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SIX-MAN, SELF-CONTAINED CARBON DIOXIDE CONCENTRATOR SUBSYSTEM FOR SPACE STATION PROTOTYPE (SSP) APPLICATION

FINAL REPORT

by
G. D. KOSTELL, F. H. SCHUBERT, J. W. SHUMAR,
T. M. HALLICK and F. C. JENSEN

MAY, 1974

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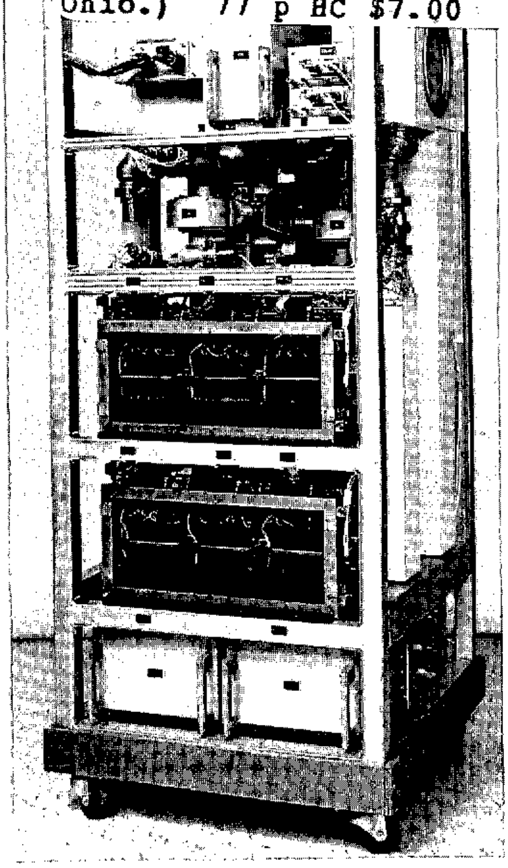

Prepared Under Contract No. NAS2-6478

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 January 31, 1974 under NASA Contract NAS2-6478. The Program Manager was Franz H. Schubert. Technical support was provided by:

Personnel	Area(s) of Responsibility
Timothy M. Hallick	System Testing
Fred C. Jensen	Mechanical Design
George D. Kostell	Electrical Design and Checkout
Glenn A. Little	Mechanical Checkout and Assembly
J. David Powell	Electrical Design
Jon J. Schneider	Maintainability and Human Engineering
John W. Shumar	Product Assurance
Richard A. Wynveen	Program Administrator, 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 Concentrating Subsystem (CS-6) for Space Station Prototype (SSP) use was successfully designed, fabricated, and tested. The design of the unit was based on the specifications and requirements for the Environmental Control and Life Support System (EC/LSS) of the SSP.

Two full-size mockups of the CS-6 were constructed to aid in subsystem design and packaging, with special emphasis placed on subsystem maintenance. All subsystem interfaces, whether electrical or mechanical, were designed for compatibility with SSP requirements and operation. Nine different types of SSP commonality components were used in the design of the subsystem.

A Product Assurance Program incorporated quality assurance, reliability, maintainability, safety, and material conformance. Activities included preparation of 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, and Nonmetallic and Metallic Materials Lists.

Ground Support Accessories (GSA) were designed to simulate interfaces for subsystem checkout and testing. Specifically, the GSA provided electrical power, process gases, and parametric data display allowing real time indication of operating status in engineering units. A Ground Support Panel was designed and fabricated to allow for CS-6 operation without a Data Acquisition Unit (DAU) and without the computerized subsystem control provided within the SSP by the Acceptance Checkout Equipment (ACE) or Information Management System (IMS).

A test program was successfully completed which covered Shakedown Testing, Design Verification Testing (DVT), and Acceptance Testing. All phases of system testing were done at SSP operating conditions with the CS-6 exceeding its design point performance prediction.

Complete subsystem documentation was prepared. It consisted of design documents (e.g., drawings, design specifications) interface documents (e.g., interface specifications), and product assurance documents (e.g., materials lists).

INTRODUCTION

Under NASA Contract NAS2-6478, Life Systems, Inc. developed a Six-Man, Self-Contained, Electrochemical Carbon Dioxide Concentrating Subsystem (CS-6). This subsystem was designed as the Carbon Dioxide Collection Subsystem (CCS) of the Air Revitalization Group (ARG) of the Space Station Prototype (SSP). The development of this system was divided into three phases: (1) design of the CS-6 per requirements and specifications of the SSP program, (2) fabrication of the CS-6 per SSP specifications and requirements, and (3) Shakedown Testing, Design Verification Testing (DVT), and Acceptance Testing of the CS-6.

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

1. Design and develop the CS-6 according to SSP specifications, requirements, and philosophies for incorporation into the NASA SSP life support system.

2. Design, fabricate and modify Ground Support Accessories (GSA) for Shakedown, Design Verification, and Acceptance 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 design and test phases.

4. Test components to design and performance criteria prior to subsystem assembly and conduct subsystem Shakedown, Design Verification, and Acceptance Tests at SSP operating conditions.

5. Completely prepare all subsystem documentation (drawings, specifications, test plans, Product Assurance documentation, etc.).

This report covers the phase of work performed by Life Systems, Inc. under NASA Contract NAS2-6478 to design, fabricate and test the CS-6 for SSP application.

CS-6/SSP DESIGN REQUIREMENTS

The design, performance and interface requirements for the Carbon Dioxide Collection Subsystem (CCS) for the SSP program evolved from the SSP General Specification SVHS-4655, Revision G, "General Design and Performance Requirements for a Space Station Prototype," written by the SSP Prime Contractor. This specification, in addition to the "Design Criteria Handbook," SSP Document No. 9, Paragraph 11.0, revised August 28, 1972, were the main documents specifying the system interface requirements in the CS-6 design. In addition to these two documents, other information assimilated through design review meetings and telephone conversations with NASA Johnson Space Center (JSC) and SSP Prime Contractor personnel was used in the CS-6 design.

SSP Background

The SSP program and its two main phases:[(1)] Preliminary Design, and Detailed Design, Procurement/Fabrication and Checkout, covered a period of four years. During Phase 2-A of the program, two major decisions were made: the maximum allowable partial pressure of CO_2 (pCO_2) was decreased from 1013 to 400 N/m^2 (7.6 to 3.0 mm Hg), and the Molecular Sieve Carbon Dioxide Removal Subsystem, with associated solar heat collection equipment, was replaced by an electrochemical CCS. Life Systems, Inc. became involved in supplying the CCS for the SSP in October, 1972 with the task of supplying a backup system for SSP application. Previous electrochemical carbon dioxide (CO_2) collection work done by Life Systems' personnel spanned a nine-year period with over 400,000 electrochemical cell-hours of operating time accumulated. A second phase of Life Systems' involvement began in December, 1972 when it was chosen to supply the CCS for the SSP program.

(1) References cited are on page 65.

CS-6/SSP Design Reviews

A series of design reviews were held to establish and evaluate SSP design philosophies and to insure compatibility of the CS-6 with SSP design requirements. These design reviews involved representatives of NASA Ames Research Center (ARC), NASA JSC, the SSP Prime Contractor, NASA Marshall Space Flight Center (MSFC),[a] and Life Systems, Inc. The various design review meetings held, agencies represented, and meeting dates are shown in Table 1.

CS-6 SUBSYSTEM

The function of the CS-6 CCS for the SSP program is to remove 6.0 kg (13.2 lb) per day of CO_2 from the cabin atmosphere and deliver the CO_2 premixed with hydrogen (H_2) to the Carbon Dioxide Reduction Subsystem (CRS). The CO_2 removed will be subsequently processed by the CRS for eventual recovery of oxygen (O_2).

The CS-6 consists of electrochemical modules, whose function is to remove CO_2 from the process air stream, and mechanical and electrical components which enable automatic operation and provide for internal as well as remote monitoring of the subsystem. Monitoring will shut the subsystem down following the failure of any key component within the subsystem or interruption of the necessary service from a supporting subsystem.

Subsystem Design and Mockups

Table 2 shows the design specifications for the CS-6. Three major specification modifications affecting the CS-6 were made during the course of SSP development: (1) allowable downtime of the subsystem was increased from less than 10 minutes to 8-12 hours, (2) inlet pCO_2 was decreased from 400 to 381 N/m^2 (3 to 2.86 mm Hg), and (3) the availability of 28 VDC and 115 VAC, 60 Hz power was eliminated.

Subsystem Mockups

Two full-scale mockups were built during the course of the design and development of the CS-6. These mockups were used at formal design reviews as well as in-house design discussions on meeting all SSP design, packaging and maintainability specifications.

Figure 1 shows the CS-6 mockup prior to the Approval Design Review (ADR) held at Life Systems. Figure 2 shows the mockup of the final CS-6 design, revised to incorporate the maximum number of SSP commonality components.

Subsystem Features

The following is a summary of features incorporated into the CS-6 design:

1. Insitu maintenance at the individual cell level for increased subsystem reliability and longer module operating life without replacement.

2. Automatic subsystem nitrogen (N_2) purge during appropriate mode transitions (e.g., upon startup, shutdown, etc.).

(a) Represented at software meetings only.

TABLE 1 CS-6/SSP DESIGN REVIEW MEETINGS

Meeting	Agencies Represented	Date
SSP Air Revitalization Group (ARG) Approval Design Review (ADR)	NASA ARC, NASA MSFC, NASA JSC, SSP Prime Contractor, Life Systems, Inc.	May 1-5, 1972
CS-6/SSP Electrical Interface Meeting	NASA JSC, Life Systems, Inc.	June 19, 1972
CS-6 Interim Design Review (IDR)	NASA ARC, NASA JSC, SSP Prime Contractor, Life Systems, Inc.	July 6-7, 1972
CS-6 ΔIDR	NASA ARC, NASA JSC, SSP Prime Contractor, Life Systems, Inc.	August 3-4, 1972
CS-6 ADR	NASA ARC, NASA JSC, SSP Prime Contractor, Life Systems, Inc.	October 2-3, 1972
SSP Software Meeting	NASA JSC, NASA MSFC, SSP Prime Contractor, SSP Data Management Subcontractors, Life Systems, Inc.	October 4-5, 1972
SSP Software Meeting	NASA JSC, NASA MSFC, SSP Prime Contractor, SSP Data Management Subcontractors, Life Systems, Inc.	November 16-17, 1972
CS-6 ΔADR	NASA ARC, NASA JSC, SSP Prime Contractor, Life Systems, Inc.	January 16-18, 1973
CS-6/SSP Electrical Interface Meeting	NASA JSC, SSP Prime Contractor, Life Systems, Inc.	February 1-2, 1973
CS-6 Fabrication Review Meeting	NASA JSC, Life Systems, Inc.	May 2, 1973

TABLE 2 CS-6 DESIGN SPECIFICATIONS

Number of Crew (Continuous)	6
CO_2 Removal Requirements	
Nominal (48-Hr Average), kg/d (Lb/Day)	6.0 (13.2)
Maximum (4-Hr Duration), kg/d (Lb/Day)	9.3 (20.4)
Cabin Atmosphere	
Total Pressure, kN/m^2 (Psia)	101-105 (14.7-15.2)
Temperature, K (F)	291-297 (65-75)
Dew Point Temperature, K (F)	281-287 (46-57)
O_2 Partial Pressure, kN/m^2 (Psia)	21.0-22.6 (3.04-3.28)
CO_2 Partial Pressure	
Nominal, N/m^2 (mm Hg)	<400 (<3)
Operating Range, N/m^2 (mm Hg)	200-400 (1.5-3)
Diluent	Air Constituents
Process Air	
Total Pressure, N/m^2 (Inch Water)	Ambient + 1495 (+ 6)
Temperature, K (F)	Dew Point + 3.34 (+ 6)
Dew Point Temperature, K (F)	281-283 (46-50)
O_2 Partial Pressure, kN/m^2 (Psia)	21.0-22.6 (3.04-3.28)
CO_2 Partial Pressure	
Nominal, N/m^2 (mm Hg)	381 (2.86)
Operating Range, N/m^2 (mm Hg)	200-385 (1.5-2.89)
Diluent	Air Constituents
Cooling Air	
Total Pressure, N/m^2 (Inch Water)	Ambient + 1495 (+ 6)
Temperature, K (F)	Process Air Dew Point + 3.34 (+ 6)
H_2 Supply	
Total Pressure, kN/m^2 (Psia)	<138 (<20)
Temperature, K (F)	291-297 (65-75)
Dew Point Temperature, K (F)	283-289 (50-60)
H_2 + CO_2 Exhaust	
Total Pressure	Ambient
Electrical Power	106-122 VRMS, 400 ±40 Hz, 3Ø, 5 Wire
Purge Supply	
Type Gas	N_2
Pressure, kN/m^2 (Psia)	310 (45)
Packaging	Self-Contained
Gravity	0-1 g
Allowable Downtime	8-12 Hr
Duty Cycle	Variable[a]

(a) The SSP Specification cites potential orbital On/Off cyclic operation.

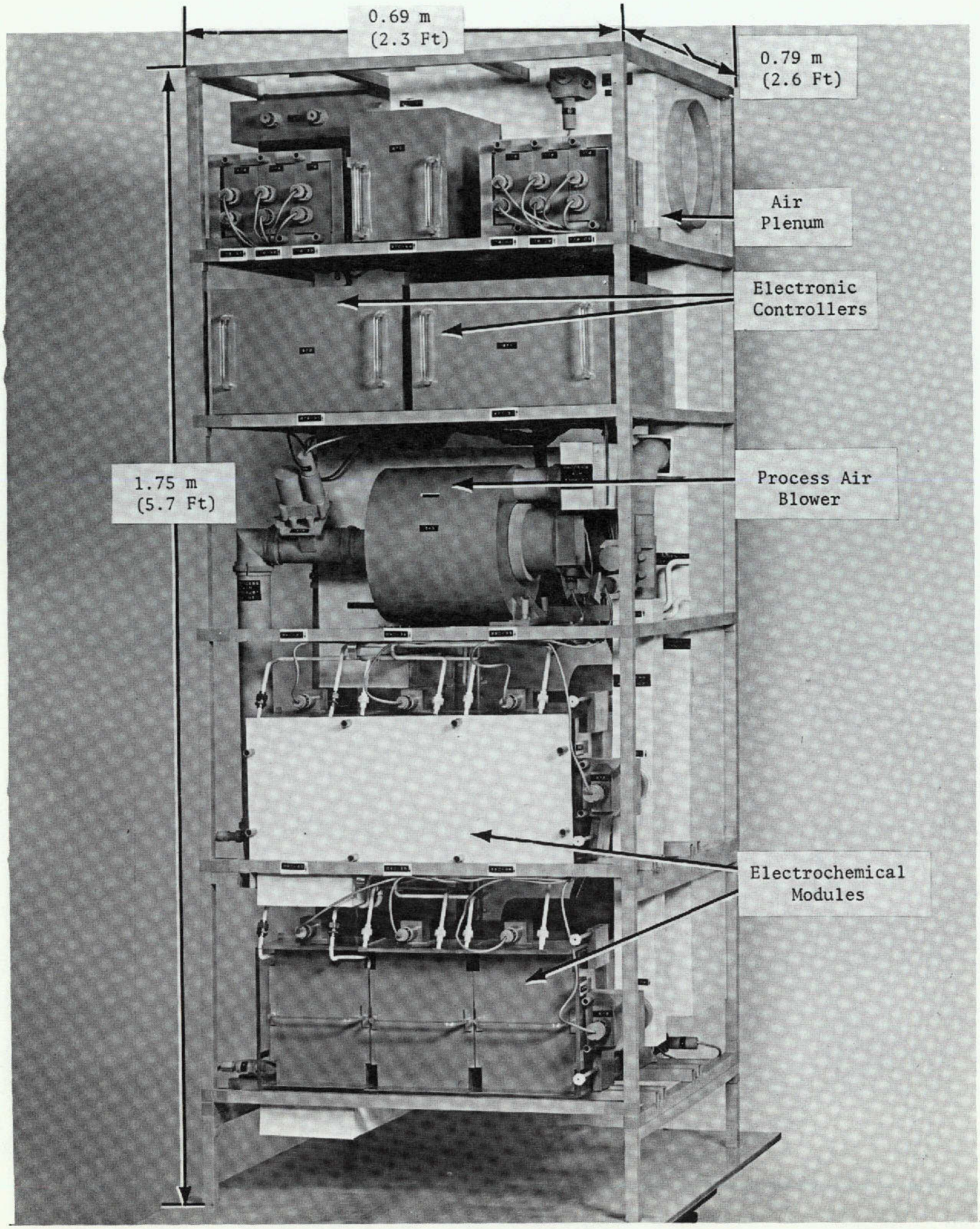


FIGURE 1 CS-6 MOCKUP (FIRST VERSION)

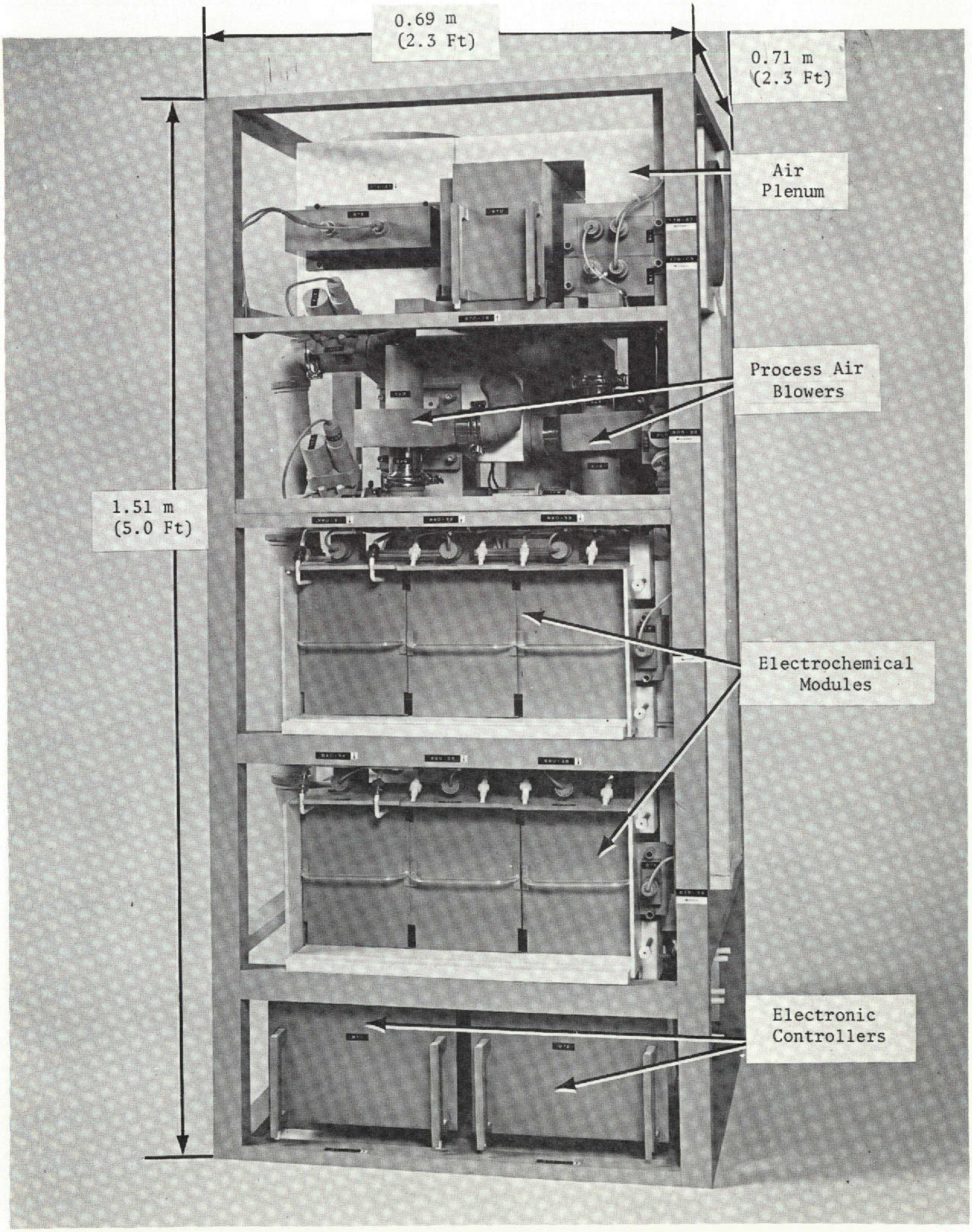


FIGURE 2 CS-6 MOCKUP (FINAL VERSION)

3. Ninety-six cells combined into six, 16-cell modules to reduce auxiliary hardware requirements and to enhance subsystem maintainability.

4. Captive fasteners and easily maintainable fluid connections for all Line Replaceable Units (LRUs) and interface connections.

5. Subsystem controls which (a) maintain a constant CO_2 removal rate or regulate this rate to match requirements reflected in the observed cabin pCO_2 level, (b) maintain a constant process air flow rate or regulate this rate to match requirements reflected in the observed cabin pCO_2 level, and (c) maintain a constant process-air-inlet-dew-point-to-module temperature differential.

6. Automatic sequencing of the subsystem controlled variables when going from one steady-state mode of operation to another.

7. Optical isolation of all subsystem input commands (eliminates ground loops and prevents the transmission of spurious false signals).

8. "Black Box" component level maintainability (LRU).

9. Electronic circuitry compatible with the SSP Item 970 Data Acquisition Unit (DAU), the Acceptance Checkout Equipment (ACE) computer at JSC, and the Information Management System (IMS) computer at MSFC.

10. Overrides on all valves and blower speeds.

11. Rack and panel mounted electronic circuitry.

12. Compatibility with NASA flammability, outgassing, odor, and materials specifications.[2]

13. Air cooling of the electronics.

14. Extensive use of SSP commonality components.

15. Single power source (115 VAC, 400 Hz, 3Ø).

16. Self-contained protection for safety critical parameters (emergency controller).

17. Fault Detection and Isolation Analysis (FDIA) sensors and circuits to isolate any failed LRU.

Subsystem Operation

Figure 3 is a schematic of the CS-6. It shows the functional location of all subsystem components and all gas and electric interconnections.

