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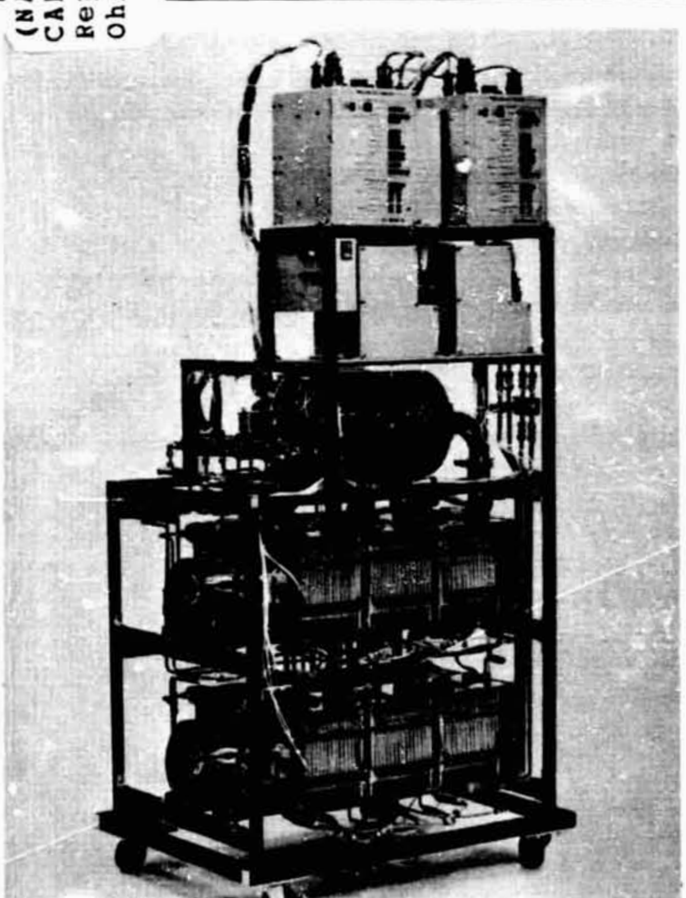
SIX-MAN, SELF-CONTAINED CARBON DIOXIDE CONCENTRATOR SUBSYSTEM

FINAL REPORT

by
J. D. POWELL, F. H. SCHUBERT, R. D. MARSHALL
and J. W. SHUMAR

JUNE, 1974



Prepared Under Contract No. NAS2-6478

by

Life Systems, Inc.
Cleveland, Ohio 44122

for

AMES RESEARCH CENTER
National Aeronautics & Space Administration

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FOREWORD

The development work described herein was conducted by Life Systems, Inc. during the period April 1, 1972 to December 31, 1973 under NASA Contract NAS2-6478. The Program Manager was Franz H. Schubert. Technical support was provided as follows:

Personnel	Areas of Responsibility
Timothy M. Hallick	Parametric, endurance and parallel technology testing
David E. Keck	Electrical checkout and assembly
Richard D. Marshall	Parallel technology testing
J. David Powell	Electrical design
Franz H. Schubert	Mechanical and system design
John W. Shumar	Product Assurance Program
Richard A. Wynveen	Program Administration, electrochemical support

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

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SUMMARY

A six-man, self-contained Electrochemical Carbon Dioxide (CO_2) Concentrating Subsystem was successfully designed and fabricated. It was a preprototype engineering model designed to nominally remove 6.0 kg (13.2 lb) CO_2/day with an inlet air CO_2 partial pressure (pCO_2) of 400 N/m^2 (3 mm Hg) and an overcapacity removal capability of 12.0 kg (26.4 lb) CO_2/day. The design specifications were later expanded to allow operation at Space Station Prototype (SSP) CO_2 Collection Subsystem operating conditions.

A Parametric Test Program was successfully completed. The subsystem was tested over a range of operating conditions, including hydrogen (H_2) flow rates of 8.3 x 10^{-5} to 22.2 x 10^{-5} m^3/s (5 to 13.3 l/min), process air flow rates of 0.011 to 0.029 m^3/s (23 to 61 scfm), pCO_2 from 80 to 1025 N/m^2 (0.6 to 7.7 mm Hg), temperatures from 293 to 302K (67F to 85F) and current densities from 5.4 to 43 mA/cm^2 (5 to 40 ASF). The subsystem underwent endurance testing at SSP operating conditions for 189 days. Total accumulated operating time was 209 days.

The subsystem was designed with electronic control and monitoring instrumentation to regulate performance, analyze and display performance trends, and detect and isolate faults. The control and monitoring functions were physically separated by housing the respective circuits in separate enclosures.

Ground Support Accessories (GSA) were included to provide electrical power, process fluids, heat removal and parametric data displays allowing real time indication of operating status in engineering units.

A self-contained, Oxidizable Contaminant Removal Subsystem (OCRS) was designed, fabricated, tested and incorporated into the six-man CO_2 concentrator's GSA to eliminate trace contaminants from the process air although the major portion of the endurance test was completed, as requested by the National Aeronautics and Space Administration (NASA), with the OCRS turned off.

A Product Assurance Program incorporated Quality Assurance, Reliability, Maintainability, Safety and Material Conformance. Activities included conducting a Design Review Meeting and preparing a Failure Mode Effects and Criticality Analysis (FMECA), a Fault Detection and Isolation Analysis (FDIA), a Single Point Failure Analysis (SPFA), a Safety Hazard Analysis (SHA), and Nonmetallic and Metallic Materials Lists.

A parallel technology program verified baseline designs and advanced electrochemical concentrator technology. This program included: an experiment to determine the water vapor pressure above aqueous solutions of cesium carbonate (Cs_2CO_3); a 245-day endurance test including parametric scans at SSP operating conditions on a three-cell submodule having the six-man baseline configuration, a five-part test program on the one-man system after its 180-day endurance test under Contract NAS2-6118[1], a task to design, fabricate and incorporate electrochemical module fault prediction circuits into the one-man system, the design and fabrication of

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

a CO_2 removal process efficiency computer; the design and evaluation of a humidity exchanger, the evaluation of methods of using CO_2 concentrator power, and the design, fabrication and evaluation of a module moisture balance control.

A program to design, fabricate, and test a self-contained, six-man CO_2 concentrating subsystem according to SSP specification was completed. The unit was delivered to NASA, Johnson Space Center (JSC), for testing with the other SSP subsystems. The report on the SSP CO_2 Collection Subsystem is contained in a separate document[2].

A program to develop a steady-state computer simulation (mathematical model) of an electrochemical depolarized CO_2 concentrator was completed. The results of this program are contained in a separate document[3].

INTRODUCTION

Under the National Aeronautics and Space Administration (NASA) Contract NAS2-6478, Life Systems, Inc. developed two six-man, self-contained Electrochemical Carbon Dioxide Concentrating Subsystems. The first subsystem, referred to as the CX-6 (Carbon Dioxide Concentrator, Experimental, Six-Man Subsystem), was designed as a preprototype engineering model and experimentally characterized through extensive parametric and endurance testing. The second subsystem, referred to as the CS-6 (Carbon Dioxide Concentrator, Space Station Prototype, Six-Man Subsystem), was designed according to Space Station Prototype (SSP) specifications, was fabricated, assembled, and was design verification and acceptance tested prior to being shipped to NASA JSC.

The program consisted of three major phases of activities:

1. Development of the CX-6.
2. Incorporation of SSP operating conditions for the CX-6 including, as a goal, SSP design specifications[4,5] and NASA Flammability and Outgassing Specifications[6] (CX-6 modified).
3. Development of the CS-6.

In parallel with the development of the two subsystems, activities were conducted to advance the technology of the electrochemical carbon dioxide (CO_2) removal method and to support CX-6 and CS-6 developments.

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

1. Develop a six-man, preprototype engineering model of the CO_2 concentrator (CX-6) capable of removing 6.0 kg (13.2 lb) CO_2/day with an inlet CO_2 partial pressure (pCO_2) of 400 N/m^2 (3 mm Hg). The subsystem would have a designed CO_2 removal capability of 12.0 kg (26.4 lb) CO_2/day and include provisions to analyze performance trends, detect faults, isolate faults, and, in time, predict failures.

2. Fabricate Ground Support Accessories (GSA) for parametric and life testing of the subsystem.

3. Implement a Product Assurance Program to integrate reliability, maintainability, safety, quality assurance and material control concepts into the subsystem during the total development phase.

4. Conduct component checkout, calibration, and design verification tests, subsystem shakedown and design verification tests, subsystem parametric or off-design verification tests, a six-month subsystem endurance test, and a series of parametric tests on the one-man CO_2 concentrating subsystem (CX-1)[1] following the completion of its testing under NAS2-6118 to obtain data on performance changes and degradation rates following extended operation.

5. Prepare a mini-Preliminary Design package relating the electrochemical CO_2 concentrator design to the SSP program.

6. Conduct tests and analyses in parallel with the development to advance subsystem technology, design and performance, and, where appropriate, evaluate new innovations.

7. Develop a six-man, self-contained electrochemical CO_2 concentrator according to SSP specifications (CS-6) to enable incorporation into the Air Revitalization Group (ARG) of the SSP Life Support System.

Tasks 1, 2, 3, 4, and 6 were concerned with the development of the CX-6 and parallel technology activities while Tasks 5 and 7 were limited to the development of the CS-6.

This report emphasizes the activities associated with the CX-6 and with the technology tasks. Only a brief summary of CS-6 activities is presented. A complete description of the CS-6 development activities is presented in Reference 2.

CARBON DIOXIDE CONCENTRATOR SUBSYSTEM (CX-6)

The CX-6 consists of two groups of hardware: the CO_2 removal hardware and the CO_2 instrumentation hardware. The CO_2 removal hardware includes all the electrochemical and mechanical components needed to continuously remove 6.0 kg (13.2 lb) CO_2/day from a 101 kN/m^2 (14.7 psia) atmosphere having a pCO_2 of 400 N/m^2 (3 mm Hg). The CO_2 instrumentation hardware includes all the electrical and electronic components and sensors needed to continuously control and monitor the CO_2 removal process. In addition, this hardware has built-in provisions to check out the monitoring instrumentation operability.

Subsystem Design

Table 1 shows the design specifications used for the CX-6. The table contains two columns. The first column shows the specifications to which the CX-6 was originally designed. The second column shows SSP design specifications incorporated during the second phase of the program.

TABLE 1 SUBSYSTEM DESIGN SPECIFICATIONS

	CX-6	CX-6 Modified
Number of Crew (Continuous)	6	6
CO_2 Removal Requirements, kg/d (Lb/Day)		
Nominal (48-Hour Average)	6.0 (13.2)	6.0 (13.2)
Maximum (4-Hour Duration)	12.0 (26.4)	9.3 (20.4)
Cabin Atmosphere		
Total Pressure, kN/m^2 (Psia)	101-105 (14.7-15.2)	101-105 (14.7-15.2)
Temperature, K (F)	291-297 (65-75)	291-297 (65-75)
Dew Point Temperature, K (F)	281-287 (46-57)	281-287 (46-57)
O_2 Partial Pressure, kN/m^2 (Psia)	20.9-22.6 (3.04-3.28)	20.9-22.6 (3.04-3.28)
CO_2 Partial Pressure, N/m^2 (mm Hg)		
Nominal	400 (3)	<400 (<3)
Operating Range	0-2000 (0-15)	200-400 (1.5-3)
Diluent	Air Constituents	Air Constituents
Process Air		
Total Pressure, kN/m^2 (Psia)	101-105 (14.7-15.2)	Ambient + 1.49 (+ 0.22)
Temperature, K (F)	291-297 (65-75)	Dew Point + 3.3 (+ 6)
Dew Point Temperature, K (F)	282-287 (49-57)	281-283 (46-5
O_2 Partial Pressure, kN/m^2 (Psia)	20.9-22.6 (3.04-3.28)	20.9-22.6 (3.04-3.28)
CO_2 Partial Pressure, N/m^2 (mm Hg)		
Nominal	400 (3)	381 (2.86)
Operating Range	0-2000 (0-15)	200-385 (1.5-2.89)
Diluent	Air Constituents	Air Constituents
Cooling Air		
Total Pressure, kN/m^2 (Psia)	101-105 (14.7-15.2)	Ambient + 1.49 (+ 0.22)
Temperature, K (F)	280-282 (44-49)	Process Air Dew Point + 3.3 (+ 6)
H_2O Supply (Humidification)		Not Applicable[a]
Pressure, kN/m^2 (Psia)	207 (30)	
Temperature, K (F)	278-295 (40-72)	
Purity	(b)	

(a) The module's internal humidifiers were eliminated from the SSP design because of the closer tolerance on process air dew point specification, 282 ±1K (48 ±2F).

(b) Per NASA JSC Specification SD-W-0020, "Potable Water Specifications," dated May 16, 1970.

continued-

Table 1 - continued

	CX-6	CX-6 Modified
H_2 Supply		
Total Pressure, kN/m^2 (Psia)	117-152 (17-22)	<138 (<20)
Temperature, K (F)	291-297 (65-75)	291-297 (65-75)
Dew Point Temperature, K (F)	283-289 (50-60)	283-289 (50-60)
$H_2 + CO_2$ Exhaust		
Total Pressure	Ambient	Ambient[a]
Electrical Power		
DC	28 VDC	28 VDC
AC	120 VAC, 60 Hz, Single Phase	120 VAC, 60 Hz, Single Phase
Purge Supply		
Type Gas	N_2	N_2
Pressure, kN/m^2 (Psia)	310 (45)	310 (45)
Coolant Liquid		
Type Fluid	H_2O	H_2O
Pressure, kN/m^2 (Psia)	241 (35)	241 (35)
Temperature, K (F)	280-282 (44-48)	280-282 (44-48)
Packaging	Self-Contained	Self-Contained
Gravity	0-1 g[b]	0-1 g[b]
Allowable Downtime	10 Min[c]	8-12 Hr
Duty Cycle	Continuous	Variable[d]

(a) During the 189-day endurance test portion, the CX-6 was operated for the final 1500 hours at elevated $H_2 + CO_2$ backpressures of up to 31 kN/m^2 (4.5 psia) above ambient to demonstrate operability of the electrochemical modules at projected CS-6 operating conditions for the SSP.

(b) The CX-6 must be designed without functional limitations for 0 g application.

(c) As a design goal and the major reason why a two-loop concept was selected with each loop able to handle the total CO_2 removal load.

(d) The SSP specification cites potential orbital On/Off cyclic operating mode.

A major difference in the two sets of specifications is the source for the process and cooling air. For SSP application, both process and cooling air are supplied from the Cabin Temperature and Humidity Control Subsystem (CTHCS) instead of directly from the cabin atmosphere. This results in a narrower process air dew point range.

Other significant specification differences were the allowable downtime and the process air inlet pCO_2. In the modified version, from 8 to 12 hours of downtime were specified while the previous specification called for less than 10 minutes. The decrease in inlet pCO_2 from 400 to 381 N/m^2 (3 to 2.86 mm Hg) resulted from crew distribution possibilities within the SSP modules. For any crew distribution, the pCO_2 must be maintained at 400 N/m^2 (3 mm Hg) or less in any SSP module.

Subsystem Design Concepts

The subsystem was designed for self-contained operation, i.e., all those functions required to remove 6.0 kg (13.2 lb) CO_2/day are contained within the CX-6 itself. Functions performed by other subsystems of a total life support system were simulated by GSA.

For operation of the CX-6 under the original process air humidity range specifications, the internal cell humidification concept developed and tested for the one-man system[(1)] had been selected. The modified specification limited the process air dew point to 282 ±1K (48 ±2F). Internal humidification was therefore not required. To maintain flexibility, however, the subsystem was designed with modules having internal humidification. For operation under the modified specification, the internal humidifier cavities were drained and the water supply was disconnected at the subsystem interface.

To handle the maintenance downtime requirement of less than 10 minutes the CX-6 was designed with two loops, with either loop capable of handling the required 6.0 kg (13.2 lb) CO_2/day removal rate. Maintenance could be performed on one loop while the other loop performs the CO_2 removal function. For the SSP application with its mandatory longer maintenance downtime of 8 to 12 hours, the two-loop concept was not required.

Subsystem Features

The following is a summary of features that were incorporated into the CX-6 design:

1. Automatic system startup and shutdown with one button activation.

2. A two-loop configuration to minimize chance of loss of the CO_2 removal function and subsequent impact on interfacing subsystems (CO_2 reduction, water electrolysis, etc.). The goal was a maintenance downtime of 10 minutes or less. Each loop could operate independently.

3. Each loop was designed for a CO_2 removal rate of 6.0 kg (13.2 lb/day in an attempt to retain a subsystem CO_2 removal rate of 6.0 kg (13.2 lb/day) even after 180 days of endurance operation.

4. Insitu maintenance at the individual cell level for increased subsystem reliability and longer module operating life without replacement.
5. A two-minute automatic start/stop, fail-safe nitrogen (N_2) purge.
6. Modules equipped with internal humidifiers to enable subsystem operation over a wider range of air inlet humidity.
7. Ninety cells combined into two 45-cell modules to reduce auxiliary hardware requirements and to enhance subsystem maintainability.
8. A hydrogen (H_2) bypass valve to permit continuous H_2 flow to other subsystems, even though the CX-6 has both loops shut down, resulting in minimum perturbation of other life support subsystems.
9. Quick-connects for all Line Replaceable Units (LRUs) and interface connections.
10. A controller that maintains a constant CO_2 removal rate or regulates this rate to match requirements reflected in the observed pCO_2 level.
11. Liquid (water) cooling of the electronics.
12. Maintainable instrumentation divided into three types with separate power supplies for each and housed in separate enclosures: Control, Monitoring, and Built-In Checkout (BIC).
13. DC-to-DC converters to electronically isolate the subsystem (protecting the electronics from 28-volt input noises and transients and prevents transmission of spurious failure signals to other instrumentation, equipment or subsystems).
14. A 28-VDC subsystem except for the two process air blowers and the two cooling air blowers which use 115V, 60 Hz.
15. Sensor level maintainability.
16. Electronic circuitry designed to readily adapt to computerized control and monitoring.
17. Manual override on blower speed, module current and module temperature controls.
18. Voting capability on the H_2-in-air sensor by using three redundant sensors for output comparison; dual redundancy for the module temperature sensor by having two sensors with indication if sensor output of one differs from that of the other.
19. Vented boxes for all electrical circuits.
20. NASA Flammability and Outgassing Specification[6] as a design goal.

Subsystem Operation

Figure 1 is a simplified schematic of the CX-6 showing the two-loop approach. The subsystem operates as follows: process air is drawn through the modules from the GSA by staged centrifugal blowers. Blower speed, hence, air flow rate is controlled through blower voltage regulation. Hydrogen and N_2 purge gases are supplied from GSA. The H_2 flow can be directed either through the electrochemical modules or it can bypass the subsystem during shutdown of both loops. The two-loop paths of H_2 and CO_2 exiting from the modules are isolated by check valves. Static water addition to the internal humidifiers (when used) from GSA equipment is automatically controlled as water evaporates from the humidifiers within the modules. The cooling air fans circulate cold air over external fins of the modules. The independent on-off cooling fan operation is determined by the temperature level sensed in the air exit manifold of the modules.

Subsystem Control and Monitoring

Three parameters are controlled during CX-6 operation:

1. Individual submodule current since CO_2 removal rate is a direct function of current.

2. Module temperature to maintain the cells at proper moisture balance, i.e., to prevent cell dryout or flooding.

3. Process air blower speed to enable operation at optimum CO_2 removal efficiency while maintaining cell temperature.

There are two control modes: Mode A and Mode B. In Control Mode A, the three controlled parameters are manually set and automatically maintained at the desired level independent of variations in other parameters.

In Control Mode B, current, process air blower speed, and module temperature are automatically varied as a function of external input signals from the process air or cabin pCO_2 and dew point sensors. The current level and air flow rate are controlled as a function of process air pCO_2. As cabin pCO_2 increases, reflecting insufficient CO_2 removal, the current and process air flow rate increase proportionally. Module temperature is controlled as a function of process air dew point and is maintained at a constant differential above the incoming air dew point for proper moisture balance within the cells.

To enable performance trend analysis, fault detection and fault isolation, critical parameters of the CO_2 removal process are monitored. Sensors are located throughout the subsystem to identify when parameters fall outside tolerable limits. The sensor information is displayed on the instrumentation panels of the CX-6. It is used in manual isolation and identification of faulty components and conditions. The sensor information is also used in analyzing the trend of the CO_2 removal process. A self-checking feature of the monitoring instrumentation is also provided by means of the BIC unit.

The relationship between the plumbing hardware and the control and monitoring instrumentation is shown in Figure 2.

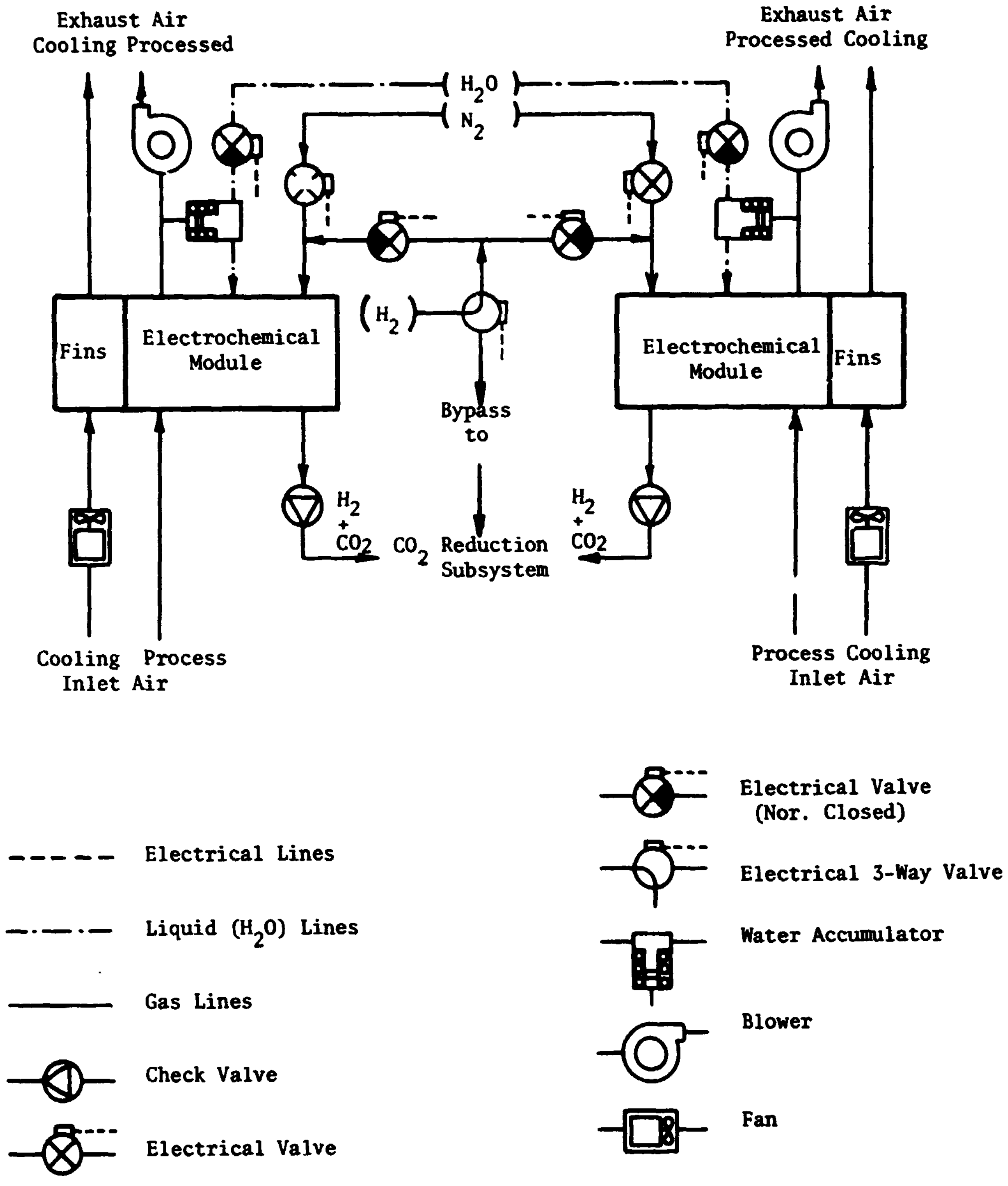


FIGURE 1 SIMPLIFIED SCHEMATIC OF THE CX-6

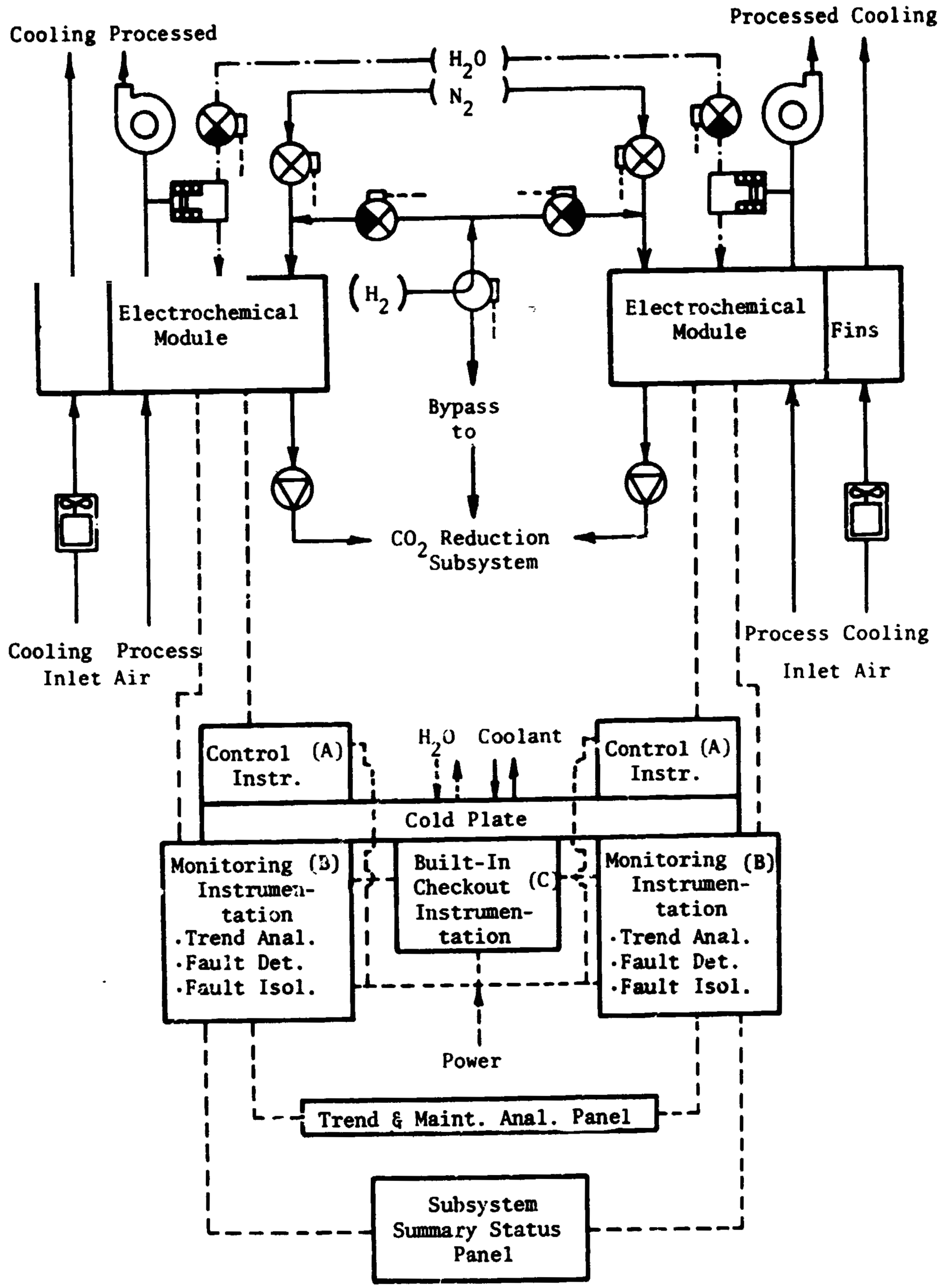


FIGURE 2 CO_2 REMOVAL AND INSTRUMENTATION HARDWARE SCHEMATIC

Hardware Description

The CX-6 was designed and fabricated based on a LRU and a Line Replaceable Component (LRC) concept. All major components such as modules, blowers, accumulators, valves, instrumentation enclosures, etc. are easily maintainable using minimum tools, fluid line quick-connects and electrical connectors. If a portion of an LRU can be maintained after its removal, it becomes a LRC of the LRU. The total subsystem consists of a series of LRUs mounted in a supporting structure with interconnecting plumbing and wiring.

The CX-6 was subdivided into 17 LRU's and 10 LRC's as shown in Tables 2 and 3, respectively. These tables also show the maintenance accessibility of the respective LRUs or LRCs.[7] Each LRU has a specification which completely describes it and its function. Appendix A contains a typical specification.

The detailed subsystem schematic, including LRUs, is shown in Figure 3. Photographs of the assembled CX-6 are shown in Figures 4 and 5. The major LRUs are identified on the figures. Figure 6 is an installation drawing of the CX-6 showing the overall dimensions and identifying the interface locations.

CO_2 Removal Hardware

The CO_2 removal hardware consists of electrochemical modules, process air blowers, cooling air blowers, H_2 solenoid valves, H_2 bypass solenoid valve, water solenoid valves, N_2 solenoid valves, H_2 check valves, water accumulators, process air filters, and the H_2 flow sensor and distribution mountings.

Electrochemical Modules. The function of the electrochemical modules is to remove CO_2 from the process air. Each of the two electrochemical modules consists of three 15-cell submodules, a process air inlet sensor, a process air exhaust sensor, two module compression plates, and a cooling shroud. The three submodules are retained between two module compression plates. The process air inlet and exhaust sensors are mounted to the compression plates. A removable front cooling shroud cover permits insitu cell maintenance of individual cells. The two 45-cell modules of the CX-6 are shown in Figure 7.

The three submodules form common process air inlet and exhaust manifolds. Air flows in parallel through all 45 cells. Hydrogen and water for humidification (when used) are supplied separately to each of the three submodules. Hydrogen and CO_2 exhaust gas is vented individually from each submodule.

Electrochemical Submodules. Each of the three electrochemical submodules consists of 15 individual cells retained between two stainless steel endplates. The 15 cells are thermally insulated from the stainless steel endplates by two, quarter-inch thick polysulfone insulation plates to minimize thermal end effects. Figure 8 shows end views of two different 15-cell submodules, one with and one without its cooling shroud installed.

Process air flows through the 15 cells in parallel while H_2 flows through the cells in series. The cells are electrically connected in series. The humidifier cavities of the 15 cells are connected in parallel with water drawn into

TABLE 2 CX-6 LINE REPLACEABLE UNITS

Item No.	LRU	Part No.	No. Req.	Maintenance Access		
				Front	Back	Left-Side
1	Module, Electrochemical	292	2	X		X
2	Blower, Process Air	297	2	1[a]	1[a]	
3	Blower, Cooling Air	296	2		X	
4	Valve, Solenoid, H_2	274	2			X
5	Valve, Solenoid, H_2 Bypass	249	1			X
6	Valve, Solenoid, H_2O	250	2		X	
7	Valve, Solenoid, N_2	275	2			X
8	Valve, Check, H_2	290	2			X
9	Accumulator, H_2O	235	2		X	
10	Filter, Process Air	248	2		X	
11	Instrumentation, Control	313	2	X		
12	Instrumentation, Monitor	314	2	X		
13	Instrumentation, Built-In Checkout	315	1	X		
14	Sensor, Fluid Flow	307	4	2[a]	2[a]	
15	Sensor, Differential Pressure, H_2-to-Air	200	2		X	
16	Sensor, Differential Pressure, Air-to-H_2O	230	2	X		
17	Mounting, H_2 Flow Sensor and Distribution	317	2	X		

(a) Number of LRUs accessible from designated direction

TABLE 3 CX-6 LINE REPLACEABLE COMPONENTS

Item No.	LRC	Part No.	No. Req.	Maintenance Access: Front	Back	Left-Side
1	Submodule	291	6	X		
2	Sensor, Process Air Inlet	327	2	X		
3	Sensor, Process Air Exhaust	326	2	X		
4	Sensor, Blower Speed	321	2	X		
5	PC[a] Card B2, Temperature Monitor	278	4	X		
6	PC Card B3, Gas Flow Monitor	279	8	X		
7	PC Card B4, Liquid Flow Monitor	280	2	X		
8	PC Card B6, Transducer Monitor	282	8	X		
9	PC Card B7, Voltage Level Monitor	283	2	X		
10	PC Card B8, Coolant Flow Monitor with Logic	284	2	X		

(a) PC = Printed Circuit

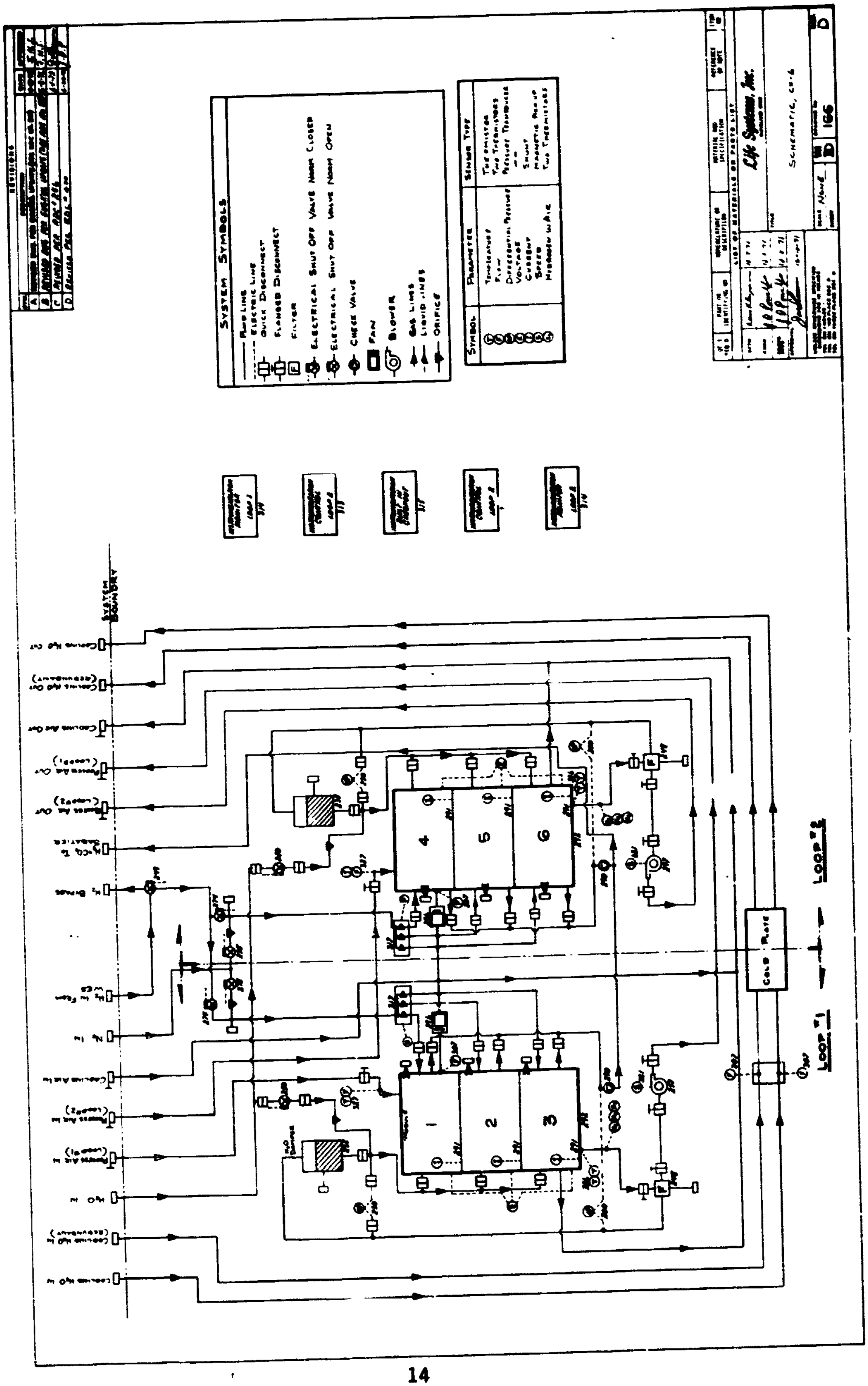


FIGURE 3 DETAILED CX-6 SCHEMATIC

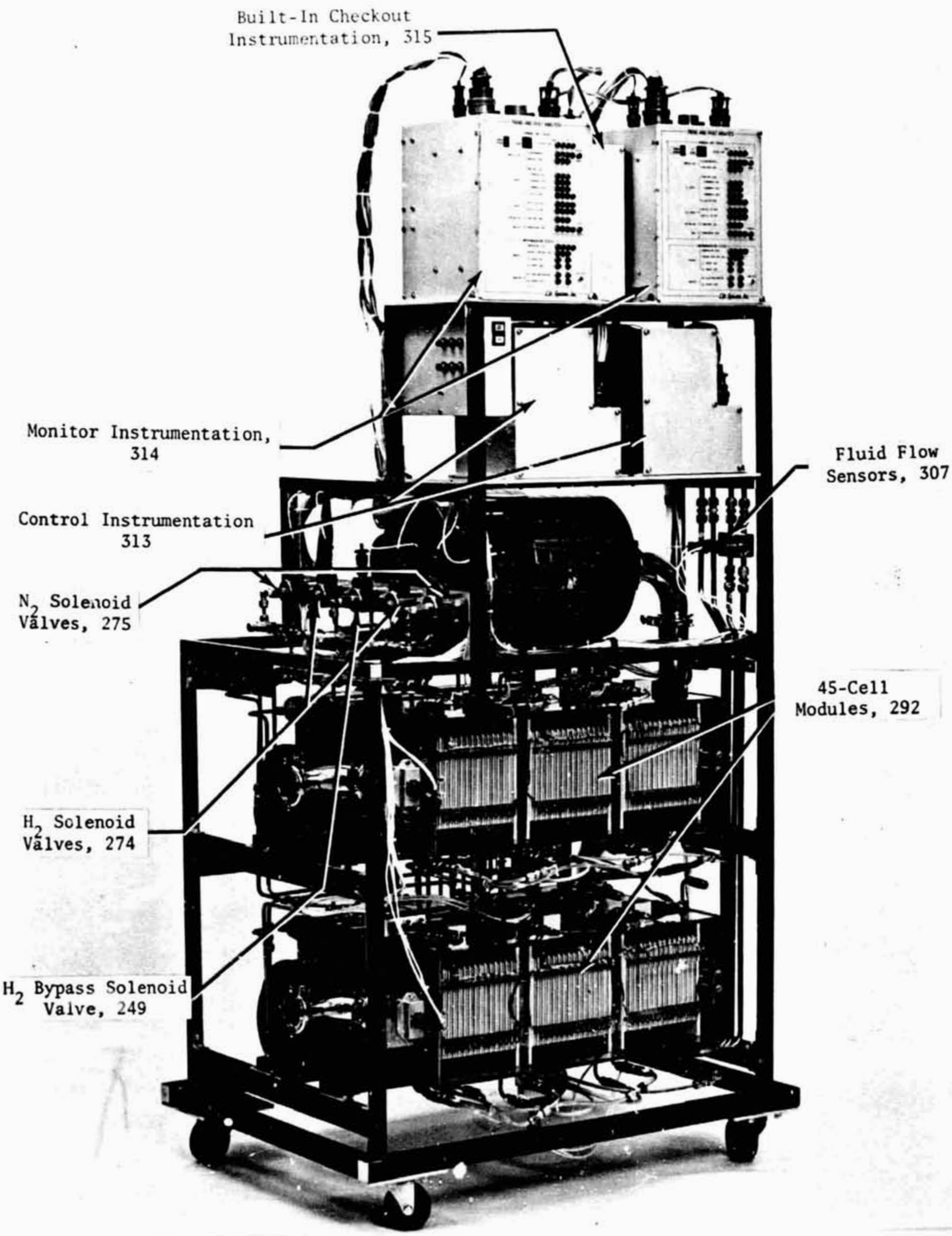


FIGURE 4 CX-6 (FRONT VIEW)

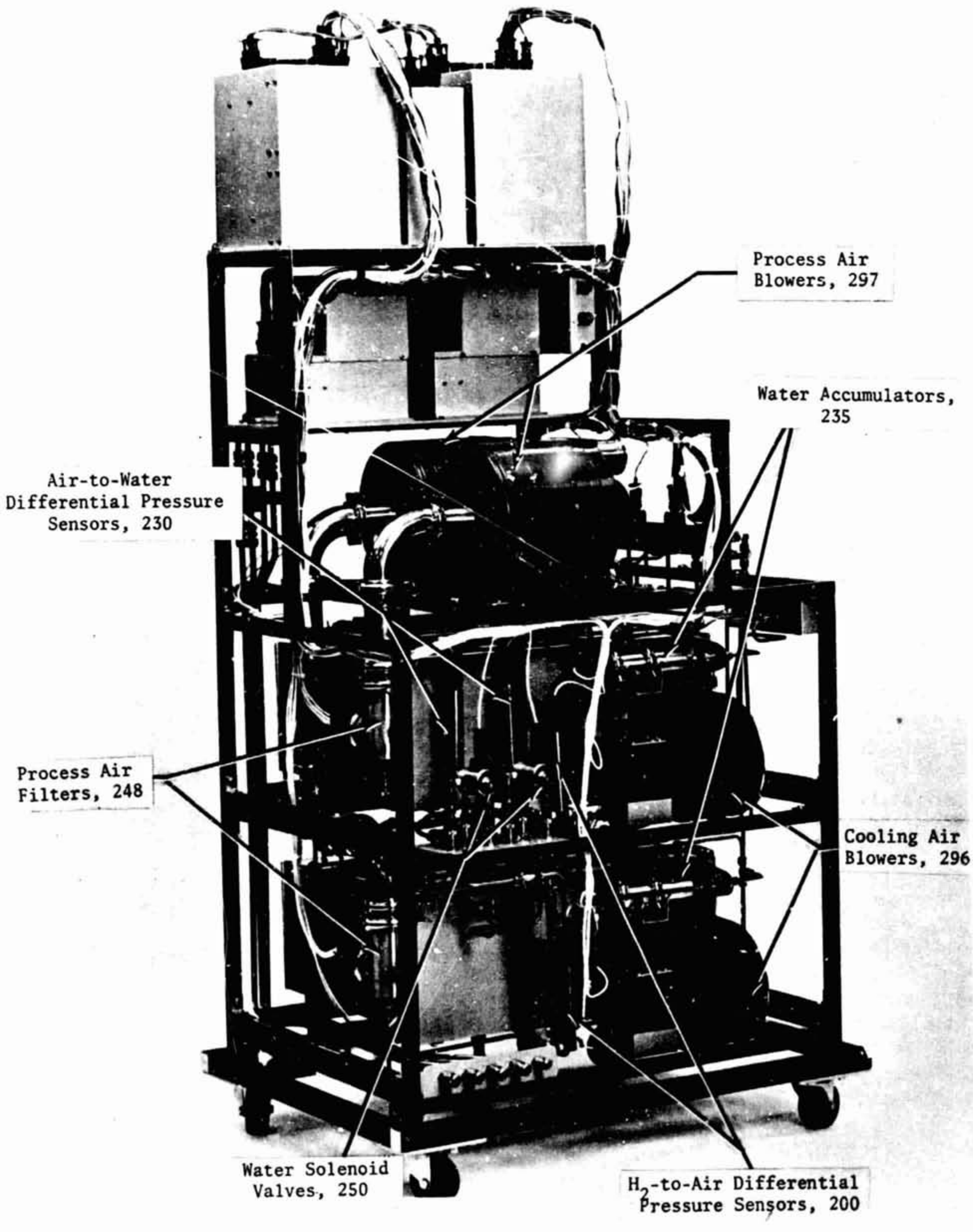


FIGURE 5 CX-6 (REAR VIEW)

