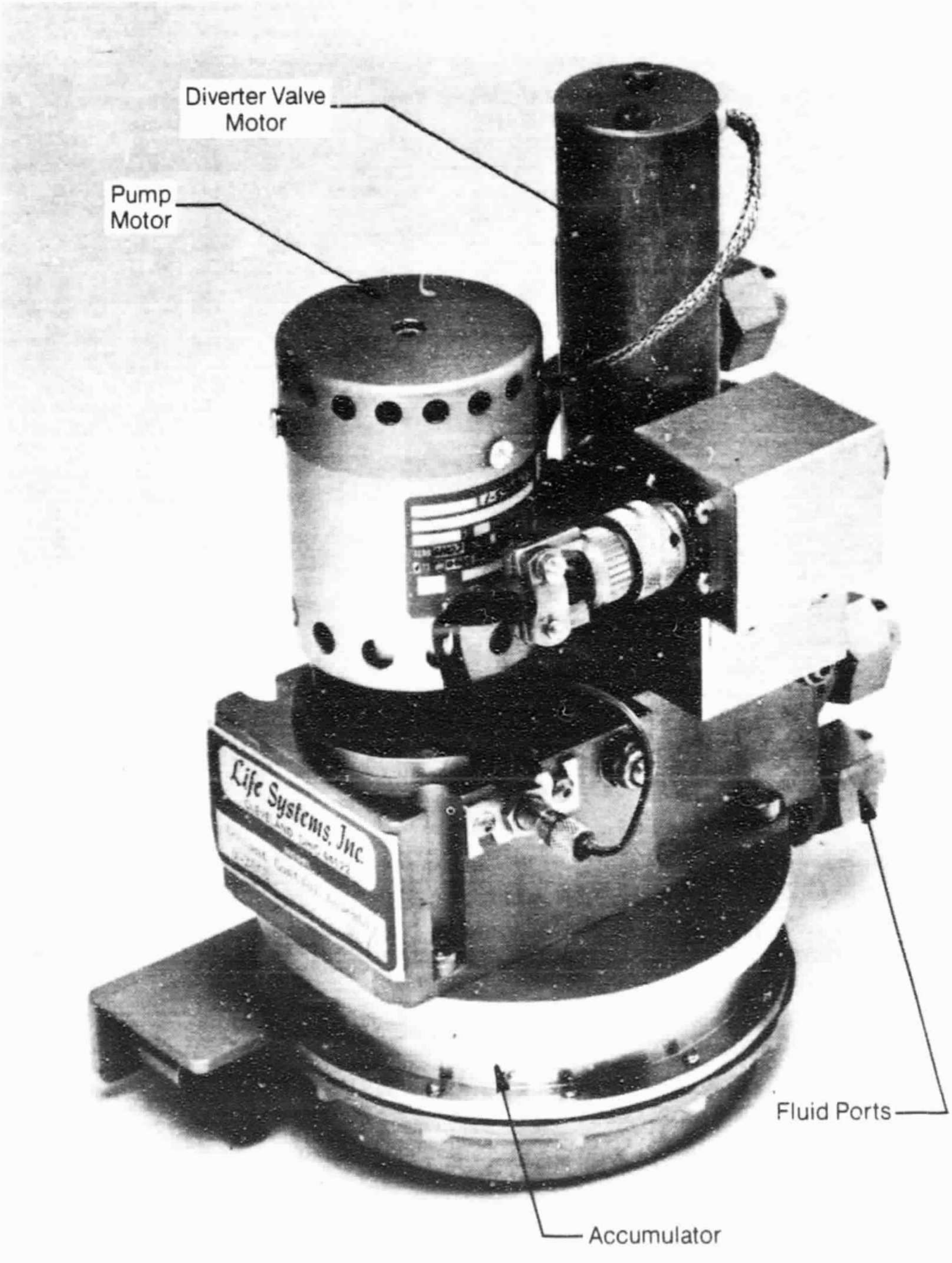

FIGURE 10 COOLANT CONTROL ASSEMBLY

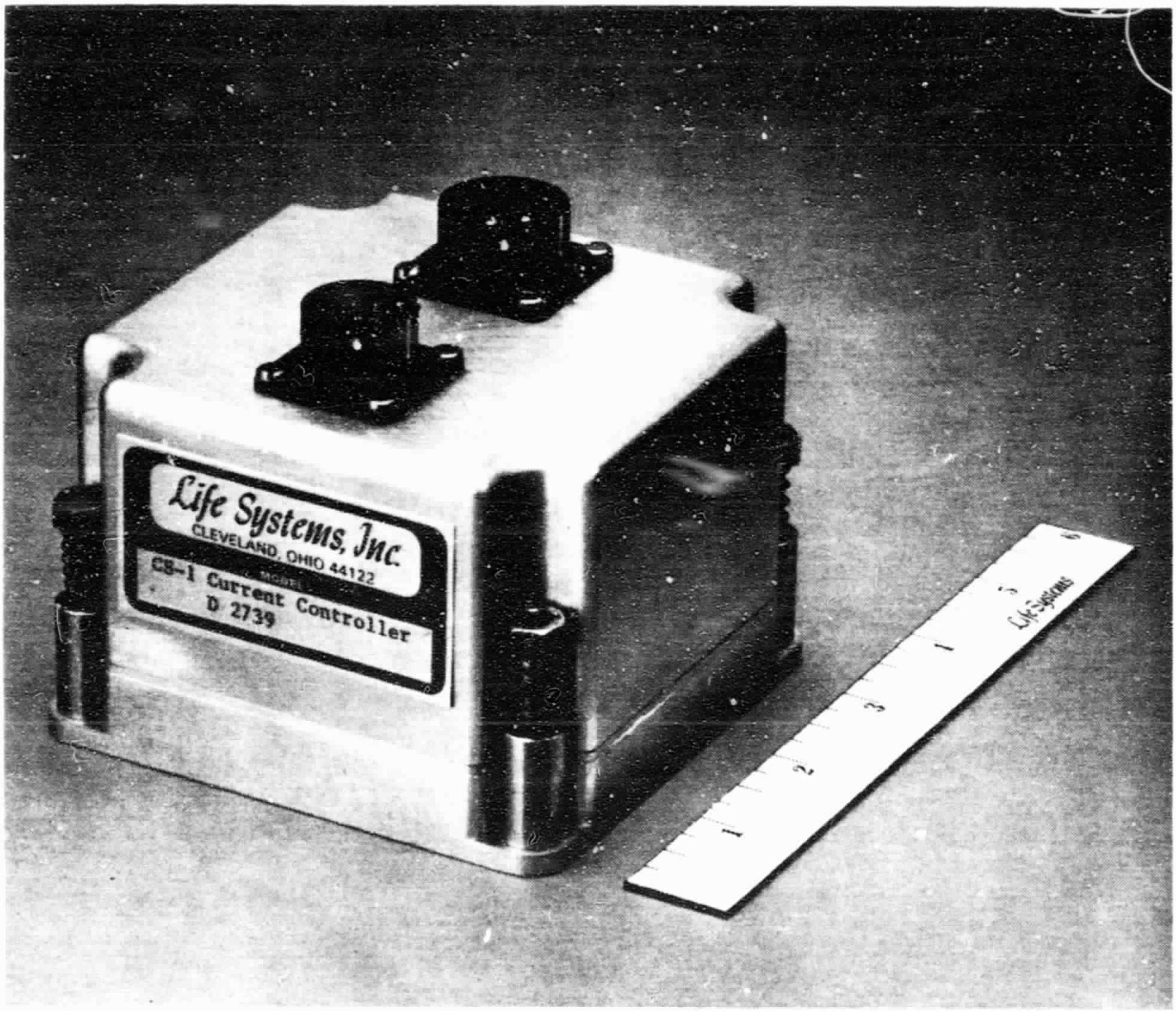

FIGURE 11 CS-1 CURRENT CONTROLLER

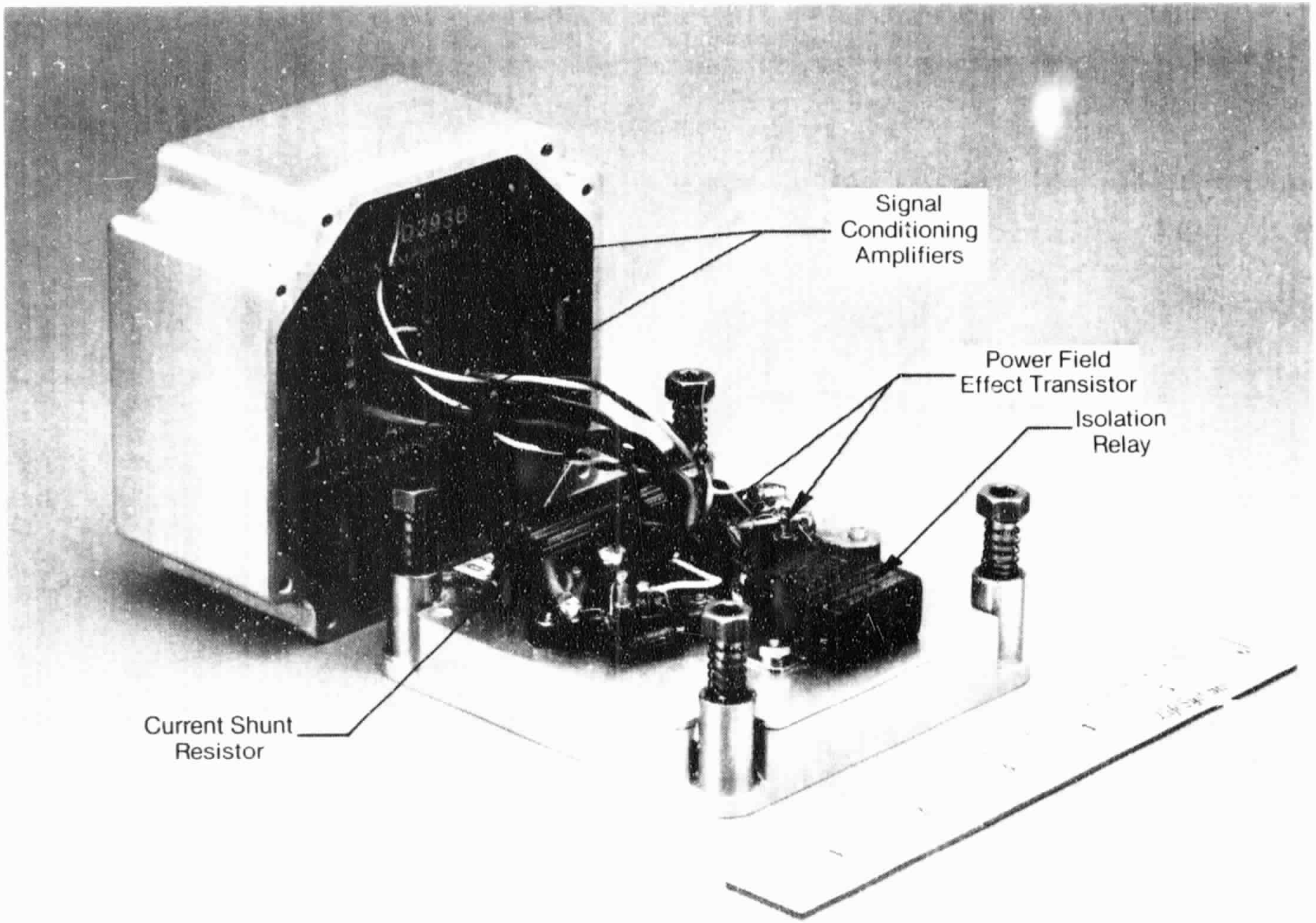

FIGURE 12 CS-1 CURRENT CONTROLLER-DISASSEMBLED

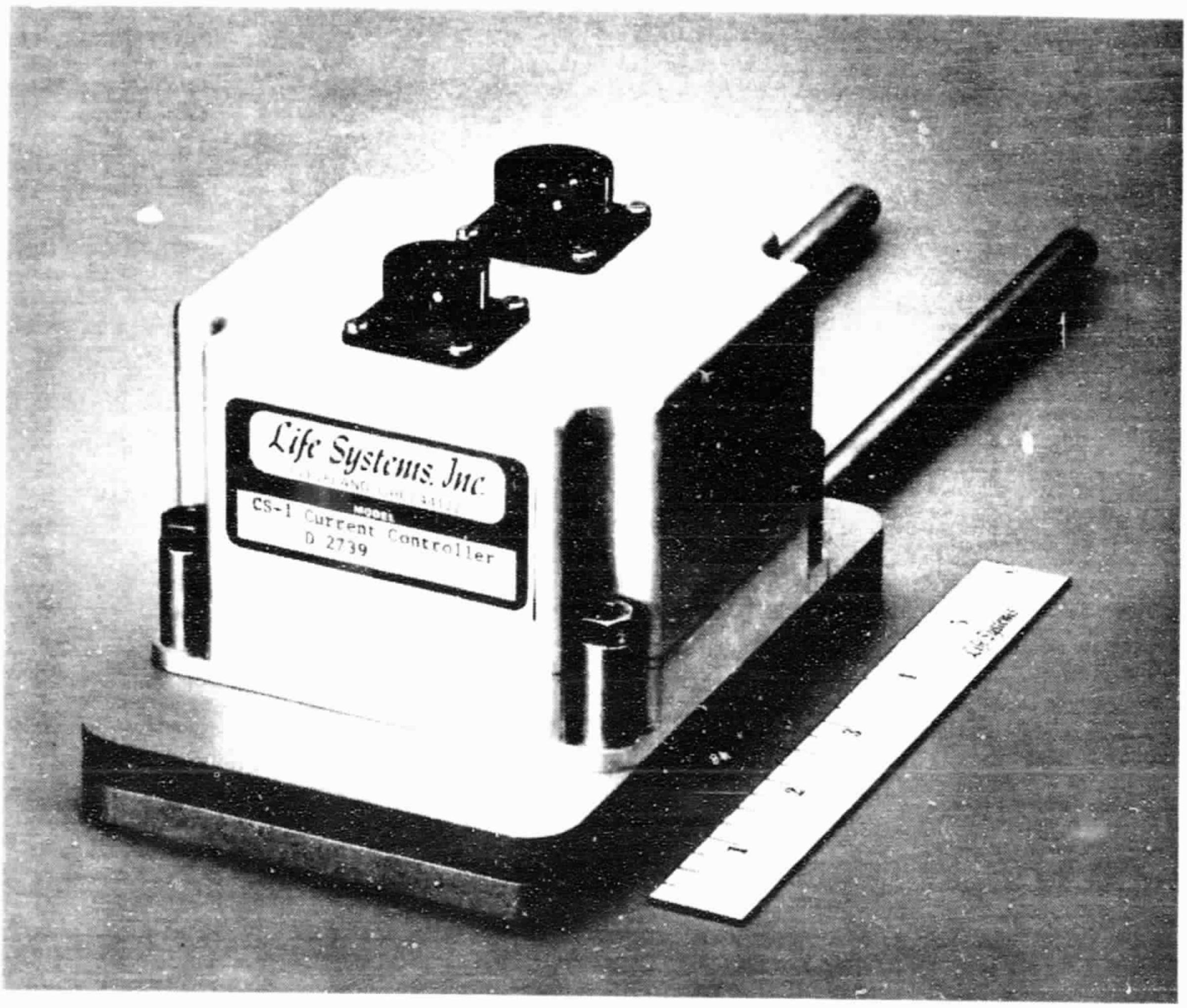

FIGURE 13 CS-1 CURRENT CONTROLLER/HEAT SINK

given in Table 3. This current controller can accommodate multi-person EDCMs. The maximum power dissipation capability of the current controller is 200 W. During CS-1 testing the nominal power dissipated was 25 W.

TABLE 3 CS-1 CURRENT CONTROLLER/HEAT SINK CHARACTERISTICS SUMMARY

Current Range, A	0-25
Supply Voltages, VDC	± 15, 28
Power Required, W	3
Max. Power Dissipation, W	200
Coolant Flow, dm^3/min (gal/min)	0-15 (0-4)
Temperature, K (F)	280-289 (45-60)

	Current Controller	Heat Sink
Weight, kg (lb)	1.0 (2.2)	0.82 (1.8)
Volume, dm^3 (in^3)	0.62 (38)	0.26 (16)
Dimensions, cm (in)	9.9 x 9.4 x 6.6 (3.4 x 3.7 x 2.6)	15 x 9.9 x 1.8 (5.9 x 3.9 x 0.7)

M/E A Packaging

The assembled CS-1 M/E A is shown in Figure 14. The major subassemblies, as indicated, are the FCA, the CCA, the EDCM and inlet and outlet process air ducts. Each of the latter includes an isolation/filter valve, a dew point temperature sensor and a dry bulb temperature sensor. The dew point sensor is a commercial chilled mirror type sensor in which the electronics were incorporated in the C/M I. The temperature sensors are resistive thermal device (RTD) types. In addition, the inlet duct contains an air/liquid heat exchanger (not shown) which preconditions the process air prior to entering the EDCM.