Operating Modes

The CS-6 has five modes of operation: Normal, Dump, Standby, Shutdown, and

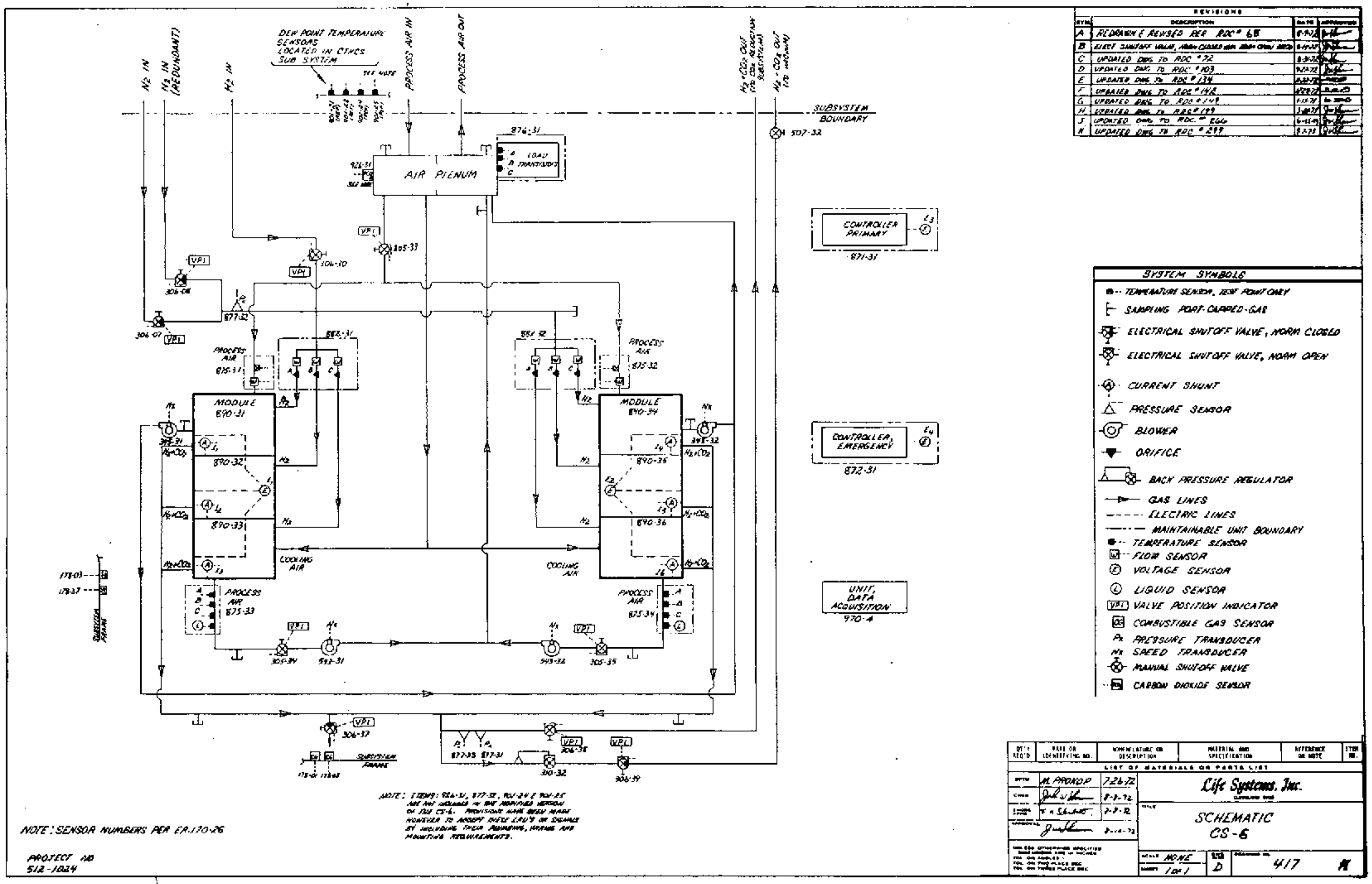


FIGURE 3 CS-6 SCHEMATIC

Purge. The first mode of operation, Normal Mode, is one in which the subsystem is operating in a normal fashion with the H_2 and CO_2 exhaust from the CS-6 vented to the CRS. 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 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 vaccum with N_2. The final mode of operation is the Shutdown Mode which places the CS-6 into a shutdown condition. While the subsystem is in a shutdown condition, subsystem parameters are continually being monitored and data is being sent to the data management system. Figure 4 illustrates the permissible transitions between the five operating modes. The detailed and individual steps required for the various mode transitions are shown in Figure 5. Table 3 summarizes the steady-state valve positions and other controlled variables for each of the five operating modes.

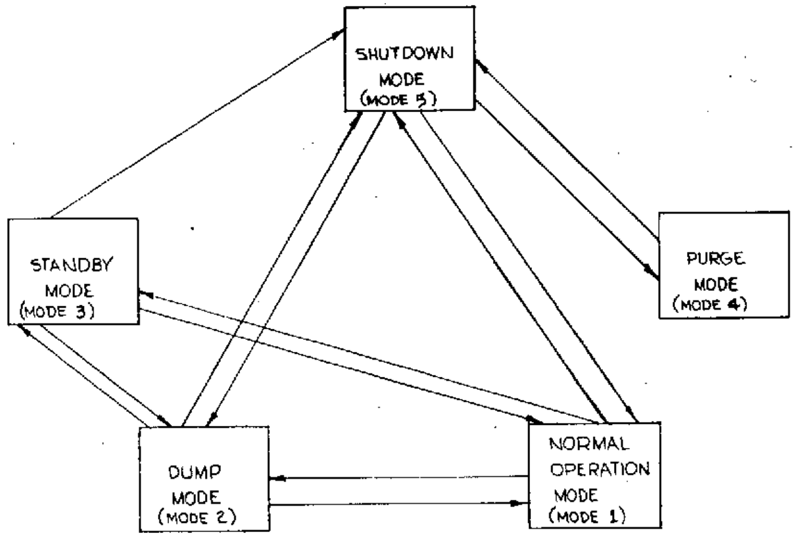
Fluid Streams

Three major fluid streams flow through the CS-6: the process air stream, the H_2 and CO_2 stream (with possible N_2 purging) and the cooling air stream. Process air and cooling air are drawn from a 0.236 m^3/s (500 scfm) air stream exhausting from the Cabin Temperature and Humidity Control Subsystem (CTHCS) of the ARG. This air stream enters the CS-6 through the inlet chamber of the air plenum (see Figure 3) and is returned to the main air distribution system from the exit chamber of the air plenum. The two plenum chambers are connected with a straight rectangular flow section sized to produce a 374 N/m^2 (1.5 inch water) pressure drop at the maximum flow rate of 0.236 m^3/s (500 scfm) of air.

Process Air Stream. Air is drawn by two process air blowers (543-31, -32)[a] from the inlet chamber of the air plenum through the cathode compartments of the electrochemical cells and returned to the air plenum exhaust chamber. Each of the two blowers draws air through three modules (890-31, -32, -33 and 890-34, -35, -36) of 16 cells each (48 cells total). The process air leaves the inlet chamber of the air plenum in a common line and passes through a decompression isolation valve (305-33) before separating into two equal flows of 1.27 x 10^{-2} m^3/s (27 scfm) (at nominal conditions) each, one to each of the two groups of three modules. In each of the two individual paths the air flows through a process air inlet sensor (875-31 or 875-32), through the 48 cells in parallel, combines to flow through the process air exhaust sensor (875-33 or 875-34), passes through a decompression isolation valve (305-34 or 305-35) and is forced by a process air blower (543-31 or 543-32) into a common return duct before returning to the air plenum exhaust chamber. The three decompression isolation valves isolate the cathode compartments of all six modules during cabin decompression to prevent escape of water vapor from the cell electrolyte. The process air sensors at the inlet to the modules measure air flow rate using a two-thermistor type flow sensing device and also measure process air inlet temperature which is only used as a test point. The process air sensors at the exhaust of the modules use three redundant thermistors to measure process air exhaust temperature (equivalent, by definition, to module temperature) and also use a fourth thermistor to detect any liquid entrained in the exhaust air stream of

(a) Numbers in parenthesis refer to SSP Component Item Numbers as indicated in Figure 3.

REVISIONS			
SYM.	DESCRIPTION	DATE	APPROVED



PERMISSIBLE TRANISITIONS BETWEEN STEADY STATE OPERATING MODES

FROM		TO	
SHUTDOWN	(5)	(1)	NORMAL
SHUTDOWN	(5)	(2)	DUMP
SHUTDOWN	(5)	(4)	PURGE
STANDBY	(3)	(1)	NORMAL
STANDBY	(3)	(2)	DUMP
STANDBY	(3)	(5)	SHUTDOWN
NORMAL	(1)	(2)	DUMP
NORMAL	(1)	(3)	STANDBY
NORMAL	(1)	(5)	SHUTDOWN
DUMP	(2)	(1)	NORMAL
DUMP	(2)	(3)	STANDBY
DUMP	(2)	(5)	SHUTDOWN
PURGE	(4)	(5)	SHUTDOWN

PROJECT NO. 512-1024

QT'Y REQ'D	PART OR IDENTIFYING NO.	NOMENCLATURE OR DESCRIPTION	MATERIAL AND SPECIFICATION	REFERENCE OR NOTE	ITEM NO.

LIST OF MATERIALS OR PARTS LIST

DFTM.	RON JACKSON	12-4-72	Life Systems, Inc. CLEVELAND OHIO
CHKR.	[signature]	1/2/73	TITLE
ENGRG. APPD.	[signature]	1/2/73	CS-6 OPERATING MODES
APPROVAL	[signature]	1/3/73	

UNLESS OTHERWISE SPECIFIED DIMENSIONS ARE IN INCHES
TOL. ON ANGLES ±
TOL. ON TWO-PLACE DEC. ±
TOL. ON THREE-PLACE DEC. ±

SCALE	NONE	DWG SIZE	B	DRAWING No.	543
SHEET	1 OF 1				

FIGURE 4 CS-6 ALLOWABLE TRANSITIONS BETWEEN OPERATING MODES

Life Systems, Inc.

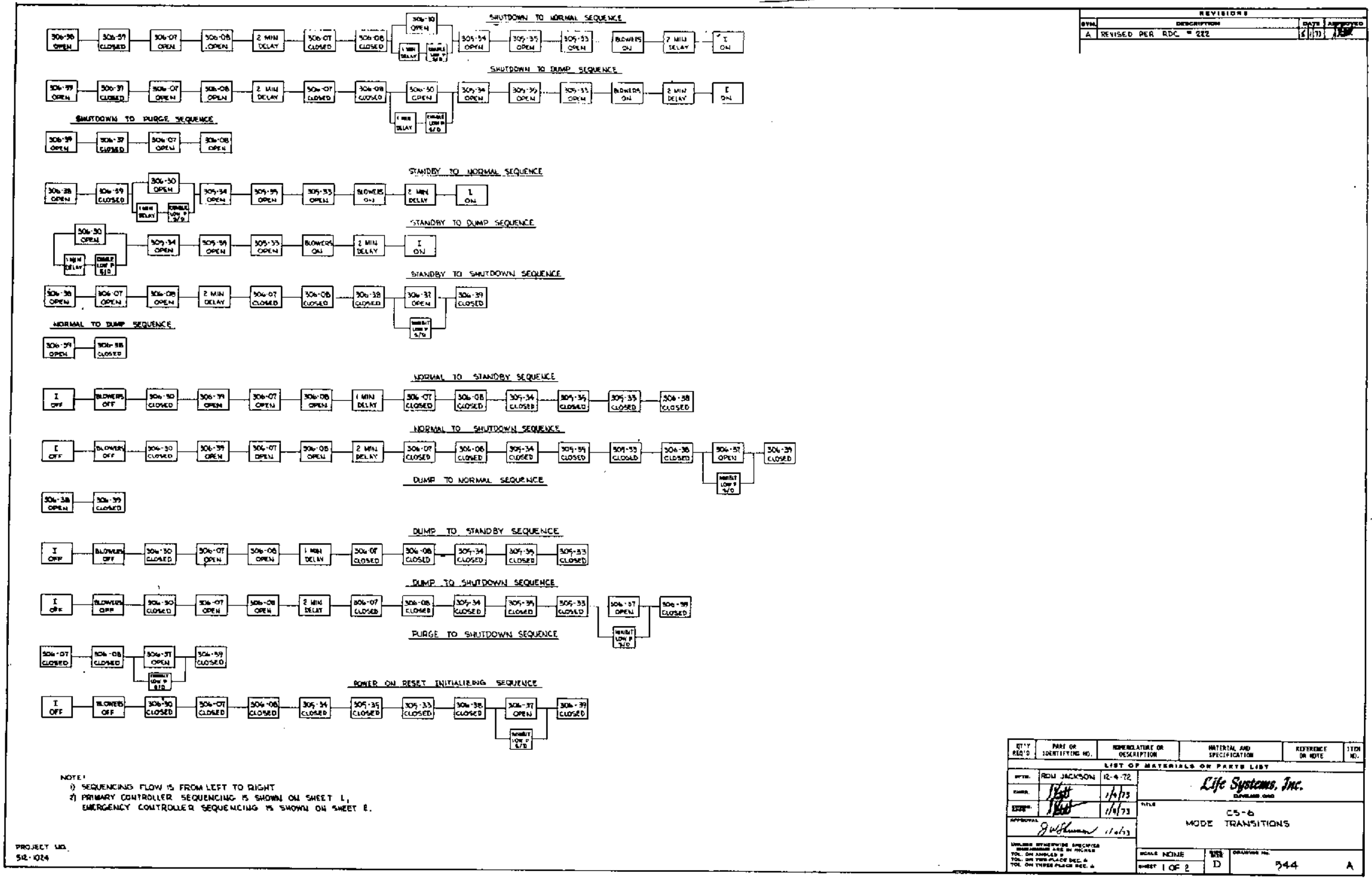


FIGURE 5 CS-6 MODE TRANSITIONS

continued-

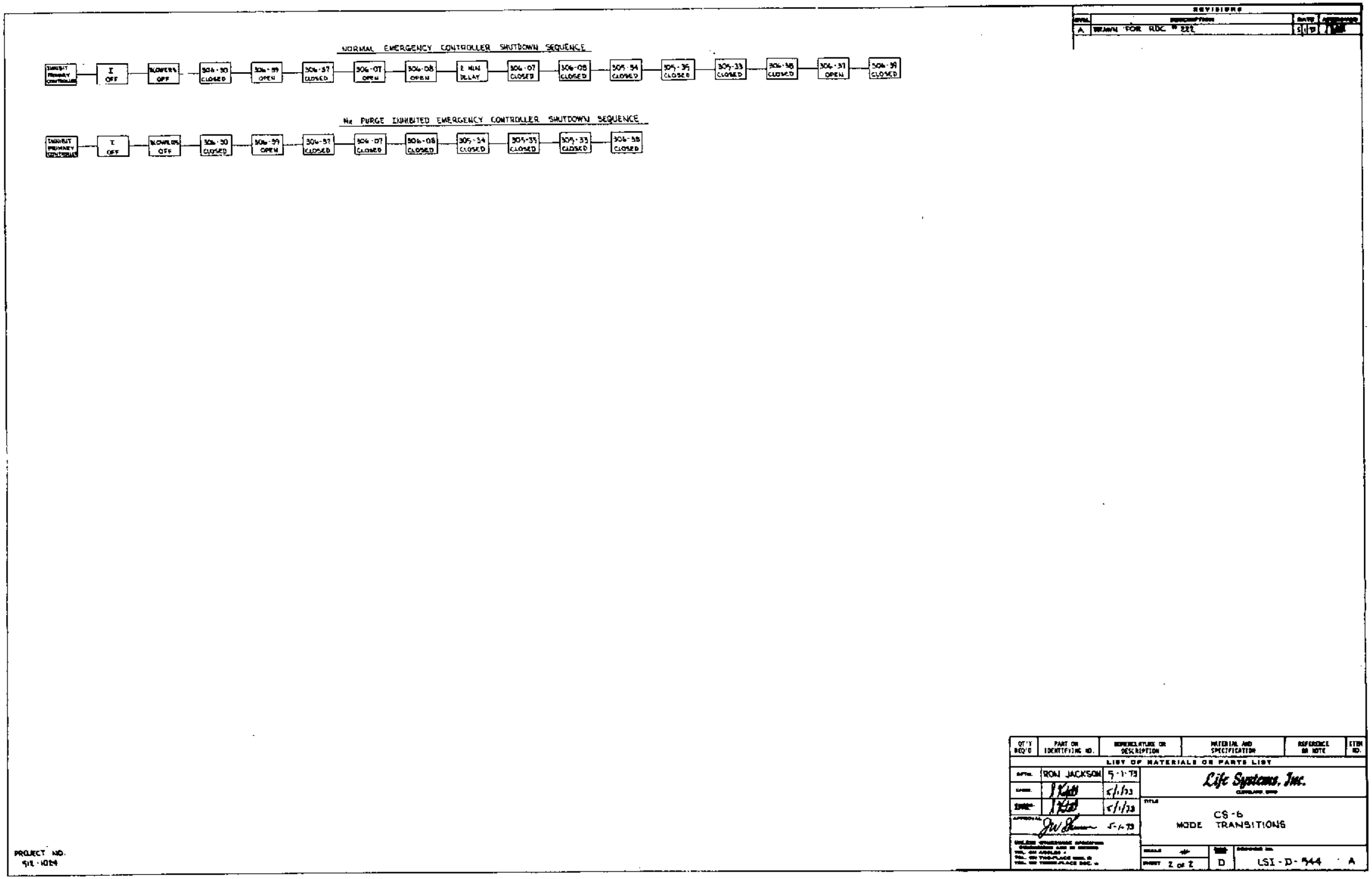


FIGURE 5 - continued

TABLE 3 CS-6 CONTROLLED VARIABLES, STEADY-STATE CONDITIONS

Mode	Control Variables										
	Valve 305-33	Valve 306-07	Valve 306-08	Valve 306-30	Valve 305-34	Valve 305-35	Valve 306-38	Valve 306-39	Valve 306-37	Module Current	Blowers 543-31 543-32
Shutdown (5)[a]	Closed	Closed	Closed	Closed	Closed	Closed	Closed	Closed	Open	Off	Off
Standby (3)	Closed	Closed	Closed	Closed	Closed	Closed	Closed	Open	Closed	Off	Off
Normal Operation (1)	Open	Closed	Closed	Open	Open	Open	Open	Closed	Closed	On	On
Dump Operation (2)	Open	Closed	Closed	Open	Open	Open	Closed	Open	Closed	On	On
Purge (4)	Closed	Open	Open	Closed	Closed	Closed	Closed	Open	Closed	Off	Off

(a) Mode Number, as defined in Figure 4.

the modules. The process air blowers are located downstream of the modules to eliminate adverse effects on module moisture balance due to the air temperature rise caused by blower heat generation.

Hydrogen, Carbon Dioxide and Nitrogen (Purge) Stream. Hydrogen gas is supplied at a nominal flow rate of 1.77×10^{-4} ±1% m^3/s (10.6 ±1% slpm) from the Oxygen Generation Subsystem (OGS) of the ARG. The H_2 enters the CS-6 through a shutoff valve (306-30) after which it is divided into six equal flows by two H_2 flow and distribution mountings (882-31, -32). Each item 882 provides two functions: it divides the flow into three equal portions through the use of fixed orifices and it senses the H_2 flow rate in each of the three paths using a two-thermistor flow sensing arrangement. The outputs of the flow sensors provide information to the FDIA circuits.

Each of the three flow paths from the two H_2 flow and distribution mountings is connected to one electrochemical module. The H_2 flows in series through each of the 16 cells of a module. As H_2 flows through the module, a portion of it is consumed while CO_2, transferred from the cathode side, is continuously added to the H_2 stream. The mixed H_2 and CO_2 exhausts from the six modules are combined to either flow through a shutoff valve (306-38) to the CRS (Normal Mode) or through a backpressure regulator (310-32), a shutoff valve (306-39) and a hand valve (507-32) to vacuum (Dump Mode).

At a nominal flow rate of 1.77×10^{-4} m^3/s (10.6 slpm) the pressure drop across the H_2 flow and distribution mounting is 21 kN/m^2 (3.0 psid) while the pressure drop across a module is approximately 1034 N/m^2 (0.15 psid). By flowing the H_2 in series through the 16 cells of each module, each cell is supplied a minimum of 16 times the excess (above stoichiometric requirements) H_2 it would receive in a parallel arrangement. The series flow pattern eliminates the complication of subdividing the total H_2 stream into 96 parallel flow paths with a potential H_2 starvation problem.

The pressure level within the anode compartments of the modules is maintained at 34.5 ±6.9 kN/m^2 (5 ±1 psig) by regulator (310-32) during the Dump Mode or, when supplying H_2 and CO_2 to the CRS, by a similar backpressure regulator located in the CRS. Both pressure regulators are adjustable over a range of 6.9 to 69.0 kN/m^2 (1 to 10 psig) but will be set at a nominal value of 34.5 kN/m^2 (5 psig). Three pressure transducers (877-31, -32, -33) are located in the H_2, and H_2 and CO_2 passages of the CS-6. One pressure transducer (877-32) (not included in present design configuration due to overall curtailment of SSP activities) is located upstream of the H_2 flow and distribution mountings while the other two pressure transducers are located downstream of the modules in the combined anode gas exhaust line. High and low pressure shutdown levels are provided to both the primary (871-31) and the emergency (872-31) controllers. High H_2 and CO_2 backpressure could lead to eventual matrix breakthrough while low backpressure indicates lack of H_2 which may result from a cell matrix failure or interruption of the supply stream from the OGS.

The H_2 passageways of the CS-6 interface with the 207 kN/m^2 (30 psig) N_2 supply of the ARG of the SSP through two service lines (one redundant) which permit purging the passageways of H_2 during a subsystem shutdown, during subsystem startup or as commanded by the Purge Mode. The primary and redundant service lines interface through two shutoff valves (306-07, -08). Nitrogen flow, when required, is equally divided between the six modules through the two H_2 flow and distribution mountings. The same orifices that divided the H_2 flow provide an equal flow rate of 3.0×10^{-5} m^3/s (1.8 slpm) of N_2 to each module at a supply pressure of 207 kN/m^2 (30 psig). A two minute N_2 purge is supplied both during subsystem startup and shutdown. The resulting N_2 volume flowing during this time is approximately five times the volume of the H_2 passageways, sufficient to lower the H_2 level to safe values.

An exhaust valve (306-37) permits venting of the H_2 passageways to ambient following the N_2 purge prior to entering the Shutdown Mode. This purge is automatically accomplished and the pressure normally retained in the H_2 passageways by the pressure regulator or by the regulator located within the CRS is released. The exhaust of valve (306-37) is directed against the sensing element of a combustible gas sensor (178-02) to verify that complete purging of the H_2 passageways has been accomplished. This same sensor, in conjunction with a similar sensor (178-01) and an additional pair of sensors (178-03, -37), also performs a leak detection function by being mounted above H_2-carrying components and connections. Signals from these sensors are sent to FDIA and shutdown circuits. Automatic shutdowns for combustible gas are included in both primary and emergency controllers. As an added safety feature, the hand valve (507-32) provides for manually isolating the CS-6 from vacuum.