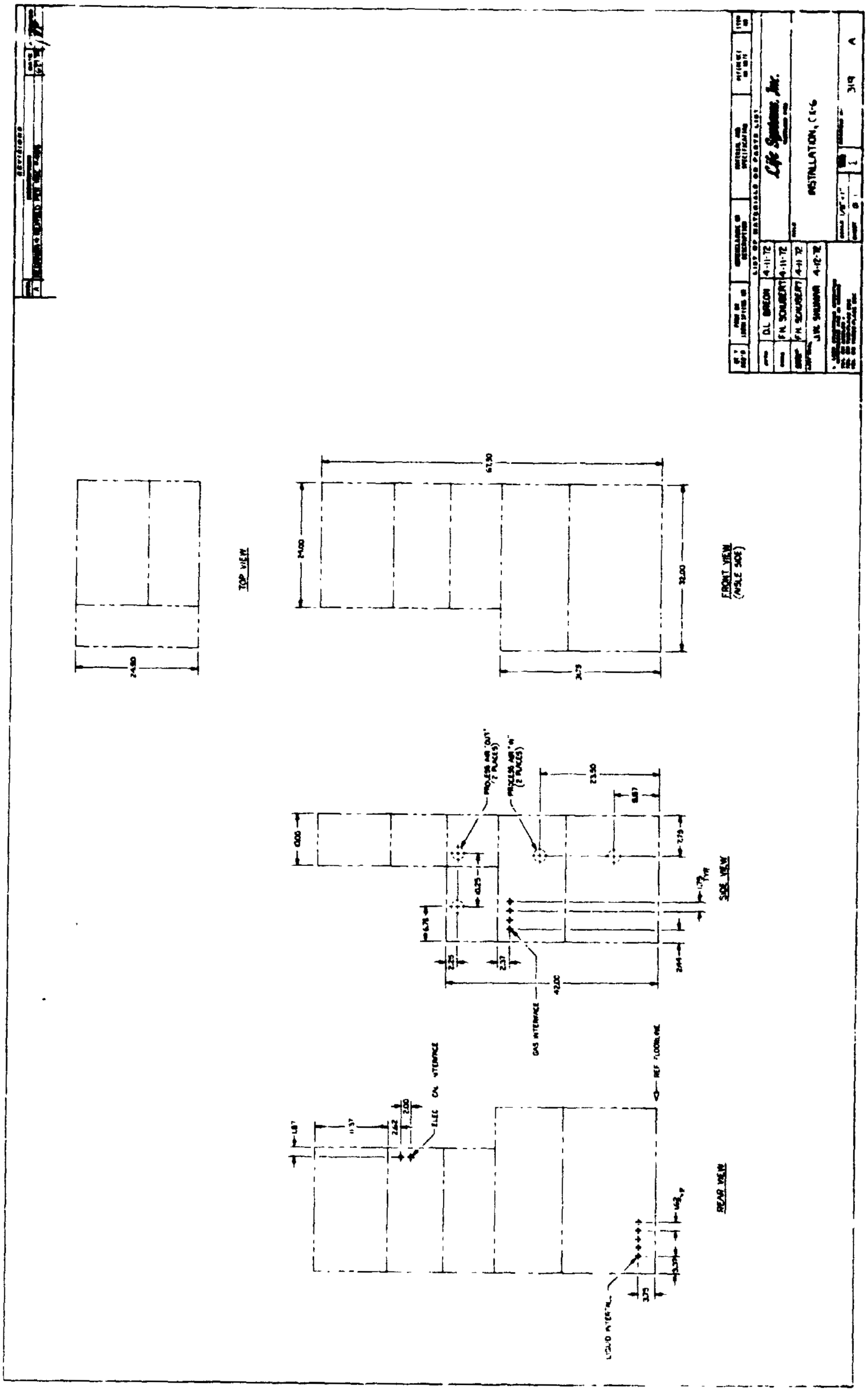


FIGURE 6 CX-6 INSTALLATION DRAWING

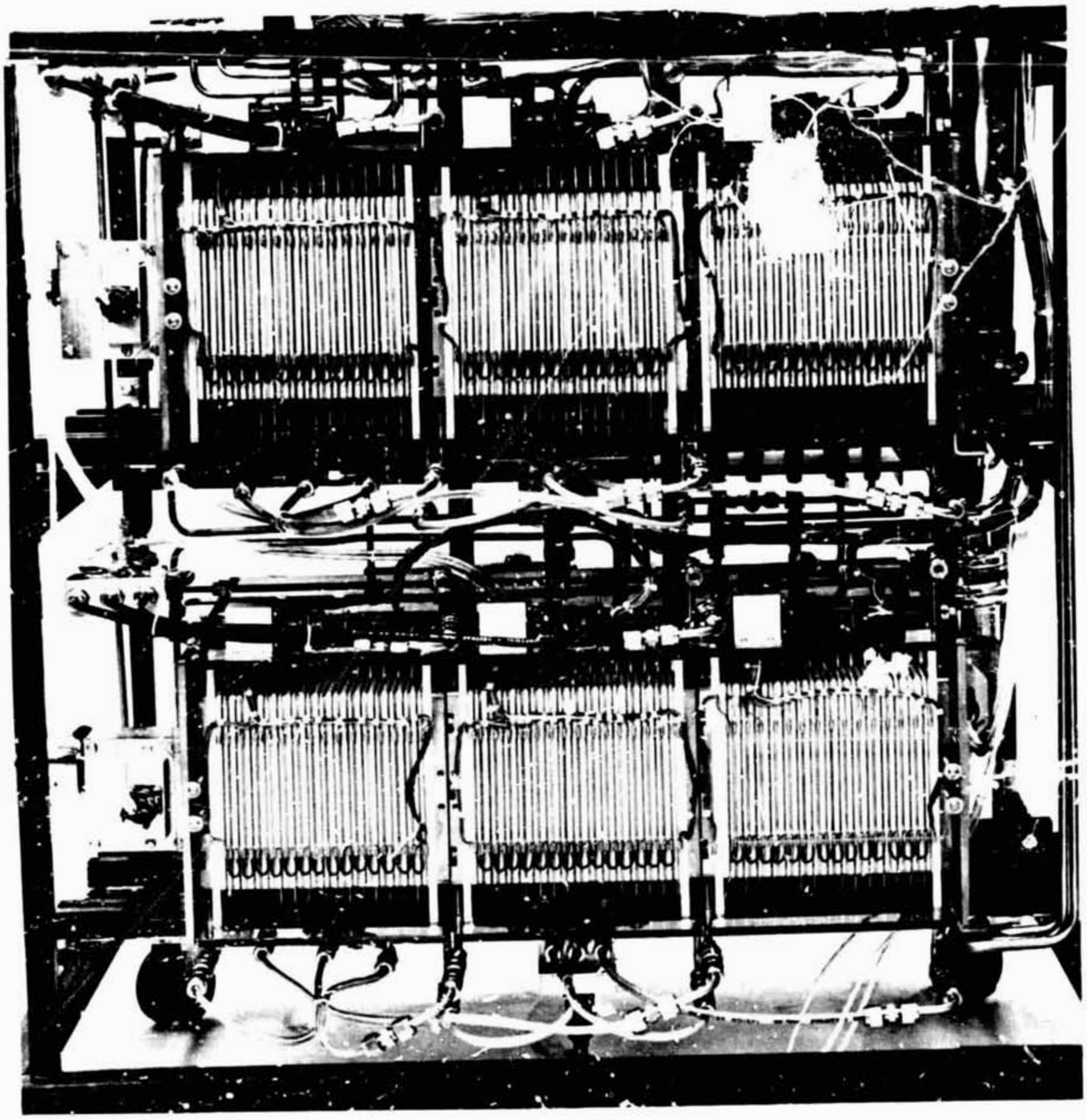


FIGURE 7 INSTALLED CX-6 MODULES

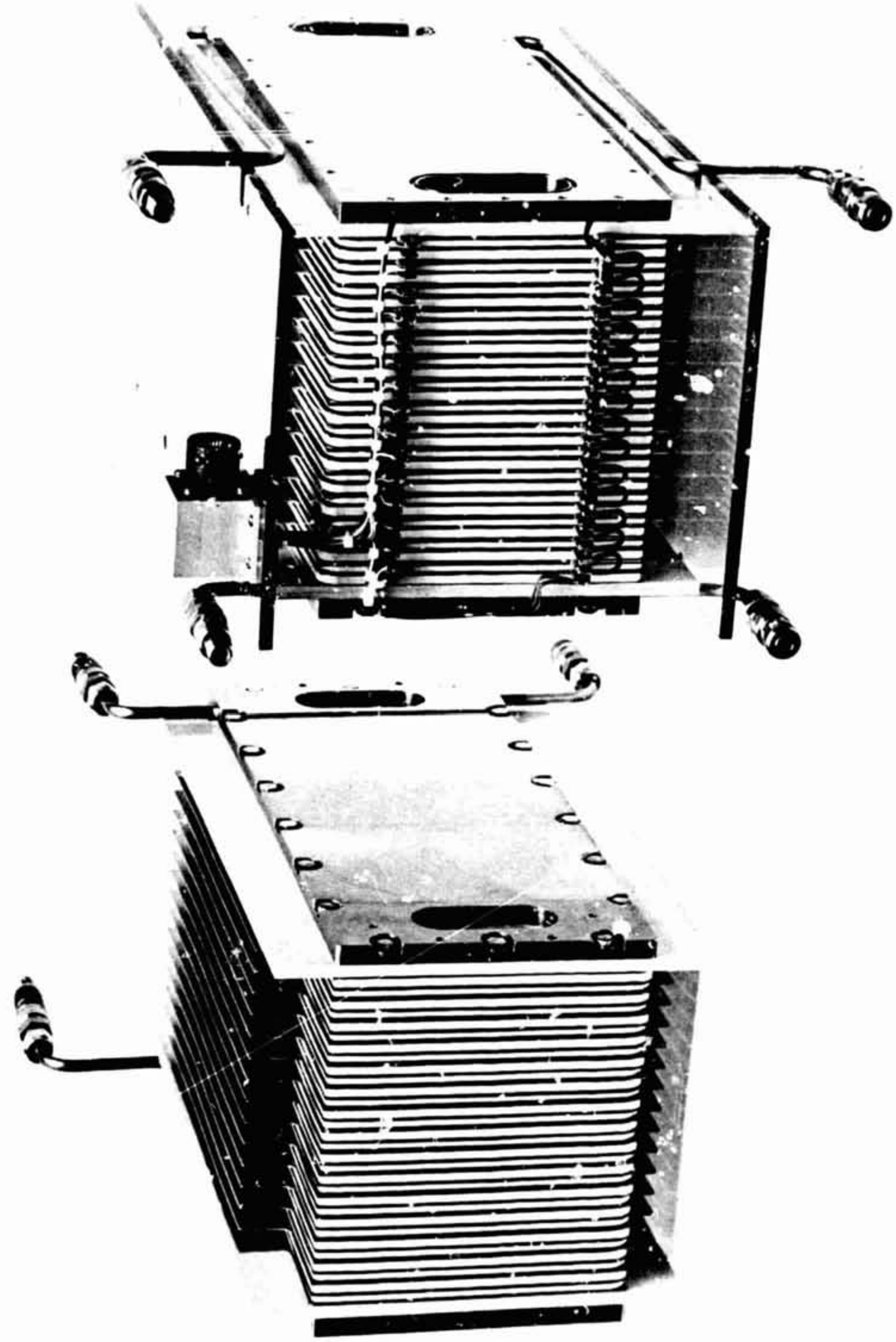


FIGURE 8 CX-6 15-CELL SUBMODULE

the cavities as required. For operation with the modified specification these cavities were drained and served only as cell spacers.

Each of the 15 cells consists of three polysulfone parts (cathode frame, anode frame and humidifier cavity), two current collectors (cathode side and anode side) and the electrode-electrolyte retaining matrix-electrode sandwich. The nickel current collectors, with attached metal screen, form the two gas compartments.

A Teflon screen-asbestos matrix-Teflon screen composite forms the humidifier membrane and separates the air compartment from the humidifier cavity. Figure 9 is a photograph of the cell parts while Figure 10 is a single-cell functional schematic. Table 4 lists submodule design data for the modified specification of the CX-6.

Process Air Blowers. The function of the process air blowers is to draw air through the electrochemical modules. The CX-6 has two process air blowers, one for each 45-cell module. The blowers are located downstream of the modules to eliminate the effects of air temperature rise caused by blower heat generation. The blowers selected for the CX-6 are multistage centrifugal blowers. The blowers are foot-mounted, having electrical connectors and quick-connect inlet and outlet flanges for ease of maintenance.

Cooling Air Blowers. The cooling air blowers blow precooled air over external fins of the electrochemical modules to maintain module temperature at the desired level. Each 45-cell module has one blower. The blower is of the centrifugal type with a directly coupled induction motor. The blower is flange-mounted and has an electrical connector.

Solenoid Valves. The CX-6 has four types of solenoid valves: H_2 bypass solenoid valve, H_2 solenoid valve, N_2 solenoid valve and water solenoid valve. The function of the H_2 bypass solenoid valve (one valve used in the CX-6) is to bypass the H_2 flow from the oxygen (O_2) generation subsystem in case both loops of the CX-6 are shut down. This valve is a three-way, solenoid-operated valve with the normally closed port connected to the H_2 supply lines of the two modules. This insures fail-safe stoppage of H_2 flow to the subsystem in case of a power failure.

The CX-6 has two H_2 solenoid valves. Their function is to stop or provide H_2 flow to the electrochemical modules. The valves are two-way, solenoid-operated and normally closed, again resulting in a fail-safe operation if power should be interrupted.

The subsystem has two N_2 solenoid valves to permit N_2 purging of either or both loops during a shutdown. The valves are two-way, solenoid-operated and normally open to permit purging during a [illegible]er failure.

The CX-6 has two water solenoid valves, one for each of the 45-cell modules. The valves control the water fill of the water accumulators and are actuated by limit switches located within the water accumulator. The valves are two-way solenoid-operated and normally closed.

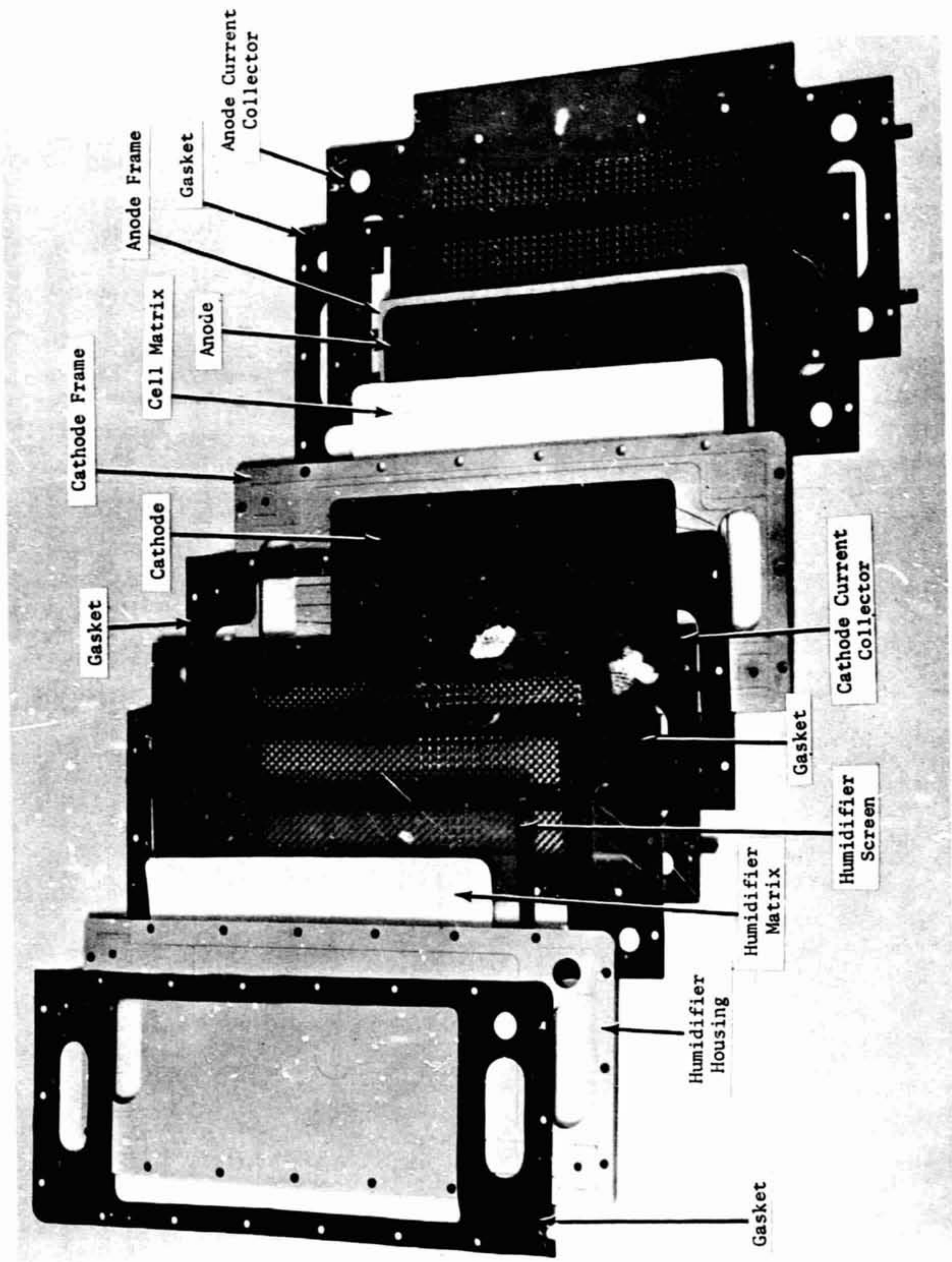


FIGURE 9 CX-6 CELL PARTS

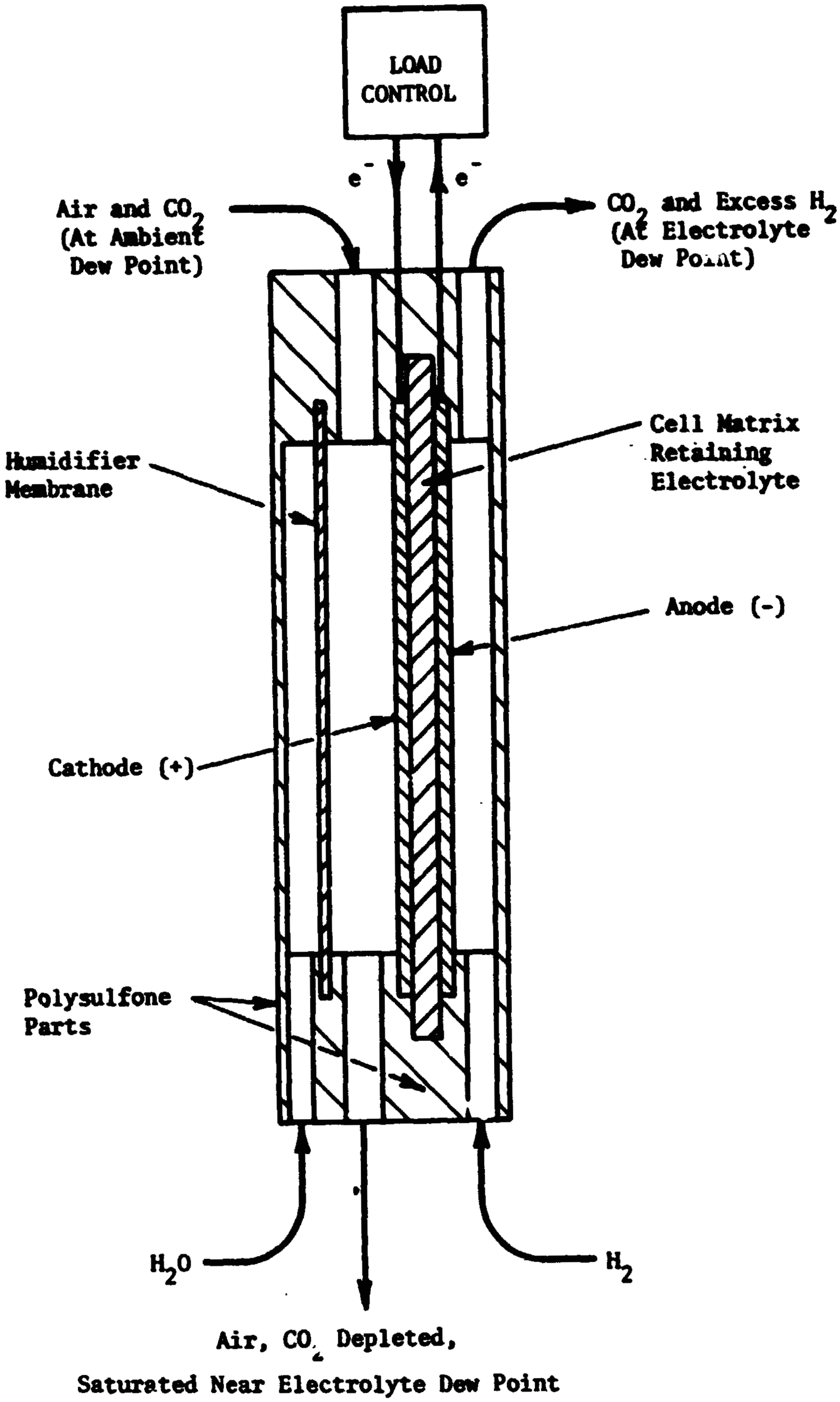


FIGURE 10 CX-6 SINGLE-CELL SCHEMATIC

TABLE 4 SUBMODULE DESIGN DATA FOR MODIFIED CX-6 SPECIFICATIONS

	Nominal Design	Maximum Design
Nominal Operating Conditions		
pCO_2 at Inlet, N/m^2 (mm Hg)	351 (2.63)	373 (2.80)
pCO_2 at Exit, N/m^2 (mm Hg)	200 (1.50)	199 (1.49)
Current, A	4.88	8.10
Current Density, mA/cm^2 (ASF)	21.5 (20.0)	35.5 (33.0)
Module Temperature, K (F)	291 (65)	291 (65)
Process Air Flow, m^3/s (Scfm)	4.25×10^{-3} (9.0)	34×10^{-3} (72)
H_2 Flow, m^3/s (l/Min)	2.92×10^{-5} (1.75)	3.21×10^{-5} (1.92)
Performance Characteristics		
Number of Cells	15	15
CO_2 Removal		
kg/d (Lb/Day)	1.00 (2.20)	1.54 (3.40)
kg/h (Lb/Hr	0.0416 (0.092)	0.0643 (0.142)
kg CO_2/kg O_2, Transfer Index	1.9	1.65
CO_2 Removal Efficiency, %	69	60
Average Cell Voltage, V	0.25	0.12
Heat Generated, W (Btu/Hr)	72 (245)	144 (491)
O_2 Consumed		
kg/d (Lb/Day)	0.524 (1.156)	0.937 (2.065)
kg/h (Lb/Hr)	0.0218 (0.048)	0.0390 (0.086)
H_2O Produced		
kg/d (Lb/Day)	0.591 (1.302)	1.057 (2.330)
kg/h (Lb/Hr)	0.0246 (0.054)	0.0440 (0.097)
Reliability Data		
Failure Rate, Failure/Hr	1.76×10^{-6}	
MTBF, Hr	0.6×10^{6}	
Spares (No. of Modules)	3 (180-Day Mission Profile)	

The gas-carrying valves are connected via quarter-inch tube fittings. The two water solenoid valves are equipped with double-ended shutoff, quick-connects to prevent gas from entering the liquid loop during maintenance. All valves are equipped with electrical connectors.

H_2 Check Valves. The function of the H_2 check valves is to isolate the H_2/CO_2 gas mixtures exiting from the two 45-cell modules. This enables maintenance to be performed on one loop while the other loop is in operation without allowing H_2 gas to escape to the atmosphere. The check valves operate on a simple poppet and spring design with an O-ring seal and have a cracking pressure of 2.3 kN/m^2 (1/3 psid). The valves are mounted via quarter-inch tube fittings.

Water Accumulators. The function of the water accumulators is to supply feed water at the required pressures to the humidifier cavities of the electrochemical modules. The subsystem has two accumulators, one for each 45-cell module. The accumulator uses a piston-cylinder arrangement with a rolling diaphragm seal. The required water pressure is provided by a spring and a reference pressure from the module process air outlet. The water pressure is always kept below the module process air pressure to prevent flooding of the air cavities. A permanent magnet mounted to the piston actuates two micro-reed switches. These switches trigger a circuit which controls automatic refilling of the accumulator by operating the respective water solenoid valve. The filling is upon demand as water is required to humidify the air within the modules.

The accumulator has an electrical connector for the reed-switch signals. Mechanical liquid connections are made by quarter-inch quick-disconnects with double-ended shutoff. The unit, therefore, can be replaced and maintained without allowing air to enter the fluid lines. Figure 11 shows an assembled and a disassembled water accumulator.

Process Air Filters. The function of the process air filters is to remove possible entrained liquid droplets from the module process air exhaust. Moisture can only be present during operation with out-of-tolerance conditions at the process air interface or due to possible failure of a humidifer membrane.

The filter consists of a cone-shaped hydrophobic screen, 170-mesh Teflon, supported by a 10-mesh stainless steel screen. The screens are mounted in a stainless steel cylinder. Quick-connect flanges are used to attach the filters directly to the process air exhaust sensor blocks downstream of the modules.

Each loop has one process air filter located between the 45-cell module and the process air blower. Figure 12 shows an assembled and a disassembled process air filter.

H_2 Flow Sensor and Distribution Mounting. The function of the H_2 flow sensor and distribution mounting is to divide the incoming H_2 flow equally between the six submodules of the CX-6. The unit also senses flow rate levels to each of the six submodules. Each loop of the subsystem contains one H_2 flow sensor and distribution mounting. The mounting is a stainless steel machined block that internally manifolds the H_2 flow into three parallel flow paths using three orifices to provide equal flow.

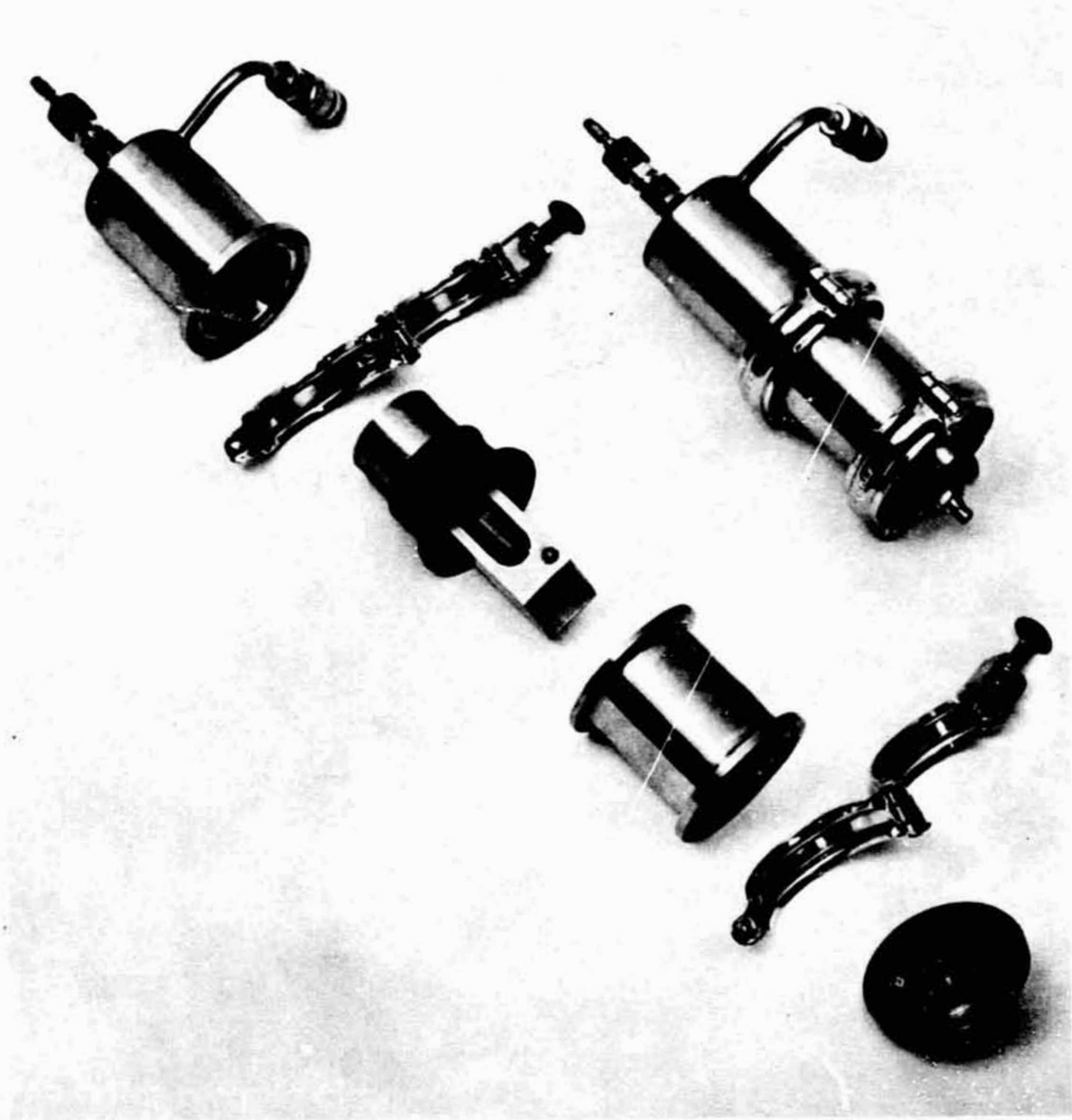


FIGURE 11 CX-6 WATER ACCUMULATOR

FIGURE 12 CX-6 PROCESS AIR FILTER

The H_2 flow sensors, located downstream of each of the three orifices, consist of two electrically-matched thermistors wired externally to a bridge circuit and amplifier to produce a voltage signal proportional to H_2 flow rate. The six thermistors are threaded directly into the stainless steel housing and are wired to an electrical connector. The mechanical connections to the mounting are made via quarter-inch tube fittings.

CO_2 Instrumentation Hardware

Instrumentation is needed in the CX-6 for the following reasons:

1. To control parameters which must be maintained at specific operating points or within specified ranges.
2. To control parameters which must track certain input signals provided from external sources.
3. To control startup, shutdown and power-down mode sequences.
4. To monitor safety-related parameters to protect equipment and personnel.
5. To montior parameters for trend analysis and fault isolation.
6. To provide readouts of subsystem parameters in engineering units on the Ground Checkout Unit (GCU).

The CO_2 instrumentation hardware was designed to operate from 28-VDC power. Only the four blowers in the CX-6 use 115-VAC, 60 Hz power. Because of the two-loop design concept, two identical control and two identical monitoring instrumentation packages were used. A single BIC package is capable of checking all of the monitor cards in both monitoring instrumentation packages. The five instrumentation packages are shown in Figure 4.

The two packages on the top shelf with the indicators on their front panels contain all monitor instrumentation circuits. Located between these two packages is the BIC package. Below these, on the second shelf, are the two packages which contain all system control circuits. Also visible in this figure are the circuit breakers and the manual START-STOP pushbuttons.

Besides the control, monitoring and BIC instrumentation, the CO_2 instrumentation hardware consists of a variety of sensors. The fluid flow sensors and H_2-to-air and air-to-water differential pressure sensors are LRUs. The process air inlet and exhaust sensors and the blower speed sensors are LRCs.

Control Instrumentation. The control instrumentation provides the circuits for automatic start sequencing with delayed module current, automatic shutdown sequencing with N_2 purge, automatic control of module current and temperature and blower speed control with provisions for automatic or manual adjustments.

Description. Two control instrumentation packages are required, one for each of the two loops. The control instrumentation is contained in an anodized aluminum enclosure designed to be mounted with quick-connect fasteners to a cold plate. Each of the two packages has its own power supplies. The enclosure has four electrical connectors on its outside surfaces. Figure 13 is a photo of the control instrumentation package with its front cover removed. The components of the control instrumentation package are listed in Table 5. Figure 14 is a photo of the six Printed Circuit (PC) cards of the control instrumentation.

The control instrumentation package contains three manual/automatic switches and three manual adjustment controls. These controls are normally covered by a front panel as shown in Figure 4. The front cover is removed to provide access to the controls during parametric testing.

Operation. Figure 15 is a block diagram of the control instrumentation. The first control system shown across the top is the closed-loop current control for the three submodules. One input set point is used to simultaneously control the three currents.

The electrochemical modules generate voltage during operation. Each submodule is connected through a current measuring shunt to a load transistor. The shunt signal and an input set point signal are compared and the difference between these two signals is used to drive the load transistors. In the manual mode (Mode A), the set point signal level is determined by the manual adjustment setting. In the automatic mode (Mode B), the signal is derived from an external pCO_2 sensor.

The second control system, shown in Figure 15, is an open-loop speed control for the process air blower. The speed control logic contains phase-shifting, pulse-generating circuits to drive the power control TRIAC. This results in a variable voltage supply for the process air blower adjusted either manually or automatically. In the latter the signal is derived from the pCO_2 sensor.

These two systems can be used in Mode B to control module currents and process air blower speeds simultaneously, based on one external pCO_2 sensor or computer-generated signal.

The third control system, shown in Figure 15, is the module temperature control. This closed-loop control compares the module temperature (as measured by thermistors in the process air exhaust sensor) to either a manual or external input signal and turns the cooling blower on and off to control module temperature.

The last control system, shown in Figure 15, is the sequence control. It controls sequencing of the five solenoid valves, application of current to the modules, and power to the process air blowers in response to manual START/RESET or STOP signals, or automatic shutdown signals from the monitoring instrumentation package. It also provides automatic reset signals to the monitoring instrumentation package during startup. An automatic shutdown or a manual STOP signal initiates an automatic N_2 purge sequence

Monitoring Instrumentation. The monitoring instrumentation provides safety measures for personnel and equipment through automatic shutdown features and trend analysis capabilities. It also aids in detecting and isolating faults to the LRU level. The monitoring instrumentation provides the circuits which

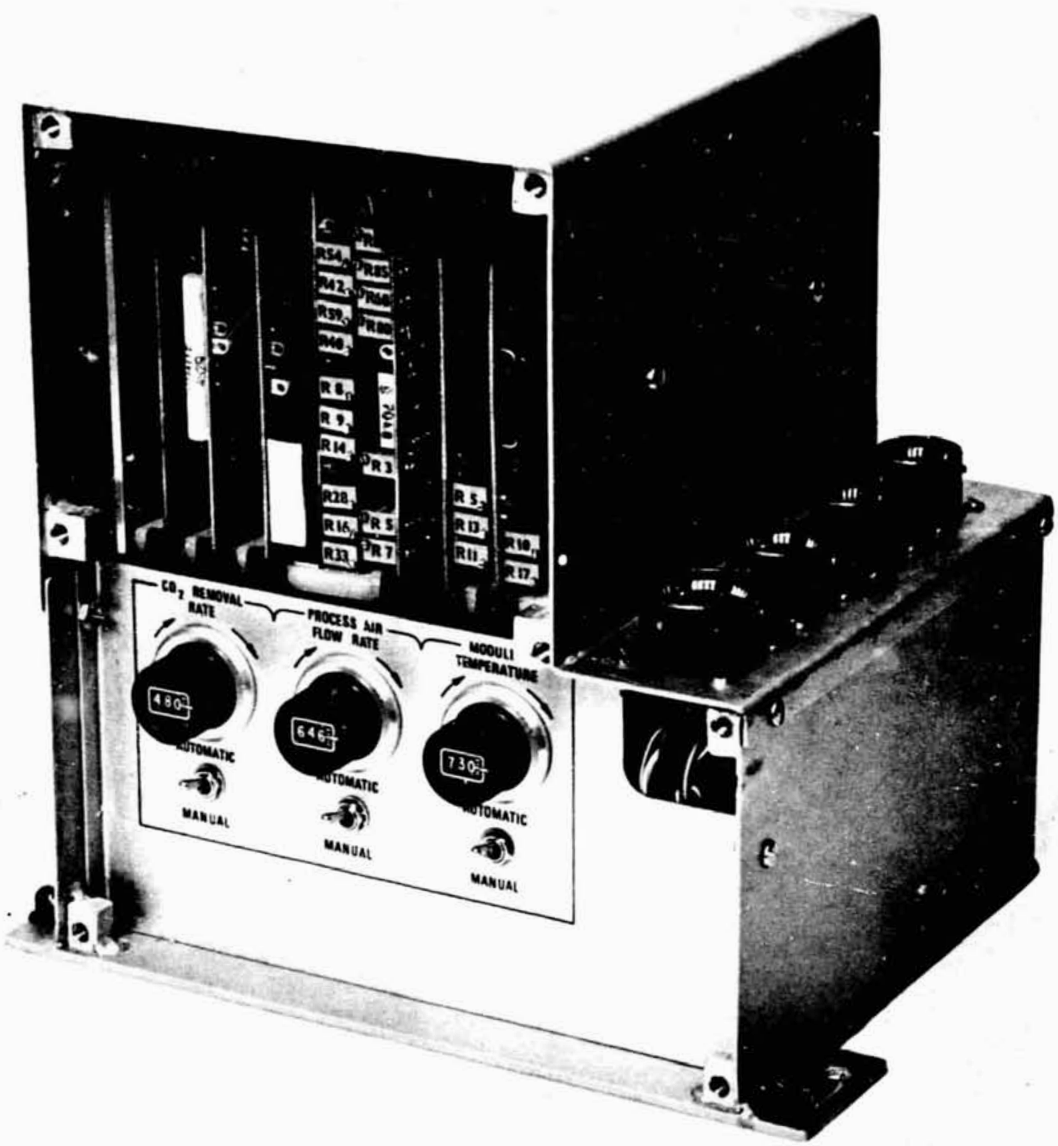


FIGURE 13 CX-6 CONTROL INSTRUMENTATION PACKAGE

TABLE 5 CONTROL INSTRUMENTATION PACKAGE COMPONENTS

PC Card Assembly

Card No.	Name	No. Reqd.
A1	Control Instrumentation Power	1
A2	Purge and Shutdown Logic	1
A3	Start and Reset Logic	1
A4[(a)]	Load Control	1
A5	Temperature Control	1
A6	Speed Control	1
	TOTAL	6

28V Input DC/DC Converters

Output Voltage	Major Use	No. Reqd.
±15	Amplifiers, Oscillators	1
+5	Logic	1
+24	Lamps, Relays, Solenoid Valves	1
	TOTAL	3

Heat-Sink Assembly

3 Load Transistors

3 Load Transistor Driver Transistors

4 Solenoid Valve Driver Transistors

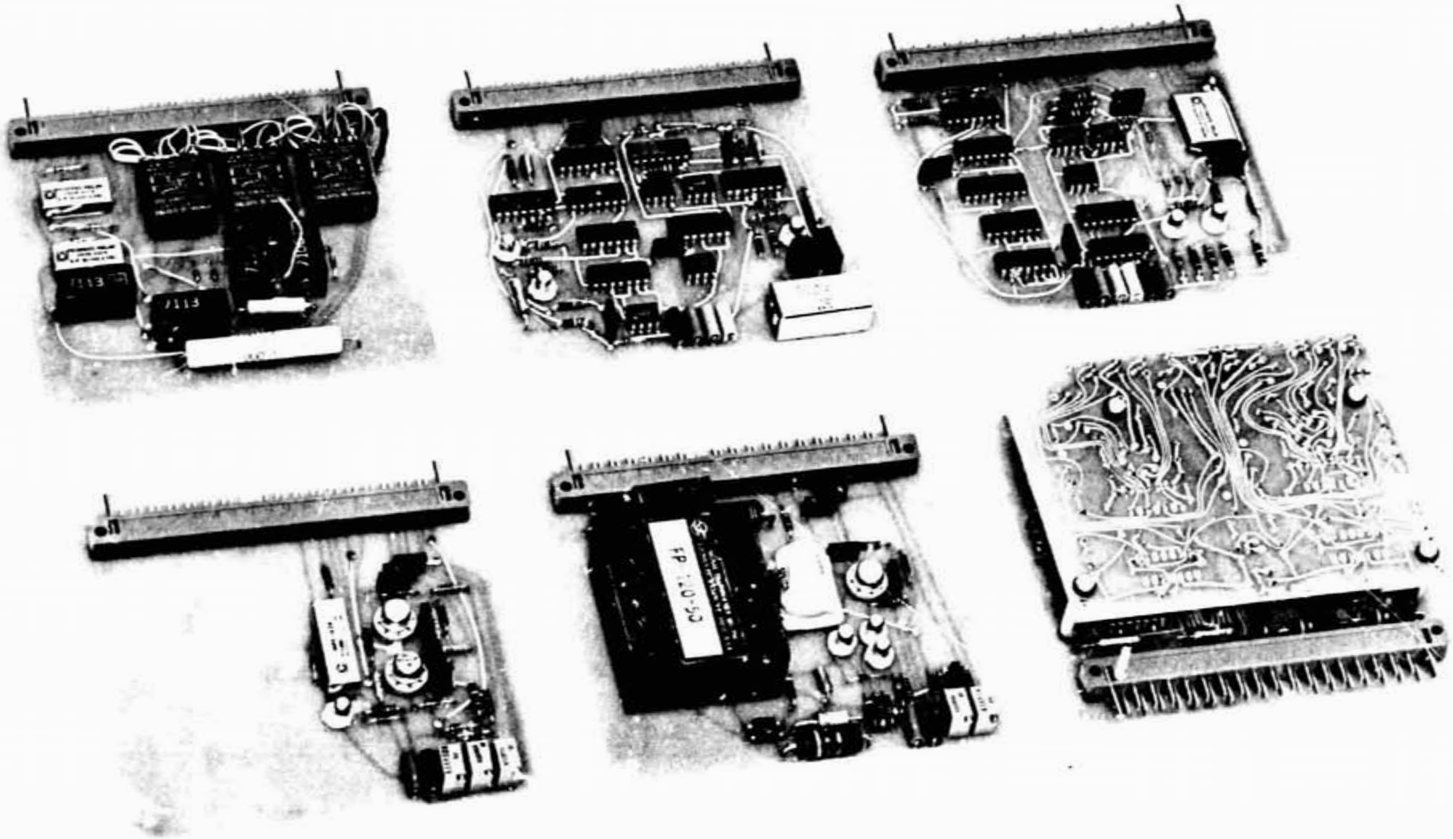
4 Solenoid Valve Diodes

2 AC Thyristors

3 Current Shunt Resistors

(a) double-width card assembly

CONTROL INSTRUMENTATION POWER — OPERATION, SHUTDOWN AND PURGE LOGIC — START AND RESET LOGIC



TEMPERATURE CONTROL — SPEED CONTROL — LOAD CONTROL

FIGURE 14 CONTROL INSTRUMENTATION PC CARDS

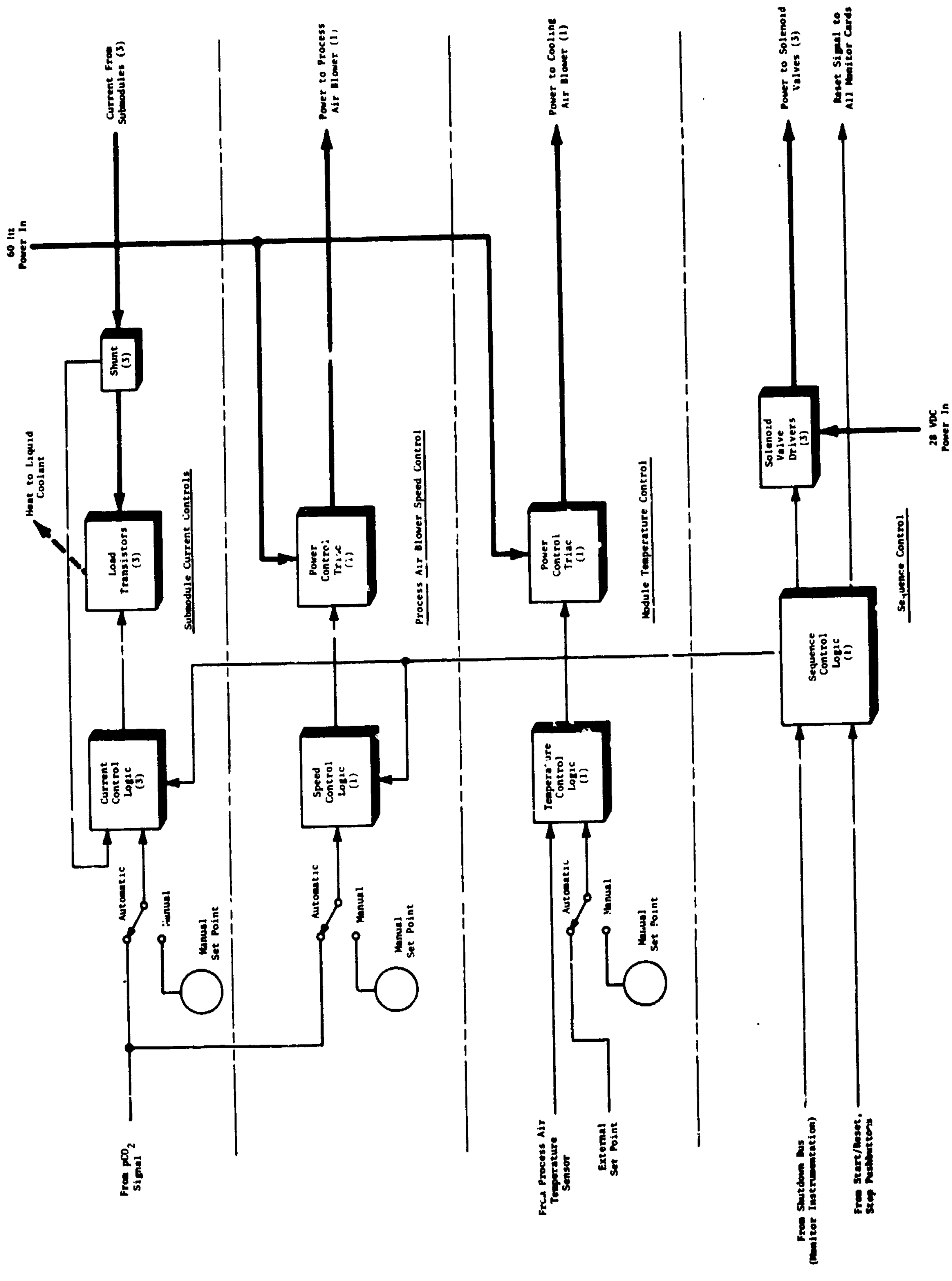


FIGURE 15 CONTROL INSTRUMENTATION BLOCK DIAGRAM

monitor module temperature and control instrumentation temperatures; H_2, process air, cooling air, and liquid coolant flows; H_2 and water pressures; individual voltages; and process air contamination. The levels of the monitored parameters are displayed on the Trend and Fault Analysis Panel, a part of the monitoring instrumentation package.