Figure 15 shows EDC CO_2 removal subsystems at various person capacities to illustrate the flexibility of achieving multi-person systems with the basic CS-1 design. It is noted that only the height dimension changes. Detailed characteristics of one to 12 person sizes are given in Table 4. It should be noted that the listed weights assume a light-weight end plate construction.

Table 5 summarizes the CS-1 M/E A weight, power and heat rejection requirements.

Control and Monitor Instrumentation

The function of the CS-1 C/M I is to provide for automatic mode and mode transition control, automatic shutdown for self-protection, monitoring of subsystem parameters and interfacing with ground Test Support Accessories (TSA) and data acquisition facilities. Under this program a new series of instrumentation based on microcomputer technology was developed. The CS-1 C/M I, termed the Model 220, represents a major size reduction from the prior series of instrumentation. The weight, volume and power consumption were reduced by over 75%.

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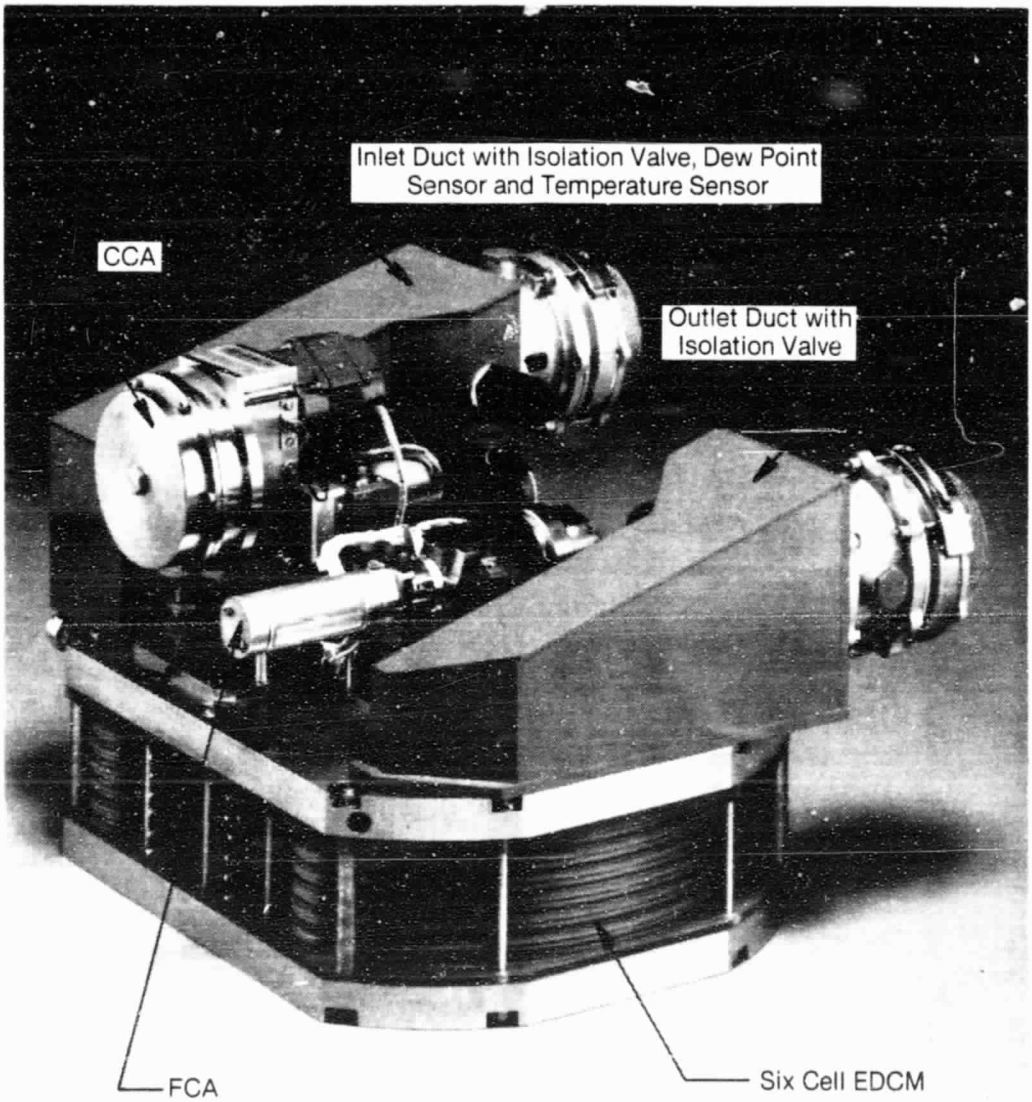
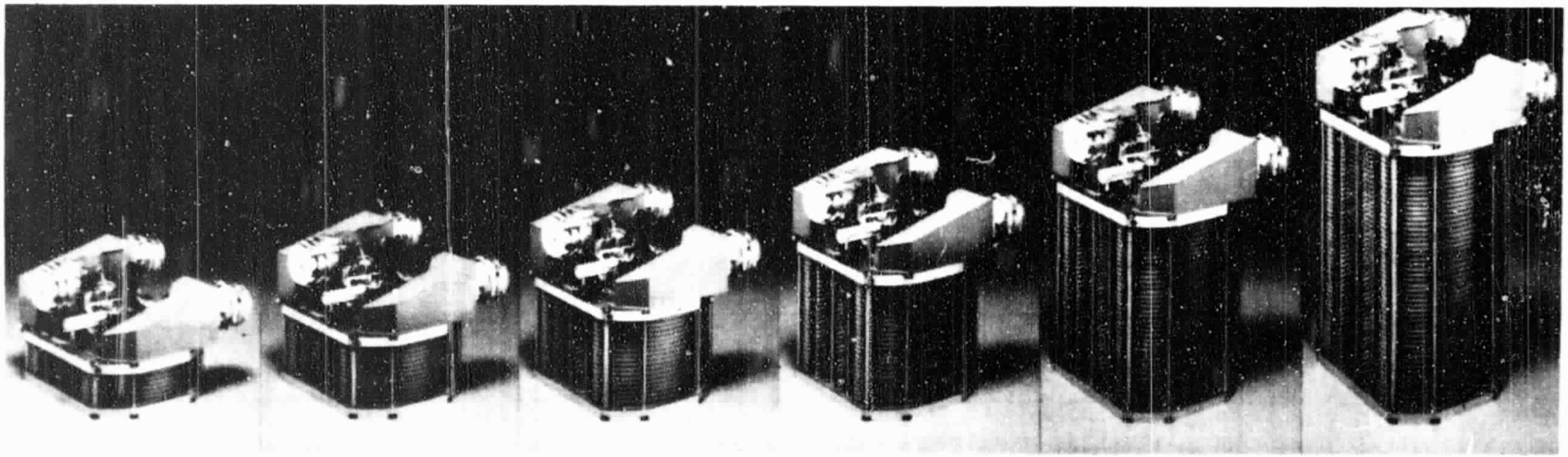


FIGURE 14 CS-1 MECHANICAL/ELECTROCHEMICAL ASSEMBLY



Person Capacity 1 2 3 4 6 8

FIGURE 15 MULTI-PERSON EDC CO_2 REMOVAL SUBSYSTEMS

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TABLE 4 CHARACTERISTICS OF EDC CO_2 REMOVAL SUBSYSTEMS

Model No.	No. of Cells[a]	Capacity, People @ 3 mm Hg	Capacity, People @ 12 mm Hg	Weight, kg (lb)	Volume, dm^3 (ft^3)	Dimensions, cm (in) Ht	Dimensions, cm (in) Wd	Dimensions, cm (in) Ln	Power, W DC Out	Power, W AC In	Heat Load, W
CS-1	6	1	2	23 (50)	45 (1.6)	34.0 (13.4)	39.4 (15.5)	34.3 (13.5)	10	50	114
CS-2	12	2	4	28 (62)	54 (1.9)	40.1 (15.8)	39.4 (15.5)	34.3 (13.5)	40	50	158
CS-3	18	3	6	34 (74)	62 (2.2)	46.2 (18.2)	39.4 (15.5)	34.3 (13.5)	70	50	201
CS-4	24	4	8	39 (86)	71 (2.5)	52.3 (20.6)	39.4 (15.5)	34.3 (13.5)	100	50	245
CS-6	36	6	12	50 (110)	88 (3.1)	65.4 (25.4)	39.4 (15.5)	34.3 (13.5)	160	80	364
CS-8	48	8	16	61 (134)	105 (3.7)	76.7 (30.2)	39.4 (15.5)	34.3 (13.5)	220	80	450

a. Based on 2.20 lb CO_2/person·day.

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TABLE 5 CS-1 MECHANICAL COMPONENT WEIGHT, POWER AND HEAT REJECTION SUMMARY

Item No.	Component	No. Req'd	Unit Weight,[a] kg (lb)	Total Weight, kg (lb)	Total AC Power, W	Total DC Power, W	Heat Rejection, W
1	EDCM[b]	1	46.3 (101.9)	46.3 (101.9)	—	-27	41
2	Assembly, Fluids Control	1	1.7 (3.8)	1.7 (3.8)	—	2[c]	2
3	Assembly, Coolant Control	1	2.7 (6.0)	2.7 (6.0)	75	—	75
4	Heat Exchanger, Liq/Liq	1	0.8 (1.8)	0.8 (1.8)	—	—	—
5	Filter/Isolation Valve	2	0.7 (1.5)	1.4 (3.0)	—	—	—
6	Sensor, Dew Point	2	0.2 (0.5)	0.4 (1.0)	—	1	1
7	Sensor, Temperature	2	0.1 (0.2)	0.2 (0.4)	—	1	1
8	Interface, Inlet Air (w/Heat)	1	2.2 (4.8)	2.2 (4.8)	—	—	—
9	Interface, Outlet Air	1	1.2 (2.7)	1.2 (2.7)	—	—	—
10	Assembly, Current Controller	1	1.8 (4.0)	1.8 (4.0)	—	3	30[d]
			—	58.5 (129.4)	75	-27	150

(a) Dry weight.
(b) Does not have honeycomb end plates.
(c) Steady-state operation sensors.
(d) The 27 W of EDCM power is converted to heat.

Four operating modes are available for the subsystem, as shown in Figure 16 with separate Normal modes corresponding to the operating conditions of either Shuttle or Central (i.e., Space Station) application. Each mode is defined in Table 6.

General Description

The CS-1 C/M I receives and transmits signals from and to the M/E A sensors and actuators. Through these it controls and monitors subsystem pressures, flow rates, temperatures, cell voltages, current and valve positions in each operating mode. It implements each mode, whether initiated automatically or manually and provides fail-safe operational changes to protect the CS-1 if malfunctions occur.

Internally, process operating mode control is a relatively complex operation. It includes selection of different unit processes, selection of valve positions, sequencing of valve positions, sequencing of actuators and checking parametric conditions as a transition (e.g., Shutdown to Normal Central) proceeds. However, this procedure for control is fully automated by the C/M I so that the operator only needs to press the Mode Enable and the desired mode buttons to initiate transition sequences.

Hardware Description

The 220 C/M I is shown in a series of photographs, Figures 17-20. These illustrate, respectively, the front view, rear view, the total assembly without its protective dust cover and an exploded view indicating the major assemblies. There are five major assemblies in the 220 C/M I:

1. Computer card cage containing the microprocessor's central processing unit (CPU) along with support cards (memory, analog/digital conversion (A/D), digital input and output, etc.).

2. Power supply module for supplying ±15 V and +5 V from the input power of +28 V.

3. Signal conditioning card cage and 11 signal conditioning cards for conditioning the sensor outputs and providing actuator drive signals.

4. Power assembly for supplying those sensors and actuators which require drive current for their operation (dew point, flow, and motor actuation)

5. Front panel assembly with status indication and mode transition selection buttons.

Design characteristics of the Model 220 C/M I are given in Table 7. The C/M I uses Erasable Programmable Read-Only Memory (EPROM) for its program storage. It also uses some Random Access Memory (RAM) for data storage. This permits the access of the real-time data by an external monitor through a standard communications link.

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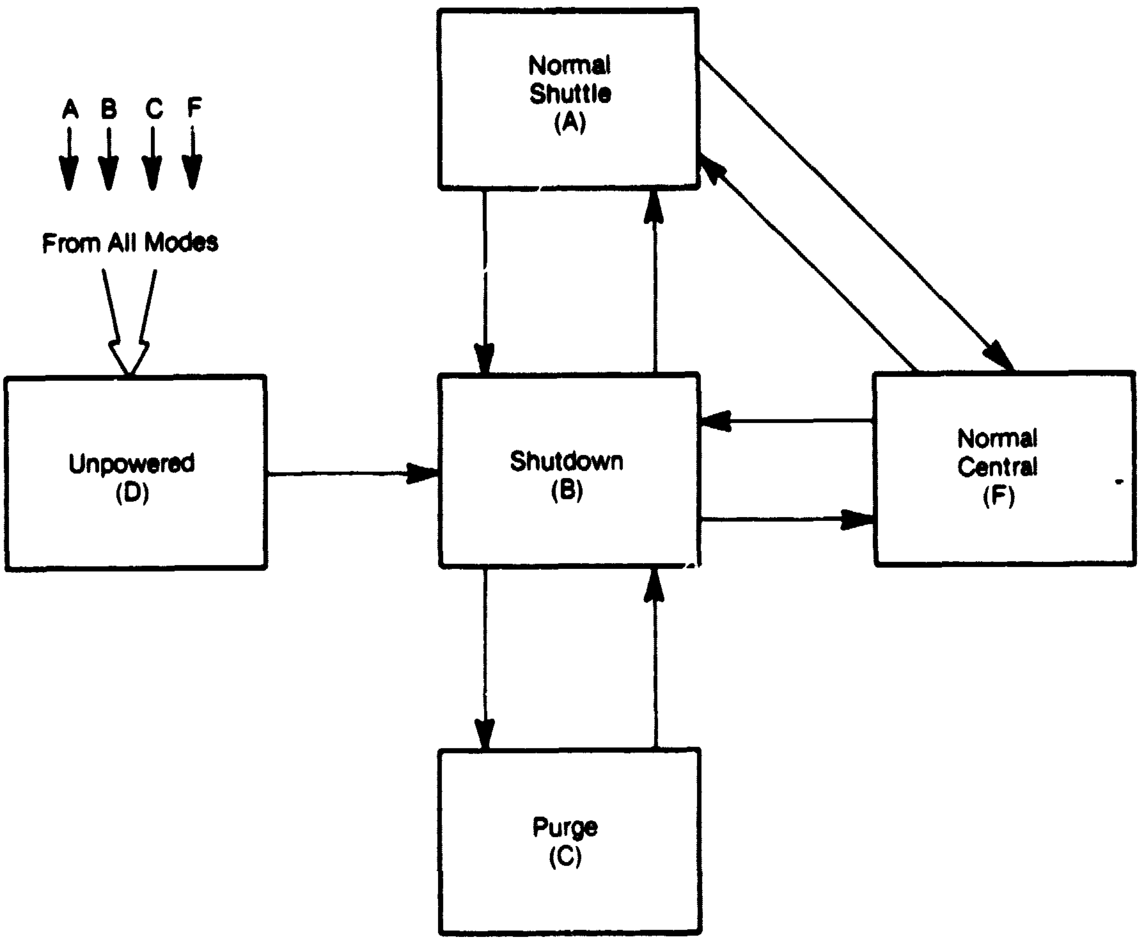

- 5 Modes
- 4 Operating Modes
- 13 Mode Transitions
- 9 Programmable, Allowed Mode Transitions