Cooling Air Stream. Cooling air is drawn from the inlet chamber of the air plenum by two independent vane axial cooling air blowers (345-31, -32) across the external fins of the cells. Two parallel and independent cooling air streams exist with each of the blowers serving one group of three modules. The amount of cooling required is determined by a signal based on a temperature differential between the dew point temperature of the incoming process air and the dry bulb temperature of the exiting process air from the modules. The two cooling air streams return simultaneously to the exit chamber of the air plenum.

To maintain moisture balance within the electrochemical cells, (i.e., prevent flooding or dryout) the temperature differential between the dew point of the incoming air and the dry bulb of the exiting air must be maintained at 10.55 ±1.67K (19 ±3F) for cells charged with 61.5 ±0.5% cesium carbonate (Cs_2CO_3) by weight and at the nominal conditions for the CS-6. The temperature differential signal is created by subtracting the temperature level sent from either of two CTHCS temperature probes (901-21, -22) (one in each CTHCS section) from the process air exhaust temperature level as measured by the redundant thermistors in the process air sensors (875-33, -34). Using the temperature signal from the CTHCS (equivalent, by definition, to process air inlet dew point) as a basis to control module temperature results in automatic module temperature tracking based on the level of the incoming process air dew point. Thus, moisture balance is automatically maintained for the process air inlet dew point range of 278 to 282K (41 to 49F) expected from the CTHCS.

The temperature of each of the two groups of three modules is controlled separately. Control is achieved by continuous modulation of cooling air blower speed resulting in a variation of cooling air flow rate over the external fins of the modules.

Maximum cooling air flow rate per group of three modules with a single blower is 9.2×10^{-2} m^3/s (195 scfm) at a maximum pressure drop of 747 N/m^2 (3 inch water).

The total air stream in the exit portion of the air plenum also serves to cool the load transistor mounting (876-31). The load transistor mounting is attached to a finned mounting plate with fins extending into the exit chamber of the plenum.

CS-6 Controllers

Electronic control circuits for the CS-6 are incorporated into two electronic enclosures called the primary controller (871-31) and the emergency controller (872-31). 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 either ACE or IMS, to interface with ACE/IMS for component overrides used in FDIA routines, to initiate shutdowns for out-of-tolerance conditions for three subsystem parameters, and to process sensor information for presentation to ACE/IMS via the DAU. The purpose of the emergency controller is to shut the subsystem down should ACE/IMS, via the primary controller or the primary controller itself, fail to do so. Functional block diagrams of the primary and emergency controllers are shown in Figures 6 and 7. Table 4 identifies all subsystem shutdowns and their respective actuation levels.

Primary Controller Operation. The primary controller controls three parameters critical to the operation of the CS-6. These parameters are module current, process air flow rate, and process air inlet-dew-point-to-module-temperature differential. Two control modes can be selected (by actuation of a switch located within the primary controller), Mode A and Mode B. In Control Mode A, the current and process air flow rate are a function of a potentiometer setting which is initially adjusted within the primary controller to a desired, constant level. In Control Mode B, both parameters are a function of an external 0-5 VDC signal, which may originate from either a cabin or process air pCO_2 sensor. Module temperature control is independent of Control Mode A or B. Trim adjustments are available within the primary controller to individually adjust, as may be required, the current to each of the six modules and/or the process air flow rates through each group of 48 cells.

In Control Mode A, the current is adjusted to 4.88 A for each 16 cell module which results in a current density of 21.5 mA/cm^2 (20 ASF). In Control Mode B, current is a function of cabin pCO_2 controlled between 333 and 373 N/m^2 (2.5 and 2.8 mm Hg). At or below the 333 N/m^2 (2.5 mm Hg) pCO_2 level, the current is automatically adjusted to 2.7 A or 11.8 mA/cm^2 (11 ASF). At or above the 373 N/m^2 (2.8 mm Hg) pCO_2 level, the current is automatically adjusted to 7.6 A or 33.4 mA/cm^2 (31 ASF). Between the high and low pCO_2 levels the current is varied linearly between the maximum and minimum values indicated.

A closed loop speed control concept is used for the process air blowers. In Control Mode A the total process air flow rate is adjusted to a constant 2.5×10^{-2} m^3/s (54 scfm). Control Mode B allows the air flow rate to vary linearly from 1.9×10^{-2} m^3/s to 3.4×10^{-2} m^3/s (40 scfm to 72 scfm) for a cabin pCO_2 range of 333 N/m^2 to 373 N/m^2 (2.5 mm Hg to 2.8 mm Hg). At lower than 333 N/m^2 (2.5 mm Hg) pCO_2, the process air flow rate remains constant at 1.9×10^{-2} m^3/s (40 scfm) while at values greater than 373 N/m^2 (2.8 mm Hg), the air flow rate remains constant at 3.4×10^{-2} m^3/s (72 scfm).

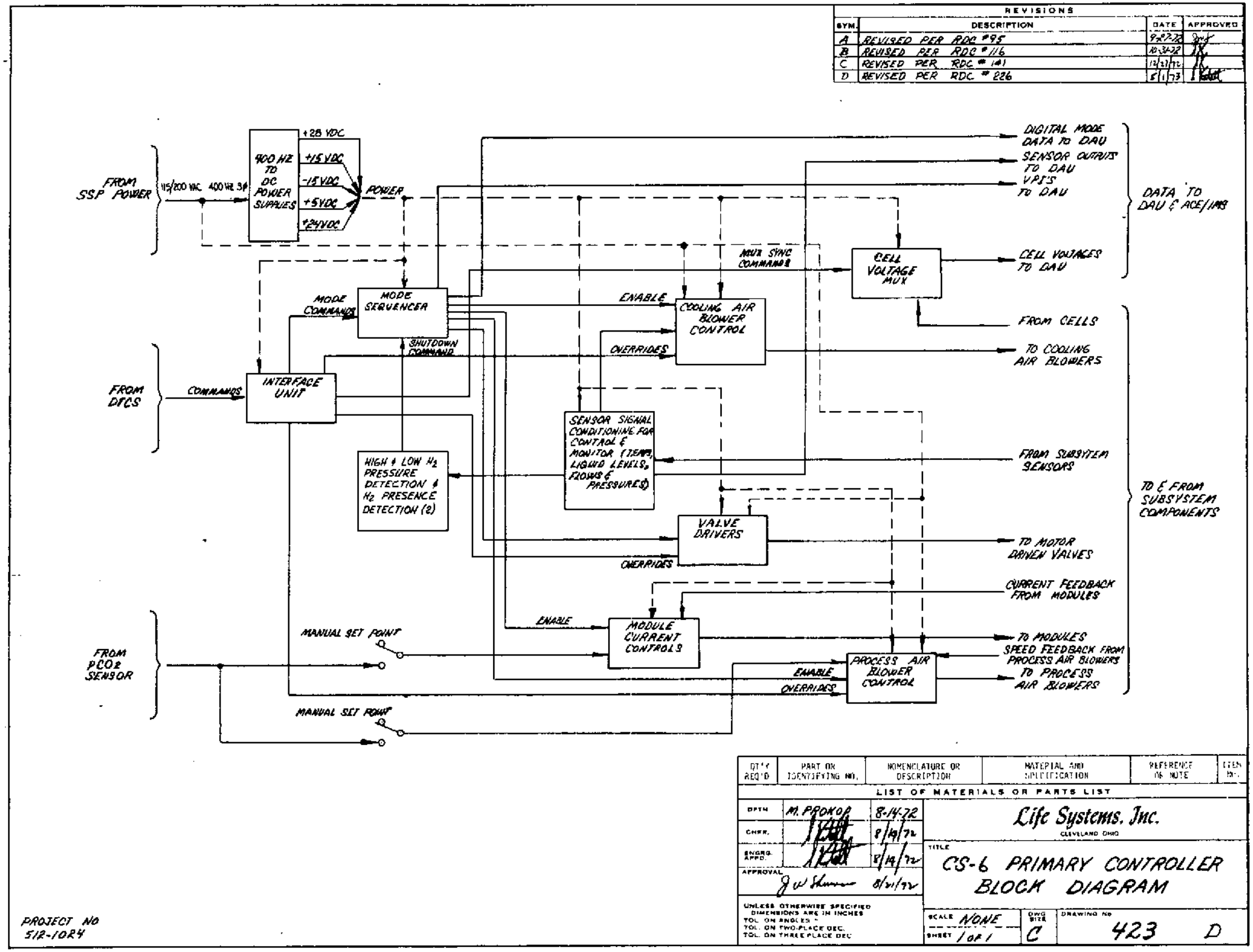


FIGURE 6 PRIMARY CONTROLLER BLOCK DIAGRAM

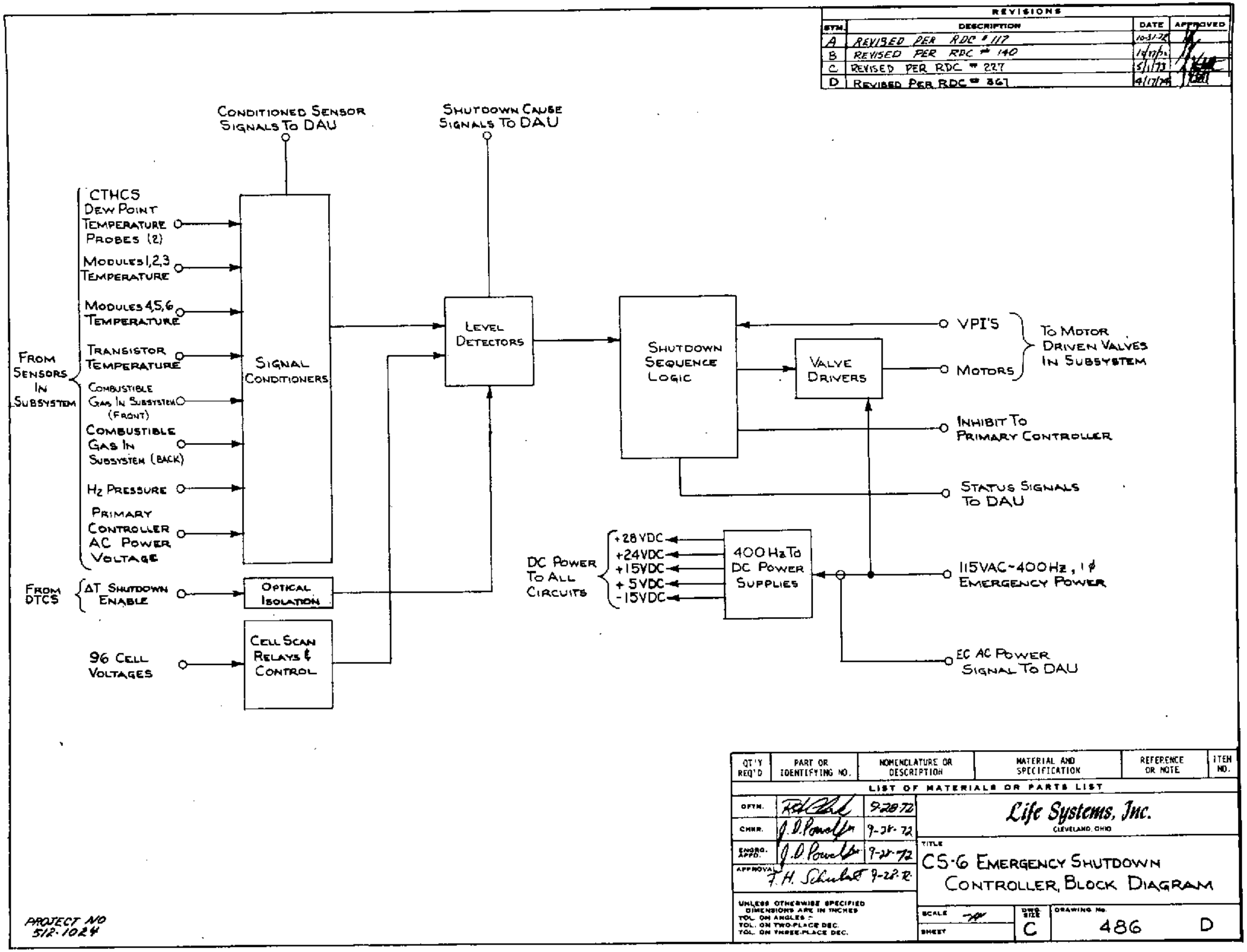


FIGURE 7 EMERGENCY CONTROLLER BLOCK DIAGRAM

TABLE 4 CS-6 SHUTDOWN LEVEL SUMMARY

Parameter	Shutdown Level ACE/IMS	PC[a]	EC[b]
High H_2 Pressure, kN/m^2 (Psig)	45 (6.5)	48 (7.0)	52 (7.5)
Low H_2 Pressure, kN/m^2 (Psig)	21 (3.0)	17 (2.5)	14 (2.0)
High Combustible Gas Sensor (Front), % H_2-in-Air	1.0	1.5	2.0
High Combustible Gas Sensor (Back), % H_2-in-Air	1.0	1.5	2.0
Module to Dew Point ΔT, K (F)			
Low	9.4 (17)	-	8.9 (16)
High	11.7 (21)	-	12.2 (22)
Low Cell Voltage, V	-0.10	-	-0.25
High Transistor Temperature, K (F)	355 (180)	-	366 (200)

(a) PC = Primary Controller
(b) EC = Emergency Controller

The speed of the cooling air blowers in the system is modulated by a composite signal which is a function of incoming process air dew point and the module temperature. This speed control system automatically controls module temperature as a function of the dew point of the incoming process air.

The constant values selected for current and process air flow rate for Control Mode A are sufficient to maintain the modules of the Space Station at 400 N/m^2 (3.0 mm Hg) pCO_2 or less for the SSP specified CO_2 generation profile. In this control mode the cabin volume is allowed to act as an accumulator since CO_2 removal rate does not necessarily match CO_2 generation rate. In Control Mode B the removal rate of CO_2 closely follows the generation rate of CO_2. In this mode, smaller fluctuations in cabin pCO_2 occur since the CO_2 removal rate is a function of cabin pCO_2, which is directly related to CO_2 generation rate. A higher average CO_2 removal efficiency is achieved with Control Mode B due to the higher average process air inlet pCO_2 and higher air flows at higher current densities.

In addition to controlling the above parameters, the primary controller sequentially actuates subsystem components to place them in the proper configuration as dictated by either an operating mode command from ACE/IMS or, by an out-of-tolerance condition. The sequence control area contains sequences to configure the system into Normal Mode, Shutdown Mode, Purge Mode, Dump Mode or Standby Mode. Initiation of the proper sequence for the CS-6 to enter any mode except Shutdown Mode can only begin upon receipt of the mode command from ACE/IMS. The sequence for the CS-6 to enter Shutdown Mode, however, can be initiated by either a command from ACE/IMS or by a shutdown command from within the primary controller.

A shutdown command internal to the primary controller is initiated when crew safety or major equipment damage (that which cannot be repaired by replacing a LRU) are concerned and when corrective action cannot wait more than one minute to complete. Three parameters of the CS-6 qualify. They are high or low H_2 pressure as sensed by the H_2 pressure transducer and the presence of H_2 being sensed by one of the combustible gas sensors.

Low H_2 pressure can be an indication of a H_2-to-air crossover. However, no combustible mixture will result even if all the H_2 flowing were to mix with the process air. High H_2 pressure indicates a blockage, an improperly positioned valve or possibly a leakage of the H_2 or N_2 supply valves into the anode gas passages of the subsystem. If this pressure exceeds the breakthrough pressure of the matrices of the cells, irreversible damage could occur. Hydrogen pressure buildup can occur very rapidly and could cause damage in less than the one minute worst case time period ACE/IMS might take to recognize this high pressure condition and command subsystem shutdown.

External leaks of H_2 to ambient may cause combustible gases to be released into the cabin atmosphere. Immediate subsystem shutdown is required to prevent localized H_2-in-air buildup beyond the explosive limit (4% H_2-in-air). Combustible gas sensors are mounted in two locations on the subsystem, above H_2-carrying components in the rear of the subsystem and above similar components in the front of the subsystem. A sensor from each location is routed to the circuits of the primary controller for shutdown.

The quantitative values at which primary controller initiated shutdowns occur are 48 kN/m^2 (7.0 psig) for high H_2 pressure, 17 kN/m^2 (2.5 psig) for low H_2 pressure, as sensed by the pressure transducer (877-31), and a 1.5% H_2-in-air mixture ratio as sensed by either the front (178-03) or rear (178-01) located combustible gas sensor.

During all mode transitions that result in the CS-6 being configured into the Shutdown Mode, the low pressure shutdown signal is inhibited prior to depressurization of the anode gas compartments. This prevents an emergency controller shutdown sequence from being initiated each time that the subsystem is being shut down. The high H_2 pressure and the combustible gas sensor signals are never inhibited.

A number of circuits in the primary controller are grouped together to function as an Interface Unit (IU). The IU provides the required optical isolation for all input commands from ACE/IMS and retains all mode commands in a solid-state memory. The IU is designed such that all component override commands must be continuous while all mode commands must have a minimum time duration of 100 milliseconds. The IU also interfaces with the signals from ACE/IMS indicating which one of the two sections within the CTHCS is operating, provides the master/slave circuitry for interfacing with the DAU and provides a clock interface between ACE and the primary controller cell voltage multiplexer.

A cell voltage multiplexer is contained in the primary controller. This multiplexer presents the 96-cell voltages to the DAU as three groups of 32. The cell group being sent to the DAU can change upon command from the Digital Test Command Sequencer (DTCS) (part of ACE) or upon receiving a pulse from an internal clock within the primary controller. The recommended multiplex command rate from the DTCS is one clock pulse every 10 seconds. All three cell groups therefore, are monitored every 30 seconds. Also sent to the DAU from the multiplexer are two digital bits identifying which of the three groups of cell information is being sent to ACE/IMS.

Additional circuits are located in the primary controller to process information sent to ACE/IMS. The types of information processed by these circuits are analog items such as process air flow, module temperature and process air blower speed. In addition, digital information is processed by the primary controller to indicate to ACE/IMS shutdown causes and system mode status.

Emergency Controller Operation. The major functional part of the emergency controller is a shutdown sequencer which provides for proper component sequencing during an emergency controller initiated subsystem shutdown. Out-of-tolerance condition for any one of eight independent subsystem parameters can cause the emergency controller to initiate a shutdown sequence. The first condition is a high or low differential between the module temperature and the dew point temperature of the inlet process air. The module temperature is compared against the dew point temperature from the CTHCS subsystem and if the module temperature either exceeds a level of 12.2K (22F) above the dew point temperature of the inlet process air, or drops to less than 8.9K (16F) above the dew point temperature, the shutdown sequence will be initiated in the emergency controller.

Each of the two sections[(a)] in the subsystem have separate high and low temperature differential shutdowns. A shutdown command from either section, however, will shut down the total subsystem. The second condition to cause an automatic shutdown is when the power transistors in the primary controller heat sink assembly heat up to over 366K (200F). The third condition is the detection of a greater than 2% H_2-in-air mixture sensed by a combustible gas sensor (178-37) located in the front of the subsystem. The fourth is caused by a similar H_2-in-air percentage sensed by a combustible gas sensor (178-02) located in the rear of the subsystem. The fifth condition is the detection of a H_2 exhaust pressure (pressure transducer 877-33) in excess of 52 kN/m^2 (7.5 psig) which shuts the subsystem down without a N_2 purge. The sixth condition for a shutdown is the detection of the loss of primary controller power. The seventh condition for a shutdown is H_2 exhaust pressure less than 14 kN/m^2 (2.0 psig), again detected by LRU 877-33. The eighth emergency controller initiated shutdown is caused by the detection of low cell voltage in any one of the 96 cells. Cell voltage scanning circuits automatically and continuously scan each of the 96 cells and if any of the cell voltages drop below -0.25V, the shutdown sequence in the emergency controller will be initiated.

The emergency controller provides an inhibit signal to the primary controller as soon as an emergency controller shutdown sequence has been initiated. Once the emergency controller shutdown sequence has been started, it is carried through to completion. After the shutdown sequence is initiated or after it is completed, the only means by which the emergency controller can be reset is by removing emergency power. The emergency controller sends outputs to ACE/IMS via the DAU to indicate when the controller is in the shutdown mode and which parameter has initiated the subsystem shutdown.

Subsystem Interfaces

The CS-6 removes CO_2 from the cabin atmosphere and delivers it premixed with H_2 to the CRS (Sabatier Reactor). At this interface, the nominal supply rate of H_2 to the CRS in the CS-6 exhaust gas stream is 0.036 kg/h (0.079 lb/hr) while the nominal CO_2 supply rate is 0.25 kg/h (0.55 lb/hr). The CS-6/CRS interface requires that the ACE/IMS computer system recognize when the CRS is not operating and configure the CS-6 into the Dump Mode.

The H_2 required for the operation of the CS-6 is supplied by the OGS. The nominal H_2 consumption rate for the CS-6 is 0.0166 kg/h (0.0365 lb/hr) and the dew point of the H_2 gas stream is 262K (13F). The CS-6/OGS interface also requires that the ACE/IMS computer system recognize when the OGS is not operating and configure the CS-6 in Shutdown Mode.

The process air for the CS-6 is supplied by the CTHCS which controls the temperature and the dew point temperature of the incoming process air. Precise control of these two parameters is essential for optimum CS-6 operation.

A supply source of N_2 is also a required interface for the CS-6. Nitrogen is used as the purge gas for all safety-required purging of the subsystem. The

(a) Section one consists of submodules 890-31, -32 and -33. Section two consists of submodules 890-34, -35 and -36.

required N_2 flow rate for a nominal two minute purge is 0.68 kg/h (1.50 lb/hr) at a regulated pressure of 207 kN/m^2 (30 psig).

Commands to the CS-6 subsystem as well as data acquisition are handled by an electrical interface with the ACE/IMS computer. There are 42 separate command stimuli required of the ACE/IMS computer system and 126 pieces of measurement data sent out to the ACE/IMS computer system via the DAU. A listing of the CS-6 measurement data mix is shown in Table 5.

A complete definition of all functional interfaces is found in Engineering Report ER-170-39, "The Electrochemical CO_2 Concentrating Subsystem Interface Specifications for the SSP."

Hardware Description

The CS-6 was designed and fabricated based on a LRU concept. All major components such as modules, blowers, valves, etc. can be easily maintained using minimum tools, fluid line quick-connects and electrical connectors. The total subsystem consists of a series of LRUs mounted in a supporting structure with interconnecting plumbing and wiring. Figure 8 shows a front view and Figure 9 a back view of the complete CS-6 subsystem. 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^2). The CS-6 is subdivided into 15 LRUs as shown in Table 6. A short functional description of each LRU follows.

1. Electrochemical Module (SSP Item 890) - The electrochemical module removes CO_2 from the process air. This is done via an overall reaction of:

$$O_2 + 2CO_2 + 2H_2 = 2CO_2 + 2H_2O + \text{Elec. Energy} + \text{Heat} \qquad (1)$$

   Figure 10 shows the electrochemical module.