Description. Two monitoring instrumentation packages are required, one for each of the two loops. The monitoring instrumentation is contained in an anodized aluminum enclosure and is mounted with quick-connect fasteners to the CX-6 frame. The enclosure has six electrical connectors on top. Each of the two packages has its own power supplies. Figure 16 shows the inside of a monitoring instrumentation package.

Figure 17 is a photo of the Trend and Fault Analysis Panel on the front cover of the monitoring instrumentation package. The readouts on this panel are indicator lamps in five columns: G, A, FR, R and Sensors Differ. (G is green, A is amber, FR is flashing red and R is red.) These stand for the normal, caution, warning and alarm levels, respectively. The lights on this panel provide positive indication of normal operation,as well as lock-in or storage to prevent a momentary caution, warning or alarm from going undetected. The panel contains a push-to-test button to check for lamp status.

Table 6 lists the components of the monitoring instrumentation package. Figure 18 is a photo of six typical monitoring instrumentation PC cards.

Operation. Table 7 lists the parameters monitored and the levels at which the Trend and Fault Analysis Panel lights switch from green to amber, amber to flashing red and for subsystem critical parameters from flashing red to red. When a red level signal is reached the CX-6 is automatically shut down. The outputs from the monitoring instrumentation go to four places: Trend and Fault Analysis readouts, control instrumentation for automatic shutdown purposes, a Subsystem Status Summary Panel, and ground checkout equipment for parameter readout in engineering units.

The circuits required for monitoring one specific subsystem parameter are contained on one PC card. All monitoring instrumentation cards are basically the same. The only differences are the signal conditioning circuit, the number of levels in the level detection and storage area, and the direction for trend. Figure 19 is a block diagram of a typical monitoring instrumentation PC card.

A switch circuit is used to select either the signal from a sensor or an artificial stimulus from the BIC equipment. The signal is then sent to the signal conditioning circuit. In some cases the signal conditioning function is performed at the sensor level thus eliminating the need for the signal conditioning circuit. All signal conditioning is designed to produce a 0 to 5 volt DC signal as the parameter being monitored varies over its normal range.

Following the signal conditioning circuit are either two- or three- level detector circuits which can detect either increasing or decreasing levels. These circuits break up the analog signal into three or four ranges. The level detector output

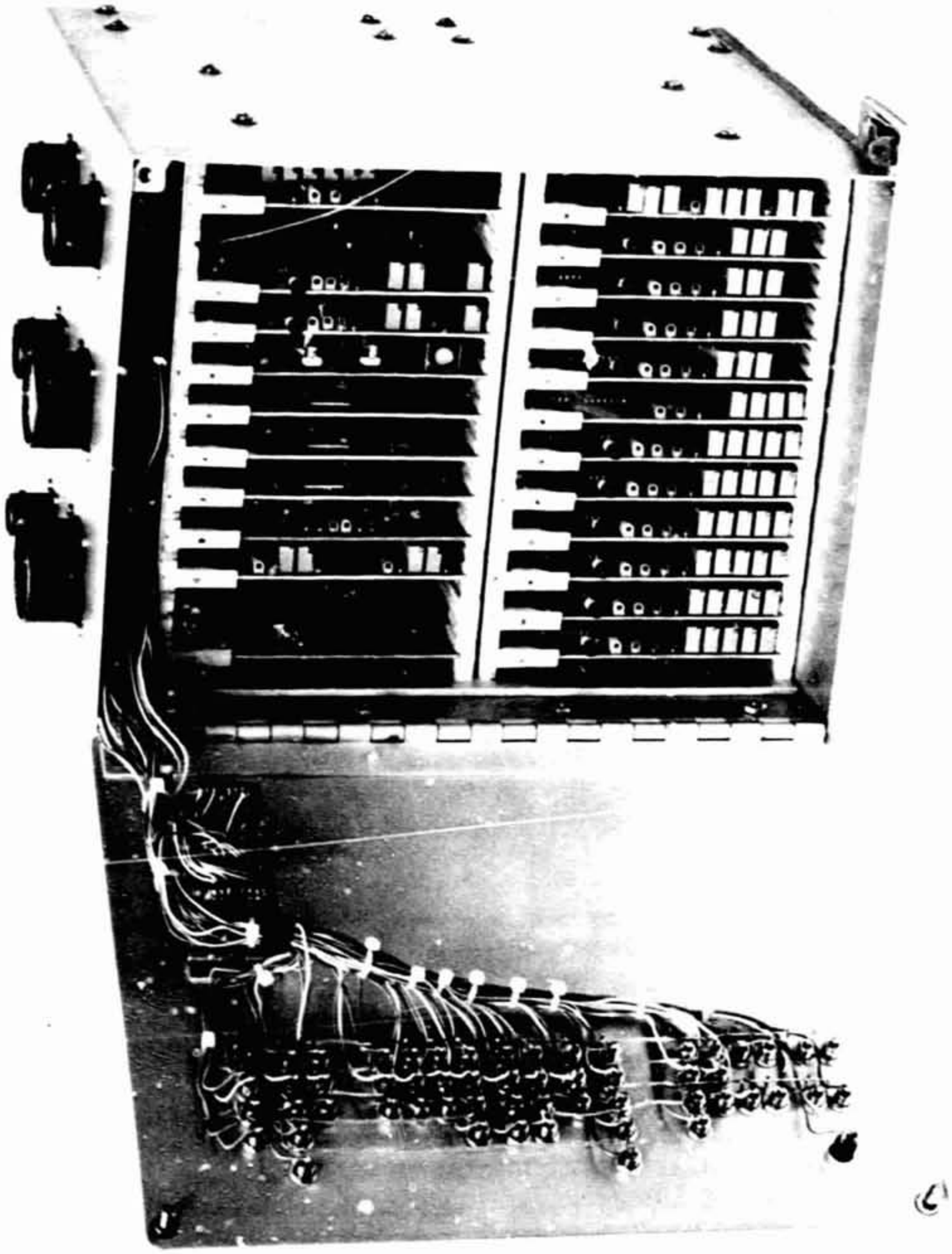


FIGURE 16 CX-6 MONITORING INSTRUMENTATION PACKAGE

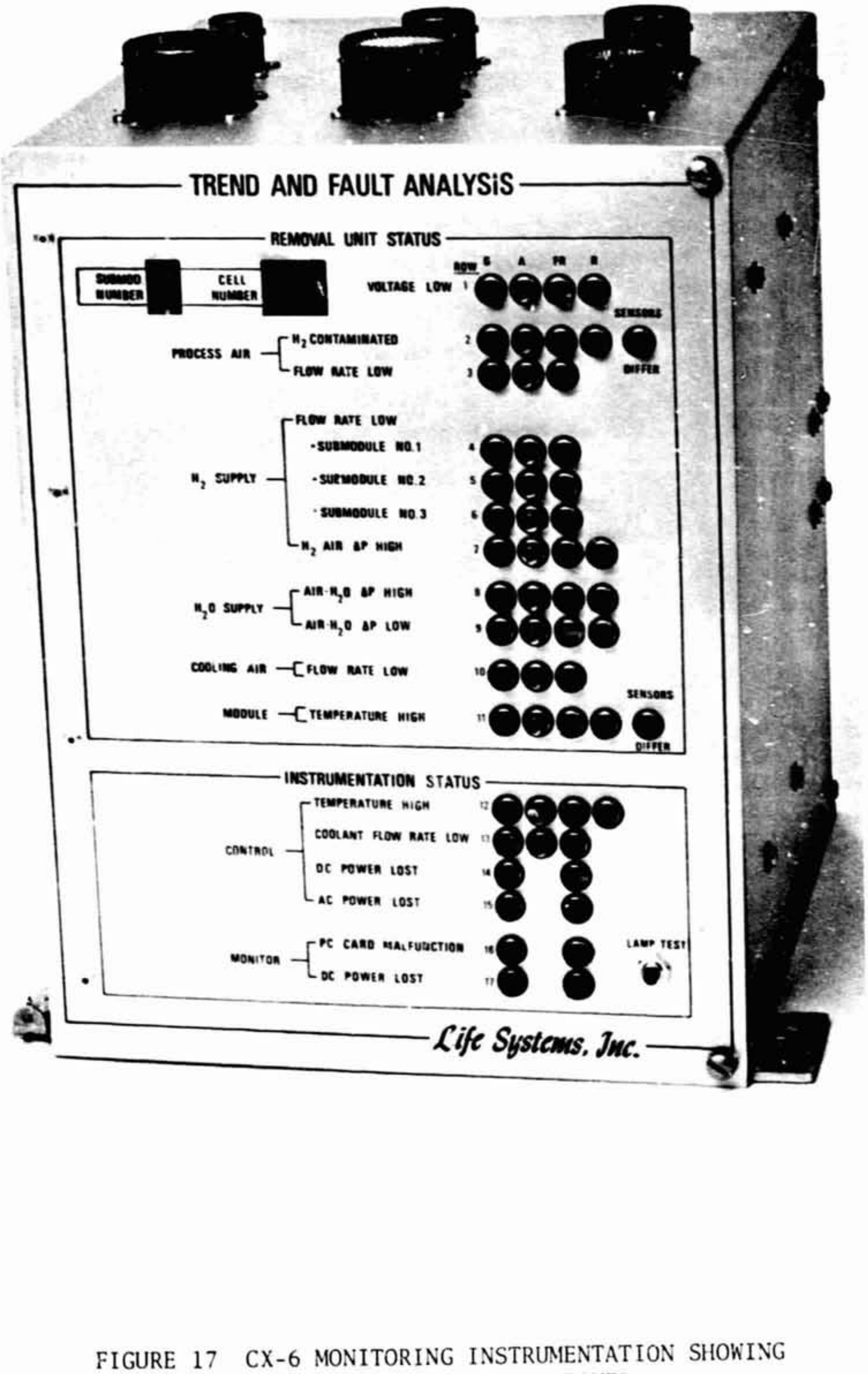


FIGURE 17 CX-6 MONITORING INSTRUMENTATION SHOWING TREND AND FAULT ANALYSIS PANEL

TABLE 6 MONITOR INSTRUMENTATION PACKAGE COMPONENTS

PC Card Assembly

Card No.	Name	No. Reqd.
B1	Monitor Instrumentation Power	1
B2	Temperature Monitor	2
B3	Gas Flow Monitor	4
B4	Liquid Flow Monitor	1
B5	Three-Sensor Voting Logic	1
B6	Transducer Output Monitor	4
B7	Voltage Level Monitor	1
B8[a]	Cooling Flow Monitor	1
B9	Sensor Scan Control Logic	1
B10	Scan Counter and Relays	3
B11	Status Indicator Logic	1
B12	Two-Sensor Discrepancy Detector	1
B13	Process Efficiency Computer	1
	TOTAL	22

28V Input DC/DC Converters

Output Voltage	Major Use	No. Reqd.
±15	Amplifiers, Level Detectors, Multipliers	1
+5	Logic	2
+24	Lamps, Relays	1
	TOTAL	4

(a) double-width card assembly

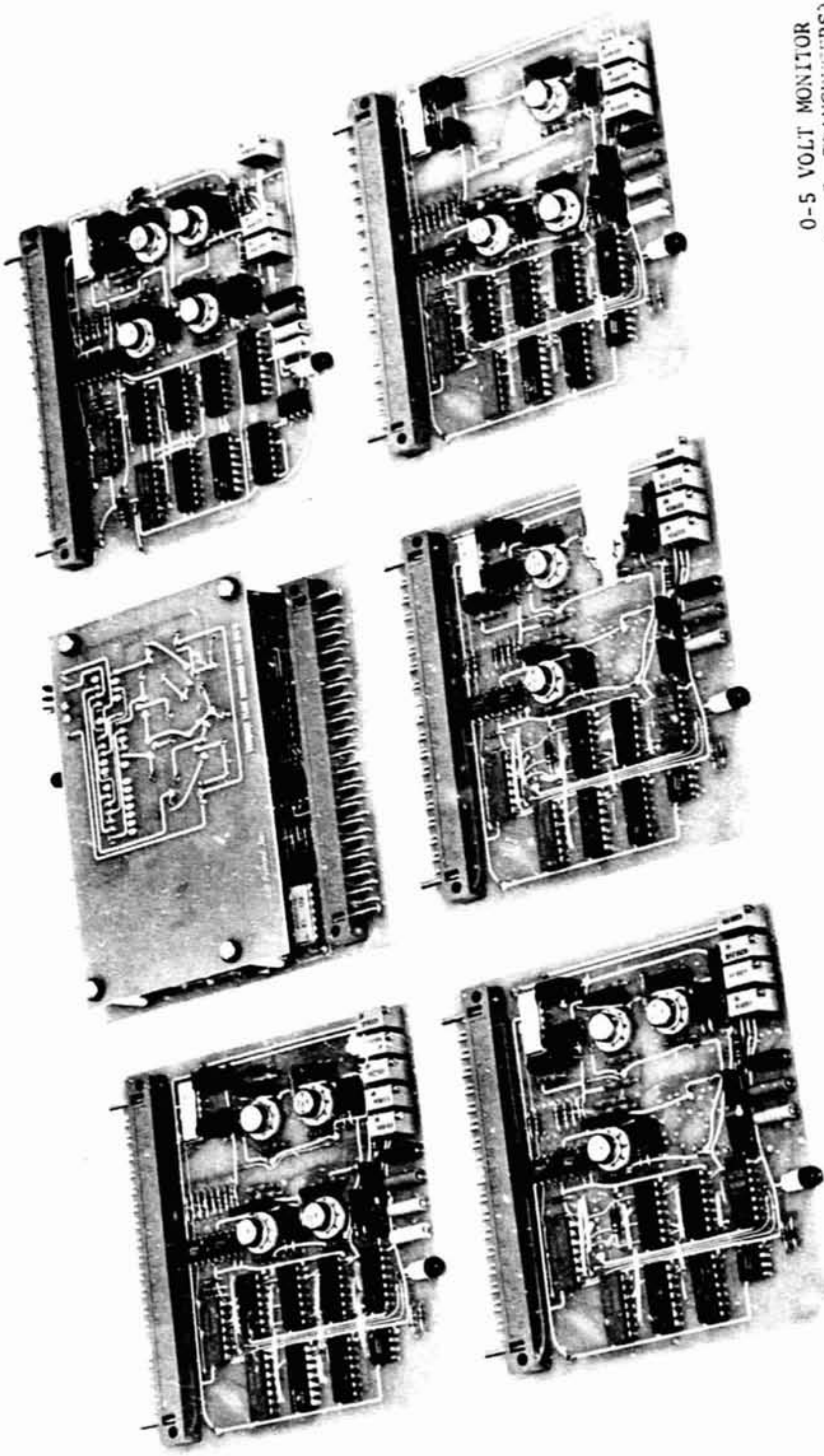


FIGURE 18 MONITORING INSTRUMENTATION PC CARDS

TABLE 7 PARAMETERS MONITORED AND CHARACTERISTICS

Parameter	PC Card Type	PC Card Location	Trip Levels G to A	Trip Levels A to FR	Trip Levels FR to R	Units
Module Temperature	B2	M	292.4 (67)	293.3 (68.5)	294.1 (70)	K (F)
Control Instrumentation Temperature	B2	L	333 (140)	355 (180)	366 (200)	K (F)
H_2 Flow, Submodule 1	B3	N	3.51×10^{-5} (2.1)	1.84×10^{-5} (1.1)	---	m^3/s (1/Min)
H_2 Flow, Submodule 2	B3	O	3.51×10^{-5} (2.1)	1.84×10^{-5} (1.1)	---	m^3/s (1/Min)
H_2 Flow, Submodule 3	B3	P	3.51×10^{-5} (2.1)	1.84×10^{-5} (1.1)	---	m^3/s (1/Min)
Process Air Flow	B3	Q	7.08×10^{-3} (15)	4.72×10^{-3} (10)	---	m^3/s (Scfm)
Liquid Coolant Flow	B4	R	7.36×10^{-6} (7)	5.26×10^{-6} (5)	---	m^3/s (Gph)
Air-Water Pressure (High)	B6	T	13.8 (2.0)	17.2 (2.5)	20.7 (3.0)	kN/m^2 (Psid)
Air-Water Pressure (Low)	B6	U	10.3 (1.5)	8.6 (1.25)	6.9 (1.0)	kN/m^2 (Psid)
H_2-Air Pressure	B6	S	13.8 (2.0)	20.7 (3.0)	34.5 (5.0)	kN/m^2 (Psid)
H_2-In-Air	B5 & B6	W,V	1.0	1.5	2	%
Cell Voltage	B7	I	0.1	0	-0.1	Volt
Module Cooling Air Flow	B8	J	0.0826 (175)	0.0566 (120)	---	m^3/s (Scfm)

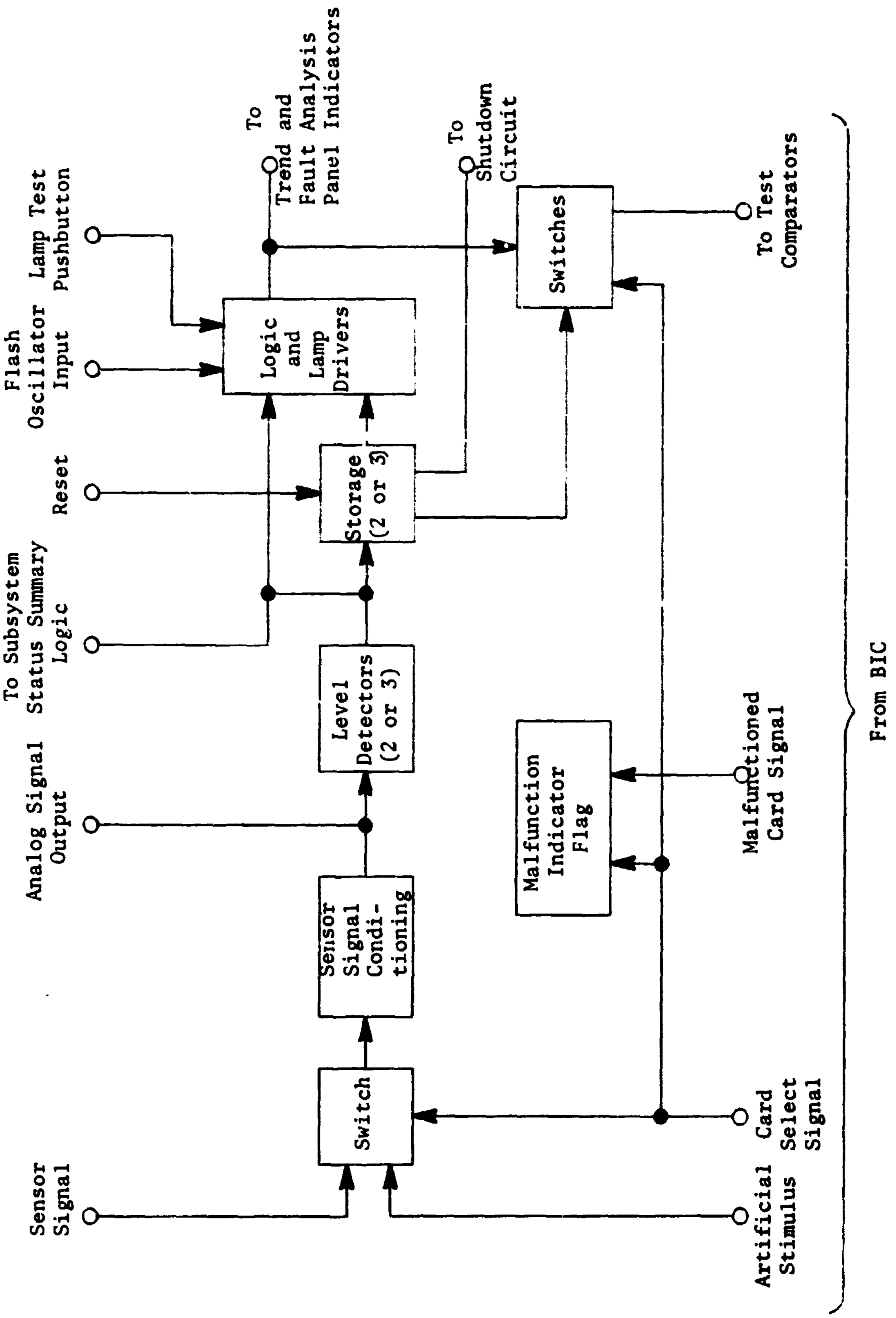


FIGURE 19 MONITORING INSTRUMENTATION PC CARD BLOCK DIAGRAM

is connected to a storage circuit that keeps track of signals which have exceeded levels and then returned. The level detector outputs are also connected to the subsystem status summary logic which, in turn, is used to drive a Subsystem Status Summary Panel. The storage output, along with the level detector output, is connected to logic and lamp driver circuits which feed the indicator lamps on the Trend and Fault Analysis Panel.

A storage reset is obtained by operating the START/RESET pushbutton on the subsystem control panel. To test the lamps, a lamp test input is provided to the lamp drivers. An oscillator signal is provided to the lamp drivers for the flashing red indication. The two switches connected to the storage, the logic and lamp driver outputs and the malfunction flag indicator are part of the BIC equipment and are discussed below.

Individual cell voltages are monitored sequentially by a scanning circuit. Each monitoring instrumentation package scans 45 cells. Two critical parameters in each loop (i.e., module temperature and H_2-in-air) are monitored with redundant sensors. The redundant sensor signals are compared within the monitoring instrumentation package. Out-of-tolerance deviation between signals illuminates the respective "Sensors Differ" lamp on the Trend and Fault Analysis Panel.

Built-In Checkout (BIC) Instrumentation. The BIC instrumentation is a small, special-purpose computer designed to automatically check the performance of the monitoring instrumentation circuit cards (B2, B3, B4, B6, B7 and B8, see Table 6). The BIC accomplishes this sequentially by testing one card at a time. Also, the BIC has automatic or manual test sequence initiation.

Description. Only one BIC is used to check out both monitoring instrumentation packages. The BIC instrumentation is contained in an anodized aluminum enclosure and mounts with a quick-connect fastener. The container has three electrical connectors on its top surface. The components of the BIC are listed in Table 8. Figure 20 is a photo showing the BIC instrumentation in relationship to the control and monitoring instrumentation packages.

Operation. The function of the BIC instrumentation is to test the monitoring instrumentation circuit cards. One card at a time is sequentially selected by a two-wire-per-card, decimal-selection system. The card-select signal connects the input and output switches to the artificial stimulus and test comparitors, respectively.

For each card selected the test sequence continues as follows (see Figure 19):

1. The information contained in the storage circuit is transferred to a temporary storage area in the BIC.

2. The storage on the selected card is reset.

3. The artificial stimulus is stepped through three or four levels, as required, and then returned to the green level.

TABLE 8 BUILT-IN CHECKOUT INSTRUMENTATION PACKAGE COMPONENTS

PC Card Assembly

Card No.	Name	No. Reqd.
C1	Output Selector and Comparator	1
C2	Reference Input Selector	1
C3	PC Card Selector	1
C4	BIC Test Control Logic	1
C5	Reference Signal Generator	2
	TOTAL	6

28-Volt Input DC/DC Converters

Output Voltage	Major Use	No. Reqd.
±15	Bias and Reference Signal Generators	1
±5	Logic	1
	TOTAL	2

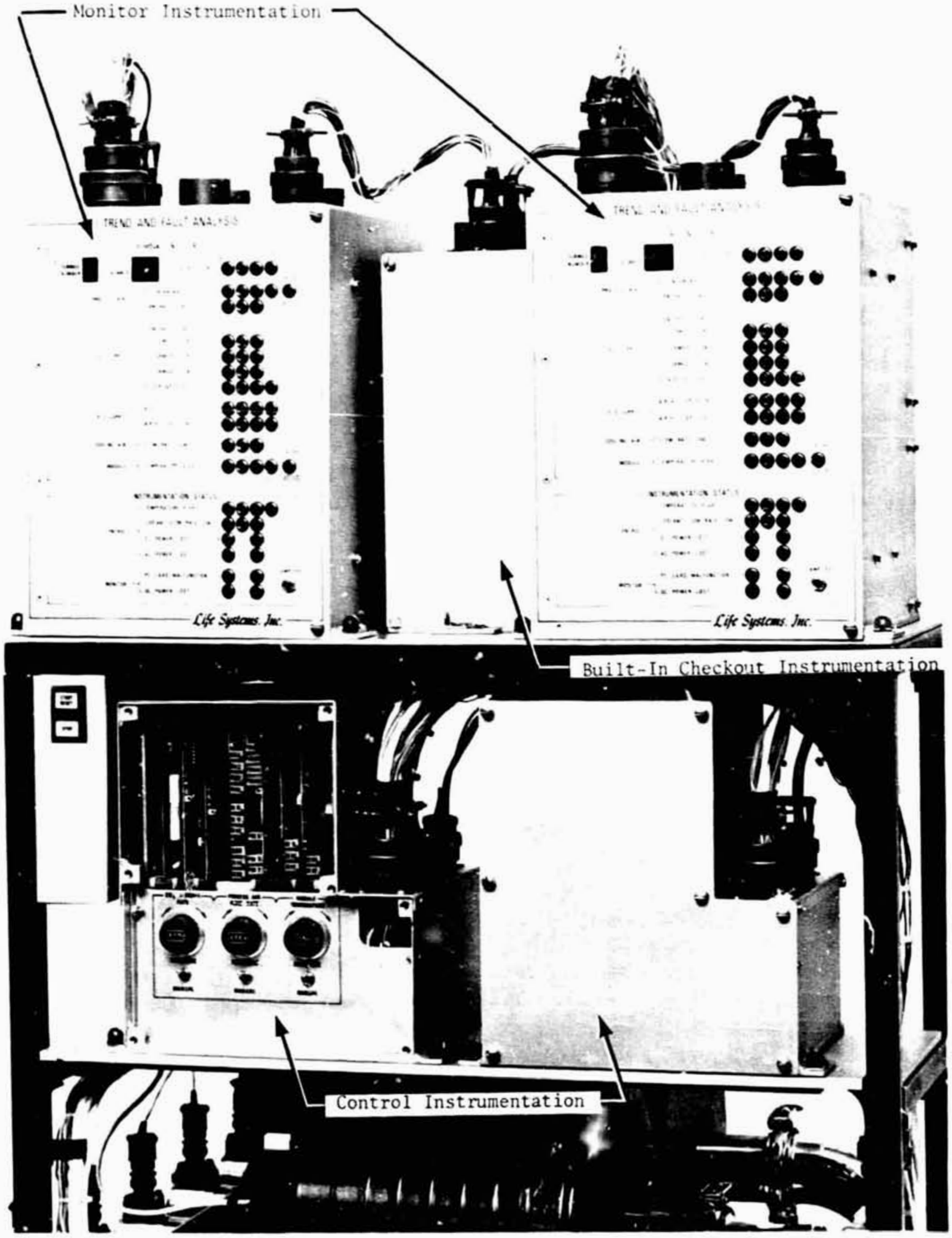


FIGURE 20 CX-6 INSTRUMENTATION PACKAGES

4. The card output levels are compared to proper levels by the test comparitor for each input.

5. The card storage circuit is reset.

6. The temporarily stored information is returned to the card from the BIC storage.

7. The card select code is changed and the next card is selected.

If, at any time during the test, an improper response is received from the card, a flag signal is sent to the card to light the malfunction flag indicator on the card. The flag signal is also sent to an indicator on the monitoring instrumentation Trend and Fault Analysis Panel.

Sensors. There are seven types of parameters monitored by the CX-6 sensors: temperature, flow, blower speed, pressure, H_2-in-air, current and voltage. The sensors monitor and convert parameter levels (except voltage and current) into electrical signals which are processed by the instrumentation. Table 9 is a list of the CX-6 sensors. The table shows the function, type, range, location and use for each sensor.

Temperature Sensor. The function of the temperature sensor is to convert temperatures in the range of 283 to 311K (50 to 100F) to an electrical signal which can be processed by signal-conditioning electronics into the desired 0 to 5 volt range.

The temperature sensors used in the CX-6 system are glass-coated, bead thermistors with a resistance of 100K ohms at 298K (77F) mounted in threaded metal rods. Thermistors are stable, have large responses to temperature changes and do not require a reference temperature device. The glass-encased thermistor is resistant to chemicals and has a fast response time.

Flow Sensor. The function of the flow sensor is to monitor the flow rate of the subsystem fluids. Each flow sensor consists of two thermistors mechanically identical to the temperature sensors but with an electrically lower resistance 2,000 ohms at 298K (77F). The two thermistors are electrically heated by passing a current through them. Both heated thermistors are exposed to the fluid but only one extends into the flowing stream. The other thermistor is mounted in a stagnant fluid zone. As a result, the flowing fluid will cool the sensing thermistor but not the reference thermistor.

The temperature difference between the two thermistors will increase as the fluid flow rate increases. This temperature difference is converted to an electrical signal. Ambient temperature changes in the flowing fluid will not significantly affect the signal level because both thermistors will experience the same temperature change.

Blower Speed Sensor. The function of this sensor is to monitor the rotational shaft speed of a blower. A toothed wheel is mounted on the blower shaft. As the wheel rotates, it passes by the sensing end of a magnetic, variable re-

TABLE 9 CX-6 SENSORS

Function	Type	Range	Located In	Control	Used For Monitor[a] T	S	D	GCU (b)	No. Per Loop
Processed Air Out Temperature	Thermistor	283 to 311K (50 to 100F)	LRC 326	X				X	1
Processed Air Out Temperature	Thermistor	283 to 311K (50 to 100F)	LRC 326		X	X	I		1
Process Air In Temperature	Thermistor	283 to 311K (50 to 100F)	LRC 327					X	1
H_2 in Processed Air Out	Two Thermistors, One Catalyzed	0 to 2%	LRC 326		X	X	I		3
Process Air In Flow	Two Heated Thermistors	0 to 0.0189 m^3/s (0 to 40 Scfm)	LRC 327		X		D		1
H_2 In Flow	Two Heated Thermistors	0 to 4.18 x 10^{-5} m^3/s (0 to 2.5 l/Min)	LRU 317		X		D		3
Cooling Water In Flow	Two Heated Thermistors	0 to 1.05 x 10^{-5} m^3/s (0 to 10 Gph)	LRU 307		X		D		1
Process Air Blower Speed	Magnetic Pickup	0 to 377 rad/s (0 to 3600 Rpm)	LRC 321					X	1
H_2-To-Air Differential Pressure	Pressure Transducer[c]	0 to 34.5 kN/m^2 (0 to 5 Psid)	LRU 200		X	X	I	X	1
Air-To-Water Differential Pressure	Pressure Transducer[c]	0 to 34.5 kN/m^2 (0 to 5 Psid)	LRU 230		X	X	B	X	1
Submodule Current	Shunt	0 to 20 A	LRU 313	X				X	3
Cell Voltage	Voltage Taps	0 to 1.5 V	LRU 292		X	X	D	X	45
Cooling Air In Flow	Two Heated Thermistors	0 to 0.0944 m^3/s (0 to 200 Scfm)	LRU 307		X		D		1

(a) T=Trend (green, amber, flashing red); S=Shutdown (red); D=Direction (I=Increasing, D=Decreasing, B=Both).
(b) GCU=Ground Checkout Unit, parametric data readouts.
(c) Pressure transducers have built-in signal conditioning.

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luctance pickup, producing an electrical pulse for each tooth. This signal is converted to a voltage which is proportional to the blower speed of 0 to 377 rad/s (0 to 3600 rpm).

Pressure Sensor. The function of the pressure sensor is to convert pressures to electrical signals to be used in monitoring circuits. The pressure transducers operate over 0 to 34.5 kN/m^2 (0 to 5 psid) differential pressure range, are powered by 24 VDC, and provide an internally conditioned, 0 to 5 volt output.

H_2-in-Air Sensor. The function of the H_2-in-air sensor is to detect the presence of small quantities of H_2 in the process air as it leaves the modules. This sensor is designed to operate in the 0 to 2% H_2-in-air range.

Each H_2-in-air sensor consists of two thermistors. A platinum catalyst is attached to the sensing end of one thermistor. Both thermistors will indicate identical temperature levels when they are exposed to air containing no H_2. As small amounts of H_2 are introduced into the air, the exothermic reaction of the H_2 and O_2 will occur on the catalyzed thermistor. The temperature of the catalyzed thermistor will then increase above the temperature of the uncatalyzed thermistor. The difference in temperature between the two thermistors is converted to an electrical signal by circuits in the instrumentation equipment.

Current Sensor. The function of the current sensor is to measure submodule currents and convert them to a voltage which is used in the current control system. The current sensors are precision-resistors used as shunts. These shunts are loca[illegible] in the control instrumentation package.

Voltage Sensor. The function of the voltage sensor is to monitor the cell and submodule voltages. All 90 cell voltages are monitored by means of a scanning system built into the monitoring instrumentation. The voltage sensors are simply voltage taps on the cells of each submodule.

Sensor LRUs. The sensor types described above are contained in several LRUs and LRCs. Some contain more than one sensor. The following sections describe these sensor assemblies.

Fluid Flow Sensor. The function of the fluid flow sensor LRU 307 is to measure the cooling air flow to the modules and the liquid coolant water flow to the CX-6 cold plate. Each sensor consists of two flow sensor thermistors mounted in a specially machined fitting.

There are four fluid flow sensors used in the CX-6, two in the cooling air flow paths (one per loop), one in the primary liquid coolant loop and one in the redundant liquid coolant loop.

To maintain the LRU concept the sensors have electrical connectors and require only a wrench for removal. An O-ring seal prevents fluid leakage of the flow being measured into the atmosphere.

Figure 21 shows the two fluid flow sensors installed in the liquid coolant lines.

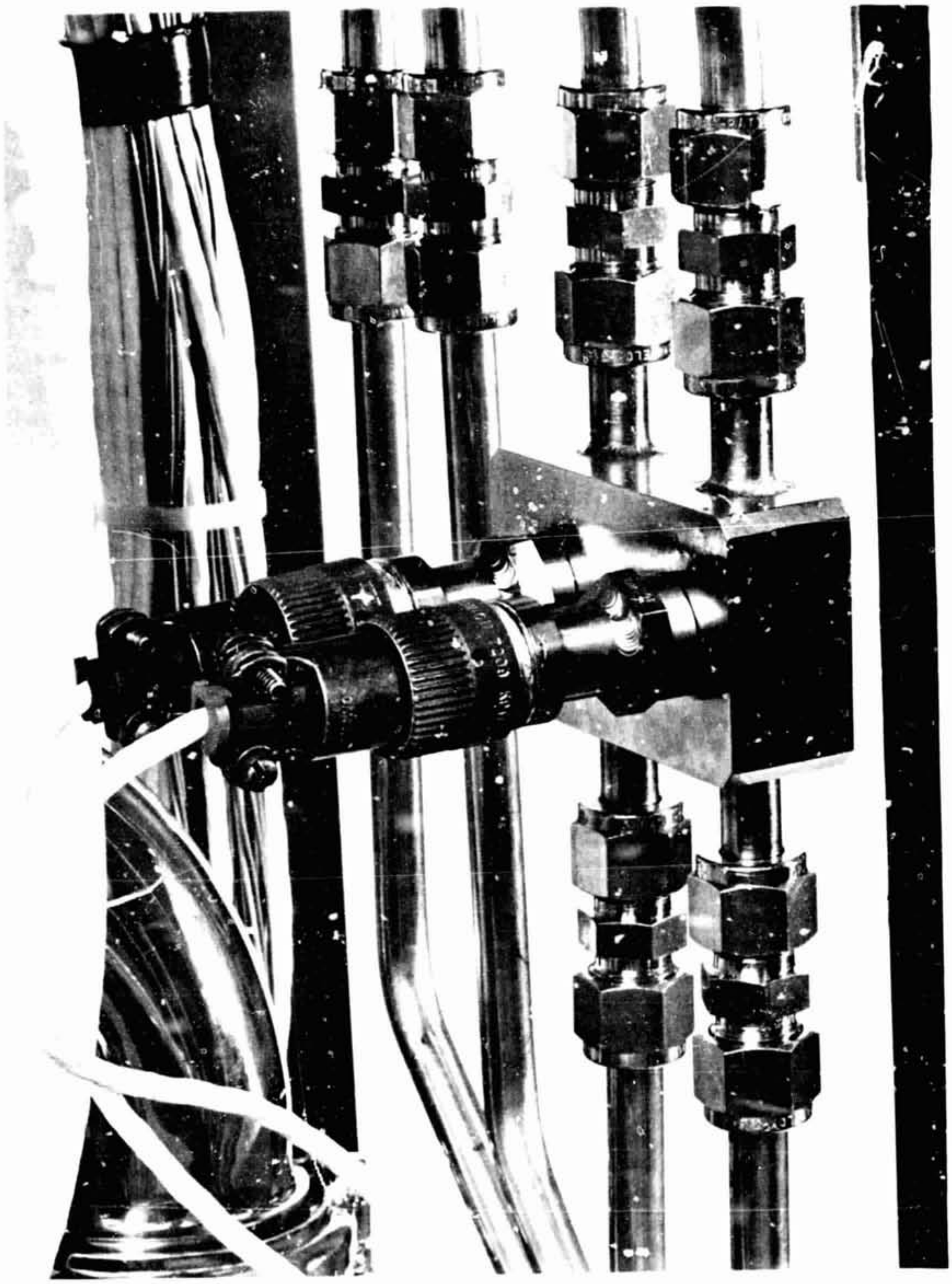


FIGURE 21 INSTALLED FLUID FLOW SENSOR

Differential Pressure Sensors. There are four differential pressure sensors used in the CX-6, two each of two types. Two sensors (LRU 230) are used to measure the air-to-water differential pressures, one in each loop, and two sensors (LRU 200) are used to measure the H_2-to-air differential pressures, also one in each loop. Off-the-shelf differential pressure transducers with built-in signal conditioning were used. The four transducers were bulkhead-mounted having having quarter-inch tube fittings for the gas line connections and double-end shutoff quick-connects for the liquid line connections.