FIGURE 16 CS-1 MODES AND ALLOWABLE MODE TRANSITIONS

TABLE 6 CS-1 MODE DEFINITIONS

Mode (Code)	
Shutdown (B)	The EDCM is not removing CO_2. Module current is zero, the CCA pump is off and all valves are closed. The system is powered and all sensors are working. The Shutdown Mode is called for by: • Manual actuation • Low EDCM individual cell voltage • Low H_2 pressure • High H_2 pressure • Low outlet process air RH • High outlet process air RH • Second failure of triple redundant sensors for pressure, relative humidity, temperature and combustible gas concentration (capability only) • Power on reset (POR) from Unpowered Mode D • Mode transition from Shutdown Mode (B) to Normal Shuttle (A), Normal Central (F), or Purge (C) was not successful. All transitions to the Shutdown Mode except POR and Purge include a timed purge sequence as part of the mode transition sequence.
Normal Shuttle (A)	The EDCM is operating at the constant current density of 19.4 mA/cm^2 (18.0 ASF) sized to perform the CO_2 removal function for one-person assuming an inlet pCO_2 level of 667 Pa (5.0 mm Hg). The Normal Shuttle Mode is called for by: • Manual actuation
Normal Central (F)	The EDCM is operating at a constant current density of 21.3 mA/cm^2 (19.8 ASF) sized to perform the CO_2 removal function for one-person assuming an inlet pCO_2 level of 400 Pa (3.0 mm Hg). The Normal Central Mode is called for by: • Manual actuation
Purge (C)	The EDC is being purged with N_2 through all H_2 lines, H_2 carrying module cavities and out through the vent line. Module current and the CCA pump are off. This is a continuous purge until a new mode is called for. The Purge Mode is called for by: • Manual actuation
Unpowered (D)	No electrical power is applied to the EDC. Actuator positions can only be verified visually. Process air flow is stopped. There is no N_2 or H_2 flow. The Unpowered Mode is called for by: • Manual actuation (circuit breaker) • Electrical power failure • C/M I failure as detected by the Built-in Diagnostic (BID) circuit and supply power to the C/M I is interrupted

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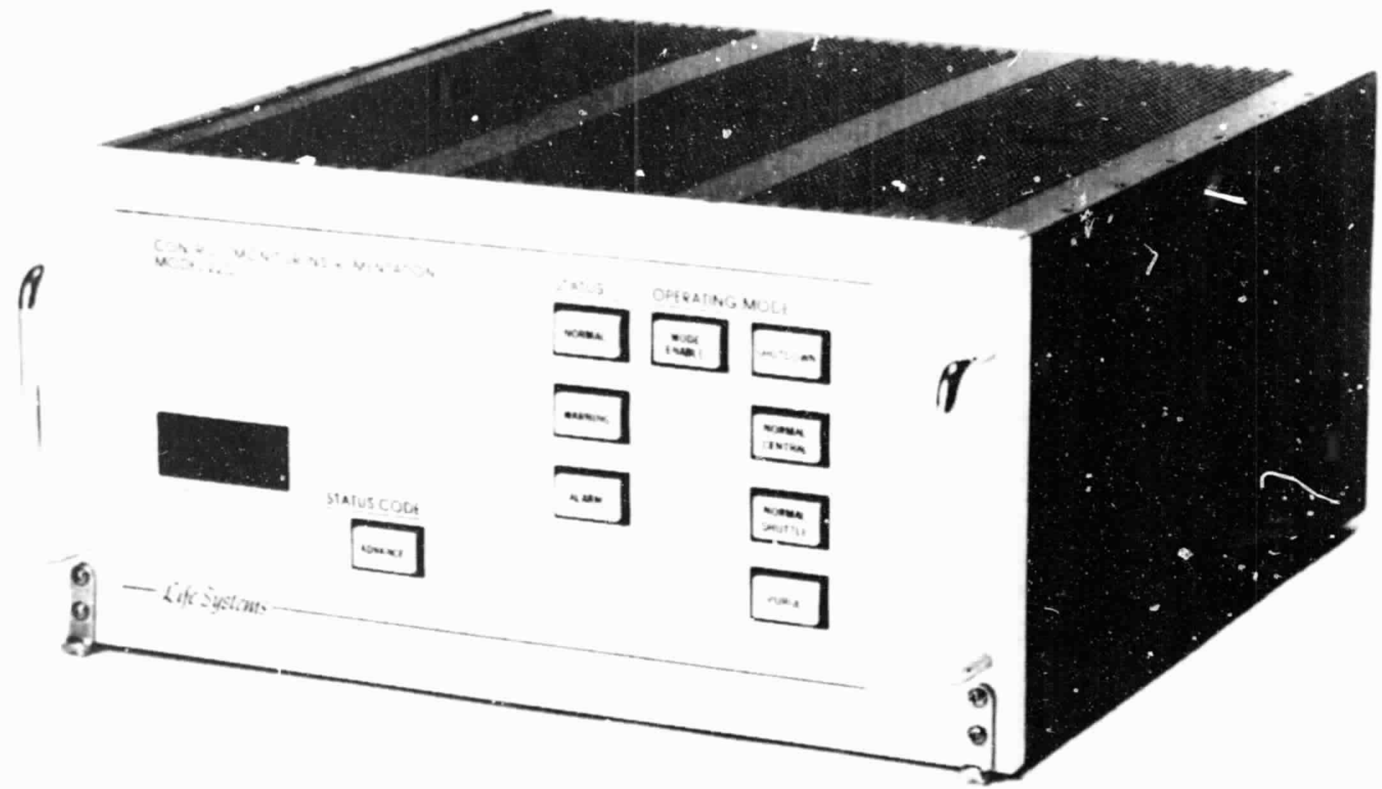

FIGURE 17 MODEL 220 C/M I (FRONT VIEW)

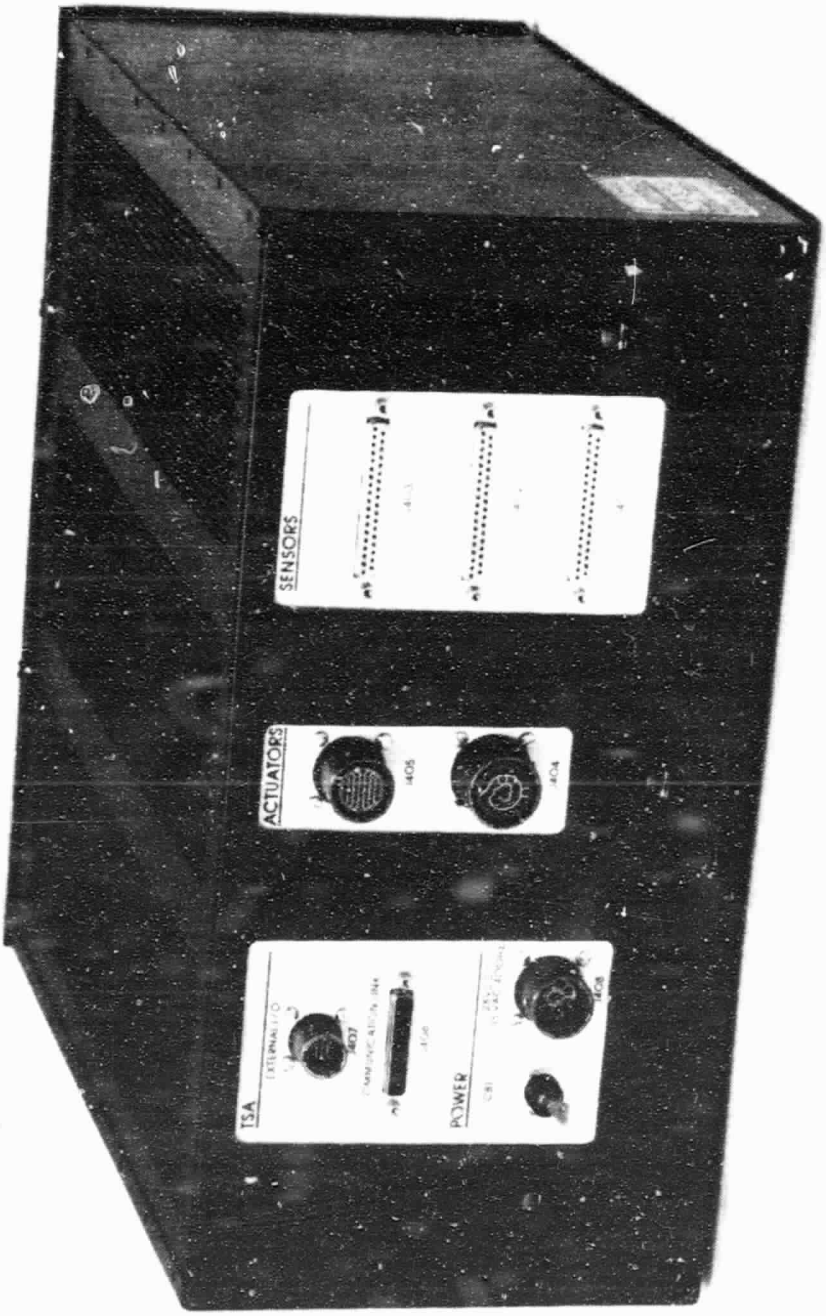

FIGURE 18 MODEL 220 C/M I (REAR VIEW)

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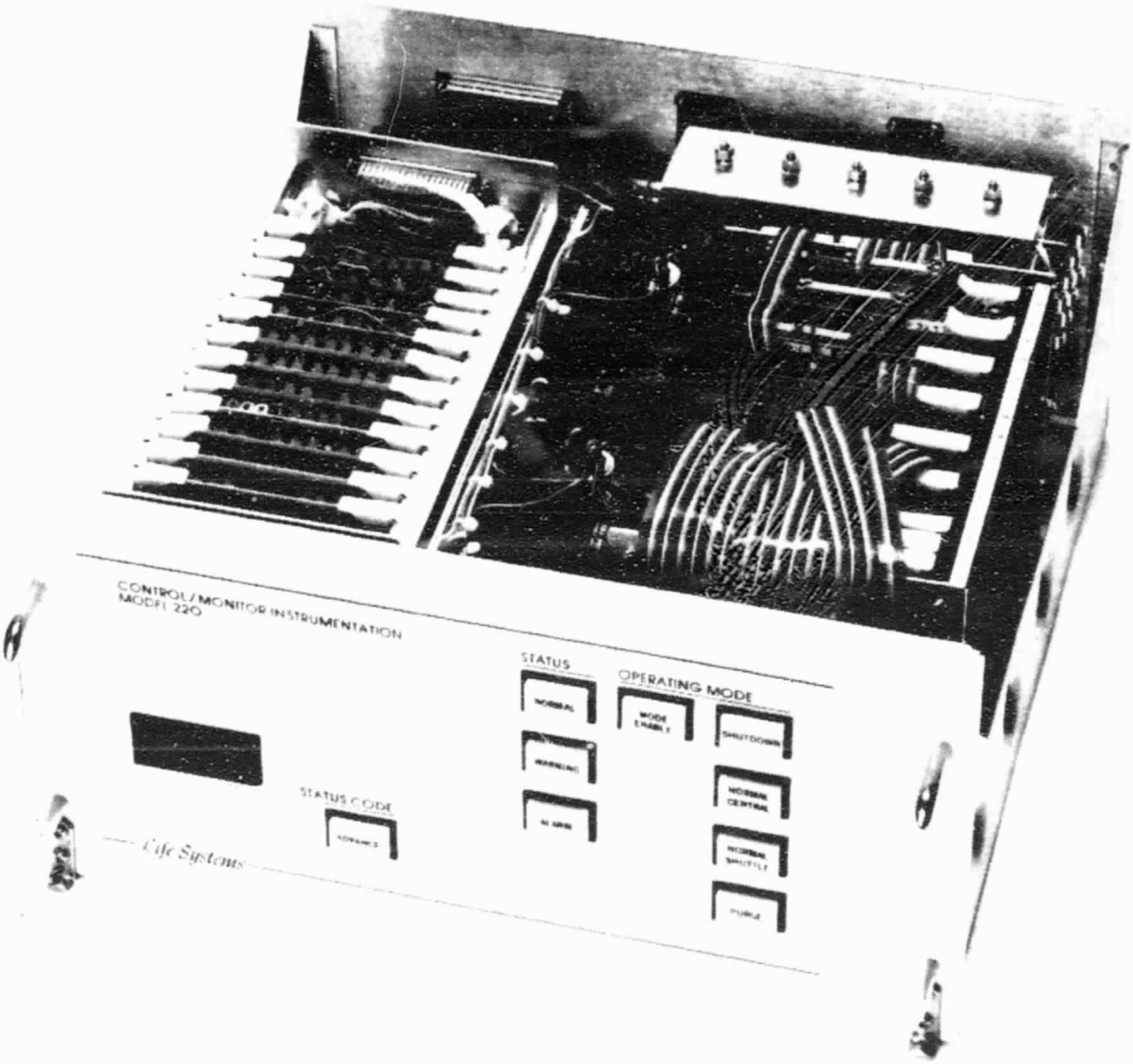

FIGURE 19 MODEL 220 C/M I (INTERNAL PACKAGING)

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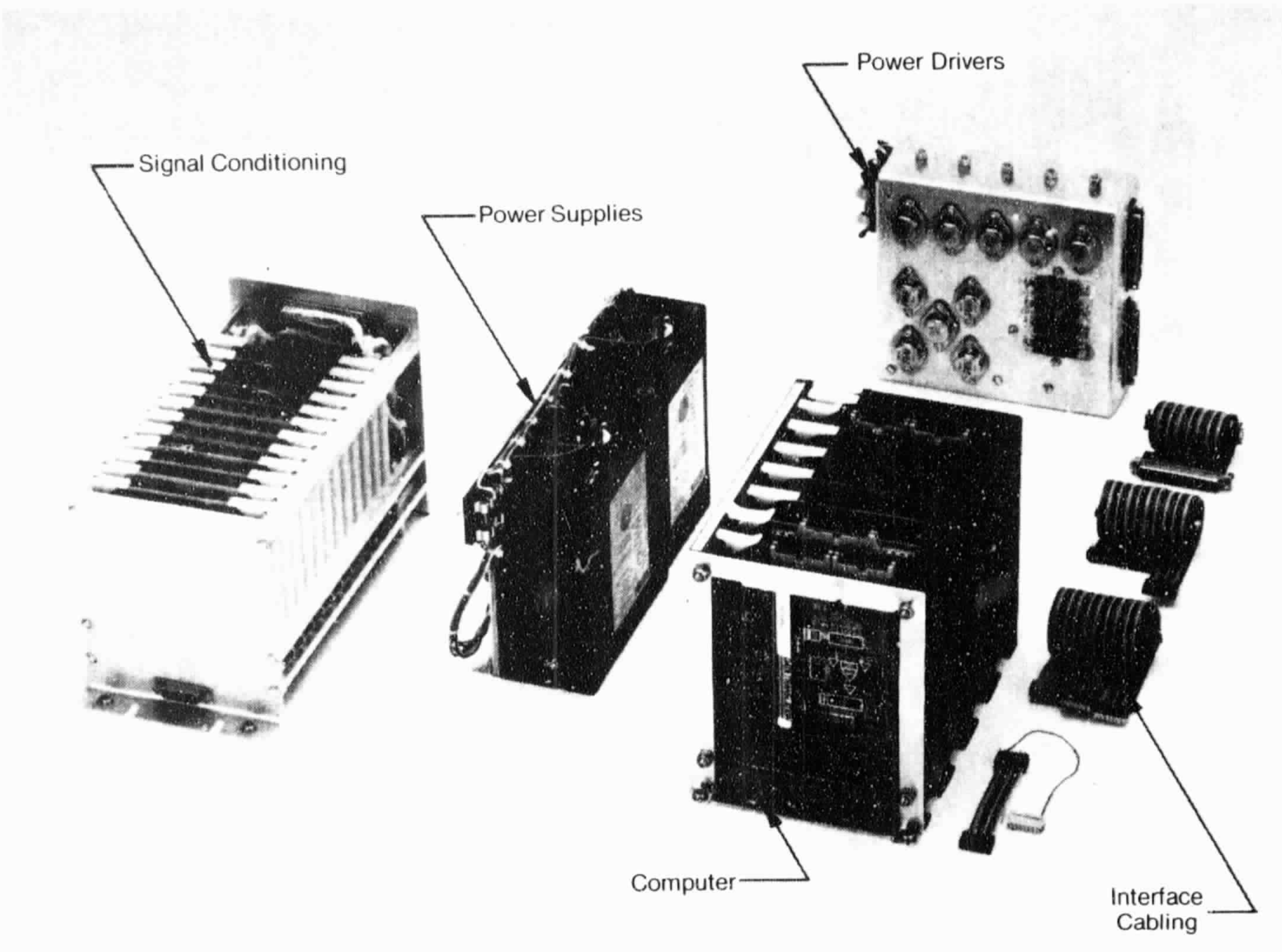