2. Cooling Air Blower (SSP Item 345) - The cooling air blowers draw air from the subsystem air plenum over external fins of the electrochemical modules to maintain module temperature at the desired level. Figure 11 shows a cooling air blower.

3. Process Air Blower (SSP Item 543) - The process air blowers draw air through the electrochemical modules. The blowers are located downstream of the modules to eliminate the effects of air temperature rise caused by blower heat generation. Figure 11 shows a process air blower.

4. Combustible Gas Sensor (SSP Item 178) - The combustible gas sensors sense leaks in H_2-carrying components and verify complete subsystem purging. Figure 12 shows a combustible gas sensor.

5. Process Air Sensor (SSP Item 875) - A process air sensor is mounted at the air inlet to each section of electrochemical modules and another at the process air exhaust of each section of modules. The inlet

TABLE 5 CS-6 MEASUREMENT DATA MIX

Type or Range of Measurement	Quantity
0 to +5 VDC	48
-0.5 to +1.250 VDC	32
Frequency	2
0/5V discrete	44
Total Pieces of Data	126

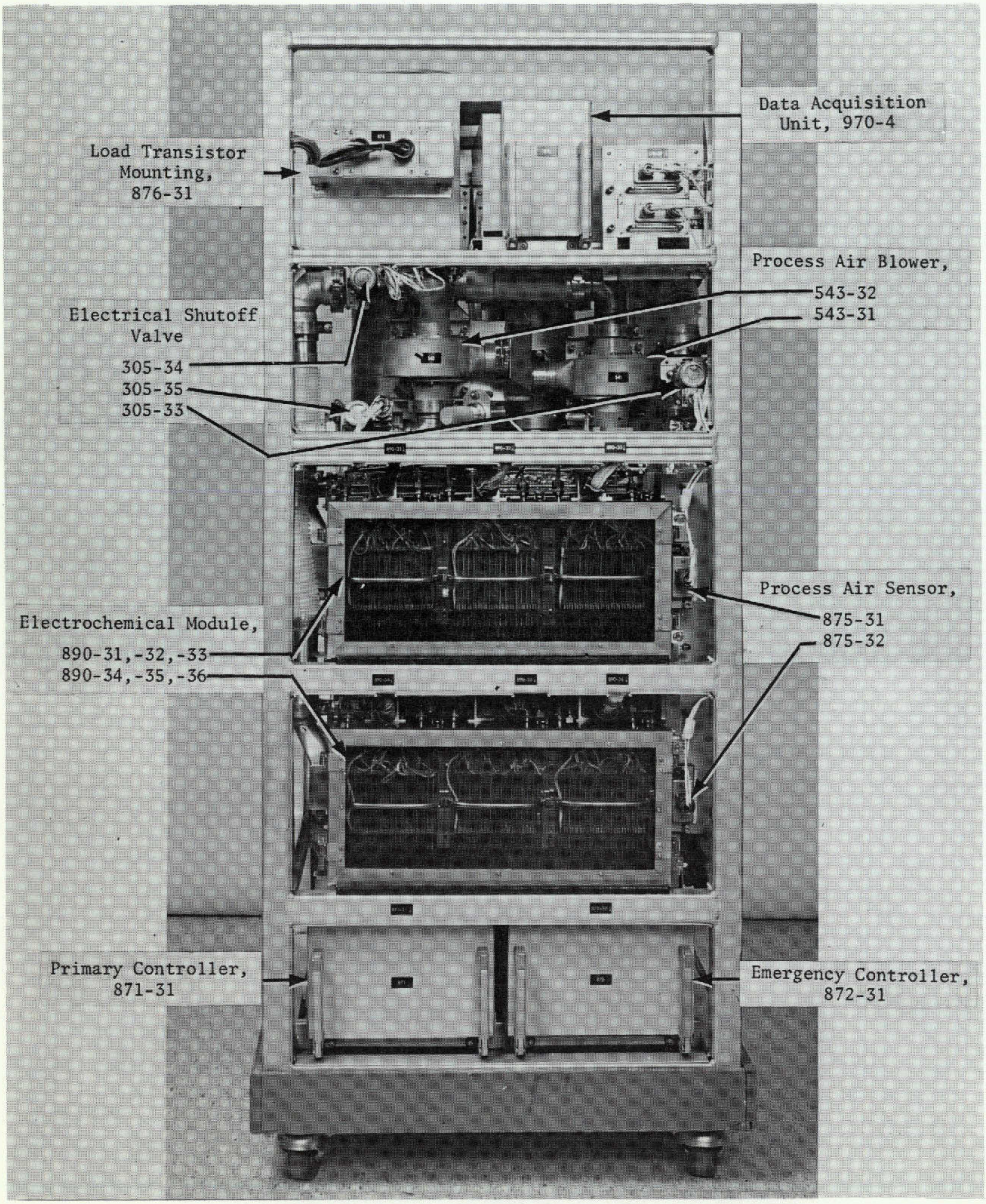


FIGURE 8 CS-6 SUBSYSTEM (FRONT)

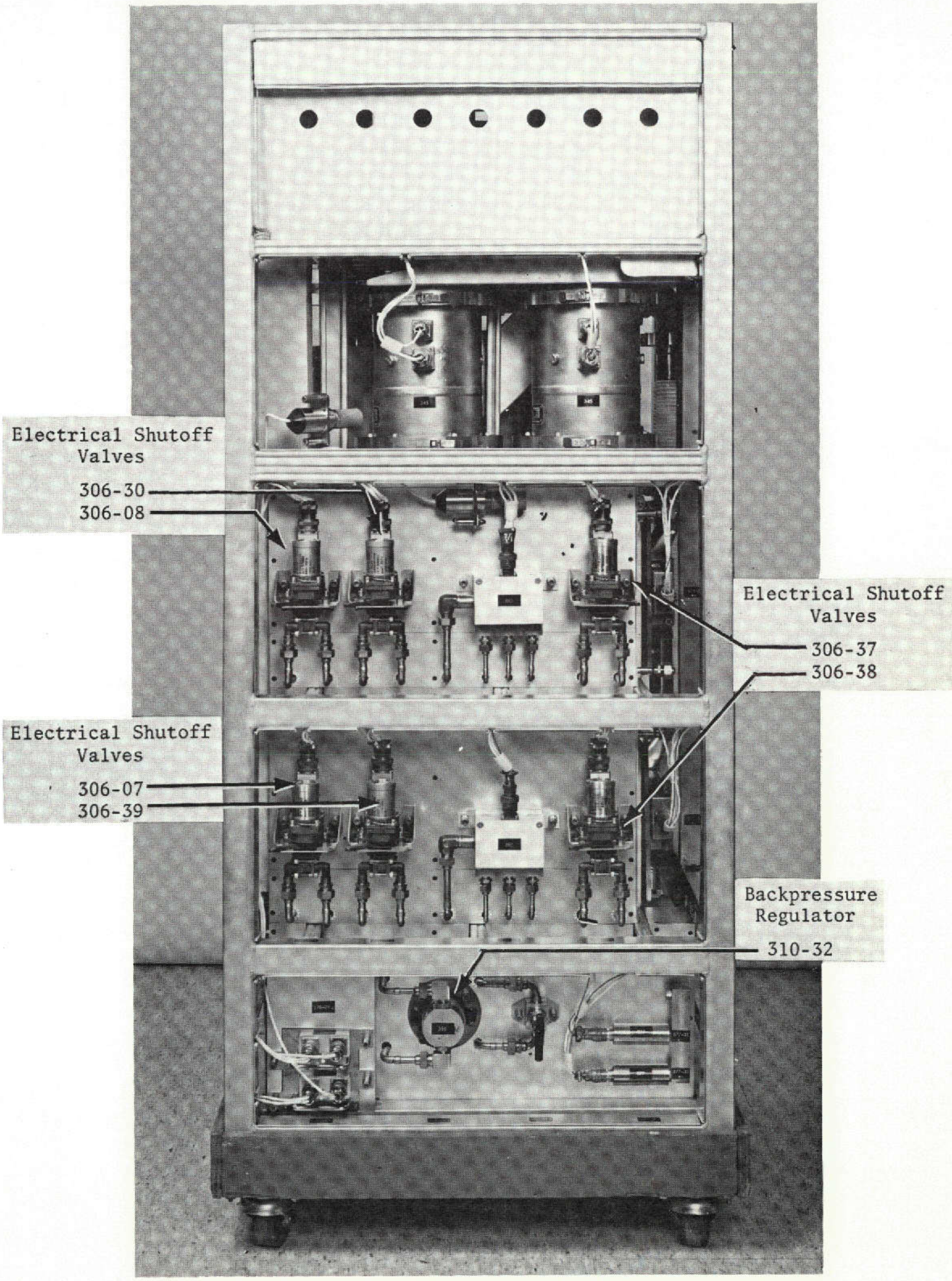


FIGURE 9 CS-6 SUBSYSTEM (BACK)

TABLE 6 CS-6 LINE REPLACEABLE UNITS

Item	Qty. No.	LSI Part No.	Description/Title/Name	Dwg. No.	SSP Item No.
1	6	410	Module, Electrochemical	LSI-J-410	890-31 890-32 890-33 890-34 890-35 890-36
2	2	N/A[a]	Blower, Process Air		543-31 543-32
3	2	N/A[a]	Blower, Cooling Air		345-31 345-32
4	4	501	Sensor, Process Air	LSI-D-501	875-31 875-32 875-33 875-34
5	3	N/A[a]	Valve, Shutoff, Electric, Manual Override		305-33 305-34 305-35
6	6	N/A[a]	Valve, Shutoff, Electric, Manual Override		306-07 306-08 306-30 306-37 306-38 306-39
7	2	437	Mounting, H_2 Flow & Distribution	LSI-D-437	882-31 882-32
8	1	N/A[a]	Valve, Regulator, Backpressure		310-32
9	2	N/A[a]	Sensor, Pressure		877-31 877-33
10	4	N/A[a]	Sensor, Combustible Gas		178-01 178-02 178-03 178-37
11	1	440	Controller, Primary	LSI-J-440	871-31
12	1	442	Controller, Emergency	LSI-E-442	872-31
13	1	N/A[a]	Unit, Data Acquisition	LSI-A-451	970-4
14	1	475	Mounting Load Transistors	LSI-D-475	876-31
15	1	N/A[a]	Valve, Shutoff Manual		507-32

(a) N/A = Not Applicable

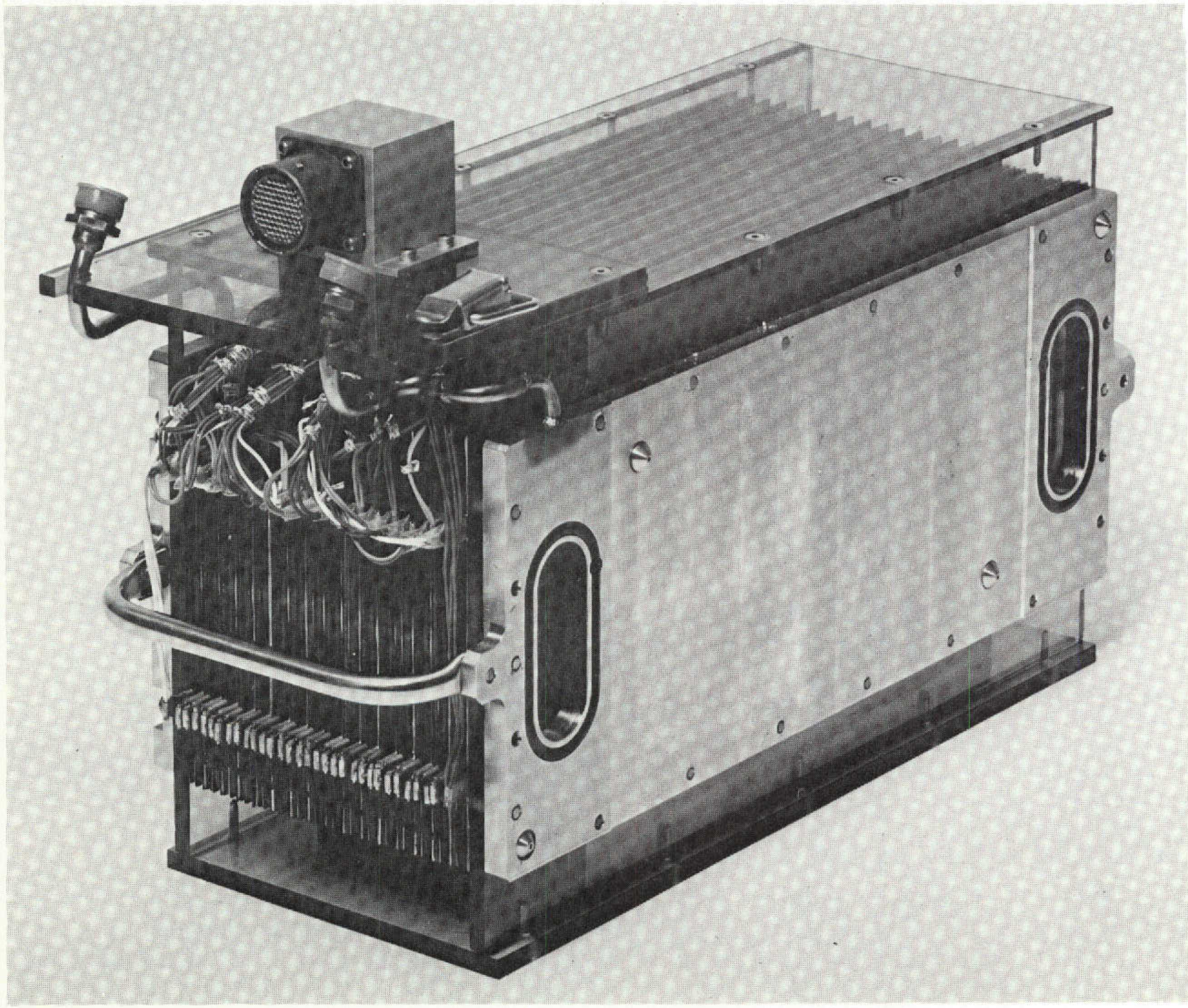


FIGURE 10 ELECTROCHEMICAL MODULE

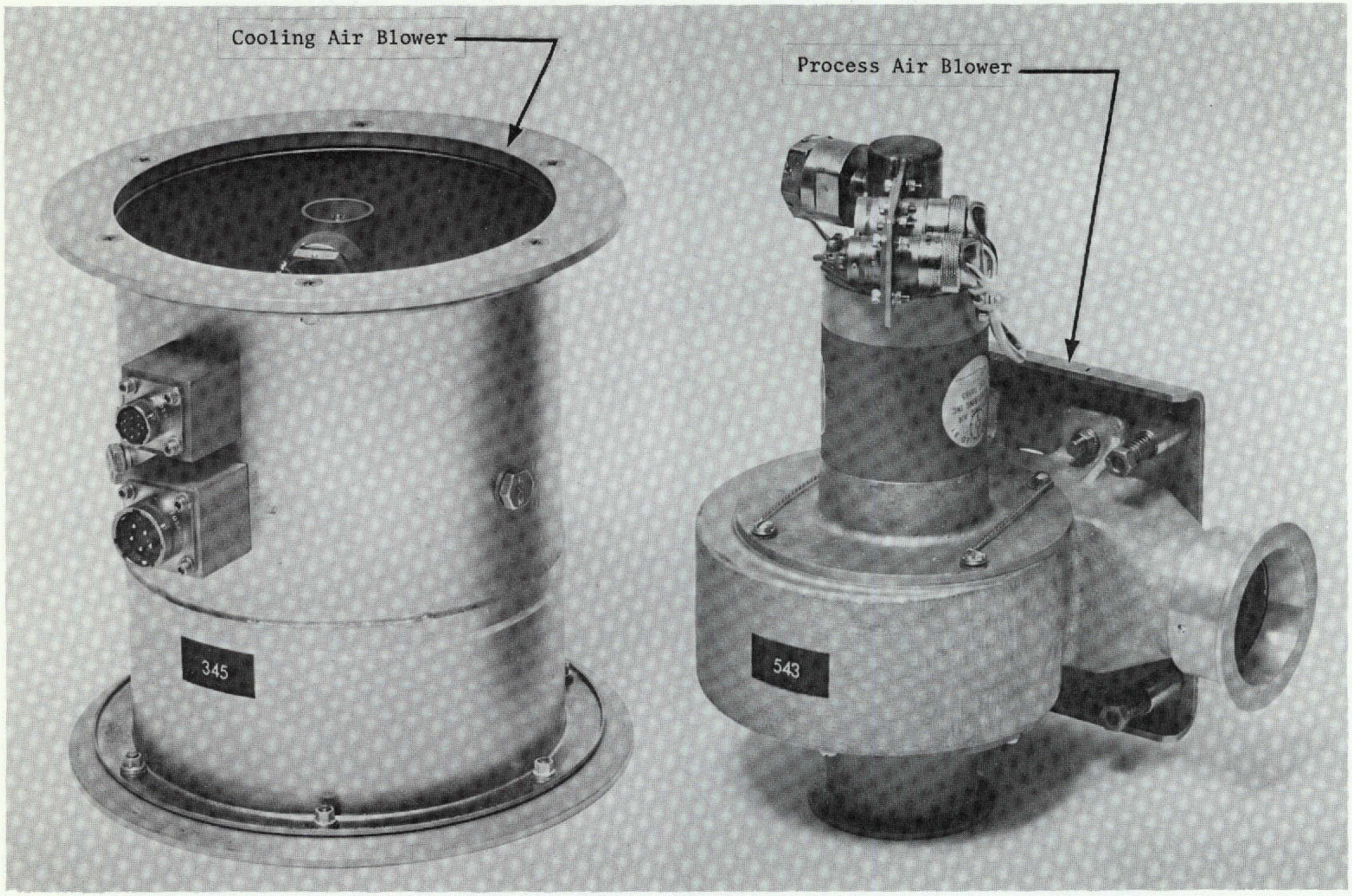


FIGURE 11 COOLING AIR BLOWER AND PROCESS AIR BLOWER

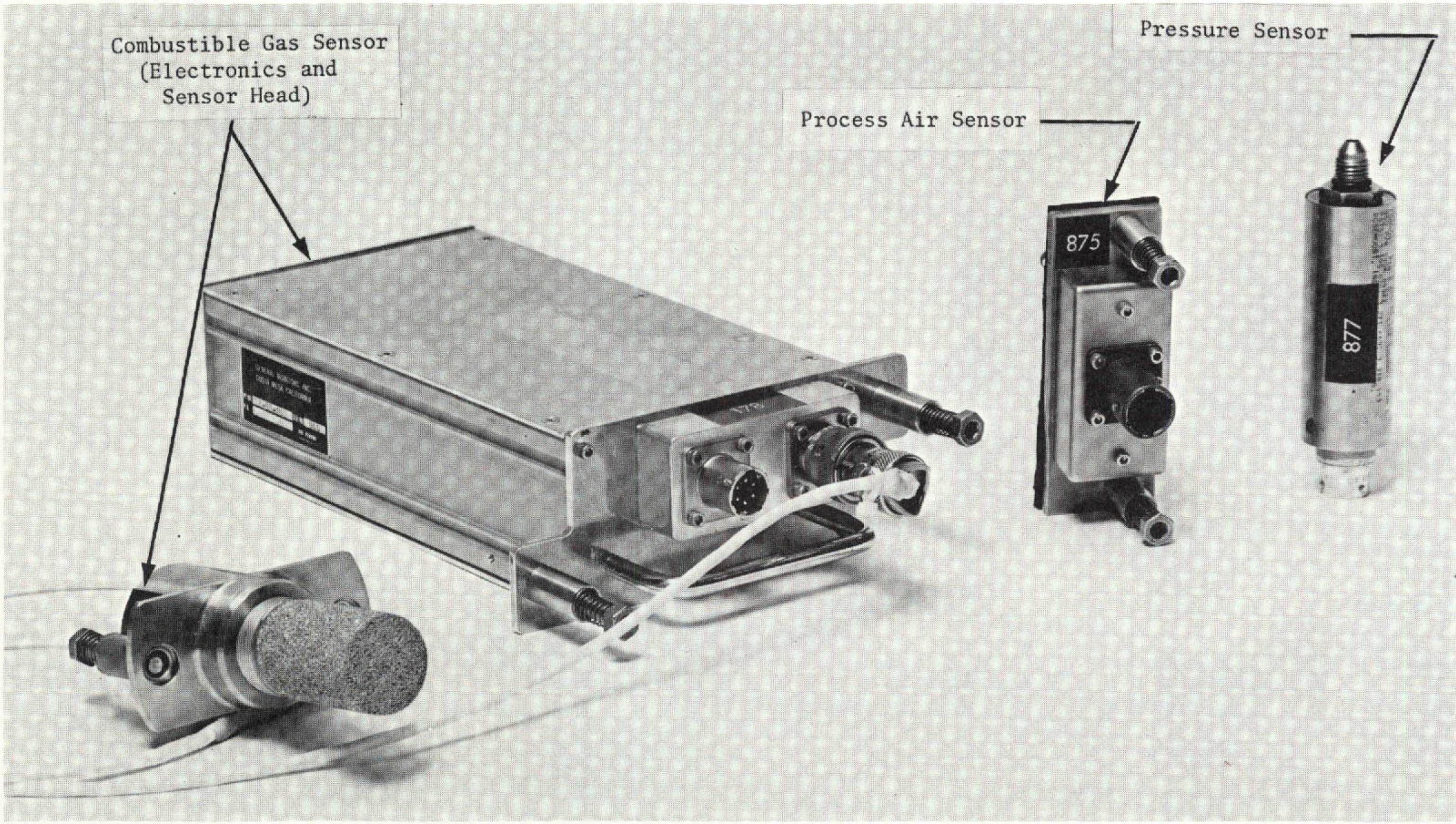


FIGURE 12 COMBUSTIBLE GAS SENSOR, PROCESS AIR SENSOR AND PRESSURE SENSOR

sensor measures air flow rate and air inlet temperature. The process air sensor at the exhaust of the modules measures process air exhaust temperature and detects any liquid entrained in the exhaust air stream of the modules. Figure 12 shows a process air sensor.

6. Pressure Sensor (SSP Item 877) - The function of the pressure sensor is to sense the pressure in the H_2 inlet line and the H_2 + CO_2 outlet lines to insure that both pressure levels are within specifications. Figure 12 shows a pressure sensor.

7. Manual Override, Electric Shutoff Valve (SSP Item 306) - The manual override, electric shutoff valve opens and closes various gas paths as required during the operation of the subsystem. Figure 13 shows a manual override, electric shutoff valve.

8. Manual Shutoff Valve (SSP Item 507) - The manual shutoff valve provides manual isolation from vacuum of the subsystem H_2 + CO_2 exhaust, when required. Figure 13 shows a manual shutoff valve.