Process Air Inlet Sensor. The process air inlet sensor, LRC 327, performs two functions: it supplies signals to the process air flow rate indication on the Trend and Fault Analysis Panel, and supplies a temperature signal to the GS... The flow sensing is accomplished through a matched pair of flow thermistors while the process air temperature is sensed with a temperature thermistor.

The CX-6 has two process air inlet sensors, one mounted in the process air stream to each electrochemical module. The sensors are mounted with four bolts to blocks attached to the module compression plates. A gasket seal isolates the process air stream from the atmosphere.

Process Air Exhaust Sensor. The process air exhaust sensor LRC 326 performs functions: it senses the presence of H_2 in air, and senses module temperature. Figure 22 is a photo of a process air exhaust sensor. The sensor consists of three H_2-in-air sensors and two temperature sensors. The three H_2-in-air sensors are used to generate signals for voting logic and to drive indicators on the Trend and Fault Analysis Panel. One of the two module temperature sensors is used for module temperature control while the output of the other is used to supply signals for the indicators on the Trend and Fault Analysis Panel.

The CX-6 has two process air exhaust sensors, one each mounted in the process air stream from each of the two electrochemical modules. The sensors are mounted with four bolts to blocks attached to the module compression plates. A gasket seal isolates the process air stream from the atmosphere.

Blower Speed Sensor. The function of the blower speed sensor, LRC 321 is to measure the rotational speed of the process air blower. Two blower speed sensors are used in the CX-6, one for each process air blower. The sensors are bolted to the process air blower housings.

GROUND SUPPORT ACCESSORIES (GSA)

Various items of support equipment were designed, built and used in the operation of the CX-6. Their function was to supply the fluids, electrical inputs, controls and instrumentation displays required for parametric and endurance testing of the CX-6. Six GSA were provided:

1. Fluid Supply Unit (FSU)

2. Air Supply Unit (ASU)

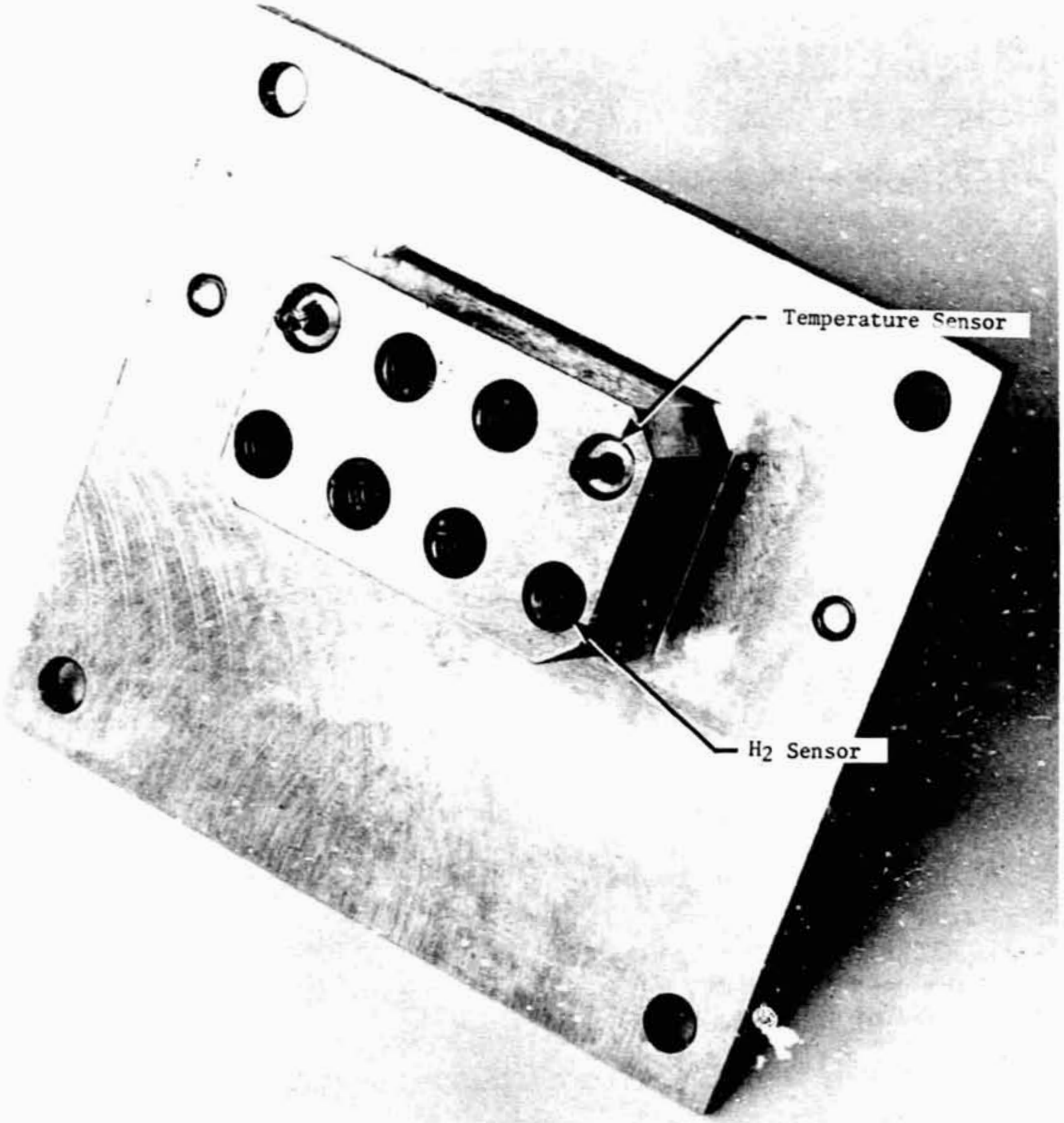


FIGURE 22 PROCESS AIR EXHAUST SENSOR

3. Coolant Supply Unit (CSU)

4. Power Supply Unit (PSU)

5. Ground Accessories Control Unit (GACU)

6. Ground Checkout Unit (GCU)

A block diagram of the GSA is shown in Figure 23.

Fluid Supply Unit

All components of the FSU are housed in a single cabinet. The flows and pressures of water and gases used by the CX-6 and the GSA are controlled and monitored from the control panel at the front of the cabinet as shown in Figure 24. The FSU supplies fluids to the ASU and CX-6 for the following requirements:

ASU

- CO_2 - to maintain desired pCO_2 in the CX-6 process air loop
- H_2O - to maintain desired dew point in the CX-6 process air loop
- O_2 - to maintain pO_2 at 21% in the process air loop (closed loop operation)
- Air - to maintain desired total air pressure (leakage makeup in closed-loop operation)

CX-6

- H_2 - for depolarization of the cell anodes
- N_2 - for purging of H_2 lines and anode gas cavities after either or both loops of the CX-6 have shut down
- H_2O - for internal humidification (when required)

The FSU contains solenoid shutoff valves for CO_2, O_2 and N_2. The N_2 solenoid valve is a normally open type. Normal operation of the N_2 valve is controlled by a battery-powered circuit to provide properly terminated N_2 purge during a line power failure. A complete power failure (i.e. line and battery) will cause a failsafe continuous N_2 purge of the CX-6. The CO_2 and O_2 supply valves are normally closed and will shut off gas supplies during a power failure.

Tap water is supplied to the FSU. Water used for CX-6 internal humidifiers passes through two ion exchange resin cartridges located in the FSU to remove anions, cations and dissolved CO_2. Tap water is directly routed from the FSU to the ASU.

The FSU contains an H_2 humidifier capable of delivering H_2 having a dew point from 280K (45F) to ambient temperature.

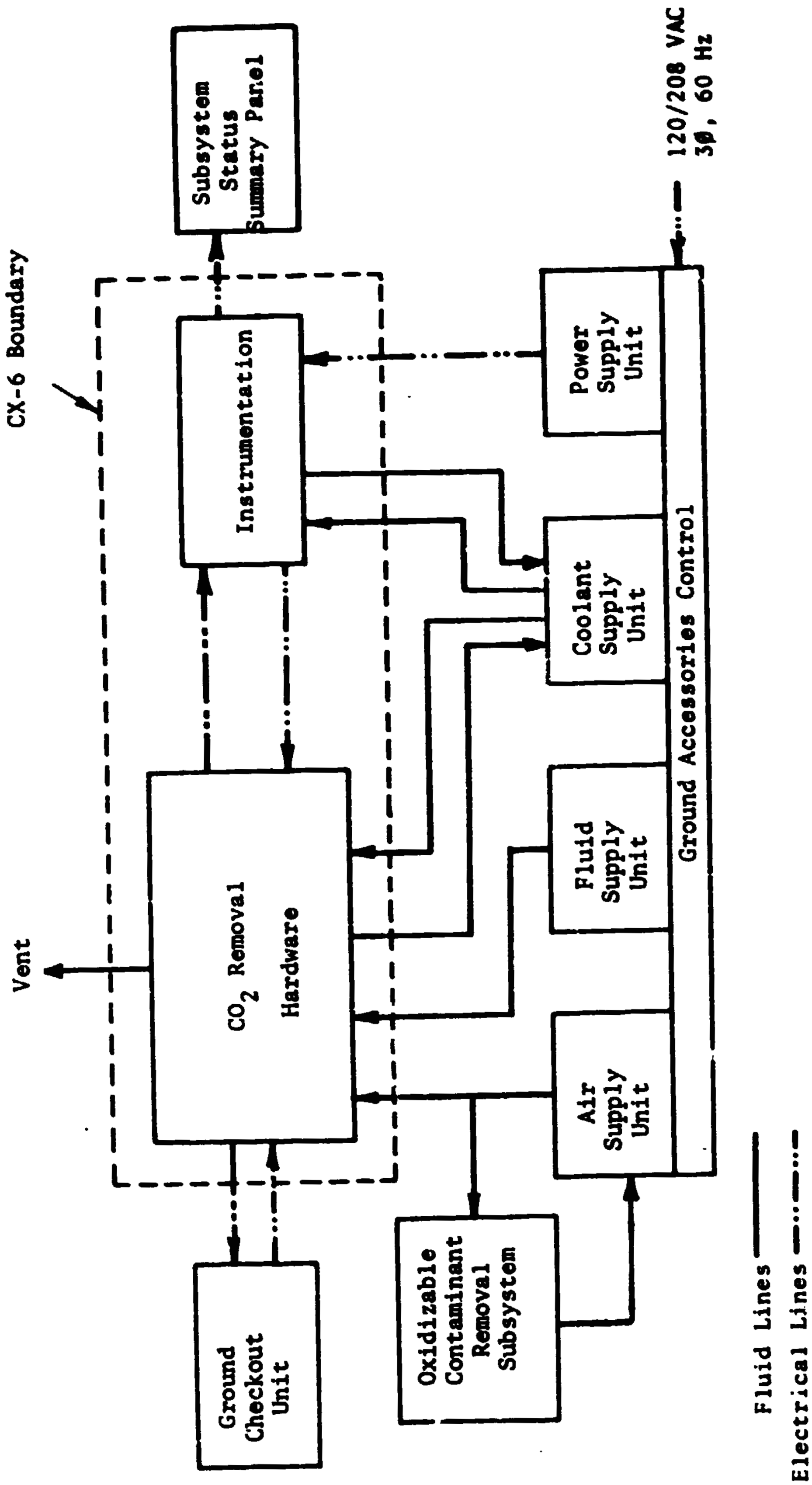


FIGURE 23 GROUND SUPPORT ACCESSORIES BLOCK DIAGRAM

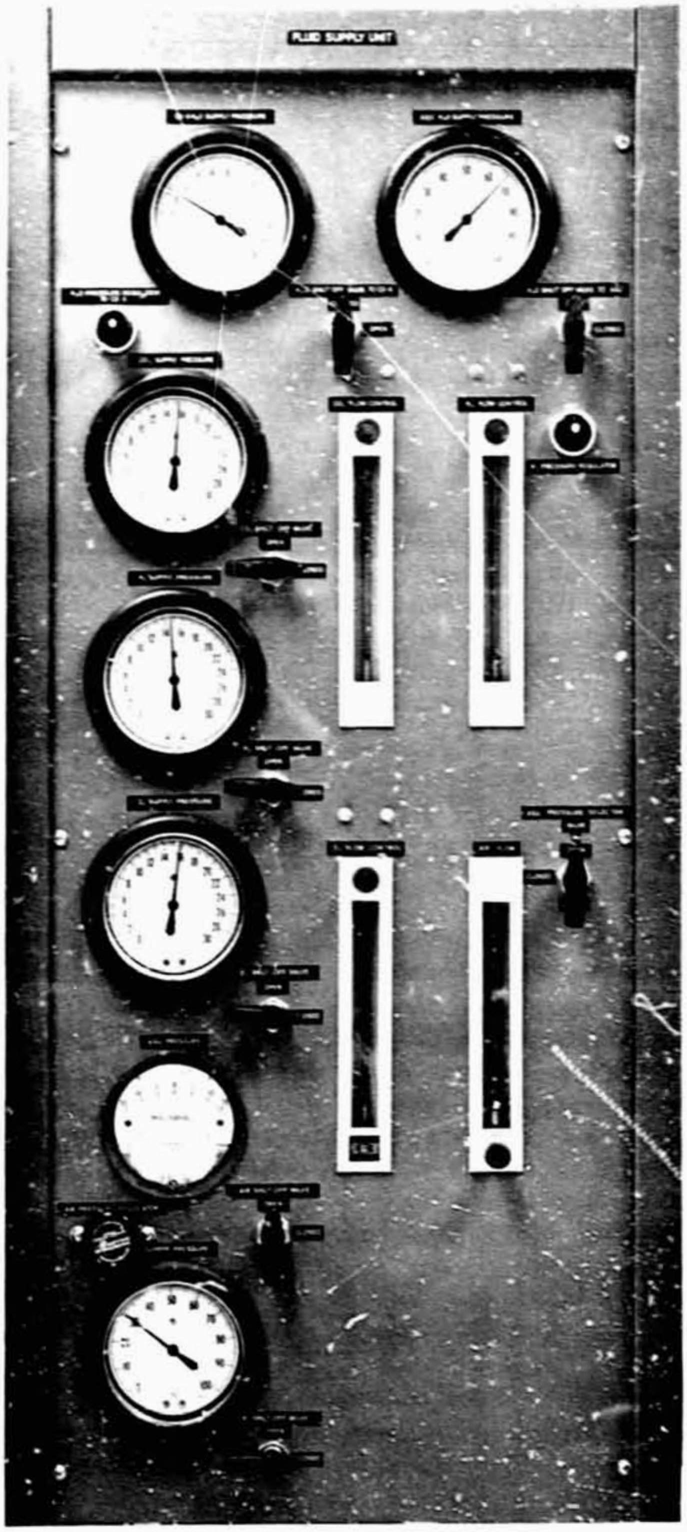


FIGURE 24 FLUID SUPPLY UNIT FRONT PANEL

Air Supply Unit

The ASU supplies process air to the CX-6 at the desired pCO_2, pO_2, temperature and dew point. The process air loop flowing through the CX-6 and the ASU can be operated in either a closed or open loop manner. In the closed loop operation, air is recirculated and only make-up gases are added. In open loop operation the ASU conditions ambient air to the desired pCO_2, temperature and dew point. The process air exiting the CX-6 is returned to ambient.

The major components of the ASU are a cabin simulator tank, a temperature and humidity controller, instrumentation and piping and valves.

Cabin Simulator Tank

This tank has been fabricated from clear, half-inch plexiglas with a volume of 0.40 m^3 (14 ft^3). It serves as a mixing chamber for make-up gases that are added to the process air. Its volume allows for added control during transient periods. The tank interfaces with the Oxidizable Contaminant Removal System (OCRS). When operation with the OCRS is desired, 4.72 x 10^{-3} m^3/s (10 scfm) of air is continuously circulated through the OCRS and back to the tank to maintain levels of trace contaminant within acceptable ranges. The OCRS is discussed in more detail on page 83.

Temperature and Humidity Controller

The temperature and humidity controller maintains process air dry bulb and dew point temperatures by sequentially saturating, condensing and heating the process air.

Instrumentation

The pCO_2, humidity, total pressure and temperature of the process air are sensed at the inlet and outlet of the CX-6. Total air flow is measured with a Pitot tube and slant manometer upstream of the CX-6.

Piping and Valves

Three-inch polyvinylchloride (PVC) pipe, two-inch flexible duct and PVC ball valves were used to interconnect the major components.

Coolant Supply Unit

The functions of the CSU are to supply liquid coolant to the CX-6 instrumentation cold plate and to provide a cold air source for cooling of the CX-6 modules.

Liquid Loop

A self-contained, refrigeration unit supplies chilled water to the CX-6 interface. This unit can supply up to 7.57 x 10^{-4} m^3/s (12 gpm) of coolant at 274.7K (35F).

Air Loop

A standard air conditioning unit controls the temperature and circulates cooling air through an external plenum. Cooling air is drawn from and returned to this plenum by the CX-6, as required for cooling the electrochemical modules. This unit can supply up to 0.189 m^3/s (400 scfm) of cooling air at 278.6K (42F).

Power Supply Unit

The function of the PSU is to supply electrical power to the CX-6 interface. The PSU consists of a 115-VAC, 60-Hz, single-phase power supply and two identical AC-powered, 28-VDC power supplies, each capable of generating 25 amps. The two 28-VDC supplies are connected together with diodes so that with a failure in one, the other will take over automatically. Protection against building power failure is provided by a 28-VDC battery supply designed for 20-minute control operation. The batteries are recharged from the standby DC power supply upon resumption of the normal line power.

Ground Accessories Control Unit

The function of the GACU is to control the GSA for CX-6 operation. The GACU is located in the same cabinet as the PSU and contains switches and meters for controlling and monitoring various subsystem parameters of the CX-6 test setup. The GACU control panel is shown in Figure 25.

The GACU contains a N_2 purge time delay circuit so that in the event of line power failure the CX-6 will be purged, but not continuously. A switch located on the control unit allows manual closing, manual opening or normal, automatic purge valve operation.

The CO_2 and O_2 fed to the process air stream passes through solenoid valves located in the PSU but controlled by the GACU. When the CX-6 is manually shut down or both loops shut down due to a malfunction, the CO_2 and O_2 flows are stopped by a signal originating from the CX-6. Provisions are made to allow for manual shutoff of the solenoid valves.

The GACU serves as an AC power distribution and protection center for the power required for all the GSA and the CX-6. There are circuit breakers on each of the lines and indicators on the panel noting when power is applied to the various units.

Ground Checkout Unit

The function of the GCU is to display CX-6 parameter levels in engineering units. It is not necessary that the GCU be connected to operate the CX-6. It is only required when parametric data is desired. The GCU consists of a parametric data display (Figure 26) and a parametric cell voltage display (Figure 27). The GCU is directly connected to the CX-6. Switches on the parametric data display select which loop is connected to the readouts. The parametric data display is

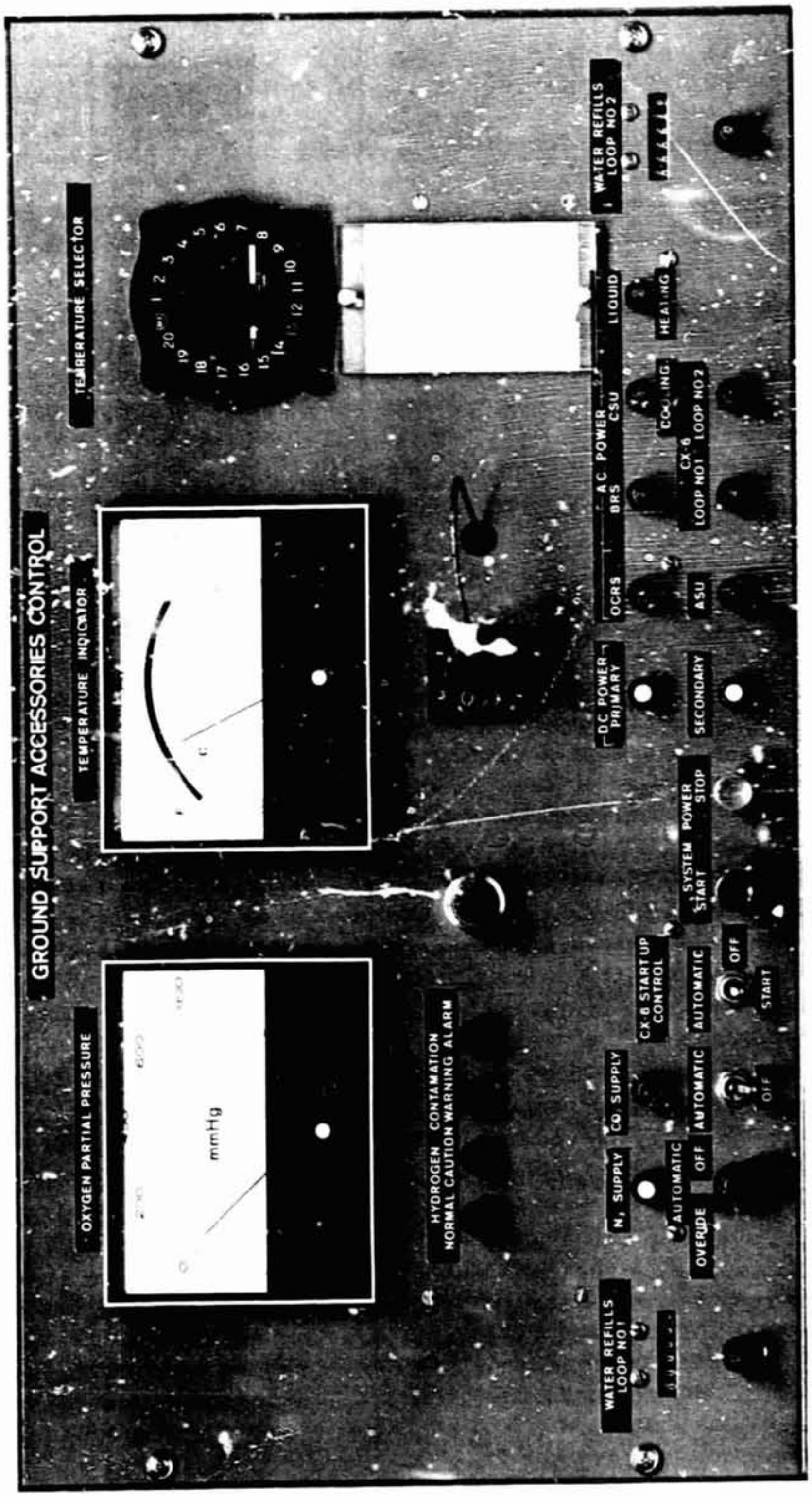


FIGURE 25 GROUND ACCESSORIES CONTROL UNIT PANEL

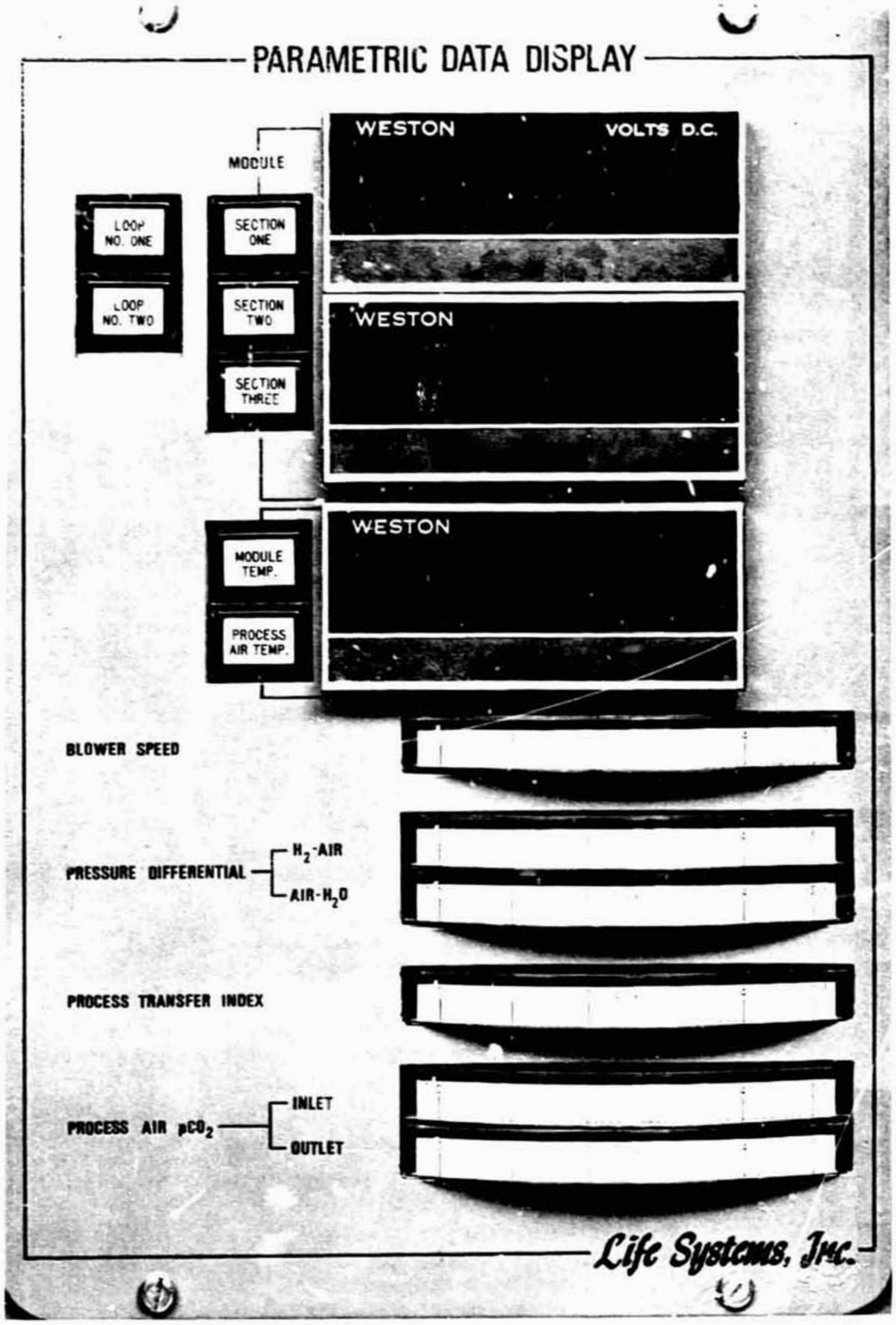


FIGURE 26 GROUND CHECK[illegible] UNIT
PARAMETRIC DISPLAY PA[illegible]

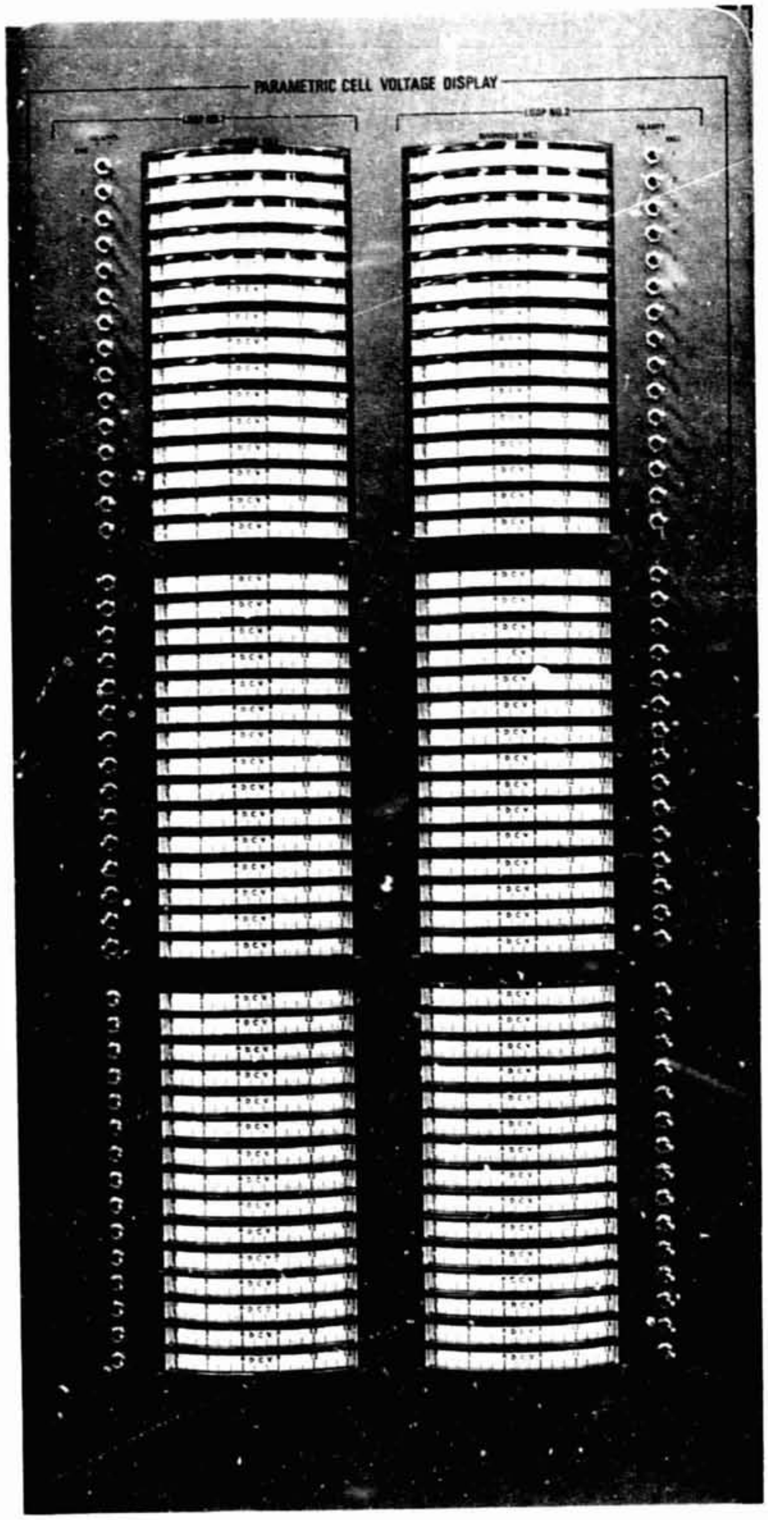


FIGURE 27 GROUND CHECKOUT UNIT
PARAMETRIC VOLTAGE DISPLAY PANEL

both portable and capable of being rack-mounted. Polarity selection switches on the parametric voltage display allow reading of both positive and negative voltage levels for all 90 cells of the CX-6.

PRODUCT ASSURANCE PROGRAM

The Product Assurance Program encompasses the activities associated with Quality Assurance, Maintainability, Reliability, Safety and Materials Control.

Quality Assurance

The Quality Assurance activities for the CX-6 consisted of the following:

1. Performance and documentation of receiving, in-process and final inspections of all CX-6 components received and manufactured.

2. Maintaining records of all supplier inspections and certifications and all nonconforming items and corrective actions.

3. Insuring configuration control by monitoring the Drawing and Change Control Procedures.

4. Monitoring subsystem design verification tests and off-design verification tests.

5. Monitoring the endurance test of the CX-6.

6. Insuring that workmanship was consistent with the one-man system built on Contract NAS2-6118.

7. Monitoring electrical engineering conformance to Q-11.

Maintainability

The maintainability features incorporated into the CX-6 follow. For more detail on maintenance procedures, see Reference 7.

Subsystem Overdesign

The CX-6 is designed to remove 6.0 kg (13.2 lb) of CO_2/day at its nominal design current density of 21.5 mA/cm^2 (20 ASF). Operation at over 43 mA/cm^2 (40 ASF) has been demonstrated with a resulting CO_2 removal rate of 12.0 kg (26.4 lb) CO_2/day.

Subsystem Derating

The CX-6 CO_2 design removal efficiency had been established at 1.9 kg (lb) CO_2/kg (lb) O_2 consumed. Test data indicate that the unit has a capacity of 2.3 kg (lb) CO_2/kg (lb) O_2 consumed, representing a 17% allowance for performance degradation.

Overdesign of CX-6 Hardware

Electronic parts have been derated by 30% or more. The subsystem current controller has been designed for 20A while normal operation is 4.88A. The process air blower is designed to operate at 9.44×10^{-3} m^3/s (20 scfm); its maximum capacity is 0.0189 m^3/s (40 scfm).

Automatic Control

A controller is incorporated in the CX-6 to vary process air flow rate and module current to compensate for increased or decreased CO_2 generation rates.

Provisions for Ease of Maintenance

The CX-6 contains 34 LRUs of 17 different types and 38 LRCs of 10 different types. The maintenance access for all LRUs is from the front, back or left side of the unit. The maximum LRU or LRC maintenance time is 40 minutes. Table 10 lists the tools required to remove and replace the LRUs and LRCs as well as maintenance access and time required to accomplish the maintenance.

Trend Analysis

The trend analysis instrumentation included in the CX-6 provides advance warning of out-of-specification operating conditions. This serves to avoid subsystem shutdowns by alerting test engineers of problems before they degrade subsystem performance.

Ten-Minute Downtime Specification

The subsystem contains a mixture of operating redundancy and spares so as to allow continued operation in spite of repairs being made to the subsystem. The CX-6 consists of two operating redundant loops. Each loop is capable of removing 6.0 kg (13.2 lb) CO_2/day for a limited time.

Equipment Protection

Four equipment proteciton features have been included in the CX-6 to increase the Mean-Time-Between-Failures (MTBF) of the subsystem:

1. Incorporation of sensors.
2. Incorporation of current limiting devices (circuit breakers).
3. Incorporation of a process air filter to protect components from contamination caused by GSA failure.
4. Incorporation of closed-loop temperature control to maintain module temperature which prevents loss of moisture balance and therefore increases cell and module MTBF.

Maintenance Tasks

A maintenance task list was prepared and is presented in Table 11.

TABLE 10 CX-6 MAINTENANCE SUMMARY

Part No.	Description	Tools Req'd	Maintenance Access	Time Req'd
292	Module, Electrochemical (three submodules)	2, 10	Front, Left Side	40 Min
297	Blower, Process Air	6	Front (1), Back (1)	12 Min
296	Blower, Cooling Air	3, 4, 10	Back	6 Min
274	Valve, Solenoid, H_2	3, 7	Left Side, Rear, Front	6 Min
249	Valve, Solenoid, H_2 Bypass	3, 7	Left Side, Back	6 Min
250	Valve, Solenoid, Water	NR(a)	Back	3 Min
275	Valve, Solenoid, N_2	3, 7	Left Side, Front	6 Min
290	Check Valve, H_2	7, 8	Left Side	6 Min
235	Accumulator, Water	7	Back	6 Min
248	Filter, Process Air	7	Right Side	12 Min
313	Instrumentation, Control	NR	Front	6 Min
314	Instrumentation, Monitor	NR	Front	6 Min
315	Instrumentation, Built-In Checkout	NR	Front	6 Min
307	Sensor, Fluid Flow	9	Front (2), Back (2)	6 Min
200	Sensor, Differential Pressure, H_2-to-Air	7	Back	6 Min
230	Sensor, Differential Pressure, Air-to-Water	NR	Back	3 Min
317	Mounting, H_2 Flow Sensor and Distribution	5, 7	Front	6 Min
291	Submodule, Electrochemical	2, 10	Front, Left Side	20 Min
327	Sensor, Process Air, Inlet	1	Front	6 Min
326	Sensor, Process Air, Exhaust	1	Front	18 Min
321	Sensor, Blower Speed	2	Back	12 Min
278	PC Card Assembly B-2	NR	Front	5 Min
279	PC Card Assembly B-3	NR	Front	5 Min
280	PC Card Assembly B-4	NR	Front	5 Min
282	PC Card Assembly B-6	NR	Front	5 Min
283	PC Card Assembly B-7	NR	Front	5 Min
284	PC Card Assembly B-8	NR	Front	5 Min

TOOLS

1. 1/8" Slot-type Screwdriver
2. 3/16" Slot-type Screwdriver
3. 1/4" Slot-type Screwdriver
4. #2 Phillips Head Screwdriver
5. 3/8" Open-end wrench
6. 7/16" Open-end Wrench
7. 9/16" Open-end Wrench
8. 5/8" Open-end Wrench
9. 3/4" Open-end Wrench
10. 7/16" Hex Socket Wrench with 6" Handle

(a) NR = None Required

TABLE 11 CX-6 MAINTENANCE TASK LIST

Task No.	Maintenance Task Description	Maintenance Task Type: Servicing	Scheduled Maintenance	Potential Unscheduled Maintenance
1	Review Subsystem Status Summary Panel	X[(a)]		
2	Check process air filters		X[(b)]	
3	Replace light bulbs			X[(c)]
4	Replace Line Replaceable Units or Components (LRUs or LRCs)			X
5	Perform insitu cell maintenance			X

(a) A flight system would accomplish this function through a computerized system of instrumentation.
(b) A flight system would have the filter monitored or would only need checking if the subsystem failed.
(c) A flight system would use the more reliable Light-Emitting Diodes (LEDs).

Reliability

The reliability activities completed are described below.

Electronics Parts List

An Electronics Parts List, Ames Research Center Form ARC-23, was prepared and submitted.

Reliability Analysis

A reliability mathematical model and analysis was performed on the CX-6 design. The spared reliability of the CX-6 is 0.9997. This exceeds the reliability goal of 0.998 for the system. The MTBF is 4355 hours. The spares required for the CX-6 to attain this reliability are presented in Table 12.

Failure Mode Effects and Criticality Analysis (FMECA)

The FMECA performed on the CX-6 analyzed all possible equipment failure modes and classified each according to criticality. The criticality levels are:

I Failure - A single failure which could cause loss of personnel.

IIa Failure - A single failure whereby the next associated failure could cause loss of personnel.

IIb Failure - A single failure whereby the next associated failure could cause return of one or more personnel to earth, or loss of subsystem function(s) essential to continuation of space operations and scientific investigation.

III Failure - A single failure which could not result in loss of primary or secondary mission objectives or adversely affect crew safety.

The results of the FMECA revealed twelve criticality II failure modes. Seven were associated with external H_2 leakage from components in the H_2 line. One was associated with H_2 crossover in the electrochemical modules. One was the fail-low failure mode of the H_2-in-air sensors. Two were associated with the failure modes of the H_2 bypass solenoid. The last was caused by the fail-open failure mode of the H_2 check valve.

Single-Point Failure Analysis (SPFA)

A single-point failure is a single failure which could cause loss of personnel, could cause return of one or more men to earth or could make it possible for the next associated failure to cause loss of personnel (criticality I and IIa failure modes).

TABLE 12 CX-6 SPARES

Part No.	LRU/LRC Title	No. of Spares Req'd.
297	Blower, Process Air	2
296	Blower, Cooling Air	1
274	Valve, Solenoid, H_2	1
249	Valve, Solenoid H_2 Bypass	1
250	Valve, Solenoid, Water	1
275	Valve, Solenoid, N_2	1
290	Valve, Check, H_2	1
235	Accumulator, Water	1
248	Filter, Process Air	1
313	Instrumentation, Monitor	1
314	Instrumentation, Control	1
307	Sensor, Fluid Flow	1
200	Sensor, Differential Pressure, H_2-to-Air	1
230	Sensor, Differential Pressure, Air-to-Water	1
317	Mounting, H_2 Flow Sensor and Distribution	1
231	Submodule	3
327	Sensor, Process Air Inlet	1
326	Sensor, Process Air Exhaust	1
278	PC Card B2, Temperature Monitor	1
279	PC Card B3, Gas Flow Monitor	1
280	PC Card B4, Liquid Flow Monitor	1
282	PC Card B6, Transducer Monitor	1
283	PC Card B7, Voltage Level Monitor	1
284	PC Card B8, Coolant Flow Monitor with Logic	1

Analyses were performed on the CX-6 for the following five hazardous failure modes:

1. External H_2 leakage from all components and fittings in the H_2 lines.
2. Gas crossover in the electrochemical modules.
3. Fail-in-bypass failure mode of the H_2 bypass solenoid valve.
4. Fail-open failure mode of the H_2 check valve.
5. Fail-low failure mode of the process air exhaust sensor..

The SPFA describe the safety consequences of each hazardous failure mode, document the corrective action taken to minimize the hazard, and detail the justification for retaining the hazard.

Safety

The Safety Program consisted of identifying dangerous subsystem characteristics and failure modes, performing a Safety Hazard Analysis, reviewing nonmetallic and metallic materials lists, reviewing designs and design changes for potential safety problems and reviewing NASA alerts for safety information.

The SHA was conducted on all criticality I and IIa failure modes as determined in the FMECA. Analyses were performed for the following five hazardous failure modes:

1. External H_2 leakage from all components and fittings in the H_2 lines.
2. Gas crossover in the electrochemical modules.
3. Fail-in-bypass failure mode of the H_2 bypass solenoid valve.
4. Fail-open failure mode of the H_2 check valve.
5. Fail-low failure mode of the process air exhaust sensor.

As a result of the safety activities associated with the design of the CX-6, various personnel and equipment protection features were incorporated.