FIGURE 20 MODEL 220 C/M I ILLUSTRATING MAJOR ASSEMBLIES

TABLE 7 MODEL 220 C/M I DESIGN CHARACTERISTICS

Dimensions (HxWxD), cm (in)	19 x 39 x 40 (7.4 x 15.3 x 15.6)
Power Input, W	80
C/M I Power Consumption, W	67
Input Voltage, VDC	28 ± 4
Computer Assembly	
Bus	STD—8088
Microprocessor	Intel 8088
Machine Cycle Time, nsec	200 (5 MHz)
EPROM Memory, Bytes	32 K
RAM Memory, Bytes	16 K
Digital I/O	64 TTL Lines
A/D Converter	
Channels	32 single ended
Resolution	12 bits
Full Scale Ranges	± 10 mV to ± 10 V
D/A Converter	
Channels	4 single ended
Resolution	12 bits
Full Scale Range	± 10 VDC @ 5 mA
Serial Communications	1 RS232 Port
Signal Conditioning Assembly	
Card Slots	12 Max.
Input Sensor Types:	Differential Voltage Wein Bridge RTD Reluctance Pickup (Speed) Dew Point Sensor LVDT
Total Number of System Inputs	19
System Outputs:	
Total Number	7
Thermoelectric Cooler	2 @ 2 Amps Max.
DC Motors (28 VDC)	2
AC Motor (115 VAC @ 400 Hz)	1 on/off
Analog Current Setpoint	1 @ 0 to 5 VDC
Current Control—On/Off	1 @ 0 to 5 VDC
Communications	
Front Panel	
Operating Mode	5 Pushbuttons
Status	3 Indicators
Error Code	8 Digit Display
Error Code—Advance	1 Pushbutton
Communications Link	1 Asynchronous RS232 Port
Shutdown Inputs	1 @ 5 VDC
Shutdown Outputs	2 @ 5 VDC
Operating Modes	
Number of Operating Modes	4
Number of Allowable Mode Transitions	9

The size, weight and power summary of the C/M I is shown in Table 8. The previously mentioned size reduction, of approximately 75% in weight, volume and power, is evident in Figure 21, which compares the 220 C/M I with the prior version Series 100 C/M I. The computer section alone represented almost a 90% reduction in weight and power consumption with an increase in reliability by using non-volatile (EPROM) memory versus the volatile or magnetic core memory of the Series 100.

A separate enclosure houses controls that permit override of the actuators during startup testing. This unit is shown in Figure 22. It was designed to be used directly in-line with the actuator cables going to the CS-1. The subsystem can be operated with the unit installed or not. (With the four actuator switches in the auto position, the signals pass directly through the unit.) Except for the very initial stages of the testing, the CS-1 was operated with the actuator override controls removed from the subsystem.

TEST SUPPORT ACCESSORIES

Test Support Accessories (TSA) were developed and/or refurbished for the program. This included major revisions of the TSA for the CS-1 testing and minor upgrades to the three test stands for the EDC component endurance testing.

CS-1 TSA

The CS-1 TSA provides the following:

1. Process air at the desired flow rate, dew point, temperature and pCO_2 levels
2. N_2 and H_2 gases at the desired pressures and flow rates
3. Coolant simulating a central spacecraft coolant source.
4. Electrical power at 28 V for the C/M I and 115 V, 400 Hz for the CCA pump
5. Electrical circuitry to permit shutdown interface between the CS-1 and the TSA
6. Gas analysis equipment for measuring CS-1 performance.

Figure 23 shows the gas/coolant supply schematic and Figure 24 shows the arrangement for gas sample analysis. Performance of the CS-1 based on air side (e.g., pCO_2) measurements and H_2/CO_2 exhaust measurements (e.g., flow rate) is determined with this equipment.

EDC Component TSA

Figures 25, 26 and 27 illustrate the three test stands that were used to perform the continued endurance testing of the three major components of the

TABLE 8 MODEL 220 C/M I WEIGHT, SIZE AND POWER CONSUMPTION SUMMARY

Assembly	Weight, kg (lb)	Size HxWxD, cm (in)	Power, W
Computer	3.0 (6.6)	17.8 x 14.5 x 20.8 (7.0 x 5.7 x 8.2)	31.1
Signal Conditioning	2.5 (5.4)	15.7 x 13.2 x 24.9 (6.2 x 5.2 x 9.8)	10.6[a]
Power Supplies (+5, ± 15 VDC)	4.0 (8.9)	16.5 x 6.4 x 22.9 (6.5 x 2.5 x 9.0)	16.6[b]
Power Drivers	0.9 (2.0)	17.3 x 17.8 x 6.4 (6.8 x 7.0 x 2.5)	11.9[a]
Front Panel	0.8 (1.8)	18.8 x 38.9 x 3.3 (7.4 x 15.3 x 1.3)	6.3[c]
Connectors/Wiring	0.4 (1.0)	—	—
Enclosure	1.9 (4.1)	18.8 x 38.9 x 39.6 (7.4 x 15.3 x 15.6)	—
Total	13.5 (29.8)	18.8 x 38.9 x 39.6 (7.4 x 15.3 x 15.6)	76.5

a. With no subsystem sensors or actuators connected.
b. Represents conversion efficiency from 28 VDC supply.
c. Assumes average of two indicators on during normal operation.