9. Manual Override, Electric Shutoff Valve (SSP Item 305) - The manual override, electric shutoff valve opens and closes the process air paths as required during the operation of the subsystem. Figure 13 shows a manual override, electric shutoff valve (305).

10. Backpressure Regulator Valve (SSP Item 310) - The backpressure regulator valve insures that the exhaust from the six modules is kept at a constant backpressure. Figure 14 shows the backpressure regulator valve.

11. H_2 Flow and Distribution Mounting (SSP Item 882) - The H_2 flow and distribution mounting divides the H_2 flow into three equal portions through the use of fixed orifices and senses the H_2 flow rate in each of the three parallel paths. Figure 14 shows a H_2 flow and distribution mounting.

12. Primary Controller (SSP Item 871) - The primary controller controls all functions critical to the operation of the subsystem and interfaces with the SSP Data Management System. Figure 15 shows the primary controller.

13. Emergency Controller (SSP Item 872) - The emergency controller shuts down the subsystem should any parameters reach levels where crew safety could be compromised or where equipment could be permanently damaged. Figure 15 shows the emergency controller.

14. Load Transistor Mounting (SSP Item 876) - The load transistor mounting provides for an air-cooled mounting of the load transistors required in the closed loop current control system for the electrochemical modules. Figure 15 shows the load transistor mounting.

15. Data Acquisition Unit (SSP Item 970) - The DAU selects, conditions, and digitizes its complement of input signals, and stores them for subsequent output to the ACE/IMS Data Management System.

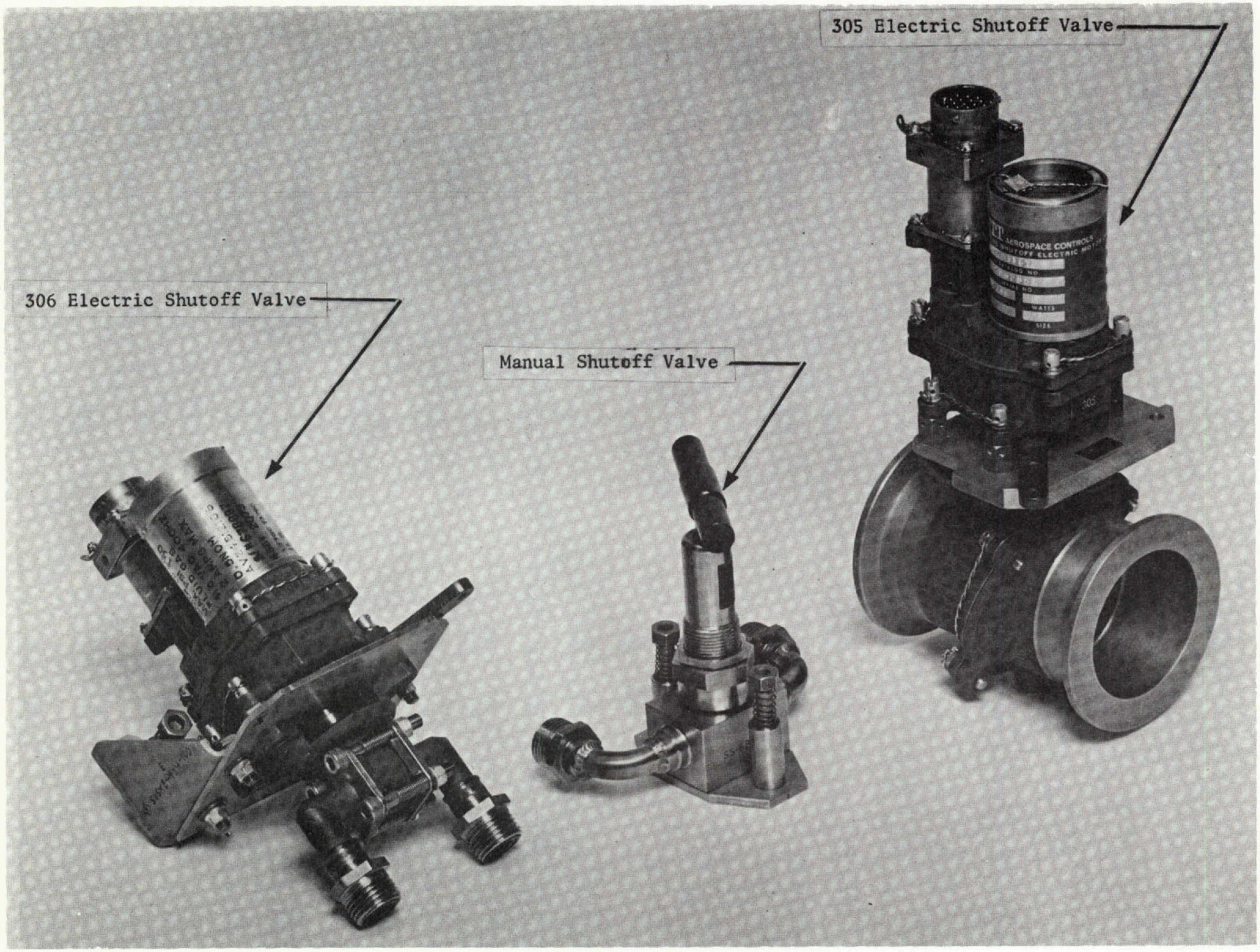


FIGURE 13 ELECTRIC SHUTOFF VALVE (306), MANUAL SHUTOFF VALVE AND ELECTRIC SHUTOFF VALVE (305)

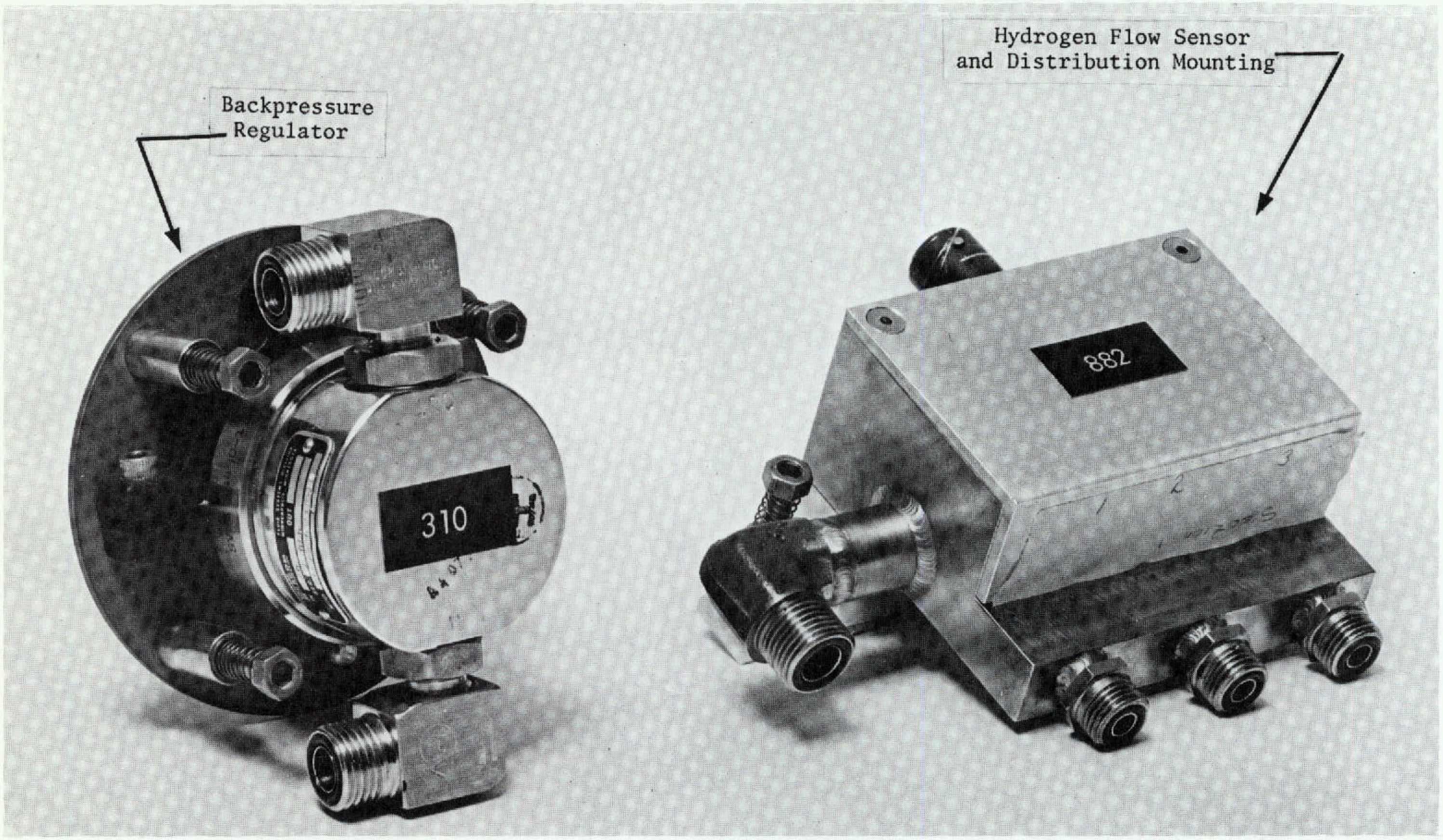


FIGURE 14 BACKPRESSURE REGULATOR AND H_2 FLOW AND DISTRIBUTION MOUNTING

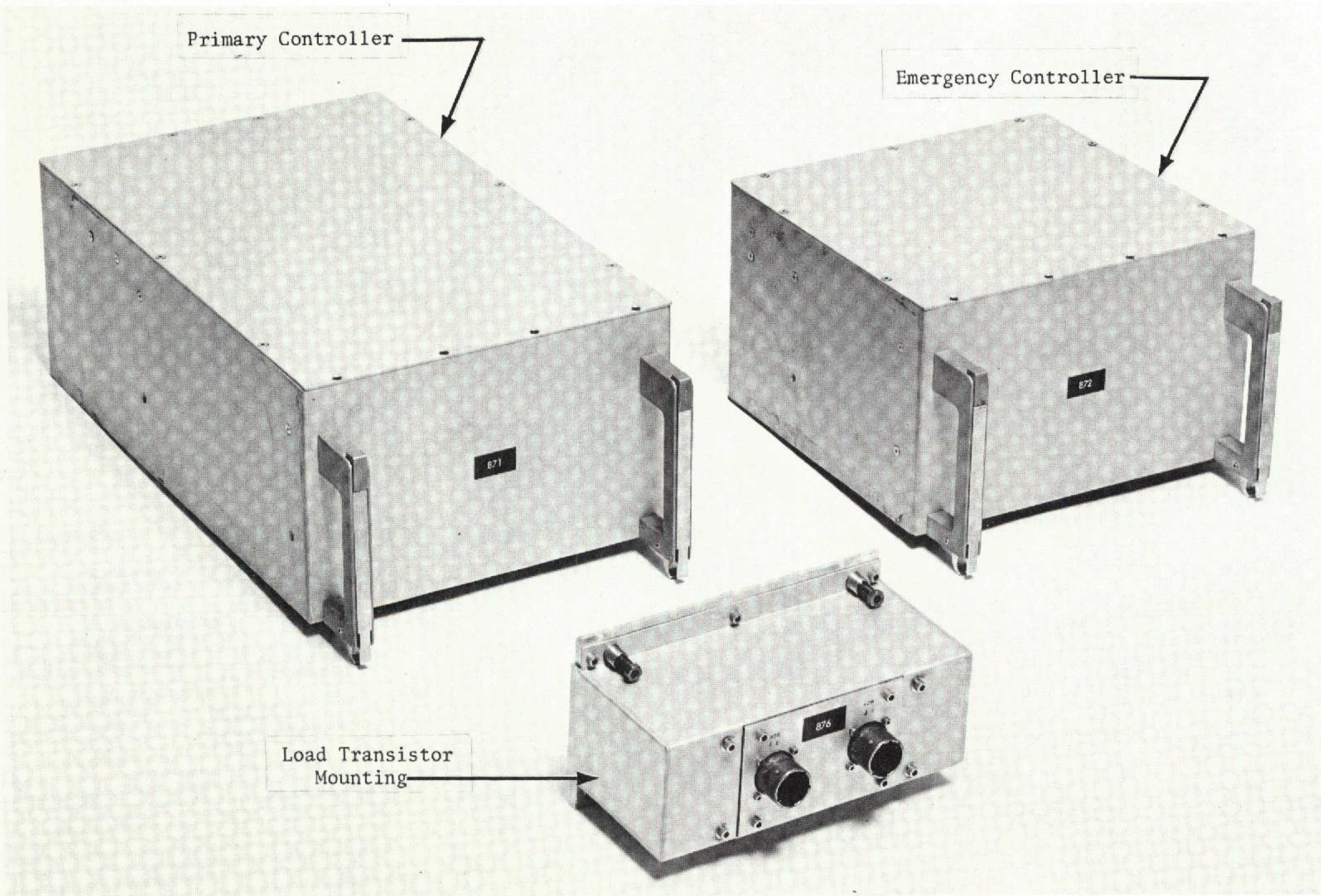


FIGURE 15 PRIMARY CONTROLLER, LOAD TRANSISTOR MOUNTING
AND EMERGENCY CONTROLLER

PRODUCT ASSURANCE PROGRAM

The Product Assurance Program implemented for the design, development, fabrication, assembly and testing of the CS-6 included Quality Control, Reliability, Maintainability, Materials Control, and Safety.

Quality Control

The Quality Control functions performed during the design, development, fabrication, assembly and testing of the CS-6 were the following:

1. Preparation of the Quality Assurance Program Plan for the CS-6 (ER-170-8A).

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

3. Maintenance of records of all supplier inspections and certifications of all non-conforming items, and corrective actions.

4. Maintenance of configuration control by ensuring that the Life Systems Drawing and Change Control procedures were followed.

5. Monitoring of component and subsystem DVTs and of the final Subsystem Acceptance Test. This included review of test plans and test results.

6. Monitoring electrical engineering conformance to NASA/Ames Reliability and Quality Assurance Requirement, Q-11, "Electrical/Electronic Equipment and Assemblies."

7. Participation in design reviews.

8. Preparation of the Acceptance Data Log (see Table 7).

Reliability

The reliability tasks performed are listed below.

Reliability Math Model and Block Diagram

A reliability analysis (ER-170-14B) was performed on the CS-6 design. The reliability goal for the CCS of the SSP ETC/LSS was 0.999750 for a two-year mission with 180 day resupply intervals. The analysis revealed that in order to exceed the reliability goal, spares as listed in Table 8, would be required. The spared reliability of the CS-6 is 0.999979. The expected number of failures for the 180-day mission profile is 0.870; this results in a Mean-Time-Between-Failure (MTBF) of 4,966 hours.

Failure Modes, Effects and Criticality Analysis (FMECA)

The FMECA (ER-170-16B) presents all hypothesized equipment failure modes and classifies each according to criticality as listed below.

TABLE 7 ACCEPTANCE DATA LOG CONTENTS

1.	As-Built Configuration List	ER-170-11a[a]
2.	Assembly/Inspection Record	ER-170-11b
3.	Rejection and Rework Record	ER-170-11c
4.	Design Verification and Electrochemical CO_2 Collection Subsystem Level Test Procedures and Data	ER-170-11d
5.	Design Verification and Electrochemical CO_2 Collection Subsystem Level Test Failure Reports	ER-170-11e
6.	Waiver/Deviations	ER-170-11f
7.	DD Form 250	ER-170-11g

(a) Life Systems, Inc. Engineering Report

TABLE 8 SPARES LIST

SSP Item No.	LSI Part Number	Name	Launch Spares
890	410	Module, Electrochemical	2
None	None	Electrochemical Cells	4[a]
305	N/A[b]	Valve, Shutoff, Electric, Manual Override	3
875	501	Sensor, Process Air	2
543	N/A	Blower, Process Air	3
178	N/A	Sensor, Combustible Gas	3
306	N/A	Valve, Shutoff, Electric, Manual Override	4
882	437	Mounting, H_2 Flow & Distribution	2
877	N/A	Sensor, Pressure	3
310	N/A	Valve, Regulator, Backpressure	2
345	N/A	Blower, Cooling Air	3
871	440	Controller, Primary	2
872	442	Controller, Emergency	2
876	475	Mounting, Load Transistors	2

(a) Four electrochemical cells can be maintained insitu without altering module performance.
(b) N/A = Not Applicable

Criticality

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

The analysis was used to identify safety hazards and single failure points and was used in conjunction with the FDIA to ensure that instrumentation for complete fault isolation was included in the subsystem design. An example of an FMECA is presented in Figure 16.

The FMECA identified 11 criticality IIa failure modes. Eight are associated with external leakage of the components in the H_2 or $H_2 + CO_2$ lines. Two are associated with H_2 crossover in the electrochemical modules. The other is the "fail low" failure mode of the combustible gas sensors.

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 of the FMECA).

An SPFA (ER-170-17B) was performed on the CS-6 for three 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, and
3. combustible gas detector failure exhibiting a continually low output reading.

The SPFA described the safety consequences of each hazardous failure mode, documented the corrective action taken to minimize the hazard and detailed the justification for retaining the hazard.

Failure Reporting Procedure/Reliablility Data Reports

A Failure Reporting Procedure (ER-170-18) was prepared to establish and document the requirements for reporting, investigating and correcting component and subsystem failures during DVT and Acceptance Testing of the subsystem.

Life Systems, Inc. CLEVELAND, OHIO 44122	**FAILURE MODE, EFFECTS & CRITICALITY ANALYSIS**	PAGE OF	REVISION LTR. / DATE

TITLE: VALVE, SHUTOFF, ELECTRICAL, MANUAL OVERRIDE ITEM 305-33, 34, 35

☐ SUBSYSTEM ☐ LOOP ☒ COMPONENT

PART NO.	RELIABILITY LOGIC NO.	NAME	FUNCTION
430	21 & 24	Electrical Shutoff valve with manual override	To isolate the electrochemical modules in the event of cabin depressurization

FAILURE MODE AND CAUSE:	CRITICALITY
a) fail open	III
b) fail closed	III
c) external leakage	III

FAILURE EFFECT ON COMPONENT/FUNCTIONAL ASSEMBLY:

a) air flows through valve at all times
b) air flow through the valve ceases
c) cabin air leaks into process air stream through the valve

FAILURE EFFECT ON SYSTEM/SUBSYSTEM:

a) Unable to isolate the electrochemical modules in the event of cabin depressurization. Module moisture balance would be lost. All modules would have to be replaced.
b) Unable to start CO_2 collection function after depressurization until maintenance on 305 valve is performed.
c) none

FAILURE DETECTION METHOD:

a) Fault Detection Isolation Analysis A.1.2
b) Fault Detection Isolation Analysis A.1.1
c) None, except if valve also leaks when in closed position. If so, then it is impossible to isolate the electrochemical modules in the event of cabin depressurization. Module Moisture balance would be lost.

CREW ACTION REQUIRED:	TIME REQD.	TIME AVAIL.
a) Close 305 valve using manual override, replace 305 valve before restarting subsystem	24 min	
b) Replace 305 valve	5 min	
c) Replace 305 valve	5 min	

FIGURE 16 FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS

A Reliability Data Report (ER-170-19) was prepared for the four component failures that occurred during the DVT and Acceptance Testing of the CS-6. The four failures were:

1. A process air blower (SSP Item 543) failed when the set screw holding the rotor to the blower shaft became loose and allowed the rotor to contact the blower housing.
2. A microswitch on motor-driven N_2 purge valve (SSP Item 306-08) failed. The microswitch was not sensing that the valve was in the closed position.
3. Both motor-driven N_2 purge valves (SSP Items 306-07 and 306-08) exhibited internal leakage. The leak rate was 0.167 cm^3/s (10 sccm) at a N_2 pressure of 207 kN/m^2 (30 psig).
4. Combustible gas sensor (SSP Item 178-03) failed with its output continually reading low. The sensor read -3.17 volts in all tested atmospheres (e.g., 0.5% H_2-in-air and 1.9% H_2-in-air).

Fault Detection/Isolation Analysis (FDIA)

A FDIA (ER-170-25B) was performed on the CS-6. The purpose of the FDIA was to establish the instrumentation requirements for complete automatic fault detection and isolation of each LRU and to document, in the form of block diagrams, the logic required to isolate a malfunction. Work on the software package ceased at the 80% complete level as a result of the SSP program replan.[1]

The FDIA logic consists of four routines: a Mode Test, a Monitoring Routine for the mode in which the CS-6 is operating, a Monitoring Logic Routine for Continuously Monitored Parameters, and a Fault Isolation Routine. The Mode Test Routine and examples of the Monitoring Logic for Continously Monitored Parameters Routine and the Fault Isolation Routine are presented in Figures 17, 18 and 19, respectively.

Maintainability

The maintainability activities performed in conjunction with the design of the CS-6 were:

1. Participation in design and mock-up reviews to ensure that the SSP maintainability guidelines were satisfied.
2. Documentation of design features that result in increased MTBF or decreased maintenance time (e.g., subsystem overdesign, equipment protection features, labeling of LRUs, etc.). These are documented in the Maintainability Analysis Summary Report (ER-170-24).
3. Preparation of CS-6 Operation and Maintenance Manual (ER-170-36).

A maintenance summary describing the tools required, maintenance access, and maintenance time required is presented in Table 9. An example LRU maintenance procedure is listed in Figure 20.