Personnel Protection Features

1. An overtemperature limit on the air cathode exhaust senses for any heat-producing gas recombination.
2. A sensor detects the presence of H_2 in the air cathode exhaust.
3. Trend analysis indicates two levels of off-design operation (caution and warning) prior to the point where personnel would come into danger.

4. All equipment is grounded to protect against electrical shock.

5. Electronic adjustments are located at the front of the subsystem to avoid exposure to voltage hazards during subsystem diagnosis.

6. Critical liquid and gas lines are color-coded to prevent incorrect connections.

7. Rotating equipment is limited to the four air blowers. The blowers have all rotating parts enclosed.

8. Low-speed air blowers limit noise pollution.

9. All H_2 lines are purged with N_2 prior to and after maintenance.

10. The CX-6 materials were selected in accordance with NASA Flammability and Outgassing Specifications[6] to increase the subsystem safety with regard to fire hazards and outgassing.

11. All liquid lines are stainless steel or Teflon to avoid fluid contamination.

12. A check valve isolates each loop of the CX-6 H_2 supply during maintenance on LRUs in the H_2 lines.

13. Quick-connects with double-end shutoffs protect against leaks when replacing water-carrying LRUs.

14. Electrical equipment which presents a shock hazard is covered with a protective guard.

15. The "hot" electrical connectors are always the female socket.

16. A lamp test button is used to verify operability of all panel indicators.

Equipment Protection Features

1. An automatic startup sequence eliminates subsystem startup errors.

2. DC/DC converters protect the electronics from input noises and transients and prevent spurious failure signals to other instrumentation or equipment.

3. The submodule liquid lines are locatred below subsystem instrumentation packages and are operated at a negative pressure relative to ambient to minimize leakage.

4. Redundant (two) module temperature sensors sense module air exit temperature.

5. A high H_2-to-air pressure differential (ΔP) shutdown protects the submodule against cell matrix breakthrough.

6. A high and low air-to-water ΔP shutdown protects the submodule from flooding.

7. A temperature shutdown is provided for excessive submodule temperature.

8. A temperature sensor in the control instrumentation packages protect the electronic parts from high-temperature damage.

9. A filter in the process air line prevents particulate contaminants and moisture droplets from entering the process air blower and the cabin.

10. A low cell-voltage shutdown protects against out-of-tolerance operation.

11. Separate power supplies are used for each instrumentation package.

12. Redundant wire bundles are routed separately and in different locations.

13. A lamp-test button is used to verify the operability of all panel indicators.

14. Trend analysis indicates two levels of off-design operation to protect the subsystem from improper operating conditions, malfunction or equipment degradation.

15. Power supplies are designed to accept peaks and transients by proper selection of component ratings.

16. Circuit breakers protect equipment from ge due to high current drain.

17. All electronic component are grounded.

18. Manual override techniques on critical automatic functions permit safe operation during an emergency.

19. No H_2-carrying LRU can be maintained prior to N_2 purge.

Materials Control

The method employed for evaluating metallic and nonmetallic CX-6 materials is summarized in Figure 28. This method of materials acceptances functions as follows. Drawings are used to control the material identification. The metallic materials are evaluated for acceptability through analysis. They are either found acceptable or the design is modified to incorporate an acceptable material

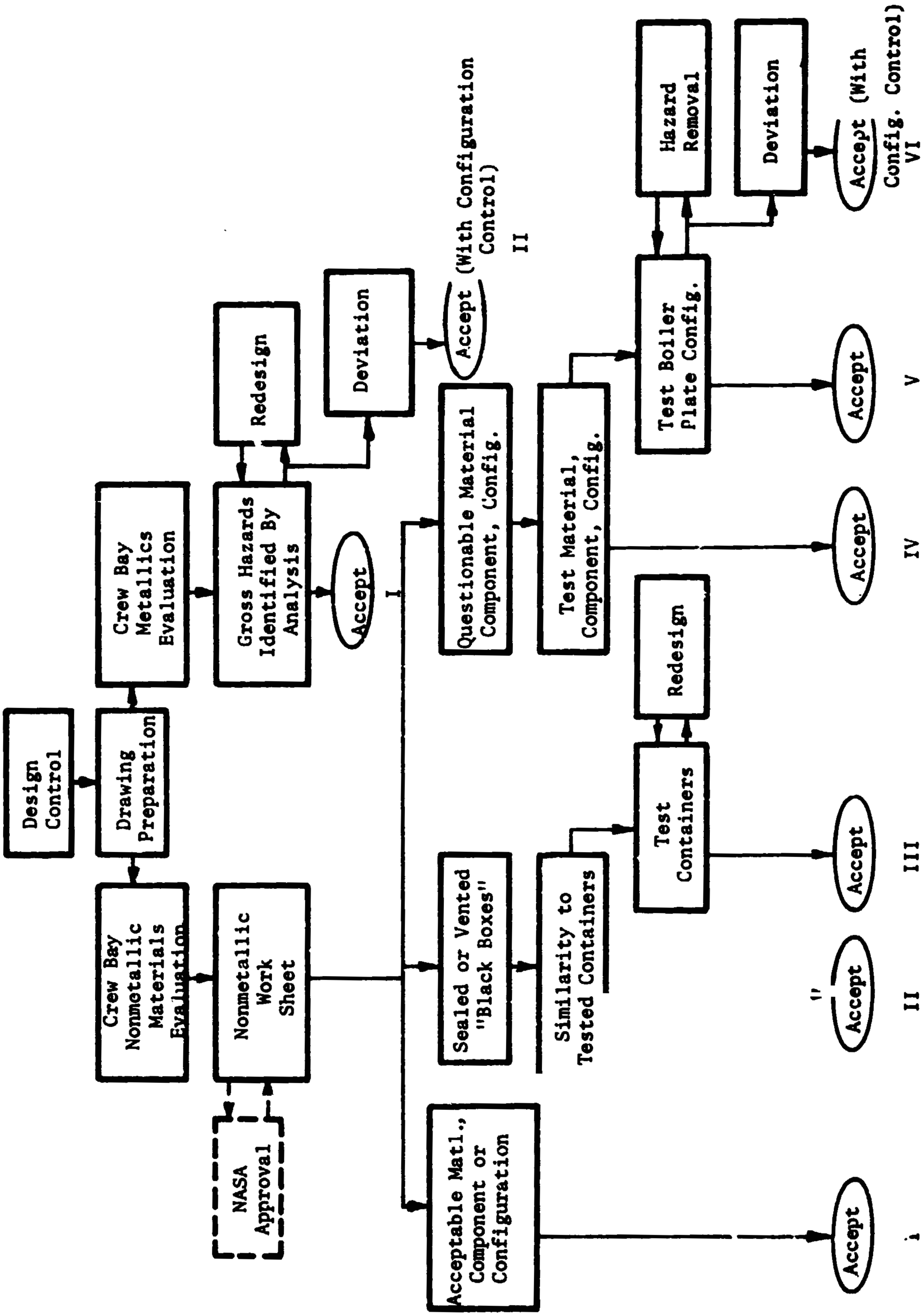


FIGURE 28 MATERIALS EVALUATION PROCEDURE

(I). If an acceptable metallic material cannot be identified, a deviation request would be submitted, for acceptance of the material with configuration control (II).

The nonmetallic materials are also evaluated for acceptability. Nonmetallic materials are listed on the Nonmetallic Work Sheet. Their acceptance results, via any one of three routes are shown in Figure 28. Acceptance, is, therefore, a result of (1) prior demonstration of its acceptability; (2) being enclosed in a sealed or vented container that (a) is similar to a previously tested container or (b) was specifically designed and successfully tested; or (3) actual testing at NASA facilities.

The actual testing is done on the material itself, and if found unacceptable, on the material's boiler plate configuration. If acceptance by testing proves unsuccessful and hazard removal is not possible, a deviation is submitted.

The nonmetallic materials in the CX-6 were screened for acceptance per NASA Flammability and Outgassing Specifications[6]. Several nonmetallic materials did not meet the flammability requirements; for these, acceptable replacements or configurations were identified. A summary of the nonmetallic and metallic materials contained in the CX-6 is listed in the Material Data Summary, Tables 13 and 14, respectively.

TEST PROGRAM

The major objective of the test program was to experimentally characterize the CX-6, with special emphasis on the determination of subsystem performance variations with time and its ability to satisfy the reliability and maintainability goals used in projecting the application of the electrochemical CO_2 removal technique to future manned space missions. To accomplish this objective, a five-part test program was completed:

1. Component checkout and calibration tests
2. Submodule checkout tests
3. CX-6 shakedown tests
4. Parametric tests
5. 180-day endurance test

The CX-6 test facility, including the subsystem and GSA, is shown in Figure 29.

Component Checkout and Calibration Tests

Component checkout tests were performed for all CX-6 and GSA components. Calibration tests were performed on the following CX-6 components: temperature sensors, pressure sensors, flow sensors, module temperature controller, cooling air blower, process air flow rate controller, process air blower and current controller. Calibration tests were performed on the GSA interface simulation and parameter monitoring equipment: flow meters, pressure gauges, pressure regulators, voltmeters, ammeters and temperature indicators.

Life Systems, Inc. CLEVELAND, OHIO 44122	MATERIAL DATA SUMMARY	☒ NONMETALLIC ☐ METALLIC	NO.	REVISION LTR.
	TITLE CX-6 NONMETALLIC MATERIAL SUMMARY		PAGE 1 OF 1	DATE 4/13/72

CHEMICAL GENESIS	MFGR'S DESIGNATION	MANUFACTURER	LOCATION	WEIGHT	EXPOSED AREA	MATL. CODE	REF.
Polycarbonate	Lexan	General Electric	P/N 314	0.2 LB	13.9 IN^2	BECAXX	
Polysulfone	P-1700	Union Carbide	P/N 292	26.8	1,241.0	DKC1XX	
Polysulfone	Thermalux	Westlake Plastics	P/N 292	42.0	6,694.0	DUC1XX	
Asbestos	Paper & Board	Johns-Manville	P/N 292	5.6	0	DTFLXX	
Ethylene Propylene	Nordel 50-01	E.I. duPont deNemours	P/N 292	9.8	137.0	CHDDXX	
Polypropylene		E.I. duPont deNemours	P/N 292	1.0	0	DDBSXX	
Fluorinated Ethylene Propylene	Teflon	E.I. duPont deNemours	P/N's 292,313,317,249,250,274,275, 248,200,230,314,315	1.2	655.0	DKBOXX	
Fluoro Silicone	Proprietary	Amphenol	P/N's 292,313,296,235,317,297,314, 326,327,315	0.05	0	CHEGGU	
Polyarylsulfone		3M Company	P/N's 292,313,296,235,317,297,314, 326,327,315	0.08	0	DKC1XX	Mil-P 46133
Epoxy-Fiberglass Laminate	G-10 11558-G1-2	General Electric	P/N's 313,314,315	5.2	0	CRFVBG	
Diallyl Phythylate	DAP		P/N's 313,314,315	3.4	0	DKXXXX	Mil-M 14F
Polyolefin	FIT	Alpha	P/N's 313,314,307,297	0.2	3.2	EHCEXX	
Ceramic		Motorola	P/N's 313,314	0.9	0	BEHUXX	
Nylon		E.I. duPont deNemours	P/N's 313,314	0.9	0	DKBSXX	
Fluorel	L-3217	Raybestos Manhattan	P/N's 296,317,326,327	0.2	0.6	CHDEXX	68-0991 68-1010
Nitryl-Dacron Laminate	3-175-175 CBJ	Bellofram	P/N 235	0.43	9.2	BEDJXX	
Ethylene Propylene	E540-80	Parker Seals	P/N's 292,235,290,248	0.04	9.1	CHDDXX	
Epoxy	Eccobond 787	Emerson & Cuming	P/N's 235,307,297	0.09	4.2	ABBGGS	69-1545
Silicone	RTV-732	Dow Corning	P/N's 307,317,326,327	0.07	0.3	AEDSXX	68-1123 68-1049
Epoxy	Proprietary	Wabash Magnetics	P/N's 249,250,274,275	0.8	67.3	BABGGU	
Epoxy	Stycast 2651	Emerson & Cuming	P/N 314	0.1	0	BABGXX	LMS CH 1264-02 LM 432- G041-6
Acrylic	H Red CP Polarizer	Polaroid	P/N 314	0.003	0.3	DUAKXX	
Alkyd Resin-Titanium Dioxide	11-6 Universal Gray	Tempo Products Co.	P/N 297	0.3	1,941.0	ATAOGS	

TABLE 13 CX-6 NONMETALLIC MATERIAL SUMMARY

Life Systems, Inc. CLEVELAND, OHIO 44122	MATERIAL DATA SUMMARY	☐ NONMETALLIC ☒ METALLIC	NO.	REVISION LTR.
	TITLE CX-6 METALLIC MATERIAL SUMMARY		PAGE 1 OF 1	DATE 4/13/72

CHEMICAL GENESIS	MFGR'S DESIGNATION	MANUFACTURER	LOCATION	WEIGHT	EXPOSED AREA	MATL. CODE	REF.
Stainless Steel	300 Series	U. S. Steel	P/N's 292,296,235,307,317,297,290, 249,250,274,275,248,200,230,314, 326,327	107.7 LB	5,342.0 IN^2	EXGIXX	
Carbon Steel	1010-1050	U. S. Steel	P/N's 296,297,249,250,274,275	80.1	1,080.0	EXGIXX	
Nickel	Nickel 200	International Nickel Co	P/N's 292,313,296,297,314,315	165.0	5,272.0	EXGIXX	
Aluminum	6061-3003	Alcoa Aluminum	P/N's 292,313,296,235,307,317,297, 249,250,274,275,314,326,327,315	47.8	4,004.0	EXFKXX	
Copper	#10, #22	Belden	P/N's 292,313,297,249,250,274,275, 314,315	17.9	11.2	BDHMXX	
Platinum	Platinum Black	Engelhard	P/N's 292,326	Proprietary	0	BDGIXX	
Beryllium Copper		Amphenol	P/N's 313,249,250,274,275,314	0.2	0	BDGIXX	
Aluminum, Nickel, Cobalt	Alnico	Arnold Engineering Co.	P/N 235	0.03	1.8	BDGIXX	
Lead-Tin	Solder SN 60	Multicore Solders Ltd.	P/N's 292,313,314	1.5	0	BDGIGS	
Gold	Atomex	Engelhard	P/N's 292,313,314	0.3	2,627.0	AMGIXX	
Zinc	Zinc Plate	Skinner Valve	P/N's 274,275,250,249	0.06	120.4	AKHAXX	

TABLE 14 CX-6 METALLIC MATERIAL SUMMARY

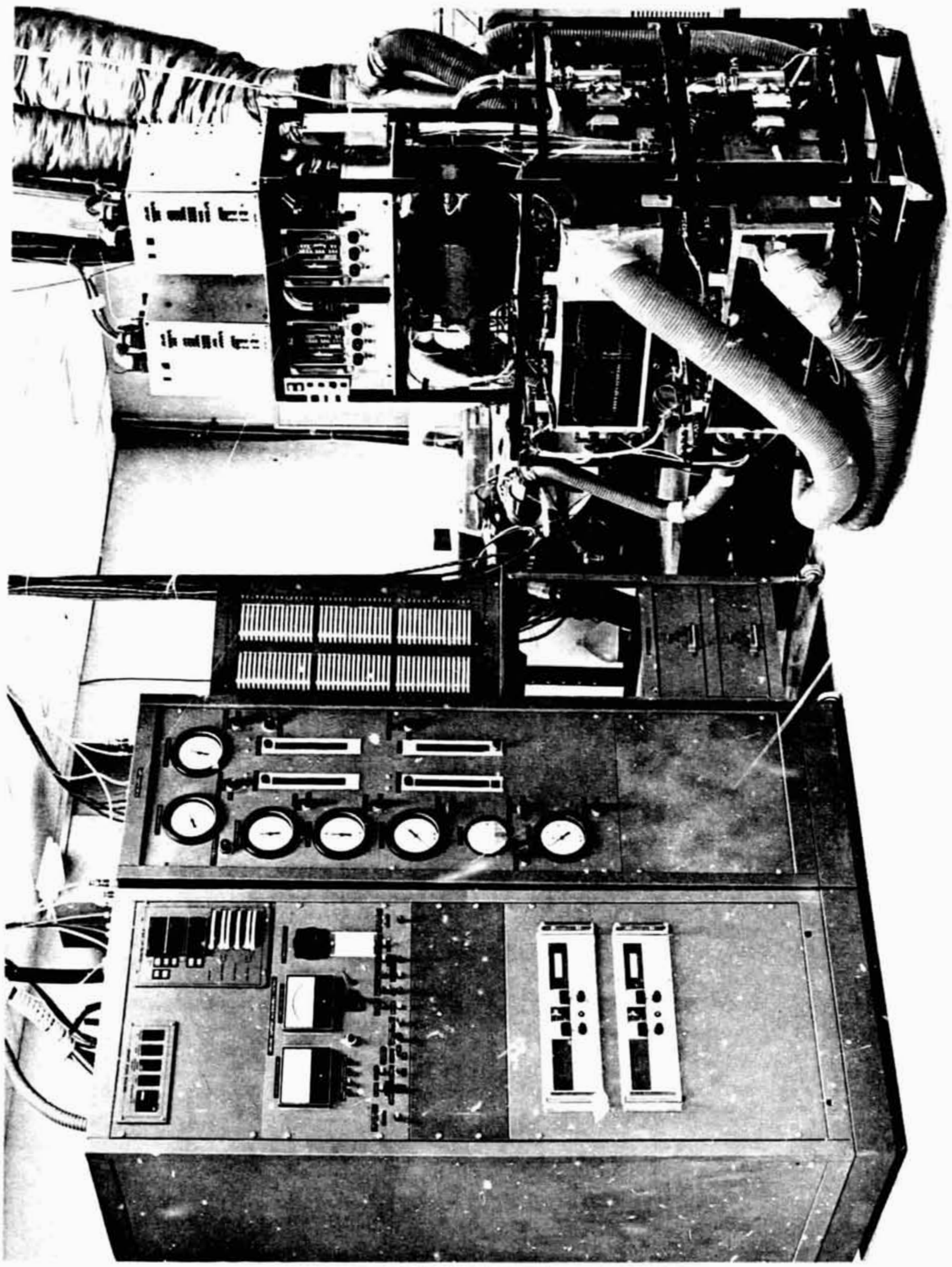


FIGURE 29 CX-6 TEST FACILITY

In addition, all trip levels on the circuit cards were set based on simulated levels at the sensor input points to the cards. The magnitudes of these trip levels in engineering units are shown in Table 7.

Submodule Checkout Tests

Submodule checkout tests were performed to insure that the module CO_2 removal and electrical performance met or exceeded the design point. The submodule checkout tests were conducted using the one-man system (CX-1) test facility[1]. A current density span was performed on each submodule and the results are shown in Figures 30 and 31. All submodules exceeded the CO_2 removal design point of 1.9 kg (lb) CO_2/kg (lb) O_2 and the average cell voltage design point of 0.30V at start-up. (An average cell voltage of 0.25V was projected as a design point after 180 days of operation.)

CX-6 Shakedown Test

After all components had been assembled and integrated into the self-contained subsystem, which, in turn, was integrated with the GSA, a shakedown test was initiated. As a result of the shakedown test the following actions were taken.

Self-Contained Subsystem

1. The O-rings between the 15-cell submodules provided insufficient sealing and were replaced with gasket seals.

2. Power line filters were added to process air blower controls to eliminate control interactions.

Ground Support Accessories

1. The wet-bulb sensing controller of the ASU temperature and humidity control unit did not have sufficient accuracy to maintain constant process air dew point and was removed from the system. The refrigerant loop expansion valve was replaced with an adjustable constant pressure regulator to control the pressure and hence the temperature at which the refrigerant evaporates in the process air condenser coil. The control of the condenser coil temperature resulted in the desired process air dew point control.

Parametric Testing

A parametric test program was conducted to characterize the performance of the six-man subsystem. The effects of five parameters on performance were investigated: process air pCO_2, current density, process air flow rate, H_2 flow rate and operating temperature. Table 15 summarizes the ranges over which the parameters were varied during the testing. A total of 480 hours of subsystem operation was accumulated during the parametric test program.

Measure of Performance

Two parameters can readily be used to describe the performance of an electro-

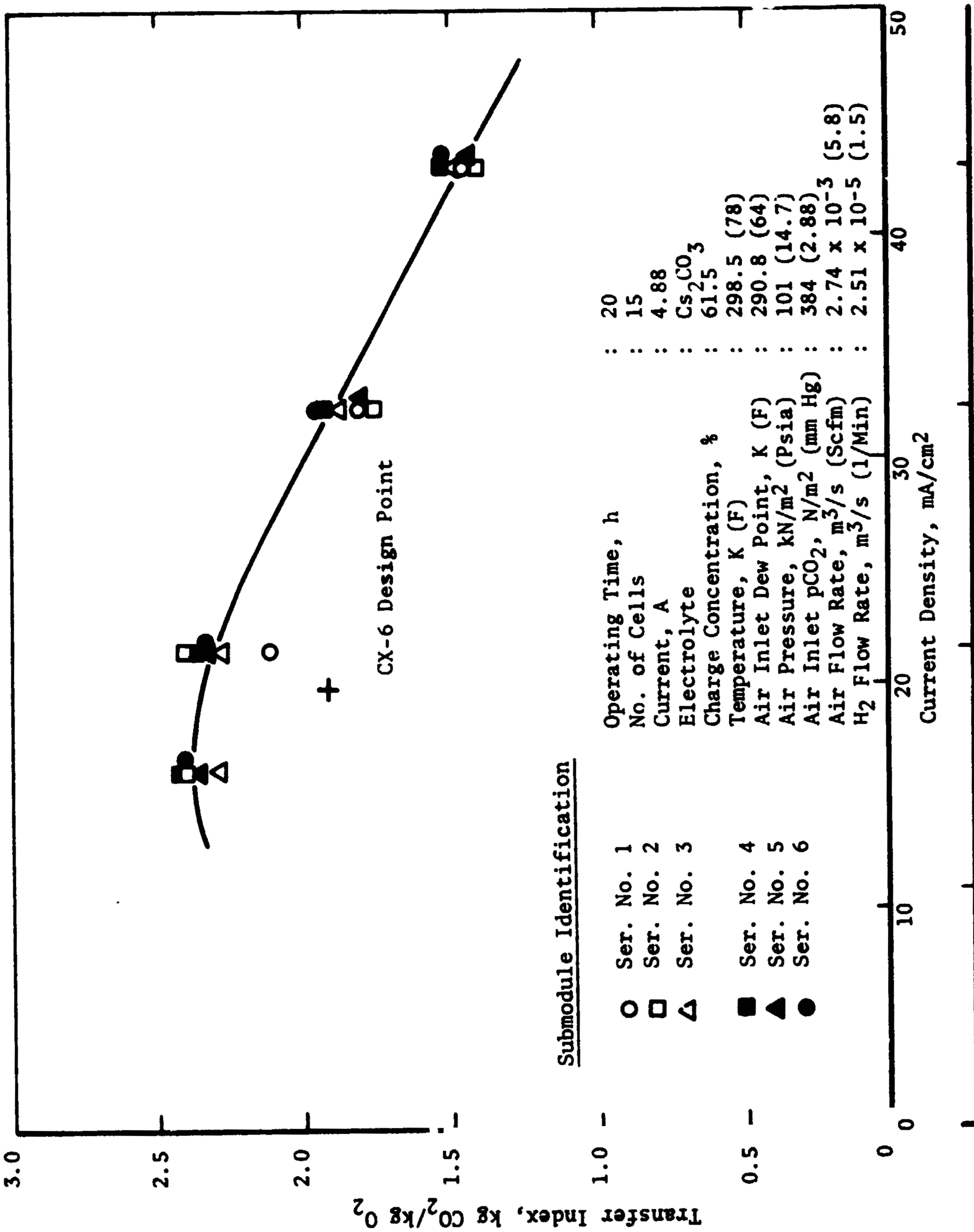


FIGURE 30 EFFECT OF CURRENT DENSITY ON SUBMODULE CO_2 REMOVAL EFFICIENCY

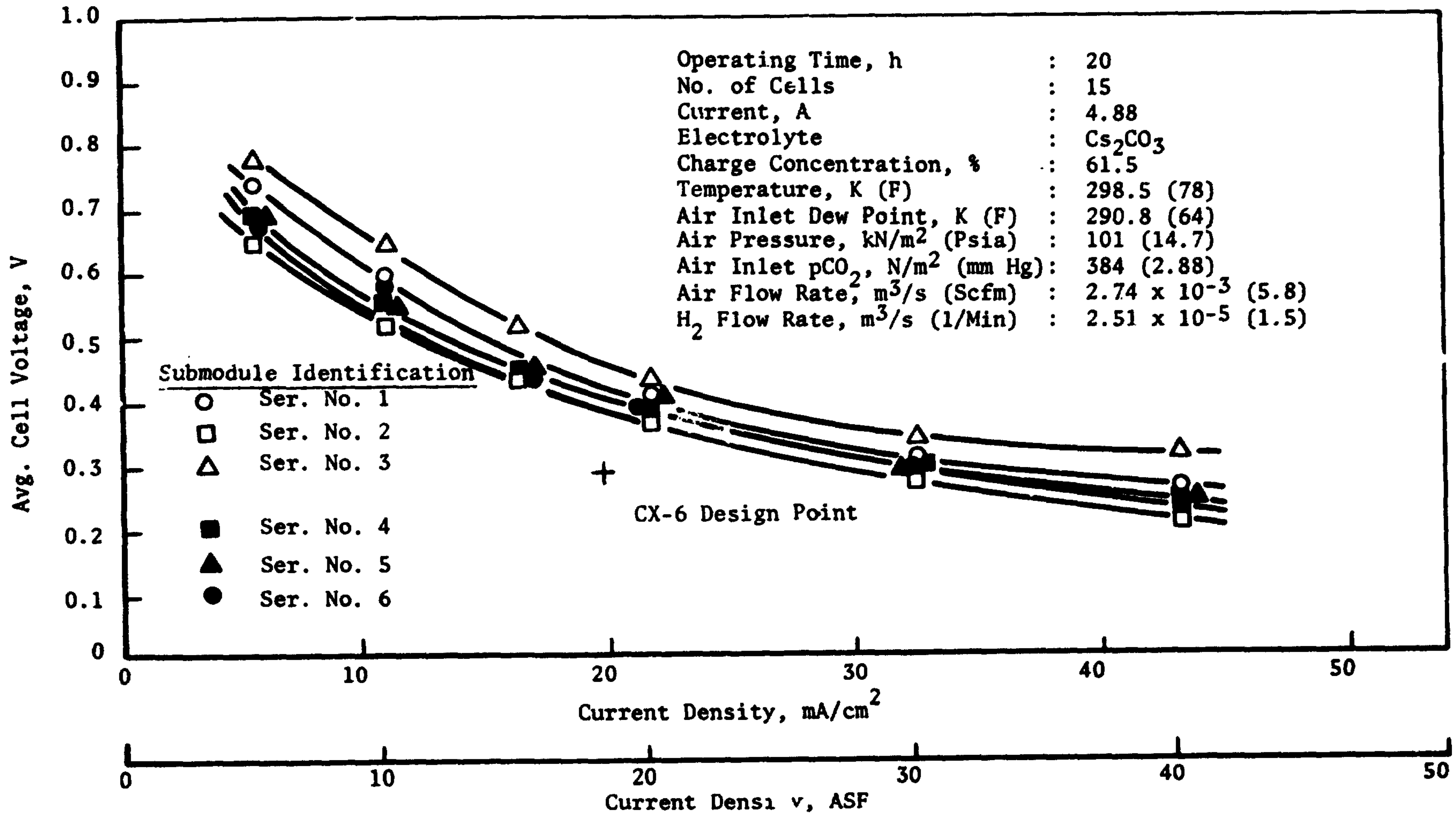


FIGURE 31 EFFECT OF CURRENT DENSITY ON SUBMODULE AVERAGE CELL VOLTAGE

TABLE 15 SUMMARY OF CX-6 PARAMETRIC PERFORMANCE CHARACTERIZATION CURVES

Parameter Varied	Range	Curve Reflecting Performance	Temp, K(F)	Air Inlet Dew Point, K(F)	Press, (Psia)	pCO_2, (mm Hg)	H_2 Flow, m^3/s (Slpm)	Air Flow, m^3/s (Scfm)	Current, A
Process Air pCO_2	80 to 1025 N/m^2 (0.6 to 7.7 mm Hg)	Figure 32	292(67)	282(47.5)	101(14.7)	Var[a]	1.5×10^{-4} (9.0)	0.021(44)	4.88
Current Density	5.4 to 43 mA/cm^2 (5 to 40 ASF)	Figure 33	292(67)	282(48)	101(14.7)	360(2.70)	1.5×10^{-4} (9.0)	0.019(40)	Var
Process Air Flow Rate	0.011 to 0.029 m^3/s (23 to 61 Scfm)	Figure 34	292(67)	282(47.5)	101(14.7)	365(2.74)	1.5×10^{-4} (9.0)	Var	4.88
H_2 Flow Rate	8.3×10^{-5} to 22.2×10^{-5} m^3/s (5.0 to 13.3 l/Min)	Figure 35	293(67.5)	283(49.5)	101(14.7)	377(2.83)	Var	0.020(42.5)	4.88
Temperature	293 to 302K (67.5 to 85.0F)	Figure 36	Var	Var	101(14.7)	353(2.65)	1.5×10^{-4} (9.0)	0.021(44)	4.88