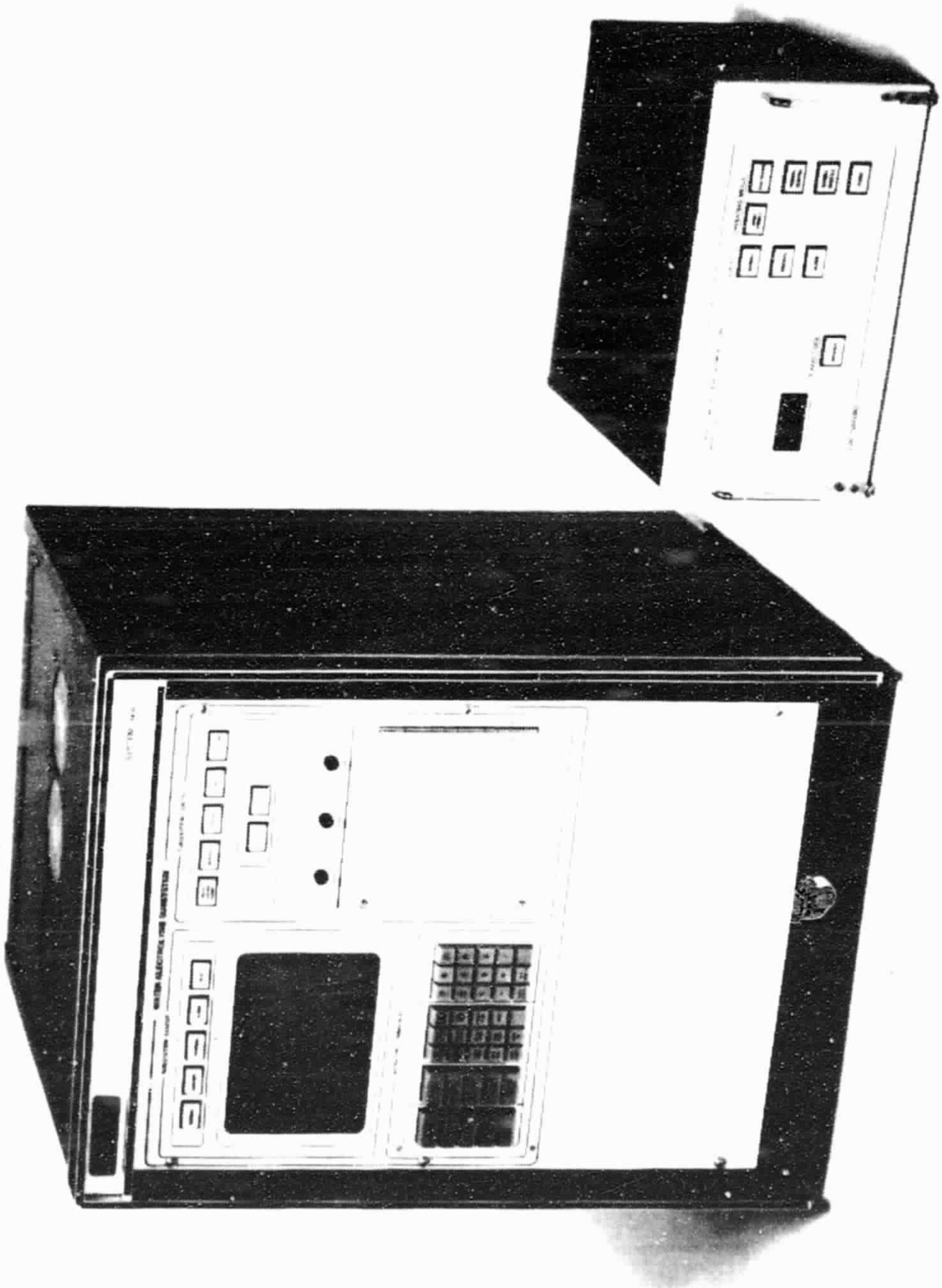

FIGURE 21 SERIES 100 versus 200 C/M I SIZE COMPARISON

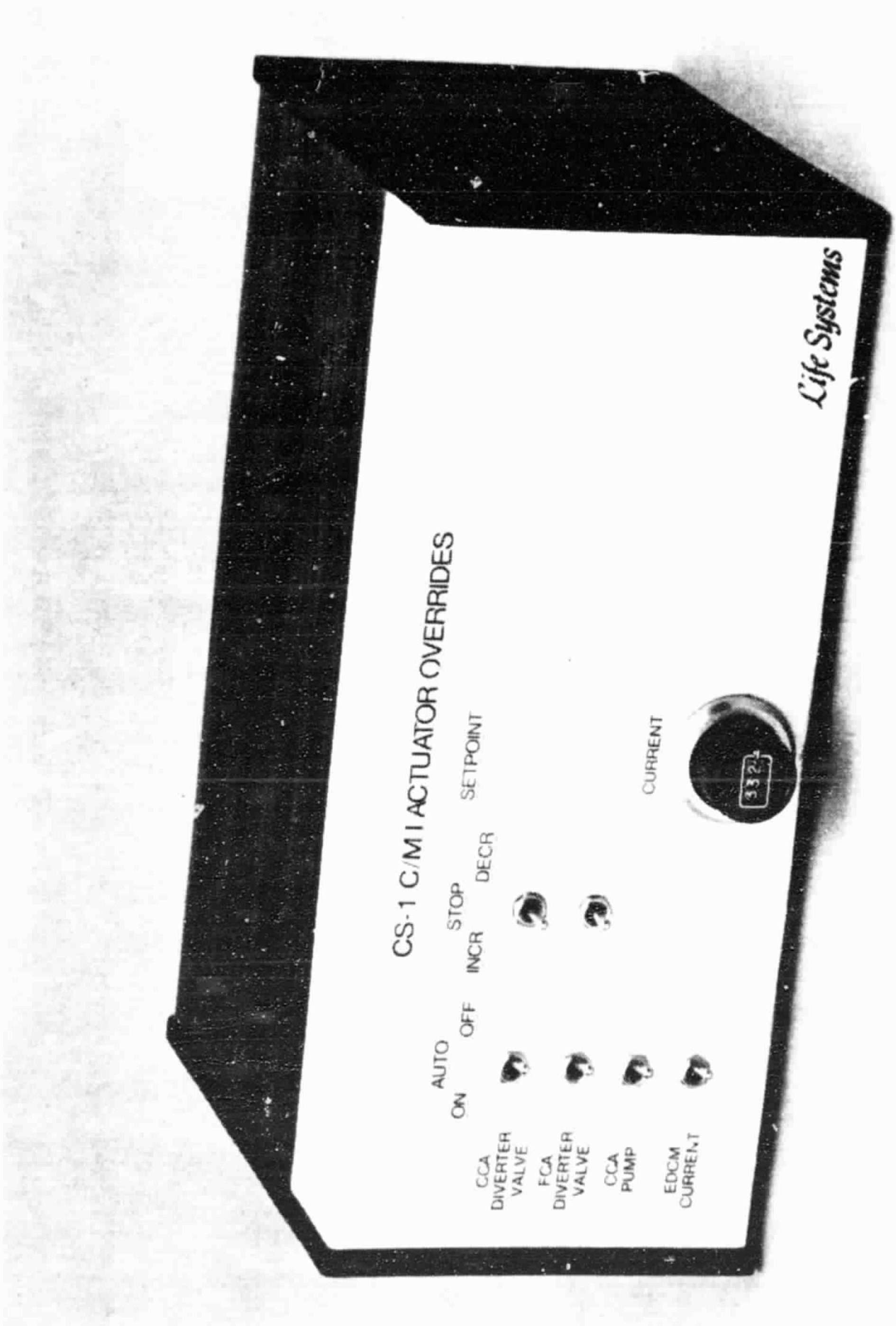

FIGURE 22 CS-1 C/M 1 ACTUATOR OVERRIDES

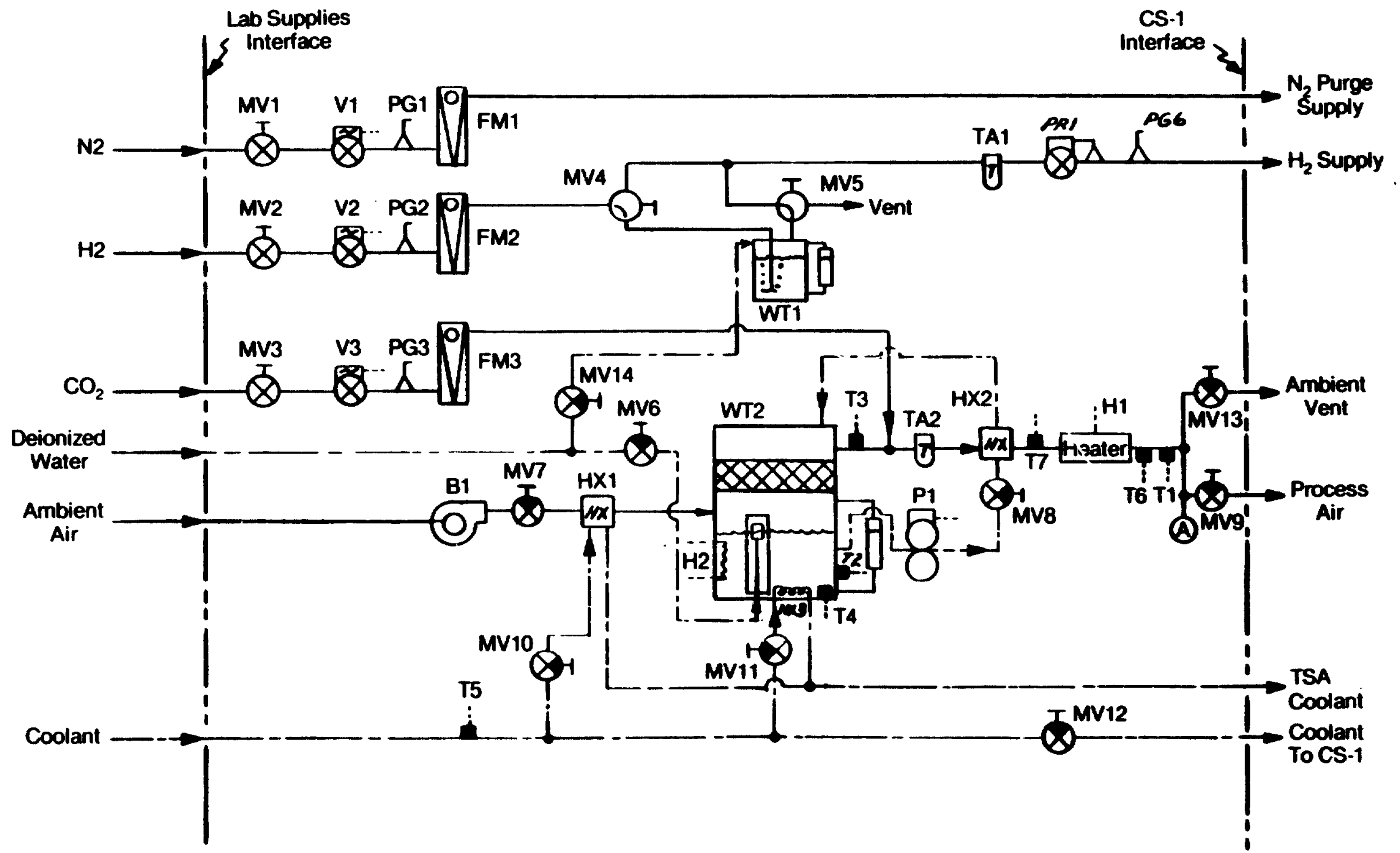

FIGURE 23 CS-1 TSA-GAS/COOLANT SUPPLY

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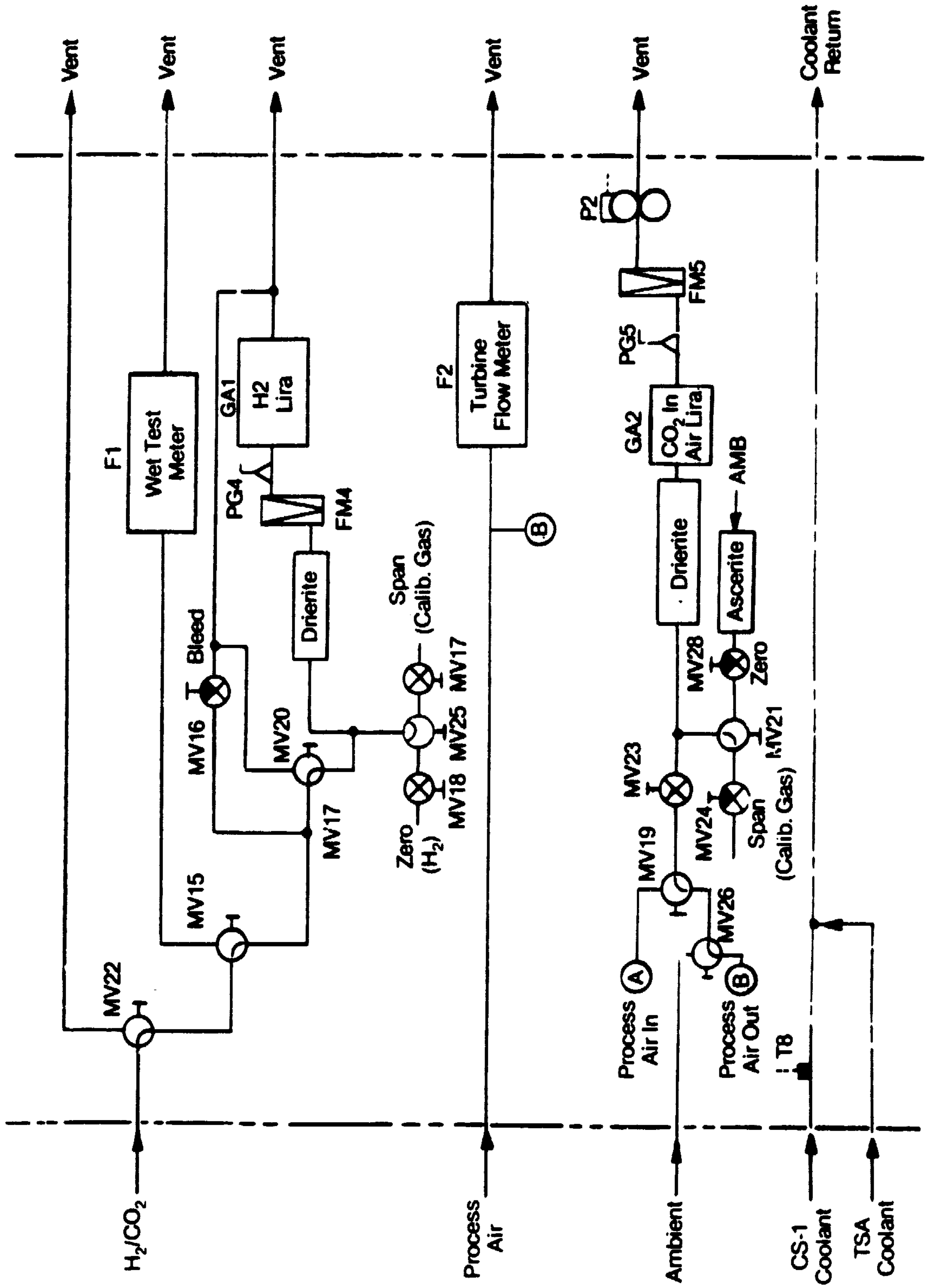

FIGURE 24 CS-1 TSA-GAS SAMPLE ANALYSIS

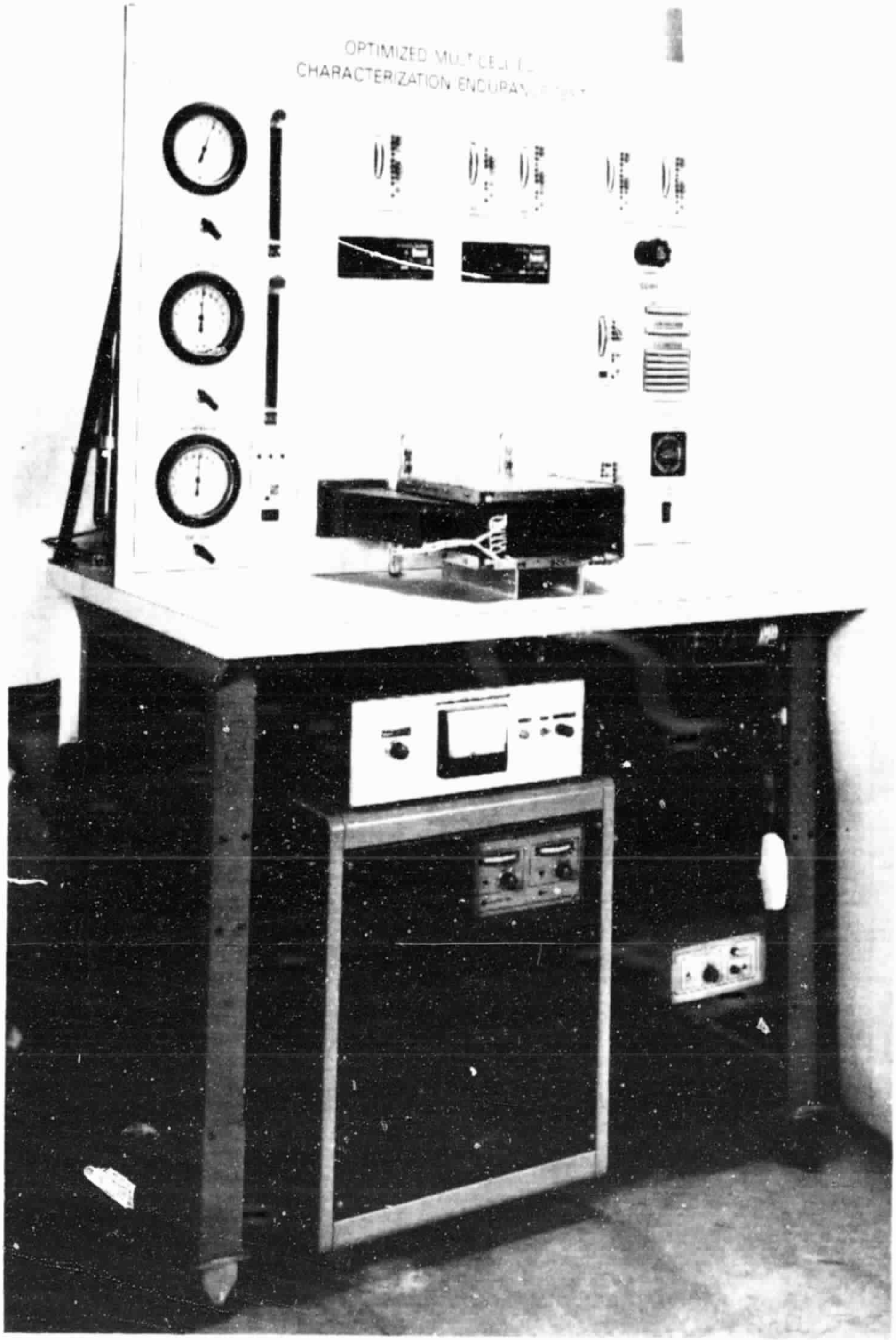

FIGURE 25 LIQUID-COOLED EDCM TEST STAND

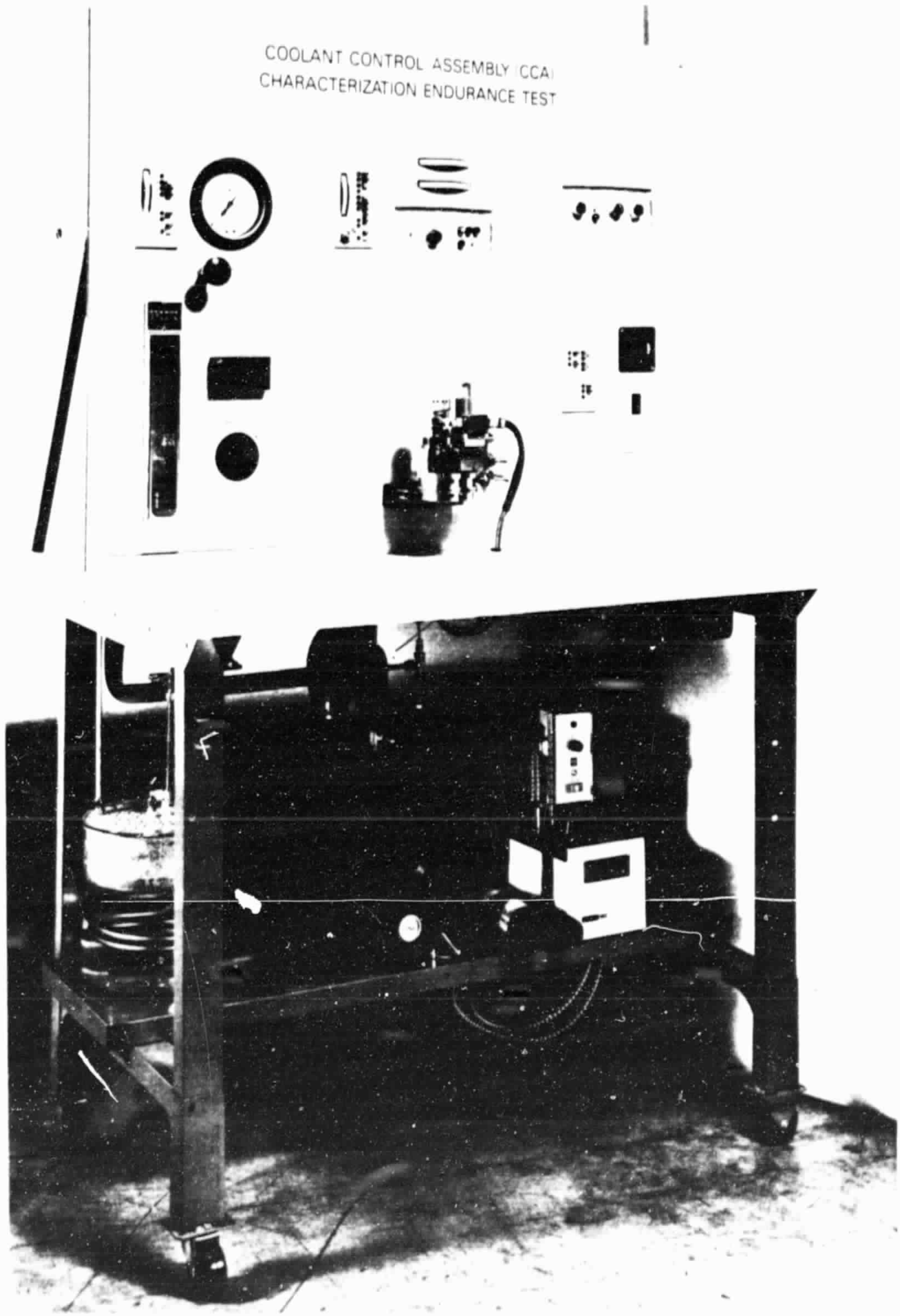

FIGURE 26 COOLANT CONTROL ASSEMBLY TEST STAND

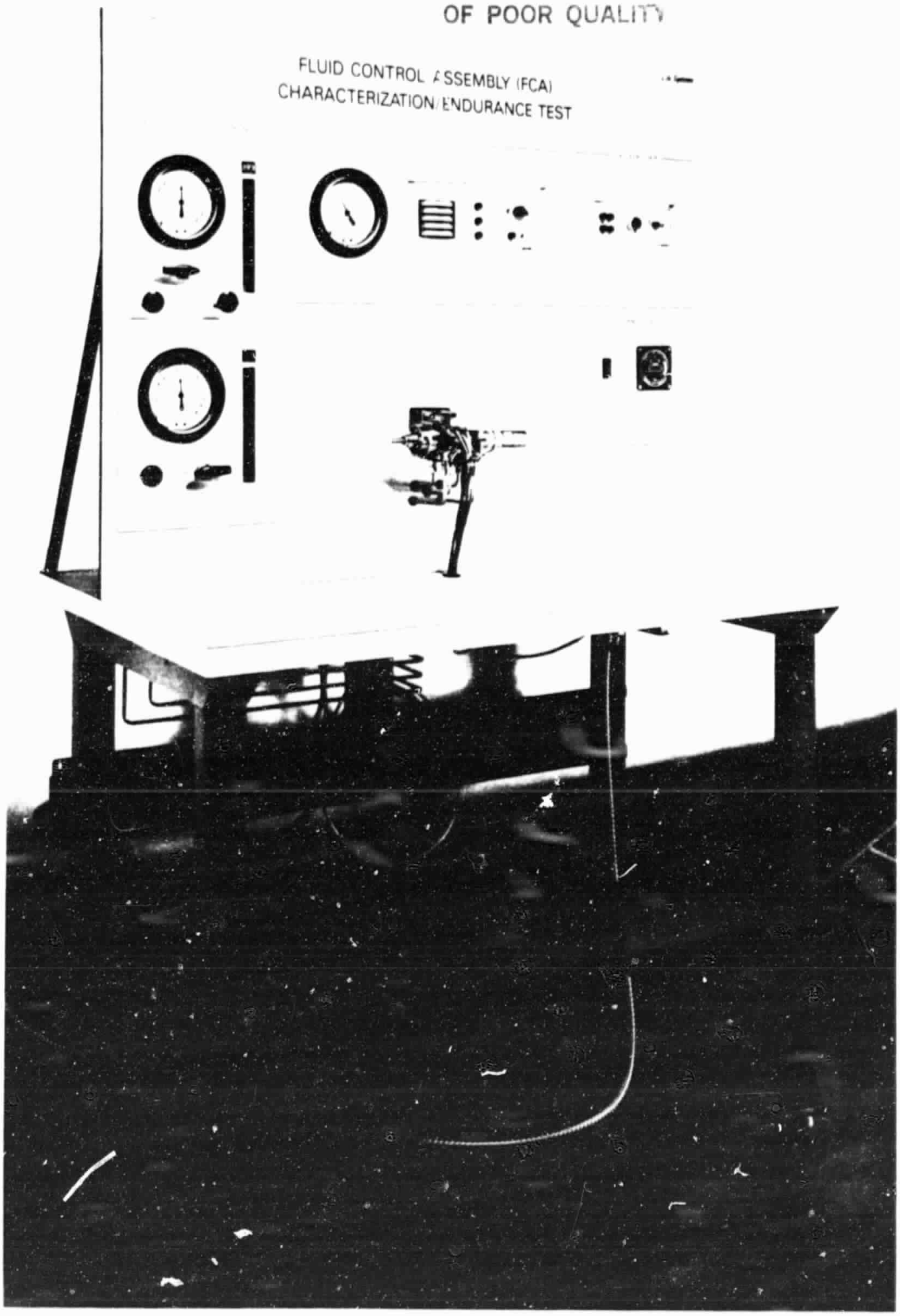

FIGURE 27 FLUIDS CONTROL ASSEMBLY TEST STAND

EDC; the liquid cooled EDCM, an FCA and a CCA. These stands were developed under a prior program[11] and were refurbish· ·s required for the testing under this program.

TESTING

Testing of the CS-1 followed fabrication of the module and the TSA. Endurance testing of the EDC components for over 360 days was also conducted. These tests are described below.