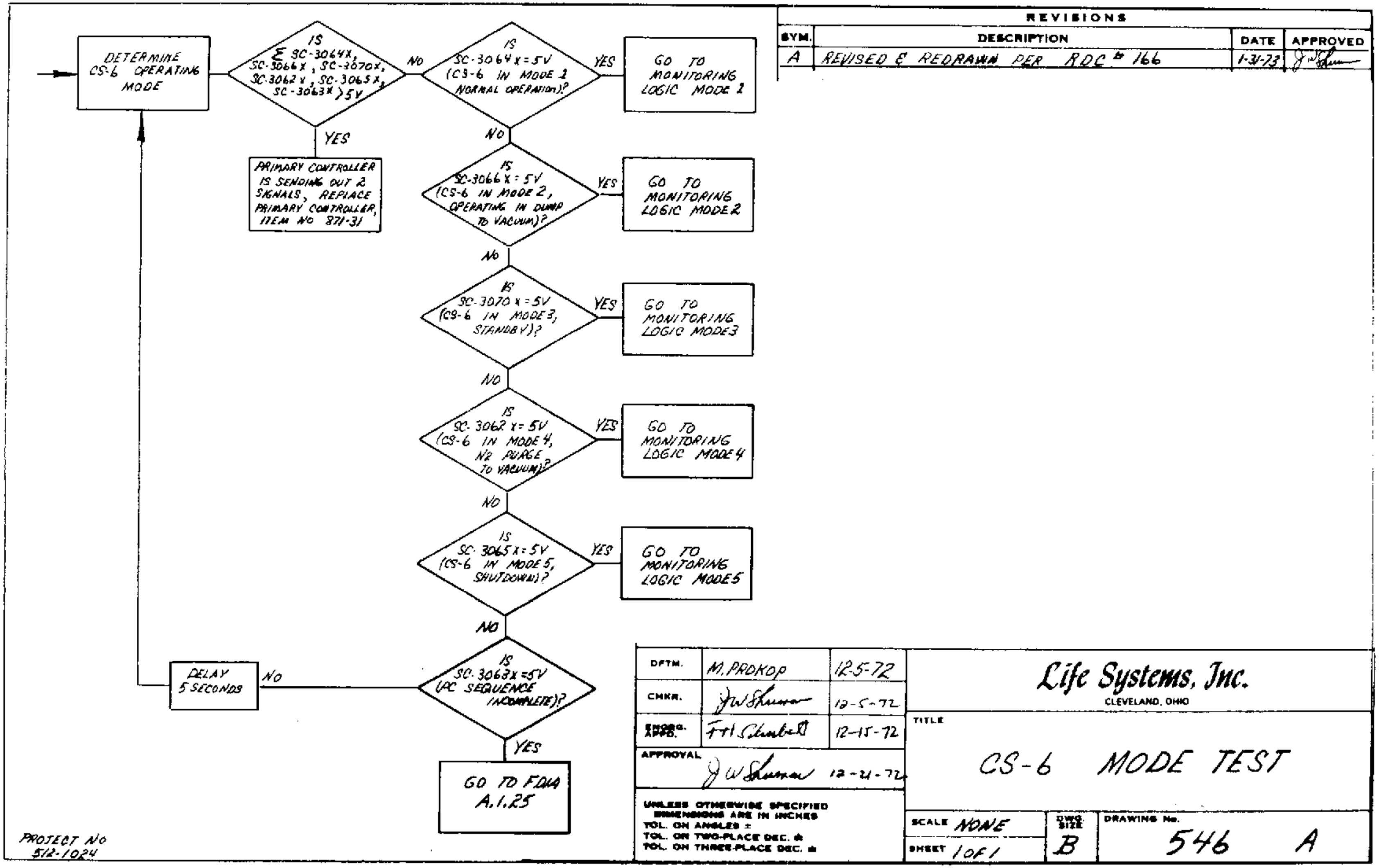


FIGURE 17 CS-6 MODE TEST ROUTINE

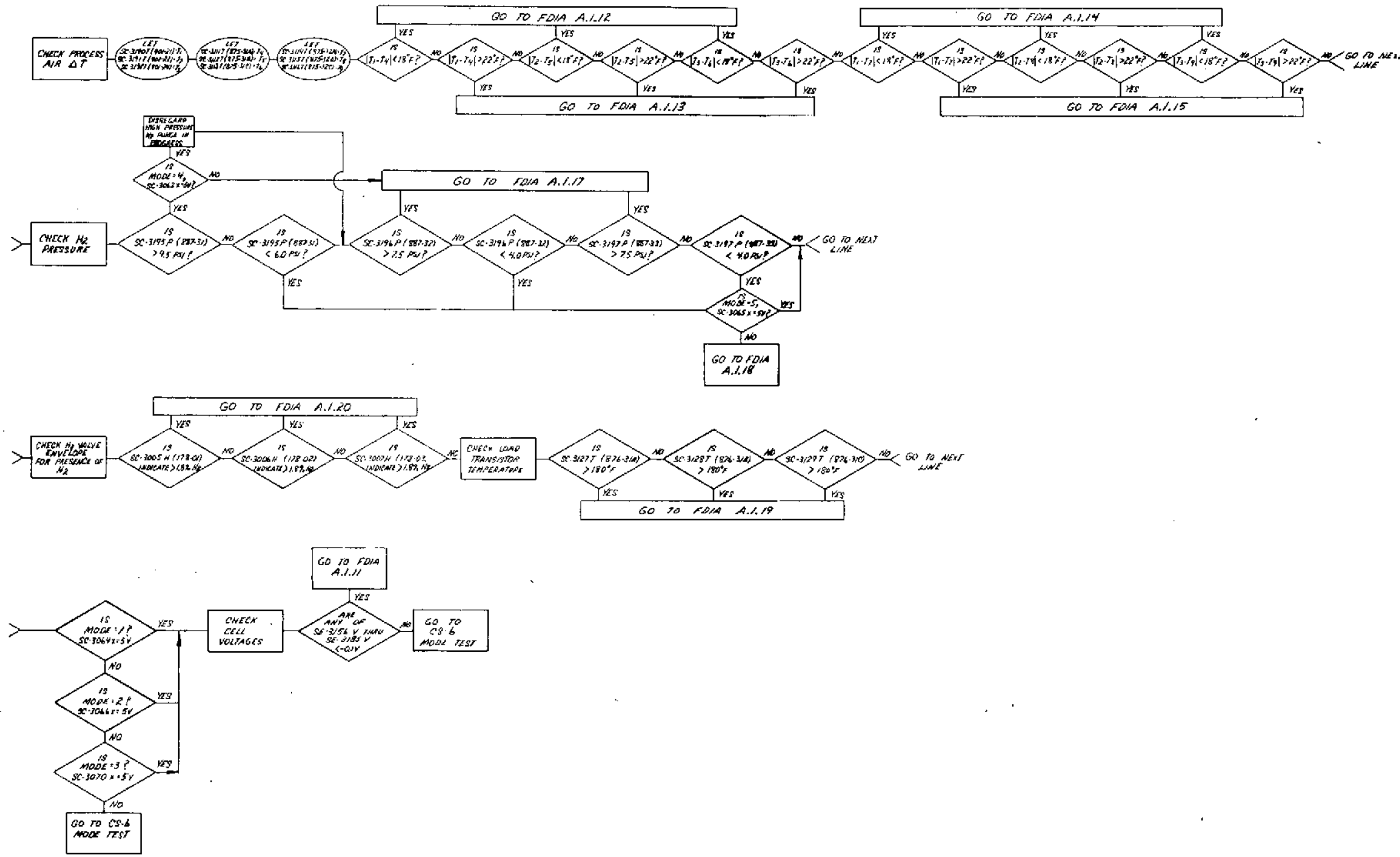


FIGURE 18 CS-6 SAMPLE MONITORING LOGIC FOR CONTINUOUSLY MONITORED PARAMETERS

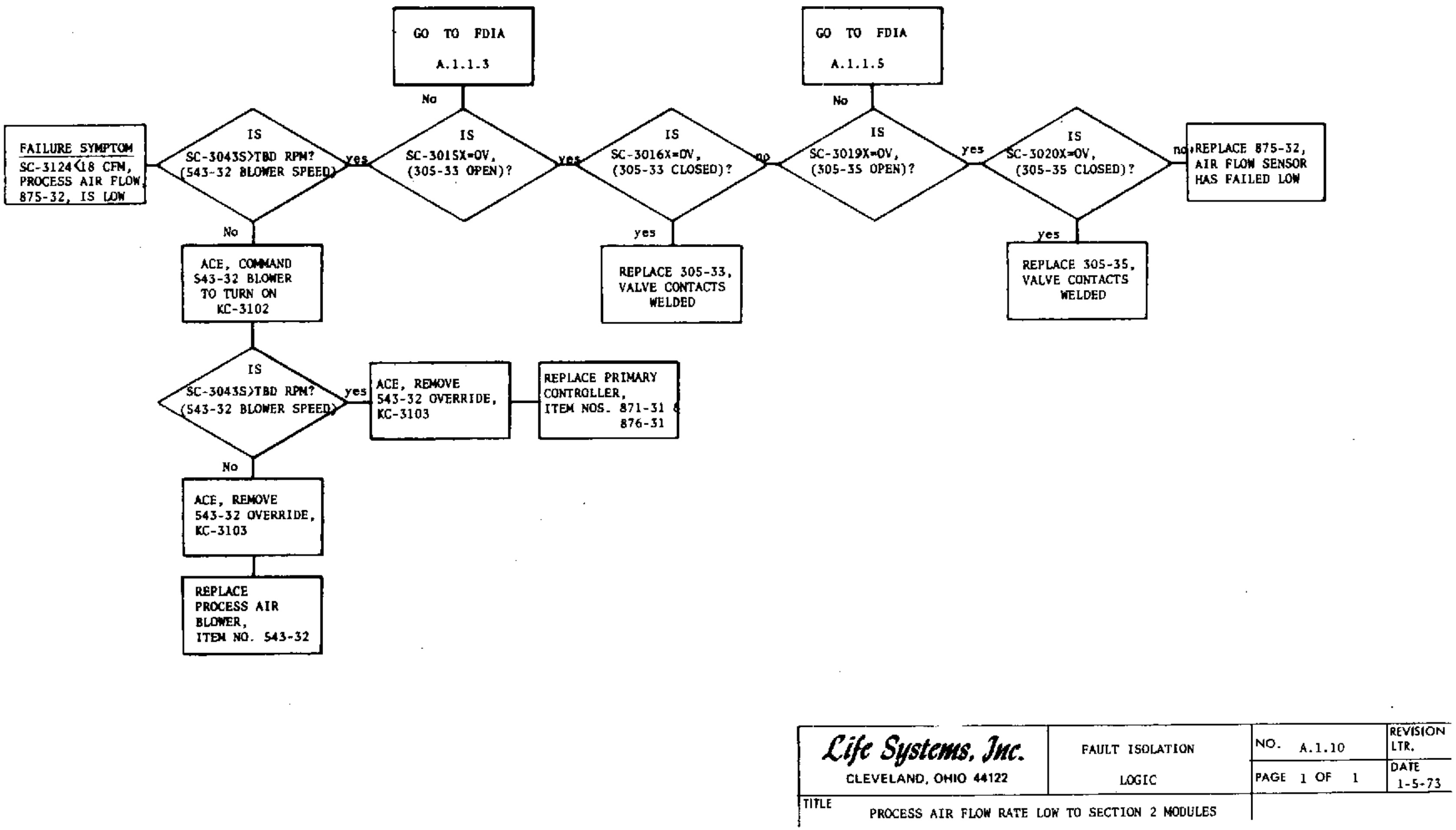


FIGURE 19 CS-6 SAMPLE FAULT ISOLATION ROUTINE

TABLE 9 MAINTENANCE SUMMARY

SSP Item No.	LSI Part No.	Description	Tools Req'd[a]	Maintenance Access	Time Req'd
890	410	Module, Electrochemical	2,5,6	Front	0.3 hr
543	NA[b]	Blower, Process Air	4[c]	Front	0.2 hr
345	NA	Blower, Cooling Air	NR[d]	Rear	0.1 hr
875	501	Sensor, Process Air	4[c]	Front (2), Rear (2)	0.1 hr
877	NA	Sensor, Pressure	7	Rear	0.1 hr
178	NA	Sensor, Combustible Gas	4[c]	Front (2) Rear (2)	0.1 hr
305	NA	Valve, Shutoff, Electric	NR	Front	0.1 hr
306	NA	Valve, Shutoff, Electric	3,4[c]	Rear	0.1 hr
507	NA	Valve, Shutoff, Manual	3,4[c]	Rear	0.1 hr
882	437	Mounting, H_2 Flow Sensor and Distribution	2,3,4[c]	Rear	0.1 hr
310	NA	Regulator, Backpressure	3,4[c]	Rear	0.1 hr
871	440	Controller, Primary	NR	Front	0.1 hr
872	442	Controller, Emergency	NR	Front	0.1 hr
970	NA	Unit, Data Acquisition	NR	Front	0.1 hr
876	475	Mounting, Load Transistor	1	Front	0.1 hr

(a) Tools Required:
1. 3/16" Allen Wrench
2. 5/8" Open-end Wrench
3. 13/16" Open-end Wrench
4. 3/8" Socket Driver
5. 7/16" Socket with Driver
6. 7/16" Socket with Torque Driver
7. Special 3/4" Open-end Wrench

(b) NA - Not Applicable
(c) Tool No. 1 may be substituted for No. 4.
(d) NR - None Required

LRU Title: Blower, Process Air

SSP Item No.: 543

LSI Part No.: N/A

No. Required: 2

Subsystem SSP Item Nos.: 543-31 and -32

Tools Required: 3/8" Socket Driver

Maintenance Access: Front

Time Required: 0.2 hours

Special Precautions: Blower housing may be hot

Procedure

A. Removal

A.1 Initiate shutdown mode and remove system power (see Operating instructions).

A.2 Locate failed blower in CS-6.

A.3 Detach the two electrical connectors by rotating counter-clockwise.

A.4 Release retaining clamps at the air inlet and outlet connections of the blower using 3/8" socket driver.

A.5 Remove blower by loosening the four (4) mounting bolts using 3/8" socket driver.

B. Installation

B.1 Identify location for new blower installation.

B.2 Utilizing 3/8" socket driver, attach the blower to system frame with mounting bolts but do not tighten.

B.3 Align retaining clamps at air inlet and outlet connections and secure using 3/8" driver.

B.4 Tighten blower mounting bolts with the 3/8" driver.

B.5 Attach the two electrical connectors by pushing forward and rotating clockwise.

FIGURE 20 PROCESS AIR BLOWER MAINTENANCE PROCEDURE

Nonmetallic Materials Control

The objective of the Nonmetallic Materials Control Program was to identify all nonmetallic materials present in the CS-6. These were screened for acceptability to CSD-SS-012, "Nonmetallic Materials Requirements for Manned Testing of the Space Station Prototype Environmental/Thermal Control and Life Support System." Unacceptable materials were either (1) replaced by acceptable alternates, (2) protected by a nonflammable coating and tested for acceptance in this configuration, (e.g., Fluorel coated Nopco G 306 SE foam), or (3) tested for acceptance in its "as used" configuration.

For those materials that did not meet the requirements of CSD-SS-012 and for which acceptable alternate materials could not be found, a Nonmetallic Materials Requirement Waiver was prepared.

The Nonmetallic Materials List (ER-170-28E) and Nonmetallic Materials Requirement Waiver (ER-170-29C) were submitted to NASA JSC for Material Review Board (MRB) action. Complete approval for the nonmetallic materials present in the CS-6 was obtained. A sample nonmetallic materials list is shown in Figure 21.

Safety

The Safety Program was carried out in conjunction with the design and development of the CS-6 and consisted of:

1. Preparation of the CS-6 Safety Design Criteria (ER-170-67) and monitoring of subsystem and component design for compliance to the Safety Design Criteria.

2. Identification of dangerous subsystem characteristics and failure modes. This was done in conjunction with the FMECA performed on the system.

3. Performance of a Safety Hazard Analysis (SHA) (ER-170-27C) for all Criticality I and IIa failure modes.

4. Review of the Nonmetallic Materials Lists and the Nonmetallic Materials Waivers Requests.

5. Review of designs and design changes for potential safety problems.

6. review of NASA Alerts for safety information.

7. Review of test plans and procedures having safety significance.

8. Work in conjunction with subsystem designers and program management to reduce Safety Catastrophic and Safety Critical Hazards to the Safety Negligible category. A definition of Safety Hazard Categories is presented in Table 10.

9. Review of Reliability Data Reports (failure reports) for their impact on safety.

CREW SYSTEMS DIVISION SSP ETC/LSS MATERIALS REVIEW BOARD (CSD/MRB)
NONMETALLIC MATERIALS MASTER LOG

ADDITION TO LSI ER-170-2RE

MLN: SSP-7018 — PAGE 1 OF 1

SUBSYSTEM: CO_2 COLLECTION	DATE: July 18, 1973
COMPONENT: See Remarks — ITEM NO.: See Remarks	REQUESTING ORGANIZATION: Life Systems, Inc.
DRAWING NO.: N/A	SUBSYSTEM MANAGER (OR DESIGNEE): John W. Shumar

CSD MRB APPROVAL (Concurrence): [signature] [signature] [signature] 8/15/73 [signature] [signature] CHAIRMAN: [signature]

LINE NO.	WAIVER REQUEST NUMBER	MATERIAL GENERIC NAME	MANUFACTURER AND MATERIAL SPECIFICATION	MANUFACTURER'S MATERIAL DESIGNATION	INTENDED MATERIAL USAGE	USAGE CATEGORY CSD-SS-012	USAGE ENVIRONMENT	WT. (lbs)	EXP. AREA (in²)	BOARD DECISION: ACPT.	COND. ACPT.	REJ.	REMARKS OR RECOMMENDATIONS
1		Nomex* Lacing Tape	Gudebrod Bros. Silk Co., Inc.	R&D 1127	Wire ties in controller	F	Cabin atmosphere in vented cont.	35.0	0	✓			Incorporated in Primary Controller, SSP Item No. 871-31
2		Nomex Lacing Tape	Gudebrod Bros. Silk Co., Inc.	R&D 1127	Wire ties in controller	F	Cabin atmosphere in vented cont.	35.0	0	✓			Incorporated in Emergency Controller, SSP Item No. 872-31
3		Nomex Lacing Tape	Gudebrod Bros. Silk Co., Inc.	R&D 1141	Wire ties for subsystem wiring	See Remarks E	Cabin atmosphere	40.0	0	✓			Will be incorporated in subsystem wiring. In this application the material will be completely covered by 3M361 glass [illegible] tape
4		Temp-Lace	Gudebrod Bros. Silk Co., Inc.	Teflon Style 302	PC Board Wire Ties	F	Cabin atmosphere in vented cont.	25.0	0	✓			Incorporated in Primary Controller, SSP Item No. 871-31
5		Temp-Lace	Gudebrod Bros. Silk Co., Inc.	Teflon Style 302	PC Board Wire Ties	F	Cabin atmosphere in vented cont.	25.0	0	✓			Incorporated in Emergency Controller, SSP Item No. 872-31

MRB COMMENTS OF CONDITIONS OF ACCEPTANCE

*DuPont Registered Trademark

FIGURE 21 CS-6 SAMPLE NONMETALLIC MATERIALS LIST

TABLE 10 HAZARD CATEGORIES

Four hazard categories are defined for condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, subsystem failure or component malfunction will cause or result in the following:

Hazard Category	Will Cause or Result In
1. Safety Catastrophic	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, subsystem failure or component malfunction will cause death or incapacitating injuries to personnel by severe degradation of system performance or subsequent system loss.
2. Safety Critical	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, subsystem failure or component malfunction will cause personnel injury or serious damage to other equipment, which will result in a hazard requiring immediate corrective action for personnel or system survival.
3. Safety Marginal	Condition(s) such that environment, personnel error, design characteristics, procedural deficiencies, subsystem failure or component malfunction will degrade system performance but which can be counteracted or controlled without major damage or any injury to personnel.
4. Safety Negligible	Conditions(s) such that personnel error, design characteristics, procedural deficiencies, or subsystem failure or component malfunction will not result in major system degradations, and will not produce system functional damage or personnel injury.

An example of a SHA, which details the method of detecting the hazard, the backup provisions provided to ensure safety, the corrective action available to the crew to correct the hazardous condition and the equipment failure mode that can create the hazard is presented in Figure 22.

GROUND SUPPORT ACCESSORIES

Various items of support equipment were designed, built and/or modified to supply the process fluids, including process and cooling air, the electrical power and the command and data display interface required for Shakedown, Design Verification, and Acceptance Testing of the CS-6. Four GSA were provided:

1. Fluid Supply Unit (FSU)
2. Air Supply Unit (ASU)
3. Power Supply Unit (PSU)
4. Ground Support Panel (GSP)

Fluid Supply Unit

The FSU controls and monitors the flows and pressures of gases used by the CS-6 and the ASU. The FSU supplies gases to the ASU and the CS-6 for the following requirements:

<u>ASU</u>

- CO_2 - to maintain desired pCO_2 in the CS-6 process air
- Air - to maintain desired total air pressure (leakage makeup for closed-loop operation)

<u>CS-6</u>

- H_2 - for depolarization of the cell anodes
- N_2 - for purging of H_2 lines and anode gas cavities prior to startup or during shutdown of the unit

Air Supply Unit

The ASU supplies process air to the CS-6 at the desired pCO_2, temperature and dew point. The major components of the ASU are a cabin simulator tank, a temperature and humidity controller, instrumentation, piping and valves. The process air loop through the CS-6 and the ASU can be operated as either a closed or open loop. In the closed loop operation, air is recirculated and only makeup gases are added. In open loop operation, the ASU conditions ambient air to the desired pCO_2, temperature and dew point with the process air exiting the CS-6 returned to ambient. All testing of the CS-6 was done under open loop operation. In addition to the requirement for process air, CS-6 testing required a source of cooling air which was supplied by a ground support air conditioner.

Equipment Involved

All components, valves and fittings in the hydrogen (H_2) gas line. Also the O-ring and gasket seals in the modules.

Hazard Description

Hydrogen leak into the cabin atmosphere.

Hazard Category (per Safety Manual OP-108)

Marginal

Equipment Usage/Mission Phase

Provides for H_2 supply to the electrochemical modules during all manned phases of a mission or manned chamber test.

Method of Detecting Hazard

All H_2 components are contained within a confined region of the CS-6. Four combustible gas sensors are mounted within the envelope at strategic locations to detect the presence of H_2. The output of the four sensors is monitored every two seconds by ACE/IMS. When H_2 in excess of 1.0% is indicated by any one sensor, the subsystem will be shut down.

The H_2 flow sensors and the triply redundant H_2 pressure sensors are also used to detect external leakage of H_2 components.

LSI Equipment Action

External leakage failure mode of all components in the H_2 line caused the hazard. A minor leak in a confined area can lead to an H_2-air mixture above the explosive limit.

Backup Provisions

Two of the combustible gas sensors are wired to the primary controller and two are wired to the emergency controller. The primary and emergency controllers act as a backup for ACE/IMS. They will shut down the CS-6 when H_2 is in excess of 1.5% and 2.0%, respectively, is indicated by a combustible gas sensor.

In addition, the H_2 loop is proof-tested to six times the design operating pressure.

Corrective Action Available to Crewmen

Verify that the CS-6 has been shut down and purged. Locate the leaking component utilizing nitrogen (N_2) gas and the ultrasonic leak detector. Replace the faulty component.

FIGURE 22 CS-6 SAMPLE SAFETY ANALYSIS

Power Supply Unit

The PSU provides electrical power to the CS-6. This power is in the form of a nominal 115/208 VRMS 3Ø, 400 Hz WYE connected supply. The PSU is an uninterruptible supply normally using 60 Hz ground based power. In the event of a ground based power failure, the storage batteries contained in the PSU continue to supply the power required which allows the CS-6 to continue operation during a short ground based power outage.

Ground Support Panel

The GSP monitors, displays and controls various key functions of the CS-6. It is mounted in place of the DAU and allows manual control and testing of the CS-6 without the DAU or the ACE/IMS Data Management System.