(a) Var = Variable

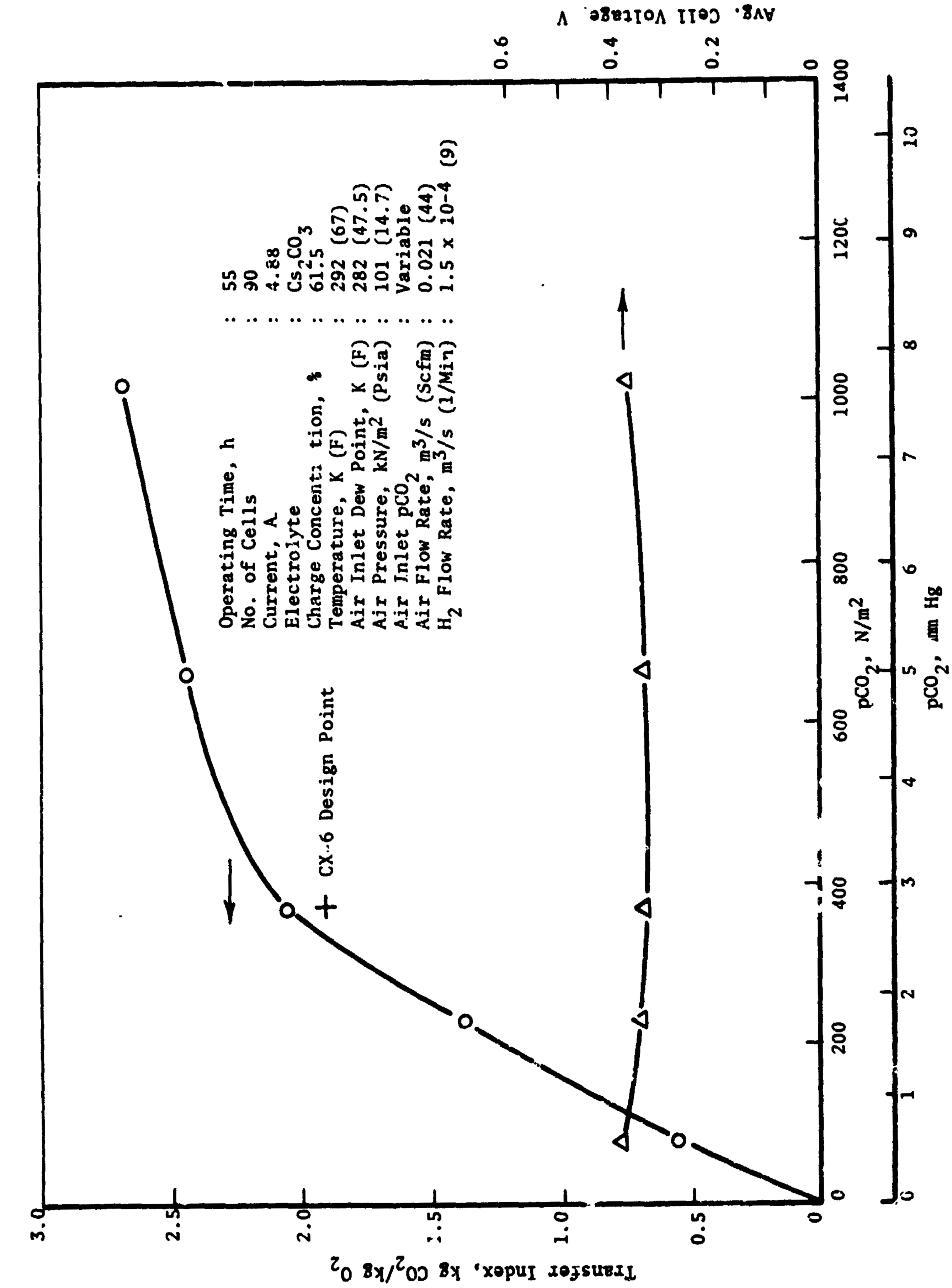


FIGURE 32 EFFECT OF pCO_2 ON TI AND AVERAGE CELL VOLTAGE

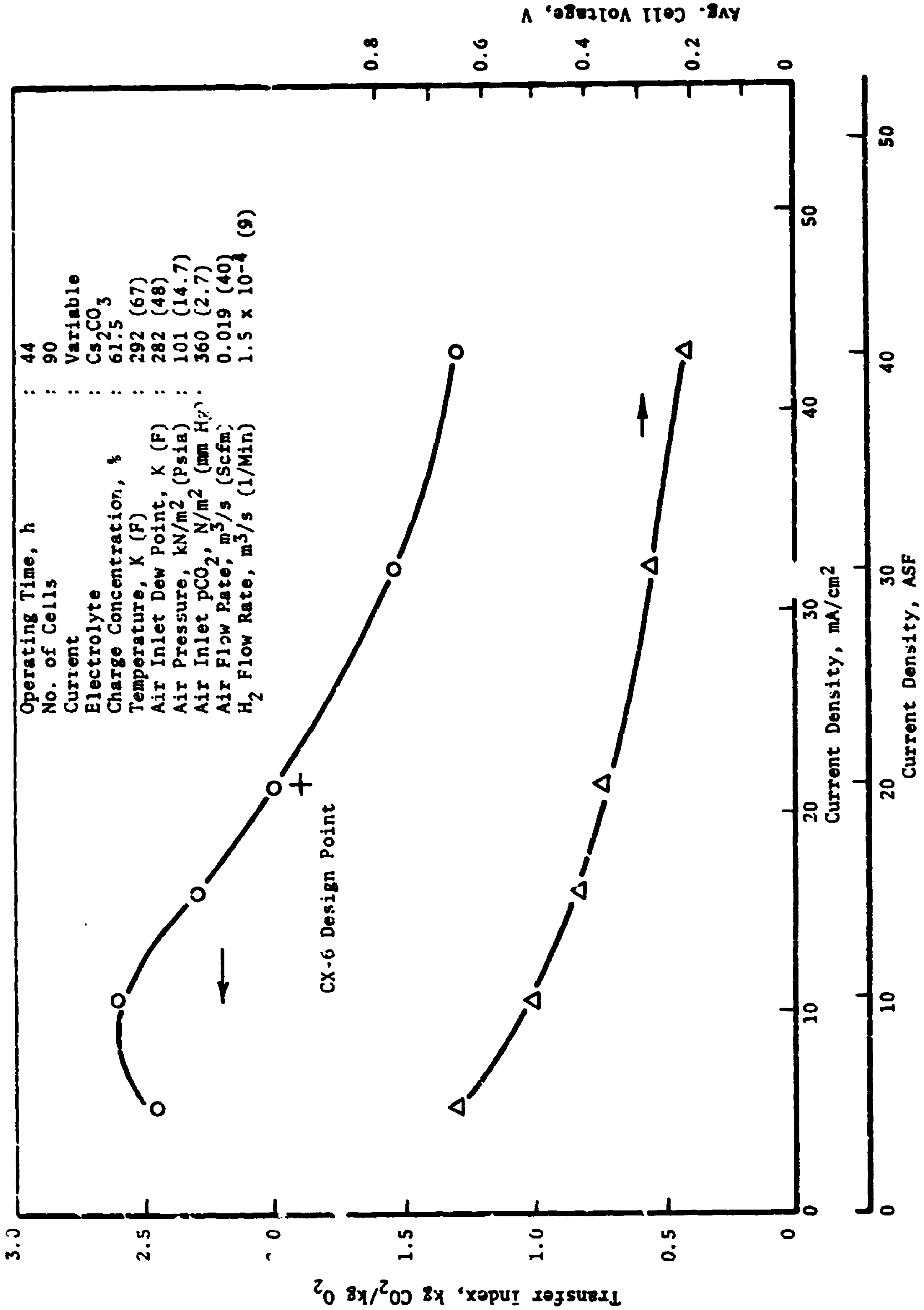


FIGURE 33 EFFECT OF CURRENT DENSITY ON TI AND AVERAGE CELL VOLTAGE

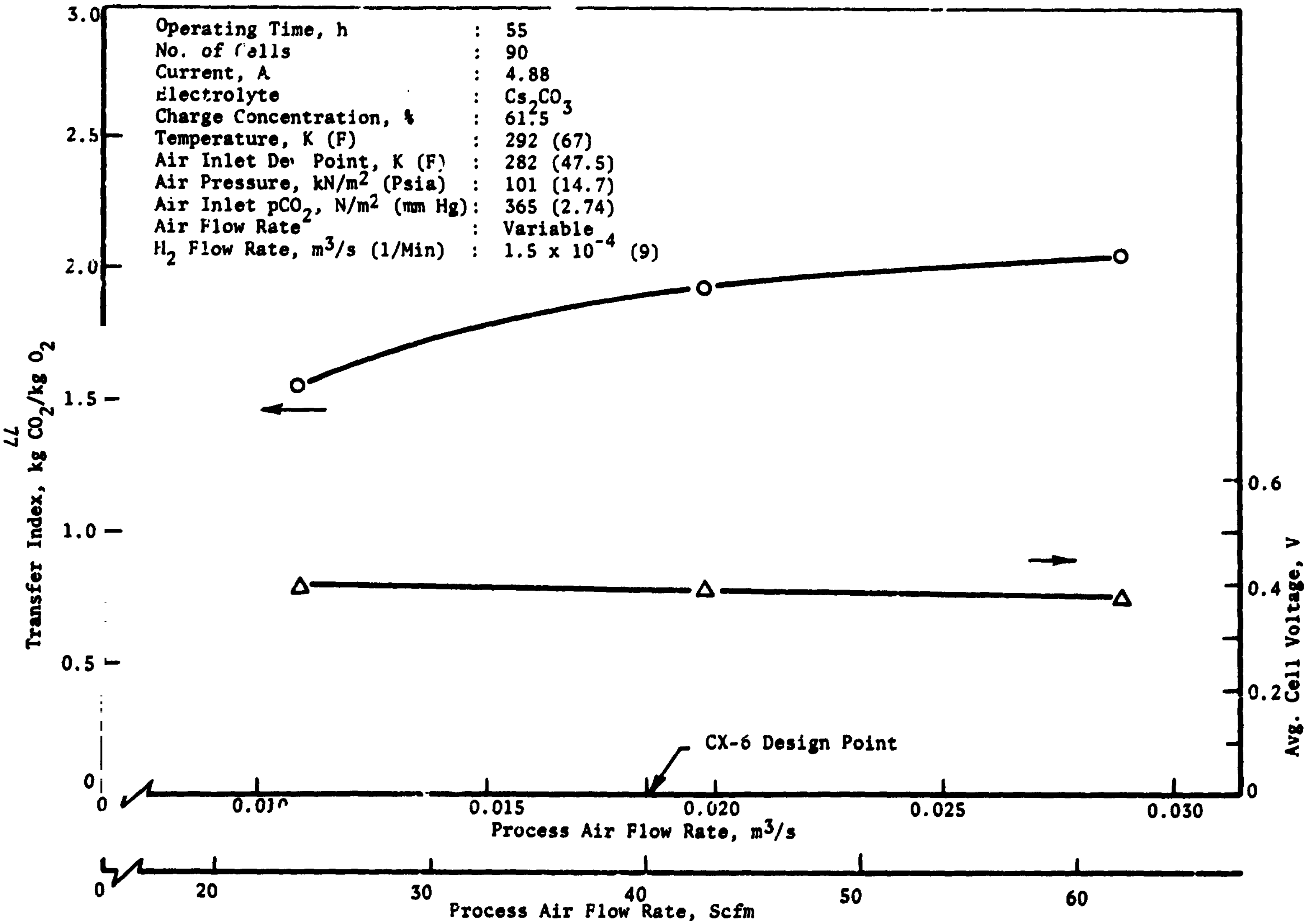


FIGURE 34 EFFECT OF PROCESS AIR FLOW RATE ON TI AND AVERAGE CELL VOLTAGE

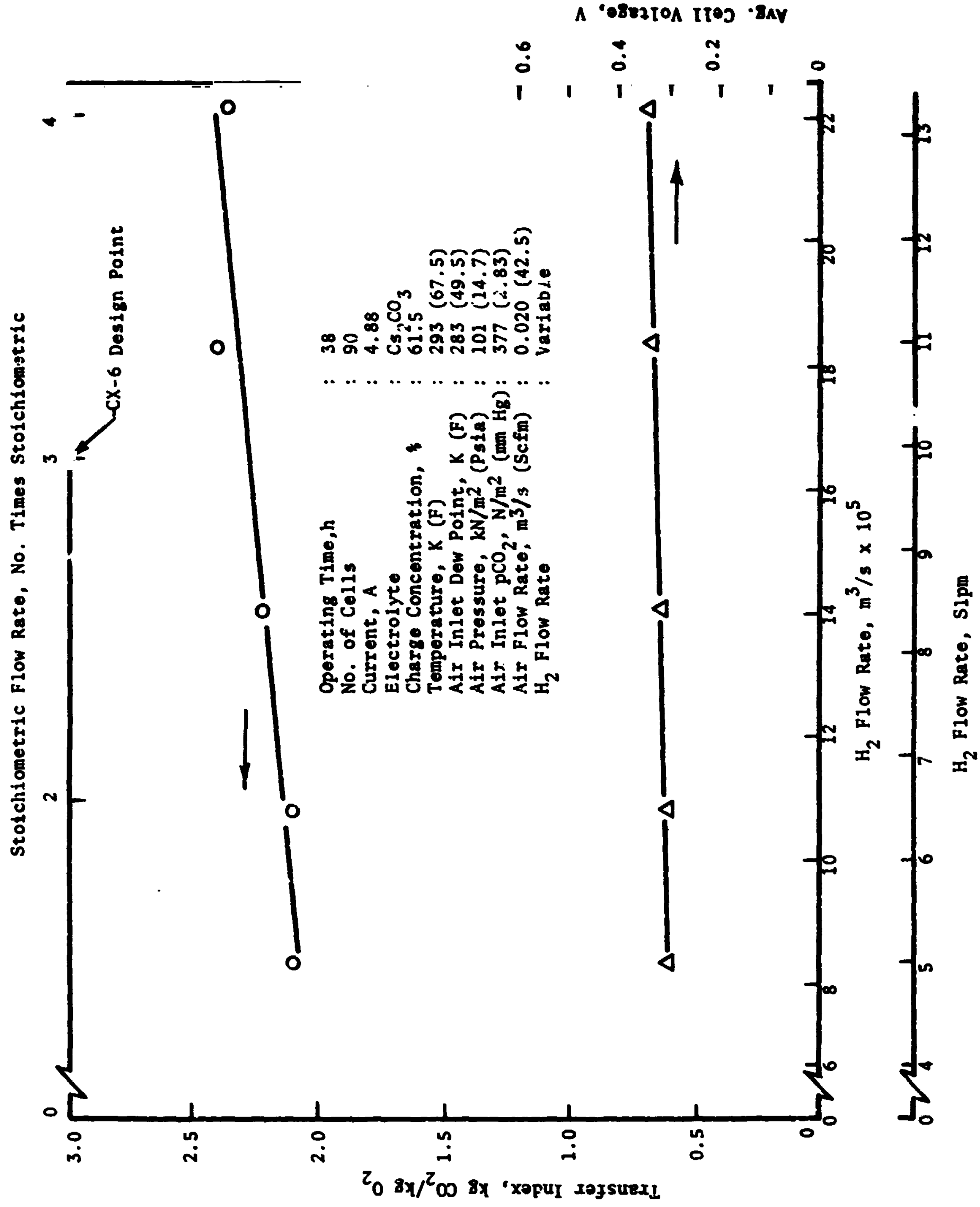


FIGURE 35 EFFECT OF H_2 FLOW RATE ON TI AND AVERAGE CELL VOLTAGE

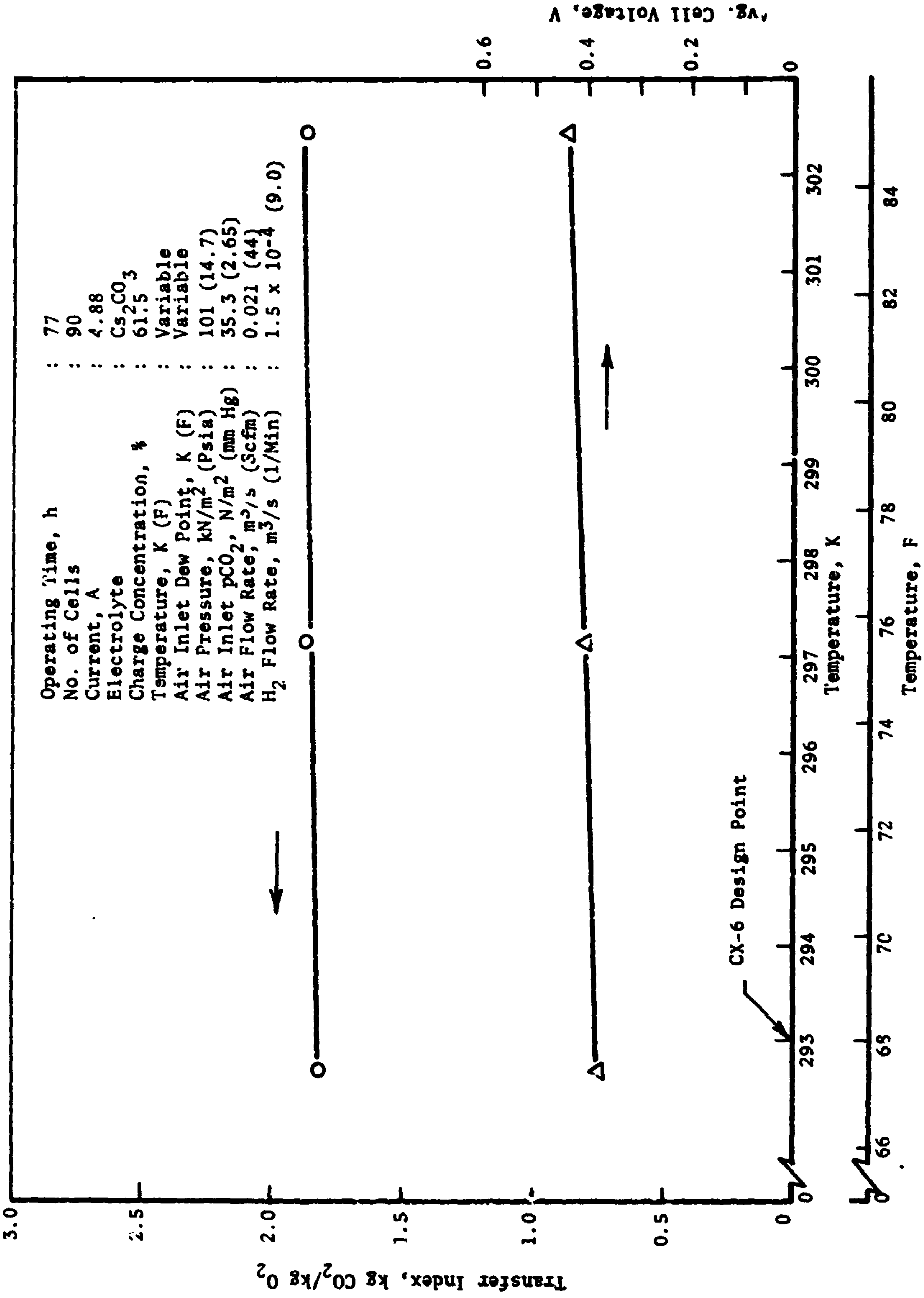


FIGURE 36 EFFECT OF MODULE OPERATING TEMPERATURE ON TI AND AVERAGE CELL VOLTAGE

chemical CO_2 concentrator: CO_2 removal efficiency and electrical efficiency.

Carbon dioxide removal efficiency can be expressed by a term called the Tranfer Index (TI) which relates CO_2 removal directly to O_2 consumption and is defined as the ratio of the mass of CO_2 removed to the mass of O_2 consumed. Based on the stoichiometry of the reactions involved, the TI is 2.75 kg (lb) CO_2/kg (lb) O_2.

Electrical efficiency is reflected by cell voltage. Since a CO_2 concentrator produces electrical power, a high cell voltage reflects a high electrical efficiency. The theoretical voltage for the electrochemical reaction is 1.23V while a typical operating voltage is 0.30V.

Effect of pCO_2

Figure 32 shows the effect of pCO_2 on TI and average cell voltage for the range in pCO_2 of 80 to 1025 N/m^2 (0.6 to 7.7 mm Hg) at the indicated operating conditions. Transfer Index increases and average cell voltage decreases slightly as pCO_2 increases.

The pronounced change of the slope in TI near 400 N/m^2 (3.0 mm Hg) indicates a change in the limiting CO_2 transfer mechanism. Parallel investigations have shown that the steep portion of the TI curve is dominated by mass transfer limitations of CO_2 within the cathode or process air compartment while the flatter portion results when reaction limitations dominate.[3]

Effect of Current Density

Figure 33 shows the effect of current density on TI and average cell voltage for the range in current density of 5.4 to 43 mA/cm^2 (5 to 40 ASF). As current density increases, average cell voltage decreases. A maximum value for TI of 2.6 occurs at approximately 11 mA/cm^2 (10 ASF). The TI decreases for both lower and higher current density values. The curve for TI indicates that while increasing current above the maximum TI value will result in increased amounts of CO_2 transferred, the efficiency at which this increased transfer is achieved decreases.

The decreasing cell voltage and increasing current density reflects an increasing amount of waste heat that must be removed from the electrochemical cells by the cooling air stream, since waste heat generated is a direct function of current and the difference between theoretical and actual cell voltage.

Effect of Process Air Flow Rate

Figure 34 shows the effect of process air flow rate on TI and average cell voltage for the range in air flow rate of 0.011 to 0.029 m^3/s (23 to 61 scfm). The TI increases and average cell voltage decreases slightly as air flow increases. The rise in TI with increasing air flow is the result of an increase in the CO_2 mass transfer coefficient and in the effective or average pCO_2 level within the cathode compartment.[3] Above a certain air flow level inc ses in CO_2 transfer will diminish with increasing air flow rate.

The cause for the slight variation in average cell voltage with changing air flow is probably due to small variations in temperature and dew point levels of the process air caused by the changing air flow through GSA humidity control components.

Effect of H_2 Flow Rate

Hydrogen flow rate was varied from 8.3×10^{-5} to 22.2×10^{-5} m^3/s (5 to 13.3 l/min). This range in flow rate corresponds to 1.5 to 4.0 times the amount required stoichiometrically by the electrochemical reaction. Both TI and average cell voltage increases linearly with H_2 flow rate as shown in Figure 35. For the range tested the TI and cell voltage increases from 2.1 to 2.3 kg (lb) CO_2/kg (lb) O_2 and from 0.31 to 0.34V, respectively.

Effect of Module Temperature

The effect of module temperature on TI and cell voltage was investigated for the range from 293 to 302K (67.5 to 85F). For this range, only a minimal (<2%) increase in both TI and average cell voltage results with increasing temperature as shown in Figure 36.

Endurance Testing

The endurance testing of the CX-6 was started immediately following the 480 hours of parametric tests. Figure 37 shows the TI and average cell voltage of the CX-6 as a function of time. Also indicated are the ranges in operating conditions experienced during the endurance test. A total of 4,536 hours (189 days) were accumulated during this phase of testing, bringing the total number of operating hours for all testing to 5,016 hours or 209 days.

Transfer Index

A gradual decrease in TI was observed during the first 550 hours of endurance testing (see Figure 37). The cause was traced to deterioration of the polycarbonate structural cell material causing an inward leakage of ambient, low pCO_2 air into the cells' process air inlet manifolds and compartments, thus lowering the TI. Subsequently, the polycarbonate parts were replaced with polysulfone parts and, after the modules were recharged with electrolyte, testing was resumed. Following recharge, the TI gradually increased, exceeding the design point level of 1.9 after approximately 500 hours. For the remainder of the test (in excess of 3,000 hours) the TI remained level and stayed above the design point.

Cell Voltage

The average cell voltage remained between 0.25 and 0.35 volts for the total test time without deterioration. The fluctuations in the voltage are attributed to controlled and uncontrolled variations in process air humidity levels and anode gas (H_2 and CO_2 mixture) backpressure variations.

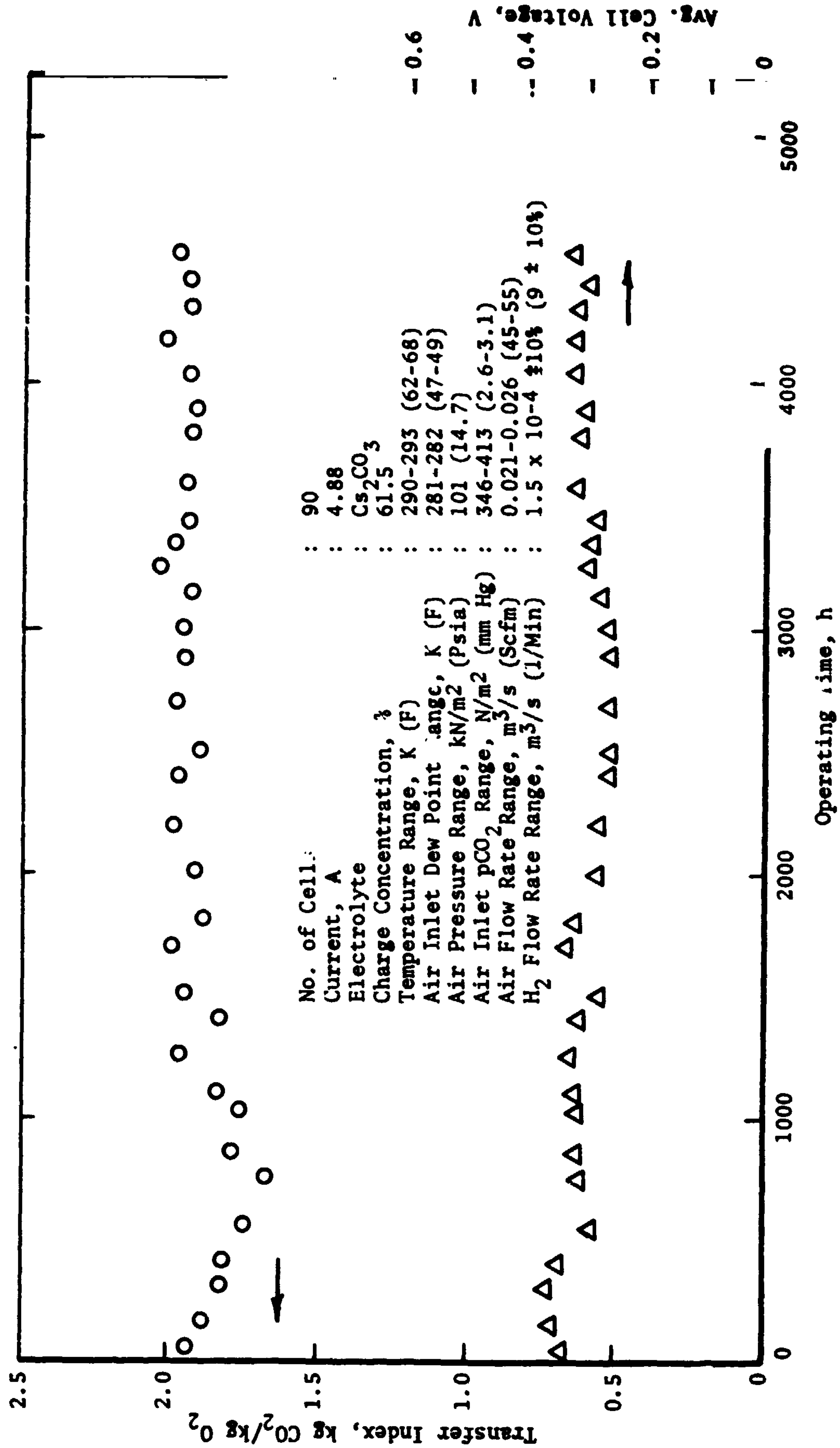


FIGURE 37 CX-6 180-DAY ENDURANCE TEST

Backpressure

To demonstrate compatibility of the CX-6 with the elevated anode exhaust gas backpressure of 31.0 kN/m^2 (>4.5 psig) required for SSP integration, the CX-6 was operated at increased backpressure levels for the last 1500 hours of testing. The backpressure was increased in three successive increments of 10.3 kN/m^2 (1.5 psig) each. A total of 220, 190 and 1100 hours of operation were accumulated at 10.3, 20.6 and 31.0 kN/m^2 above ambient (1.5, 3.0 and 4.5 psig), respectively. The increase in cell voltage shown near the 3000 hour time period is due to the increased anode gas backpressure. As expected, no effect on TI due to backpressure was noticed.

Insitu Cell Maintenance

During the endurance testing the insitu maintenance concept of individual cells was successfully demonstrated. Six cells were electrically isolated while physically remaining within the electrochemical modules and exposed to all process gas streams. The cells were electrically reconnected in pairs after 324, 811 and 3377 hours, respectively. Higher than average cell voltages were experienced immediately after reconnection with average levels reached within less than 100 hours.

Shutdowns

A total of 29 automatic shutdowns were experienced during the 189 days of endurance testing. Table 16 lists the shutdown cause, the frequency and the number of shutdowns attributable to a specific cause. The manual shutdowns at test termination and at the polycarbonate replacement are not included in Table 16.

The longest uninterrupted operating span was 29 days, being terminated by a loss of building electrical power.

OXIDIZABLE CONTAMINANT REMOVAL SUBSYSTEM

The OCRS is a self-contained subsystem designed with a capacity to remove oxidizable trace contaminants from the atmosphere of a six-man regenerative life support system. The major components are a catalytic oxidizer, two acid gas-sorbent canisters, an ammonia-sorbent canister, a blower and control and monitoring instrumentation. These components are packaged into an easily maintainable, compact subsystem (Figure 38). The OCRS operates in parallel with the CX-6 through the cabin simulator tank of the ASU. A Trend and Fault Analysis Display Panel is provided using PC cards common with those of the CX-6.

Figure 39 is a block diagram of the OCRS.

Process Description

A centrifugal blower circulates ambient air through the subsystem at a rate of 4.72×10^{-3} m^3/s (10 scfm). Downstream of the fan the flow passes through two prefilter beds before entering the catalytic oxidizer. These prefilter beds are

TABLE 16 CX-6 ENDURANCE TEST SHUTDOWN CAUSE SUMMARY

	Cause	Frequency	Shutdown Number
1.	Loss of building power[a]	4	2,17,28,29
2.	Operator error	1	13
3.	Failure of GSA	19	1,3,4,5,7,8,9 12,14,15,16 18,21,22,23 24,25,26,27
4.	Electronic component malfunction[b]	4	10,11,19,20
5.	Mechanical component malfunction[c]	1	6

(a) Duration of building power loss exceeded GSA backup capability.
(b) Includes failure of two thermistors, one voltage operation-amplifier and one temperature shutdown circuit component.
(c) Includes failure of one hydrogen flow and distribution block.

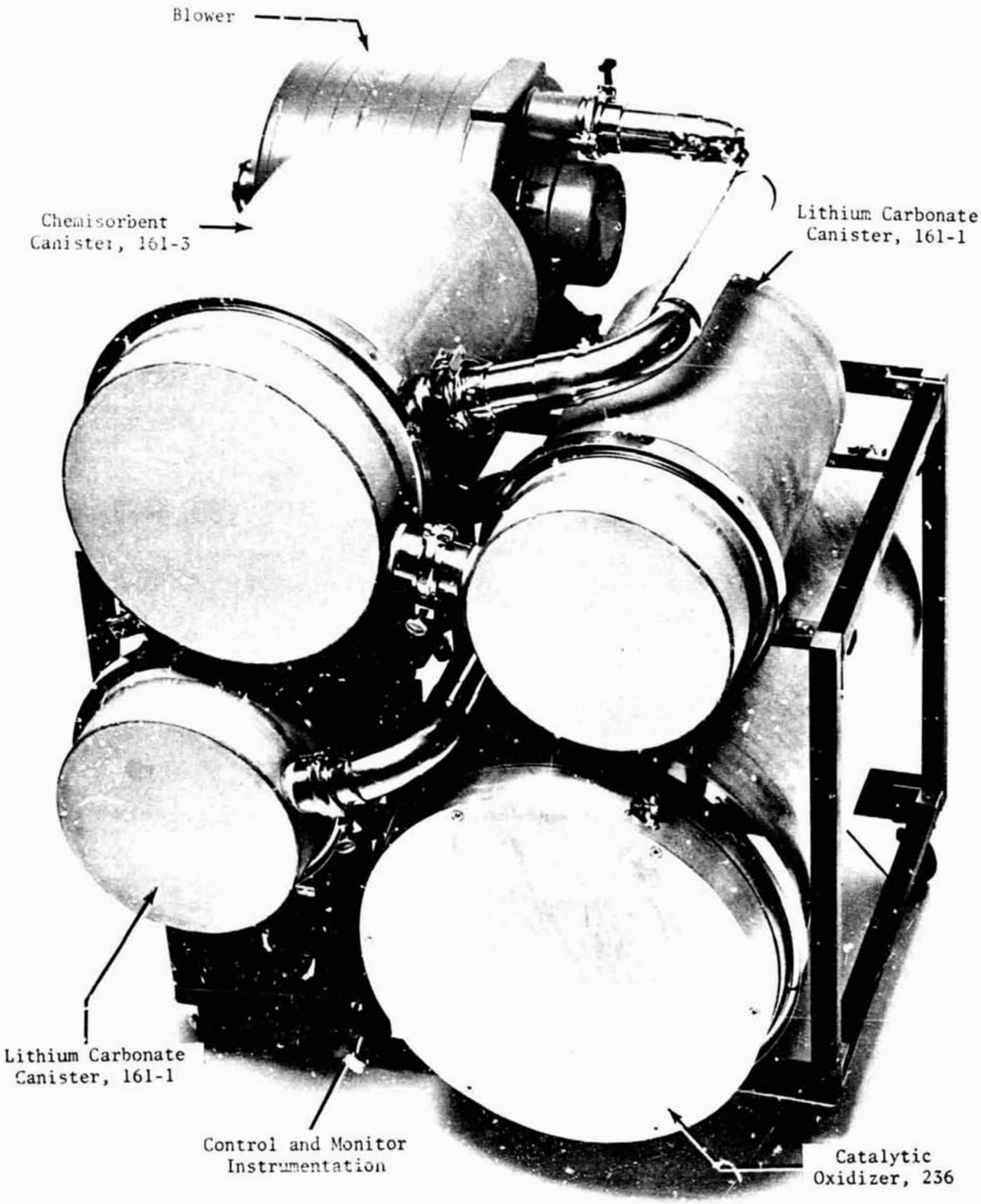


FIGURE 38 OXIDIZABLE CONTAMINANT REMOVAL SUBSYSTEM

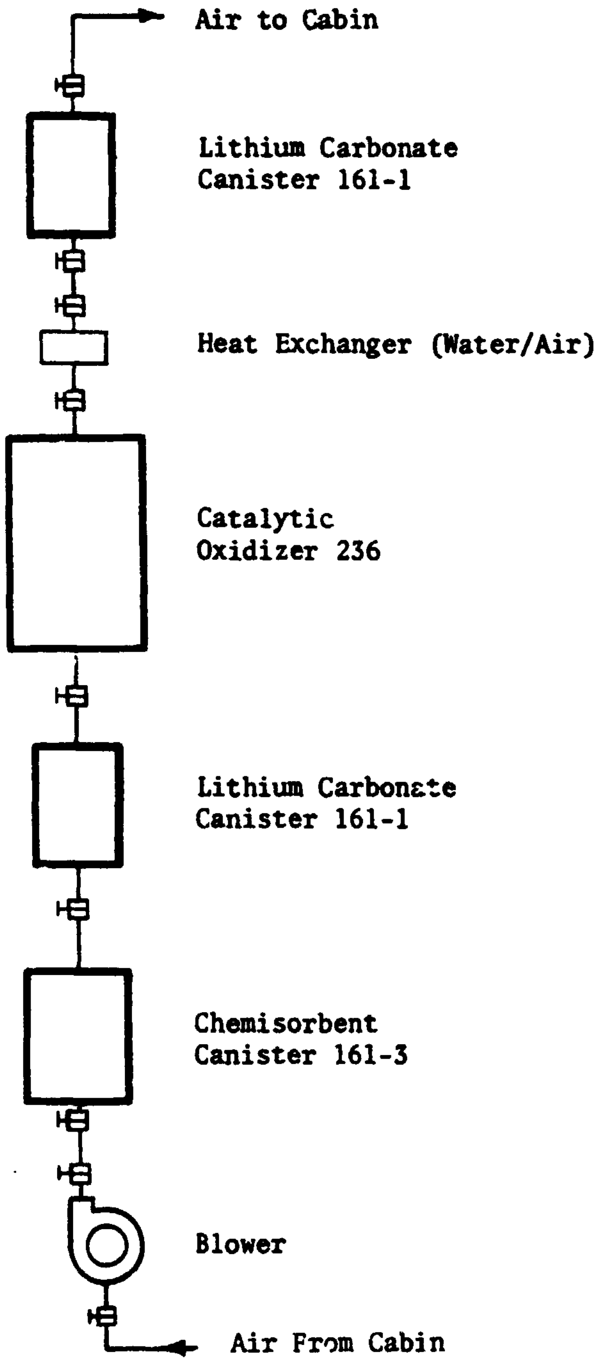


FIGURE 39 OXIDIZABLE CONTAMINANT REMOVAL SUBSYSTEM BLOCK DIAGRAM

used to remove contaminants that would poison the catalyst within the oxidizer. The first prefilter bed or chemisorbent canister contains sorbeads coated with copper sulfate to absorb trace ammonia from the process air. The second prefilter bed contains lithium carbonate to remove trace acid gases. This canister was initially charged with lithium hydroxide. During operation lithium carbonate is formed by the reaction of CO_2 in the process air with the lithium hydroxide. Within the catalytic oxidizer air is passed through the cold side of the regenerative heat exchanger where it is preheated by the hot outlet gas. An electrical heater further raises the gas temperature to the required reaction temperature of 644K (700F). Gas then passes through the catalyst bed where contaminants are oxidized. The exiting gas is cooled to 394K (250F) in the incoming regenerative heat exchanger and to 294K (70F) in a compact water air heat exchanger located just outside the catalytic oxidizer.

A postsorbent bed of lithium carbonate (CO_2 neutralized lithium hydroxide) downstream of the catalytic oxidizer absorbs possible undesirable products of combustion.

Hardware Description

The OCRS hardware consists of three canisters, catalytic oxidizer, blower, liquid/air heat exchanger and control and monitoring instrumentation. The overall size of the subsystem is 71.1 cm (28 in) high, 63.5 cm (25 in) wide and 63.5 cm (25 in) deep.

Canisters

The chemisorb and the two lithium carbonate canisters are of axial flow design and fabricated from aluminum with Teflon-coated interiors. Each canister contains a 2-micron Teflon filter at each end of the sorbent bed. Quick-connect inlet and outlet flanges are used. Both flanges are located near the front of the canister such that each canister can be removed and replaced from the front of the subsystem. The two lithium carbonate canisters were designed to be interchangeable to minimize spares requirements.

Catalytic Oxidizer

The catalytic oxidizer's primary components are a regenerative heat exchanger, an electric air heater and a catalyst bed. Figure 40 shows a functional schematic of the oxidizer. The heat exchanger is a five-pass, finned tube design. The materials of construction were nickel and 300 series stainless steel.

A 1000-watt, cartridge-type heater with an Incoloy sheath is used. The catalyst bed is made up of 0.32 cm (0.125 in) pellets of 0.5% palladium on alumina. The interior of the catalytic oxidizer is insulated with flexible insulation which reduces heat losses and maintains the exterior aluminum shell surface temperature below 322K (120F).

Blower

The OCRS blower is a seven-stage centrifugal type and is driven by a directly coupled induction motor. The blower is foot-mounted and has quick-release

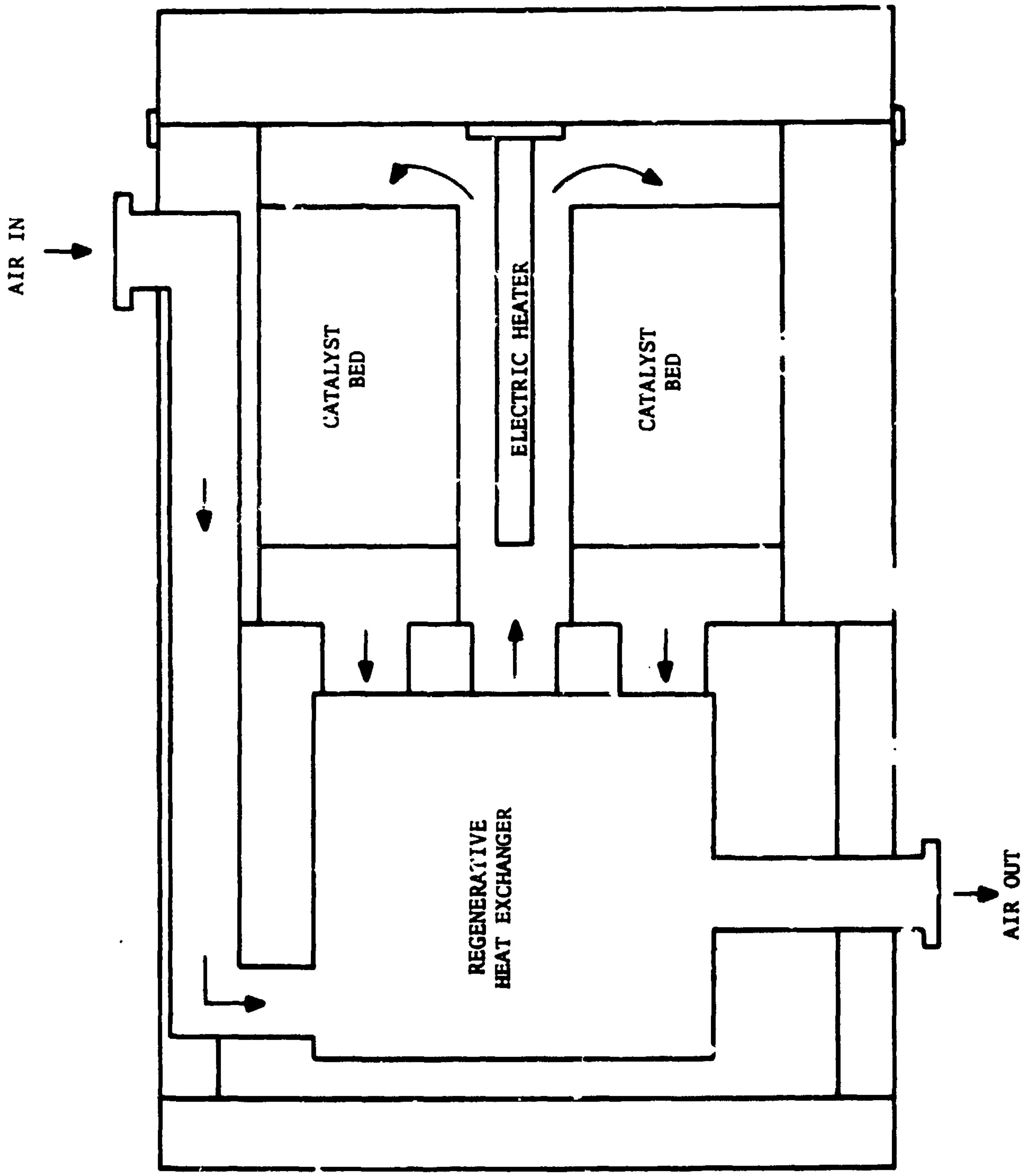


FIGURE 49 CATALYTIC OXIDIZER SCHEMATIC

flanges for the process air connections.

Heat Exchanger

The liquid/air heat exchanger is a compact, finned tube heat exchanger modified for the OCRS application.

Control and Monitoring Instrumentation

The control and monitoring instrumentation uses PC cards common to the CX-6.

The control instrumentation uses a closed-loop control to maintain the catalyst bed at 644K (700F). The air temperature is sensed at the bed inlet to provide the control signal for the On/Off heater control.

The monitoring instrumentation monitors subsystem parameters, displays their relative values on the Trend and Fault Analysis Panel of the OCRS and where necessary, sends a shutdown signal to the control instrumentation if a critical parameter is at an out-of-tolerance level.

The parameters monitored are blower speed, air flow rate, heater temperature (high), catalyst bed temperature (high or low) and regenerative heat exchanger temperature (high). For a high heater and catalyst bed temperature, the subsystem is automatically shut down.

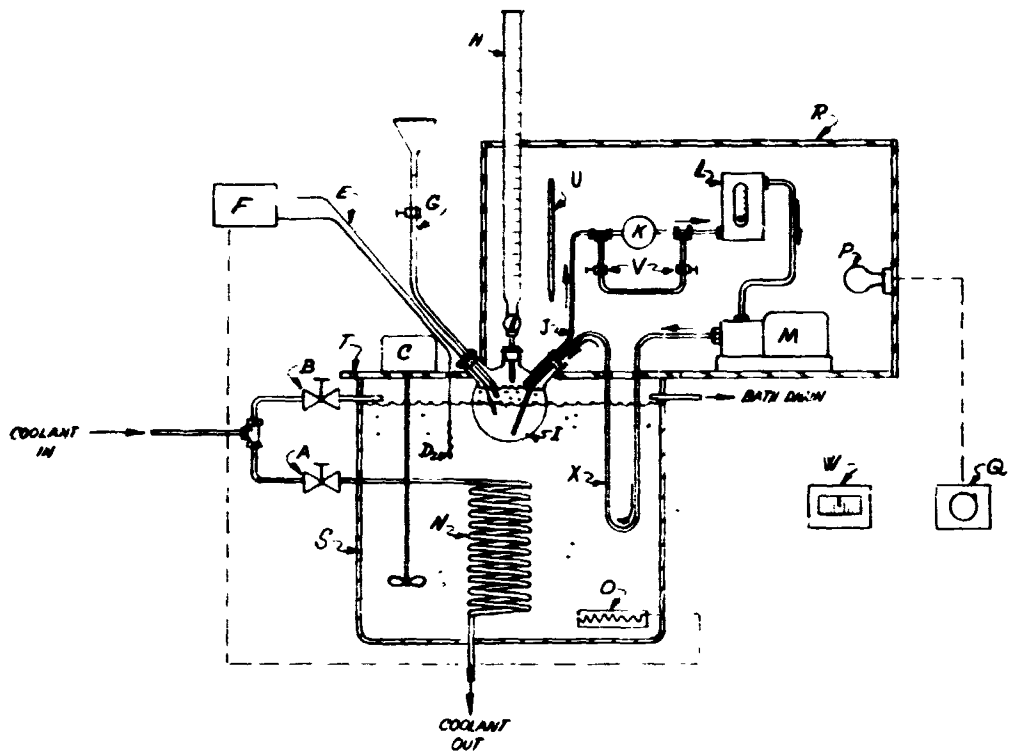
The monitoring instrumentation of the OCRS can interface with the BIC of the CX-6 to automatically identify malfunctioned PC cards. This information is displayed on the Trend and Fault Analysis Panel of the OCRS.

PARALLEL TECHNOLOGY PROGRAM

Several tests, studies, and analyses were completed to support the development of the CX-6 and CO_2 concentrator technology. These activities included determination of the water vapor pressure of aqueous solutions of Cs_2CO_3, a 245-day endurance and SSP support test of a three-cell submodule, a parametric post-endurance test program on the one-man CO_2 concentrator subsystem (CX-1), development of a fault prediction concept, design and fabrication of a process efficiency (CO_2 removal) computer, evaluation of a process air humidity exchanger, studies to identify the use of the CO_2 concentrator generated electrical power, and the development of a humidity controller.

Cesium Carbonate Water Vapor Pressure Determination

An experiment was completed to measure the water vapor pressure above aqueous solutions of Cs_2CO_3 for 30 to 70% Cs_2CO_3 by weight over a temperature range of 283 to 305K (50 to 90F). Figure 41 shows the test apparatus used in the vapor pressure measurements. The solution was held in a three-neck flask for temperature monitoring, circulation of the vapor above the solution and the addition of distilled water. Distilled water used to dilute the Cs_2CO_3 mixture was added insitu so the flask would not have to be removed from the test setup to change



LEGEND

(A) VALVE-COOLANT IN
(B) VALVE-BATH WATER IN
(C) AGITATOR
(D) THERMOCOUPLE CONNECTED TO "F"
(E) THERMOCOUPLE OR THERMOMETER
(F) OGDEN TEMPERATURE CONTROLLER
(G) TYGON TUBING W/CLAMP & FUNNEL
(H) 50 ML BURRETTE
(I) 500 ML 3 NECKED FLASK
(J) AIR OUTLET FROM FLASK
(K) DEW POINT SENSOR CONNECTED TO MODEL 880 HYGROMETER
(L) NEEDLE VALVE FLOW CONTROL
(M) DIAPHRAM PUMP
(N) 20 FT, 1/4 DIA COPPER TUBING
(O) HEATER COIL
(P) LIGHT BULB
(Q) POWERSTATT
(R) PLEXIGLASS BOX
(S) BATH
(T) PLEXIGLASS COVER
(U) THERMOMETER
(V) TYGON TUBING W/CLAMPS
(W) MINI MITE TEMPERATURE READOUT
(X) AIR COOLANT LOOP
— — — ELECTRIC LINE

FIGURE 41 APPARATUS FOR WATER VAPOR PRESSURE MEASUREMENT

C-2

Cs_2CO_3 concentration. The Cs_2CO_3 solution was maintained at a constant temperature by emersing the flask in a constant temperature bath. The apparatus allowed the gas above the Cs_2CO_3 solution to be circulated at a controlled flow rate through the dew point sensor. The measurement apparatus was enclosed and a light bulb was used to maintain the temperature of the apparatus above that of ambient air to prevent condensation in the gas lines. As the gas was circulated, the dew point was measured to give the water vapor pressure above the solution. The results of the water vapor pressure measurements are shown in Figure 42.

Three-Cell, 245-Day Endurance and SSP Support Tests

The purpose of the test was to verify the changes made in baseline electrochemical cell design (from CX-1 to CX-6 baseline design) prior to testing the CX-6 subsystem. Testing included operation at both CX-6 and modified CX-6 (SSP) conditions. The latter was included to verify the operability of the CX-6 baseline cell at projected SSP operating conditions as early as possible in the development of the CX-6.

Test Hardware

A three-position (module or single-cell) test stand was designed and fabricated. Figure 43 shows a schematic of one of the three identical test setups provided by the test stand. The stand features independent cell and inlet air dew point temperature controls capable of supplying air and dew points as low as 278K (41F). The stand is equipped with a low-voltage shutdown circuit for cell protection.

A three-cell submodule having the baseline materials of construction (LSI baseline electrodes, asbestos cell matrix, nickel exmet gas compartment spacers, nickel cooling fins and polysulfone structural cell frames and cell humidifier housings) was used for the test.

Test Results

A 5874-hour (245 days) endurance test was completed. Figure 44 shows the TI and individual cell voltages as a function of time. Table 17 is a list of the shutdowns that occurred during the testing as indicated in Figure 44.

At 4028 hours the test stand was modified to run at SSP conditions (submodule temperature from 298.5 to 293K (78 to 68F), nominal). A drop in the individual cell voltages is noted and was expected since cell voltage is a function of operating temperature. The TI was unaffected by the change to SSP running conditions.

At 4820 hours the module was subjected to SSP support parametric tests which lasted for 307 hours, as referenced in Figure 44. At the conclusion of the parametric support tests the cell was returned to nominal SSP conditions for the remaining portion of the endurance test.

The purpose of the SSP support tests was to characterize concentrator performance over the range of SSP operating conditions. These tests provided specific operating data for expected ranges in air inlet dew point temperature, process air flow rate and current density.