CS-1 Testing

A total of over 1,800 hours of CS-1 testing was achieved, versus the program goal of 60 days (1,440 hours). As discussed below, the performance of the CS-1 was excellent.

Checkout Testing

During checkout testing all test stand control circuits, shutdown points and sensor calibrations were verified. All interfaces with the TSA and CS-1 were checked and verified.

Shakedown Testing

The shakedown test included continuous operation over 24 hours under nominal baseline conditions. Subsequently, the shutdown and restart capabilities of the integrated CS-1 and its test stand were verified.

Design Verification Test

The Designed Verification Test (DVT) provided data over the design range of operating conditions to define normal operating characteristics of the module and establish best operating conditions. These are listed in Table 9. The established conditions were maintained during the test program unless varied parametrically or otherwise specified.

Endurance Test

The endurance tests established the ability of the module to maintain acceptable performance while running continuously for over 1,800 hours (75 days). Conditions were typically maintained within the ranges listed in Table 9. Performance during the entire 1,800 hours of CS-1 operation, including the endurance and parametric tests is plotted in Figure 28. It is apparent that the CO_2 removal efficiency averaged greater than 90% despite perturbations of pCO_2 and process air inlet conditions. The stability of the electrochemical cells is evidenced by essentially constant average cell voltage of 0.42 V per cell.

TABLE 9 NOMINAL TEST CONDITIONS

Current, A	9.9
Process Air	
Flow Rate, dm^3/s (cfm)	5.1 (10.8)
pCO_2, Pa (mm Hg)	400 (3.0)
Relative Humidity, %	56-64
Dew Point, K (F)	283-286 (50-56)
Dry Bulb, K (F)	291-293 (64-68)
Hydrogen	
Flow Rate, kg/h (lb/h)	0.006 (0.014)
Pressure, kPa (psia)	172 (25)
Module Backpressure, kPa (psia)	34.5 (5.0)
Purge Gas	
Type	Nitrogen
Pressure, kPa (psia)	207 (30)
Coolant	
Temperature, K (F)	275-277 (36-40)

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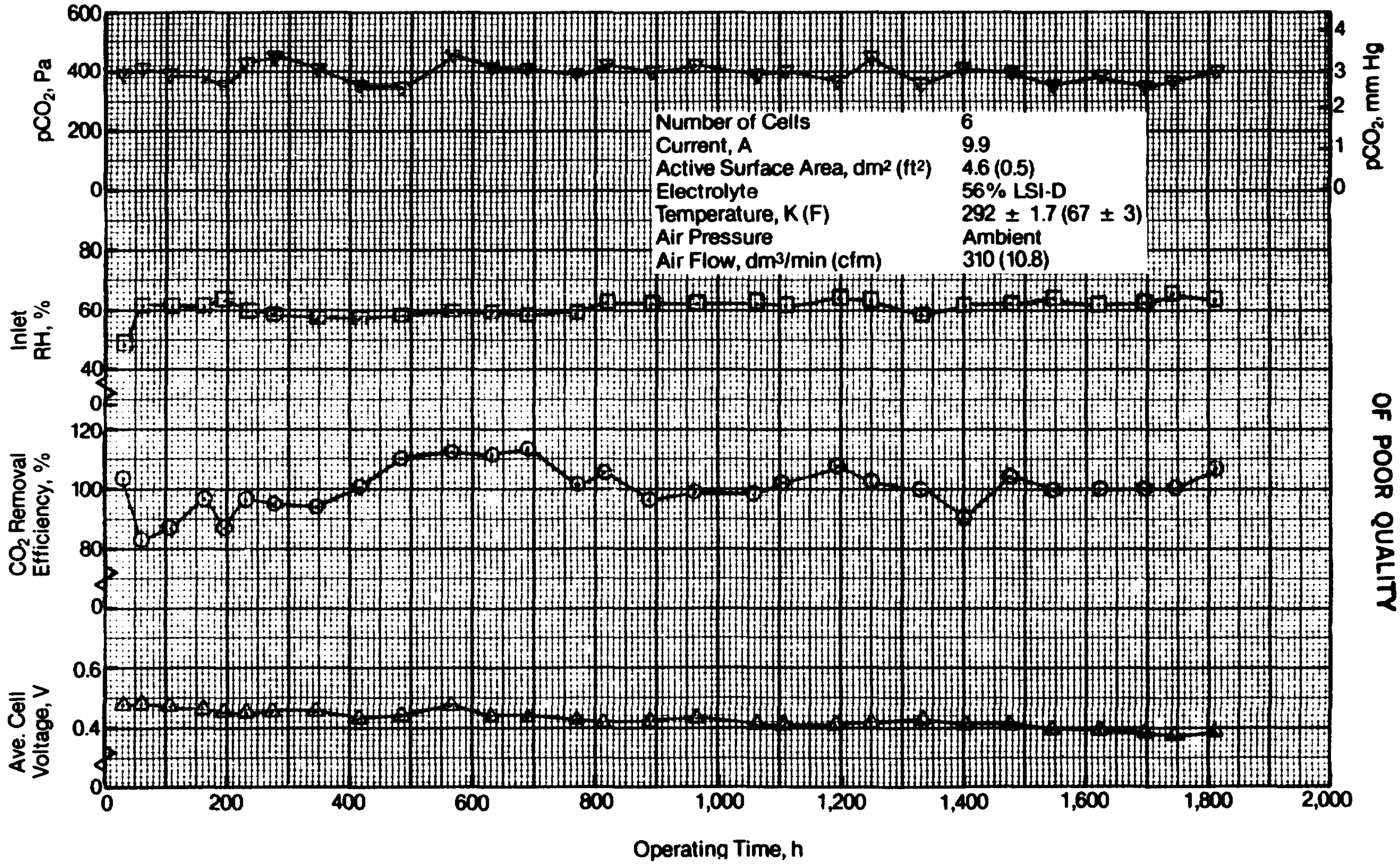

FIGURE 28 CS-1 PERFORMANCE

Parametric Tests

The parametric tests established the effects of CO_2 partial pressure (pCO_2), inlet process air RH and current density on module performance. These tests were performed before and after the endurance test to investigate the effects of long-term operation.

Variable CO_2 Partial Pressure. EDC performance at various partial pressure levels is shown in Figure 29. The CO_2 efficiency averaged approximately 100% (well above the 85% design point) at a nominal pCO_2 level of 400 Pa (3.3 mm Hg) and an anode exhaust (H_2) backpressure of 34.5 kPa (5.0 psig).

Current Density Effects. The CS-1 performance as a function of current density span is shown in Figure 30. This shows that excellent CO_2 removal performance was maintained at the various current density levels.

Process Air RH Effects. The effect of variable humidity on CS-1 performance was investigated over the range of 25 to 80% as shown in Figure 31. As seen, the effect of RH has been minimized by the inclusion of the inlet air/liquid heat exchanger in the CS-1 design. This was an important finding during the test program and verified its design function.

Conclusions of CS-1 Testing. The results of these tests verify that the CS-1 development objectives have been successfully met. Predictable, reproducible high level performance over much wider ranges of RH and H_2 backpressure than heretofore demonstrated, particularly at the modular level, were achieved. This success is attributed to the development of the unitized core, liquid-cooled cells and additionally to ensuring the inlet air enters the EDCM preconditioned to module temperatures via an air/liquid heat exchanger. These innovations shall be considered baseline for future EDCMs.

EDC Component Endurance Testing

Another task of the program was to continue endurance testing on the three major EDC subsystem components, namely an EDCM, an FCA and a CCA.

EDCM Endurance Testing

Figure 32 shows the long-term EDCM endurance test. This testing was initiated under a prior program[11] and was continued for an additional 11,500 hours under the current program. The total test time on this module is approximately 20,000 hours. It is seen that CO_2 removal performance and cell voltage remained approximately constant over the test time although both values fell off slightly.

FCA Endurance Testing

Figure 33 shows the FCA performance over approximately 9,500 hours of testing. The parameters plotted are gas (air) inlet pressure, flow rate and residence time. Residence time is related to how often the FCA valve is actuated or cycled in a given period. For a residence time of 60 minutes the FCA remains

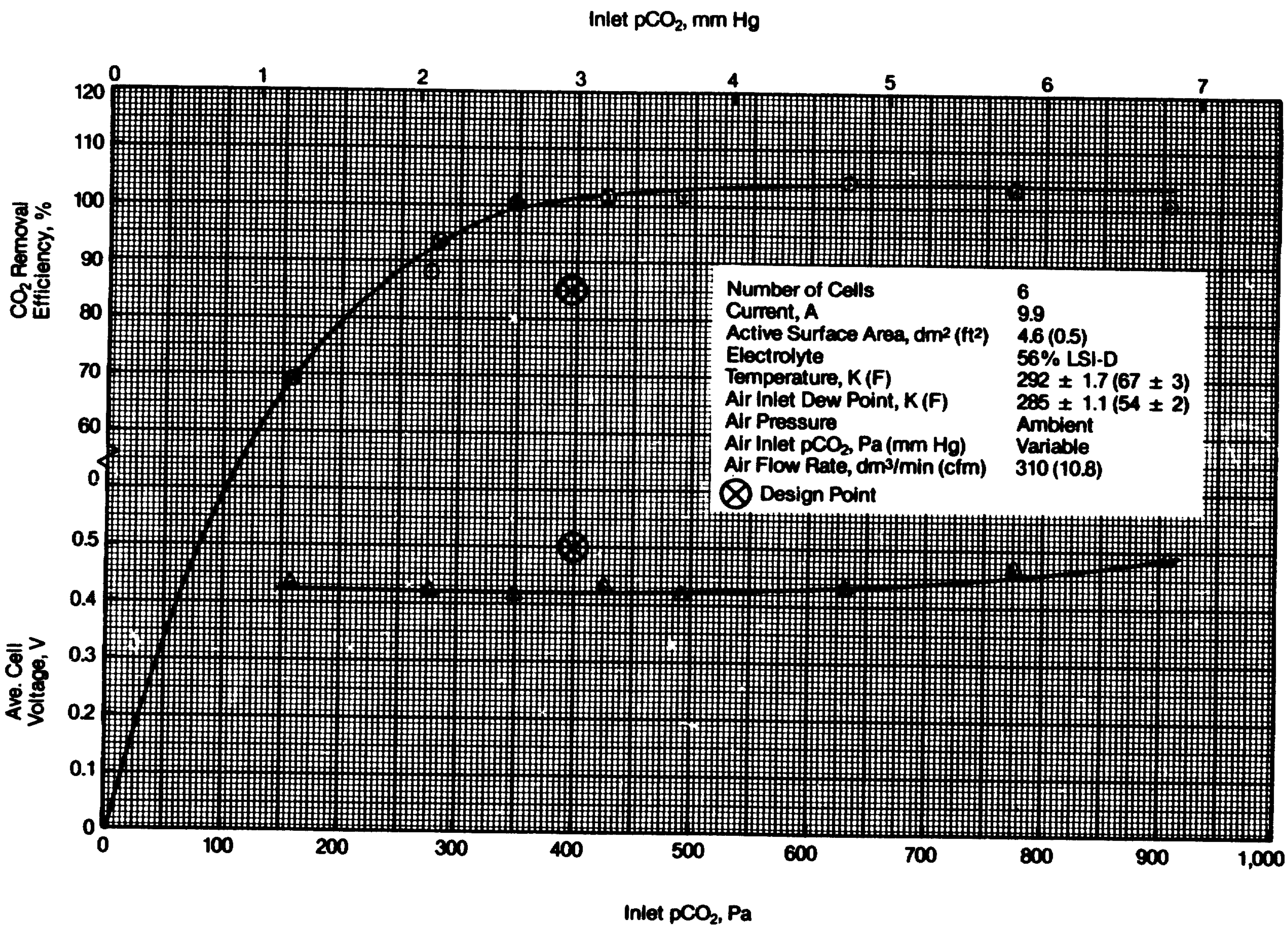

FIGURE 29 CS-1 PERFORMANCE (pCO_2 VARIATION)

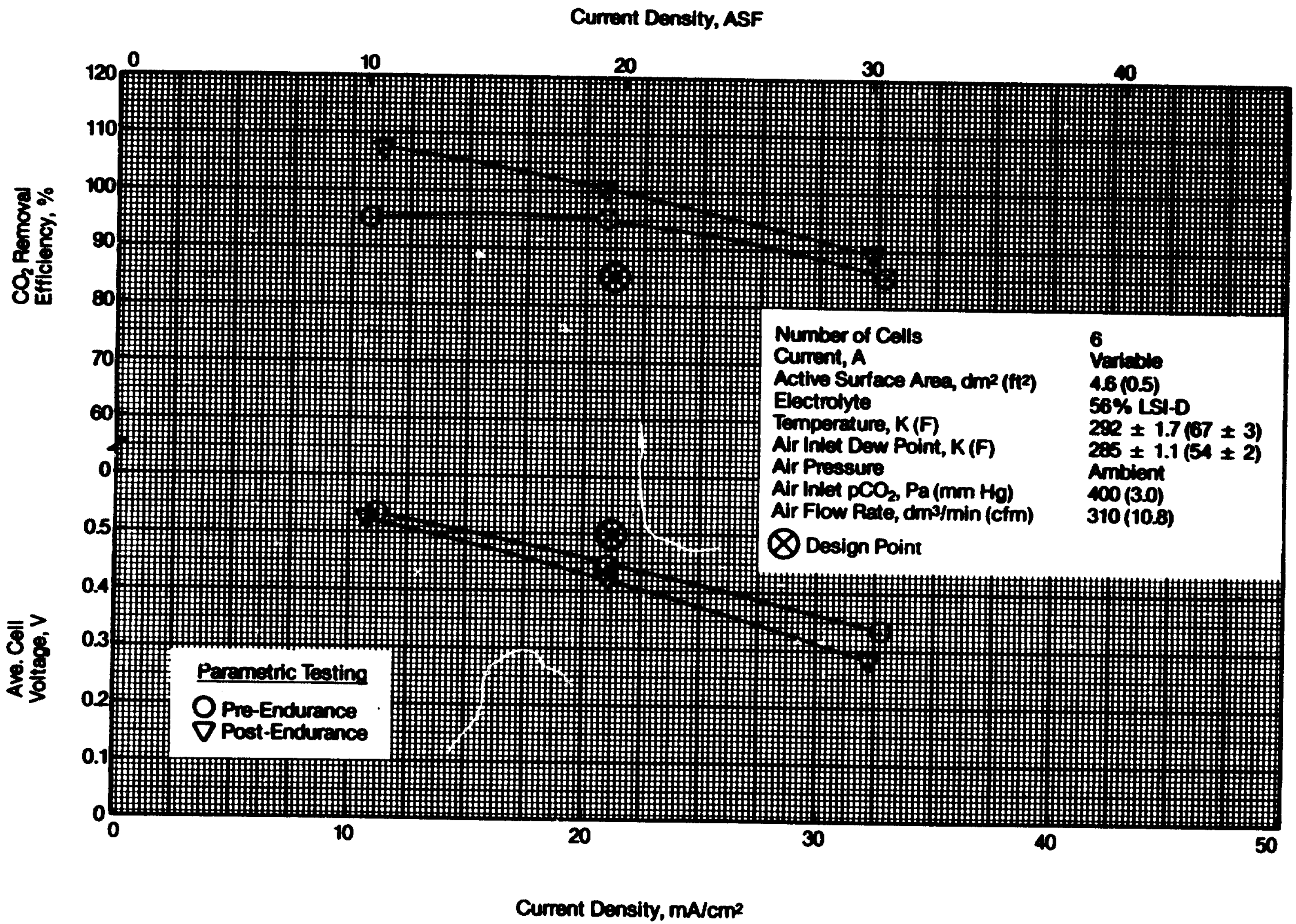

FIGURE 30 CS-1 PERFORMANCE (CURRENT DENSITY VARIATION)