The GSP provides capabilities to (1) select the desired operating mode of the CS-6, (2) override open or closed all subsystem motor-driven valves, (3) override "on" each of the subsystem's four blowers, (4) set the desired CO_2 removal rate, process air flow rate, and module-CTHCS temperature differential, and (5) advance the cell scan multiplexer.

The GSP provides data display of the following information:

1. Module Voltage
2. Module Current
3. Module Temperature
4. CTHCS Temperature
5. Process Air Temperature
6. Process Air Flow Rate
7. Blower Speeds
8. Shutdown Causes
9. Combustible Gas Sensor Levels
10. H_2 Pressure
11. Valve Positions
12. Controller Status Information (both Primary and Emergency)
13. Controller Bias Voltage Levels

Figure 23 shows the GSP mounted on the CS-6.

TEST PROGRAM

System testing of the CS-6 consisted of three major phases: (1) Shakedown Tests, (2) Design Verification Tests (DVT), and (3) Acceptance Tests. In addition to system testing, component testing and sensor calibration was performed. All functional CS-6 testing was done at SSP operating conditions.

Tests were run on the CS-6 to verify previous component data and to obtain data on component interfaces for a program mathematically modeling a Six-Man, Self-Contained, Electrochemical Concentrating Subsystem.[3] Figures 24, 25 and 26 are plots of the variation in CO_2 removal efficiency, expressed as the Transfer Index (TI), as a function of pCO_2, current density, and air flow rate, respectively.

FIGURE 23 GSP MOUNTED ON CS-6

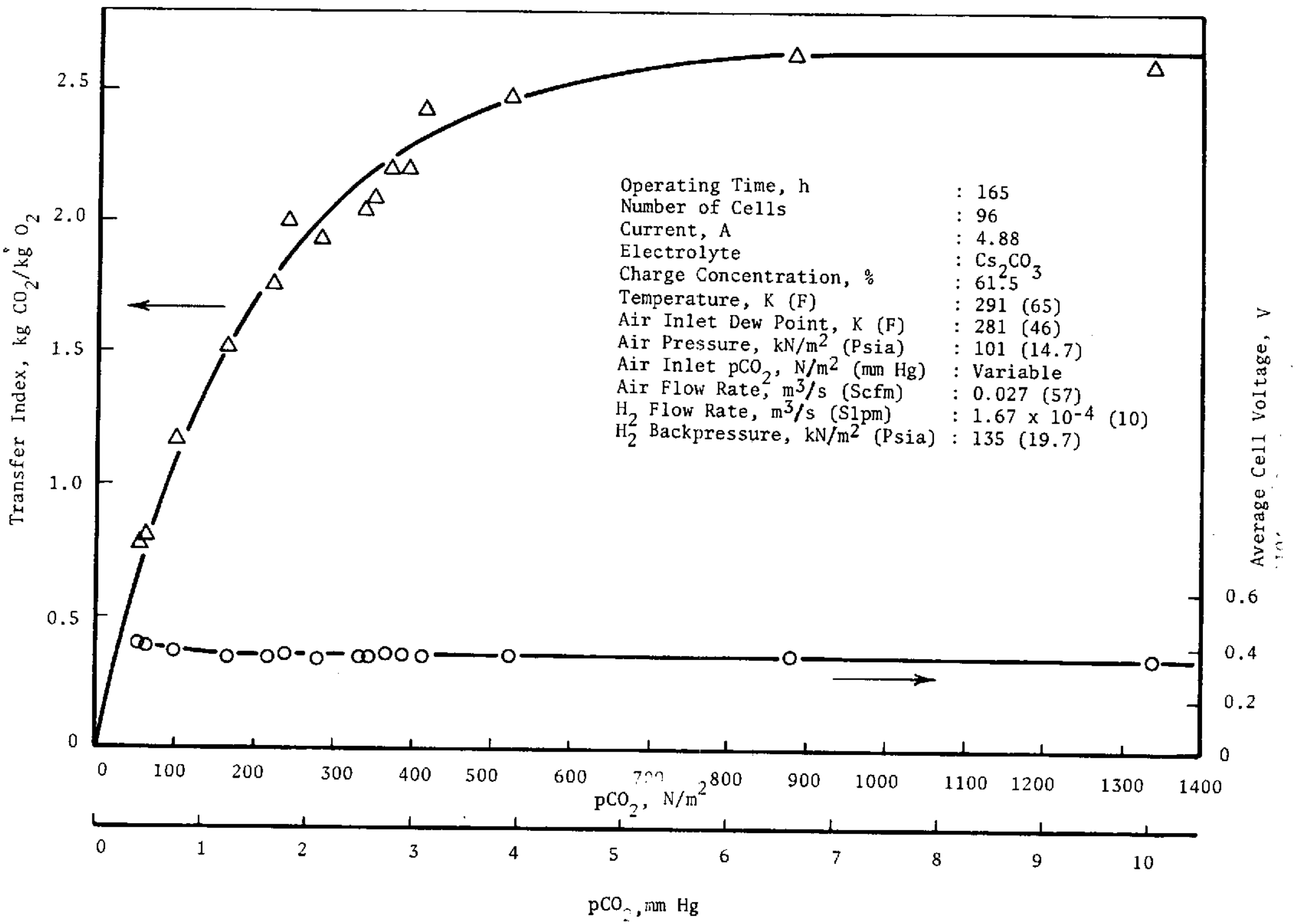


FIGURE 24 EFFECT OF pCO_2 ON TI AND AVERAGE CELL VOLTAGE

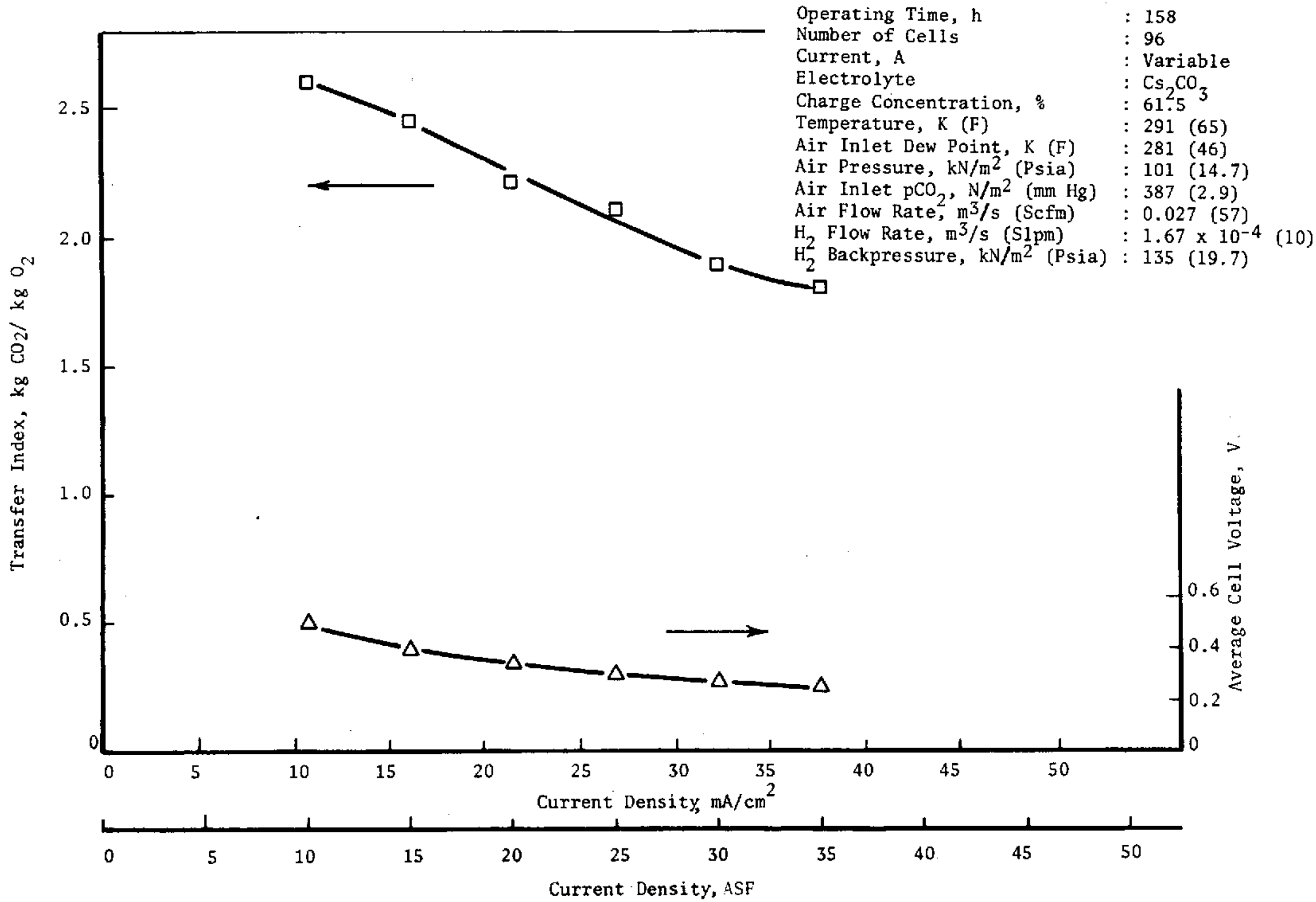


FIGURE 25 EFFECT OF CURRENT DENSITY ON TI AND AVERAGE CELL VOLTAGE

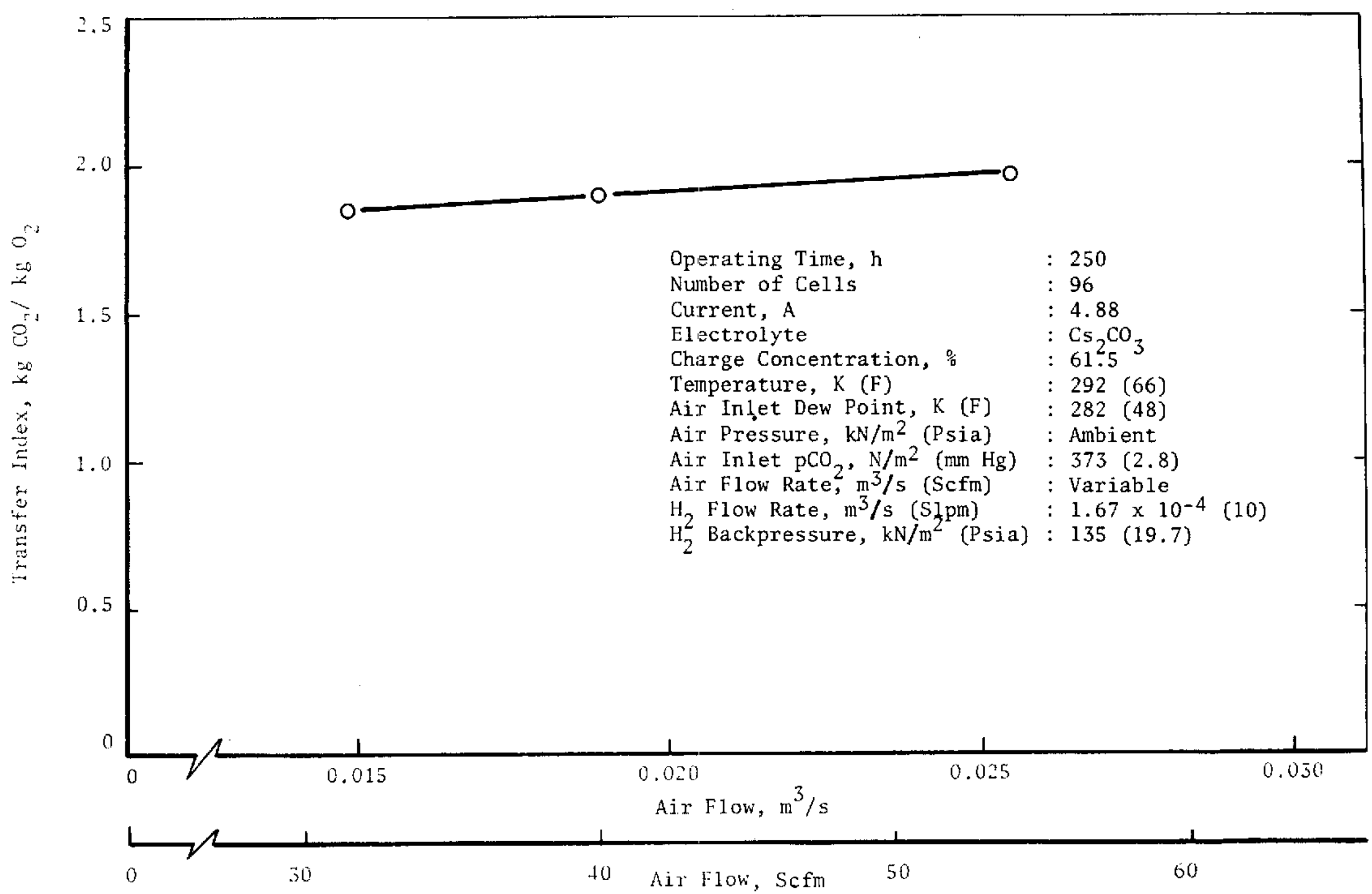


FIGURE 26 EFFECT OF AIR FLOW RATE ON TI

The TI is numerically equivalent to the kg (lb) of CO_2 transferred per kg (lb) of O_2 consumed. Based on the overall electrochemical reaction of CO_2 removal, a TI of 2.75 is equivalent to a 100% current efficiency.

Component Checkout and Calibration Tests

Component checkout tests were performed on all CS-6 and GSA components. Calibration tests were performed on CS-6 components measuring or controlling the following functions: combustible gas presence, H_2 + CO_2 backpressure and flow, module and process air inlet temperatures, cooling and process air blower speeds, process air flow rate, H_2 and N_2 flow distribution, and module current and voltage. Calibration tests were performed on the following GSA interface simulation and parameter monitoring equipment: flow meters, pressure gauges, pressure regulators, voltmeters, ammeters and temperature and dew point indicators.

All component checkout and calibration tests were completed with all set points based on simulated levels at the sensor input points.

Electrochemical Module Checkout Test

Prior operation of the electrochemical modules (890) verified that the CO_2 removal and electrical performance exceeded the design specifications.[4] The checkout tests consisted of pressurizing each module to 62.0 kN/m^2 (9.0 psig) and creating a pressure differential between the anode and cathode compartments of 51.7 kN/m^2 (7.5 psig). An electrical leakage test was performed on each module to determine if any shorts existed. All modules passed the electrical and pressure checkout tests.

CS-6 Shakedown Test

All components were assembled into the self-contained subsystem and integrated with the GSA. A shakedown test was performed on the CS-6 which resulted in the following modifications being made:

Self-Contained Subsystem

1. An antibounce circuit for the module advance command was incorporated into the primary controller. This eliminated noise susceptibility in the external cell multiplex clocking function.

2. The ground return bus for the current loop was rerouted inside the controller to eliminate instability in the current control loop.

3. Individual dampers were installed in the two cooling air return loops in the exhaust portion of the air plenum to decrease undesirable cooling air leakage flows across the fins of the modules.

Ground Support Accessories

1. Extremely low relative humidities were measured in the testing area brought about by climate changes. To alleviate the seasonal problem a

humidifier was installed upstream of the ASU to increase process air moisture to the levels required to simulate the CTHCS interface.

2. The simulated CTHCS temperature probe was encased in an aluminum block to dampen rapid temperature fluctuations and provide for improved stability of temperature monitoring.

Design Verification Test

Two major parameters are used to describe the performance of the CS-6: (1) CO_2 removal efficiency and (2) electrical efficiency. Carbon dioxide removal efficiency is reflected by the TI which is defined as the kg (lb) of CO_2 removed per kg (lb) of O_2 consumed. Based on the stoichiometry of the reactions involved, the theoretical TI is 2.75 kg CO_2/kg O_2. Electrical efficiency is reflected by cell voltage. Since an electrochemical CO_2 concentrator produces electrical power, a high cell voltage reflects a high electrical efficiency. The theoretical voltage for the electrochemical reactions is 1.23 volts.

A DVT was conducted on the CS-6 to demonstrate the subsystem's capability to remove the required amount of CO_2 (0.25 kg CO_2/h (0.55 lb CO_2/hr)) at baseline operating conditions and to establish electrical (cell voltage) and CO_2 removal (TI) efficiencies. This DVT consisted of operating the subsystem at baseline conditions for a minimum of 100 hours (cumulative) and recording data three times per day during normal working hours. Baseline operating conditions are outlined in Table 11. Figure 27 shows average cell voltage, pCO_2 of the process inlet air, TI, and the amount of CO_2 removed in kg/h (lb/hr) as a function of operating time for a part of the CS-6 DVT consisting of 48 hours of continuous operation. As can be seen from the figure, the average cell voltage for this period exceeded the design value of 0.25 volts by 0.09 volts, resulting in a 10% reduction in waste heat generation. The TI and amount of CO_2 removed consistently exceeded the design points of 1.9 kg CO_2/kg O_2 and 0.25 kg CO_2/h (0.55 lb CO_2/hr), respectively. During the DVT, special tests were performed which (1) confirmed that the anode gas backpressure did not drop below the low pressure shutdown level (20.7 kN/m^2 (3 psig)) of the primary controller due to H_2 and O_2 diffusion and chemical recombination during a simulation of the 36 minute standby portion (dark side of orbit) of cyclic operation following only a one minute duration N_2 purge, (2) established that the cooling air blower speed modulation responded properly to variations in the CTHCS dew point temperature, and (3) verified proper operation of all functional mode transitions and shutdown protections.

Acceptance Test

Acceptance Testing of the CS-6 was necessary to insure performance at SSP baseline conditions following the refurbishment and calibration adjustments made after the DVT. The Acceptance Test consisted of operation of the CS-6 at nominal, steady-state conditions for 100 hours. Uninterrupted operation was required. Figure 28 shows TI, CO_2 removal rate and average cell voltage as a function of time during the Acceptance Test. As can be seen from the figure, the Acceptance Test demonstrated that the CS-6 again exceeded the design baseline conditions of a TI of 1.9, a CO_2 removal rate of 0.25 kg/h (0.55 lb/hr) and an electrochemical

TABLE 11 BASELINE OPERATING CONDITIONS

Process Air	
Inlet	
Flow Rate, m^3/s (Scfm)	$2.5 \times 10^{-2} \pm 1.9 \times 10^{-3}$ (54 ±4)
Pressure, kN/m^2 (Psia)	101-108 (14.6-15.7)
Dew Point, K (F)	281 ±1 (46 ±2)
Dry Bulb Temperature, K (F)	284 ±1 (52 ±2)
pCO_2, N/m^2 (mm Hg)	387 ±13 (2.9 ±0.1)
Exhaust	
Flow Rate, m^3/s (Scfm)	$2.5 \times 10^{-2} \pm 1.9 \times 10^{-3}$ (54 ±4)
Pressure, kN/m^2 (Psia)	101-108 (14.6-15.7)
Dew Point, K (F)	283 ±1 (50 ±2)
Dry Bulb Temperature	
Module Exit, K (F)	291 ±1 (65 ±2)
Blower Exit, K (F)	302 ±2 (85 ±3)
Hydrogen	
Flow Rate, m^3/s (Slpm)	$1.77 \times 10^{-4} \pm 1.77 \times 10^{-5}$ (10.6 ±1.06)
Dew Point, K (F)	262-294 (13-70)
Electrochemical Module	
Current, A	4.88
Temperature, K (F)	292 ±1 (66 ±1)
Electrolyte	Cs_2CO_3
Initial Charge Concentration, Wt %	61.5 ±0.3
Anode Gas Backpressure, kN/m^2 (Psia)	135.4 ±6.9 (19.7 ±1)
Nitrogen	
Nitrogen Flow Rate, m^3/s (Slpm)	$1.64 \times 10^{-4} \pm 2.5 \times 10^{-5}$ (9.8 ±1.5)
Regulated Nitrogen Pressure, kN/m^2 (Psia)	207 ±14 (30 ±2)
Purge Duration, s (Min)	120 ±10% (2 ±10%)
Frequency	As Required
Cooling Air	
Inlet	
Dry Bulb Temperature, K (F)	284 ±1 (52 ±2)
Flow Rate, m^3/s (Scfm), Max	$1.85 \times 10^{-1} \pm 9.44 \times 10^{-3}$ (390 ±20)
Supply Pressure Range, N/m^2 (Inch Water)	Atmosphere +747-1495 (+3-6)
Exhaust	
Average Dry Blub Temperature Rise, K (F)	1.1 (1.9)
Maximum Dry Bulb Temperature Rise, K (F)	1.9 (3.4)
Pressure Drop, N/m^2 (Inch Water)	374 ±125 (1.5 ±0.5)