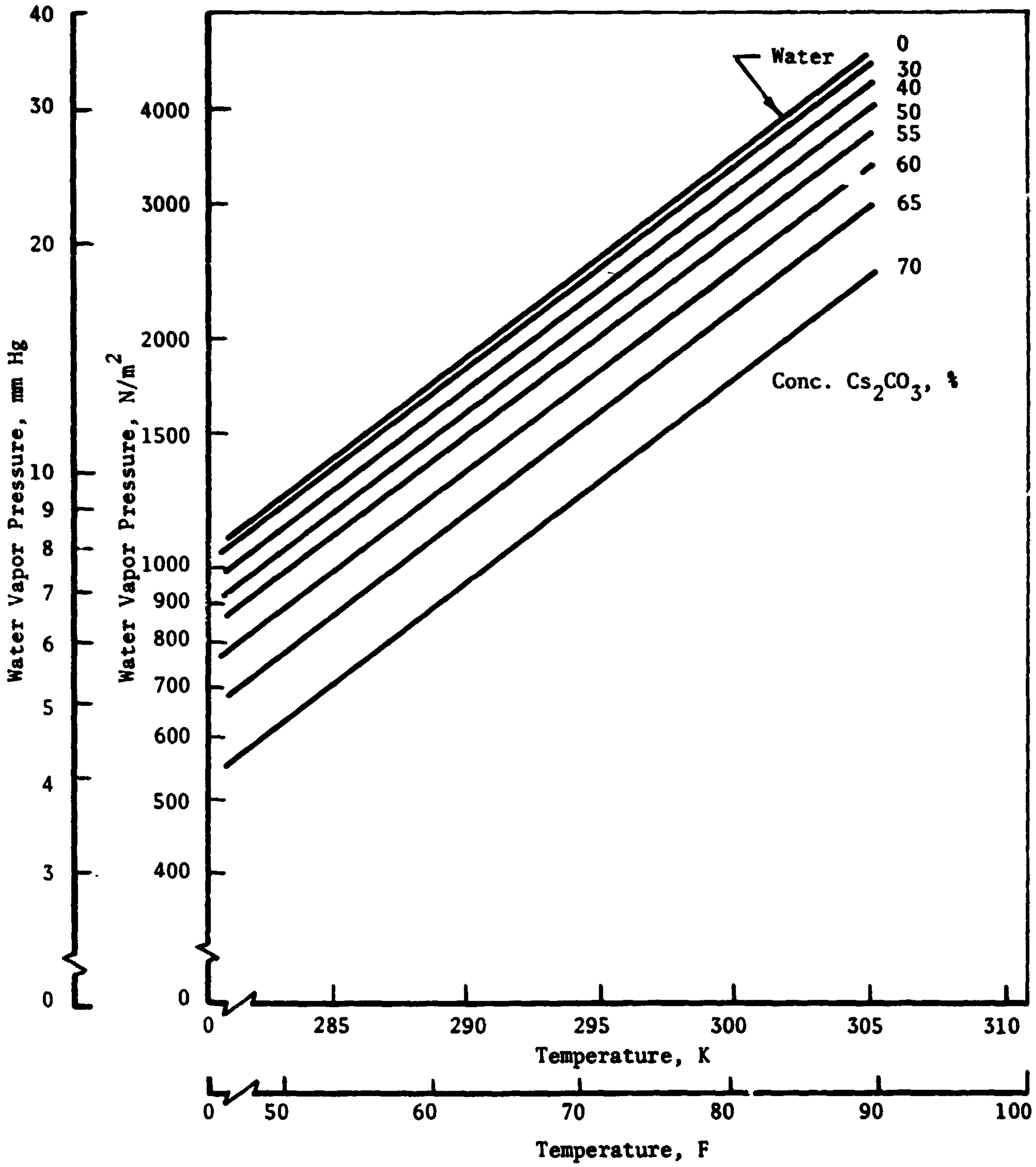


FIGURE 42 WATER VAPOR PRESSURE VERSUS TEMPERATURE FOR AQUEOUS Cs_2CO_3 SOLUTIONS

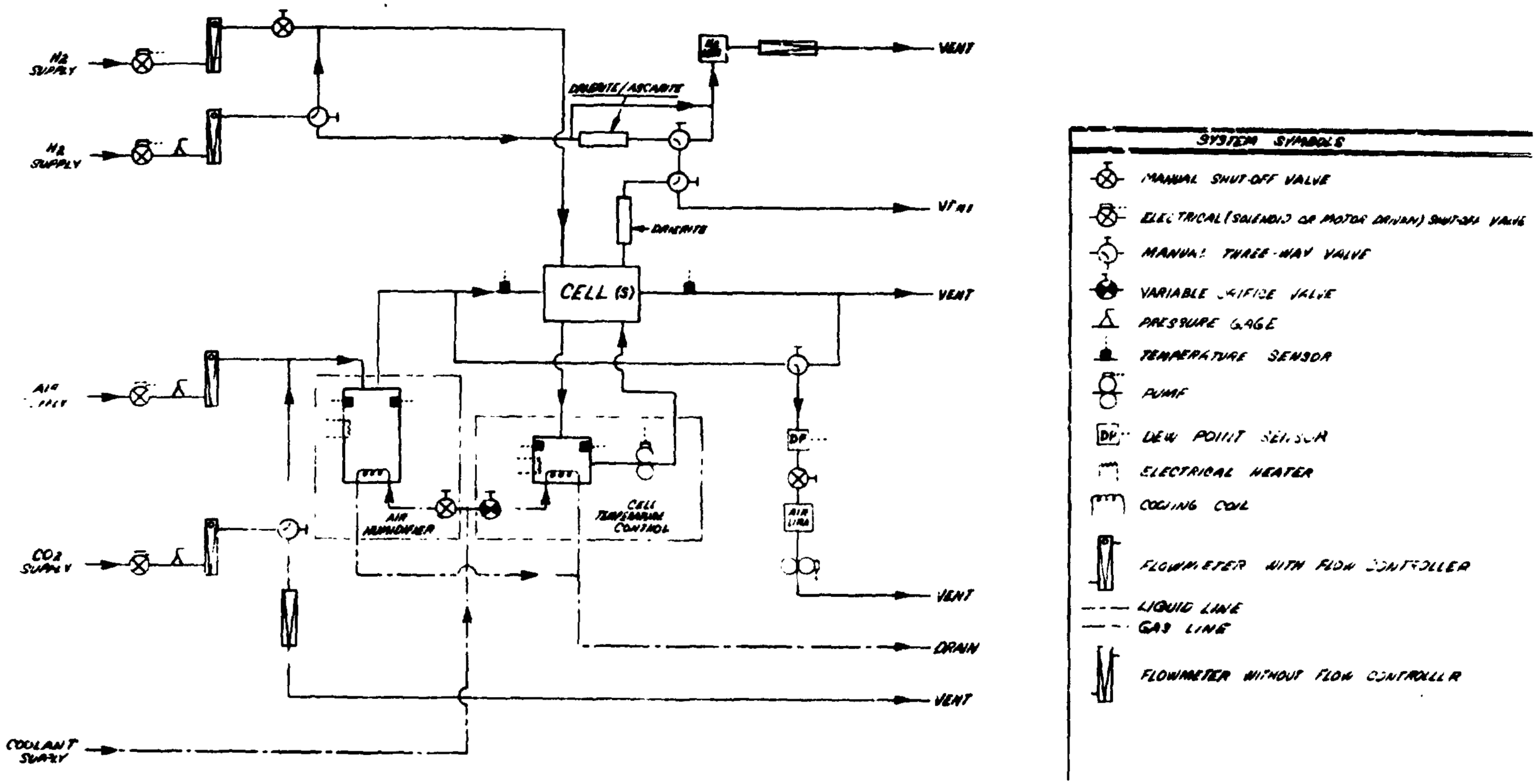


FIGURE 43 THREE-CELL ENDURANCE TEST SETUP SCHEMATIC

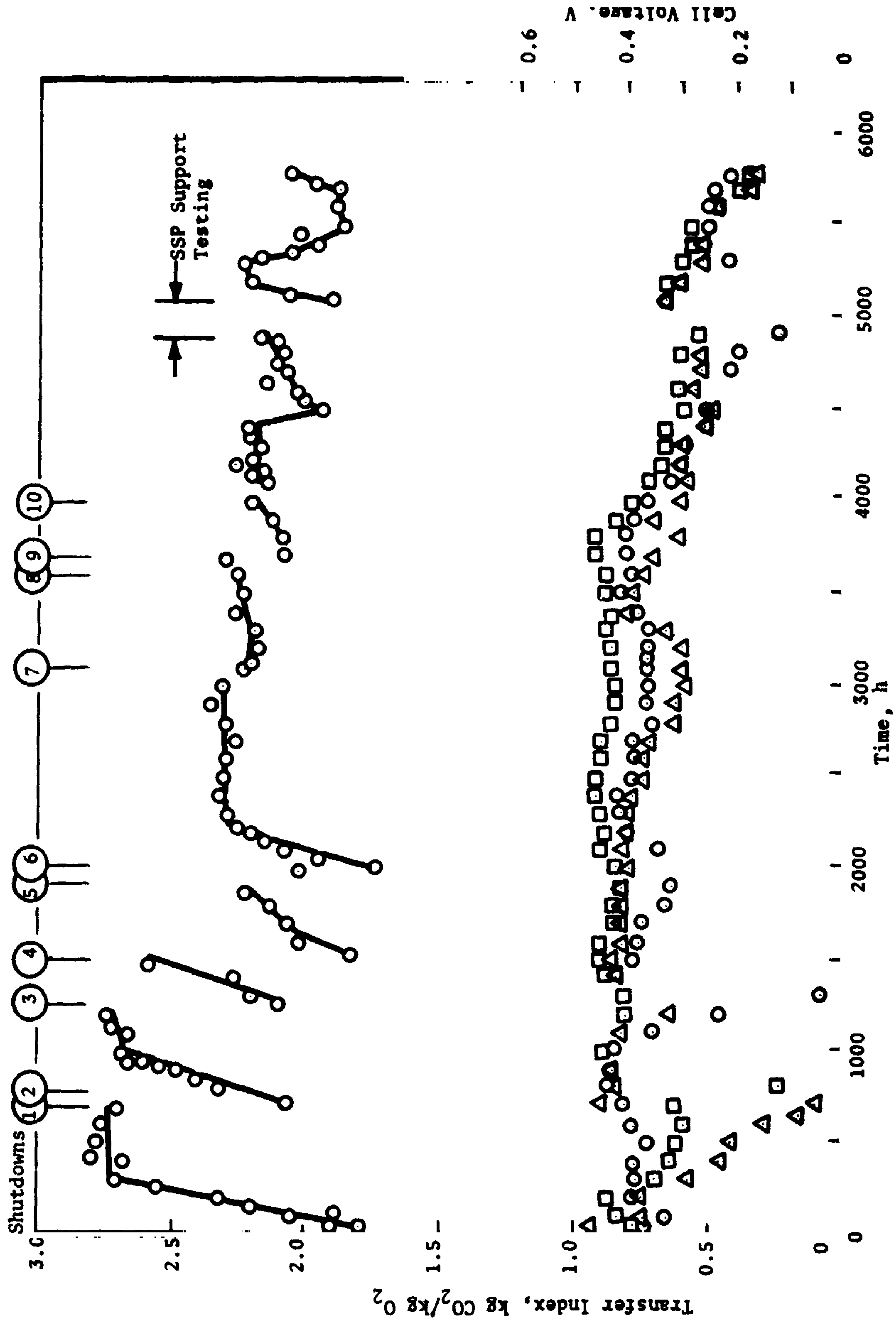


FIGURE 44 THREE-CELL ENDURANCE TEST

TABLE 17 THREE-CELL ENDURANCE TEST SHUTDOWN CAUSE SUMMARY

Cause	Frequency	Shutdown Number
1. Loss of building power	2	2, 5
2. Operator error	3	1, 3, 4
3. Conversion of cell frames from polycarbonate to polysulfone	1	6, 10
4. Failure of GSA	2	7, 8
5. Test stand modification for SSP operating conditions	1	9

Figure 45 shows that for the range of 278 to 284K (41 to 52F) in the air inlet dew point temperature the TI, as a function of inlet pCO_2 from 253 to 453 N/m^2 (1.9 to 3.4 mm Hg), falls within a narrow band (±1%). During this test the difference between module process air outlet temperature and air inlet dew point temperature was held constant at 11K (20F). Thus, the dew point temperature at a constant air inlet dew point to module temperature differential has essentially no effect on TI over the SSP operating range.

To investigate the effects of process air flow rate, tests were performed at current densities of 21.5 and 25.8 mA/cm^2 (20 and 24 ASF) for ratios of air flow rate per cell to current density of 1.30 x 10^{-5} $(m^3/s)/(mA/cm^2)$ (0.0256 scfm/ASF) and 1.58 x 10^{-5} $(m^3/s)/(mA/cm^2)$ (0.0311 scfm/ASF) over a range of pCO_2 from 267 to 400 N/m^2 (2.0 to 3.0 mm Hg). The results of these tests, shown in Figure 46, indicate that the air flow rate over the range investigated, has no significant effect on the TI.

In a third test, current density was varied from 17.2 to 30.1 mA/cm^2 (16 to 28 ASF) at a constant ratio of air flow rate per cell to current density of 1.41 x 10^{-5} $(m^3/s)/(mA/cm^2)$ (0.0278 scfm/ASF) over the pCO_2 range of 200 to 400 N/m^2 (1.5 to 3.0 mm Hg). Figure 47 shows the results of this test. The TI was above SSP design point at SSP operating conditions. Variations in TI were as expected for the range of pCO_2 and current density tested.

The test was operator-terminated after 245 days of operation (initial schedule called for only 209 days). The average TI during the test leveled off at approximately 2.20. The average cell voltage at CX-6 running conditions was 0.39 volts while for SSP operating conditions the average cell voltage was 0.25 volts.

CX-1 Post-Endurance Test Program

Five activities were carried out on the CX-1 (CO_2 Concentrator, Experimental, One-Man Subsystem) after the completion of initial parametric testing and a 180-day endurance test.(1)

Postparametric Testing

Three parametric tests to determine the effects of variations in H_2 flow rate, process air inlet pCO_2 and process air flow rate on module (15 cells) performance were conducted to evaluate CO_2 concentrator performance after long-term testing. Figures 48, 49 and 50 show the results of the tests. There was no degradation in CO_2 removal performance. A degradation in cell voltage of approximately 0.15 volts was observed for cell electrodes that had accumulated more than 6600 hours of operation.

CX-1 Disassembly and Inspection

A post-test evaluation to inspect the materials of construction and identify possible problems (such as duct blockage) that may have occurred during the 180-day endurance test was completed. No observable electrode degradation was

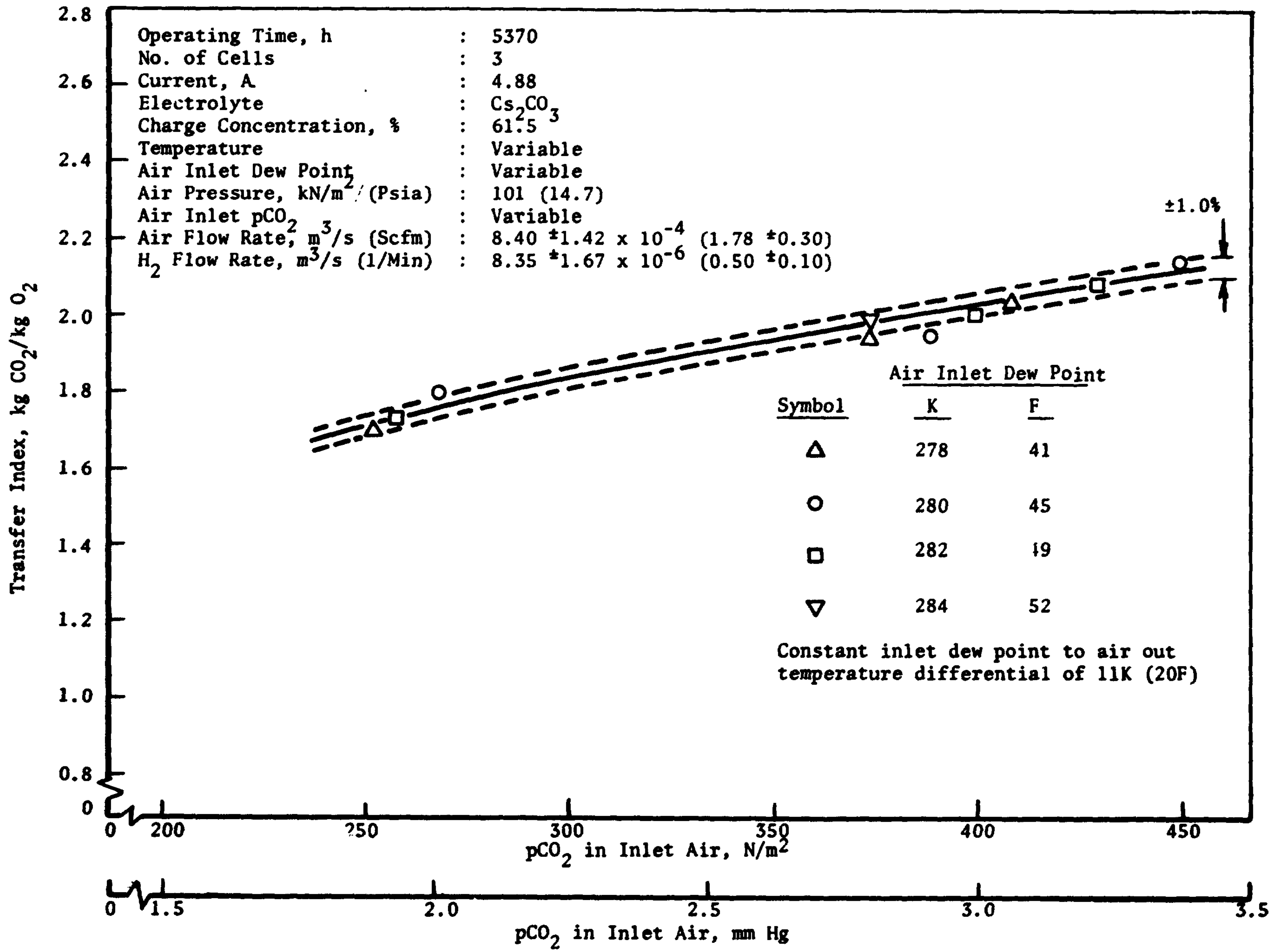


FIGURE 45 EFFECT OF TEMPERATURE ON THREE-CELL SSP MODULE

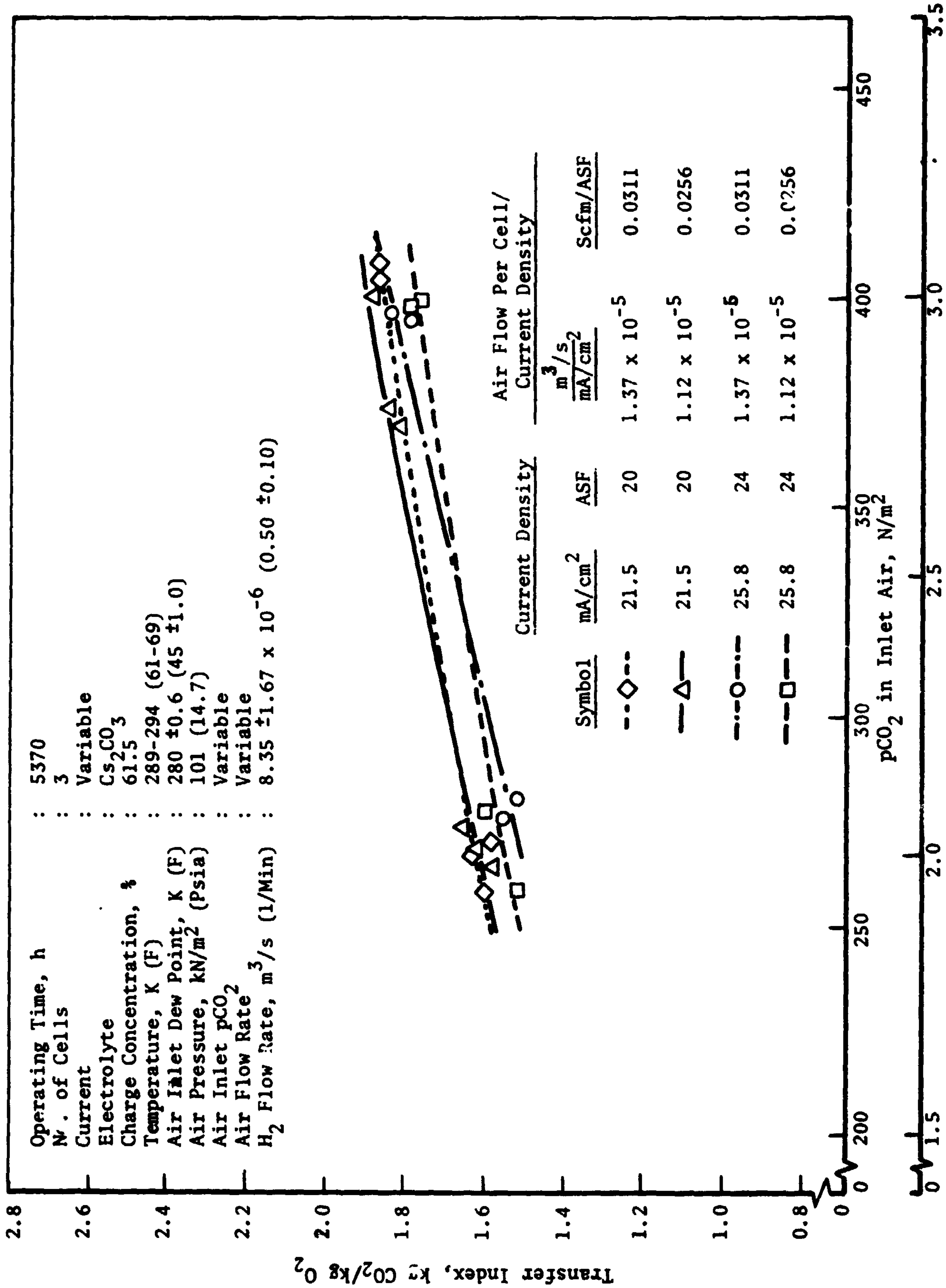


FIGURE 46 EFFECT OF PROCESS AIR FLOW RATE ON THREE-CELL SSP MODULE

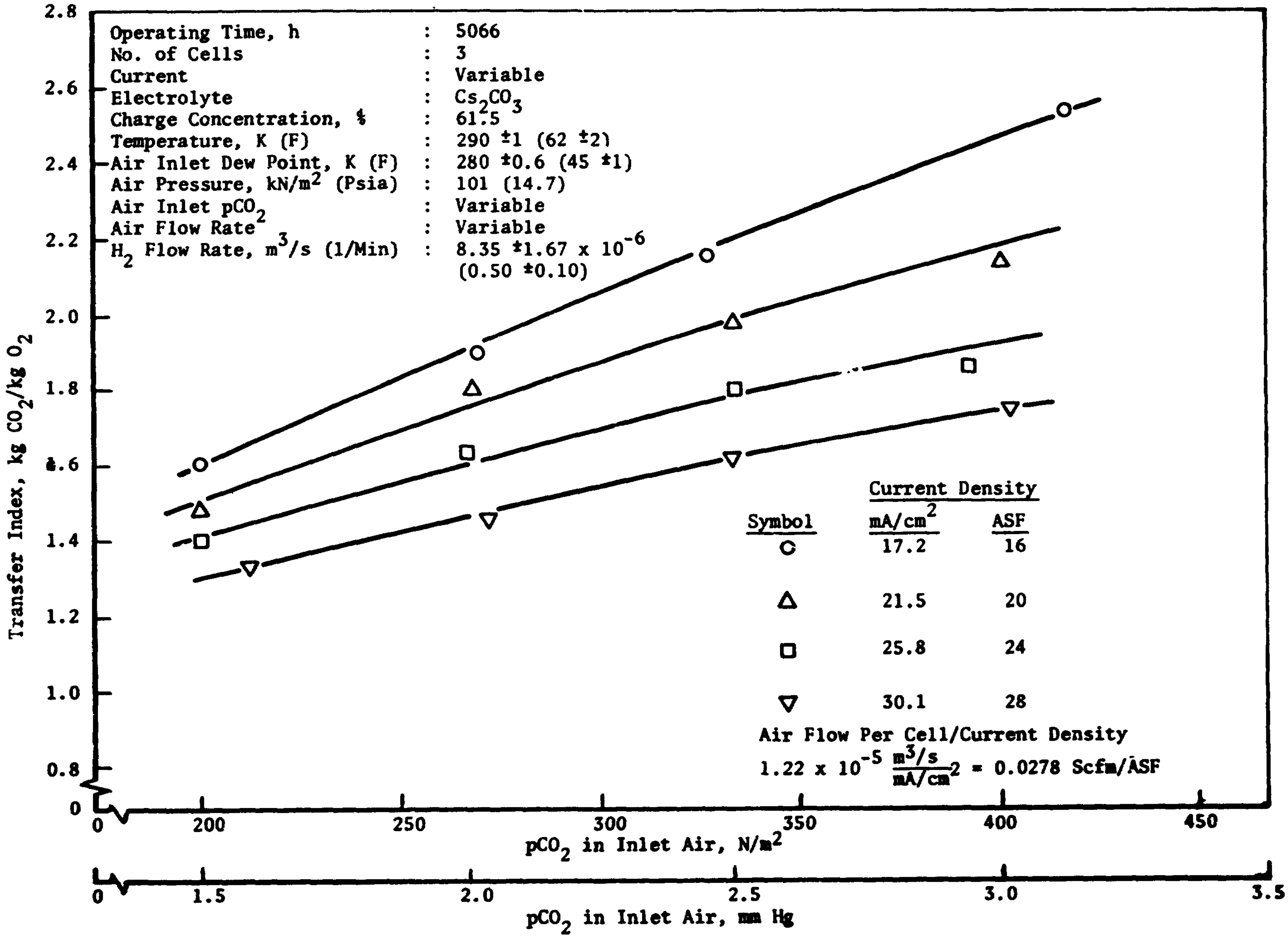


FIGURE 47 EFFECT OF CURRENT DENSITY ON THREE-CELL SSP MODULE

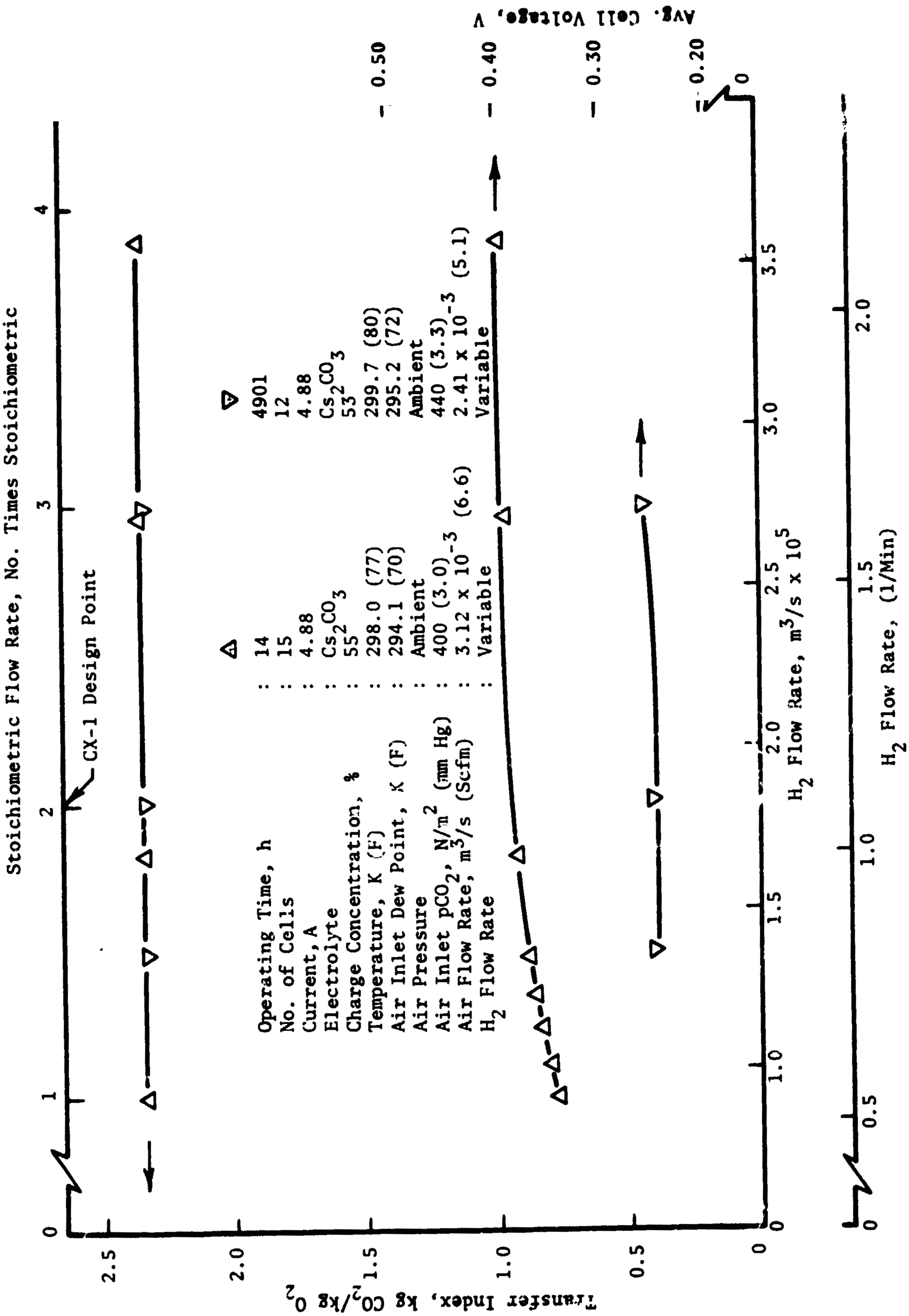


FIGURE 48 EFFECT OF H_2 FLOW RATE ON CX-1 PERFORMANCE (POST-PARAMETRIC TEST)

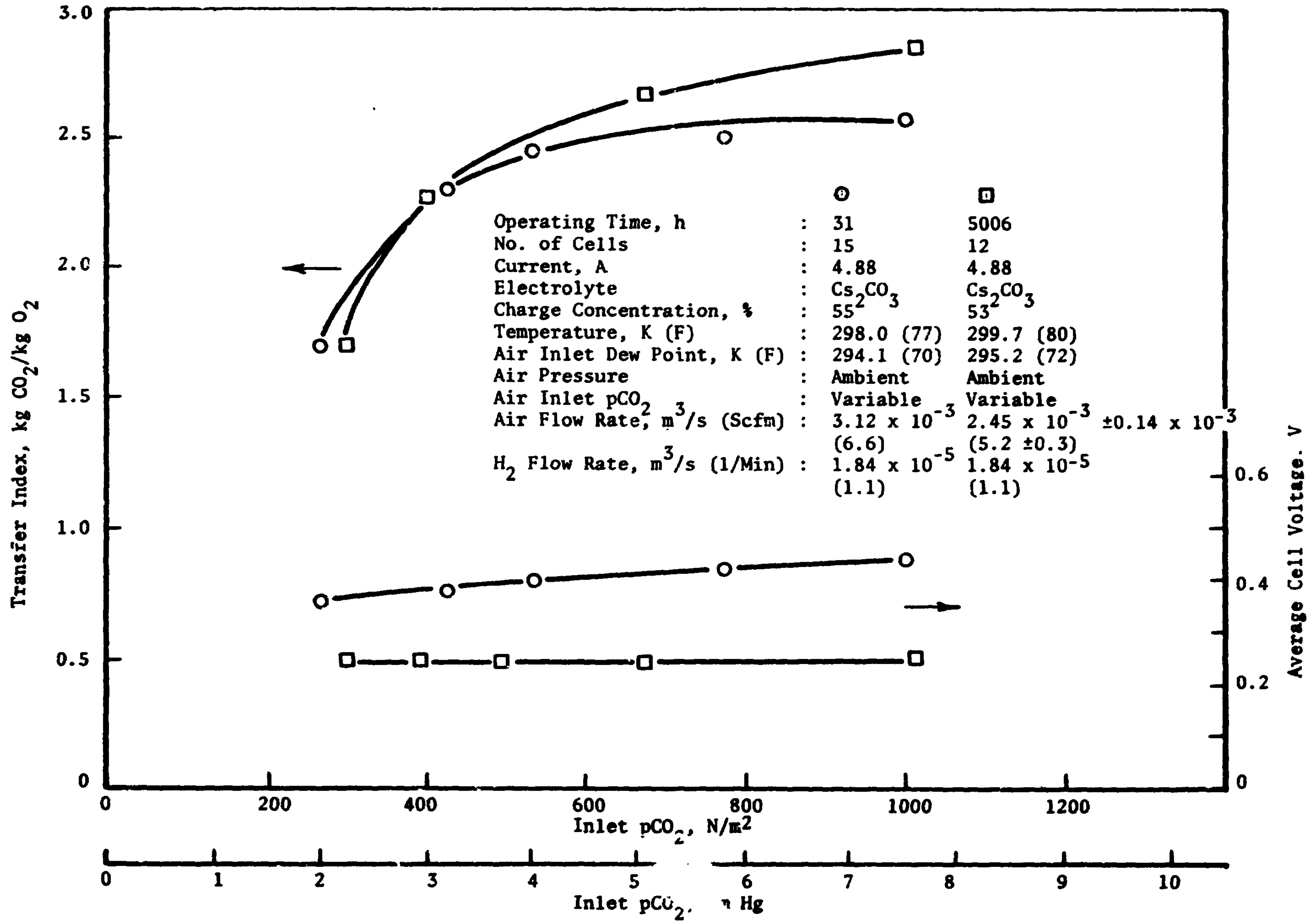


FIGURE 49 EFFECT OF pCO_2 ON CX-1 PERFORMANCE (POST-PARAMETRIC TEST)

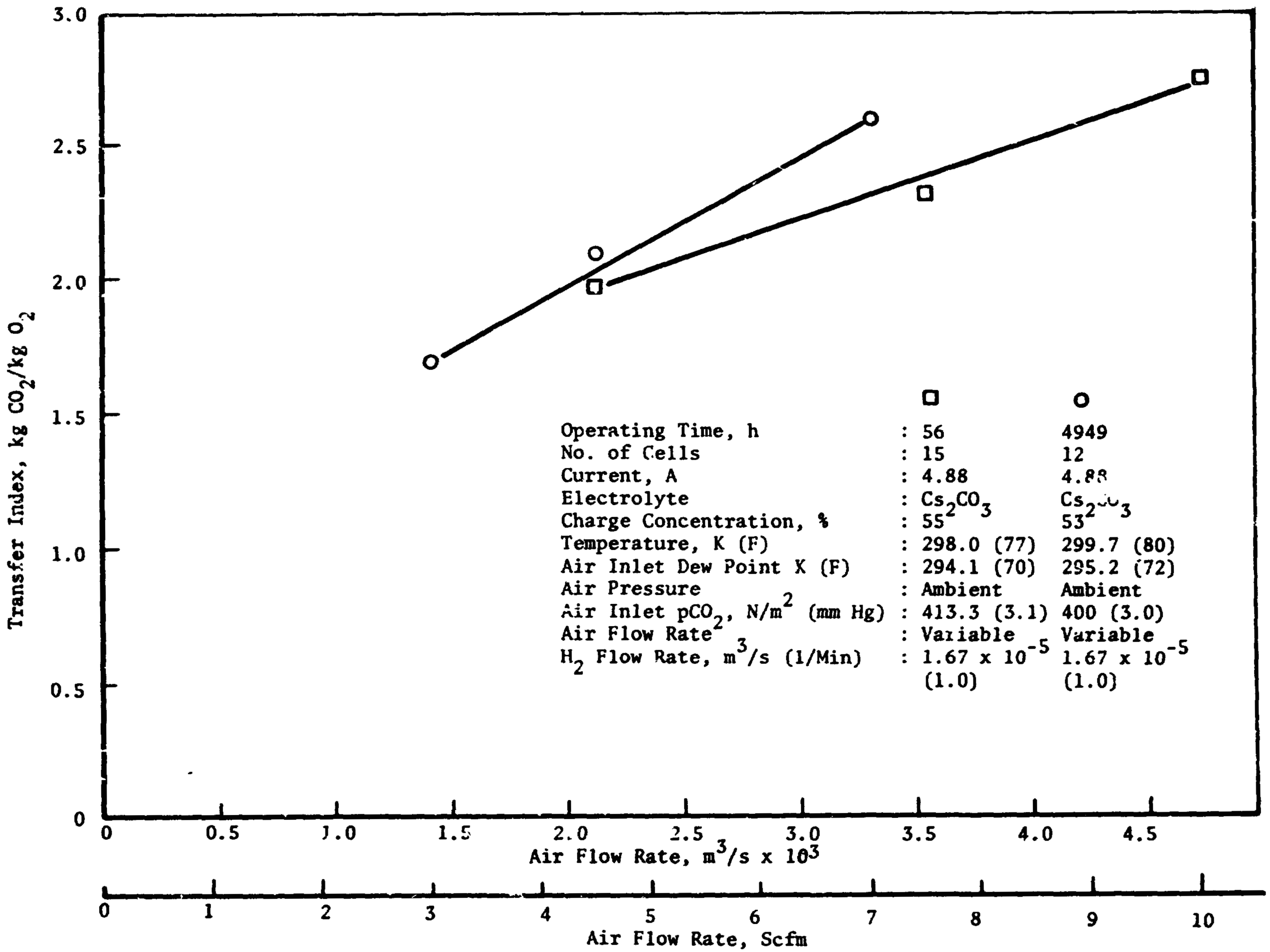


FIGURE 50 EFFECT OF AIR FLOW RATE ON CX-1 PERFORMANCE (POST-PARAMETRIC TEST)

found. Copper corrosion at the edges where the titanium cladding was bonded to the cooling fins was found. The module was reassembled with new matrices and the original electrodes, charged and performance shakedown tested to verify the module's operability. The shakedown test was successfully completed.

Effect of Process Air Inlet Dew Point

The effect of process air inlet dew point variations on module performance was determined following module reconditioning and shakedown testing. The CX-1 was operated with dew points 4.4 to 7.8K (8 to 14F) below the module operating temperature reflecting wet and dry operation (for an initial 53% Cs_2CO_3 charge).

Transfer Index increased from 2.15 to 2.32 and average cell voltage decreased from 0.33 to 0.27 volts as process air inlet dew point decreased from 4.4 to 7.8K (8 to 14F) (wet to dry) below module operating temperature of 299.7K (80F). Hydrogen inlet dew points of 233.0K (-40F) (dry H_2) and 294.1K (70F) had no observable effect on TI or average cell voltage. The H_2 flow rate for the test was 1.84×10^{-5} m^3/s (1.1 l/min).

Operation of Cells 1-8 and 8-15

The module was operated with cells 1 through 8 and then with cells 8 through 15 electrically connected. In both cases the remaining seven cells were still in the module with air and H_2 but no current passed through them. The purpose of the test was to determine the effect of cell location on CO_2 transfer.

To eliminate the effect of pCO_2 buildup in the series-connected anode gas compartments, both groups of cells were tested with and without CO_2 addition to the inlet H_2. For the cases where CO_2 was added the mixture ratio of CO_2 to H_2 simulated the exhaust from the first seven cells. Hydrogen flow was maintained at two times stoichiometric for eight cells (9.65 cm^3/s) and CO_2 addition was maintained at 7/15ths of one man's CO_2 production (2.98 cm^3/s). The results showed that for all cases tested there was no observable change in either CO_2 removal or electrical efficiency.

Cesium Carbonate Electrolyte Analysis

An analysis was completed of the Cs_2CO_3 electrolyte extracted from the cell matrices following the 180-day endurance test for nitrate and sulfate ions. These ions are products that would result from the adsorption of trace nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) contaminants in the process air feed. The analysis showed concentrations of 1.63 to 1.67 ppm nitrate ions and 83.0 to 85.0 ppm sulfate ions. These low concentrations indicated that NO_2 and SO_2 were not introduced either by the ambient air or as products of combustion from the catalytic oxidizer used during the 180-day endurance test.

Fault Prediction

A concept to predict impending failures or faults in an electrochemical module was developed and incorporated into the CX-1. The fault prediction concept is based on the general voltage/current curve for electrochemical power-producing cells. The polarization curves are divided into three polarizations: activation or catalyst oriented, concentration or mass transfer oriented and ohmic or electrolyte oriented. A general polarization curve is shown in Figure 51. Three tests are used in the fault prediction analysis (see Figure 51):

1. A test to continuously monitor the change in module voltage from startup indicating degradation in electrical performance caused by a change in module polarization

2. A test to monitor the electrical capacity of each individual cell once every 24 hours for a 15-minute test period indicating degradation in both ohmic and concentration portions of cell polarization

3. A test to monitor the module's internal resistance once every 15 minutes with a sampling time of less than 30 milliseconds indicating degradation in only the ohmic portion of the module's polarization.

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

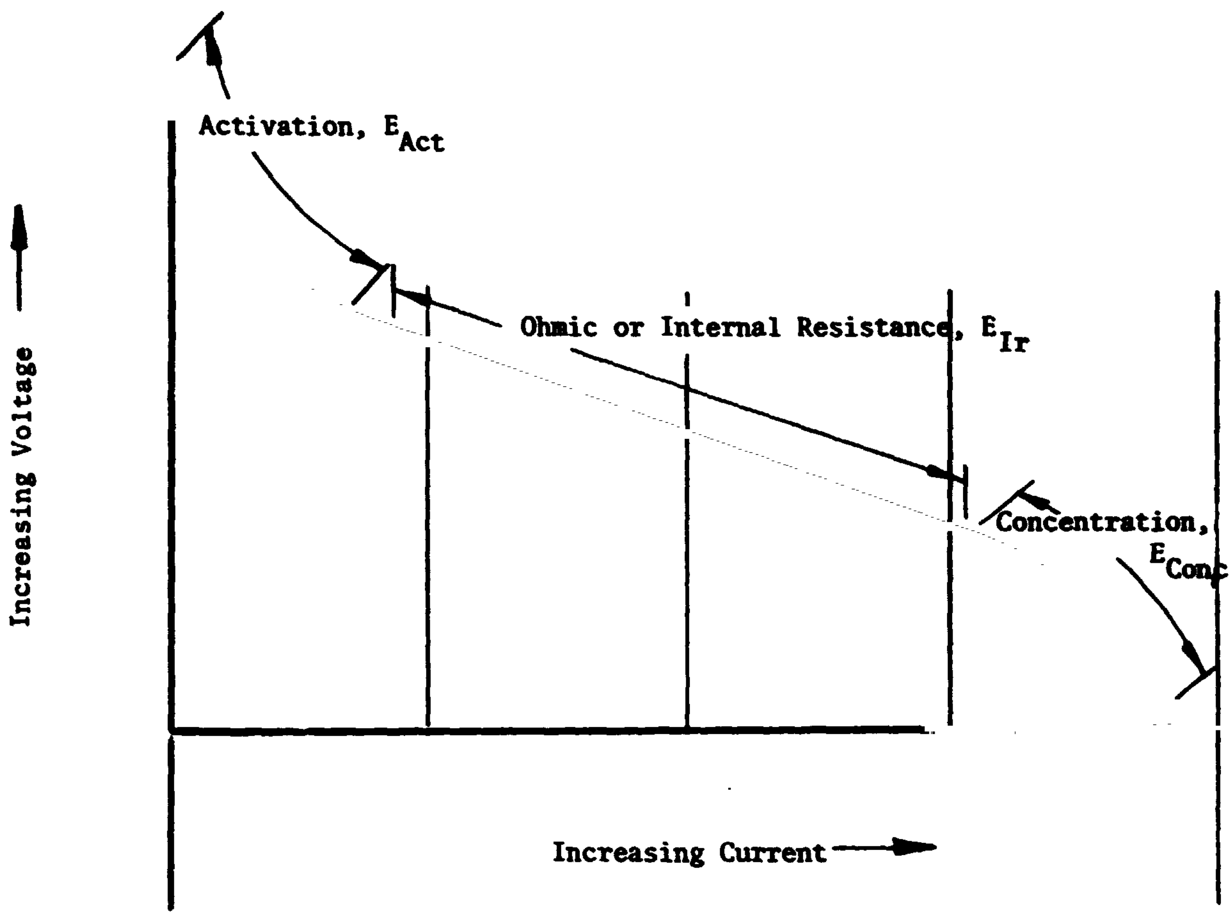
Module Voltage Change (Test No. 1)

This test monitors the change in module voltage and elapsed time (t) since system startup. It provides a direct readout of long-term changes in the three types of polarization: activation, concentration and ohmic as well as information necessary to determine the rate of change of this voltage.

The readouts for this test consist of a digital voltmeter and resettable timer. In order to display module voltage change on the digital voltmeter, a circuit has been included which automatically subtracts initial from present module voltage. Two zero buttons are operated when a module is put into service to set the initial module voltage and time at zero. From then on the change in module voltage is automatically tracked and displayed on the digital voltmeter.

Cell Moisture Balance (Test No. 2)

For 15 minutes once every 24 hours, module current is automatically increased to provide information about the cells' concentration and ohmic polarizations. An internal clock is provided which produces the automatic test sequence start signal. The test sequence consists of disconnecting the cell voltage scan from the normal trend analysis circuits and connecting them to a special test circuit which automatically monitors all cells and will cause a panel light to come on when a cell voltage drops below 0.1 volts. If, during the 15 minutes, any cell voltage drops below -0.1 volts, the test will be terminated immediately and



Fault Prediction Analysis

Test	Frequency	Relations	Fault Prediction Basis
1	Continuous	$E_{Init} - E_{@t}$	Life Trend, $E \propto E_{Act} + E_{Ir} + E_{Conc}$
2	15 Min/Day	$\Delta E_{Obs} - \Delta E_{Ref}$	Individual Cell Status, $\Delta E \propto E_{Ir}$ and E_{Conc}
3	<30 Ms/15 Min	$E_{@I} - E_{@2I}$	Module Trend, $\propto E_{Ir} \propto$ Moisture Balance

FIGURE 51 FAULT PREDICTION ANALYSIS CURVE

module current will be dropped to zero for approximately 30 seconds. The current will then be returned to its original pretest level. A red illuminated indication will be provided in the manual test-initiate pushbutton to indicate that a low cell voltage test termination had occurred. During the 15-minute test period a green light will be on in the manual test initiate pushbutton.