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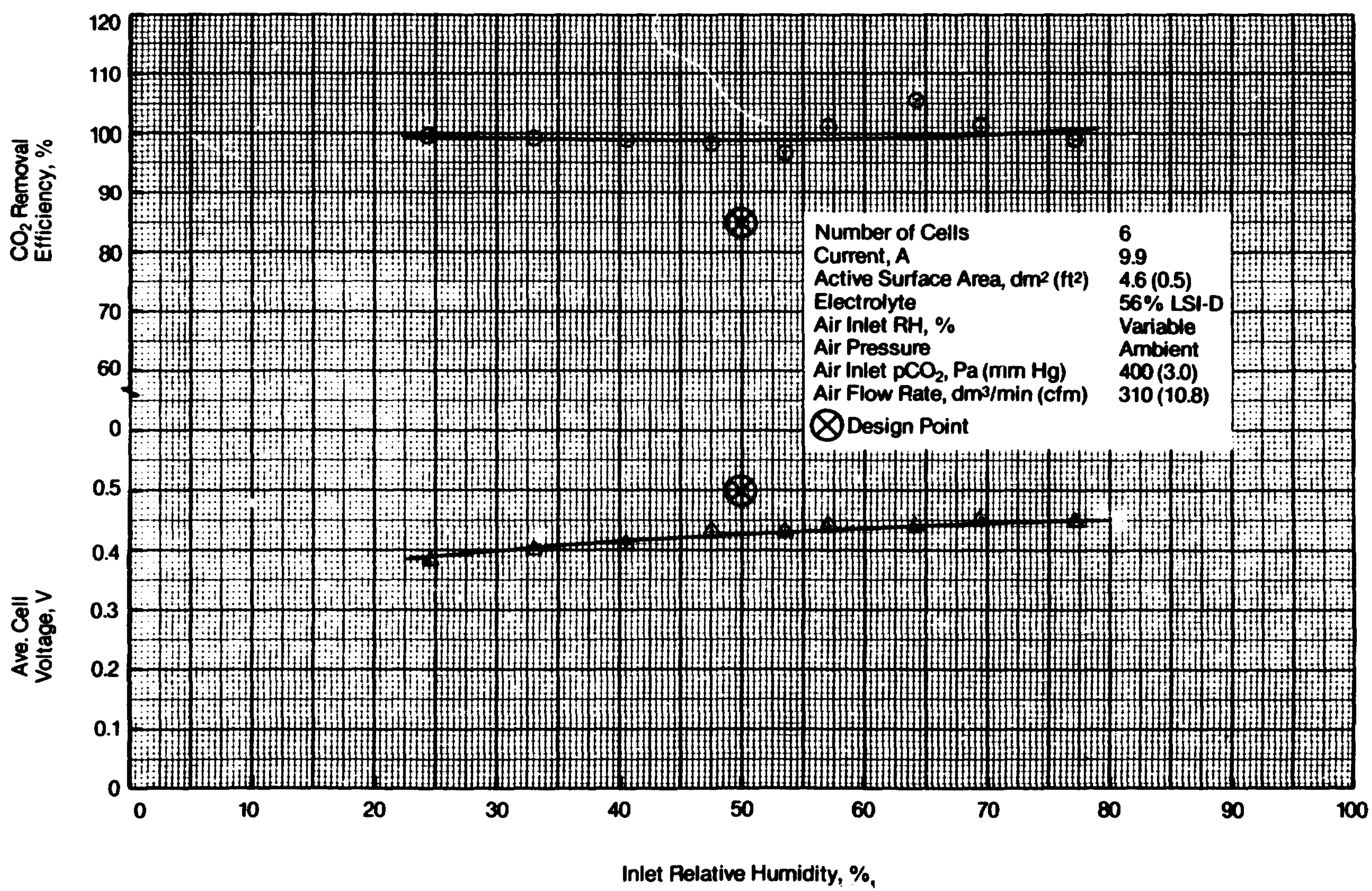

FIGURE 31 CS-1 PERFORMANCE (RH VARIATION)

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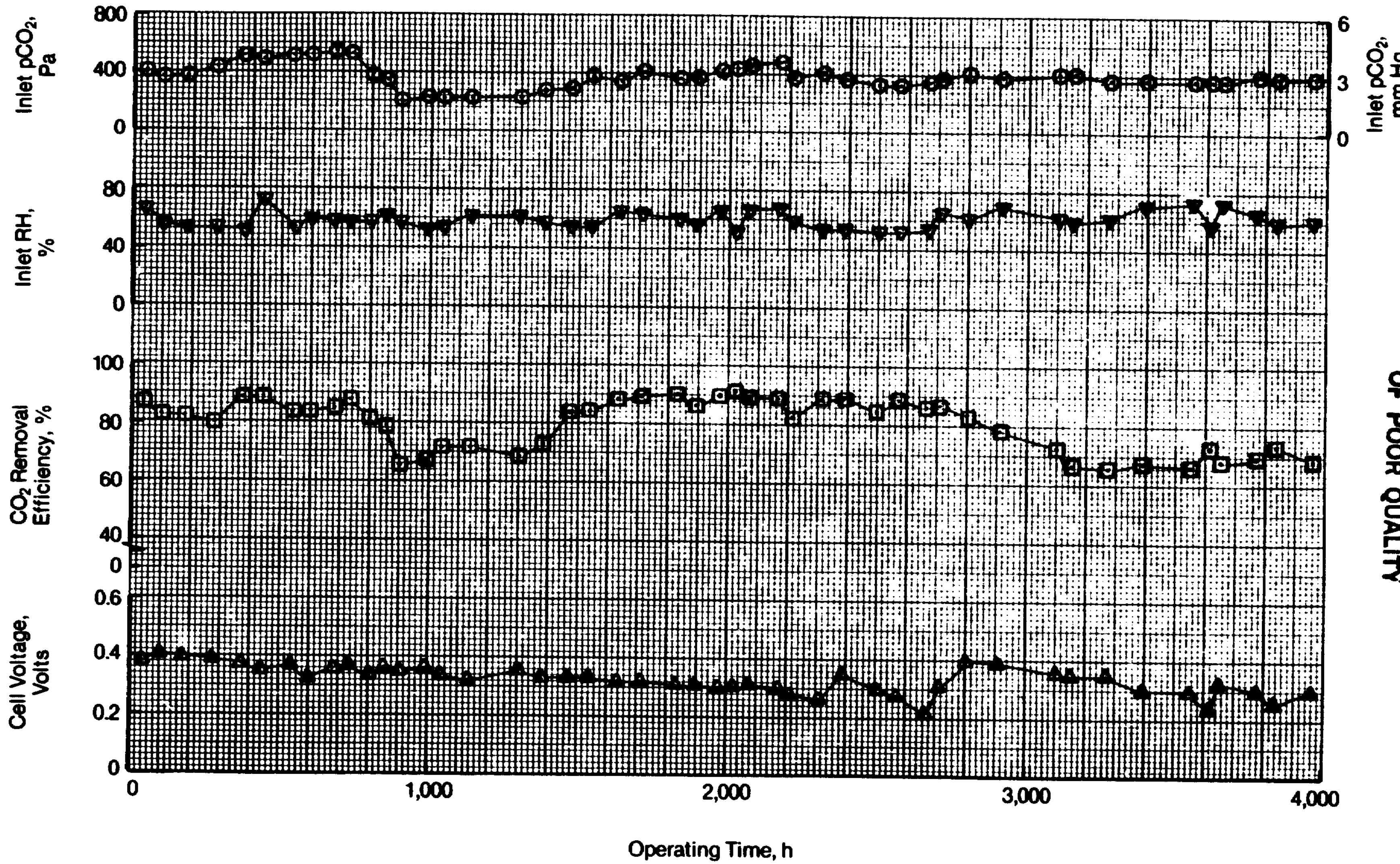

FIGURE 32 LONG TERM EDCM ENDURANCE TEST

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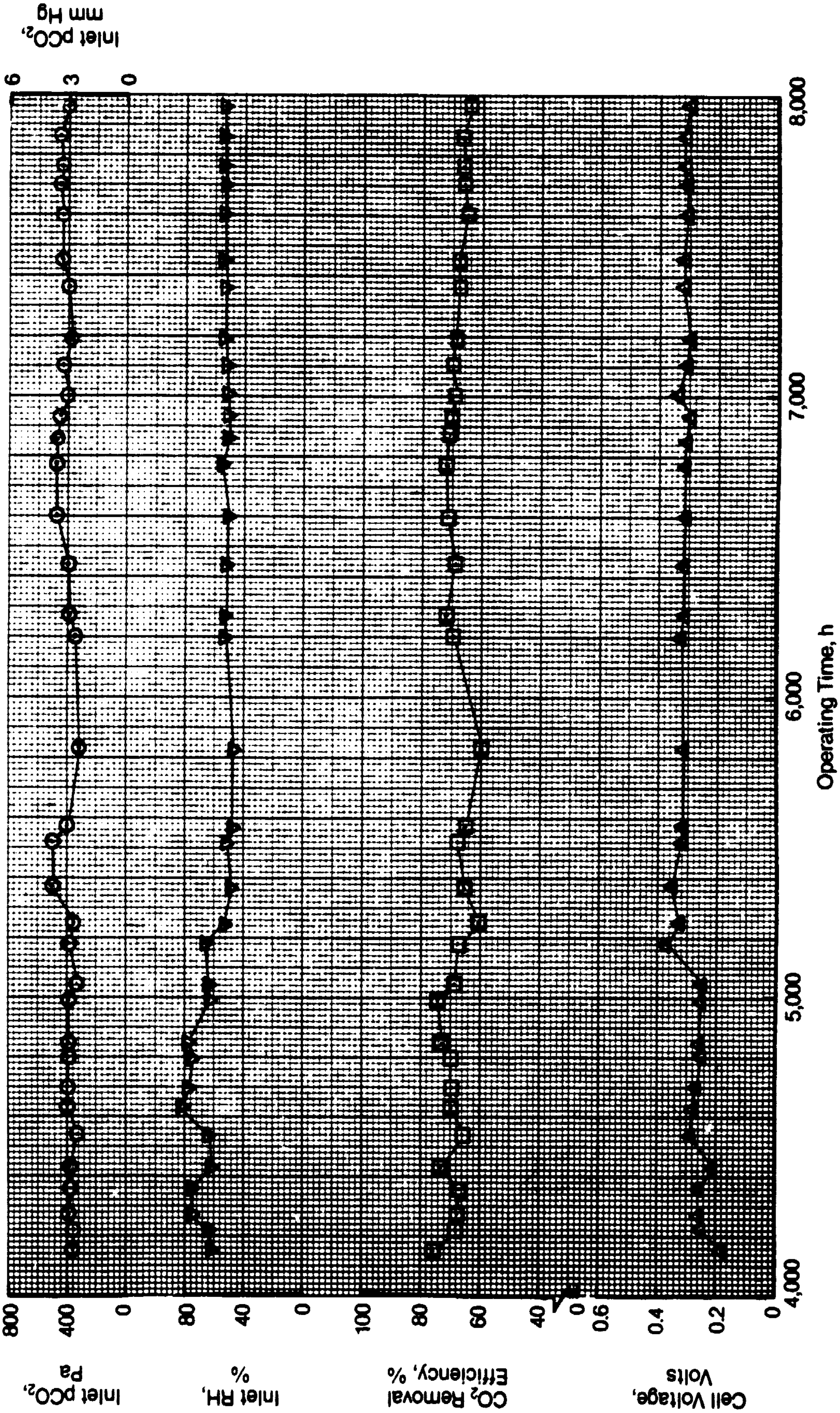

FIGURE 32 - continued.