NOTE: Baseline operating conditions outlined in Table 11

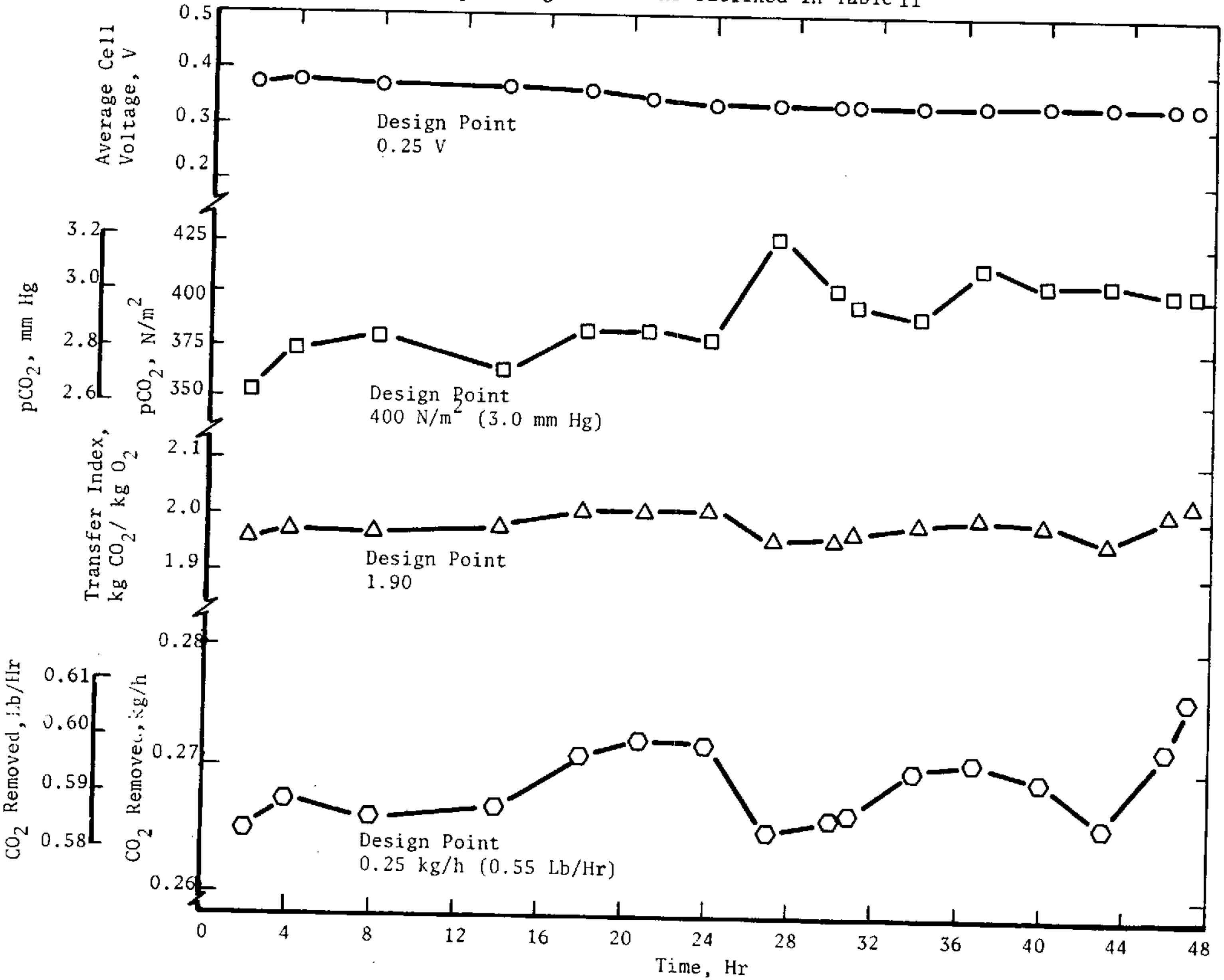


FIGURE 27 CS-6 DESIGN VERIFICATION TEST (DVT) - SUBSYSTEM PERFORMANCE

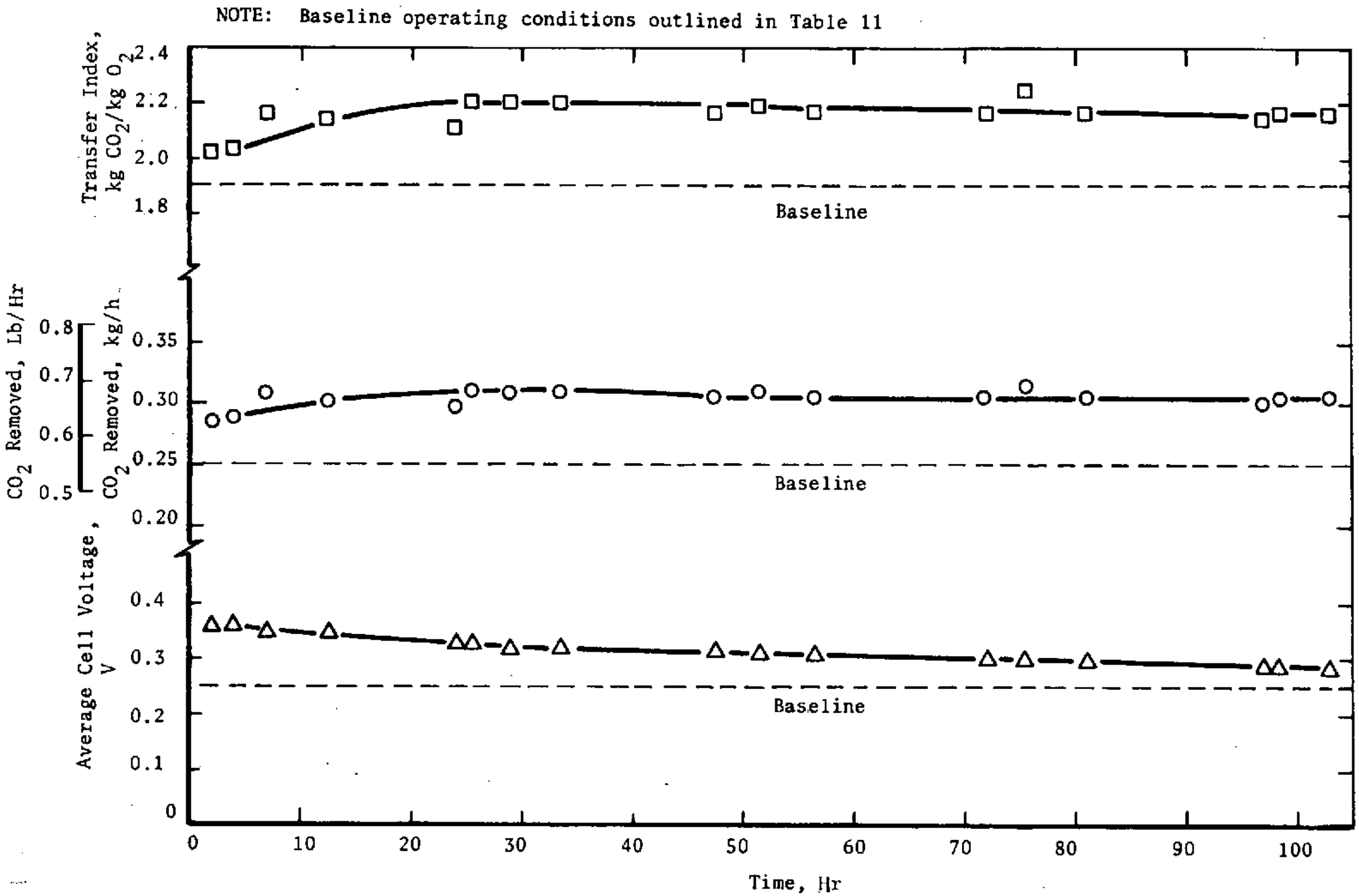


FIGURE 28 TI, CO_2 REMOVAL RATE AND AVERAGE CELL VOLTAGE VERSUS TIME (ACCEPTANCE TEST)

cell voltage of 0.25 volts. It should be noted that the electrodes used in the CS-6 electrochemical modules were the same as those used during shakedown, parametric, and 180-day endurance testing of the CX-6, Six-man, Self-Contained Carbon Dioxide Concentrator Subsystem.(5) A total of 209 days of operation had, therefore, been accumulated with these electrodes prior to their installation into the CS-6.

SUBSYSTEM DOCUMENTATION SUMMARY

Throughout the course of the design, development, fabrication and testing of the CS-6, many documents and drawings were generated by Life Systems, Inc. to (1) aid in the subsystem design and the SSP interface, (2) summarize meeting results and action items, (3) specify design requirements and test results, (4) supply required documentation for the generation of computer software, (5) supply required quality, reliability and fault diagnostic information, and (6) supply other contractually required information. This documentation can best be separated into the three areas of Design, Interface and Product Assurance. A listing of documentation in each of the areas is shown below. Two selected examples of CS-6 documentation, LRU Specification No. 882 for the H_2 Flow and Distribution Mounting, and Drawing LSI-D-501 for the Process Air Sensor, are included in Appendix A. Detailed CS-6 operating and maintenance instructions are found in the CS-6 Operations and Maintenance Manual (ER-170-36).

Design Documentation

Pertinent CS-6 design documents generated by Life Systems, Inc. were:

Document No.	Title/Description
ER-170-3	CS-6 Subsystem Test Plan
ER-170-3a through f	Individual CS-6 Component Test Plans
ER-170-45	Subsystem Component Specifications
ER-170-46	CO_2 Collection Subsystem, Performance and Design Requirements for Space Station Prototype
ER-170-52	CS-6 Control Philosophy
ER-170-65	CS-6 Software Tables and Logic Package
ER-170-77	CS-6 System Wiring List
ER-170-79	CS-6 Primary and Emergency Controller Wiring List
LSI-J-410	Electrochemical Module Assembly Drawing
LSI-D-417	CS-6 Schematic
LSI-C-423	CS-6 Primary Controller Block Diagram
LSI-D-437	H_2 Flow and Distribution Mounting Drawing
LSI-J-440	Primary Controller Drawing
LSI-E-442	Emergency Controller Drawing
LSI-D-475	Load Transistor Mounting Drawing
LSI-C-486	CS-6 Emergency Controller Block Diagram
LSI-D-489	CS-6 Subsystem Functional Block Diagram
LSI-D-496	CS-6 Primary Controller and Rack to Supporting Structure Installation Drawing
LSI-D-501	Process Air Sensor Drawing

Document No.	Title/Description
LSI-B-543	CS-6 Operating Modes
LSI-D-544	CS-6 Mode Transitions
LSI-B-545	CS-6 Controlled Variables, Steady-State Conditions
LSI-D-572	CS-6 Emergency Controller and Rack to Supporting Structure Installation Drawing

Interface Documentation

Pertinent CS-6 interface documents generated by Life Systems, Inc. were:

Document No.	Title/Description
ER-170-39	The Electrochemical CO_2 Concentrating Subsystem Interface Specifications for the SSP
ER-170-47	Interim Design Review Meeting Minutes
ER-170-51	Delta Interim Design Review Meeting Minutes
ER-170-56	CS-6/SSP Detailed Electrical Interface Specification
ER-170-61	Approval Design Review Meeting Minutes
ER-170-69	Delta Approval Design Review Meeting Minutes
LSI-D-485	CS-6 CO_2 Concentrator Subsystem Installation Drawing

Product Assurance Documentation

Pertinent CS-6 Product Assurance documents generated by Life Systems, Inc. were:

Document No.	Title/Description
ER-170-8	Quality Assurance Program Plan
ER-170-11	Acceptance Data Log
ER-170-14	Reliability Math Model and Block Diagram
ER-170-16	Failure Mode and Effects Analysis
ER-170-17	Single Point Failure Analysis
ER-170-18	Failure Reporting Procedure
ER-170-19	Component Failure Reports
ER-170-24	Maintainability Analysis Summary Report
ER-170-25	Fault Detection/Isolation Analysis Summary Report
ER-170-27	Safety Hazard Analysis Report
ER-170-28	Nonmetallic Materials List
ER-170-29	Nonmetallic Materials Requirement Waiver
ER-170-36	CS-6 Operations and Maintenance Manual
ER-170-67	Safety Design Criteria for the CS-6
ER-170-82	CS-6 Reliability Data Reports
OP-108	System Safety Procedure

CONCLUSIONS

The following conclusions are a direct result of this development.

1. The Six-Man, Self-Contained, CO_2 Concentrating Subsystem for SSP application is capable of removing 6.0 kg (13.2 lb) CO_2/day with an air inlet pCO_2 of <400 N/m^2 (<3 mm Hg).

2. The Primary and Emergency Controllers, coupled with the ACE/IMS Data Management System, provide fail-safe conditions for unattended operation.

3. The CS-6 is capable of operating at SSP interface specifications.

4. The CS-6, designed and built for manned chamber testing, received NASA approval of the nonmetallic materials present in the unit.

5. The CS-6 was designed utilizing applicable SSP commonality components including motor-operated valves, blowers, regulators and combustible gas sensors.

6. The CS-6 was designed utilizing the LRU concept for maintainability.

7. Five specific steady-state operating modes are incorporated in the CS-6 and were successfully demonstrated.

8. Closed loop control of process air inlet dew point to module temperature differential expanded the range of system operation.

9. The CS-6 was designed and operated with process and cooling air at the same conditions.

10. The CS-6 GSP was used to replace the DAU and ACE/IMS Data Management System for manual operation.

11. The CS-6 successfully passed Shakedown, Design Verification, and Acceptance Testing.

12. The CS-6 DVT results showed that the design CO_2 removal efficiency and electrical efficiency were exceeded by 6% and 25%, respectively.

13. The CS-6 testing demonstrated subsystem operation at an elevated H_2 and CO_2 backpressure of 34.5 kN/m^2 (5 psig).

REFERENCES

1. "SSP Final Report," SSP Document No. 165, Hamilton-Standard, October, 1973.

2. "Procedures and Requirements for the Flammability and Outgassing Evaulation of Manned Spacecraft Nonmetallic Materials," NASA Specification No. D-NA-0002, July 1968.

3. "Six-Man, Self-Contained, Electrochemical CO_2 Concentrating Subsystem Math Model Test Program - Test Plan," Life Systems, Inc., ER-220-3, February, 1974.

4. "Six-Man, Self-Contained, Carbon Dioxide Concentrator Subsystem, Final Report," Life Systems, Inc., ER-134-32, NASA CR 114743, June, 1974.

5. "Six-Man, Self-Contained, Carbon Dioxide Concentrator Subsystem, Annual Report," Life Systems, Inc., ER-170-73, April, 1973.

APPENDIX A
CS-6 DOCUMENTATION EXAMPLES

Life Systems, Inc. CLEVELAND, OHIO 44122	SPECIFICATION	NO. 882	REVISION LTR. B
	LINE REPLACEABLE UNIT	PAGE 1 OF 3	DATE 2/15/74
TITLE MOUNTING, H_2 FLOW SENSOR AND DISTRIBUTION		PART DRAWING NO. 438	

FUNCTION:

The H_2 Flow Sensor and Distribution Mounting divides the incoming H_2 flow equally between three electrochemical modules. It also senses the H_2 flow rates to the modules.

DESCRIPTION:

The H_2 flow branches into three flow paths from a common inlet manifold. A pressure drop producing orifice (Lee Jet No. 187-2-06000-0808) is installed in each of the three flow paths to provide equal H_2 flow rate into each of the modules. The H_2 flow sensor consists of two electrically matched thermistors wired externally to a bridge circuit and amplifier to produce a voltage signal proportional to H_2 flow rate.

DESIGN DATA:

Performance Characteristics

Operating pressure (nominal)	21 psia
Proof pressure	66 psia
Pressure drop	3.0 psid
Flow Rate	5.4 $\pm$ .5 lpm
Reliability data	
Failure rate	2.8 x 10^{-6} failures/hr
MTBF	3.6 x 10^{6} hr
Spares	2 (180-day mission profile)

Physical Characteristics — See attached Drawing No. 438

Weight	4.8 lb
Volume	0.0112 ft^3
Basic configuration	3.31 x 3.62 x 1.86 in

Material Characteristics

A. Nonmetallic
Ethylene Propylene, Teflon, L-3217 Fluorel, Silastic RTV-732, Ecco-bond 787AB Epoxy

B. Metallic
Stainless Steel, Aluminum

Electrical Characteristics

Normal thermistor resistance	2000Ω$\pm$5% @ 25C

continued-

FIGURE A-1 EXAMPLE OF A SPECIFICATION

Life Systems, Inc. CLEVELAND, OHIO 44122	NUMBER 882	REVISION LETTER B	PAGE 2

INTERFACES:

Mechanical

H_2 inlet	3/8 in CPV fitting
H_2 outlets	1/4 in CPV fitting

Electrical

Connector	Amphenol No. 348-40E10-12P1
Mounting	Panel mounted with two captive screws (Deutsch No. L7300-C-4-8)

ENVIRONMENT:

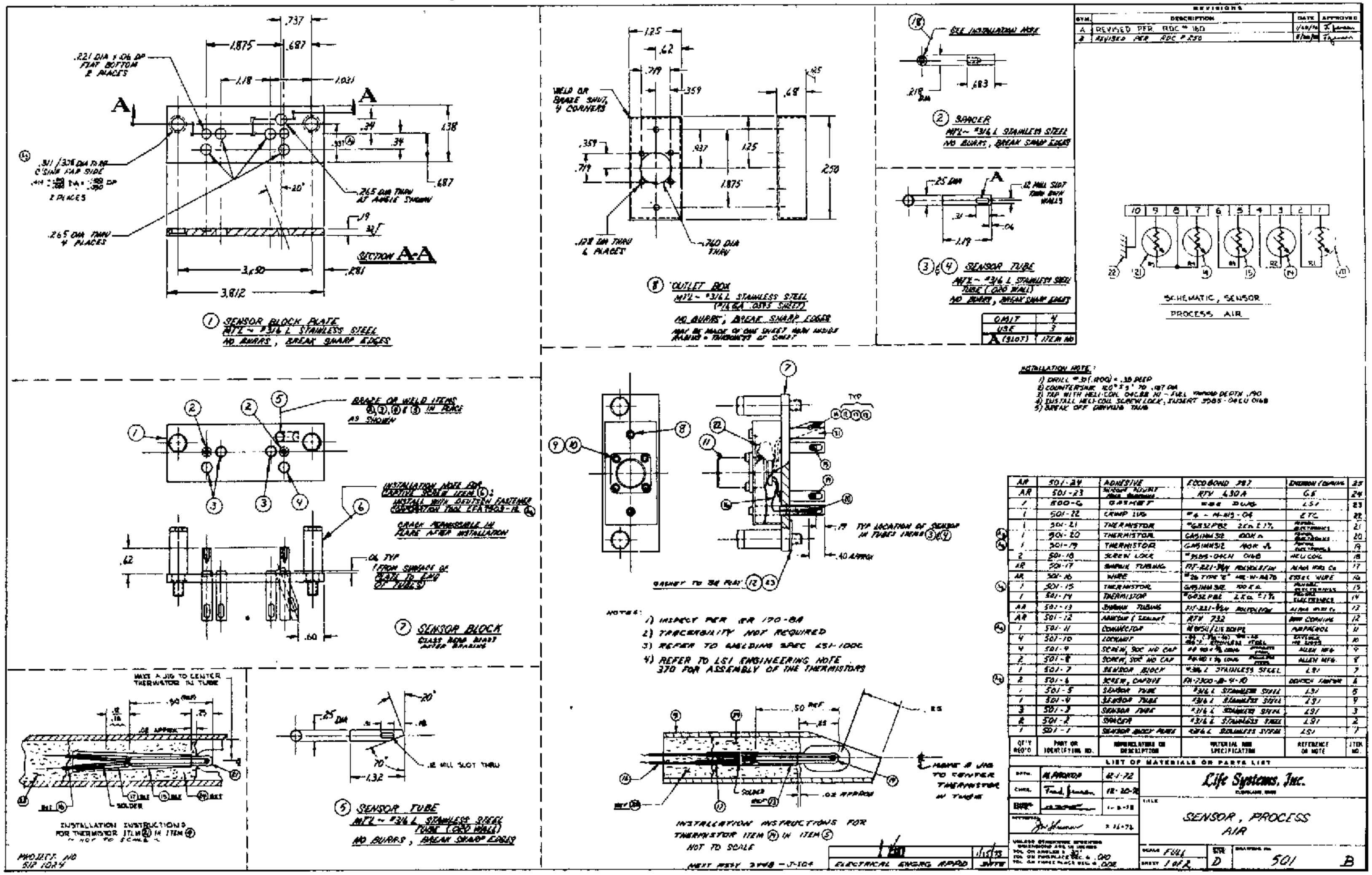
Cabin atmosphere

MAINTENANCE LEVEL AND METHOD:

Replacement of this Line Replaceable Unit is the first level of maintenance.

Time Required: 0.1 hour

FIGURE A-1 - continued



continued-

FIGURE A-2 EXAMPLE OF A LIFE SYSTEMS DRAWING

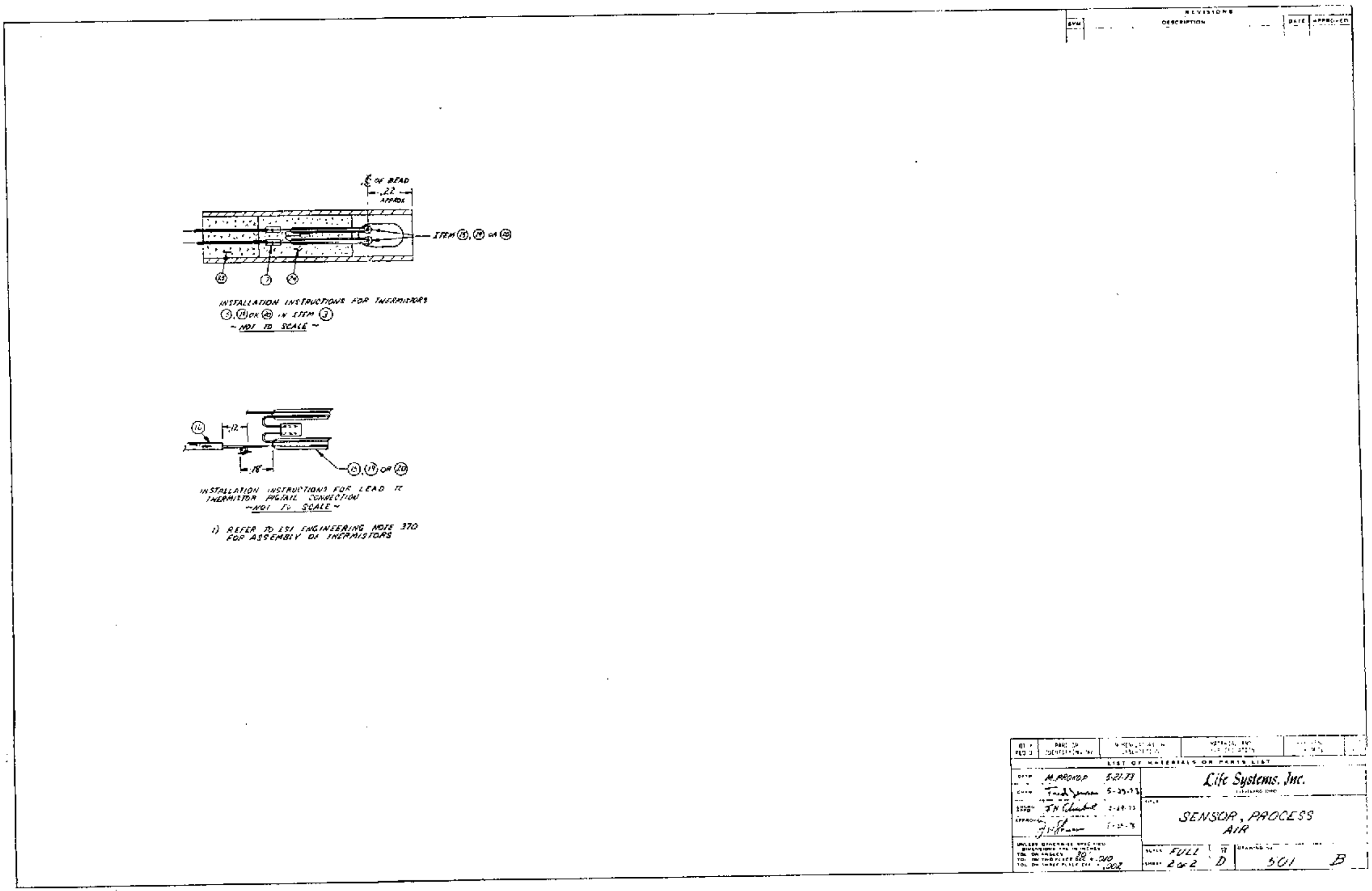


FIGURE A-2 - continued