Module Resistance (Test No. -)

Once every 15 minutes for about 30 milliseconds a module-resistance test is performed automatically. This test provides a direct readout of module ohmic polarization on a digital readout.

The automatic start signal is generated by the internal clock. During this test, the module current is controlled by the test equipment. Module current is dropped to a low value and module voltage is read and stored. Next, the module current is increased to a high value and the new (lower) module voltage is read and subtracted from the previously stored low current module voltage. The difference is displayed on a LightEmitting Diode (LED) display. The voltage difference represents the change in module voltage caused by the programmed change in module current.

The whole test sequence takes less than 30 milliseconds with the majority of the time (26 milliseconds) reserved to allow module current to reach the desired value after each change is requested. Because of this very short test time, only module ohmic polarization voltage changes which respond instantaneously to current changes are measured and displayed. A manual Module Resistance test-initiate pushbutton is provided.

Instrumentation and Display

The fault prediction instrumentation package is shown in Figure 52. Figure 53 shows the front panel of the one-man system. The fault predicton display is contained in the upper right corner and consists of:

1. A digital voltmeter to read change in module voltage.
2. A zero pushbutton to zero the digital voltmeter reading after maintenance.
3. A resettable timer to monitor time since maintenance.
4. 15 cell status indicator lights.
5. Low cell voltage indicator light.
6. Provision for manually initiating the cell moisture balance test.
7. Moisture balance test indicator light.
8. A LED digital display to read change in module voltage during the module resistance test.
9. Provision for manually initiating the module resistance test.

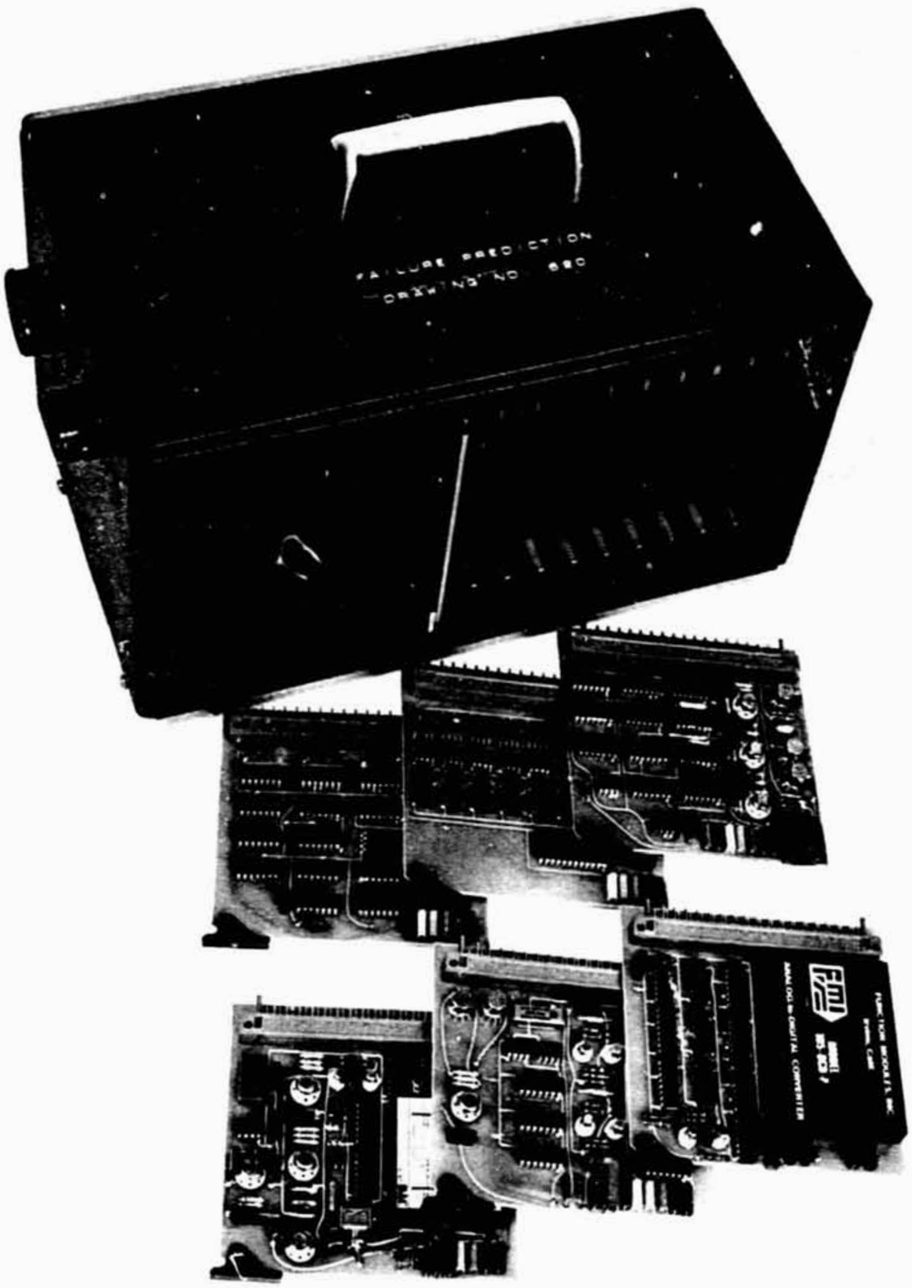


FIGURE 52 FAULT PREDICTION INSTRUMENTATION PACKAGE

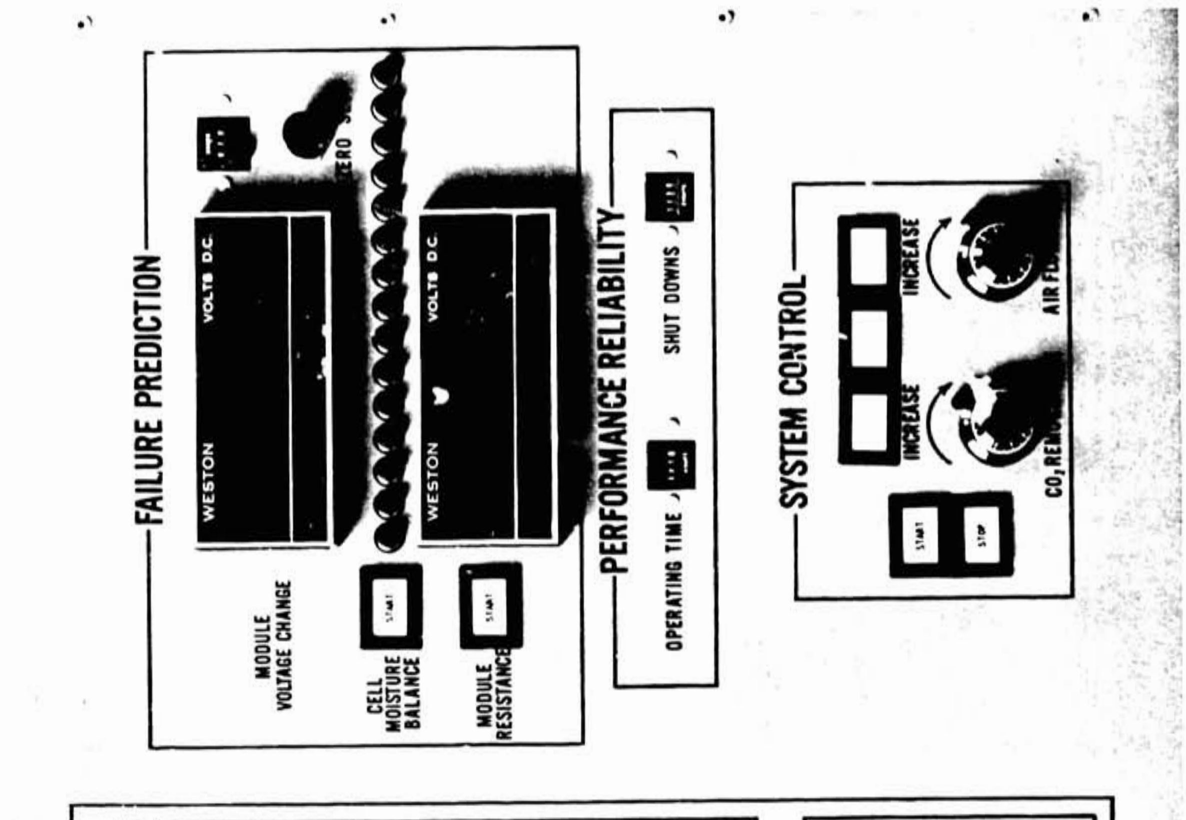


FIGURE 53 CX-1 CONTROL AND STATUS PANEL WITH FAULT PREDICTION

Fault Prediction Features

1. Operation is completely automatic.
2. Circuit cards are maintainable.
3. Information to determine long-, medium- and short-term effects in response to out-of-tolerance operating conditions on the electrochemical CO_2 removal module is provided.
4. Information which can be used to determine module expected life is automatically provided.
5. The output data can be used to correct operating conditions before module failure occurs to extend module operating life.
6. The moisture balance and resistance test currents are adjustable.
7. The concept can be adapted to other electrochemical devices.

Process Efficiency Computer

The function of the analog process efficiency computer is to provide a direct, instantaneous and continuous readout of subsystem CO_2 removal efficiency (TI). The TI calculation is based on the process air flow rate, inlet and outlet process air pCO_2 and the CX-6 submodule (15-cell) currents. Conditioned signals from the sensors that monitor these parameters are fed into the process efficiency computer where TI is calculated. A photo of the computer PC card is shown in Figure 54.

Humidity Exchanger Evaluation

A humidity exchanger was designed, fabricated and tested to remove moisture from the cathode air exhaust stream of a concentrator module and transfer it to the cathode air inlet stream. This module was constructed using two 0.076 cm (0.030 in) porous nickel placques separated by a 0.025 cm (0.010 in) asbestos matrix to provide sufficient differential pressure capability. Porous nickel alone would not support sufficient differential pressure to allow proper operation.

The tests showed that the humidity exchanger performed its function as expected. There would have to be one humidity exchanger cell per concentrator cell to properly condition the concentrator inlet air. This would result in a large humidity exchanger module which makes the concept unattractive.

Use of Concentrator Power

The power produced by the concentrator modules is converted into heat in all the CO_2 removal systems built to date. In spacecraft systems, power is usually a precious commodity. A double benefit will be realized if the power is used rather than wasted:

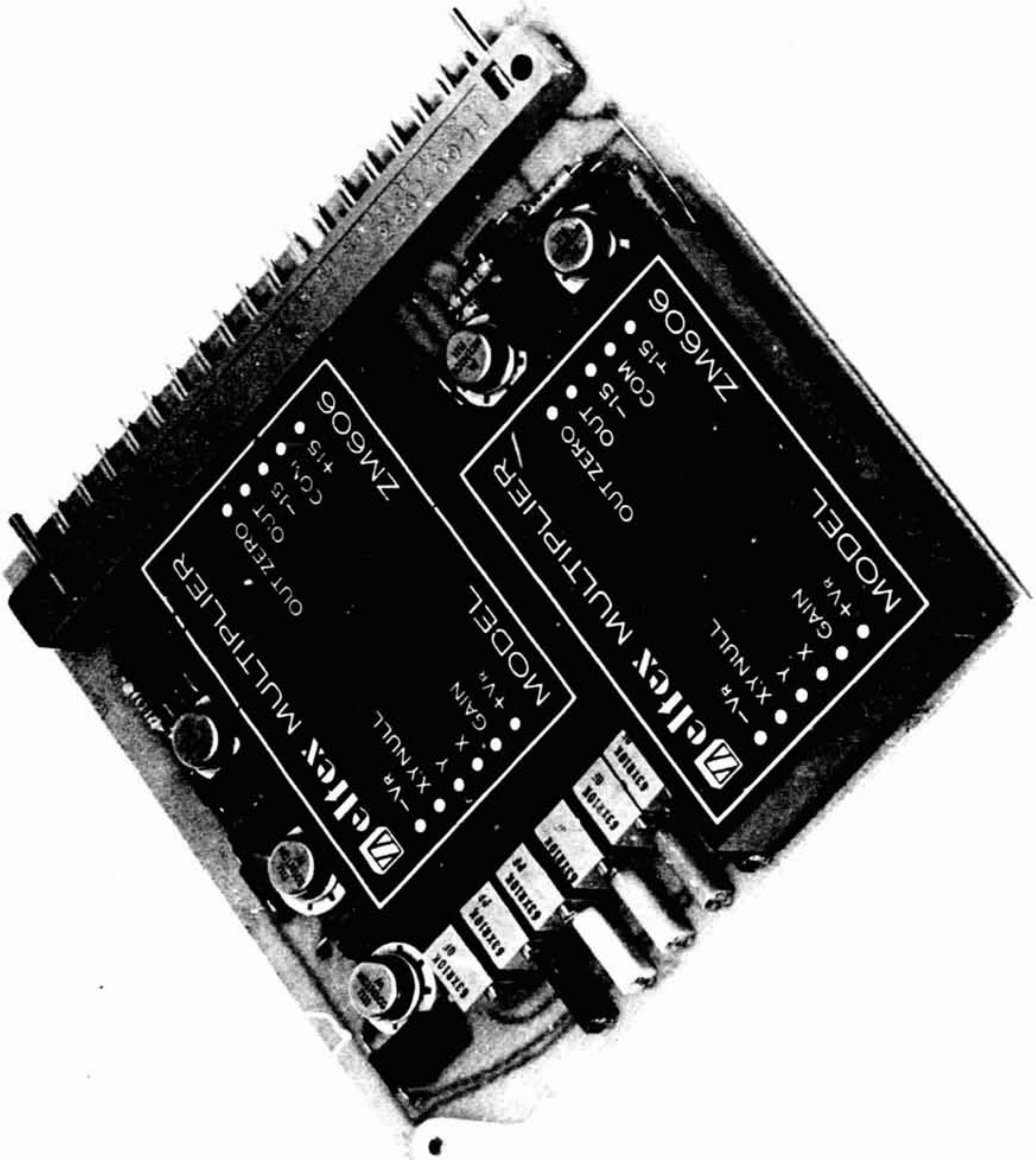


FIGURE 54 PROCESS EFFICIENCY COMPUTER PC CARD

1. The power provided by the concentrator reduces the power the spacecraft has to provide.

2. A reduction in cooling requirements for the subsystem will occur because of the reduced heat generation within the subsystem.

Each of the above produces an equivalent weight reduction in the spacecraft support subsystems. The CX-6 modules produce 154 watts of electrical (DC) power at nominal operating conditions. Assuming an 80% efficiency for the necessary conversion and interface equipment, 123 watts can be removed from the spacecraft power source requirements which saves 33.1 kg (73 pounds) at 0.268 kg/W (0.591 lb/watt) in equivalent weight and the same amount of power does not contribute to the atmospheric heat load for an additional savings of 24.5 kg (54 pounds) at 0.197 kg/W (0.435 lb/watt) in cooling equipment. The conversion and interface equipment will weigh less than 4.5 kg (10 pounds). The net system savings would then be more than 53.1 kg (117 pounds).

General Concepts For Using Concentrator Power

Two basic approaches are available for the use of the module power:

1. Use it to power some small device in the subsystem.

2. Add its power to the main power being fed to the concentrator subsystem.

In either case, the concentrator power has to be backed up by spacecraft power because the concentrator may be off at some time during its operation. Also, because of concentrator load requirements and power characteristics, some form of power conditioning with isolation must usually be used between the concentrator and the load.

Both of the above approaches can be accomplished by series or parallel methods (i.e., series means adding the voltage from the concentrator to the spacecraft voltage and parallel means adding the currents). In order to determine which approach to take a complete analysis of the specific application must be made. This study should include evaluation of the following.

1. What device (or total subsystem) to be powered.

2. Series or parallel methods.

3. Variation in concentrator power (voltage variations as well as load current variations).

4. Efficiencies of the DC/DC converter and power control needed between the concentrator modules and the load being powered.

5. Weight added compared with weight saved.

6. Reliability.

7. Spares.

Although the idea of wasting power (i.e., converting it to heat) is basically opposed to normal procedures in spacecraft designs, care must be taken to be sure that the use of this power results in a true system savings when the overall picture is analyzed.

Humidity Controller

The modules used in electrochemical CO_2 concentrating subsystems such as the CX-1, CX-6 and CS-6 require proper moisture balance to prevent cell flooding or dry out. An electronic circuit was designed, fabricated and tested with the CX-1 subsystem which provided automatic control of module moisture balance. The control operates to maintain a constant temperature difference (ΔT) between the dew point temperature (DPT) of the incoming process air and the dry bulb temperature (DBT) of the process air leaving the module.

Figure 55 is a functional block diagram of the humidity control system.

The DPT signal from dew point sensor DP1 is added to a ΔT signal from manual set point potentiometer P1. This sum DPT + ΔT is compared with the DBT signal from temperature sensor TS1 and used to control the cooling blower such that if DBT is above DPT + ΔT, the blower is on and if DBT is below DPT + ΔT, the blower is off. Thus, the control will operate to satisfy the following relationship:

$$DBT = DPT + \Delta T \quad (1)$$

or

$$DBT - DPT = \Delta T \quad (2)$$

This shows that the difference between module dry bulb temperature and process-air-in dew point temperature will be held at a constant value as set on the manual set point potentiometer. Electrical hysteresis (intentionally added) and system thermal lags serve to prevent rapid cycling of the cooling blower.

SUMMARY OF SSP CONVERSION ACTIVITIES

The electrochemical CO_2 removal technique was selected as baseline for the Air REvitalization Group (ARG) of the SSP. Subsequently, the concept demonstrated with the one-man subsystem (CX-1) and with the CX-6 was chosen by NASA as the primary SSP CO_2 Collection Subsystem.

A second six-man subsystem (CS-6) was subsequently designed and fabricated according to updated SSP design specifications and philosophies[4,5]. A detailed description of the CS-6 development activities is presented in Reference 2.

Mechanical Design and Packaging

The mechanical design of the CS-6 is functionally similar to that of the CX-6. The subsystem is constructed using the same electrochemical modules as tested in

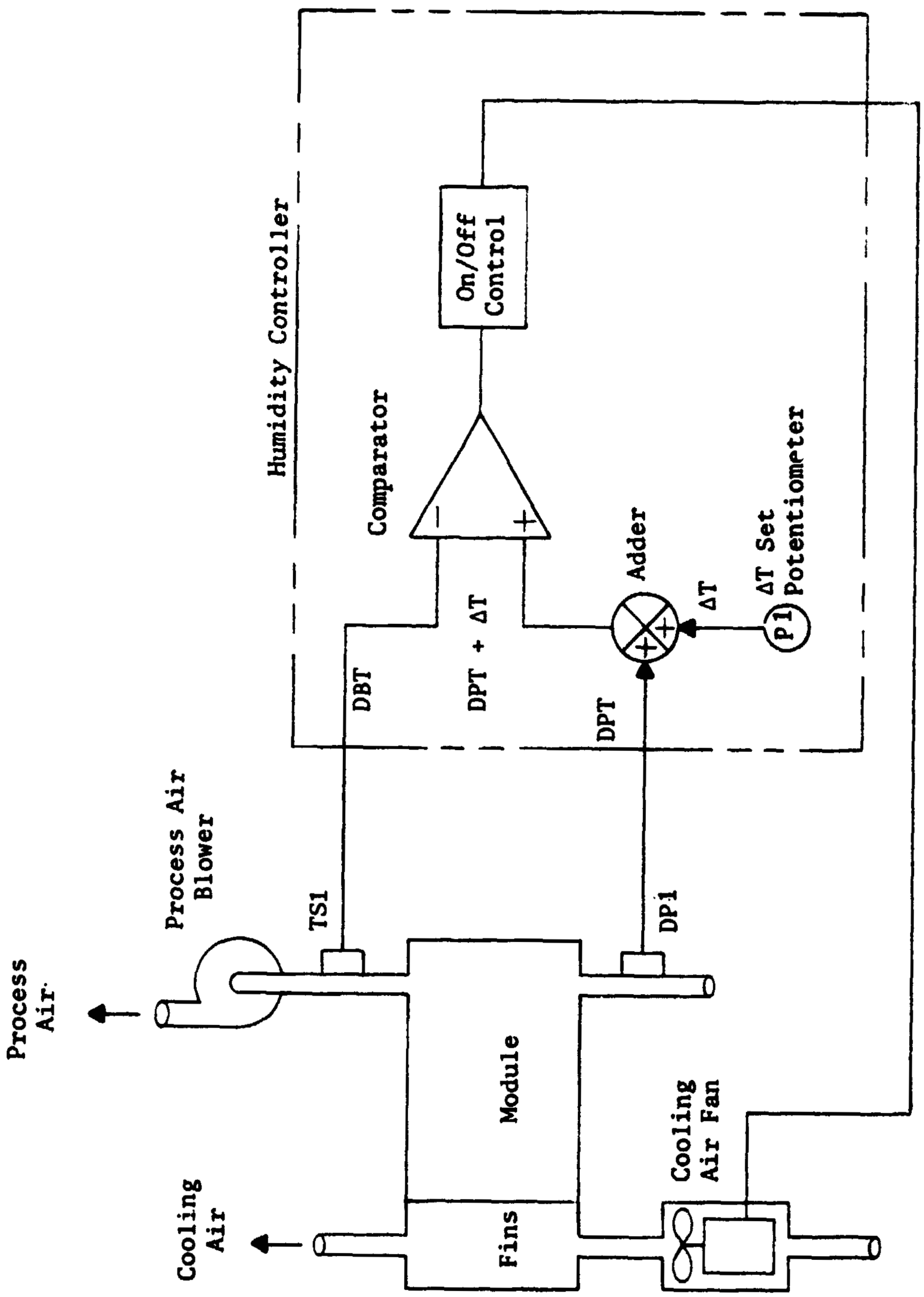


FIGURE 55 HUMIDITY CONTROL SYSTEM FUNCTIONAL BLOCK DIAGRAM

the CX-6, but expanded from 90 to 96 cells for performance derating and to allow for insitu cell maintenance. The remaining subsystem hardware is fabricated from new materials. The LRU concept is again used. Where applicable, components common to other SSP subsystems are used. This "commonality" concept reduces the total number of spares for the SSP. Table 18 lists the LRUs of the CS-6. Packaging of the subsystem evolved through a series of Design Reviews and the use of full size subsystem mock-ups.

Figures 56 and 57 are photographs of the front and rear views of the CX-6 with the locations of the major LRUs indicated. Figure 56 shows the CS-6 with a Ground Support Panel installed for testing without the SSP's computer. The overall size of the CS-6 is 1.51 m (5.0 ft) in height by 0.69 m (2.3 ft) in width by 0.71 m (2.3 ft) in depth. The resulting volume is 0.73 m^3 (26.5 ft^3). The CS-6 weighs 368 kg (809 lb) for a packaging density of 497 kg/m^3 (30.5 lb/ft^3). Efforts to optimize subsystem weight were given secondary emphasis. Primary emphasis was placed on maintainability.

Electronic Design and Packaging

The CS-6 is designed to interface with two computer systems: Acceptance Checkout Equipment (ACE) located at Johnson Space Center and Information Management System (IMS) located at Marshall Space Flight Center.

All electronics within the CS-6 are incorporated into two electronics enclosures called the Primary Controller and the Emergency Controller. The purpose of the Primary Controller is to control all parameters critical to the operation of the subsystem; to configure the subsystem in response to mode commands from ACE/IMS; to automatically shut down the subsystem for time critical parameters; to interface with ACE/IMS for component overrides used in Fault Detection and Isolation Analysis (FDIA) routines; and to process sensor information for presentation to ACE/IMS.

The purpose of the Emergency Controller is to shut down the subsystem should the Primary Controller or ACE/IMS via the Primary Controller fail to do so when subsystem operation is out-of-tolerance or when safety conditions warrant subsystem shutdown.

Operating Modes

The CS-6 has five modes of operation: normal, dump, standby, shutdown and purge. The first mode of operation, normal mode, is one in which the subsystem is operating in a normal fasion similar to the CX-6, but with the H_2 and CO_2 exhaust from the CS-6 vented to the CO_2 reduction subsystem. In the dump mode the CS-6 is operating with the H_2 and CO_2 exhaust vented to vacuum. In the standby mode the CS-6 is not operating but is standing by for a command to go back into operation. This mode is used in cyclic (dark side of earth orbit) operation. In the purge mode the CS-6 is continually being purged to vacuum with N_2. The final mode of operation is the shutdown mode. This mode places the CS-6 into a shutdown condition. Even though the subsystem is shut down, data is continually being sent to the data management system.

TABLE 18 CS-6 LINE REPLACEABLE UNITS

	SSP Item No.	Qty. Req'd	SSP Commonality LRUs
Module, Electrochemical	890	6	
Blower, Process Air	543	2	X
Blower, Cooling Air	345	2	X
Sensor, Process Air	875	4	
Valve, Shutoff, Electric, Manual Override	305	3	X
Valve, Shutoff, Electric, Manual Override	306	6	X
Mounting, H_2 Flow Sensor & Distribution Block	882	2	
Valve, Regulator, Backpressure	310	1	X
Sensor, Pressure	877	3	X
Sensor, Combustible Gas	178	4	X
Controller, Primary	871	1	
Controller, Emergency	872	1	
Unit, Data Acquisition	970	1	X
Mounting, Load Transistors	876	1	
Valve, Shutoff, Manual	507	1	X

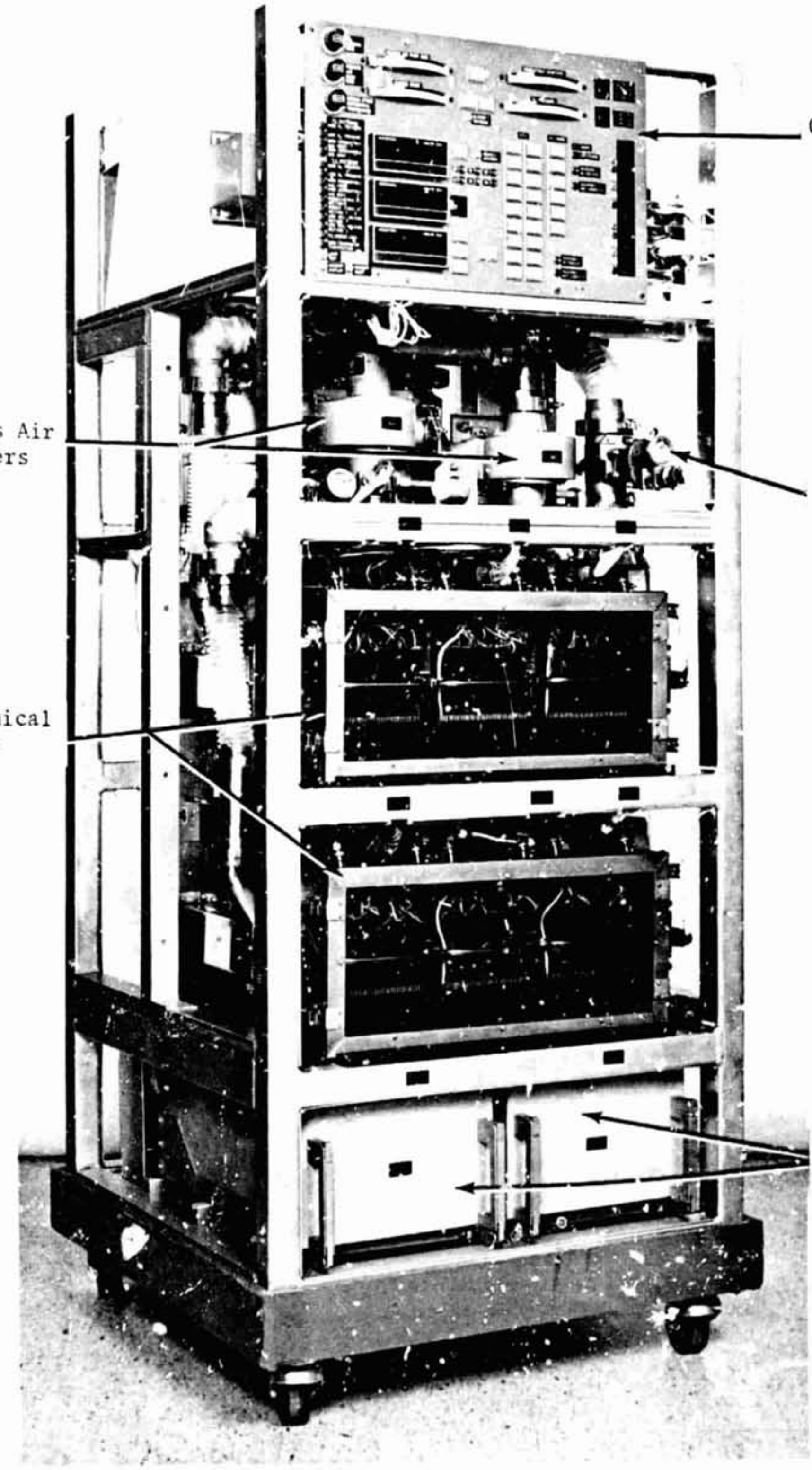


FIGURE 56 CS-6 (FRONT VIEW)

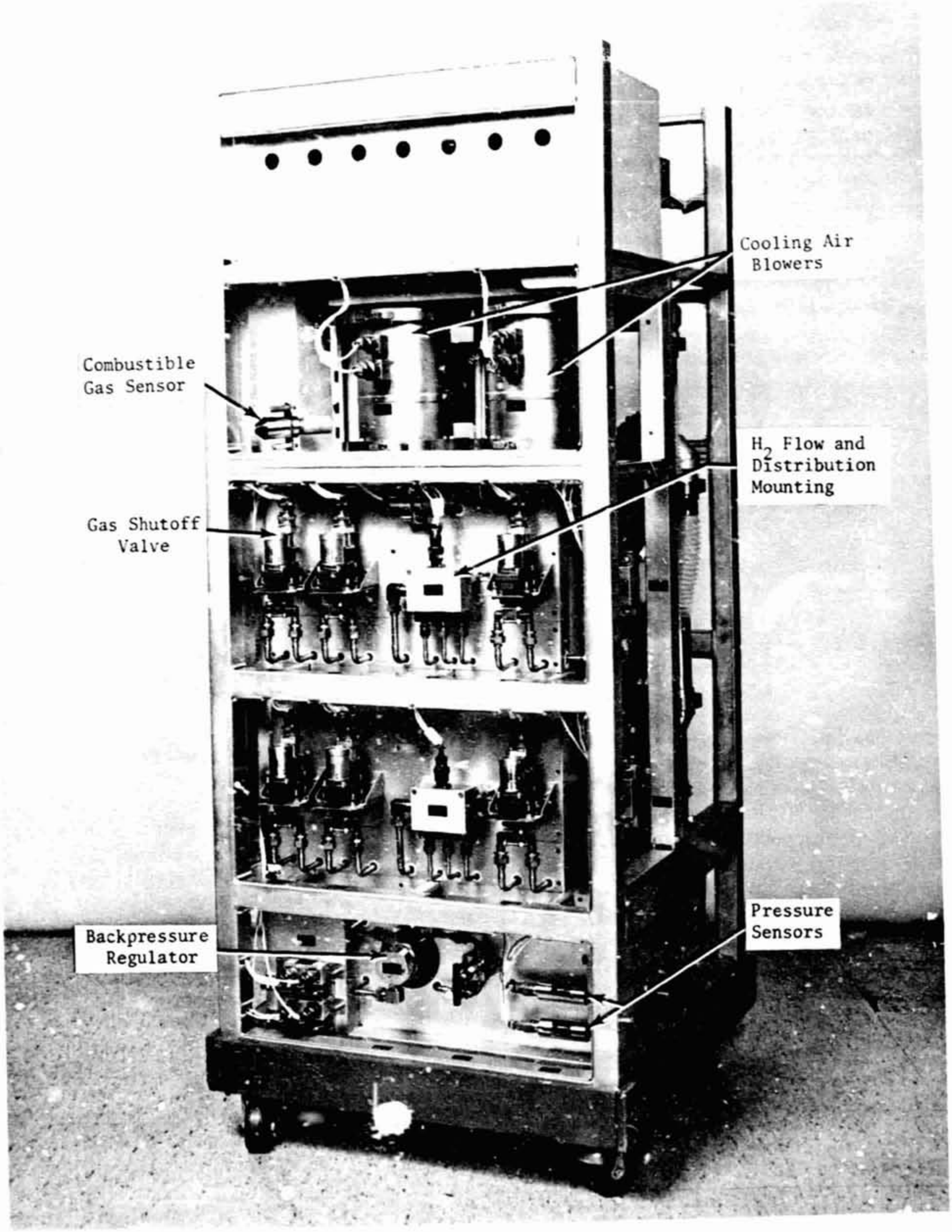


FIGURE 57 CS-6 (REAR VIEW)

CS-6 Testing

The CS-6 was subjected to subsystem shakedown tests, a 102-hour Design Verification Test (DVT), a series of parametric tests for use in a computerized mathematical model, and, prior to shipment to NASA JSC, a 100-hour continuous Acceptance Test. All testing was successfully completed with the CS-6 exceeding the design CO_2 removal efficiency by 6% and the electrical efficiency (cell voltage) by 25%. The CS-6 has been delivered to NASA JSC for integration into an ARG.

CONCLUSIONS

The following conclusions are a direct result of this development.

1. A six-man, self-contained engineering prototype CO_2 concentrating subsystem (CX-6) was successfully operated for a total of 209 days.

2. The six-man subsystem is capable of removing 6.0 kg/d (13.2 lb/day) of CO_2 from air having a pCO_2 level of 400 N/m^2 (3 mm Hg).

3. The concept used to manifold process and cooling air for 45 cells in parallel resulted in equal flow distribution.

4. The CX-6 is capable of operating with and without internal humidifiers.

5. A major contribution to successful operation is the identification of out-of-tolerance operating conditions before shutdown to enable identification of the fault before performance degradation occurred, i.e., trend analysis.

6. The control and monitoring instrumentation provided fail-safe conditions for unattended operation.

7. The CX-6 is capable of operating with SSP CO_2 Collection Subsystem interface specifications.

8. A second six-man, self-contained CO_2 Concentrating Subsystem (CS-6) was fabricated according to SSP specifications and successfully demonstrated design expectation by exceeding CO_2 removal and electrical efficiencies during subsystem DVT and a 100-hour Acceptance Test.

9. Life Systems' electrodes demonstrated successful operation for 245 days (scheduled termination) in a three-cell unit and for 224 days (209 days in CX-6 plus 15 days in CS-6) in a 90 to 96 cell subsystem.

10. Carbon dioxide removal and electrical efficiency levels and variations as a function of subsystem operating parameters were equal to those established for the one-man subsystem under Contract NAS2-6118.

11. The standby electrical power capability of the GSA protected against five momentary power interruptions and thereby increased subsystem mean-time-between-shutdowns.

12. Electrical insitu cell maintenance is an effective means of reducing subsystem spares and maintaining subsystem performance.

13. Knowledge of water vapor pressures above aqueous solutions of Cs_2CO_3 as a function of temperature and concentration allowed definition of operating tolerances and limits.

14. The materials of construction for the CX-6 baseline cells showed no signs of deterioration during the 245 days of three-cell unit operation. (All but 76 days of operation were with baseline polysulfone.)

15. The postparametric test activities on the one-man, 15-cell module following the total test program conducted under NAS2-6118 (278 days of total operation except for electrodes which operated for 361 days) showed no CO_2 removal efficiency degradation and only a 0.15-volt drop in average cell voltage.

16. An analysis for NO_2 and SO_2 in the cell matrix electrolyte of the one-man subsystem after 180 days of operation showed no buildup of these species (either due to ambient air or products of combustion from the one-man OCRS).

17. A series of parallel technology activities provided for the successful development of the CX-6 and CS-6 and helped to broaden the technology base on which the electrochemical CO_2 removal concept is based.

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4. "Design and Performance Requirements, General Space Station Prototype," Specification No. SVHS 4655, Rev. G., Hamilton Standard, Windsor Locks, Connecticut, November 1, 1972.

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7. "CX-6 Operation and Maintenance Manual," ER-134-20, Contract NAS2-6478, Life Systems, Inc., Cleveland, Ohio, June, 1973.

APPENDIX A TYPICAL LRU SPECIFICATION, BLOWER, COOLING AIR, LRU NO. 296

FUNCTION

The blower moves refrigerated air over the external fins of the electrochemical module.

DESCRIPTION

The blower is a centrifugal type with a direct coupled motor. It is foot-mounted and has quick connect inlet and outlet flanges for ease of maintenance. It is a Line Replaceable Unit (LRU).

DESIGN DATA

Performance Characteristics

Nominal Angular Velocity, rad/s (rpm) 325 (3100)

Flow		Static Pressure at 101 kN/m^2 (14.7 Psia)	
m^3/s	Scfm	N/m^2	In Water
0	0	648	2.6
0.094	200	311	1.25
0.120	255	0	0

Reliability Data

Failure rate, per Hr	10.9×10^{-6}
MTBF, Hr	0.09×10^{6}
Spares	2 (180-day mission profile)

Physical Characteristics

See Attached Drawing No. 335

Weight, kg (Lb)	4.90 (10.8)
Volume, m^3 (Ft^3)	0.00464 (0.164)
Basic Configuration, cm (In)	19.05 (7.5) dia x 25.15 (9.9) overall length

Material Characteristics

A. Nonmetallic
   Black enamel paint, Fluorel L-3217
B. Metallic
   Carbon steel, Cadmium, Aluminum

continued-

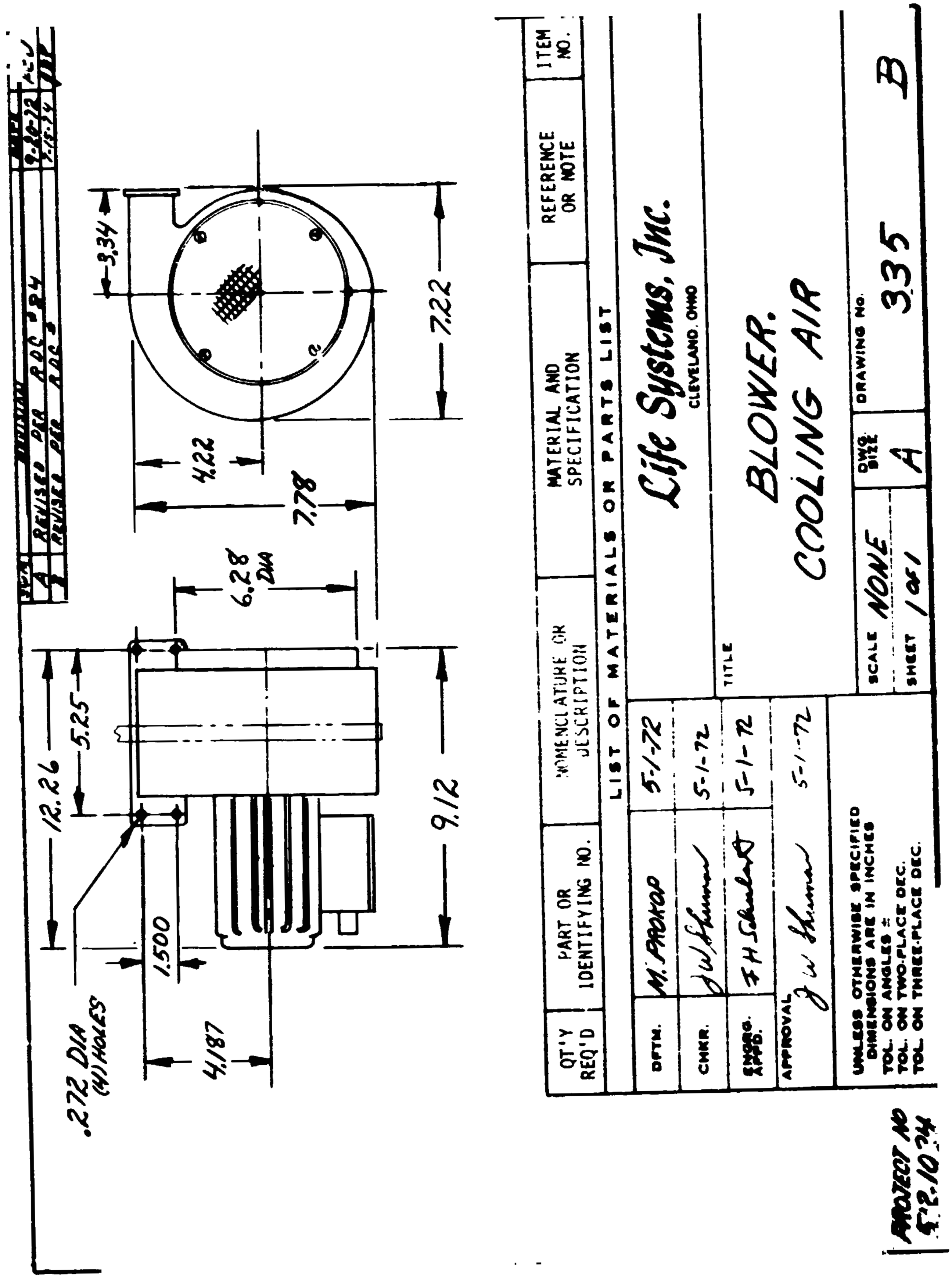

FIGURE A-1 COOLING AIR BLOWER

Appendix A - continued

Electrical Characteristics

Power input, W	160 @ 0.094 m^3/s (200 Scfm)
Voltage, V	115, 60 Hz, single phase
Insulation	Class F
Capacitor, μf	2.6 @ 330 VAC
Motor type	Induction

INTERFACES

Mechanical — See Drawing No. 335

Electrical

Connector — Amphenol No. M81511/01EA01P1

Mounting — Mounts to module backplate via four 1/4-20x1 hexhead cap screws and 1/4-20 hex nuts. Also mounts to cooling air blower support bracket via four 10-32x1/2 panhead screws. The support bracket mounts to the module backplate via two 1/4-20x1 hexhead cap screws and 1/4-20 hex nuts.

ENVIRONMENT

Cabin atmosphere

MAINTENANCE LEVEL AND METHOD

Replacement of the LRU is the first level of maintenance.

Time Required: <0.2 hour