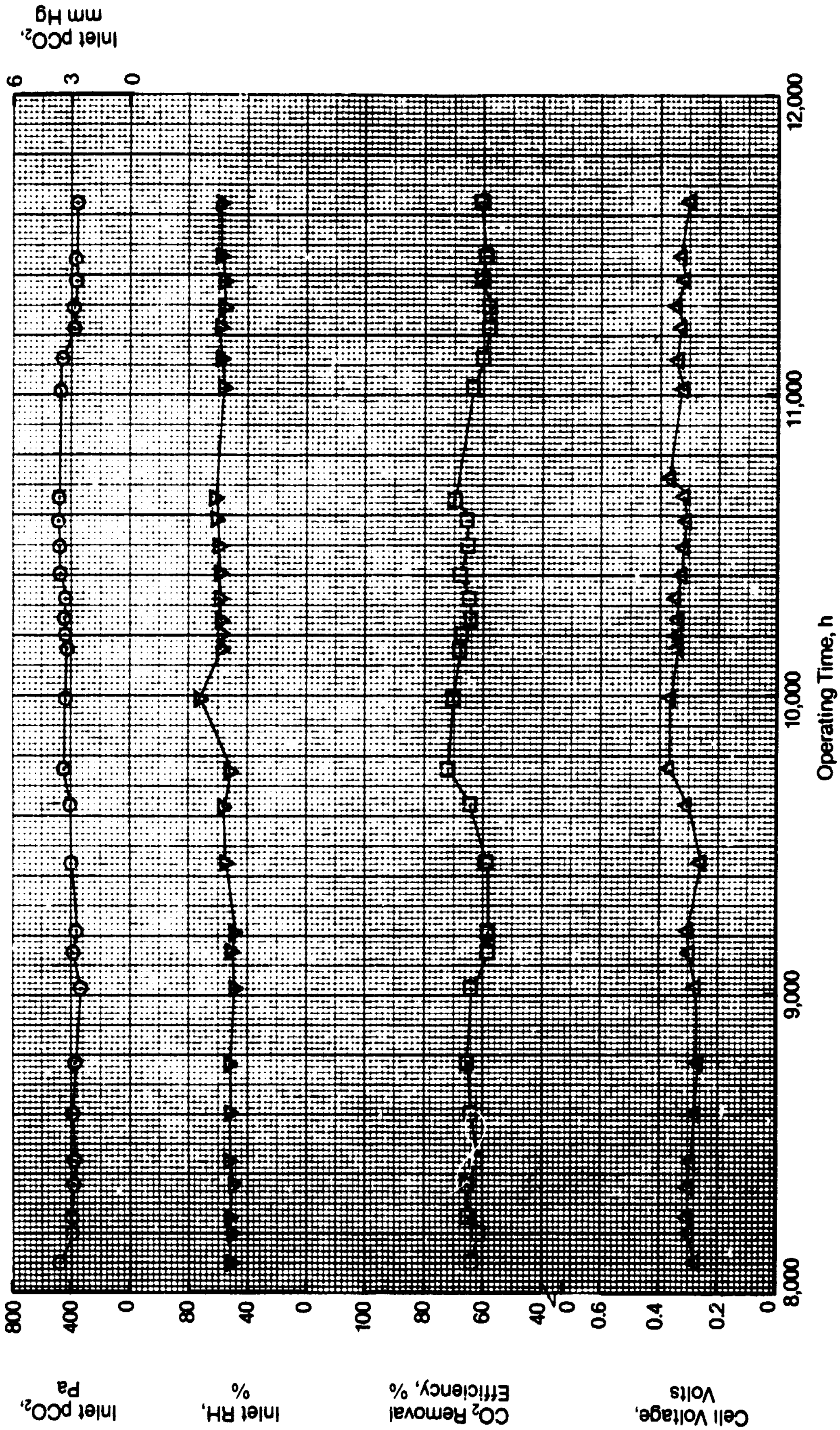

FIGURE 32 - continued

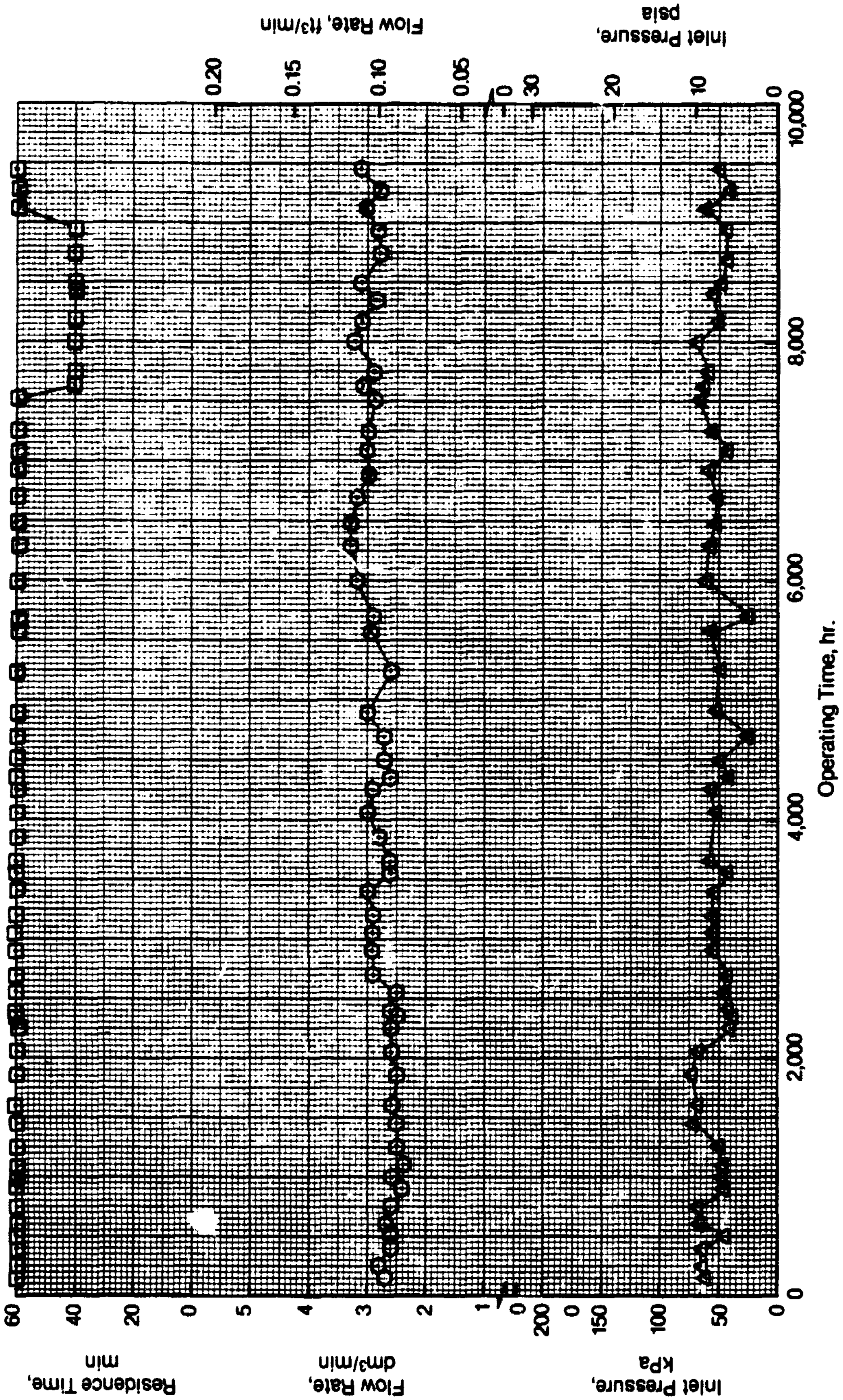

FIGURE 33 FCA ENDURANCE TEST PERFORMANCE

in each of its four states for one hour before changing states, resulting in a complete cycle every four hours or six cycles per day. Despite some shutdowns of the test stand due to electronic failures in the FCA controller, there were no problems with any mechanical parts of the FCA including the housing, valve spool, seals and drive motor over the 360 day test.

CCA Endurance Testing

Figure 34 shows the performance of the CCA over the 9,400 hours of endurance testing under this program. The parameters selected for illustrating performance are the following: (1) total mass flow rate, (2) developed pump head pressure, (3) temperature of the heat source which the CCA is trying to maintain and (4) cycle time of the heater used to simulate a varying module heat source. For the last parameter the heater is on for 30 minutes and off for 30 minutes in the case shown. The CCA diverter valve must change its position to divert more flow (heater on) or less flow (heater off) through an external heat exchanger. While this is a more dynamic variation than encountered in an application, it does provide for continuous movement and "exercise" of the CCA diverter valve assembly. The CCA pump speed was constant at 11,000 rpm throughout the testing. At one point during the testing a new design was tried - direct-drive coupling of the motor and the CCA pump. This proved to be unsuccessful, and testing with the originally designed magnetic-coupled drive was then resumed. The direct-drive coupling testing occurred over three weeks of the total testing and was terminated because of a motor bearing failure due to excessive shaft loads.

SUPPORTING TECHNOLOGY

Two activities were undertaken during the program as part of the EDC advancement. These were the preliminary design of a Triple Redundant Relative Humidity Sensor (TRRHS) and the fabrication of a EDC subsystem mockup as applied to the Space Station.

TRRHS Preliminary Design

The present method of measuring process air inlet RH to the CS-1 consists of using a commercially available dew point temperature sensor head and a dry bulb temperature sensor. Electronics for the chilled mirror-type dew point sensor are fairly complex and power consuming because a thermoelectric cooler is used that requires considerable control circuitry and power. It is desirable to replace these two sensors with a single unit of small size and also, since humidity measurement is critical to CS-1 operation, to make it triply redundant. A further requirement was to include in situ calibration with the TRRHS to verify its operation and stability over a long period of time.

An extensive literature survey was conducted, from which data for 19 key methods of dew point and RH measurement were collected, summarized and evaluated. Performance specifications defined for the TRRHS are shown in Table 10. A semi-conductor which is responsive to RH changes was selected, as shown in Figure 35. It has triple redundant sensing elements and the necessary mechanical hardware and other sensors for in situ calibration based on a two pressure calibration scheme.

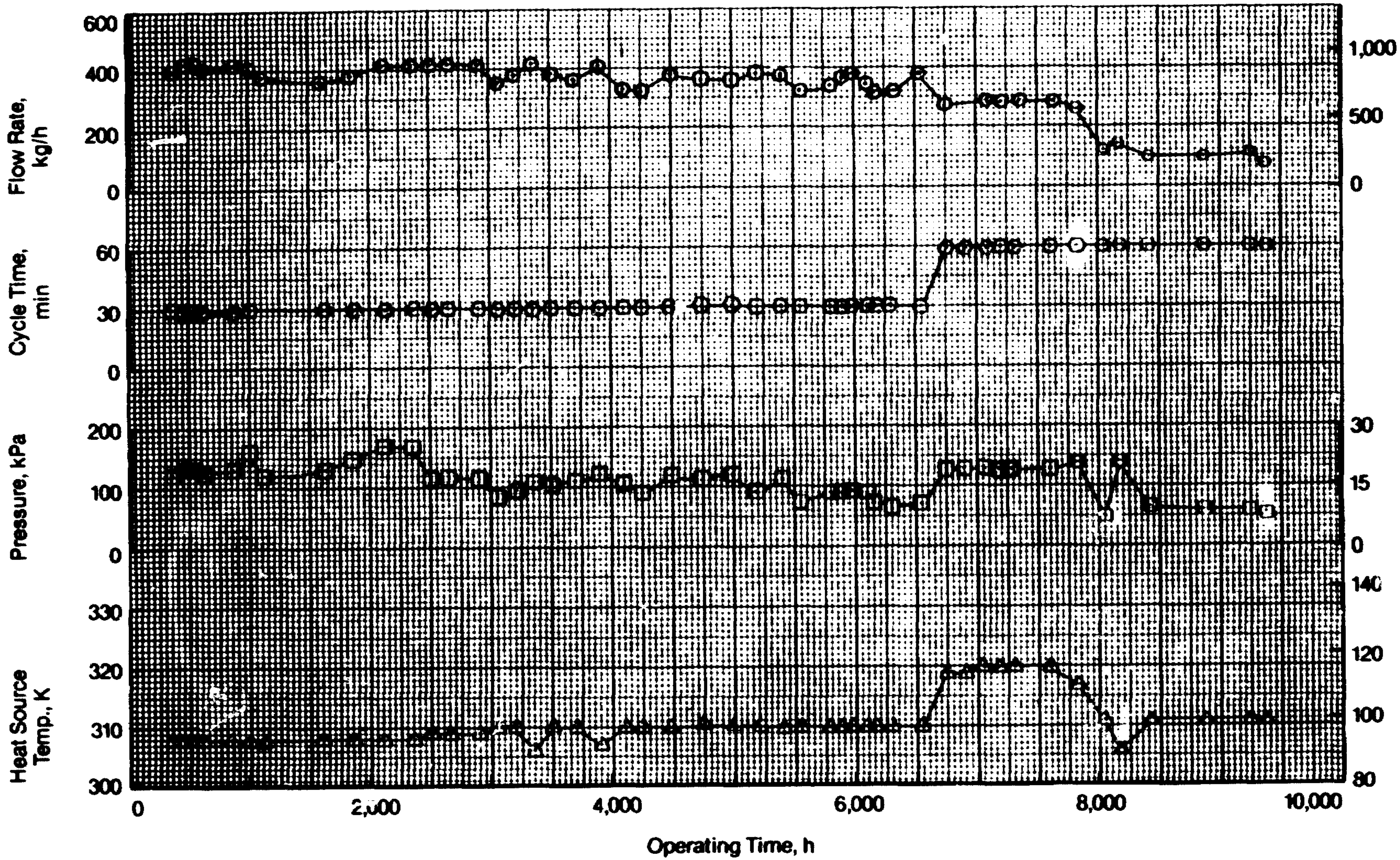

FIGURE 34 CCA ENDURANCE TEST PERFORMANCE

TABLE 10 TRRHS SPECIFICATIONS

OPERATIONAL CHARACTERISTICS	
RH Range, %	20-95
Dew Point Temperature Range, K (F)	253-321 (-4 to 118)
Temperature Range, K (F)	273-322 (32-120)
Pressure, kPa (psia)	35-140 (5-20)
Accuracy, % RH	± 3 over range
Stability (at 50% RH)	
Short-term, % RH change/month	± 3
Long-term, % RH change/year	± 10
Repeatability, % RH	± 2
Reproducibility, % RH[(a)]	± 3
Linearity, Max. % RH Deviation from a straight line over range	± 5
Response Time, sec.	
Step Increase (90% FS)	45
Step Decrease (95% FS)	60
Hysteresis, % RH midrange deviation between forward and reverse full range excursions	10
Display Resolution, !% RH	0.1
Temperature Sensitivity, % RH/K (% RH/F)	0.03 (0.05)
Air Velocity Sensitivity, % RH/m/s (%RH/ft/s)	0.03 (0.1)
Air Pressure Sensitivity, % RH/kPa (% RH/psia)	0.03 (0.2)
Shelf Life, years	5
Operating Life, years	2
Reliability (MTBF), h	10,000
Sensor Orientation Sensitivity, % RH	± 4
In Situ Calibration	
Calibration Points, % RH	
Low RH Point	40
High RH Point	80
Long-Term Stability, % RH/year	
Low RH Point	± 10
High RH Point	± 8
Repeatability, % RH	
Low RH Point	± 3
High RH Point	± 2
Accuracy, % RH	
Low RH Point	± 3
High RH Point	± 2
Reproducibility, % RH	
Low RH Point	± 5
High RH Point	± 3
Calibration Time (complete), min	5
Calibration Frequency, No./day	1

(a) Variation from one instrument to another.

continued-

Table 10 - continued

ELECTRICAL CHARACTERISTICS	
Power (total) W	10
Power Supply Voltage, VAC	115
Power Supply Frequency, Hz	60
Front Panel Controls	
Display(s)	RH-3 Digit LED
Indicators	Power On, In Calibration Mode
Control Adjustments	Power On
Rear Panel Controls	
Output	TBD
• Analog	
• Alarms	
• Other Digital Outputs/Relays	
Control Adjustments	
Sensor Cable	
PHYSICAL CHARACTERISTICS	
Sensor	
Weight, kg (lb)	0.23 (0.5)
Volume, cm^3 (in^3)	340 (21)
Dimensions, cm (in)	3.8 diam x 7.6 (1.5 diam x 3)
Mounting	Boss—Mounted
Electronic Package	
Weight, kg (lb)	4.1 (9)
Volume, dm^3 (in^3)	3.5 (216)
Dimensions, cm (in)	7.6 x 15 x 30 (3 x 6 x 12)
Mounting	Free Standing
ENVIRONMENTAL LIMITS	
Air Velocity, m/s (ft/s)	0-6 (0-20)
Air Pressure, kPa (psia)	35-140 (5-20)
Ambient Temperature, K (F)	
Sensor	273-322 (32-120)
Electronics Package	277-311 (40-100)
Shock	TBD
Vibration	TBD
EMI	TBD
Gravity, g	0-2
MAINTAINABILITY	
Line Replaceable Component	Sensor, Electronics
Replacement Time, h	0.2, 0.3
Special Tools	None

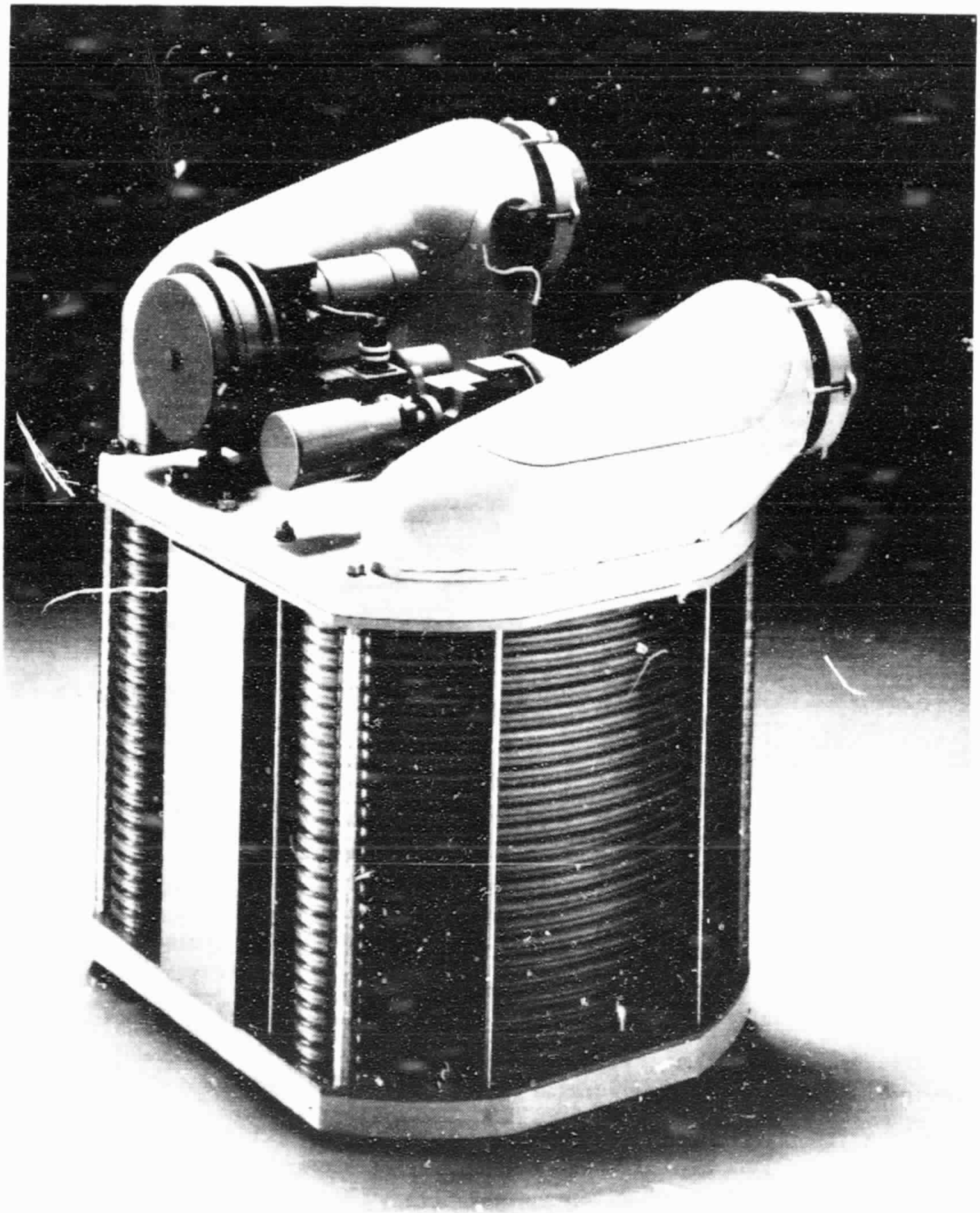

FIGURE 36 FOUR PERSON CO_2 REMOVAL SUBSYSTEM MOCKUP

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RECOMMENDATIONS

It is recommended that the current program be extended and focused on continued testing of the CS-1 concept. In addition, it is recommended that an in situ cell maintenance concept for increased EDCM reliability be incorporated into the CS-1. This concept will include compact, automatically switched relays to electrically isolate degraded cells. The integrated electrical design will minimize space requirements and resistive power losses. The CS-1 composite cell design with its allowance for a temperature difference between coolant and anode during operation will avoid cell dry out during shutdown, during which the temperature will drop to compensate for terminated water production. Inclusion of this capability, along with the development of a TRRHS, will then ready the CS-1 for the stage at which it can be incorporated into the ECLSS for the Space Station.

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